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Role of Boundaries in SOL–Edge–Core Interplay

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

How much does the part impact the whole?

Ways to approach the problem:

- ① 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;
 - ② 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)

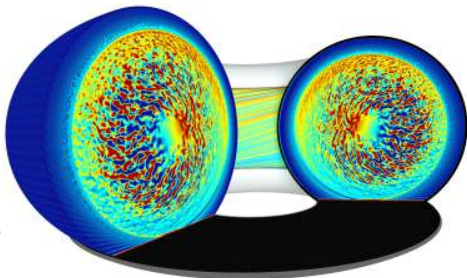
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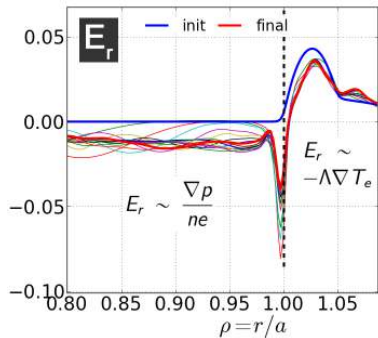
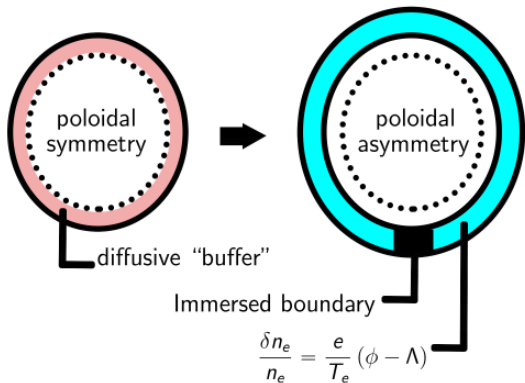
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This talk: ToreSupra limiter & SOL

SOL ↔ edge ↔ core interplay? NM'sL?



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

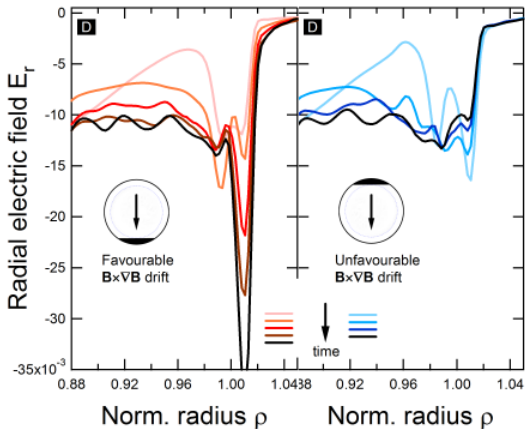


↳ E_r well develops @separatrix

[Caschera JPCS 18]

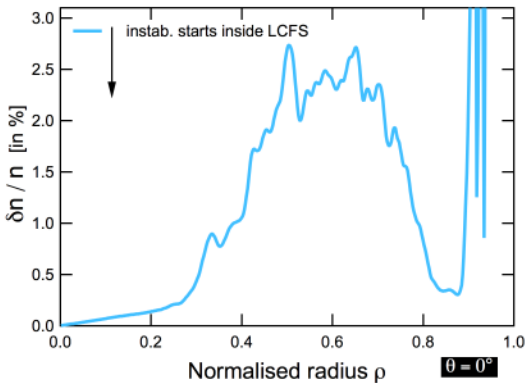
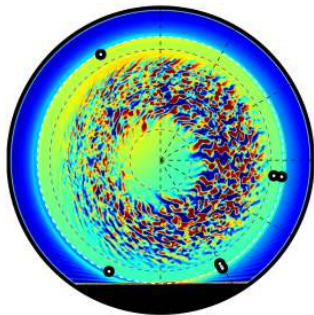
- weak edge transport barrier
- core: ITG or TEM dynamics
- SOL: electron parallel dynamics; miss convection → particule source

