Plasma–Boundary Interplay: incidence on edge turbulence organisation & barrier formation

G. Dif-Pradalier$^1$, Ph. Ghendrih$^1$, Y. Sarazin$^1$, F. Widmer$^2$, Y. Camenen$^2$, X. Garbet$^1$, Y. Munschy$^1$, V. Grandgirard$^1$, R. Varennes$^1$, L. Vermare$^3$

$^1$ CEA, IRFM, France  
$^2$ Aix Marseille Université, France  
$^3$ LPP, Ecole Polytechnique, France

Ackn.: Festival de Théorie, Aix-en-Provence
A major motivation: describe and understand whereby bifurcations to improved confinement occur

- spontaneous transitions come in many flavours: ITBs, yy-modes
  \[ \text{yy} \in \{ H; I; QH; VH; \ldots \} \]
- common grounds: self-reinforcing feedback
  - onset of differential rotation
  - steepening of \( \nabla p_i \)
  - electric field well (or hill) \( \rightarrow \) shear-induced bifurcation [Biglari PF 90, \ldots]
- narrow region, especially plasma edge \( \rightarrow \) boundary conditions

Global impact of localised boundary interactions is a classical problem
- **fluids**: Prandtl; swirling flows [torque vs. velocity [Saint-Michel PRL 13]] \( \leftrightarrow \) **forcing**
- **MFE**: upstream [core & edge] impact of magn. connection to bound. [SOL/wall]
  
  \[ \text{known importance of wall conditioning, recycling, etc.} \]

- **this work**: propagation of information? core \( \leftrightarrow \) edge \( \leftrightarrow \) SOL? mechanisms?
  relevance to global confinement? [Spoiler: there is a strong interplay]
Our goal: understand turbulence dynamics in L-mode edge
[from where bifurcation to H-mode occurs]

**this talk** understand turbulence dynamics in L-mode edge
⇒ important prerequisite for understanding edge bifurcation(s)

► Several (related) conundrums

1. is there an intrinsic problem [NM’sL?] with the plasma edge?
   ⇒ where does edge turb. come from?
   ⇒ propagation/contamination?

2. important turb. properties:
   all locally-determined?

3. what presides over the onset of edge transport barrier? Mechanism(s)?

[DIII-D #128913 L-mode (t~1.5s)]

[Ref. [10], +20%γ_{E,B}]
[GENE, -10%α/L_{ni}]
[+10%α/L_{ni}]
[-2%α/L_{ni}]

[Ref. [10], -20%γ_{E,B}]
[GENE, nominal]

[GENE-neoclassic]

[Ref. [10], nominal]

[0 0.2 0.4 0.6 0.8 1]

[0 0.2 0.4 0.6 0.8 1]

[0 0.2 0.4 0.6 0.8 1]

[0 0.2 0.4 0.6 0.8 1]

[Gorler PoP 14]
What desirable/minimal set of ingredients?

- equil. gradient length ∼(few ρ_i) ⇒ **scale separations break down** near edge
  (gradient scale ↔ F_{eq}) ⊳ (turb.scale ↔ δf ≡ F - F_{eq})

- profiles ≡ **large uncertainties** in edge; **poorly known** in SOL
  ↩ flux-driven desirable ⇒ propagation of information on global scales
  ⇒ add. symm.-breaking mechanisms edge turb.

- magnetic connection to **material boundaries**
  ↩ expect E_r shear (∇p/n vs. −∇T_e) ⇒ incidence on transp. barrier onset?
Framework: **“minimally” relevant model** to understand turbulence dynamics in L-mode edge?

**Framework** \( \equiv \) **GYSELA**  
[Grandgirard JCP 06 & CPC 16 ; Caschera JPCS 18]

\[
\frac{D F_s}{Dt} = C\left( F_s \right) + S_{\text{heat}}\left( F_s \right) - \nu M_{\text{lim}}\left( F_s - F_{\text{lim}} \right) \quad \& \quad \sum_i Z_i \delta n_i = \delta n_e
\]

- flux-driven profile evolution
- global domain \( 0 \leq r/a \leq 1.3 \)
- poloidally-localised toroidal limiter \( 1 \leq r/a \leq 1.3 \)

\( \downarrow \) penalisation technique \( \equiv \) Krook op. in gyrokinetic eq. rhs  
[Isoardi JCP 10]

- kinetic trapp. elec \( \rightarrow \) adiab. elec.

\( \downarrow \) modified QN eq. in SOL

Bohm cond. forced: \( \frac{\delta n_e}{n_e} \rightarrow e\phi/T_e - \Lambda \)

- no transport of mass
- transport of energy & momentum \( \rightarrow \) “minimal state” / “baseline” instab.
Framework: “minimally” relevant model to understand turbulence dynamics in L-mode edge?

