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Ultra long turbulent eddies, magnetic topology, and the triggering of internal transport barriers

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In this work, we use local nonlinear gyrokinetic simulations of tokamaks to demonstrate that turbulent eddies can extend along magnetic field lines for hundreds of poloidal turns when the magnetic shear $\hat{s}$ is very weak or zero [1]. We find that as the magnetic shear is lowered, the parallel eddy length scales like $1/\hat{s}$. At zero magnetic shear, their length is limited only by critical balance —the distance that electrons can travel along the field line within the lifetime of a turbulent eddy. Turbulent transport from these "ultra long" eddies is substantially impacted by parallel self-interaction, as individual ultra long eddies will often "bite their own tail" [2]. Thus the need for accurately treating field line topology—considering whether a flux surface has an integer, rational, near-rational, or irrational safety factor—becomes crucial. This is achieved by careful selection of the simulation domain length and the phase factor in the parallel boundary condition for $\hat{s}$ = 0 simulations. Consequently, we illustrate that field line topology can lead to transitions between different turbulent modes and fully stabilise Ion Temperature Gradient (ITG) turbulence, both linearly and nonlinearly. Additionally, we observe a novel physical effect termed "poloidal eddy squeezing"—when eddies become ultra long they can cover the full flux surface and, for specific values of the safety factor, strongly interact with themselves in the perpendicular direction. This can squeeze them, reducing their perpendicular size and ability to transport energy, thereby embodying an intriguing new strategy to improve confinement in tokamaks. Lastly, we explore the Internal Transport Barriers (ITBs) formation mechanism. Empirically, very weak or zero $\hat{s}$ has been identified as being one of the key conditions for facilitating ITBs [3]. We present low magnetic shear local gyrokinetic simulations that exhibit weak ITBs caused by the magnetic topology, which may inform a long-standing experimental observation that it is often easier to trigger ITBs where the safety factor has a low-order rational value [4]. Moreover, we use a novel extension of the flux tube model that enables the simulation of non-uniform magnetic shear profiles [5] to examine ITB formation at the safety factor minimum, including safety factor curvature effects. We observe a feedback mechanism of electromagnetic fluctuations on the imposed safety factor profile, occurring together with the formation of an ITB.

References:

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