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Turbulence in hot magnetized plasmas is shown to generate permeable localized transport barriers that globally organize into the so-called "**E**x**B** staircase" [G. Dif-Pradalier *et al.*, Phys. Rev. E, 82, 025401(R) (2010)]. Its domain of existence and dependence with key plasma parameters is discussed theoretically. Based on these predictions, staircases are observed experimentally in the Tore Supra tokamak by means of high-resolution fast-sweeping *X*-mode reflectometry. This observation strongly emphasizes the critical role of mesoscale self-organization in plasma turbulence and may have far-reaching consequences for turbulent transport models and their validation.

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A puzzling result in recent years in plasma turbulence has arguably been the discovery of the quasiregular pattern of $\mathbf{E}\times\mathbf{B}$ flows and interacting avalanches that we have come to call the "$\mathbf{E}\times\mathbf{B}$ staircase," or the "plasma staircase" in short [1]. This structure may be defined as a spontaneously formed, self-organizing pattern of quasiregular, long-lived, localized shear flow and stress layers coinciding with similarly long-lived pressure corrugations and interspersed between regions of turbulent avalanching. The plasma staircase exemplifies how a systematic organization of turbulent fluctuations may lead to the onset of strongly correlated flows on magnetic flux surfaces.

Flow patterning is a prominent topic in many fluid-related systems and hot magnetized plasmas are no exception to that. In fact the "staircase" name is borrowed from the vast literature in planetary flows motivated by the desire to explain the banded structure of observed atmospheres in our Solar System—including Earth [2] or Jupiter [3]—and of terrestrial oceans [4]. Just as in the geophysical or astrophysical systems where the planetary staircase strongly influences the general circulation, the plasma staircase plays an important role in organizing the heat transport [1]: avalanches and the staircase interplay, statistically interrupting at mesoscales the long-range radial avalanching that could otherwise expand over the whole system. The nonlocal heat transport thus remains contained at the mesoscale staircase step spacing, resulting in a beneficial scaling of confinement with machine size.

This flow patterning is primarily a spontaneous mean zonal shear patterning. "Zonal" denotes the axisymmetric $n=m=0$ component of the $\mathbf{E}\times\mathbf{B}$ flows [5], n and m respectively being the toroidal and poloidal mode numbers while "mean" refers to the ensemble-averaged part of the zonal flows. Remarkably, the plasma spontaneously generates robust shear patterns that endure despite the strong background turbulence and retain their coherence over long (several milliseconds) to very long (hundreds of milliseconds) periods of time. The results presented throughout this Letter are based on state-of-the-art flux-driven gyrokinetic [6] computations using the GYSELA code [7] with realistic tokamak plasma parameters. Systematic features of the plasma staircase can be inferred from extensive computational scans, see Table I. Based on these predictions, we report on the experimental observation [8] of the staircase in Tore Supra. This is a rare instance in plasma turbulence of a prediction from a numerical model leading to a discovery in observations.

A typical numerical experiment.—We mimic in GYSELA the plasma parameters of the Tore Supra shot No. 45 511 [9]: in the experiment 3 MW are injected in a deuterium plasma of relative gyroradius $\rho_\star^{-1}=a/\rho_0=357$ at mid-radius and aspect ratio $a/R_0=1/3.3$, $R_0=2.3945$ m being the major radius, ρ_0 the ion Larmor radius and a the minor radius. The plasma current is $I_p=0.8$ MA, the magnetic field on axis is $B_0=2.8$ T and the mid-radius density and temperature, respectively, read: $n_m=4\times 10^{19}$ m^{-3} and $T_m=0.8$ keV. In flux-driven GYSELA, a 3 MW volumetric heat source comparable in shape to that in the experiment is injected in the central half of a torus of same aspect ratio and major radius. The flux surfaces are

TABLE I. Where staircases are observed in GYSELA.

