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

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1. Energizing the Pedestal

The dynamics of core-edge coupling is important to optimal plasma performance. To this end, the physics of what sets the width of 'no man's land' (NML)—a strong turbulence layer at the plasma periphery, where standard Fickian gyrokinetic models fail—remains an important "known unknown" (sometimes referred to as the 'shortfall problem')[1]. Since early proposals by B.B. Kadomtsev, there has been persistent speculation that inward propagation of turbulence from the boundary is a possible means to energize the NML[2]. However, the detailed mechanism of this process has remained a mystery until recent experiments (including BES studies) observed that regular, intense gradient relaxation events generated blob-void pairs very close to the separatrix[3,4]. Blobs ($\tilde{n} > 0$) propagated outward into the SOL, while voids ($\tilde{n} < 0$) propagated inward, and so stirred the NML, as shown in Fig. 1. Here we demonstrate that this heretofore ignored process of void emission can drive a broad turbulent layer of width $w \sim 100\rho_s$, for typical parameters. The key physics effect here is Cerenkov emission of drift waves from inward-propagating voids. The theory also predicts the void lifetime as a function of δ, where the normalized turbulent diffusivity $D/D_B \sim \rho_*^{\delta}$ (D_B is Bohm). The estimated void lifetime ranges from a few to 100 μs, as shown in Fig. 2, consistent with present day experimental findings. By rewriting this result as $w \sim 100\ a\rho_*$ (assuming $a \sim L_n$) , we predict that SPARC will have a narrower NML than current machines, due to its high magnetic field and thus smaller ρ_*, whereas ITER will likely exhibit a broader NML due to its larger a. The model shows promise to resolve several questions surrounding the shortfall problem and the origin of NML.

We summarize the analysis implemented here. A propagating localized void model is used to represent the inward propagating GRE-induced density perturbation. In the near field, the void excites an interchange response, which converts to a drift wave in the far field. The latter dynamics is governed by a void-perturbation-driven Hasegawa-Mima equation, which radiates drift waves. These waves are self-regulated by self-generated shear flows, originating due to radiation-driven Reynolds stress. Of course, void-induced turbulence must be compared with possible ambient excitation. This is achieved by calculating the production ratio Ra, which measures the ratio of the Cerenkov emission contribution to local production and is given as

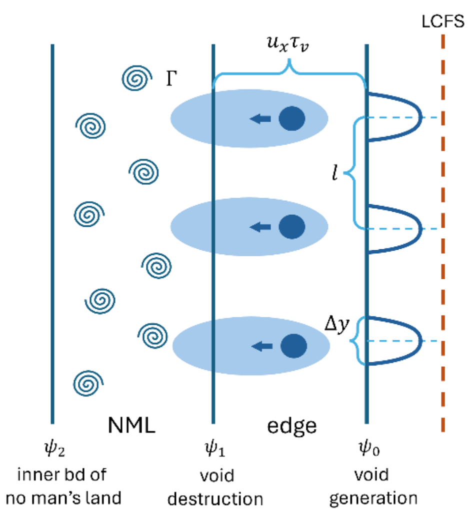

Fig. 1 How inward propagating voids energize No Man's land.

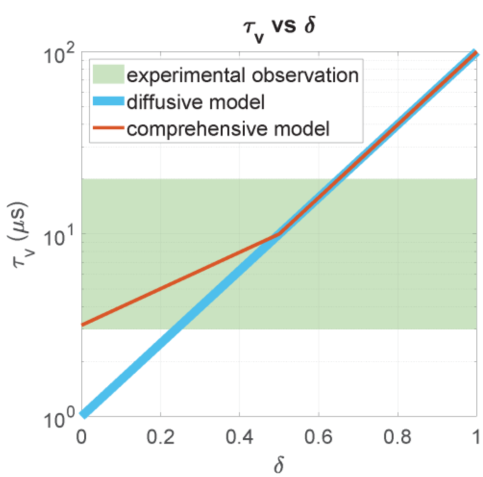

Fig. 2 Void lifetime as a function of δ.

