EUROfusion

EUROfusion Science Meeting - TSVV Final Reports (2021-2025) - Part II – Jan 28, 2026

TSVV1 “L-/H-transition and pedestal physics”

Tobias Görler + TSVV1 team

IPP Garching

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Acknowledgments / Team members

Team members 12/2025:
O. Anuaruly[1], M. Bergmann[2], B. De Lucca[1], M. Dicorato[2], G. Dif-Pradalier[3], P. Donnel[3], R. Düll[3], T. Görler[2], T. Jitsuk[4], B.F. McMillan[5], Y. Sarazin[3], F. Sheffield-Heit[2], P. Ulbl[2], L. Vermare[3], W. Zholobenko[2]

Former team members:
A. Bergmann[2], R. Brzozowski[2], A. Chandrarajan Jayalekshmi[4], G. Falchetto[3], X. Garbet[3], M. Giacomin[1], G. Di Giannatale[1], M. Hamed[4], G. Snoep[4], K. Stimmel[2], L. Leppin[2], K. Lim[1], T. Luda di Cortemiglia[2], R. Varennes[3], A. Volcokas[1]

Permanent guests:
C. Angioni[2], J.R. Ball[1], N. Bonanomi[2], S. Brunner[1], B. Chapman[6], F. Jenko[2], M.J. Pueschel[4], P. Ricci[1], L. Villard[1]

[1]Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center, CH-1015, Lausanne, CH
[2]Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany
[3]CEA, IRFM, F-13108 Saint Paul Lez Durance, France
[4]DIFFER—Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, The Netherlands
[5]Centre for Fusion, Space and Astrophysics, Department of Physics, University of Warwick, Coventry CV4 7AL, UK
[6]Culham Centre for Fusion Energy, Abingdon OX14 3DB, UK

E-TASC target deliverables (CfP 05/2020)

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

D1 - validated local & global GK sims

Validated local & global GK simulations of ion-/elect.-scale & multi-scale turbulent transport in the H-, QH-, I-, and L-mode edge

+

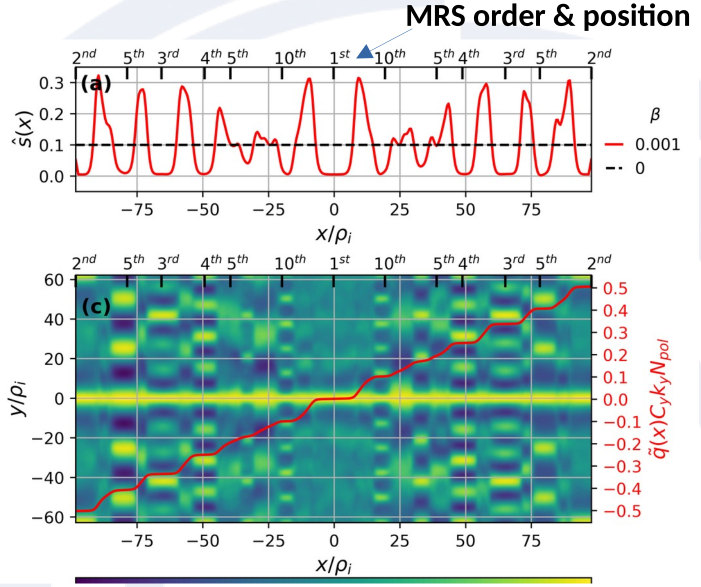
ITB physics studied & identification of key elements that could be transferred to edge

Lessons learnt from ITB studies

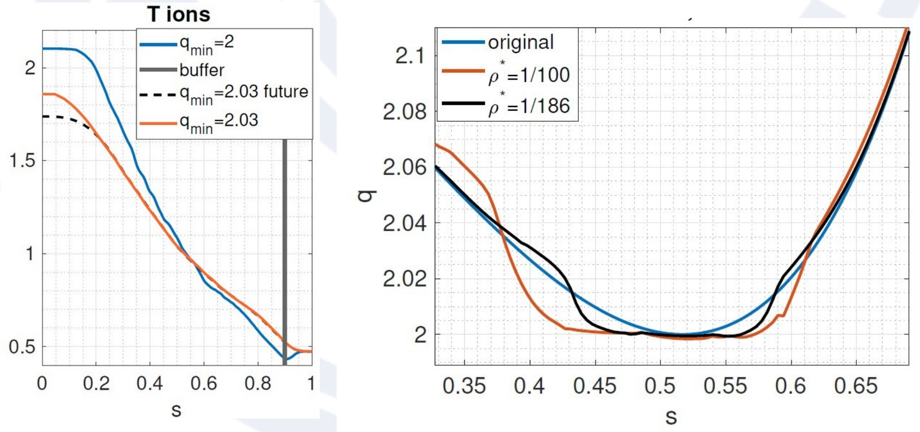
Interesting insights from low magnetic shear ITB studies:

- **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+, NF 63, 014003 (2023); PPCF 67, 015001+2 (2025)]
- **Intrinsic momentum drive at s~0 and near-rational surfaces**
  [Ball+, PRL subm. (2025)]
- **Finite β → impact of self-generated turbulent currents**
  [Volcokas+, PPCF 67, 125008 (2025), PRE 112, L043201 (2025)]
  - **stepped safety factor profile** with *s*=0 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+, PPCF 67, 075008 (2025)]
- **Relevance to low-shear edge barriers** (~large $j_{bootstrap}$ scenarios)

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

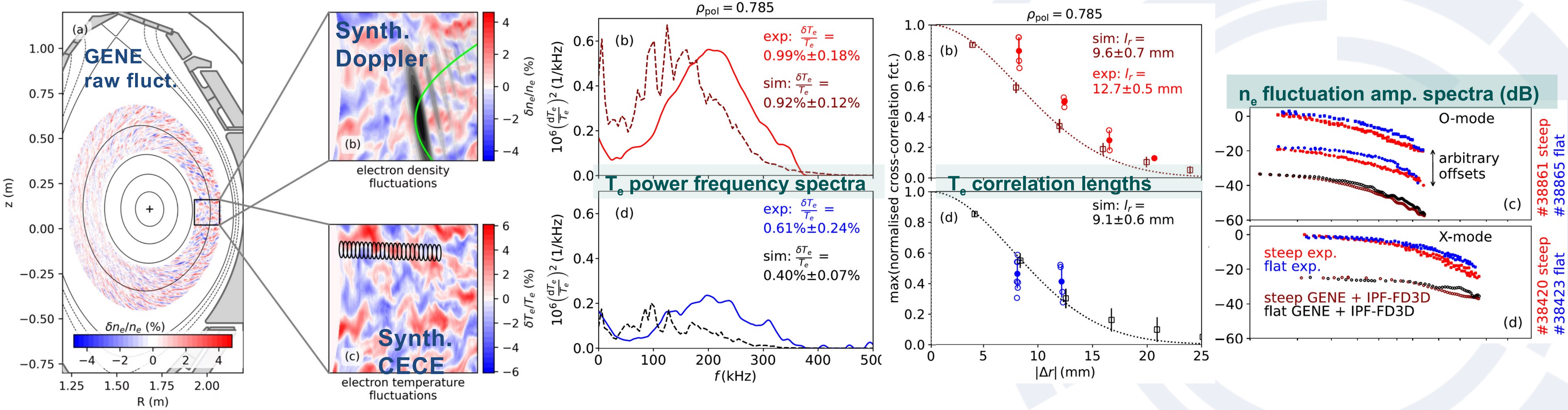


Barrier formation in flux-driven ORB5 simulations



Comprehensive outer-core validation

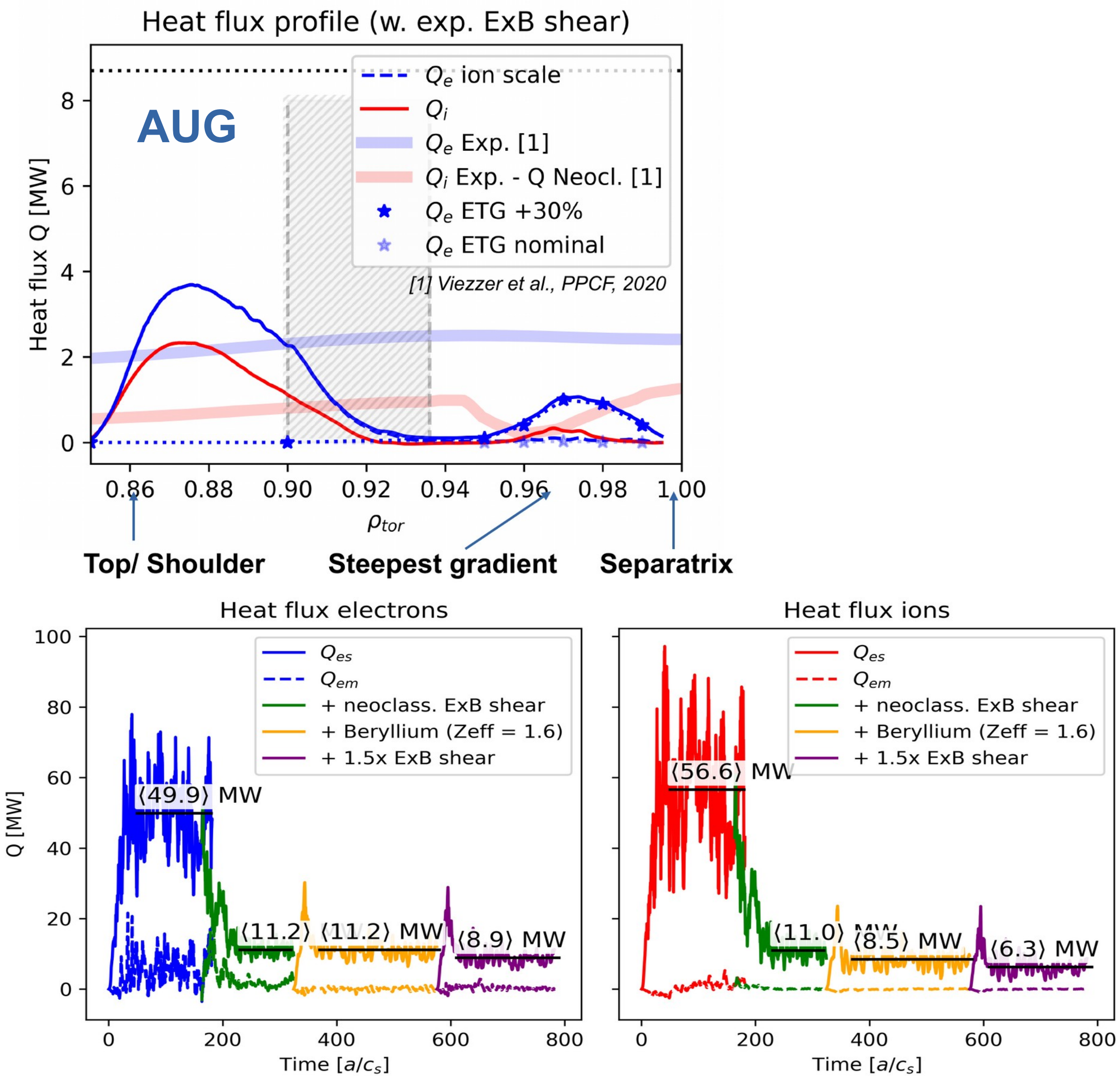
High realism of gyrokinetic outer-core simulations confirmed



