On the Physics of Intrinsic Flow in Plasmas Without Magnetic Shear

J. Li,[1] R. Hong,[2] P. H. Diamond,[1] G. R. Tynan,[2] and S. C. Thakur[2]

[1] *University of California, San Diego*

[2] *Center for Energy Research, UC San Diego*

q-profile structure is a useful "control knob" for transport. Flat q profiles, with effectively zero magnetic shear, are one particularly interesting class of $q(r)$ structure [1, 2]. However, the actual net transport in any given device is set by a synergy of $q(r)$ shape and (at least) the $E \times B$ flow profile shear and density profile peaking. Therefore, one must also address the behavior of intrinsic flows and their shear in order to understand transport in regimes of weak or vanishing magnetic shear. It has long been known that toroidal rotation is beneficial for both MHD control and suppression of microinstabilities. Intrinsic rotation is of particular interest since rotation driven by external torque (e.g. by NBI) is insufficient for ITER. Without external momentum sources, intrinsic rotation can be driven by turbulent residual stress ($-\nabla \cdot \Pi^{\mathrm{Res}}$) and local turbulent acceleration. The usual model of the residual stress $\Pi^{\mathrm{Res}}(\nabla n, \nabla T_i) \sim \langle k_\theta k_\parallel \rangle \equiv \sum_k k_\theta k_\parallel |\phi_k|^2$ requires symmetry breaking. *Conventional models of residual stress are all intimately tied to magnetic field geometry, and fail in a flat q regime, which is a leading candidate for improved confinement (JET). Interestingly, the controlled shear de-correlation experiment (CSDX), a linear device with uniform axial magnetic field, is a promising testbed for studies of intrinsic flows in such regimes without magnetic shear.* CSDX plasmas exhibit intrinsic axial flow and flow profile peaking. A global confinement transition occurs when the axial magnetic field is increased. During the transition, density and ion pressure profiles steepen, indicating the formation of a transport barrier. Axial flow shear increases and $d\langle v_\parallel \rangle/dr$ peaks–all at zero magnetic shear. Axial flow growth tracks the formation of the barrier [3].

We report on synergistic theory and experiments which investigate intrinsic flows in magnetic shear-free regimes. Recent experiments in CSDX show that the axial flow is enhanced as ∇n increases (Fig.1). A controlled density profile is achieved by scanning B. Reynolds power density on the axial shear flow is measured ($P_{\mathrm{RA}} = -\langle \tilde{v}_r \tilde{v}_z \rangle' \langle v_z \rangle$) using multi-tip Langmuir and Mach probes. *We find $P_{RA} > 0$, confirming that indeed the core axial flow gains energy directly from the turbulence.* This confirms us that the intrinsic axial flow is driven by ∇n, via electron drift wave turbulence. This result also recalls the observation of intrinsic rotation drive by edge ∇T in C-Mod [4]. We note that $\langle v_z \rangle'$ is below the threshold that can trigger parallel shear flow instability (PSFI).

We propose a simple model to understand intrinsic axial flow generation at the confinement transition in CSDX. *This involves a new dynamical symmetry breaking mechanism using a simple model of electron drift wave turbulence in the presence of axial flow shear. This mechanism does not require a particular magnetic field structure (e.g. shear) and thus is also applicable to intrinsic rotation generation in tokamaks at weak or zero magnetic shear.* The mechanism is essentially the self-amplification of the axial flow profile, i.e. a modulational instability, driven by electron drift wave turbulence. Hence, the flow profile development is due to a form of negative viscosity phenomenon. Unlike mechanisms familiar in the context of intrinsic rotation–where the residual stress produces an intrinsic torque–in this dynamical symmetry breaking scheme, the residual stress induces a *negative* momentum diffusivity correction

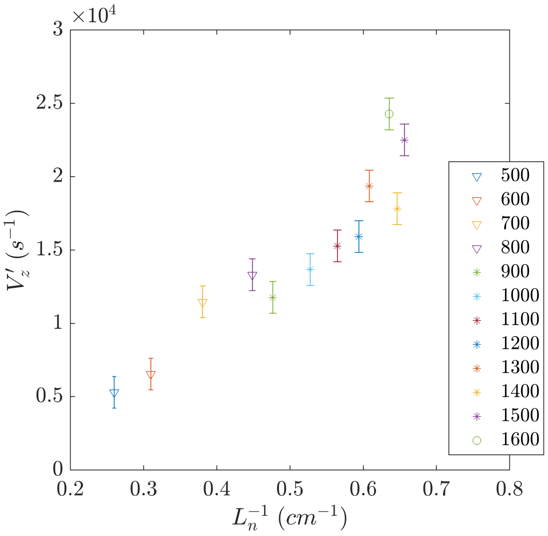

FIG. 1: Axial flow shear vs $1/L_n$ measured in CSDX.

$(\delta\Pi^{\mathrm{Res}} \sim |\chi_\phi^{\mathrm{Res}}|\delta\langle v_z\rangle')$, in response to the test flow shear. The axial flow gradient is amplified by this negative viscosity increment. In order to understand the significance of this mechanism for tokamak rotation, it's useful to make an analogy to turbulent pipe flow, where the flow shear is set by a competition between axial pressure drop and turbulent viscosity, i.e. $dV/dr \sim \Delta P/\nu_T$. For intrinsic rotation in tokamaks, a related synergy of the familiar mechanism of residual stress and the $-|\chi_\phi^{\mathrm{Res}}|$ by dynamical symmetry breaking is proposed. As a consequence, the rotation profile is enhanced by $-|\chi_\phi^{\mathrm{Res}}|$ as compared to conventional predictions, i.e. $\langle v_\parallel\rangle' \sim \Pi^{\mathrm{Res}}(\nabla n, \nabla T_i)/(\chi_\phi - |\chi_\phi^{\mathrm{Res}}|)$. Of course, should the total χ_ϕ drop strongly, the parallel shear flow instability (PSFI) [5] will be triggered, and will produce a strong nonlinear enhancement of the momentum diffusivity, thus maintaining profile regularity. Thus, the bottomline of this work is that off-diagonal turbulence effects tend to drive a residual stress and produce a negative viscosity increment.

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