TSVV-01 “L-/H-transition and pedestal physics”

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0. MISSION (2020 CALL)

- Validated local & global gyrokinetic (GK) simulations of ion-/elect.-scale, & multi-scale turbulent transport in the H-, QH-, I-, and L-mode edge
- Extensions to relevant macroscopic (MHD-like) instabilities and radial electric field development (ion orbit losses, fluid codes, eventually GK)
- Consistent application of new Task 4 edge GK code bridging core, pedestal, and Scrape-Off Layer (SOL) region including neutral physics
- An interpretative and predictive capability of L-H transitions
- Reduced transport models for the pedestal on the basis of GK simulations, involving electron-/ion-scale, and MHD-like instabilities

→ EUROfusion capability to model L-/H-transitions and pedestals

✓ **Significant advancements 2021-24**
→ see examples below
✓ Further refinement needs identified
→ **action items for 2025-2027**

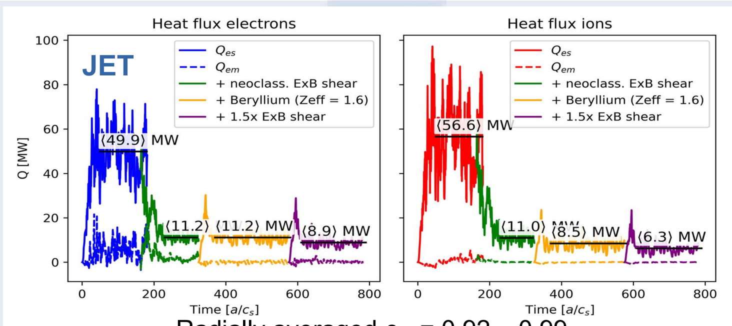
1. GK EDGE TURBULENCE CHARACTERISATION

H-mode pedestal turbulence characterisation

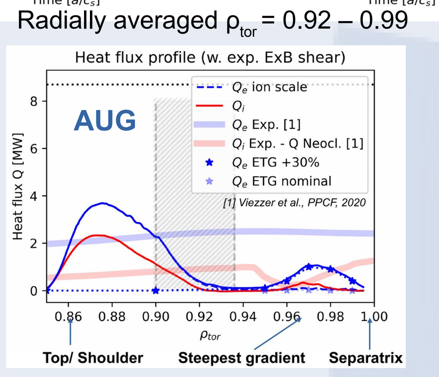
AUG/JET-hybrid H-mode pedestal studies:

- **Pedestal top turbulence mainly ion scale** (ITG/TEM/MTM)
- Pedestal often **just below KBM thresholds**
  → **electromagnetics important** but ES transport
- **Electron transport changes scale:**
  - From ion-scale TEM to **small-scale toroidal/slab ETG at pedestal foot** (high parallel resolution required) – compared w/ reduced models [Hatch et al., PoP 2022]
- **ExB + (sometimes) magn. shear stabilisation** important for **ion & electron** heat channel
- **Impurity** impact (mainly on ion heat flux)

Leppin et al, JPP 2023
Leppin et al, NF 2024 subm.



Radially averaged ρ_{tor} = 0.92 – 0.99

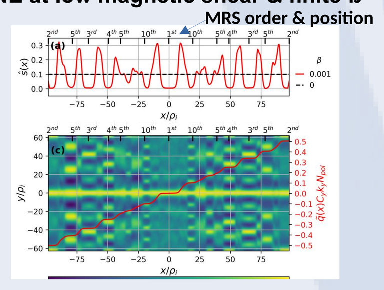


Lessons learnt from ITB studies

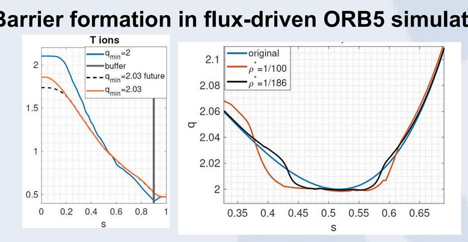
Interesting insights from low magnetic shear ITB studies:

- **Ultra-long eddies** at zero magnetic shear s in local GENE, **strong turbulence variation near rational surfaces, extreme radial profile corrugations if $0 < s \ll 1$** [Volcokas et al., NF 2023]
- **Finite β → impact of self-generated turbulent currents** [Volcokas et al., PPCF'24 accept.]
  - **stepped safety factor profile** with zero shear regions at rational surfaces
  - **possible importance for transport barrier formation**
- **Barrier formation in flux-driven ORB5** with flattened q profile around q_{min} due to turbulence-driven zonal currents (qualitatively similar to above flux-tube results), system size effects analyzed [Di Giannatale et al., ready for submission]
- **assessment of edge relevance** pending (~large bootstrap current scenarios)

Stepped safety factor profile / binormal correlation in GENE at low magnetic shear & finite ß



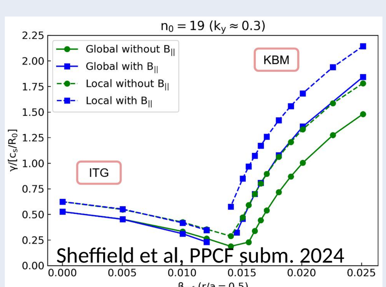
Barrier formation in flux-driven ORB5 simulations



2. TO MACROSCOPIC INSTABILITIES & E_R

GK/MHD comparisons & extensions

- **Theory of consistency between MHD, drift-kinetics, and GK** explored [McMillan, JPP 2023] w. proposed global GK code extensions. Examples:
  - parallel equilibrium currents relevant to **low-n kink physics**
  - **$B_{||}$ fluctuations** – recently implemented in ORB5 and global GENE – benchmarks and impact studies on-going

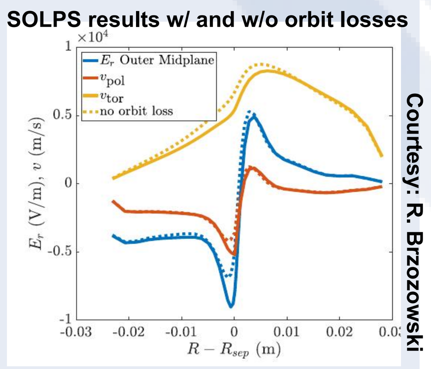


Sheffield et al, PPCF subm. 2024

Ion-orbit losses

- **Steady-state ion-orbit loss & SOLPS coupling**
  - E_r affected by ion-orbit losses (IOL)
  - Poloidal asymmetries are less strongly forced
- **Initial GRILLIX implementation** (fluid code),
  - possible application in recently launched H-mode studies → currently no qualitative changes expected

SOLPS results w/ and w/o orbit losses

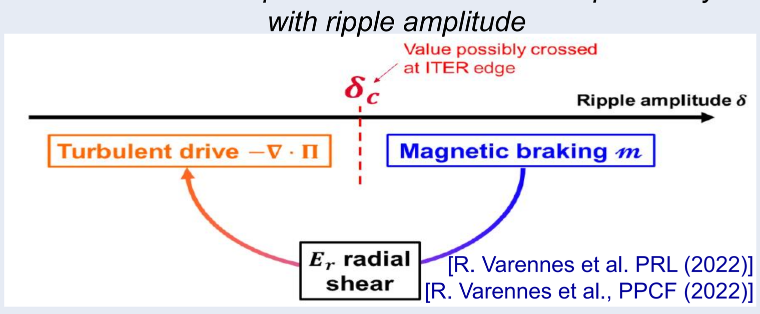


Ripple & safety factor effects on E_r

Magnetic ripple implementation in GK code GYSELA:

- **Study of combined effects of turbulence & collisional processes in rippled magn. configurations**
  - **Magnetic breaking** (~neoclass. toroidal viscosity) may **overcome turbulence as main flow drive** beyond critical ripple amp.
- Preliminary prediction of main flow control (including E_r) mechanism in ITER edge plasmas

Sketch of main plasma rotation & drive dependency with ripple amplitude



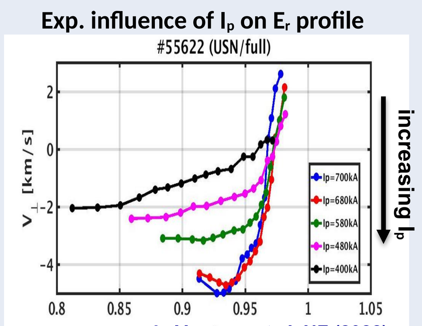
[R. Varennes et al. PRL (2022)]
[R. Varennes et al., PPCF (2022)]