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



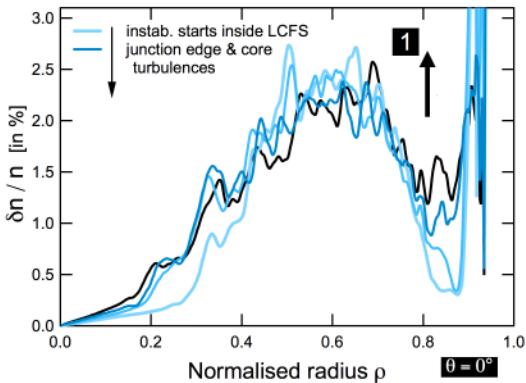
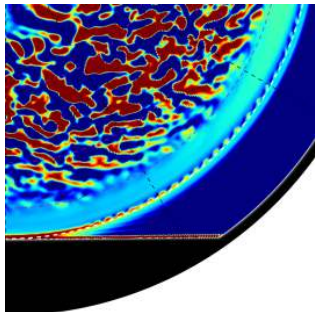
- consistent w. common observations: deeper E_r well in favourable $\mathbf{B} \times \nabla \mathbf{B}$ drift
- top vs bottom limiter: clear impact on poloidal distribution of fluctuations. . .
- . . . no visible impact on overall (surface-averaged) fluxes (so far?)

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



❶ core unstable; edge stable \rightarrow shortfall \equiv solution w/o limiter [Holland PoP 11]

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



- ① core unstable; edge stable \rightarrow shortfall \equiv solution w/o limiter
- ② edge destabilised @LCFS (inside –closed field lines) ; core \sim unaffected
 \rightarrow complex spreading pattern, mostly inward [Kadomtsev 65; Garbet NF 94, Hahn PoP 05]

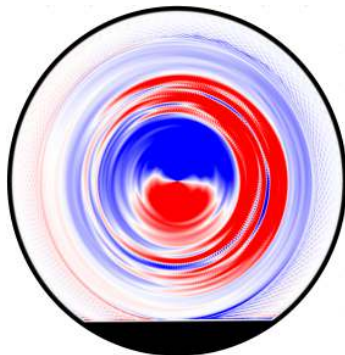
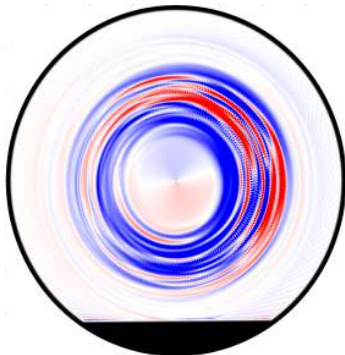
How does then turbulence contaminate the stable edge?

→ 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

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

[Mattor PRL 94; Gurcan NF 13]



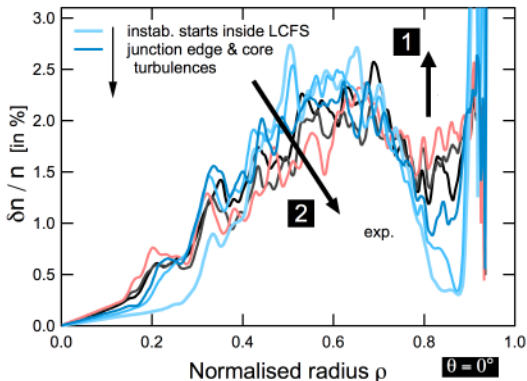
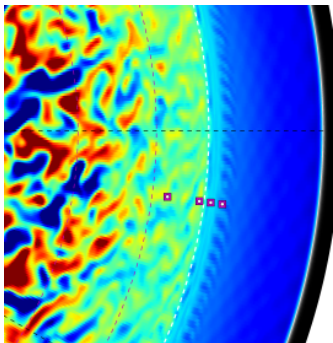
spreading flux

red \equiv outwards

blue \equiv inwards

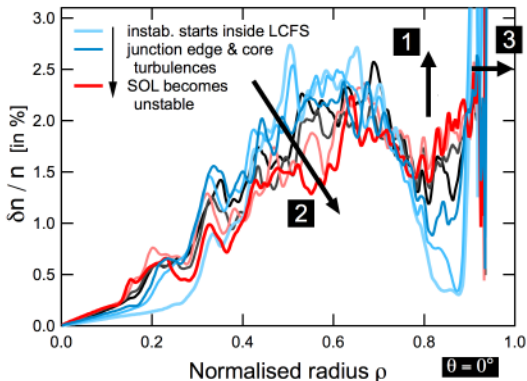
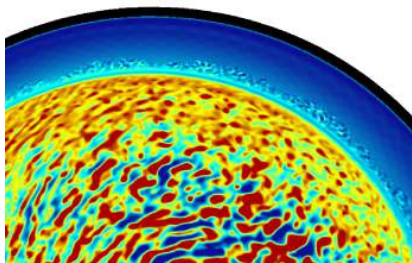
- later: edge-enhanced core spreading [edge fluct.: channel for core emptying]

