Role of Boundaries in SOL-Edge-Core Interplay

Guilhem Dif-Pradalier, E. Caschera, Y Ghendrih, P Asahi, X Donnel, C Garbet, V Gillot, G Grandgirard, C Latu, Y Passeron, et al.

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Ackn.: Festival de Théorie, Aix-en-Provence

How much does the part impact the whole?

Ways to approach the problem:

❶ stability & transport in vicinity of a given plasma state

➤ constrain profiles (local or global) → nonlinear fluxes, fluctuations

- rich physics (EM, k-space multiscale, ...)
- problems: near marginal stability (slow dynamics & multiscale interaction in real space); artificial source/sink/boundary conditions;

❷ whereby plasma reaches nonlin. state & self-organisation of transport

➤ prescribe (non-adaptive) sources/sinks & bound. conditions

→ the rest is output: nonlinear fluxes, fluctuations **& profiles**

- heavy; long times required: multiple scales interplay (Fourier & real space)

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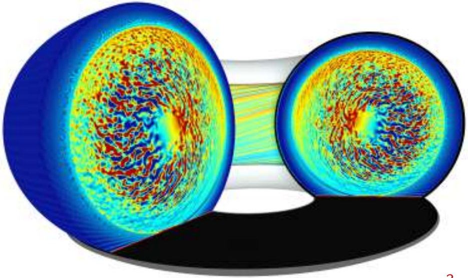
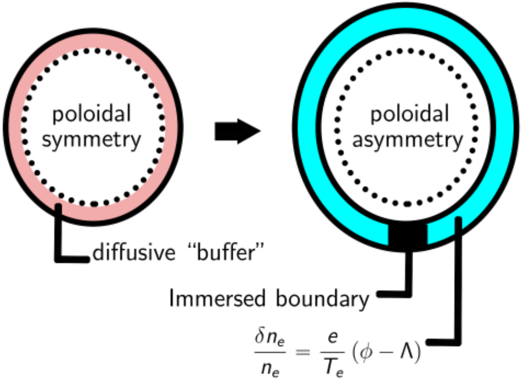
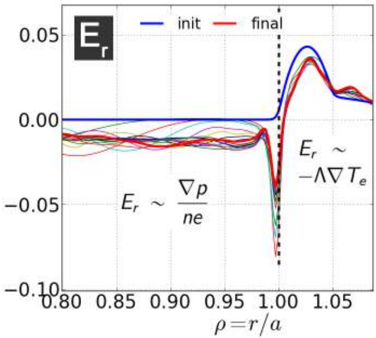


This talk: ToreSupra limiter & SOL

SOL ↔ edge ↔ core interplay? NM'sL?

Adding simplified SOL physics... without resolving sheath boundary & neutrals



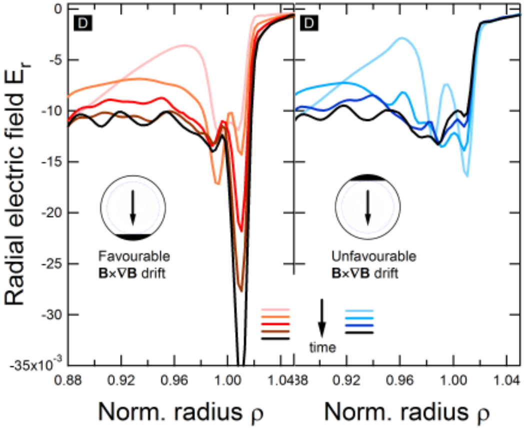


↳ E_r well develops @separatrix

[Caschera JPCS 18]

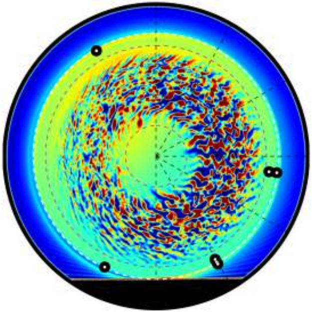
- weak edge transport barrier
- core: ITG or TEM dynamics
- SOL: electron parallel dynamics; miss convection → particule source

