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How 'the tail wags the dog': physics of edge-core coupling by inward turbulence propagation

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Turbulence is a multi-ingredient concoction containing eddys, waves, and coherent structures, etc. In tokamaks, coherent structures are present as blobs and voids, which are plasma filaments with large-amplitude positive or negative large density fluctuations and extended lifetimes. Recent BES studies confirmed that gradient relaxation events near the last closed flux surface generate pairs of blobs and voids that propagate in opposite directions, down and up the mean gradient, respectively^[1,2]. In this work, we demonstrate that this heretofore ignored process of void emission can lead to significant inward turbulence spreading, leading to the formation of a broad turbulent layer.

As indicated by experiments, while blobs move outward and detach from the bulk plasma, voids propagate inward and thus potentially couple the edge and core plasmas. This brings us to the dynamics of edge-core coupling, which is critically important to optimal plasma performance. To this end, the origin of the excess turbulence beyond the prediction of standard Fickian gyrokinetic models remains an important "known unknown". The edge-core coupling region is also referred to as "no man's land" (NML) as it falls between the domains of the well-established core and edge models. Since early proposals by B.B. Kadomtsev^[3], there has been a persistent conjecture that this excess turbulence comes from the boundary (i.e., the tail wagging the dog). Yet, a clear physical picture is still lacking, and no one has calculated the NML width. As an entity delivered from edge to core, a void is a promising mediator of the inward turbulence spreading. However, although the interaction between zonal flows and wave turbulence has been extensively studied, their interplay with coherent structures remains largely unexplored. Here, by developing a first-principles model incorporating voids into turbulence dynamics, we resolve several questions surrounding the shortfall problem and the origin of NML.

The physical picture of our model is the Cherenkov radiation of drift waves from inward-moving voids, as illustrated in Figure 1. After being generated from GREs at ψ_0 , voids (deep blue circles) excite a "radiation field", which can be further partitioned into a near field and a far field. The interchange response in the near field converts to a drift wave turbulence in the far field (light blue shades). While voids vanish at ψ_1 , void-driven drift wave turbulence can penetrate deeper and thus energize the NML ranging from ψ_2 to ψ_1 .

By balancing the contribution of the nonlocal turbulence spreading with that of the local turbulence production, the spatial extent of no man's land is obtained and found to be of $\sim 100 \rho_s$ for typical parameters. The void-excited turbulence is self-regulated by a zonal flow originating from the Reynolds stress of the "radiation field". The shearing rate of the void-driven flow is comparable to or even exceeds the ambient shear. This novel zonal flow driving mechanism provides a plausible explanation for the observed zonal flow power bursts following the detection of voids in experiments^[4]. By considering the smearing and shearing of voids by (ambient) turbulence and zonal flow, our model also predicts the void lifetime as a function of turbulence mixing length. The estimated void lifetime ranges from a few to 100 μ s, consistent with the latest experimental findings.

This study offers valuable theoretical insight into the role that voids play in edge-core coupling dynamics. The newly identified feedback loop composed of voids, drift waves and zonal flow goes well beyond the traditional drift wave-zonal flow paradigm. We expect that the physical picture proposed here applies not only to L-mode, but also to H-mode, as edge-localized modes are also a form of gradient relaxation events.

References

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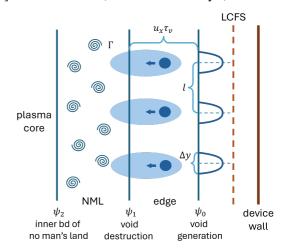


Figure 1 Illustration of the energization of no man's land by void-induced inward turbulence spreading.