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



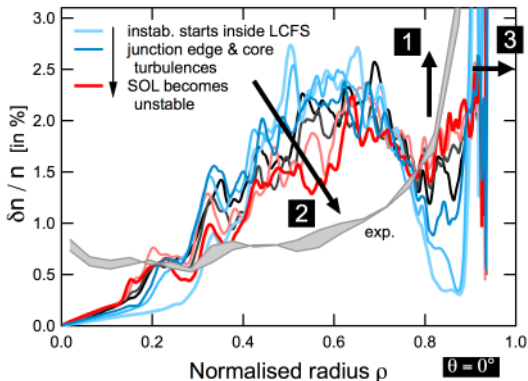
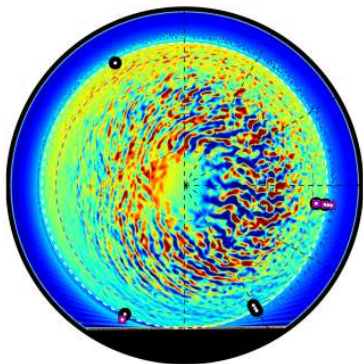
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- ③ edge & core turb. meet → core starts "emptying" → spreading in & out

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- ④ SOL becomes unstable @LCFS (outside) \rightarrow turb. spreads outwards in SOL

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Conclusions

- ▶ penalised limiter → **simplified SOL**: e^- || 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 → core ; core → edge ; SOL unstable & core/edge → 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]

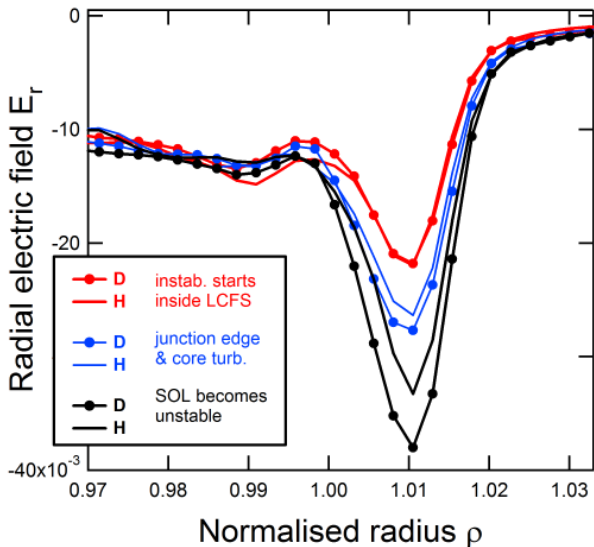
- ▶ $\frac{\partial}{\partial t}(\mathbf{F}_s) - [H, \mathbf{F}_s] = \mathbf{C}(\mathbf{F}_s) + \mathbf{S}(\mathbf{F}_s) \quad \& \quad Z_i \delta n_i + Z \delta n_Z = \boxed{\delta n_e}$
- ▶ 2 species; kin. trapped e^- ; adiab. sources; circular \mathbf{B} geom.; electrostat.

E_r dynamics is key \rightarrow preserve it

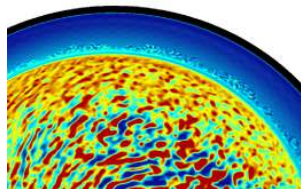
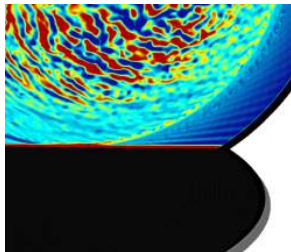
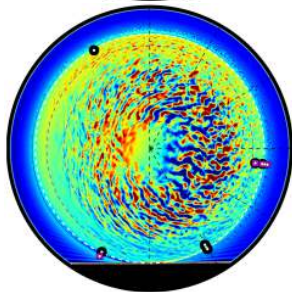
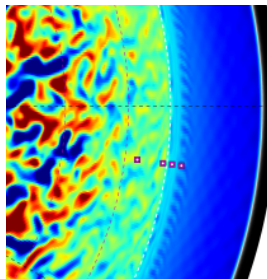
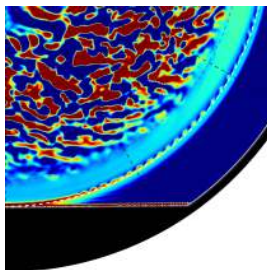
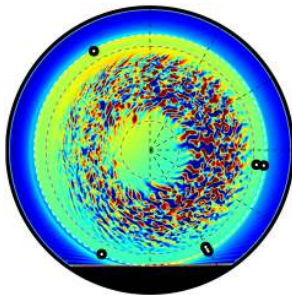
$$E_r - v_T B_\rho + v_\rho B_T = \nabla p / ne$$