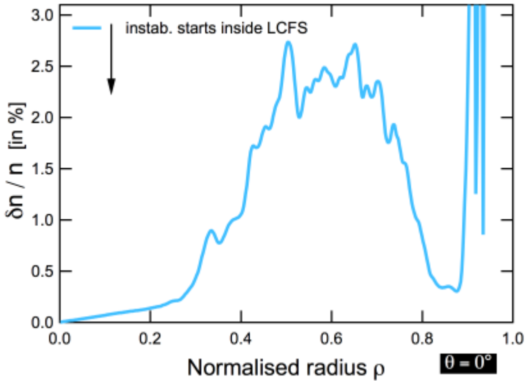
Orbit drift: an important player in the establishment of E_r well & edge/SOL dynamics



- ➤ consistent w. common observations: deeper E_r well in favourable $\mathbf{B} \times \nabla\mathbf{B}$ drift
- ➤ top vs bottom limiter: clear impact on poloidal distribution of fluctuations. . .
- ➤ . . . no visible impact on overall (surface-averaged) fluxes (so far?)

Staged & nonlinear sequence of destabilisations leads to a globally organised turb. state





❶ core unstable; edge stable ➞ shortfall ≡ solution w/o limiter [Holland PoP 11]

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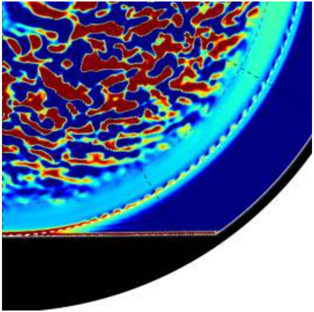
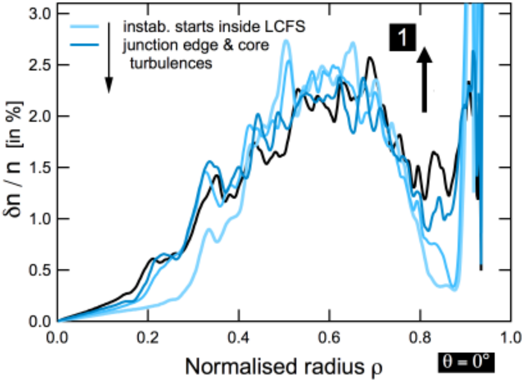




❶ core unstable; edge stable ➞ shortfall ≡ solution w/o limiter

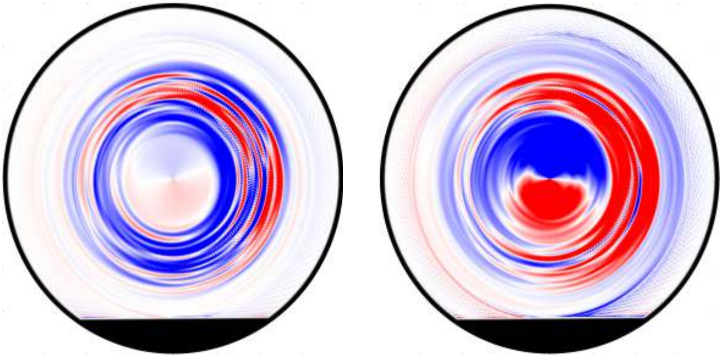
❷ edge destabilised @LCFS (inside –closed field lines) ; core ∼unaffected
➞ complex spreading pattern, mostly inward [Kadomtsev 65; Garbet NF 94, Hahm PoP 05]

How does then turbulence contaminate the stable edge? → combine near-separatrix instability & inward spreading