$$Ra = 2\pi\left(\frac{h\Delta x\Delta y}{u_x\tau_v}\right)\frac{1}{v_*\tau_v^2}\frac{\Delta y}{a}\frac{\tau_v}{\tau_w}/(\kappa\langle\tilde{v}\tilde{n}\rangle w).$$

w, the spatial extent of the region where $R_a \sim 1$, defines the width of NML. Clearly, w depends on the void magnitude $h = |n_v|/n_0$, void size Δx and waiting time τ_w between void generations, which can be further related to the amplitude, spatial scale, and frequency of GREs. For $h \sim 0.1$, $\Delta x \sim 10\rho_s$, $\tau_w \sim 10^3\omega_{ci}^{-1}$, we find the NML width $w \sim 100\rho_s$, which is consistent with previous modelling work[1].

2. Energizing the SOL—an Upper Bound on Turbulence propagation

It is now widely recognized that turbulence propagation or 'spreading' from the pedestal into the SOL is desirable for heat load broadening and to promote detachment. Especially, for next generation devices, such as ITER and SPARC, a sufficiently wide SOL is necessary to achieve acceptable boundary control. More generally, a turbulent pedestal is desirable also for impurity control and ELM mitigation. Gradient relaxation events will stir the pedestal but also energize the SOL by emitting 'blobs' ($\tilde{n} > 0$) and turbulent eddies which propagate outward into the plasma boundary region. This process is the inescapable dual of void production, discussed in Part 1. While turbulence spreading into the SOL is generally beneficial, it *is* possible to have too much of a good thing! Here, we present a simple argument which establishes an upper bound on the turbulence intensity flux into the SOL. When the bound is exceeded, SOL instability results, which can result in inward propagation of turbulence into the pedestal, leading to pedestal confinement degradation and a H→L back transition.

It is appropriate to emphasize that while SOL broadening is clearly desirable for heat load management, too much broadening can be counter-productive. To see this, recall that SOL $E \times B$ shear scales as $v_E' \sim T_{e,sep}/|e|\lambda^2$ where $\lambda \sim \lambda_q$ is the SOL width. Thus, increasing λ weakens $E \times B$ shear. SOL stability to interchange modes is maintained by $E \times B$ shear, with the marginality condition set by the balance of interchange drive with $E \times B$ shearing $c_s/\sqrt{R\lambda} \approx T_{e,sep}/|e|\lambda^2$. Thus for $\lambda_q > \left(T_{e,sep}/|e|c_s\right)^{2/3}R^{1/3}$, SOL interchange turbulence can be excited. Brown and Goldston have suggested that for λ_q broadening by collisions (i.e., as for conductive heat transport at high density), SOL interchange destabilization can trigger an H→L back transition following invasion by the pedestal turbulence[5]. The associated interchange marginality condition correlates well with the H-mode density limit, which is initiated by such an H→L back transition. *However, the proposed mechanism is far more general, and suggests a fundamental limit on the broadening of λ_q by turbulence spreading.* Using $\lambda_q \sim (\Gamma_0/\sigma)^{1/5}(Rq/c_s)^{3/4}$ for λ_q [6], interchange stability requires $(\Gamma_0/\sigma)^{1/5}(Rq/c_s)^{3/4} \leq \left(T_{e,sep}/|e|c_s\right)^{2/3}R^{1/3}$. This bounds $\Gamma_0 < \Gamma_{max}$, where Γ_0 is the turbulence intensity flux and $\Gamma_{max} \cong (T_e/|e|c_s)^{10/3}R^{5/3}/(Rq/c_s)^{15/4}\sigma \sim T_{e,sep}^{85/24}/R^{15/4}q^{15/4}$.

Interestingly, Γ_{max} decreases with R and q, and increases with $T_{e,sep}$. Γ_{max} constitutes a fundamental limit on the spreading flux which can maintain a stable SOL. It is likely an upper bound on the flux, since spreading into a weakly damped or marginal region can be expected to result in strong excitation of turbulence. Clearly, these two-sided implications of strong SOL broadening constrain the regime for viable future operations. An interesting subject of ongoing work is to ascertain possible limits on the strength of tolerable GREs.

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