- 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_ρ & v_T
 - ▶ **neoclassics** $\rightarrow v_\rho, v_T \propto \nabla T$ | \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]
 - ▶ ~~neutrals \rightarrow collisional friction~~
- open field line \equiv Scrape-Off-Layer **SOL**
 - ▶ plasma-wall interaction $\rightarrow E_r \sim -\Lambda \nabla T$
 - ▶ ion orbit losses \rightarrow polarization E_r

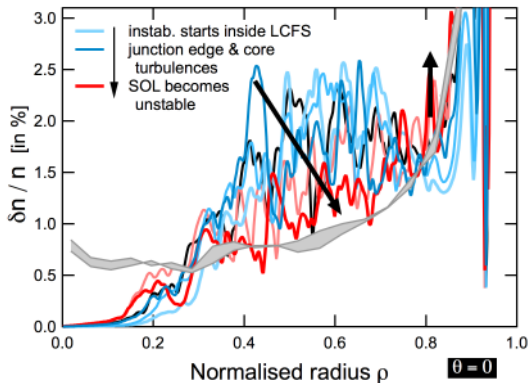
Differences in turbulence behaviour with isotope mass: connected to SOL turbulence?



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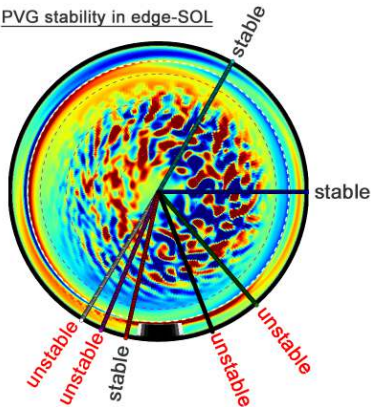
[ongoing...] Combination of near-separatrix PVG
& inward spreading

linear stability with QUALIKIZ

[Bourdelle PPCF 15]

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

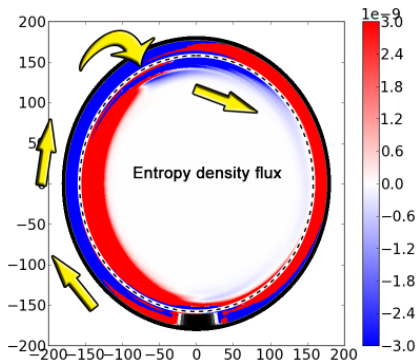
PVG stability in edge-SOL



$$\left(\frac{\partial}{\partial t} + \bar{\mathbf{v}}_{E,\theta} \frac{\partial}{\partial \theta} \right) (nl) + \nabla \cdot \Gamma_I = \text{Inj} - \text{Diss.}$$

[Gurcan NF 13]

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



Motivation: a universal trend in fluctuation measurements

... 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

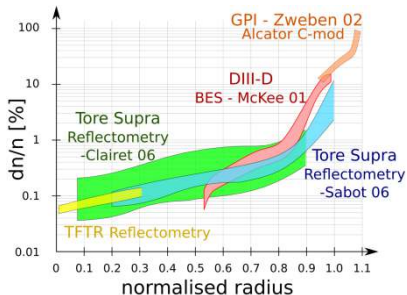
≡ *where does the turb. come from?*

- ▶ 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

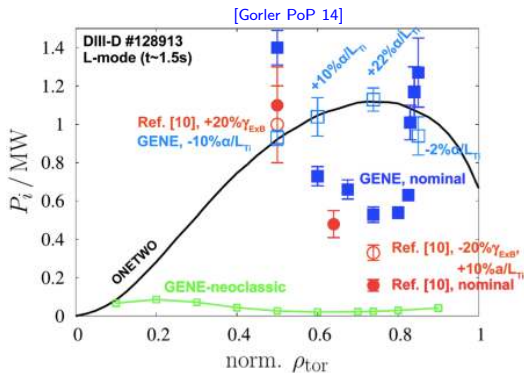
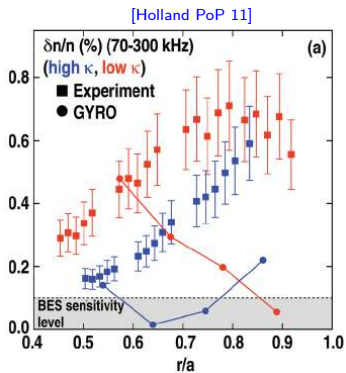
≡ *easy to under-predict fluct. levels in the edge*