- drift & limiter → poloidal asymmetry → instab. near limiter @separatrix
- fluct. advected by flow; complex fill-in pattern [limiter → top → mid-plane]
- turb. "contamination" of (marginally) stable edge

$$\left(\frac{\partial}{\partial_t} + \bar{\mathbf{v}}_{E,\theta}\frac{\partial}{\partial_\theta}\right)[nI] + \nabla\cdot\Gamma = \text{Inj}-\text{Diss.} \quad ; \quad \Gamma(r,\theta,t) \equiv \langle \mathbf{v} nI \rangle = \left\langle \int \mathbf{v}_{ExB,r}\frac{\tilde{f}^2}{F_M} \right\rangle$$

[Mattor PRL 94; Gurcan NF 13]



spreading flux

red ≡ outwards

blue ≡ inwards

- later: edge-enhanced core spreading [edge fluct.: channel for core emptying]

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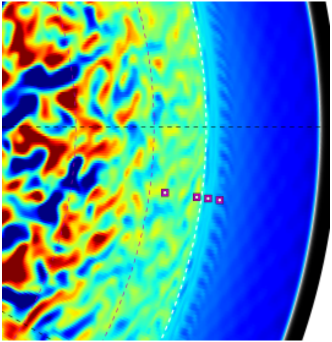

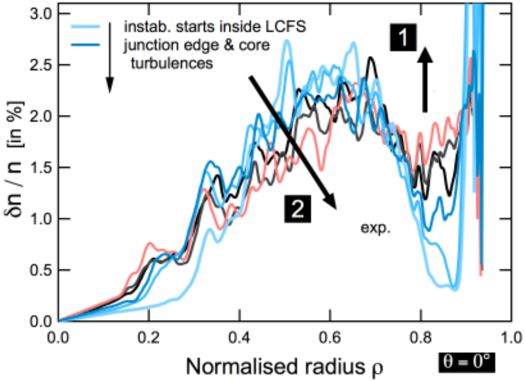

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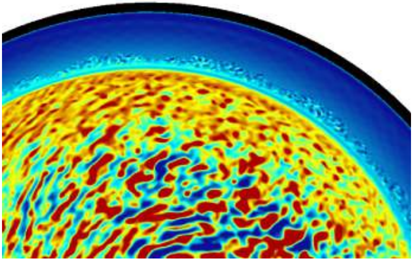

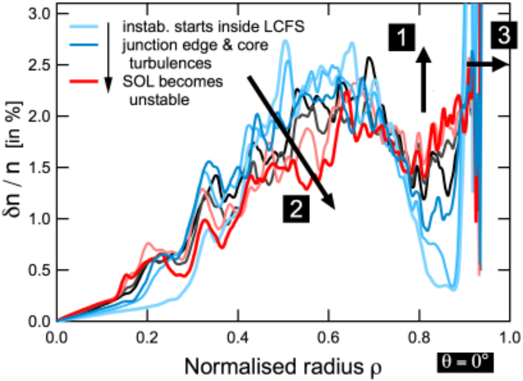

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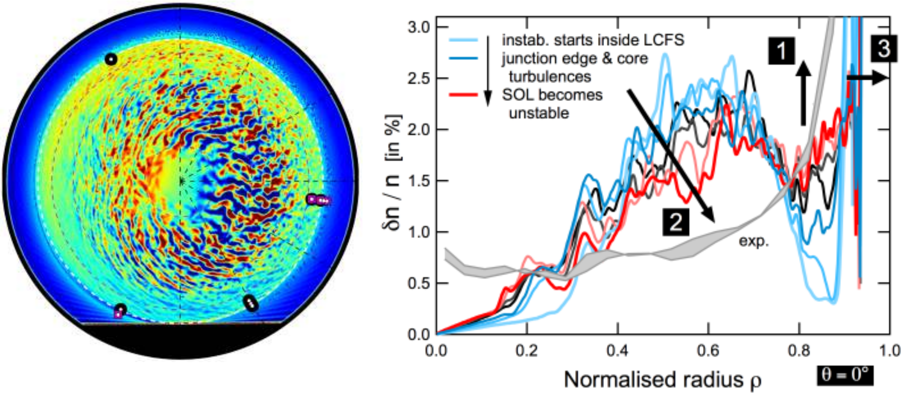