Study of **safety factor impact** on turbulent flow:

- **Qualitative comparison** of WEST and Tore Supra **E_r measurements** with GYSELA
- Combined effect of **turbulence driven flows** (weakly decreasing with q) and **collisional damping** acting on flow (increasing with q) **to recover the experimental trend**

[R. Varennes, PhD (2022),R. Varennes et al., PPCF (2024)]

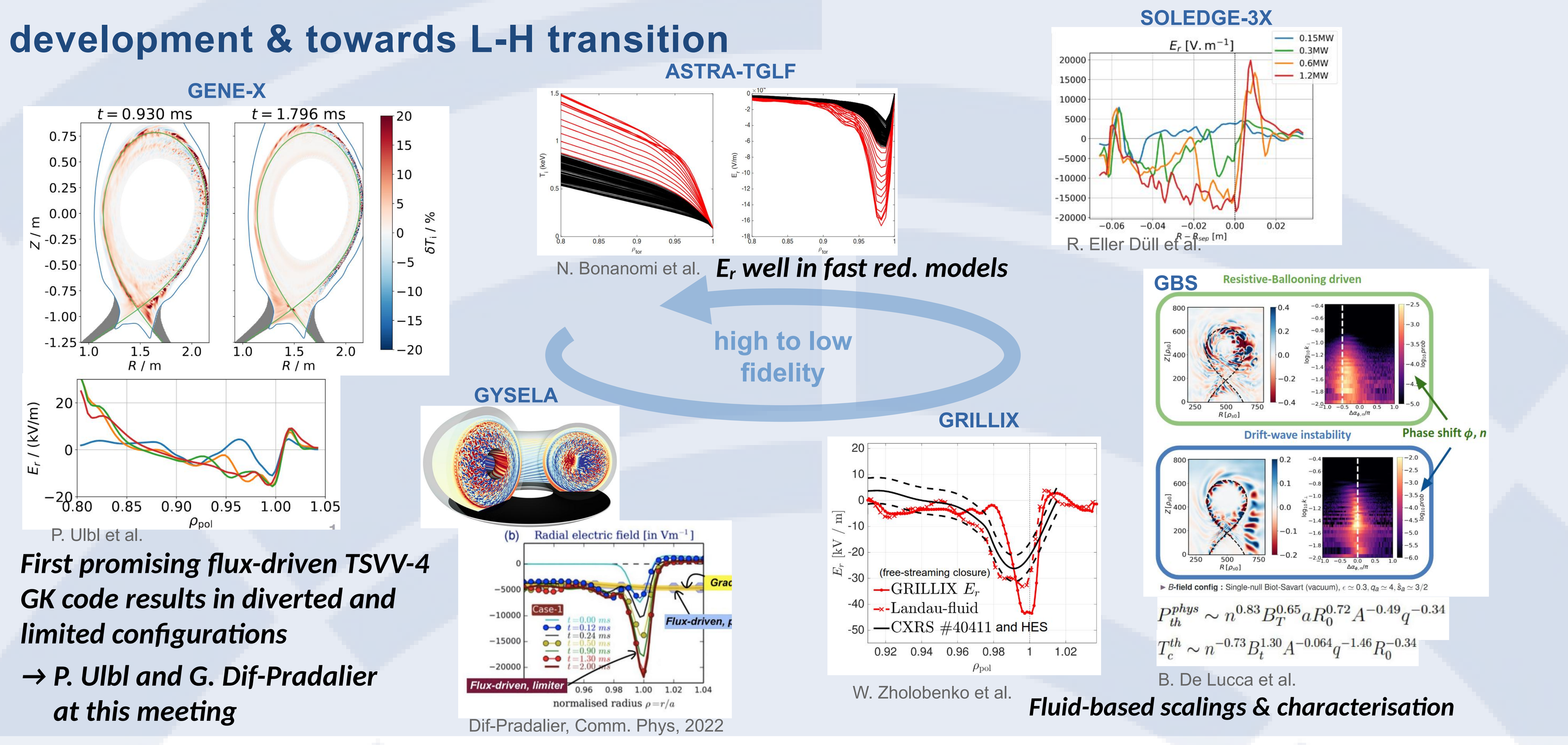
Exp. influence of I_p on E_r profile



L. Vermare et al, NF (2022)

3. TSVV4 (& 3) CODES APPLICATION

E_r development & towards L-H transition



First promising flux-driven TSVV-4 GK code results in diverted and limited configurations
→ P. Ulbl and G. Dif-Pradalier at this meeting
Fluid-based scalings & characterisation