Visible on	$\gamma_{\mathbf{E}\times\mathbf{B}}, \nabla p, L_c, v_\theta, v_\parallel, \langle \tilde{v}_{Er}\tilde{v}_{E\theta}\rangle, \langle \tilde{v}_{Er}\tilde{v}_\parallel\rangle$
$\rho_\star = \rho_i/a$	$1/75 \to 1/512$
Step spacing	Outer scale of avalanche distribution constant [$\sim 20 - 30\rho_0$] for $\rho_\star \leq 1/300$ [1]
No. of steps	$1 \to 2[\rho_\star = 1/75]; 3 \to 5[\rho_\star = 1/300]; 5 \to 7[\rho_\star = 1/512]$
Flow thickness	$\delta^{\text{flow}} \sim 10\rho_0$
Collisionality $\nu_\star$	$0.001 \to 1$
$\langle\langle R/L_T\rangle\rangle$	$4 \to 8$
$\langle\langle R/L_n\rangle\rangle$	$1 \to 4$
$\eta = L_n/L_T$	$2 \to 8$
Meandering	Stay at $\sim$ constant drive, follow $\nabla p(t)$
Strength	$\lvert\gamma_{\mathbf{E}\times\mathbf{B}}\rvert \sim$ constant for $\rho_\star \geq 1/300$
Resonant q	No correlation with low-order rationals

concentric and circular, the collisionality $\nu_\star$ profile is that of the experiment, with a central value $\nu_\star = 0.28$. The electron response is adiabatic and to slightly reduce the computational cost, the magnetic field on axis is reduced: $B_0 = 1.7$ T. This amounts to having a slightly off $\rho_\star^{-1} = 251$ value in GYSELA. Numerical convergence has been thoroughly checked.

The observation of the staircase pattern is pervasive in our flux-driven L-mode computations and especially clear when the turbulence is "near critical," i.e., when the turbulence drive is close and above the linear instability threshold. Preliminary experimental findings in Tore Supra L-mode plasmas also tend to show that this structure seems reasonably robust and not restricted to special experimental conditions. It may in fact well be that staircase patterns are largely inevitable in drift-Rossby turbulence.

The staircase manifests through the spontaneous occurrence of quasiregularly spaced profile corrugations and the emergence of a quasiregular flow and stress pattern—see Fig. 1. As seen through the radial–temporal evolution of the flux-surface averaged $\mathbf{E}\times\mathbf{B}$ shear $\gamma_{\mathbf{E}\times\mathbf{B}} = r\partial_r(E_r/rB)$, localized dipolar layers of maximum shear emerge that define "valleys" of radially concentrated mean flows and hindered turbulent transport (bottom) interspersed between regions of turbulent avalanching. All turbulence-influenced fields in Table I, amongst which the flux surface averaged poloidal $\langle v_{Er}v_{E\theta}\rangle$ and toroidal $\langle v_{Er}v_\parallel\rangle$ Reynolds stresses, the turbulent heat flux Q, turbulent parallel momentum flux $M_\parallel$ and poloidal flow v_θ display, as in Fig. 1, evidence of simultaneous mean flow formation and avalanching. Both structures are a priori mutually exclusive; the staircase elegantly resolves this problem by localizing mean zonal flow shear into thin layers (the staircase steps) whilst avalanches propagate in-between.

The radial profiles in Fig. 1 show a close-up of the radial-temporal data in the vicinity of the central staircase between

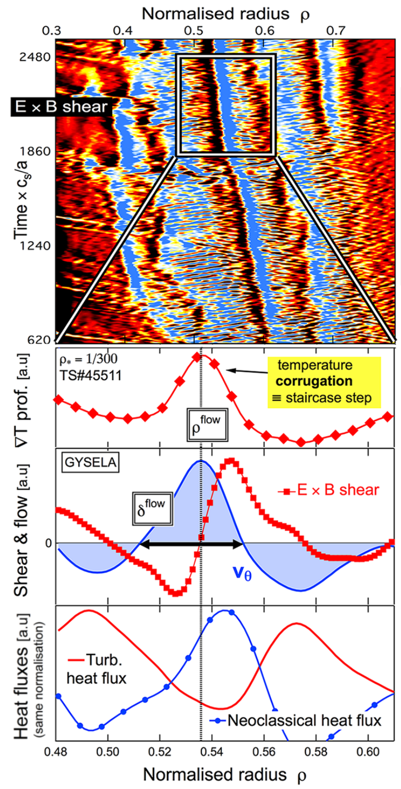

FIG. 1 (color online). Detail of the shear flow–mean profile–transport interplay next to a staircase step [a corrugation].