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Conclusions

- penalised limiter ➞ simplified SOL: $e^{-} \parallel$ dynamics; miss convection & neutrals
- interplay btw SOL, edge & core ➞ key for edge, impacts core & SOL
  - ➞ spontaneous weak transport barrier $\equiv E_r$ build-up;
  - ➞ steepness E_r affected by ion $\mathbf{B} \times \nabla B$ drift wrt limiter poloidal position
  - ➞ staged development of turbulence $\equiv$ clarifies spreading controversy
    - limiter: edge $\rightarrow$ core ; core $\rightarrow$ edge ; SOL unstable & core/edge $\rightarrow$ SOL
    - edge stable w/o limiter;

Flux-driven approach: goal is to allow for phase space exploration, preserving dynamic feedback loops

Framework $\equiv$ GYSELA [Grandgirard JCP 06 ; CPC 16]

- $\frac{\partial}{\partial t}(F_s) - [H, F_s] = C(F_s) + S(F_s)$ & $Z_i\,\delta n_i + Z\,\delta n_Z = \boxed{\delta n_e}$
- 2 species; kin. trapped e^-; adiab. sources; circular **B** geom.; electrostat.

E_r **dynamics is key** ➞ preserve it $\quad E_r - v_T B_p + v_p B_T = \nabla p / ne$

- consistent profile evolution
- large fluct. in edge
- equil. grad. length $\sim$ few tens of ρ_i

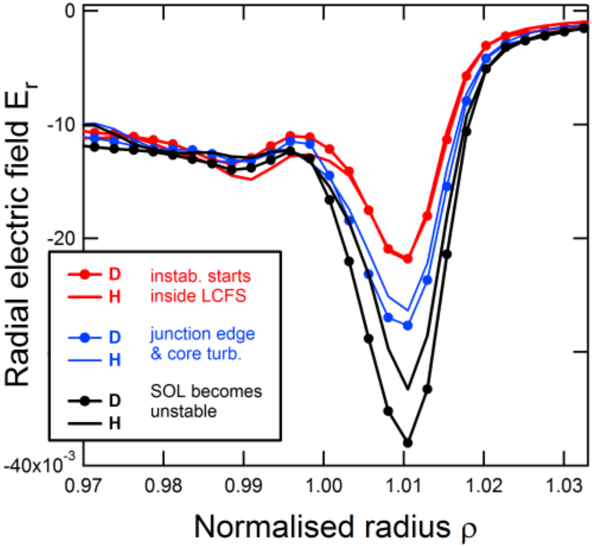
| **scale separation** assumption breaks down, especially in edge

- collisional damping: v_p & v_T
  - neoclassics ➞ $v_p,\ v_T \propto \nabla T$
  - ~~neutrals ➞ collisional friction~~

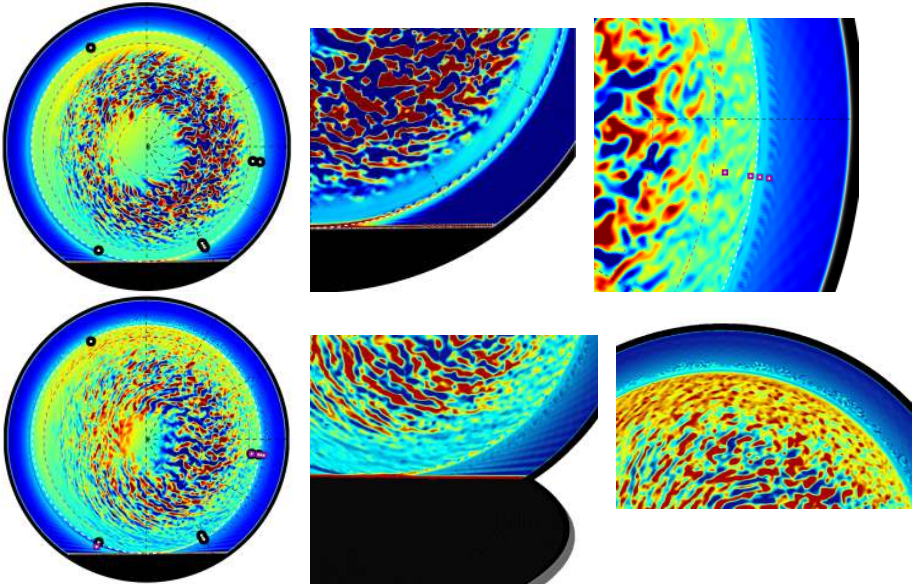
| $\exists$ synergies: non additive [Dif-Pradalier PRL 09; Abiteboul PoP 11; Grierson NF13; Idomura PoP 14; Parra PPCF 14; Vernay PoP 12; Oberparleiter PoP 16; McDevitt PRL 13]

