Indirect evidence of avalanche-like transport in TCV plasmas backed by 1D nonlinear simulations

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Introduction: Understanding turbulent transport scaling is crucial in order to reach viable fusion power plants. In particular it is essential to know if larger machines will lead to a reduced transport. The transport is expected to scale with the machine size as $D_{GB} = \rho_\star^\alpha \rho_s c_s$, with $\rho_\star = \rho_s/a$ the larmor radius $\rho_s = c_s/\omega_{cs}$ normalized by the minor radius of the tokamak a, c_s being the sound speed and ω_{cs} the gyrofrequency. The coefficient $\alpha = 1$ corresponds to the GyroBohm scaling. However, many physical effects can degrade the confinement and lead to $\alpha < 1$, pessimistic for future experimental devices. Among them, the generation of avalanches - ballistic transport events of heat and particles - could degrade the confinement. Avalanches have been shown crucial in simulations [2, 4] but remain elusive in experiments [6]. Also, the range of plasma parameters favouring avalanche-type transport remains unknown. More recently in simulations, ExB staircases have been put forward as possibly interacting with both the turbulence and avalanches [1]. Those radially localized shear layers of poloidal flows could limit the radial extension of avalanches hence improving confinement [5].

The objective of the present work is to study the generation of avalanches with a reduced model that contains two competing instabilities: interchange, linked to the curvature of the magnetic field, akin to resistive ballooning modes or ion temperature gradient in tokamaks. And drift waves, that stem from a finite parallel phase shift between density and electric potential fluctuations. Using this model, the goal is to identify regimes of avalanches and their experimental signatures that can be observed using a correlation Doppler backscattering (CDBS).

We show that avalanches are present in simulations at large magnetic curvature and that they lead to the presence of two correlation lengths in the spatial correlation function of density fluctuations: the smaller corresponds to the eddy size and the larger to the avalanche extension. Using a similar analysis with the dual channel DBS system recently installed on TCV, two slopes are found on the spatial correlation function that are identified, by analogy, as eddy size and avalanche length [3]. Finally, it is shown in simulations that zonal flows staircases are present at large magnetic curvature and that they are 'reactivated' by passing avalanches.

Tokam1d: a reduced interchange-drift waves model [7]: One considers a plasma of constant ion and electron temperatures, $\tau = T_i/T_e$, located close but inside the last closed flux surface. The plasma is assumed to be in L-mode and the magnetic field to decrease with the major radius of the tokamak: $\mathbf{B}(R) = (B_0R_0/R)\mathbf{e}_{\parallel}$. The model derives from the electron continuity (Eq.1) and charge continuity (Eq.2) equations in a slab geometry. A generalized Ohm's law closes the system by linking the parallel current to the electric field and the electron density gradient.

$$\partial_t N + \{\phi, N\} = g\partial_y(\phi - N) + \sigma\nabla_{\parallel}^2(N-\phi) + D\nabla_{\perp}^2 N + S_N \tag{1}$$

$$\partial_t \Omega + \nabla_{\perp,i}\left\{\phi, \nabla_{\perp,i}(\phi+\tau N)\right\} = +(1+\tau)g\partial_y N + \sigma\nabla_{\parallel}^2(N-\phi) + \nu\nabla_{\perp}^2\Omega \tag{2}$$