$\rho = 0.48$ and $\rho = 0.61$, averaged over 1.1 ms between $t = 1860a/c_s$ and $t = 2480a/c_s$. The staircase name comes from the fact that an initially smooth profile (here, ion temperature) organizes into a quasiregular piecewise linear steplike radial profile. As the staircase develops, strong mean gradients [hereafter named "corrugations"] appear that coincide with a strong localized dipolar mean shear, as expected from force balance. These gradients typically extend over the cm range $\delta^{\text{flow}} \sim 10\rho_0$ and define the steps of the staircase. Apart from within these steps, ambient mean gradients noted $\langle\langle \cdots \rangle\rangle$ in Table I remain at or moderately above the linear instability threshold: $\langle\langle R/L_T\rangle\rangle \in [4,9]$; i.e., in between the staircase steps the turbulence is near critical. The regions of sharp mean gradients also coincide with locations ρ^{flow} where enduring poloidal flows have nucleated. These are turbulence-driven and locally responsible for a departure from oft-invoked neoclassical predictions [10].

Generic features.—Extensive plasma parameter scans beyond those exemplified above have been run in GYSELA and are summarized in Table I. They condense most of our current knowledge of the plasma staircase and have helped finding it experimentally, as reported below. Several prominent parameter-independent features appear: the staircase existence is irrespective of the plasma size and robustly encountered from the smallest $\rho_\star = 1/75$ to today's largest tokamaks $\rho_\star = 1/512$. The step spacing is independent of the plasma size for medium-large tokamaks $\rho_\star \leq 1/300$ as shown in Ref. [1] so that practically 4 to 7 shear layers may be expected radially in, e.g., Tore Supra or ASDEX Upgrade and 6 to 10 in ITER. This pattern is further independent of core plasma collisionality $\nu_\star$ [11], of plasma shape and modeling choices [12], and is encountered for weak to moderate turbulence drives $\eta = L_n/L_T$. The strong profile stiffness and low ratio of external power over internal stored energy in future devices makes these near-critical parameters all the more relevant to next-generation plasmas. The staircase pattern is dynamical and intimately linked to that of avalanches, ubiquitous in our modeling, its step size dynamically defining the outer scale of the avalanche distribution. The turbulent transport is best described by a second moment divergent Lorentz nonlocal kernel and irreconcilable with a local or diffusive picture [1]. While most heat and momentum avalanches are stopped by the staircase shear layers—thus acting as weak or permeable transport barriers—large occasional ones may either perturb the flow pattern so that it radially meanders or may transiently destroy it. In this case, the shear layer usually reforms in the wake of the impinging avalanche, not necessarily at the exact same location. The staircase also meanders, not unlike its atmospheric counterpart, with a propensity to remain at a constant source of free energy, i.e., to track a constant value of the pressure gradient ∇p.

A difficult experimental observation.—Its direct experimental observation has so far remained elusive partly due to the following. (i) To this meandering behavior: on a 1 to 5 ms time span, Fig. 1 shows that corrugations may have significantly moved radially over a few δ^{flow}. Integration times beyond a few ms can artificially lead to smearing out the corrugations as they radially meander. (ii) Beyond meandering, the radial extent of the flow structures [the steps] with respect to the machine size $\delta^{\mathrm{flow}}/a \sim 10\rho_\star$ is small, making the experimental characterization of the gradient difficult. An unambiguous characterization of the plasma staircase thus simultaneously requires both fast (~ms) and high-resolution radial measurements ($\lesssim$cm) over a significant fraction of the radius. (iii) In addition, the signature of this structure further needs to be disentangled from the background magnetohydrodynamic (MHD) activity, absent in GYSELA, as the growth of magnetic islands at quasiregularly spaced low-order safety factor q rationals may also lead to staircase-shaped mean profiles.

Such fast, high-resolution measurements of the temperature profiles are now available for the pedestal [13] where the staircase is not expected to be observed due to the enhanced collisional dissipation and to a large turbulence drive. Alternatively, radially localized deviations of poloidal velocity from neoclassical predictions [10,14] or radially correlated probe measurements [15] may also allow for the experimental observation of the staircase, though spatially resolved measurements of poloidal flows are notoriously difficult in tokamaks.