- open field line $\equiv$ Scrape-Off-Layer $\boxed{\text{SOL}}$
  - plasma-wall interaction ➞ $E_r \sim -\Lambda \nabla T$
  - ion orbit losses ➞ polarization E_r

Differences in turbulence behaviour with isotope mass: connected to SOL turbulence?



Staged & nonlinear sequence of destabilisations leads to a globally organised turb. state



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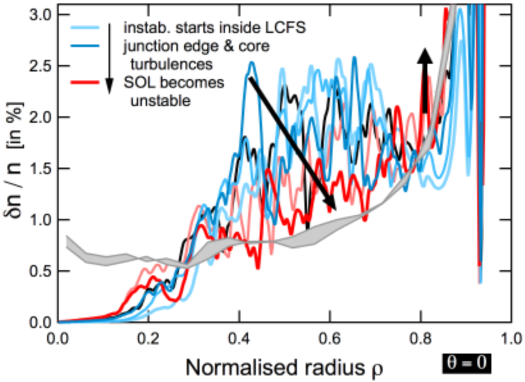

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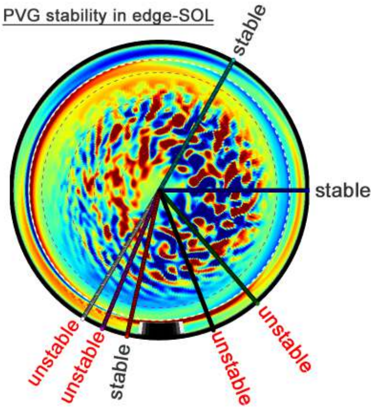
[ongoing...] Combination of near-separatrix PVG & inward spreading

<u>linear stability</u> with QuaLiKiz

[Bourdelle PPCF 15]

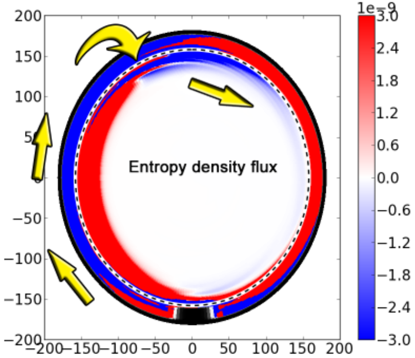
- core is near-marginal
- edge $[\rho = 0.8 \to 1]$ lin. stable
- near-limiter: PVG unstable



$$\left(\frac{\partial}{\partial_t} + \bar{\mathbf{v}}_{E,\theta}\frac{\partial}{\partial_\theta}\right)(nI) + \nabla\cdot\Gamma_I = \mathrm{Inj} - \mathrm{Diss.}$$

[Gurcan NF 13]

$$\Gamma_I(r,\theta,t) \equiv \left\langle \int \mathrm{d}^3 v (\mathbf{v}_{ExB}\cdot\nabla r)\frac{\tilde{f}^2}{F_M}\right\rangle$$



. . . a generic problem

- turb. "contamination" of marginally stable zones
  penetration/overshoot [. . . , Zahn '91, . . .]
  v.s. spreading [Hahm '91, . . .]
- self-advection of turbulence