[Höfler, Görler+, NatComm 16, 2558 (2025)]

Good agreement found for **unprecedented number of fluctuation characteristics** between **flux-matched GENE ion-scale simulations** and **AUG diagnostics** in outer-core *(optimal diagnostic coverage)*

H-mode edge / pedestal turbulence characterization



Radially averaged ρ_{tor} = 0.92 – 0.99

AUG/JET H-mode pedestals studies with GENE:

- **Pedestal top turbulence mainly ion scale** (ITG/TEM/MTM)
- Pedestal often **just below KBM thresholds** → **electromagnetics important** but ES transport still dominant
- **Electron transport changes scale:** From ion-scale TEM to **small-scale toroidal/slab ETG at pedestal foot** (high parallel resolution required)
- **ExB and (sometimes) magnetic shear stabilization** important for **ion and electron** heat channel
- **Impurity** impact (mainly on ion heat flux)

K. Stimmel+, JPP 88, 905880315 (2022)
L.A. Leppin+, JPP 89, 905890605 (2023)
L.A. Leppin+, PoP 32, 102508 (2025)

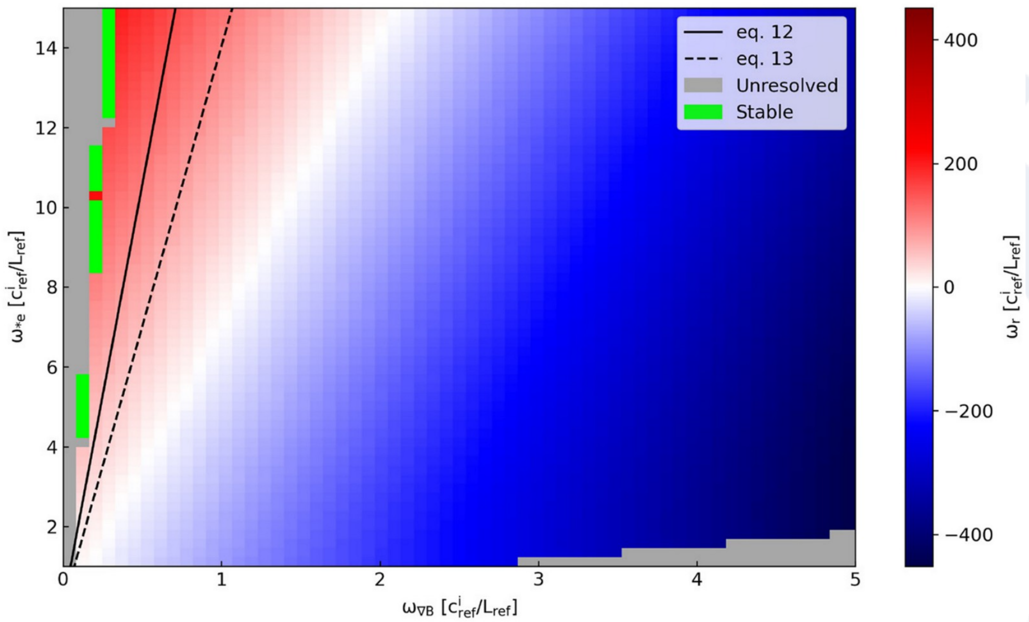
Fine-scale edge (ETG) mode characterization

Explanation for edge “ion-frequency” ETG modes found:

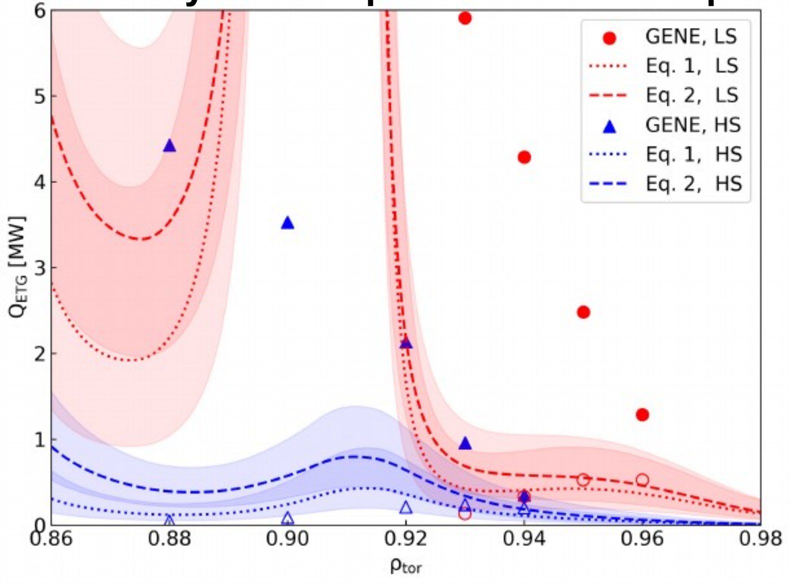
[F. Sheffield+ PoP 32, 122301 (2025)]

- **Confirmed analytically with smooth sign transition**
- Found in pedestals due large gradients, safety factor, drift frequencies and geometry effects
- In core plasmas, prevented by ETG η threshold

i/e-ETGs vs. curv. & electron diamagnetic frequency



Low(LS)/High(HS) Shaping
AUG ELMy H-mode pedestal ETG transport



Characterizations include comparisons to red. models, e.g., [Hatch+, NF 64, 066007 (2024)], [Farcas+, JPP 90, 905900510 (2024)]

- **Overall performance not bad,** e.g., for studies on prev. slide
- **Identified bottlenecks** – toroidal ETG insufficiently covered while slab-ETG (open markers) agree quite well

[F. Sheffield+, to be sub. (2026)]

D2: MHD extensions & E_r development

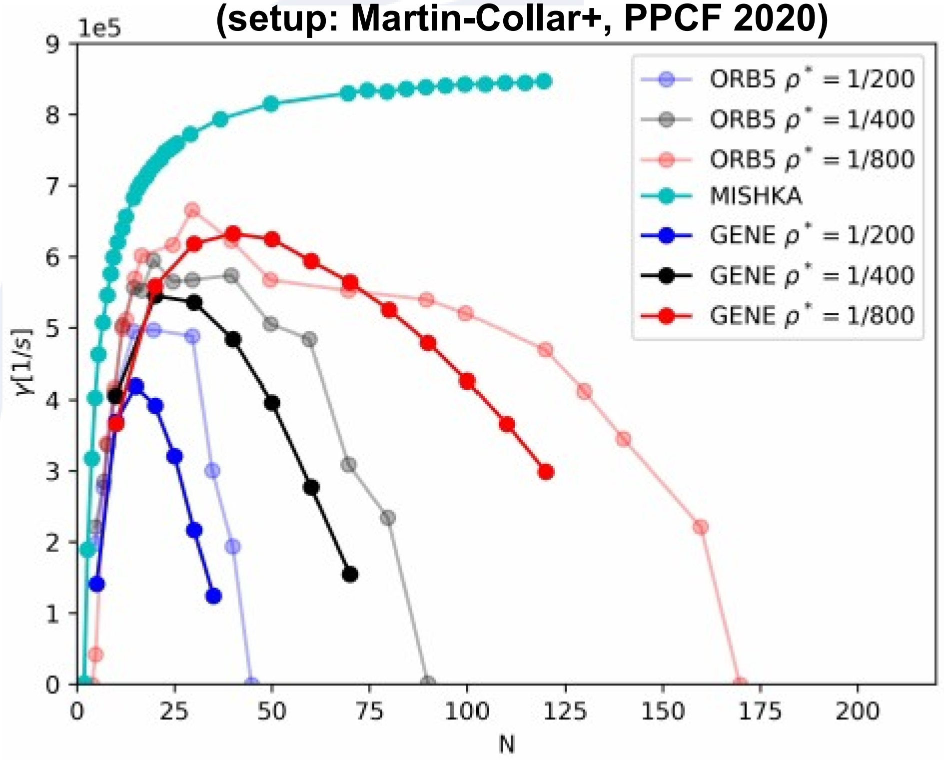
Extensions to relevant macroscopic (MHD-like) instabilities
and radial electric field development (ion orbit losses, fluid codes, eventually GK)
-
Comparison MHD-GK → adding missing physics (tearing, $B_{||}$, ..)
Neoclassic bootstrap currents studies with new full-f HAGIS version
Parametric Er development studies with global fluid & GK (full-f) codes

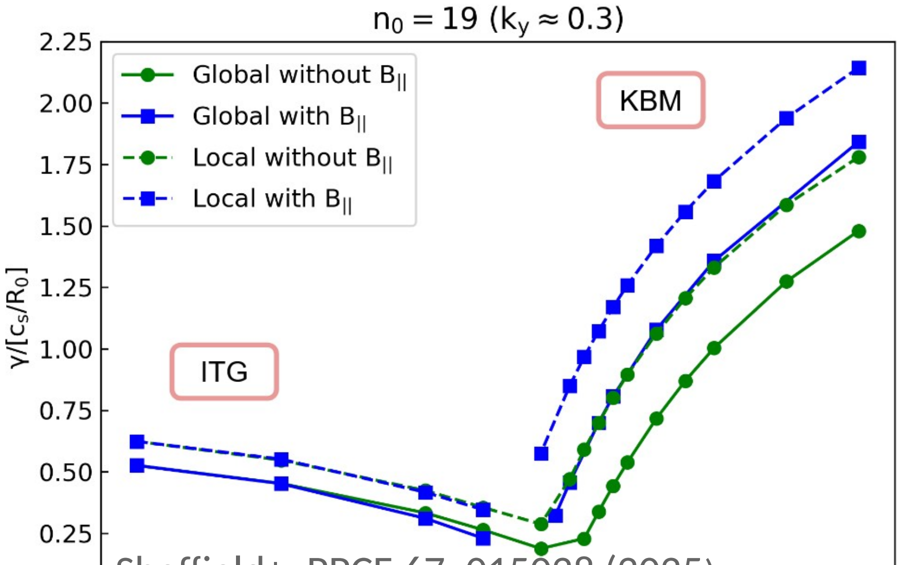
GK/MHD comparisons & extensions

- **Theory of consistency between MHD, drift-kinetics, and GK** explored [McMillan, JPP 89, 905890115 (2023)] with proposed extensions to global GK codes.