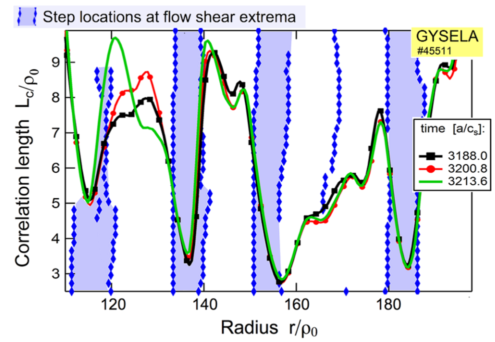

FIG. 2 (color online). Local minima of the radial correlation length of the turbulent fluctuations at three different times efficiently track the staircase steps in GYSELA.

Correlation fluctuations.—A way out of this conundrum resides in the fact that the staircase acts as a regularly spaced weak or semipermeable pattern of transport barriers [1,16]. High-resolution fast-sweeping X-mode reflectometry [17] provides turbulent fluctuation measurements (i) fast enough (3 μs) so as to effectively freeze the staircase dynamics, giving access to instantaneous radial profiles of turbulent fluctuations from which (ii) time-radius turbulence correlations are inferred [18] in the core and near the edge. The staircase is thus expected to imprint on the correlation data its quasiregular structure.

To this end, we construct in GYSELA a synthetic diagnostic of the high-resolution fast-sweeping reflectometer. The 3D correlation length L_c is the full width at half maximum of the autocorrelation C_ϕ:

$$C_\phi(r,\theta,t,\delta r) = \frac{\langle \tilde{\phi}(r,\theta,t)\tilde{\phi}(r+\delta r,\theta,t)\rangle_\tau}{[\langle \tilde{\phi}(r,\theta,t)^2\rangle_\tau \langle \tilde{\phi}(r+\delta r,\theta,t)^2\rangle_\tau]^{1/2}} \quad (1)$$

of the electric potential fluctuations $\tilde{\phi}(r,\theta,t)$ in GYSELA. It is computed as a function of time, radius, and poloidal angle, at an arbitrary value of the toroidal angle, in the present case $\varphi = 0$ [16]. The averaging operator $\langle \cdots \rangle_\tau$ is applied for sliding time windows $[t-\tau/2, t+\tau/2]$, with

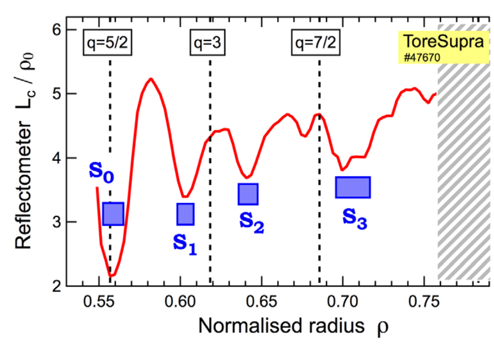

FIG. 3 (color online). The reflectometer coherence length plotted against radius shows clear experimental evidence of a staircase at locations S_1, S_2 and S_3, possibly also at S_0.

$\tau = 20\ \mu$s, so as to remove fast varying features of the electrostatic potential. The correlation length from Eq. (1) is a proxy for the coherence length of the turbulent density fluctuations accessible in experiments. In order to be as close as possible to the actual measurement, we average the correlation length L_c in GYSELA over a poloidal extension $\Delta\theta \approx 8°$ around the midplane so that it mimics the 10 cm reflectometer beam width in Tore Supra. The result is displayed in Fig. 2 at three different computing times. Remarkably, local minima of the radial correlation length L_c exactly track local extrema of the mean flow shear, thus providing a visualization of the staircase steps. Following up on this prediction, a systematic analysis of fluctuation correlation measurements has been undertaken and a large database is being built currently containing over 170 occurrences [19] of staircaselike structures, an example is shown in Fig. 3.