. . . and an old controversy

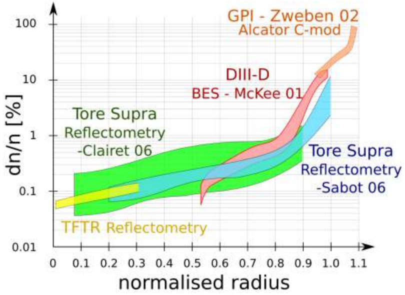
≡ *where does the turb. come from?*

- local linear instab.? [Furth '63,. . . ,Bourdelle '12]
- Scrape-Off-Layer based instability? [Berk '93]
- "core invasion" [Mattor '94]
- "edge invasion" ["tail wagging the dog",. . . , Garbet '94]

. . . the symptom of an uneasy problem

≡ *easy to under-predict fluct. levels in the edge*

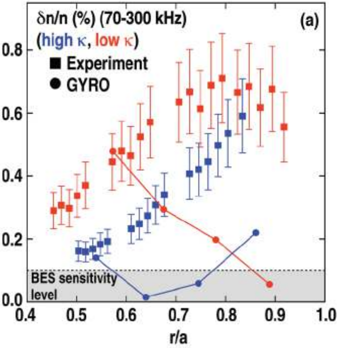
[Liewer '85, Ritz '89, Bravenec '92, Fonck '92, Paul '92, Durst '93, Cima '95, Mazzucato '96, Deng '98, Demers '01, McKee '01, Zweben '02, Sabot '06]



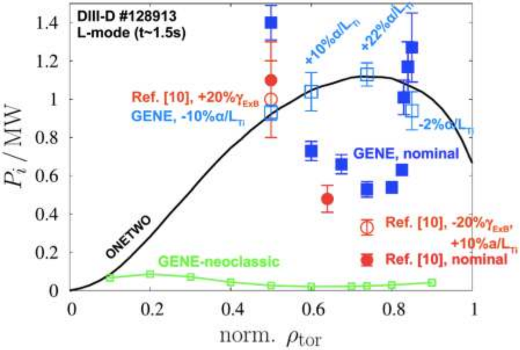
[Gerbaud '08]

Symptom of an uneasy problem: when the 'cure' is debatable

[Holland PoP 11]



[Gorler PoP 14]



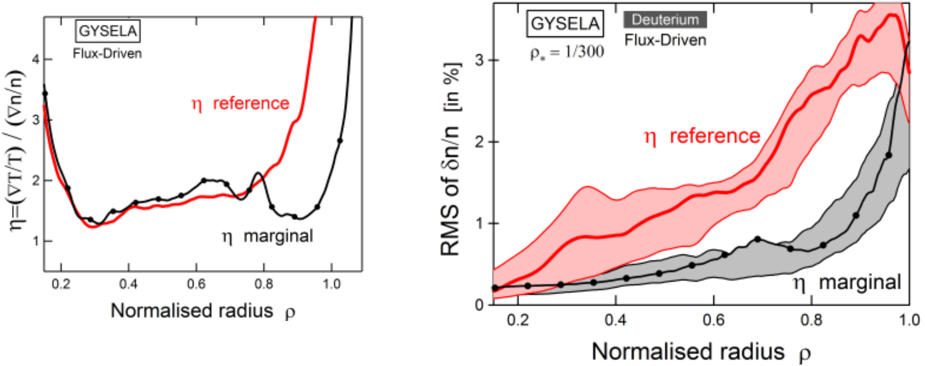
- stiffness symptom: **large variability** of flux response to modest grad. change
- "**cure**" to shortfall? [Waltz APS 17] or alerting sensitivity → **predictability**?