- **Prominent example** are parallel equilibrium currents relevant to **low-n kink physics**

Kinetic-Ballooning-Mode comparison between GK codes ORB5 and GENE with MISHKA (MHD) (setup: Martin-Collar+, PPCF 2020)





Sheffield+, PPCF 67, 015028 (2025)

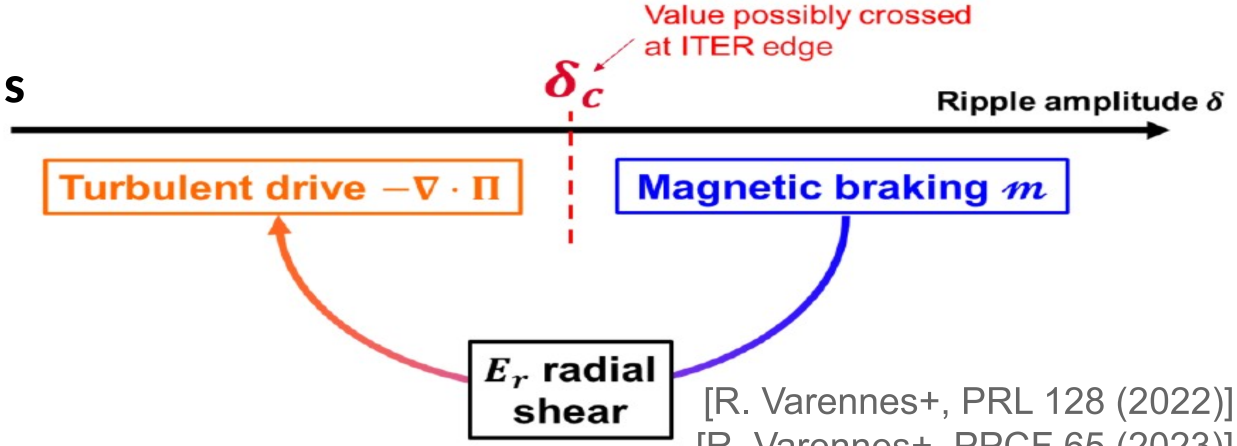
- **$B_{||}$ fluctuations** have recently been added to global ORB5 and GENE
- **Impact** currently studied in high-***β*** scenarios and on AUG pedestals
- **Linear benchmarks** between GENE and ORB5 promising but refinements on-going

GYSELA studies: Ripple and 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 braking** (~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



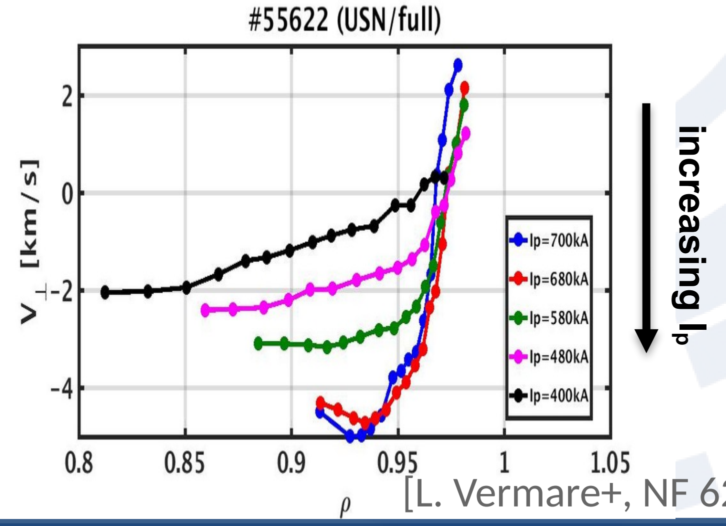
[R. Varennes+, PRL 128 (2022)]
[R. Varennes+, PPCF 65 (2023)]

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+, PPCF 66, 025003 (2024)]

Exp. influence of I_p on E_r profile



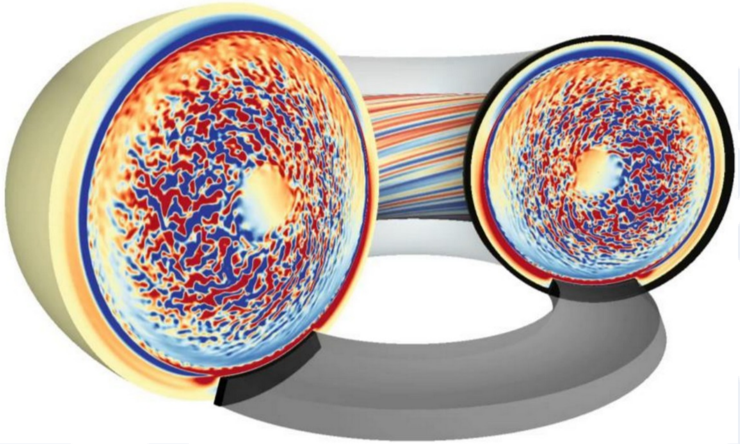
[L. Vermare+, NF 62 (2022)]

Edge radial electric field development in limited plasmas

- **Limited plasmas in GYSELA and ORB5**

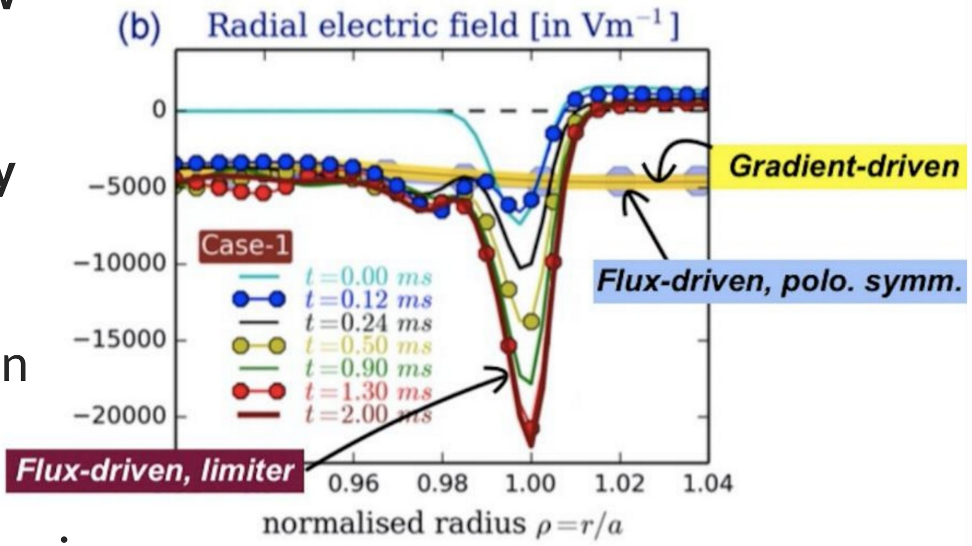
  penalization techniques on the distribution function and the quasi-neutrality equation
- **Adiabatic electron simulations give robust results**

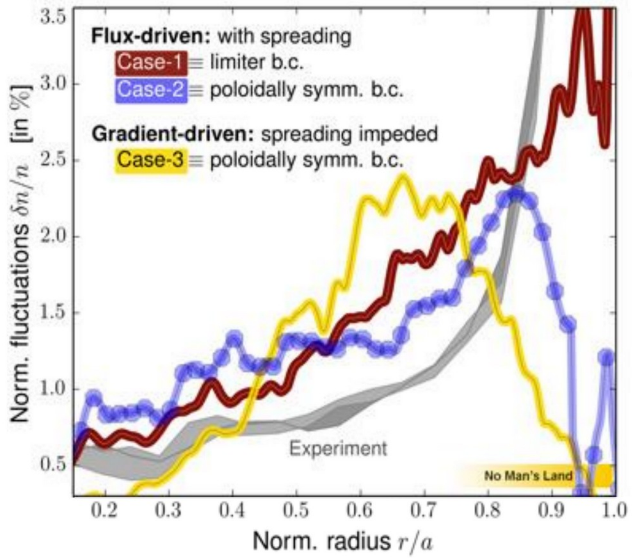
  E_r well established, fluctuations more realistic than poloidally symmetric b.c.



[Dif-Pradalier, Comm. Phys. 5, 229 (2022)]

- **Recent progress** implementing a **new quasi-neutrality (QN)** solver
  [P. Donnel+, OPS 1, 5 (2025)]
  - **Valid for any axisymetric geometry**
  - **3 models for electrons** (fully kinetic, adiabatic, trapped kinetic), LWA & **Padé** versions of polarization

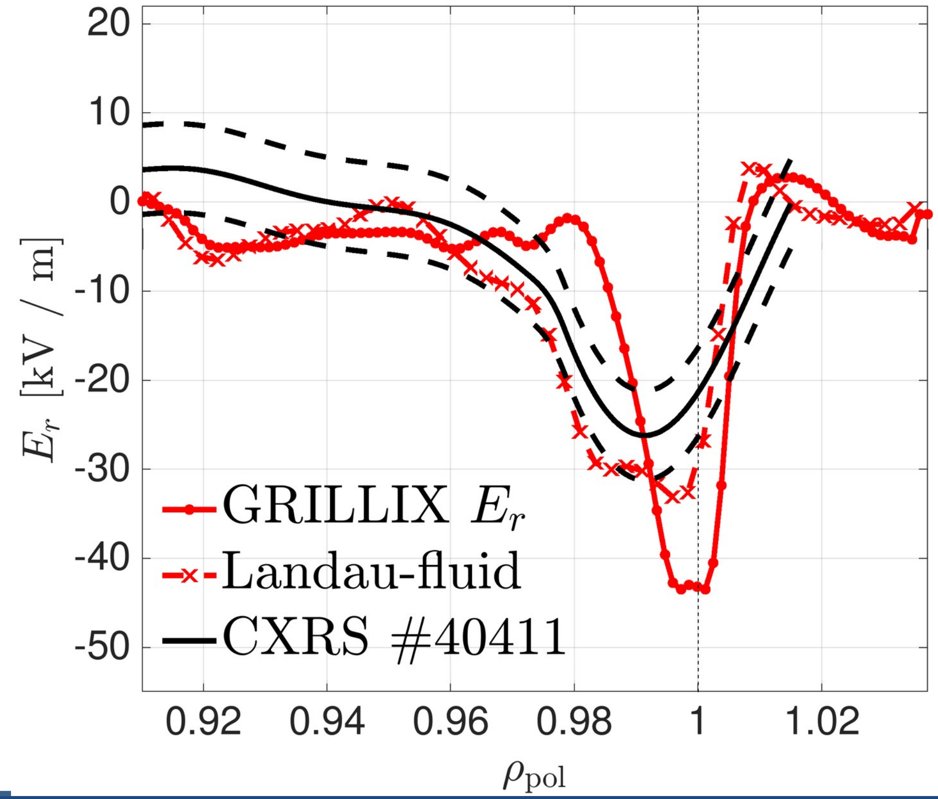


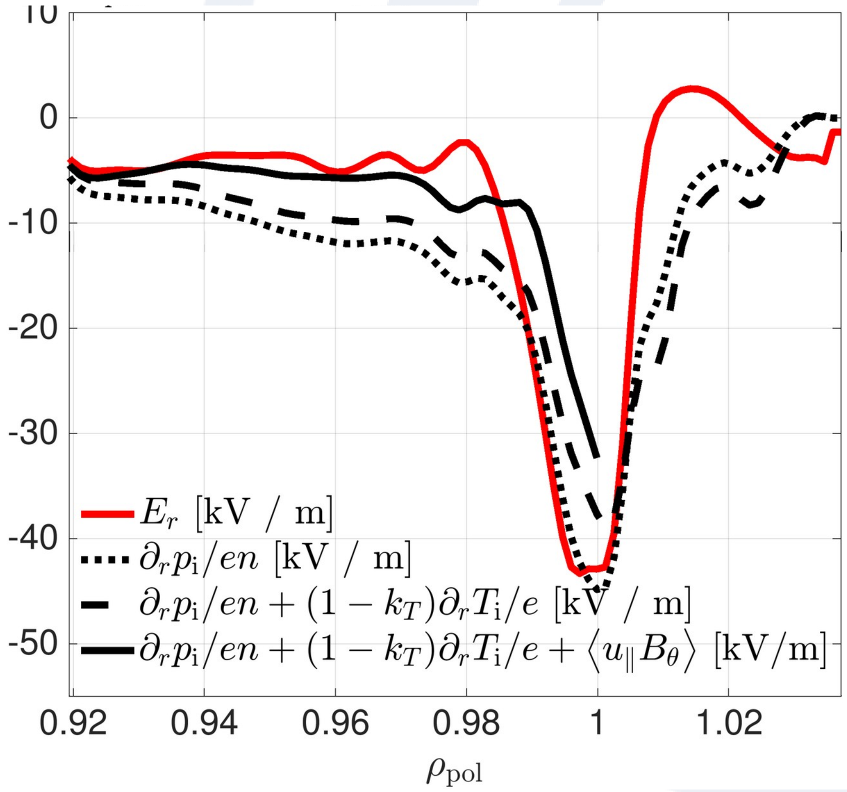


- **New ECRH heat source** for flux-driven sims.
  [Donnel+, PPCF 66, 095008 (2022); Cazabonne+, PPCF 65, 104001 (2023)]