[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

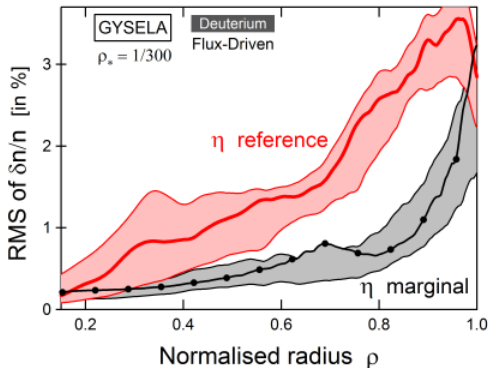
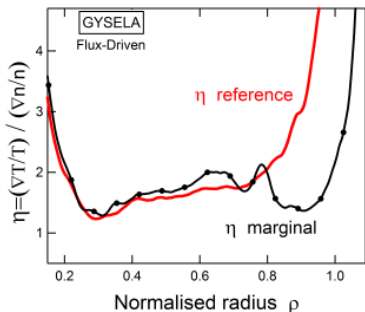


- stiffness symptom: **large variability** of flux response to modest grad. change
- “cure” to shortfall? [Waltz APS 17] or alerting sensitivity → **predictability**?

Different perspective: what ingredients are responsible for edge fluctuations?
in particular: how much do core & edge interplay? [flux-driven]

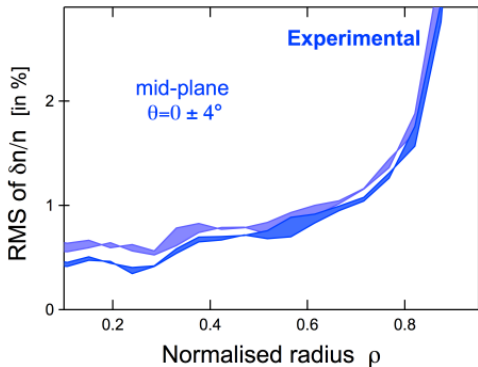
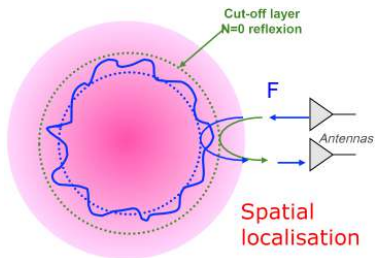
Edge–core interplay \equiv ‘contamination’ on a global scale: edge (b.c.) is not a mere bound. condition for core

“**Academic**”: 2 different comput., both flux-driven, with different turb. drive
adiab. electrons: density fixed, temperature evolves $\rightarrow \nabla n$ controls drive



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

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

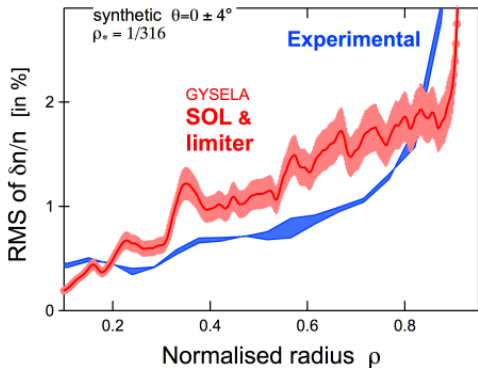
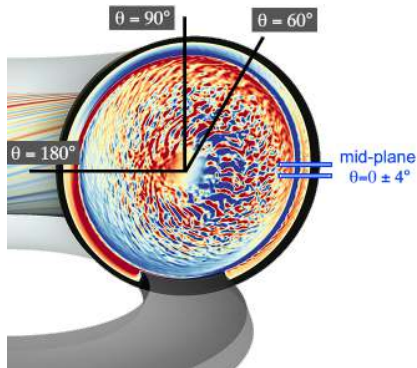


- high-quality fast-swept reflectometry

[Clairet RSI 2011]