The MHD conundrum.—Before showing experimental evidence of the staircase it is worth noticing that a turbulence-driven staircase of mean $\mathbf{E}\times\mathbf{B}$ flows may not be, in an actual device, the only mechanism that could lead to abrupt variations of the fluctuation correlation lengths. Magnetic shear or island growth—and more generally MHD activity may also be invoked. The fact that MHD activity strongly concentrates in the immediate vicinity of low-order rational values of the safety factor q helps in experimentally disentangling it from the plasma staircase. This point is illustrated in Fig. 4 where the dynamical evolution of the staircase is plotted against the (fixed) locations of the low-order $q = 1, 3/2, 2$, and $5/2$ rationals in GYSELA. A narrow time window is displayed for clarity but the conclusions hold at any given time: neither at their birth location nor during their dynamics may a clear correlation be inferred between the flow location and the low-order q rationals. Corrugations just as spontaneously arrive next to one, and depart from it. Nonlinearly, the self-organized turbulent dynamics appears largely unaffected by the vicinity of low-order q rationals, in contrast to earlier results on magnetic shear [20]: the staircase is genuinely a turbulent-borne structure.

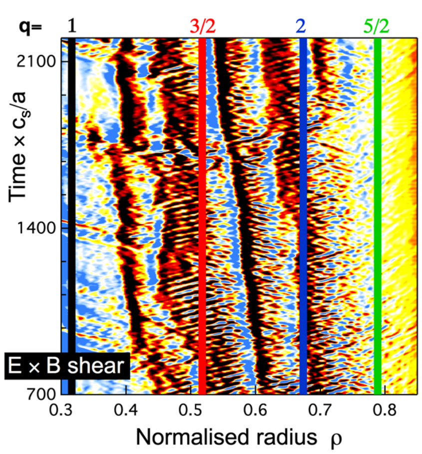

FIG. 4 (color online). The low-order $q = 1, 3/2, 2$, and $5/2$ rationals' surfaces are superimposed on top of the $\mathbf{E}\times\mathbf{B}$ shear. No clear correlation with the corrugations can be inferred.

Experimental characterization.—Eighty-three discharges with varying heating mechanisms and plasma parameters, showing over 170 local minima of turbulence coherence lengths uncorrelated to low-order q rationals are so far observed. Figure 3 shows an example from the Ohmic discharge No. 47670 at $t = 11.9$ s [unfortunately, no fast-sweep acquisition is available for shot No. 45511] computed over 2000 profiles [6 ms]. Less temporal averaging results in coarser, deeper L_c minima, yet similar in shape. We restrict ourselves to the region $\rho \le 0.75$ as farther out the reflectometer response becomes nonlinear, questioning the validity of the measured coherence lengths [21]. Four marked minima are observed. The one labelled S_0 is well correlated to the $q = 5/2$ surface while S_1, S_2, and S_3 are uncorrelated to low-order q rationals. Predicted (Fig. 2) and observed (Fig. 3) values of L_c [and of their minima] are interestingly in the same ballpark; these conclusions hold in the other discharges. Three conclusions can be drawn: (i) the S_1–S_3 minima are turbulence driven, (ii) three steps (at least) of an existing staircase are evidenced at locations S_1, S_2 and S_3. Shot No. 47670 is specially interesting as L_c displays a marked drop at S_0 where $q = 5/2$ yet with no evidence of MHD activity, which (iii) poses the question of a possible synergetic reinforcement of the staircase near low-order q rationals—possibly due to kinetic electrons (increased zonal flow inertia) or magnetic fluctuations, two currently missing ingredients in GYSELA. These facts may shed new light on earlier observations of transport barrier formation close to low-order rationals [22].

Further discussion.—In GYSELA the signature of the staircase on the radial correlation lengths of the turbulence, quite clear on the outboard midplane, becomes less marked poloidally elsewhere. While the GYSELA computations predict a quasi-$\theta \to -\theta$ symmetry, an essential poloidal inhomogeneity comes from the ballooning nature of the turbulence. The correlation between the staircase pattern and the local minima of L_c holds well for $\theta \in [-40°, 40°]$, progressively weakens as $\theta \to \pm 90°$, and disappears in the high field side (HFS) region where the turbulence is weak. These facts strongly emphasize the staircase as nonlinearly turbulence driven. Its beneficial role for confinement should also be noted: typical radial correlation lengths as in Fig. 2 in the low field side region where the staircase is present are 2 to 3 times *smaller* than those measured in the HFS ($\sim$25–30ρ_0) [7].