4. INTERPRETATIVE & PREDICTIVE CAPABILITY

LH transition: Initial theoretical power threshold scaling laws

- **Minimal model for LH transition with GBS code:**
  - Electrostatic resistive-ballooning turbulence (L-mode) to EM-suppressed resistive drift-wave (increased heating) [Rogers, Drake & Zeiler 1998]
  - Theoretical scaling law matches ITPA scaling [Martin et al. 1999]

$$P_{th}^{phys} \sim n^{0.83} B_T^{0.65} a R_0^{0.72} A^{-0.49} q^{-0.34}, \quad P^{ITPA} \sim n^{0.782} B_T^{0.772} a^{0.975} R^{0.999}$$

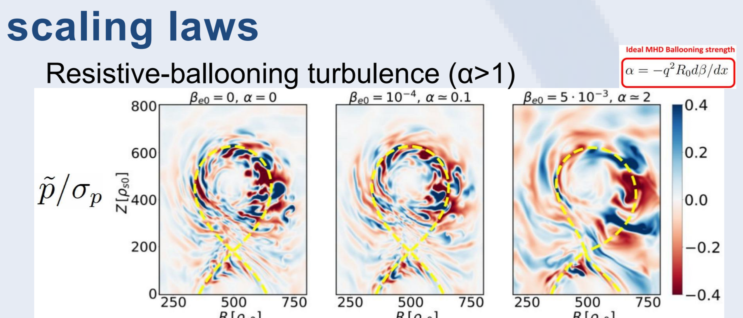
- **ExB shear impact? (Ongoing GBS work, tentative)**
  - Linear theory: ExB suppression of fluid turbulence most effective for large collisionalities → RBM turbulence (L-mode)[Giacomin22]
  - Improving model to account for ExB suppression of L-mode turbulence yields also T > T_{crit} [Righi et al 2000]

$$T_e^{th} \sim n^{-0.73} B_T^{1.30} A^{-0.064} q^{-1.46} R_0^{-0.34}, \quad T_e^{exp}(keV) = (0.39 \pm \delta) n^{-0.64 \pm 0.15} B_T^{1.69 \pm 0.18} A_{eff}^{-0.14 \pm 0.19} q^{-0.86 \pm 0.57}$$

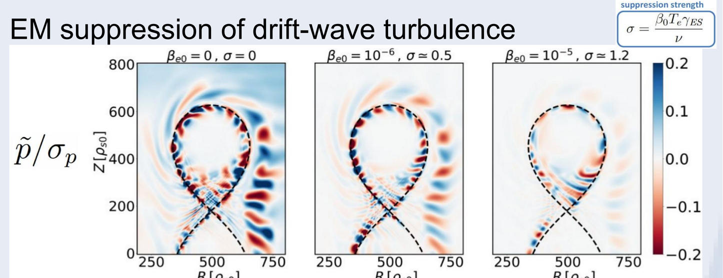
  - Modified gradient saturation mechanism [Biglari et al 1990, Garcia et al 1999] used → further studies needed; kinetic effects, small-scale physics etc missing
- **ITPA scaling for n>n_{min} critical temperature for LH transition but non-monotonic density dependence**

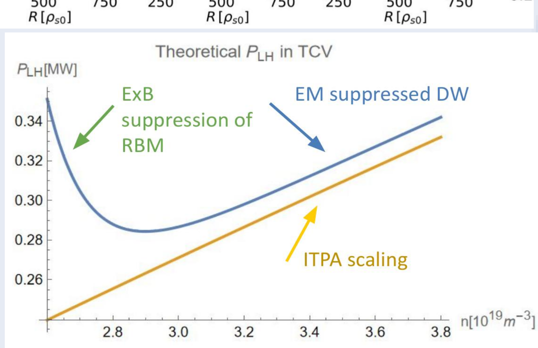
B. De Lucca et al, TSVV1 workshop 2024

Resistive-ballooning turbulence (α>1)