H-mode simulations with self-consistent E_r with GRILLIX

- **Validated, electromagnetic turbulence simulations** were performed with the **transcollisional GRILLIX model**:
  [W. Zholobenko+, NF 64, 106066 (2024)]
- The **radial electric field**, as well as all **plasma profiles, agree well with the experiment** (an ITER baseline shaped H-mode AUG #40411), particularly with neoclassical ion viscosity and the Landau-fluid closure
- A composition analysis shows a **dominant contribution from the ion pressure gradient**. Poloidal and toroidal rotation are not negligible, but tend to be balanced by the zonal flow

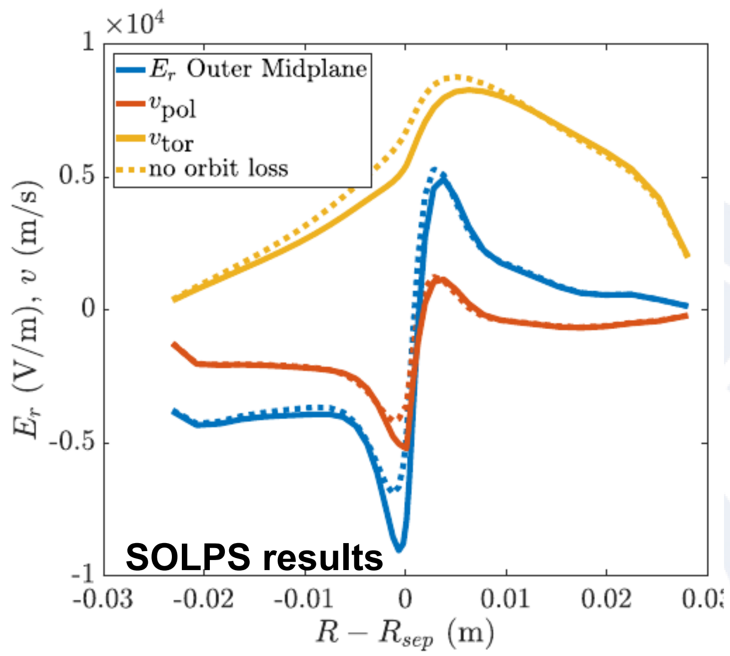




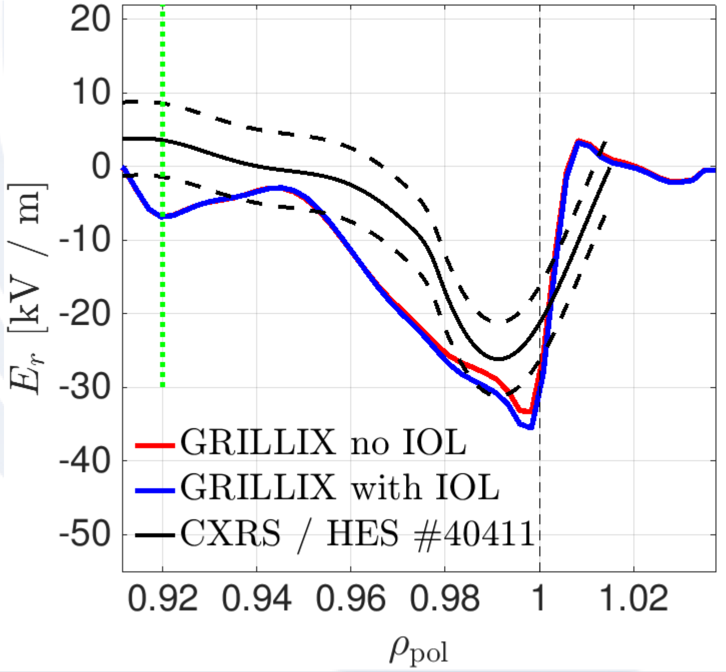
Ion-orbit loss effects

- **Ion-orbit loss model** [Brzozowski, PhD thesis, UCLA 2021]
  - E_r affected by ion-orbit losses
  - Poloidal asymmetries are less strongly forced
  - Coupled to SOLPS
- **Dedicated study of IOL model added to GRILLIX (Landau-fluid):**
  - ITER-baseline shaped AUG H-mode (see previous slide)
  - **E_r well deepens slightly, n/T change by 2-4% at most**
    → consistent with above findings and [Zhu et al., NF (2022)]
  - Based on these **single-case studies:**

    "mean-field IOL effect rather small"
- **IOL effect inherently present in TSVV4 GK codes**
  - Initial velocity space analyses and loss cone comparisons, qualitatively matching expectations



Courtesy: R. Brzozowski



Courtesy: W. Zholobenko (2025)

D4: L-H transitions: from fluid codes to TSVV4 code

An interpretative and predictive capability of L-H transitions

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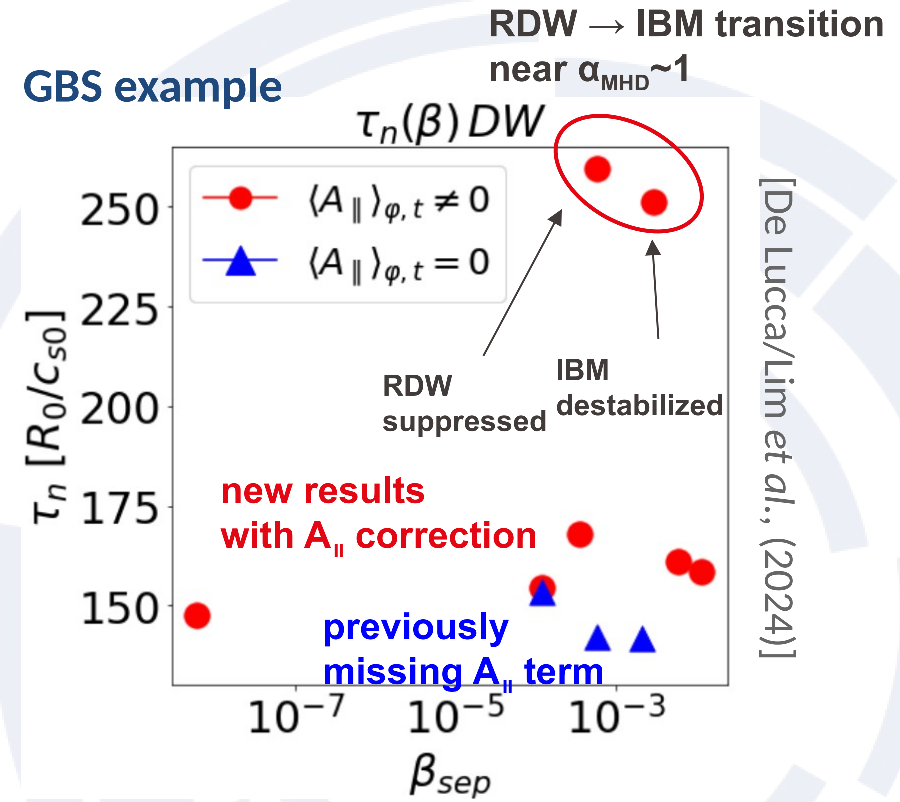
Power Ramp Studies & Scaling Laws

Electromagnetic edge turbulence with fluid codes

- **EM capabilities in GBS, GRILLIX, SOLEDGE3X greatly improved(*) (→ TSVV-3) – enables important edge physics:**
  - (Resistive) Drift-Wave stabilization
  - Inertial/Resistive Ballooning mode (I-/RBM) destabilization, also KBM in GRILLIX

(*)partly in TSVV-1: [Giacomin+, JCP 463, 111294 (2022)], [Düll+, JCP 536, 114052 (2025)], [B. De Lucca+, JPP accept. (2025)]