<u>Different perspective:</u> what ingredients are responsible for edge fluctuations?

in particular: how much do core & edge interplay? *[flux-driven]*

Edge–core interplay ≡ ‘contamination’ on a global scale: edge (b.c.) is not a mere bound. condition for core

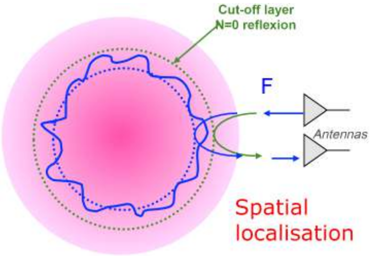
“Academic”: 2 different comput., both flux-driven, with different turb. drive
adiab. electrons: density fixed, temperature evolves ➞ ∇n controls drive

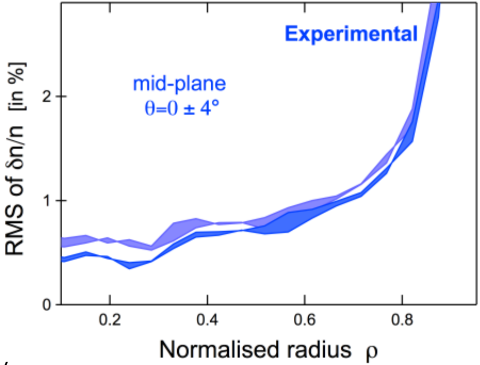


- spreading of turbulence from core not significant with low core drive
- edge boundary impacts core plasma transport & self-organisation

[Dif-Pradalier PFR 2017]

Turbulence levels in edge: Scrape-Off-Layer (SOL) boundary conditions are <u>key</u>





- high-quality fast-swept reflectometry

  [Clairet RSI 2011]

- mimic conditions TS #45511 ➞ $T_e \neq T_i,\ n_e,\ q,\ s,\ \nu_\star,\ S_{\text{heat}},\ 75\%\,\rho_\star$

  ↳ synth. diag. for GYSELA: $\theta = 0 \pm 4^\circ$

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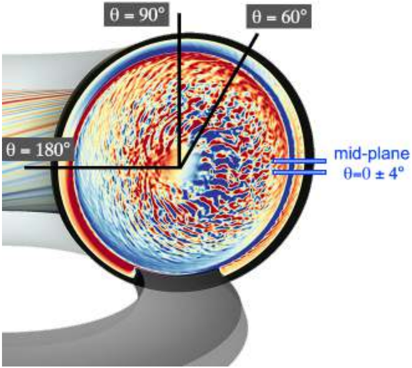

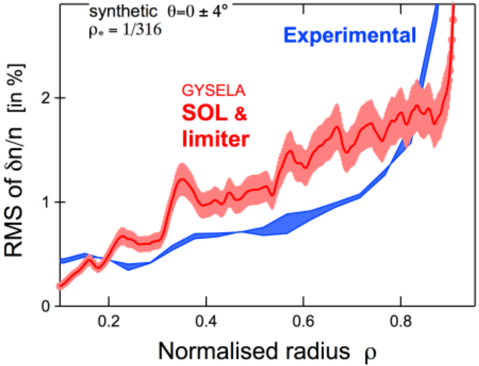

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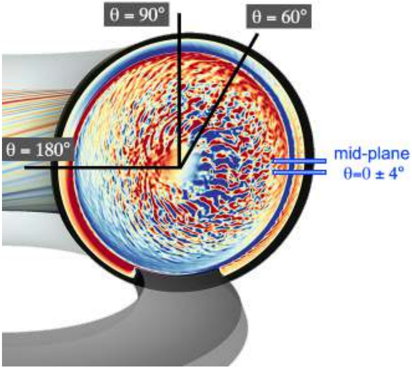