EM suppression of drift-wave turbulence

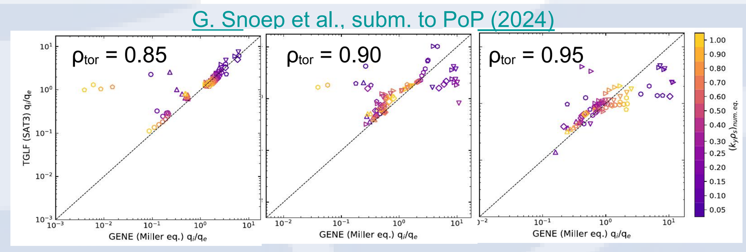


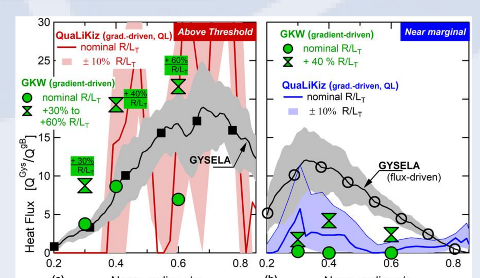


5. REDUCED TRANSPORT MODELS

- **High-dimensional micro-instability characterisation with GENE:**
  - 7 NBI-heated JET-ILW discharges, two similar P_{L-H} vs n_e scans
  - collisionality, EM, isotope mass, geometry, toroidal rotation
- **Extensive reduced model comparisons for characterisation:**
  - **QuaLiKiz useful** at ρ_{tor} <~ 0.90, **TGLF-SAT2 matches** GENE **well**
- **Flux-driven** (GYSELA) vs. **quasilinear** (Qualikiz) & **local** (GKW/GENE) **code comparisons**
  → strong **discrepancies near marginality**, extensions to kinetic electrons needed
- **Extended Microtearing Mode (MTM) transport assessments** [Hamed et al.]
  - Validated linear solver Solve-Ap, saturation via zonal flows & fields studies
- **Checking community reduced ETG models** ([Hatch et al, PoP22],[Farcas et al, JPP24], ...)

G. Snoep et al., subm. to PoP (2024)





Gillot et al, PPCF 2023

6. SUMMARY AND ACTION ITEMS 2025-2027

Achieved	Action items 2025-2027
Turbulence characterisation for L-,I-,H-,EDA-H-modes: KBM proximity, ETG relevance, ExB/magnetic shear impact, impurities, ITB insights	**ITB transferability ▪ increase validation coverage** (e.g., QCE scenarios) ▪ **further explore fine-scale** (ETG)/**cross-scale effects + impurity impact → input to flux-driven models below**
Parallel magnetic fluctuations & equilibrium currents, initial IOL assessment, radial electric field studies launched with multiple tools	Aim at further GK extensions / studies ($B_{\|\|}$,kink, tearing)
First TSVV4 code (GENE-X, GYSELA-X) applications & qualitative flux-driven fluid (TSVV3) code + reduced model (ASTRA-TGLF) comparisons	Refine Edge/SOL ↔ Er studies in comparison to experiments: • TSVV4 codes: neutrals, sheath model, ETG proxies, impurities • Fluid codes (w/ TSVV3): same + e.g., kinetic effects, IOL • Reduced models: improved separatrix b.c., mimic global effect?
Initial scaling laws from large-scale fluid code parameter scans	Revise scaling laws with latest physics amendments in codes (realistically, mostly fluid codes in upcoming years) and compare to experimental scalings
Reduced models (QuaLiKiz/TGLF vs. GK) assessments, MTM model development, heuristic model (IMEP) refinements, comparison with community ETG models	Crucial to, e.g., TSVV11: ▪ Improve MTM model ▪ assess / collaborate on ETG model development ▪ consider KBM reduced models ▪ assess near-marginality ...

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This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.