First predicted and then observed, the plasma staircase sheds new light on the permanent cross talk between all scales in plasma turbulence and establishes the critical need to treat on an equal footing the *continuum of scales* from equilibrium to fluctuations *and* intermediate mesoscales. Besides, the aforementioned mesoscale nonlocal or non-diffusive character of turbulent transport [1] results from the combined action of avalanchelike events interacting with the long lived staircase of flows, the staircase pattern solving the coexistence problem of avalanches and zonal flows. Reduced models of plasma turbulence should thus endeavour to include part of these nonlocal aspects and mesoscale dynamics in their current approaches. Additionally, the dynamical response of this pattern to external perturbations may interestingly renew the still enigmatic "nonlocality experiments" [23].

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[1] G. Dif-Pradalier, P. H. Diamond, V. Grandgirard, Y. Sarazin, J. Abiteboul, X. Garbet, Ph. Ghendrih, A. Strugarek, S. Ku, and C. S. Chang, Phys. Rev. E, **82**, 025401(R) (2010).
[2] D. G. Dritschel, and M. E. McIntyre, J. Atmos. Sci. **65**, 855 (2008).
[3] P. S. Marcus, Annu. Rev. Astron. Astrophys., **31**, 523 (1993).
[4] W. J. Merryfield, J. Phys. Oceanogr. **30**, 1046 (2000).
[5] P. H. Diamond, S.-I. Itoh, K. Itoh, and T. S. Hahm, Plasma Phys. Controlled Fusion **47**, R35 (2005).
[6] A. J. Brizard and T. S. Hahm, Rev. Mod. Phys. **79**, 421 (2007).
[7] Y. Sarazin *et al.*, Nucl. Fusion **51**, 103023 (2011).
[8] Further details on the experimental characterization of the staircase domain of existence will be found in Ref. [19].
[9] L. Vermare, P. Hennequin, Ö. D. Gürcan, C. Bourdelle, F. Clairet, X. Garbet, R. Sabot, and the Tore Supra Team, Phys. Plasmas **18**, 012306 (2011).
[10] G. Dif-Pradalier, V. Grandgirard, Y. Sarazin, X. Garbet, and Ph. Ghendrih, Phys. Rev. Lett. **103**, 065002 (2009).
[11] G. Dif-Pradalier *et al.*, Phys. Plasmas **18**, 062309 (2011).
[12] M. Nakata, and Y. Idomura, Nucl. Fusion **53**, 113039 (2013); L. Villard, P. Angelino, A. Bottino, S. Brunner, S. Jolliet, B. F. McMillan, T. M. Tran, and T. Vernay, Plasma Phys. Controlled Fusion **55**, 074017 (2013); C. Norscini *et al.*, J. Phys. Conf. Ser. **561**, 012013 (2014); T. Cartier-Michaud *et al.*, J. Phys. Conf. Ser. **561**, 012003 (2014).
[13] D. Eldon *et al.*, Rev. Sci. Instrum. **83**, 10E343 (2012).
[14] C. Chrystal, K. H. Burrell, B. A. Grierson, L. L. Lao, and D. C. Pace, Rev. Sci. Instrum. **85**, 11E302 (2014).
[15] T. Estrada, C. Hidalgo, T. Happel, and P. H. Diamond, Phys. Rev. Lett. **107**, 245004 (2011).
[16] Ph. Ghendrih *et al.*, Eur. Phys. J. D **68**, 303 (2014).
[17] F. Clairet, B. Ricaud, F. Briolle, S. Heuraux, and C. Bottereau, Rev. Sci. Instrum. **82**, 083502 (2011).
[18] G. Hornung, F. Clairet, G. L. Falchetto, R. Sabot, H. Arnichand, and L. Vermare, Plasma Phys. Controlled Fusion **55**, 125013 (2013).
[19] G. Hornung *et al.* (to be published).
[20] J. E. Kinsey, R. E. Waltz, and J. Candy, Phys. Plasmas **13**, 022305 (2006).
[21] E. Z. Gusakov, and A. V. Surkov, Plasma Phys. Controlled Fusion **46**, 1143 (2004).
[22] N. J. Lopes Cardozo *et al.*, Plasma Phys. Controlled Fusion **39**, B303 (1997).
[23] K. Ida *et al.*, Nucl. Fusion **55**, 013022 (2015).