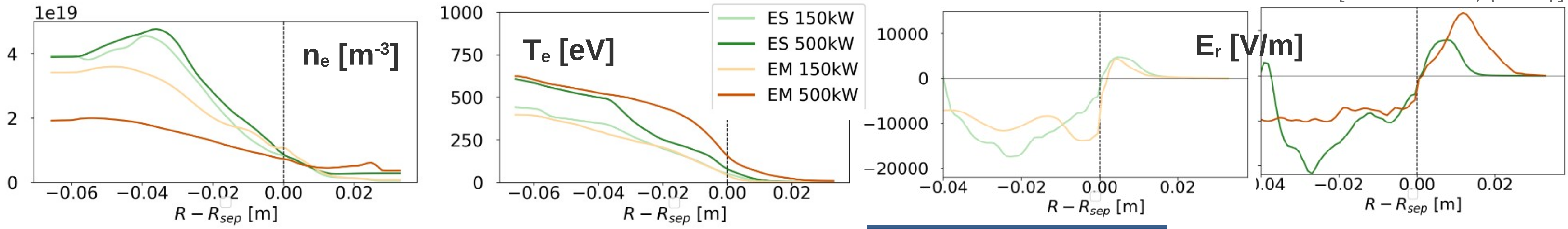
GBS example



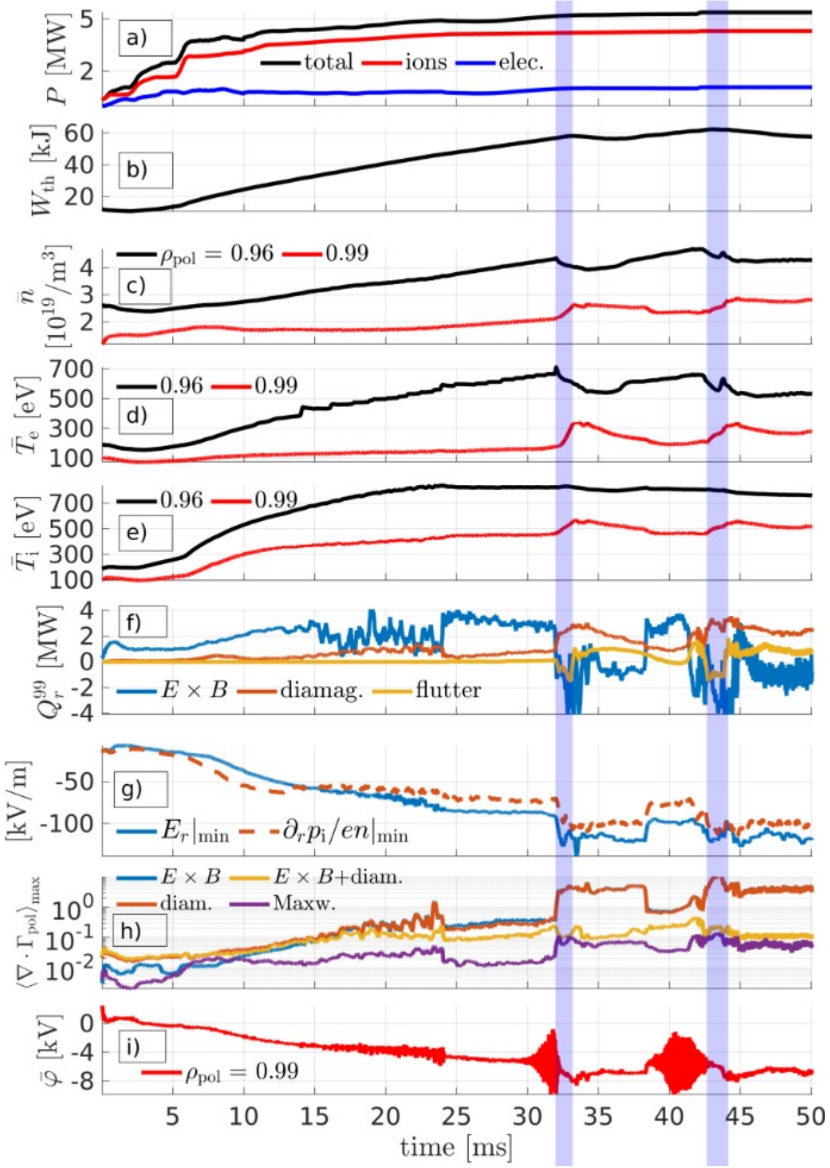
[De Lucca/Lim *et al.*, (2024)]

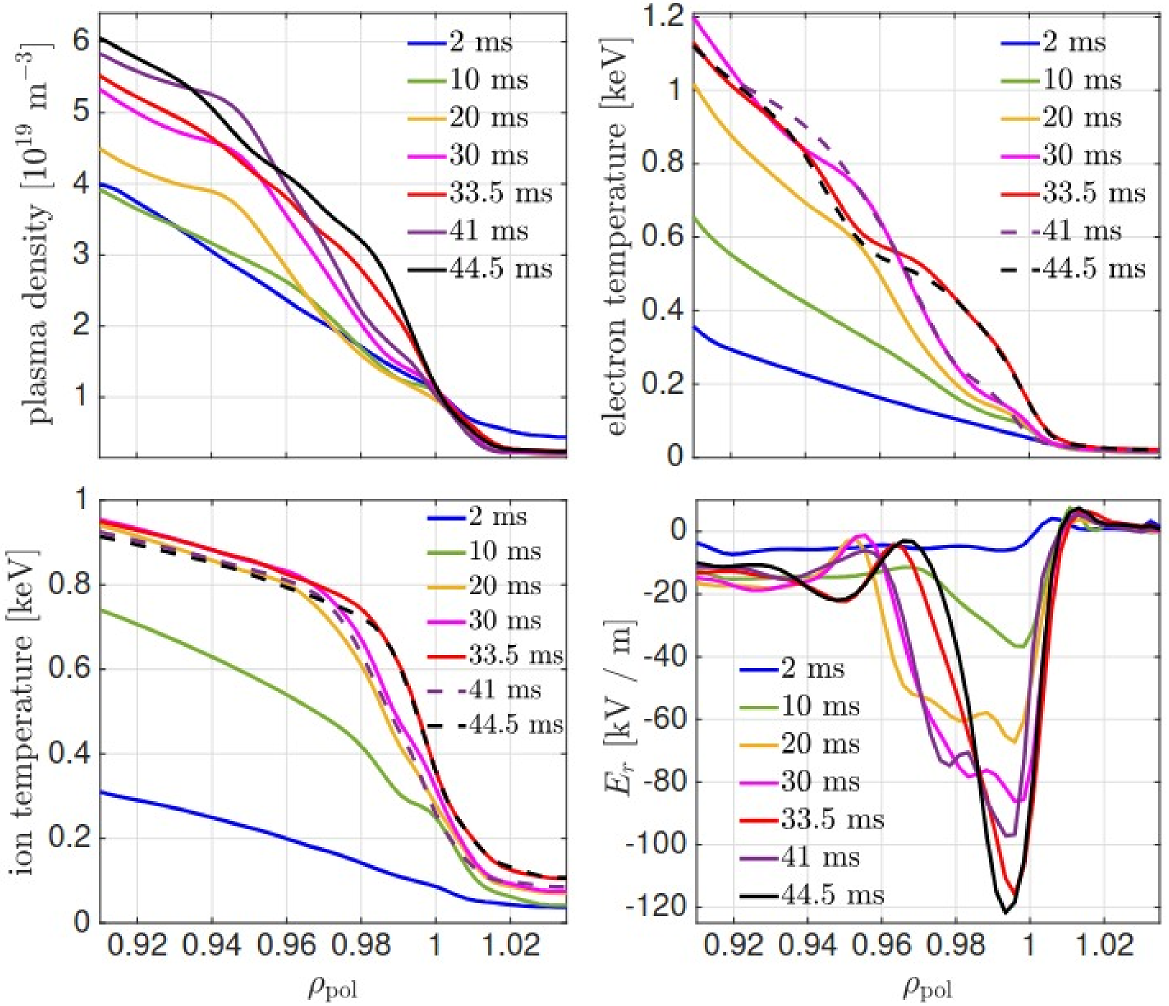
- **SOLEDGE3X power scan for TCV-X21 Benchmark Case:** particle source driven by fluid neutrals [Quadri+, NME 41 (2024)]
  - **E_r well** development + **profile steepening**
  - **EM impact visible** – however, profiles not yet converged

[R. Düll *et al.*, (2025)]



L-H (-I) power ramp with GRILLIX (EM + diffusive neutral gas model)

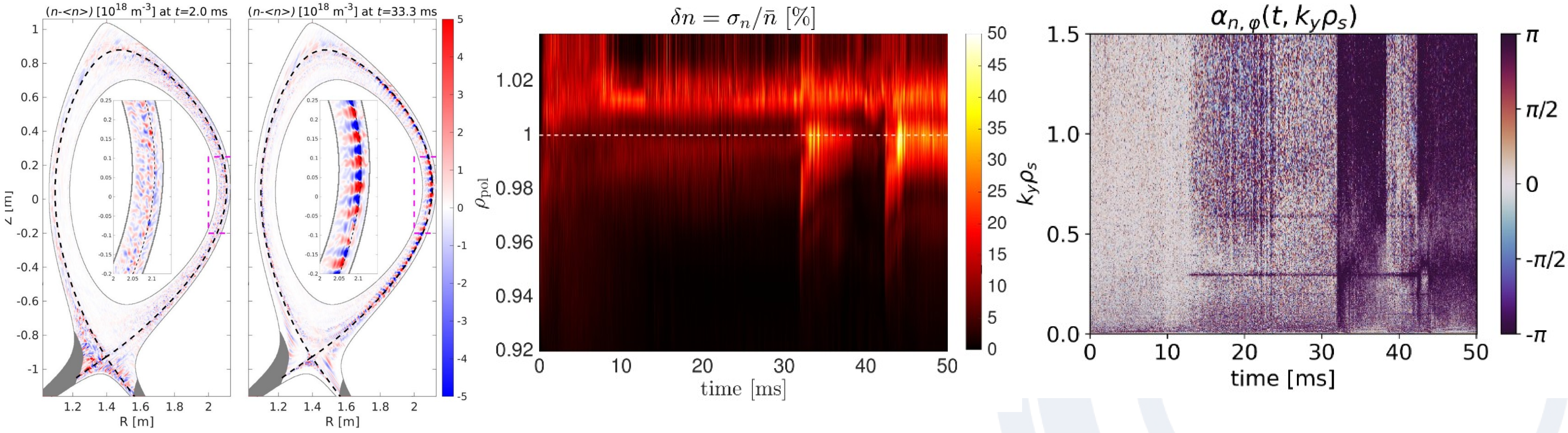




W. Zholobenko+, PRL accepted (2026)

- After 32ms of slow profile evolution, **sudden change in transport**, leads to **fast pedestal build-up**
- **Slow oscillations** reminiscent of I-phase or ELM cycles **hereafter**

Fast turbulence phase transition observed with GRILLIX



- **GAMs** found **prior** to transitions, **high-frequency oscillations** (HFO, Alfvenic) as **precursors**, and **low-frequency** (LCO) **after**
- **Cross phase (n,Φ) shifts** from **drift wave to KBM** character

- **Important step forward** – but, e.g., E_r too deep as the pedestal is too steep: missing PB modes (ELMs) and/or GK TEM/MTM/ETG → **further studies required (TSVV-A/C)**

W. Zholobenko+, PRL accepted (2026)

LH transition: Initial theoretical power threshold scaling laws

- **Based on large GBS parameter scans** (ν_{coll}, β, heat source) **identifying main modes/boundaries**, e.g., [Giacomin+, PoP 29, 062303 (2022), PRL 128, 185003 (2022)]

  → minimal model for LH transition

  – Electrostatic resistive-ballooning turbulence (L-mode) to EM-suppressed resistive drift-wave (increased heating) [Rogers, Drake & Zeiler 1998]

  – Theoretical scaling law good match with ITPA scaling [Martin et al. 1999]

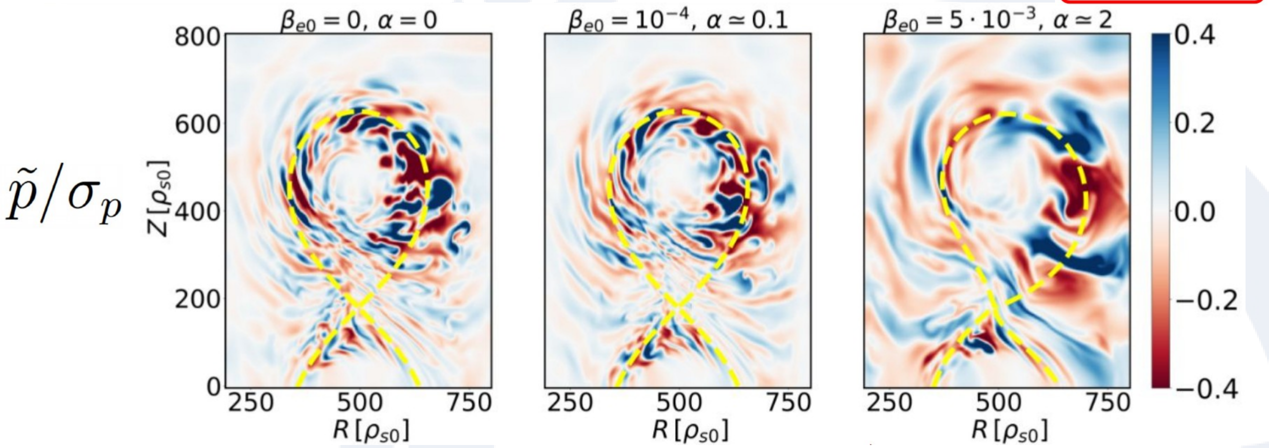
$$P_{th}^{phys} \sim n^{0.83} B_T^{0.65} a R_0^{0.72} A^{-0.49} q^{-0.34} \; , \; P^{ITPA} \sim n^{0.782} B_T^{0.772} a^{0.975} R^{0.999}$$