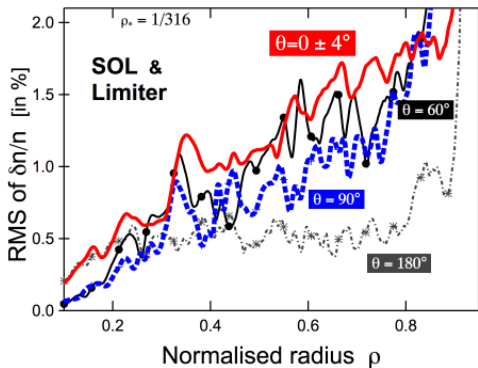
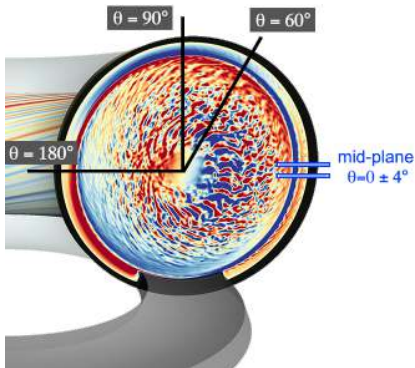
- mimic conditions TS #45511 $\rightarrow T_e \neq T_i, n_e, q, s, \nu_*, S_{\text{heat}}, 75\% \rho_*$
↳ synth. diag. for GYSELA: $\theta = 0 \pm 4^\circ$

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



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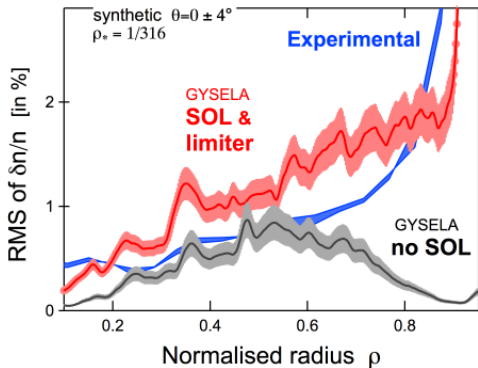
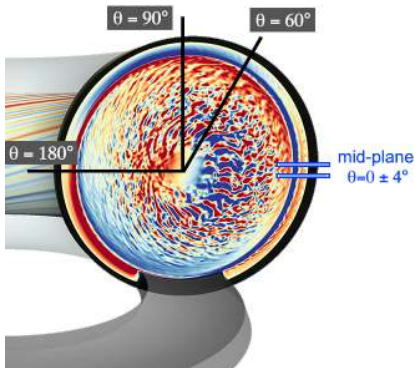
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Easy to get?

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



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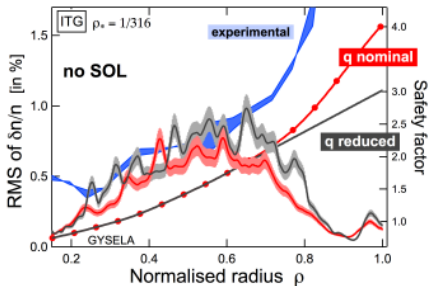
... long story short:

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

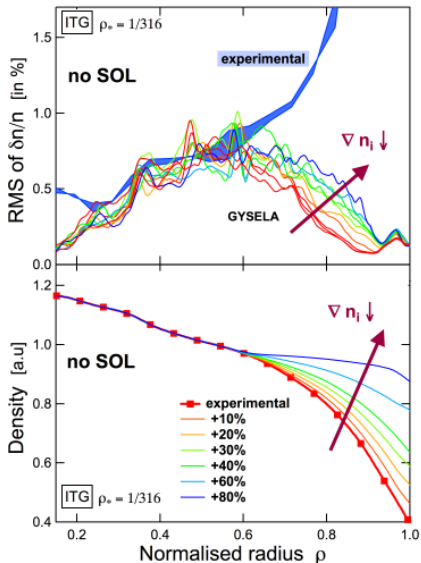
Stable edge not destabilised through combination of core spreading \oplus modification of local parameters

No cure observed with:

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



How to explain fluct. levels with SOL?



Dynamics of E_r key \rightarrow attention to its sources

vspace-6pt

Critical sources for E_r

Core (confined) plasma:

Radial force balance $\rightarrow E_r \sim \nabla p/en$

Turbulence self-generated flows (Zonal Flows):

Large fluctuations at the edge \rightarrow large E_r ?

Unconfined region ("Scrape-Off Layer"):

plasma-wall interaction $\rightarrow E_r \sim -\Lambda \nabla T$

Ion orbit losses \rightarrow plasma polarization E_r

Magnetic geometry: X-point

Unbalanced vertical charge sep. $\rightarrow E_r$

Collisional damping:

neoclassics $\rightarrow v_\theta = K(\nu_*, \epsilon) \nabla T / eB$

neutrals \rightarrow 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