<table>
<thead>
<tr>
<th>Framework ≡ GYSELA</th>
</tr>
</thead>
</table>

\[
\frac{D F_s}{Dt} = C ( F_s ) + S_{\text{heat}} ( F_s ) - \nu M_{\text{lim}} ( F_s - F_{\text{lim}} ) \quad \text{and} \quad \sum_i Z_i \delta n_i = \delta n_e
\]

- flux-driven profile evolution
- global domain \( 0 \leq r/a \leq 1.3 \)
- poloidally-localised toroidal limiter \( 1 \leq r/a \leq 1.3 \)
  - penalisation technique ≡ Krook op. in gyrokinetic eq. rhs [Isoardi JCP 10]
- kinetic trapp. → adiab. elec.
  - modified QN eq. in SOL Bohm cond. forced: \( \delta n_e/e_n \rightarrow e\phi/T_e - \Lambda \)
- circular B geometry; electrostatic; \( \rho_* = 1/300 \); with collisions

Systematic comparison TS#45511

<table>
<thead>
<tr>
<th>Flux-Driven &amp; limiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ M_{\text{lim}} \rightarrow 0 ]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flux-Driven &amp; poloidally symm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ M_{\text{lim}} \rightarrow 0 ]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gradient-Driven &amp; poloidally symm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ S_{\text{heat}} \rightarrow 0 ]</td>
</tr>
<tr>
<td>[ M_{\text{lim}} \rightarrow 0 ]</td>
</tr>
<tr>
<td>( \forall r, t \quad F_s \rightarrow \text{cst} \equiv F_{#2} )</td>
</tr>
</tbody>
</table>
How do steady states compare?

[Dif-Pradalier, under review]

1. Poloidal (a)symmetry
2. “Linear”
3. NM’s L
4. Transport barrier [vorticity dyn.]
Edge unconditionally stable, destabilised by limiter

Linear analysis of GYSELA profiles with local GKW [Peeters CPC 09]

- edge **unconditionally stable** without limiter
- edge **destabilised** locally \((r, \theta)\) with limiter

![Graph showing density and temperature profiles](image)

- interesting situation: turbulence organisation in edge? investigate \(\delta n/n\)
Turbulence organisation in the plasma edge?

- quality fast-swept reflectometry measurements
- mimic conditions TS #45511 → synth. diag. for GYSELA: $\theta = 0 \pm 4^\circ$
Turbulence organisation in the plasma edge?

forcing & boundary conditions key

- reasonable trend with limiter;
- shortfall without;
- spreading [”contamination”] key
  [Mattor; Garbet; Hahm; . . . ; Singh]

➤ sensitivity scans → robust concl.
➤ explain fluct. levels with limiter?
Wave-energy budget to quantify self-advection of turb. patches

- wave energy budget: conserved quantity \((n \cdot I)\)
  
  \[\left(\frac{\partial}{\partial t} + \mathbf{v}_{E,\theta} \frac{\partial}{\partial \theta}\right)(nl) + \nabla \cdot I = \text{Inj} - \text{Diss.}\]

- wave-energy flux: kinetic proxy for spatial turbulence spreading

  \[\Gamma_I(r, \theta, t) \equiv \left\langle \int d^3v (\mathbf{v}_{E\times B} \cdot \nabla)r \frac{f^2}{F_M} \right\rangle\]

**procedure:**

- limiter-borne poloidal asymm. \(\rightarrow\) growing patches of turb. intensity near LCFS.

- chose nonlin. time reference \(t_{\text{ref}}\)
  
  \(\Downarrow\) investigate systematic spreading increments \(\Delta S \equiv \Gamma_I(r, \theta, t) - \Gamma_I(r, \theta, t_{\text{ref}})\)

- times series of poloidal cross-sections of \(\Delta S\)
  
  \(\Delta S \geq 0 \quad \rightarrow \quad \text{radially-outward fluxes of turbulence intensity}\)

  \(\Delta S \leq 0 \quad \rightarrow \quad \text{inward fluxes of turb. intensity}\)
Limiter-borne fluctuations contaminate outer edge in staged polo. sequence; then LCFS[in]–core[out] cyclic equilibration
Persistent transport barrier @ closed–open field line interface → mechanism? assess causality?

Spontaneous $E_r$ build-up & sustenance $\Leftrightarrow (r, \theta)$ vorticity balance

$$\frac{\partial}{\partial t} \langle \Omega_r \rangle + \frac{\partial}{\partial r} \langle v_{Er} \Omega_r \rangle + \frac{\partial}{\partial r} \langle v_{*r} \Omega_r \rangle + \ldots \approx 0$$

with $\Omega_r = -E'_r$; $v_{*r} = -\frac{1}{r} \partial_\theta p_\perp$

- Mechanisms/causality? → Transfer Entropy
  
  [Schreiber PRL 00;… VanMilligen NF 14; Nicolau PoP 18]

- $\langle v_{*r} \Omega_r \rangle \rightarrow \Omega_r$ dominant flow of information
  