B. De Lucca et al, TSVV1 workshop 2024

Resistive-ballooning turbulence (α>1)

Ideal MHD Ballooning strength

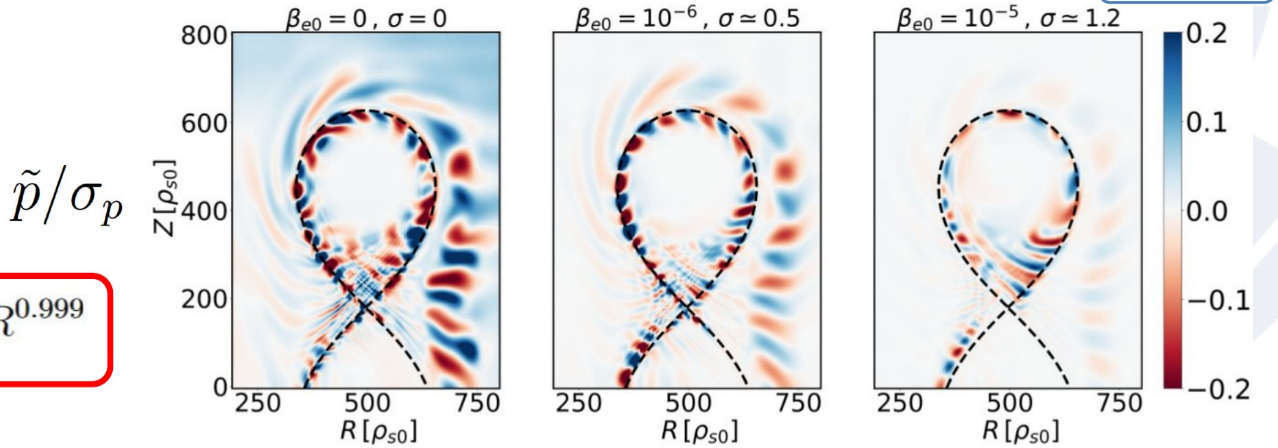
$\alpha = -q^2 R_0 d\beta/dx$



EM suppression of drift-wave turbulence

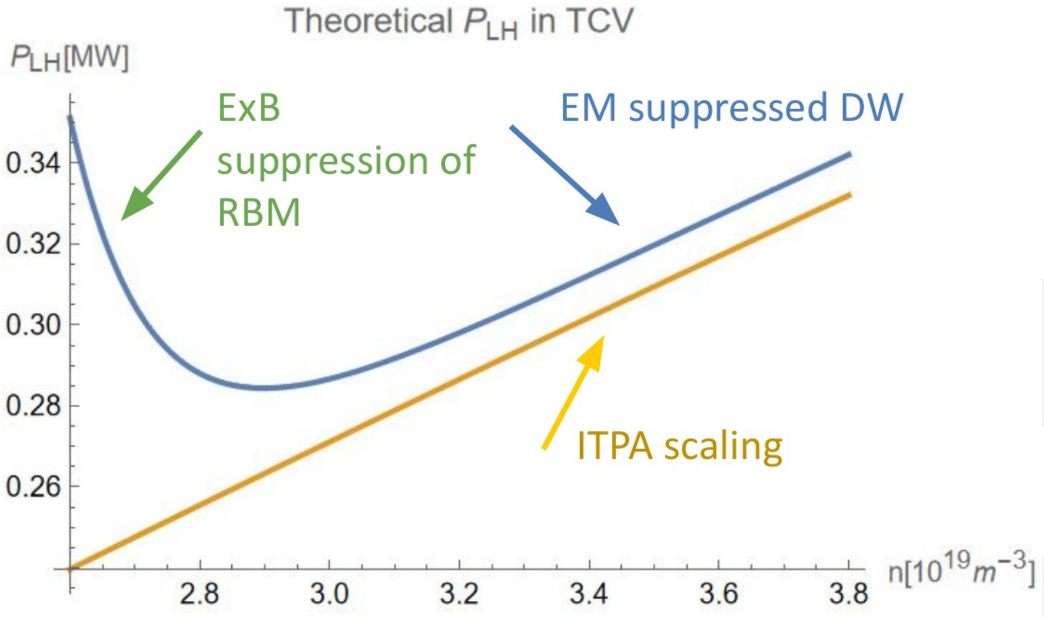
Resistive drift-wave suppression strength

$\sigma = \frac{\beta_0 T_e \gamma_{ES}}{\nu}$



LH transition: Accounting for ExB shear

- **ExB shear impact? (On-going GBS work, tentative)**
  - Linear theory: ExB suppression of fluid turbulence most effective for large collisionalities → RBM turbulence (L-mode)[Giacomin 2022]
  - Here: Modified gradient saturation mechanism [Biglari et al 1990, Garcia et al 1999] used
  - Improving model to account for ExB suppression of L-mode turbulence yields also T > T_{crit} [Righi et al 2000]



$$T_c^{th} \sim n^{-0.73} B_t^{1.30} A^{-0.064} q^{-1.46} R_0^{-0.34} \quad , \quad T_c^{exp}(keV) = (0.39 \pm \delta) n^{-0.64\pm0.15} B_T^{1.69\pm0.18} A_{eff}^{-0.14\pm0.19} q^{-0.86\pm0.57}$$

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

[B. De Lucca+, TSVV1 workshop 2024]

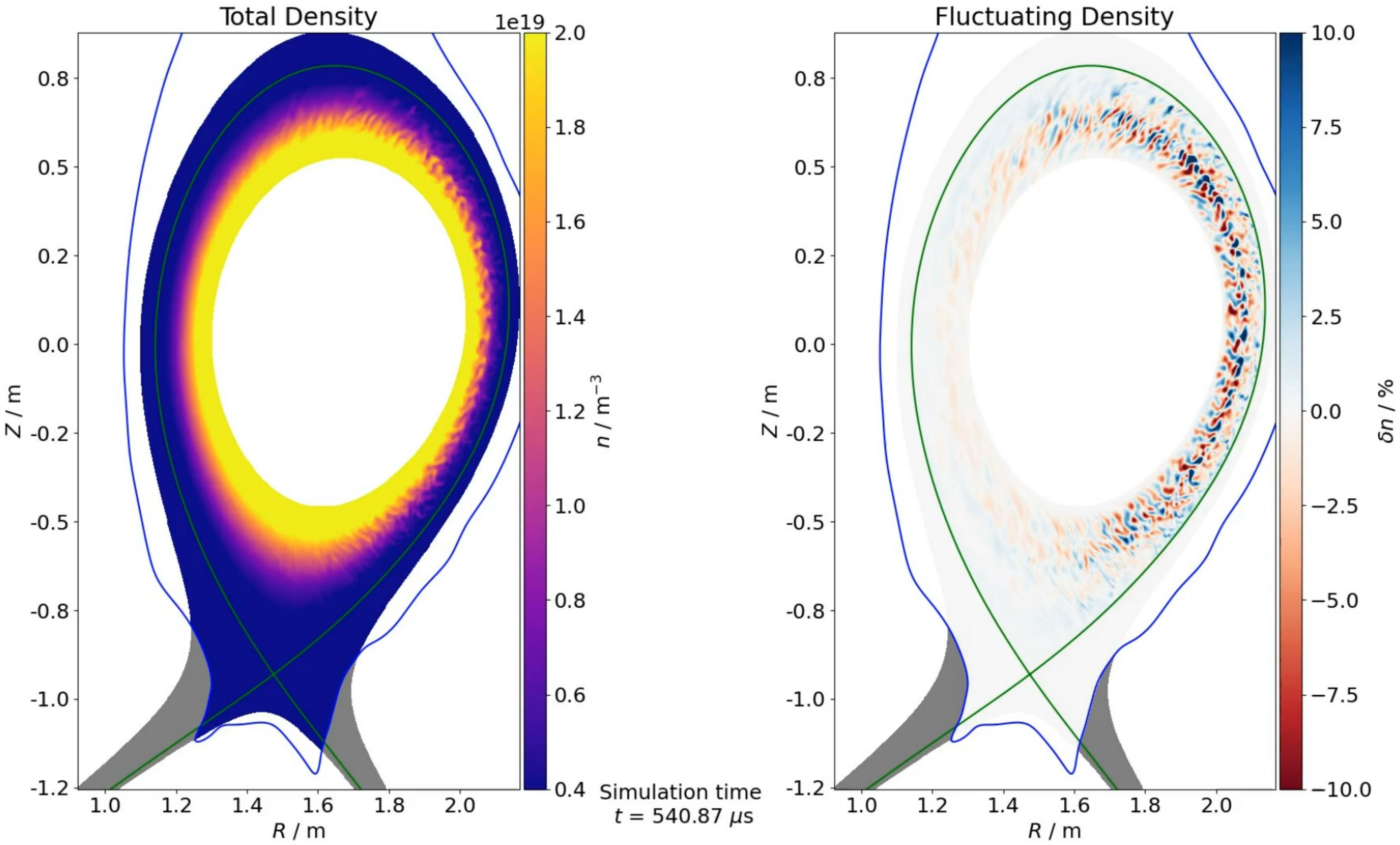
- **With ExB: ITPA scaling + critical temperature for LH transition for n>n_{thresh} but non-monotonic density dependence** → further NL studies needed, also kinetic effects, small-scale physics etc missing
- Also, **scalings for H-L backtransition & triangularity** [Lim+, NF 64, 106057 (2024)]/[Lim+, PPCF 65, 085006 (2023)]

D3: Goals for consistent application of TSVV4 code(s)

Consistent application of new Task 4 edge GK code
bridging core, pedestal, and SOL region including neutral physics
-
Comparison with previous findings, revision of separatrix b.c. etc

Towards global gyrokinetic simulations of H-mode and LH-transitions: pre-LH L-mode in AUG with GENE-X

- **Joint project:** Code developed within TSVV4, used in TSVV1 application case
- Simulation re-creates features from previous L-mode studies in AUG*
- Detailed comparison with fluid results for TCV-X21 [P. Ulbl+, PoP30 (2023)]
- Initial power-ramp studies (see next slide)



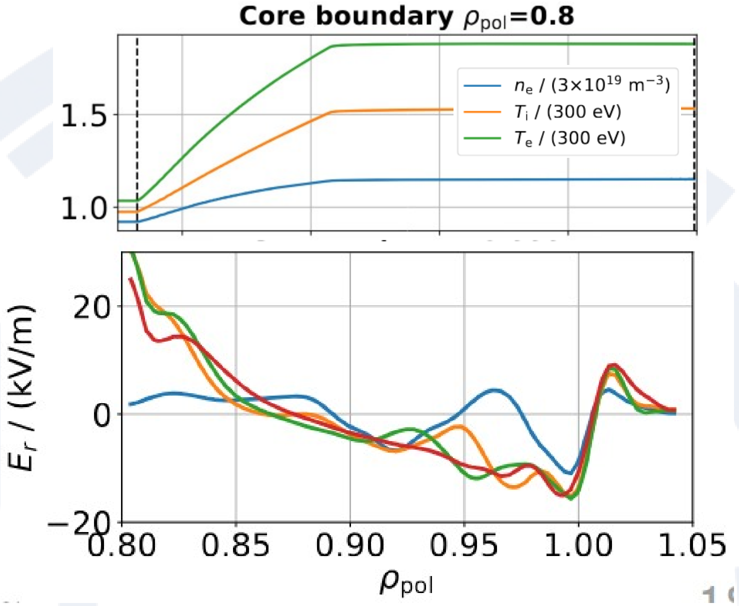
[P. Ulbl]