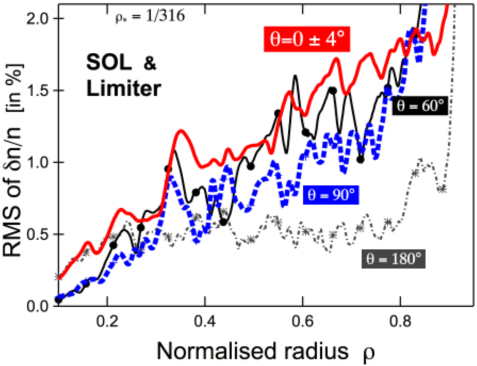

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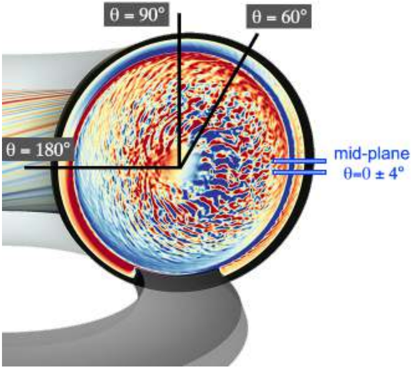
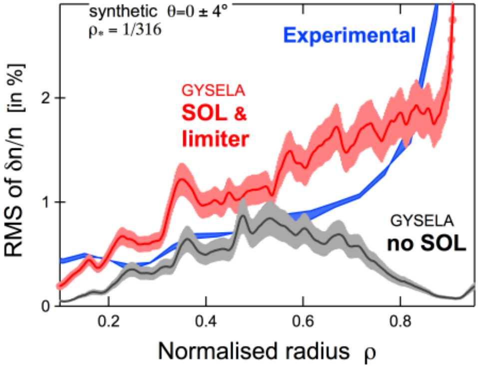
Easy to get?

Turbulence levels in edge: Scrape-Off-Layer (SOL) boundary conditions are key





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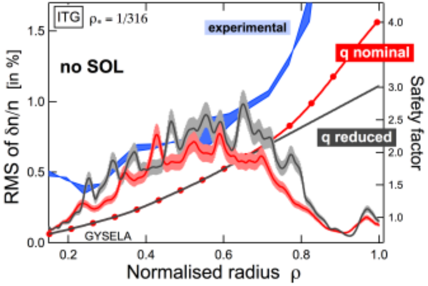
. . . long story short:

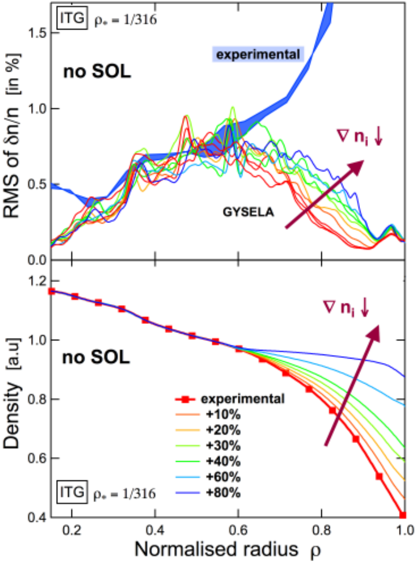
- inclusion of **SOL bound. cond.** instrumental
- scan $T_e,\ T_i,\ n_e,\ q,\ b.c.$ ➞ whence comes the turb.?

Stable edge not destabilised through combination of core spreading ⊕ modification of local parameters

<u>No cure observed with:</u>

- increased resolution
- $\nearrow$ T_e/T_i ratio
- $\searrow$ safety factor q [$\searrow$ magn. shear]
- $\searrow$ ∇n_i





How to explain fluct. levels with SOL?

Dynamics of E_r key → attention to its sources

vspace-6pt

Critical sources for E_r
Core (confined) plasma:
Radial force balance → $E_r \sim \nabla p/en$
Turbulence self-generated flows (Zonal Flows):
Large fluctuations at the edge → large E_r ?
Unconfined region ("Scrape-Off Layer"):
plasma-wall interaction → $E_r \sim -\Lambda \nabla T$
Ion orbit losses → plasma polarization E_r
Magnetic geometry: X-point
Unbalanced vertical charge sep. → E_r
Collisional damping:
neoclassics → $v_\theta = K(\nu_\star, \epsilon)\nabla T/eB$
neutrals → collisional friction
Common assumption of scale separation breaks down at the edge
Equilibrium gradient length can reach a few tens of ρ_i
Neoclassical & gyrokinetic theories need being revisited
Flux-driven approach looks appropriate