  $\Leftrightarrow$ pressure $\theta$-inhomog. & FLR  [Dif-Pradalier, submitted]
Conclusions: evidence for SOL–edge–core interplay enlightens ”shortfall conundrum” & transp. barrier onset/sustainment

- penalised limiter $\rightarrow$ simplified SOL $\Rightarrow$ miss $e^- \parallel$ dynamics; convection & neutrals
- interplay SOL, edge & core
  - spontaneous persistent transport barrier $\equiv E_r$ build-up;
  - with limiter: no “shortfall” $\equiv$ clarifies spreading controversy
    1. poloidal asymmetry (cold region...)  
    2. edge-to-core then  
    3. cyclic edge$\rightarrow$core & core$\rightarrow$edge
  - w/o limiter: edge stable & strong “shortfall” in NM’sL

Turbulence not only locally driven by local gradients but ’nonlocally’ controlled by fluxes of turb. activity, primarily (though not exclusively) coming from the edge & mediated thru interplay with material bound.

- early transp. barrier build-up $\rightarrow$ $\langle v_{Er}\Omega_r \rangle$ & $\langle v_{*r}\Omega_r \rangle$ key to $E_r$ growth
Assess flow of information in early stages of transp. barrier build-up → FLR effects & limiter-borne $\nabla p(\theta)$ are key players

$$TE_{Y\rightarrow X}(k) = \sum p(x_{n+1}, x_{n-k}, y_{n-k}) \log \left( \frac{p(x_{n+1}|x_{n-k}, y_{n-k})}{p(x_{n+1}|x_{n-k})} \right)$$

- **directional:** net flow of information $\Delta_{X,Y}(TE) \equiv TE_{Y\rightarrow X} - TE_{X\rightarrow Y}$
- time series $X, Y \in \{\Omega_r, \langle v_{Er}\Omega_r \rangle, \langle v_{*r}\Omega_r \rangle, \ldots \}$
W/o limiter: shortfall in stable edge not cured through combination of core spreading + modif. of local params.

No cure observed with:
- increased resolution
- $T_e / T_i$ ratio
- $q$ [magn. shear]
- $\nabla n_i$

How to explain fluct. levels with limiter?
Limiter-borne fluctuations contaminate outer edge in staged poloidal sequence; then LCFS[in]–core[out] cyclic equilibration...
Limiter-borne fluctuations contaminate outer edge in staged poloidal sequence; then LCFS[in]–core[out] cyclic equilibration.
Disentangling all contrib.: weight of limiter-borne fluct.;
edge → core & core → edge spreading

1 - 2 ≡ importance of near-LCFS turbulence & outside–in spreading
2 - 3 ≡ importance of inside–out spreading, amplified "beach effect"

• overpredict turb. activity $0.55 \leq r/a \leq 0.75 \rightarrow$ GD impedes redistribution
  $r/a \geq 0.8 \& r/a \leq 0.4$
• redistribution of turb. intensity bridges free energy injection near limiter
  → upstream confined core
Spontaneous & persistent transport barrier @ closed–open field line interface → mechanism?

(a) Diagram showing a closed–open field line interface with a wall and a limiter.

(b) Graph showing radial electric field [in Vm⁻¹] as a function of normalised radius ρ = r/a.

(c) Graph showing density [in m⁻³] as a function of normalised radius ρ = r/a.

(d) Graph showing temperature [in eV] as a function of normalised radius ρ = r/a.
Detailed \((r, \theta)\) vorticity balance to probe mechanisms for \(E_r\) build-up & sustainment mechanisms

- start from GK equation + \(E \times B\) velocity + gyroaverage

\[
\partial_t \langle \Omega \rangle + \nabla \cdot \langle \Gamma \rangle = \text{rhs}
\]

\[
\partial_t \langle \Omega_r \rangle + \partial_r \langle v_{Er} \Omega_r \rangle + \partial_r \langle v_\star r \Omega_r \rangle + \partial_r \left\langle \frac{1}{r} \partial_\theta v_{E \theta} \right\rangle = \\
- \partial_t \langle \Omega_\theta \rangle - \frac{1}{r} \partial_\theta \left\langle (v_{E \theta} + v_\star \theta) \Omega_\theta \right\rangle - \partial_r \frac{1}{2r} \partial_\theta \left\langle v_{E \theta}^2 \right\rangle \]

\[
+ \frac{1}{2r^3} \partial_\theta \partial_r \left\langle r^2 v_{Er}^2 \right\rangle - \frac{1}{r} \partial_\theta \left\langle v_\star r \frac{1}{r} \partial_\theta v_{E \theta} \right\rangle + \text{rhs}
\]
Persistent transport barrier @ closed–open field line interface → mechanism?
Active mechanism for persistent transport barrier @ LCFS: $\langle v_r \Omega_r \rangle \equiv$ diamagn. currents sign-discriminate vortices advected