The Plasma $\mathbf{E} \times \mathbf{B}$ Staircase: Turbulence Self-Regulation through Spontaneous Flow Patterning

G. Dif-Pradalier[1], G. Hornung[2], Ph. Ghendrih[1], F. Clairet[1], P. H. Diamond[4,5], Y. Sarazin[1], L. Vermare[3], J. Abiteboul[6], T. Cartier-Michaud[1], C. Ehrlacher[1], D. Estève[1], X. Garbet[1], V. Grandgirard[1], Ö.D. Gürcan[3], P. Hennequin[3], Y. Kosuga[7], G. Latu[1], P. Morel[3], C. Norscini[1] and R. Sabot[1]

[1]*CEA, IRFM, F-13108 St. Paul-lez-Durance cedex, France*

[2]*Department of Applied Physics, Ghent University, 9000 Gent, Belgium*

[3]*Laboratoire de Physique des Plasmas, Ecole Polytechnique, Palaiseau, France*

[4]*CASS and CMTFO, University of California at San Diego, CA, USA*

[5]*WCI Center for Fusion Theory, NFRI, Daejeon, Korea*

[6]*Max-Planck-Institut für Plasmaphysik, Garching, Germany*

[7]*Institute for Advanced Study, Kyushu University, Fukuoka 816-8580, Japan*

The $\mathbf{E} \times \mathbf{B}$ staircase [1, 2] is a spontaneously formed, turbulence-driven self-organising pattern of quasi-regular, long-lived and localised shear flow [3] and stress layers. These layers coincide with long-lived pressure corrugations and are interspersed between regions of turbulent avalanching. The typical spacing between these layers is mesoscale, noted $\Delta \sim 25 - 30\rho_i$ [1, 4] —in-between the turbulence auto-correlation length $\ell_c \sim 5\rho_i$ at micro scales and the profile macroscale $L \gtrsim 100\rho_i$, see e.g. Fig.2 in [1]— and sets the outer scale of the turbulent avalanching. Here ρ_i is ion Larmor radius. Whilst arresting, statistically, to mesoscales the detrimental avalanching these layers, located at the "steps of the staircase" are beneficial to confinement. The $\mathbf{E}\times\mathbf{B}$ staircase is thus best understood as a self-organising and dynamical set of weak or permeable transport barriers. Strong mean zonal flows are generated and endure at the steps of the staircase, resulting in localised deviations of the poloidal flow from its oft-assumed neoclassical prediction [5].

Through the existence of the staircase, at least two typical scale lengths for the turbulence are thus predicted [1]: ℓ_c and Δ, the latter being a signature of the avalanching between the above staircase flow layers. This is shown in Fig.1 where the presence of the fat tail in the autocorrelation function directly points toward the nonlocal, avalanche-mediated transport regulated by the inter-step spacing of the staircase. Recent experimental findings tend to accredit this interpretation, showing typical micro- and mesoscale turbulence lengths [6].

The most visible manifestation of the plasma $\mathbf{E}\times\mathbf{B}$ staircase is the characteristic pattern of flows and stresses that long-lastingly define “valleys” of hindered transport where a strong and localised mean flow shear radially organises the heat and momentum fluxes. This is especially visible on the strong dipolar structure of the flux-surface averaged $\mathbf{E}\times\mathbf{B}$ shear $\gamma_{\mathbf{E}\times\mathbf{B}} = r\partial_r(E_r/rB)$ shown on the top and third panels of Fig.2. This figure is based on Gysela computations mimicking the experimental parameters of the ToreSupra shot #45511 [9] and adapted from [2].

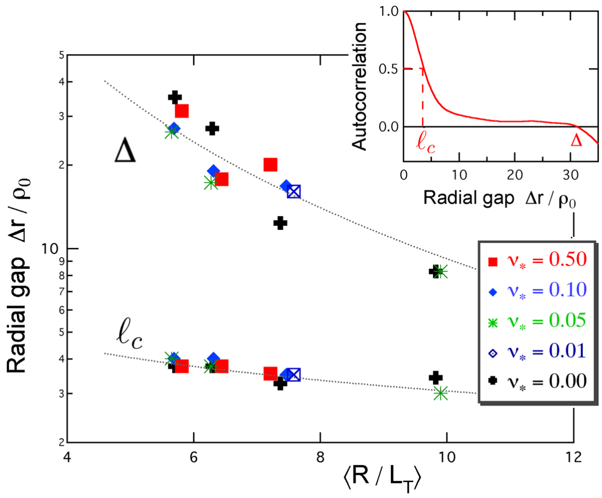

FIG. 1: Autocorrelation lengths of the electric potential from Gysela [7] as a function of both the collisionality $\nu_\star$ [8] and the normalised temperature gradient $\langle R/L_T\rangle$ at $\rho_\star = 1/128$.