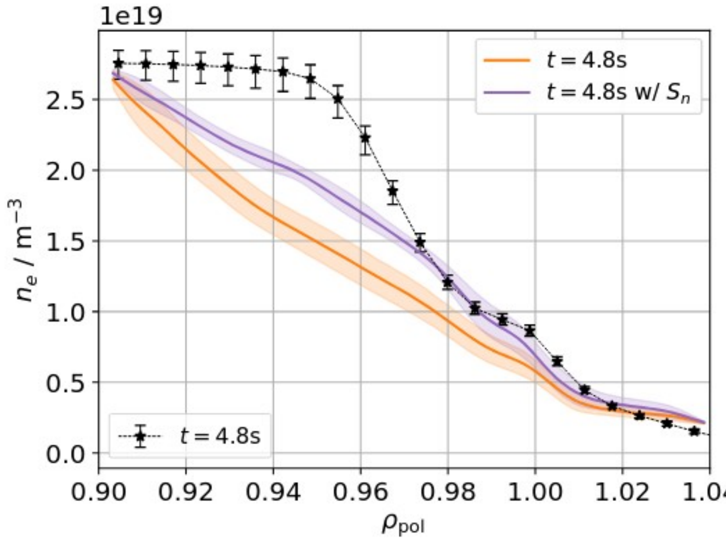
* [D. Michels, P. Ulbl+, PoP 29 (2022)]

Towards L-H transition type modeling with GENE-X

- **Initial power-ramp attempts in 2024 adjusting inner BC**
  - **promising: turbulence suppressed state** and **E_r well development**
  - **but: density** greatly **underpredicted**
- H-mode access depends on separatrix density via power threshold → crucial to achieve accurate density profiles
- Achieving realistic density profiles **requires a near-separatrix source** term, **ideally self-consistent source w/ neutral ionization**
- Now, **ad-hoc density source:** n_{sep} ↗, T_{sep} ↘ - consistent with GRILLIX results w/ and w/o neutrals [Zholobenko et. al, NF61 (2021)]
- Furthermore, implemented **Neumann b.c. for flux-driven simulations**

→ **well prepared for TSVV-A**





D5: Goals for red. transport model development for the pedestal on the basis of GK simulations

Reduced transport models for the pedestal on the basis of GK simulations, involving electron-/ion-scale, and MHD-like instabilities

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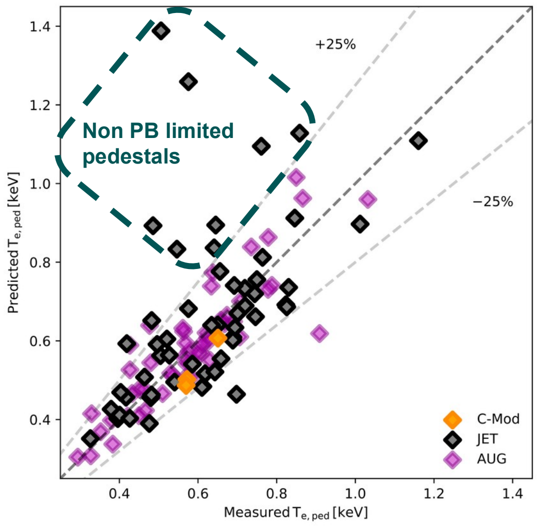
Revision of heuristic models (IMEP),
Assessment of reduced models (TGLF, QuaLiKiz) for core-edge coupled flux-driven integrated modeling, reduced models for selected edge/pedestal modes

From multi-machine validation to reactor predictions with IMEP

Integrated Model based on Engineering Parameters (IMEP)
coupling empirical pedestal transport model, TGLF (turb. transport), NLCASS (nc. transport), MISHKA (MHD stability), extended 2-point model (SOL)

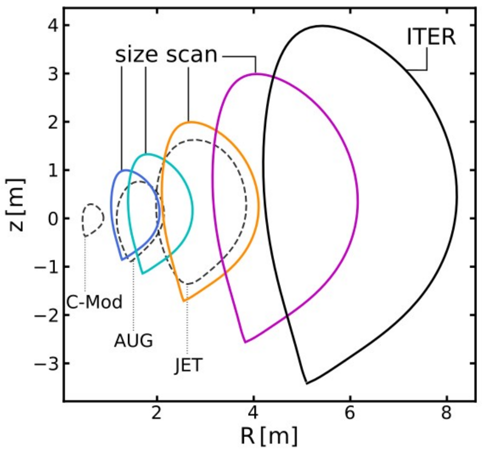
- **size scan test with resized ITER shape** (R=1.5–4.6m) at constant B_t, q_{95} (I_p increasing with R), heating power & density reveals **same trend as IPB98(y,2)**, **more optimistic than ITPA20-IL**, and similar to Bohm-gyroBohm
- **prediction for ITER 15MA baseline** gives pedestal top pressure p_{top}=140kPa (similar to EPED) and Q=12

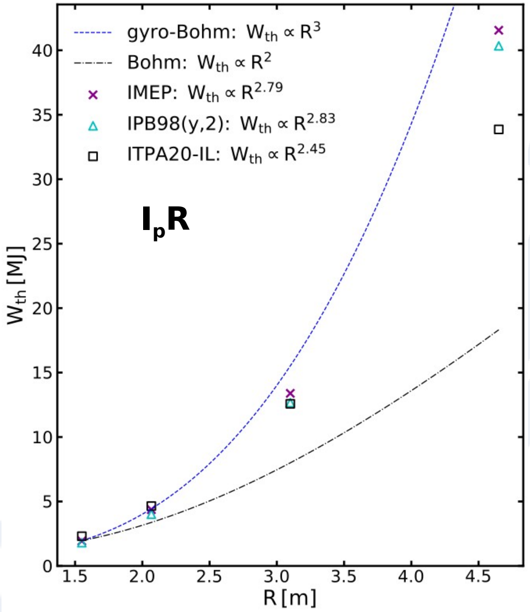


[T Luda+, *PPCF* **65** 034001 (2023)]

Recent refinements [M. Bergmann et al.]

- Handle different **ETG and MTM reduced models** for the electron heat transport to reduce reliance on exp. observations
- Consider correction term for ExB reduction
- For high density/collisionality, viscoresistive MHD required → **coupling to CASTOR-3D code**



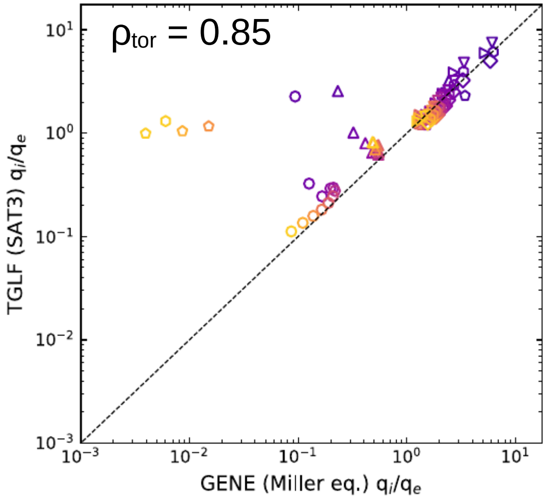


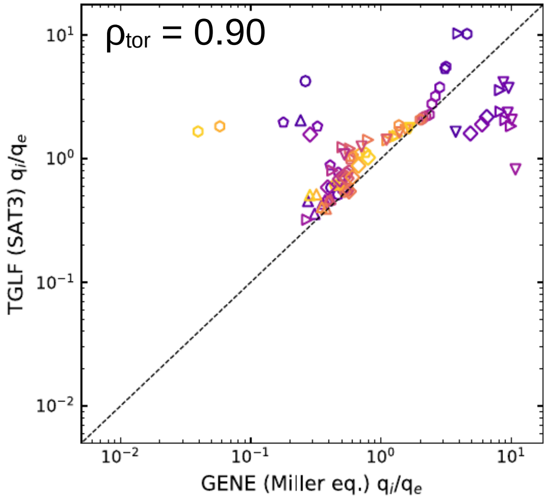
T. Luda+, NF 65, 072001 (2024)

Verification of reduced-order turbulence models

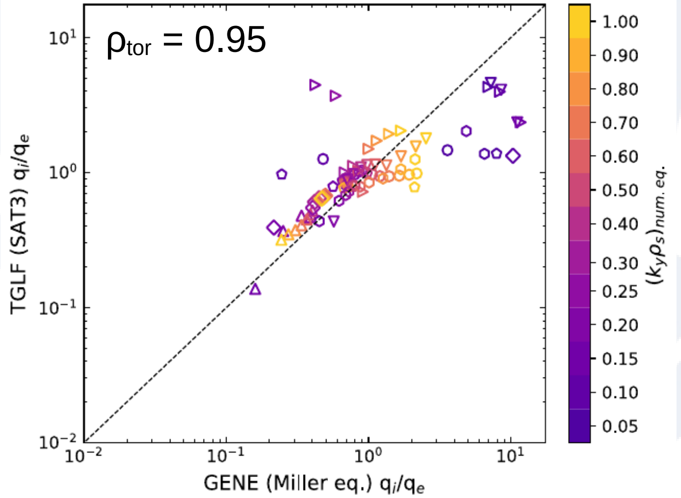
G. Snoep et al., NF subm. (2024)

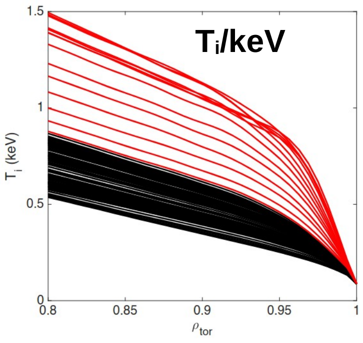
- **High-dimensional micro-instability characterisation:**
  - 7 NBI-heated JET-ILW discharges with two similar $P_{L\text{-}H}$ vs n_e scans studied with GENE
  - collisionality, EM, isotope mass, toroidal rotation, geometry with optional improved parametrization [Snoep+, PoP 30, 063906 (2023)]

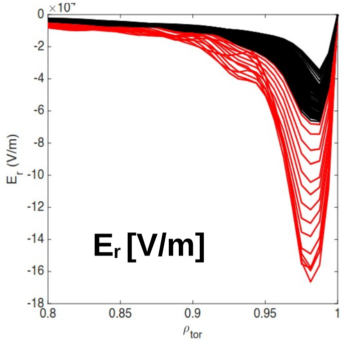




- **Extensive reduced model comparisons for characterisation:**
  - **QuaLiKiz** is **useful** at ρ_{tor} = 0.85 and 0.90, but not beyond
  - **TGLF-SAT2 matches** GENE **well**, except at 0.95 in JET scenarios at hand (collision operator not fitted beyond certain limits)







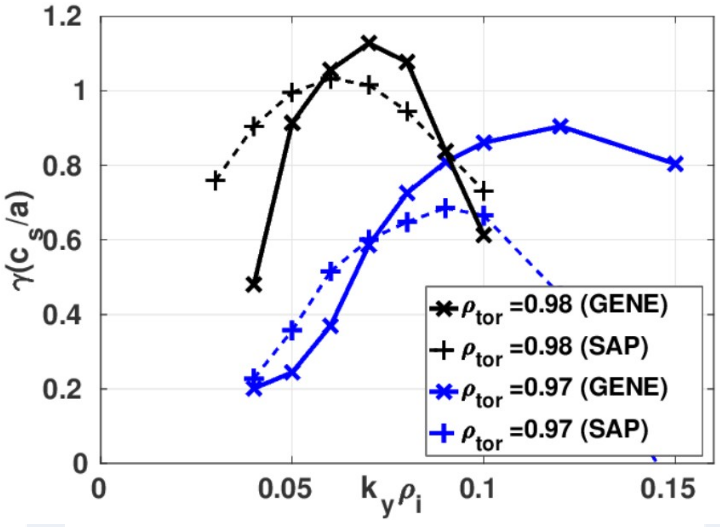
N. Bonanomi et al.

