Experimental characterization of the ExB staircase in Tore Supra

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ExB staircase: set of regularly spaced shears flow which produce a specific pattern on the properties of the fluctuations.

- ExB staircase was discovered in numerical simulations.
- **Shesterikov, PRL, 2013**
  - local minima of the fluctuations size
  - sudden variation of the tilt angle

- **Clairet, RSI, 2010**
  - radial size of the density fluctuations
  - tilt angle of the density fluctuations

- **Dif-Pradalier, PRE, 2010**
  - 2-4 distinct flows on the radial profile
  - radial extent of the flow ~ 1 cm

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- **Investigated by ultrafast sweeping reflectometry**

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Moderate fluctuation level and MHD-free plasmas are optimal conditions for the observation of the staircase reflectometer signal \( \delta S(r/a,t) \sim \tilde{n}_e \).

How to evaluate the radial variation of the:

- Size of the fluctuations?
- Tilt of the fluctuations?
The coherence quantifies the size of the fluctuations, the correlation quantifies the tilt of the fluctuations.

- **$L_{coh}$**: proxy for the size of the fluctuations
  - defined as the FWHM of the coherence
  - only turbulent frequencies are considered $|F| > 15$ kHz
  - (Hornung, PPCF, 2013)

- **$\phi$**: proxy for the tilt of the fluctuations
  - obtained by fitting an ellipse to the contour of the correlation function
  - (Pinzon, IRW12, 2015)
Local reduction of the coherence lengths observed in several plasma discharges

- **Experimental conditions:**
  $I_p=0.7\text{MA}$, $\langle n_e \rangle =1.47 \times 10^{19}\text{m}^{-3}$,
  $B_t=3.85\text{T}$, Ohmic plasmas

- $L_{\text{coh}}$: proxy for the fluctuations size

- $L_{\text{coh}}$ minima are quasi regularly spaced along the radial direction

- consistent with Gysela observations
  
  *(Dif-Pradalier, PRL, 2015)*
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- Reproducibility of the minima
  - not a random phenomena
  - robust w.r.t. the definition of \( L_{\text{coh}} \)
The tilt of the fluctuations changes sign around the radial position of $L_{\text{coh}}$ minima

- $\phi$: proxy for the tilt of the density fluctuations

- Eddies may also be tilted by the magnetic shear but this effect is small in the equatorial plane (Fedorczak, PPCF, 2013)

The profile of $\phi$ is consistent with the presence of shear flow around the minima of $L_{\text{coh}}$
The widths of the local minima increase with $\rho_s$

- The local minima of $L_{coh}$ are characterized by their width $\delta$
- $\rho_s$ is evaluated at the position of the local minima
- 179 local minima identified so far in our data base

Assuming $\delta \sim$ radial scale of a shear flow, then $\delta \sim 11 \rho_s$
- consistent with the radial extent of zonal flows ($m=0, n=0$)
- Fujisawa, Nuc. Fus., 2009
- support Gysela observations
  - Dif-Pradalier, PRL., 2015
The spacing between two successive local minima decreases slightly with $1/\rho^*$

- The step $\Delta R$ is defined as the radial spacing between two successive minima.

- Interpreting $\Delta R$ as a measure of the outer scale of the avalanches:
  - the avalanches propagate on a distance $\sim 20 \rho_s$
  - long distance propagation observed in low $\rho^*$ discharges?
The staircases are identified for a Greenwald fraction $\sim 0.3-0.5$

Taken individually, $I_p$ and $<n_e>$ cannot be used effectively to distinguish cases containing staircase

The Greenwald fraction $f_{GW} \sim <n_e>/I_p^2$ allows us to discriminate each case more efficiently:
- staircases are not observed for $f_{GW} \leq 0.25$
- mostly, staircases are observed for $f_{GW} \sim 0.4$

Interestingly, the Shimomura density predicts a transition from LOC to SOC regime for $n_S/n_{GW} \sim 0.5$ \cite{Shimomura, JEARI, 85}

Is the apparition of the staircases correlated with the LOC/SOC transition?
The staircases are abundantly observed at the transition between LOC and SOC regimes.

Relation with the TEM-ITG transition?

(Conway, Nuc.Fus, 2006; Rice, PRL, 2011; Angioni, PRL, 2011)
Staircase not observed in LOC regime as the underlying ExB flows barely affect TEM turbulence

**LOC:** quasi-coherent (QC) modes
- TEMs are dominant
  - Arnichand, Nuc. Fus., 2014
- TEM’s frequencies almost not affected by ExB flows
- consistent with GENE observations: TEM’s saturation does not primarily occur via shear flows (Merz, PRL, 2008; Vernay, PPCF, 2014)

**SOC:** broad band turbulence
- ITGs are dominant
  - Arnichand, Nuc. Fus., 2014
- strong reduction of $L_{coh}$ for all frequencies @ $r/a \sim 0.64$
Conclusions: experimental observations are consistent with the presence of ExB staircase in Tore Supra plasmas

Footprints of the staircase

- quasi regularly spaced local minima of \( L_{coh} \)
- rapid variation of the eddies tilt around \( L_{coh} \) minima

Characterization of the staircase

- \( \delta \sim 11 \rho_s \): characteristics radial extent of shear flows
- \( \Delta R \sim 20 \rho_s \): outer scales of the avalanches

Parameter space of the staircase

- \( L_{coh} \) minima observed independently of the local values of \( q \), in banana regime (\( \nu^* \sim 10^{-2} - 1 \)) and for moderate turbulent drive (\( \eta = L_n/L_T \sim 2-3 \))
- ExB staircase is difficult to observe in LOC, consistent with the fact that the underlying shear flows barely affect the TEMs
Backup
$L_{\text{coh}}$ minima were observed for a significant range of plasma parameters

- 85 out of the 243 analysed data set contain local minima of $L_{\text{coh}}$
- 179 $L_{\text{coh}}$ minima identified

$L_{\text{coh}}$ minima were observed:

- uncorrelated with the rationale q surfaces
- suggests a minor role of the MHD

- for weak collisionality $\nu^* \sim 10^{-2} - 1$ (banana regime)
- at moderate turbulent drive $\eta = L_n/L_T \sim 2-3$ (assuming $T_i = T_e$)
The hybrid heating amplifies the corrugated patterns observed on the coherence lengths

- Reflectometer acquisition

- Coherence length patterns are very similar in Ohmic and hybrid phases

- Overall increase of the coherence lengths when heating is turned on

- The local minima drift radially inward
The reduction of the coherence length is robust against the definition of $L_{\text{coh}}$. 