The system of equations involves the logarithm of the density $N = \ln n$ and the generalized vorticity $\Omega = \nabla_{\perp}(\phi + \tau N)$, the nonlinearities are contained in Poisson brackets $\{f,h\} = \partial_x f \partial_y h - \partial_y f \partial_x h$. The magnetic curvature parameter is defined as $g = \frac{2\rho_s}{R}$, with R the major radius of the tokamak. The parallel conductivity is taken constant and defined as $\sigma = \frac{\omega_{ce}}{\nu_{ei}}$, with ν_{ei} the electron-ion collision frequency. The system is flux-driven with a source of particles S_N and the damping of small scales is ensured by diffusive terms D and ν. The model is further reduced from 3-dimensions to 1 by splitting each field between an equilibrium and a fluctuating component. Single parallel and poloidal wave vectors $(k_{\parallel}, k_y)$ are retained for fluctuating quantities, so that $(\nabla_{\parallel}, \partial_y) \longrightarrow i(k_{\parallel}, k_y)$. The final system of equations then evolves 4 fields that depends on (x,t) only. Two real fields for the equilibrium components, N_{eq}, $V_{eq} = \partial_x \phi_{eq}$, and two complex fields for the fluctuating parts, N_k, Ω_k. The adiabaticity parameter is defined as $C = \sigma k_{\parallel}^2$.

Transition to avalanches in interchange dominated plasmas: A scan of g is performed at fixed $C = 10^{-3}$. It is observed that both the skewness and the kurtosis - 3rd and 4th moments of the probability distrubution function (pdf) - of the turbulent flux of particles increase with g. That means, the pdf is more asymmetric and weighted by the tails. The transport then corresponds to ballistic events that can be directly observed on the turbulent flux of particles signal.

In view of the experimental study, we look for signatures of avalanches on the density fluctuations spatial correlation function. We perform the correlation between time signals at various positions x_0 and at positions $x_0 \pm \Delta x$ until the mean correlation function is obtained. The result is shown figure 1.

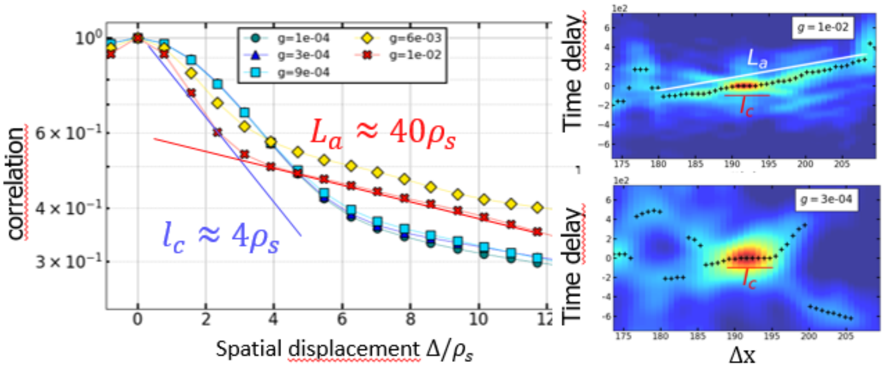

Figure 1: (left) Logarithm of the maximum of correlation at each position for 5 values of g. (right) Correlation as a function of radial displacement and delay for two examples. Dark crosses indicate the delay of maximum correlation.

Cases at low g (blue), do not exhibit large avalanches and the transport is mainly due to large eddies, see figure 1 (bottom right). At larger g, a second slope appears on the correlation function, it corresponds to the typical avalanche length for this simulation. Note that the "length" is computed as the inverse of the correlation function logarithmic slope. On figure 1 (upper right), the second slope appears with a delay, indicating a traveling event.

Indication of avalanche-like transport in TCV using CDBS: Fluctuations are studied in TCV using a dual channel V-band Doppler backscattering diagnostic. An X-mode probing wave is scattered-off density fluctuations at the cut-off layer ($k_\perp \in [4-10]cm^{-1}$). By varying the localisation of one channel respectively to the other and computing their correlation, one can obtain the small and large scale spatial correlation function. The correlation is performed on the amplitude of the CDBS signal to remove phase effect induced by velocity shear. An example of the evolution of the maximum of the correlation as a function of the separation between the channels is shown figure 2 for discharge #81069 at $\rho_{ref} \approx 0.97$.