At the mean shear location are found lasting corrugations of the mean plasma profiles, clearly visible on the second panel of Fig.2 through localised and large values of the mean temperature gradient. These corrugations of the mean profiles appear with the quasi-constant mesoscale spacing Δ that corresponds to the steps of the $\mathbf{E}\times\mathbf{B}$ staircase. This is visible on the third panel of Fig.2: the profile corrugations are co-located with strong and localised turbulence-driven poloidal flows that depart from the oft-invoked neoclassical prediction Ref.[5].

In addition, long-lasting strong and localised Reynolds stresses $\langle v_r v_\theta\rangle$ (third panel of Fig.2) organise the fluctuations on flux surfaces and provide the elasticity required for the flows to survive the impinging bath of heat and momentum avalanches. These flows define “valleys” of minimum turbulent transport (bottom panel of Fig.2) and thus act as weak or permeable transport barriers.

In-between these flow layers, nonlocal avalanching takes place, discussed in [1]. The essential conclusion is that the heat transport computed in flux-driven gyrokinetics — i.e. embedding both local/diffusive and nonlocal/non-diffusive transport with no assumption *a priori* on their respective existence nor on their respective weights— is irreconcilable with a local and diffusive approach: in-between the corrugations the typical turbulence correlation length is $\Delta \gg \ell_c$. For an experimental characterisation of nonlocality, see the review [10]. An interesting proposition as to how mesoscales could emerge as a heat flux "jamming" process may be found in [4, 11]; this approach really emphasises the plasma as a heat engine. Interestingly, the heat avalanching also goes hand-in-hand with a momentum avalanching [12, 13].

The staircase pattern is observed in computations in near-marginal turbulence drive conditions [2] and is thus reminiscent of situations described in self-organised criticality (SOC) [10, 14–19]. In the avalanching regions especially [20, 21] the plasma profiles are stiff. The staircase pattern results from a global and dynamic organisation of the turbulence at all scales: small-scale turbulence organises into avalanches and fluctuating zonal flows [3]; avalanches saturate at mesoscales through the organisation of the fluctuating zonal flows into mean zonal flows. Both avalanches and mean flows separate in space and the pattern repeats itself at macroscales.

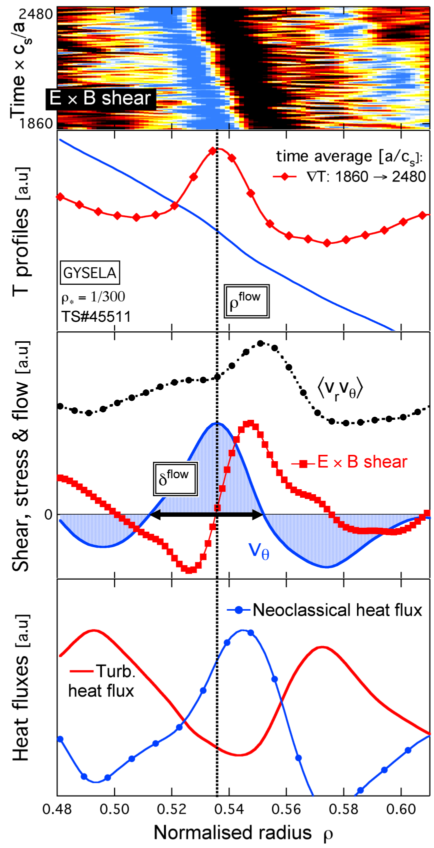

FIG. 2: Details next to a staircase step [a corrugation]. Adapted from [2].

The plasma staircase also displays a dynamics of its own: it tends to remain at constant drive R/L_T of the turbulence, it meanders within the plasma volume and when destroyed by the occasional large heat front reforms in its wake, not necessarily at its former location. The overall transport within the plasma is really that of a self-organised state in which the staircase is a key dynamical player.

Based upon the predictions from GYSELA regarding its domain of existence and dependence with key plasma parameters we went on hunting for its existence in actual experiments. The spatially resolved measurement of poloidal flows or of mean plasma profile gradients across an extended radial domain of the plasma is notoriously difficult in tokamaks. From a transport perspective corrugations act indeed so as to partially decouple at regular radial intervals the upstream from the downstream plasma. The experimental characterisation of the staircase could thus be possible provided quality measurements of turbulent fluctuations with a sufficient radial and temporal precision could be made. Fast acquisitions ($\sim$ ms), due to the potential dynamics of the structure) of radially-resolved full-radius profiles of turbulent fluctuations on the other hand are now possible on Tore Supra using fast-sweeping reflectometry [22]. A routine construction of radial profiles of turbulence correlation lengths [23] can thus be inferred from the experiment. The staircase pattern is thus identified through radially localised, abrupt and quasi-regularly spaced minima of these correlation profiles. Details may be found in [2]; 170 occurrences of this structure have so far been observed in the ToreSupra database.

The staircase is a turbulence-borne structure and shows no clear connection with low-order safety factor q rationals. This proves important to disentangling experimentally the plasma staircase from magnetohydrodynamic (MHD) activity. Ongoing work is concerned with a thorough experimental characterisation of the experimental parameter space in which the $\mathbf{E} \times \mathbf{B}$ staircase is observed [24].

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