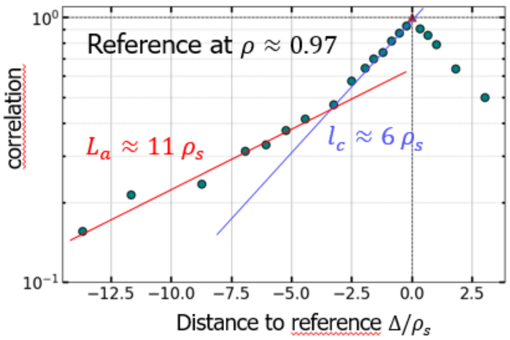

Figure 2: Max of correlation vs channels separation (logscale) for TCV#81069 at $\rho_{ref} \approx 0.97$.

Similarly to simulations, correlation is found both at small and large scale. It is indicated by two slopes on the correlation function. Using simulations as a guide, we expect the small scale (symmetric around $\Delta = 0$) to correspond to the eddy size, and the second slope to indicate the avalanche length. While the eddy size is similar to simulations, the avalanche length is much smaller. It is possible that the dominant turbulent instability, trapped electron mode for #81069, and the distance to marginality plays a role in setting the avalanche length.

Staircases 'reactivated' by avalanches: Staircases are observed in simulations at large g. In the simulations performed, avalanches were always present whenever a staircase was seen. Taking the case $g = 10^{-2}$, at position $x = 305$, the staircase interaction with passing avalanches can be observed. During the quiescent phase of the simulation, the exponential decay of the flow is governed by the friction coefficient μ. When an avalanche travels through the existing staircase, it is found to reactivate the staircase structure. This energy transfer from avalanches to staircases, although suspected, was never reported in simulations to our knowledge. Its precise mechanism and regime of occurrence will be further investigated in the future.

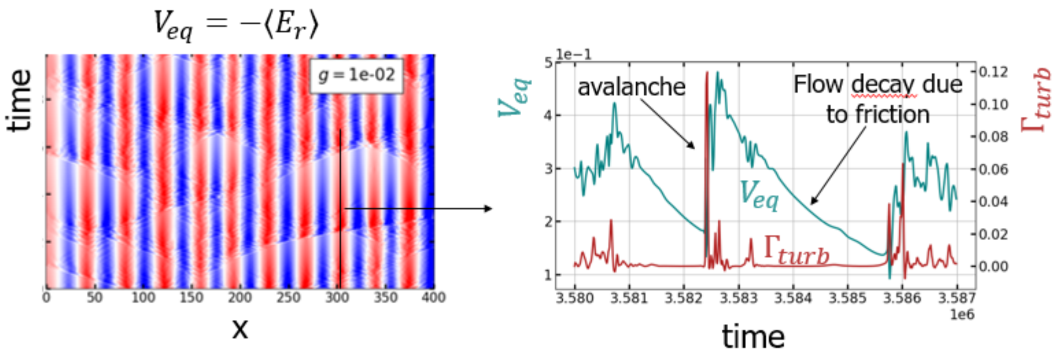

Figure 3: (left) Equilibrium flow as a function of x and time. (right) Time slice at $x = 305$.

Conclusion: Avalanche-like transport has been observed experimentally in TCV plasma using a correlation Doppler backscattering diagnostic. The shape of the correlation function corresponds to the one observed in the reduced model Tokam1D when avalanches are present. Small and large scales are identified as eddy and avalanche sizes, respectively. In simulations, avalanches appear in interchange dominated plasmas. In some regimes, they are observed to feed the staircase structures.

[1] G. Dif-Pradalier et al. In: *NF* (2017). **[2]** P. H. Diamond et al. In: *PoP* (1995). **[3]** P. A. Schneider et al. In: *NF* (2021). **[4]** Y. Idomura et al. In: *PoP* (2014). **[5]** Y Kosuga et al. In: *PoP* (2014). **[6]** P. Politzer. In: *PRL* (2000). **[7]** O Panico et al (sub). In: *JPP* (2024).