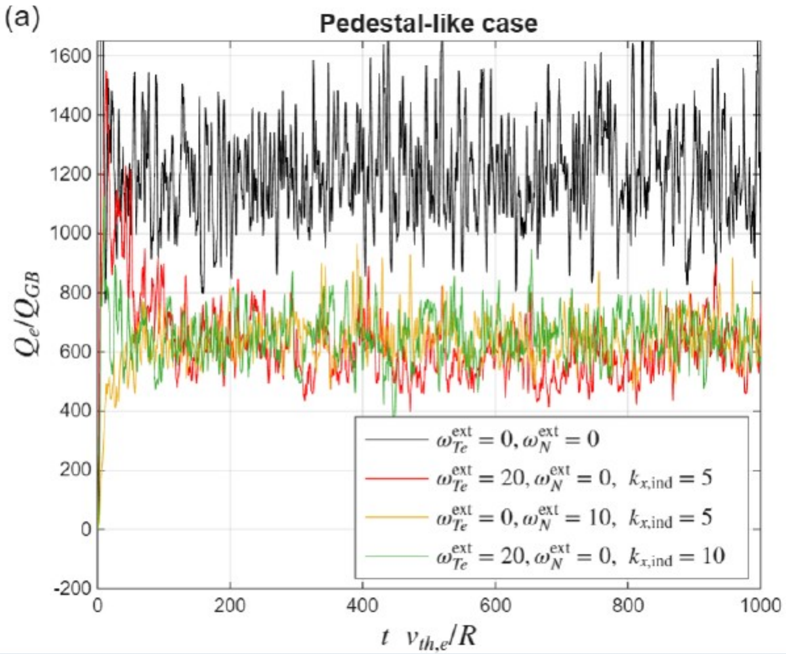
Relevant to ASTRA/TGLF-based LH modeling attempts, e.g., [Bonanomi+, EPS 2022]

Reduced model development for electromagnetic edge modes

- **Reduced model for Microtearing Modes (MTM):**
  - Parallelized **MT eigenvalue solver Solve_AP** enables **very fast computation**
  - **Good Solve_AP/GENE(linear) agreement** for JET #82585 pedestal scenario
  - **For nonlinear saturation modeling,** detailed study on role of the electric potential on MT turbulence [M. Hamed+, PoP 30, 042303 (2023)]
- **Extended KBM Eigenvalue Yielder (KEY) code ↔ more flexible geometry** comparisons to linear GENE show **good KBM growth rate & threshold match**

Solve_AP & GENE for JET #82585





Studied MTM / ETG interaction for reduced modeling:
MTM induced corrugations on pedestal electron temperature gradient modeled as sinusoidal functions

- ETG mode **splits into 3 distinct eigenvalues** (original, more+less unstable)
- **Nonlinear** GENE simulations: **significant flux reduction**(!)
- **Reason:** Profile shearing from radial variation of the mode's own phase velocity (∝local diamagnetic drift velocity & pressure gradient)

[Ajay C.J.+, NF submitted (2025)]

Possible issues for reduced modeling → near-marginality

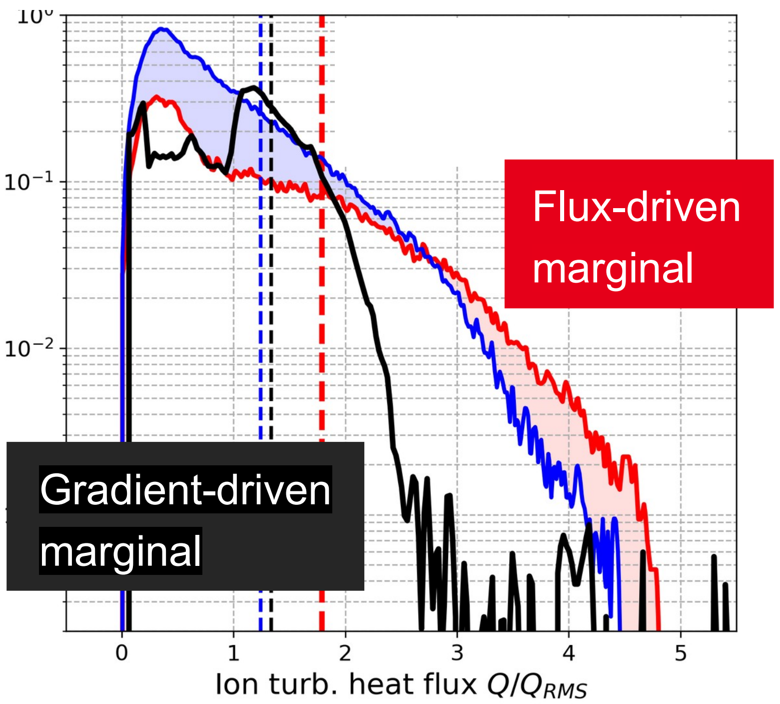
Compare: **GYSELA** (flux-driven) ↔ **GKW & GENE** (local, GK) ↔ **Qualikiz** (QL)

✓ adiabatic electrons ✗ trapped kinetic electrons (ongoing)

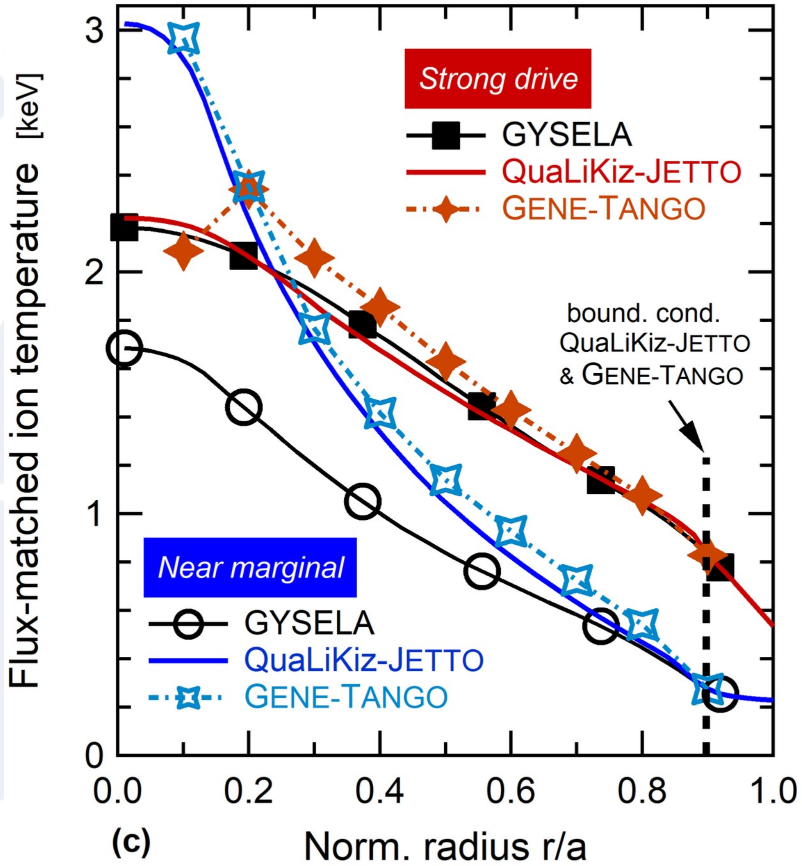
Adiabatic electron response:

Same heat fluxes, magn. equilibrium, shear rates, etc. → **what profiles?**

- Consistent fluxes across codes, when strongly driven
- Large **transport under-prediction @marginality**



[C. Gillot+, PPCF 65, 055012 (2023)]



Kinetic electrons @different forcings:

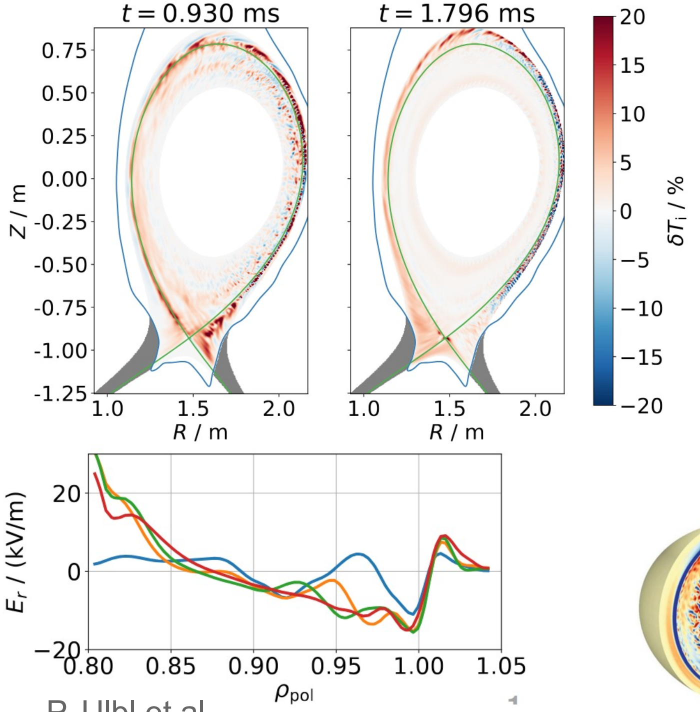
- So far: "flux-driven" *versus* "gradient-driven" GYSELA
- **Same input gradients → different output fluxes & flows**
- Comparison with GKW and Qualikiz ongoing → **TSVV-A**

G. Dif-Pradalier+, (2025)

Summary & Outlook

E_r development & towards L-H transition (flux-driven)

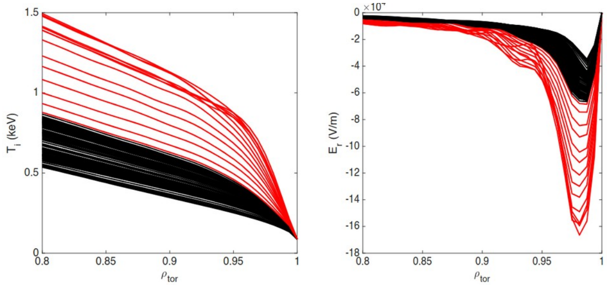
GENE-X



P. Ulbl et al.

First promising flux-driven TSVV-4 GK code results in diverted/limited configurations

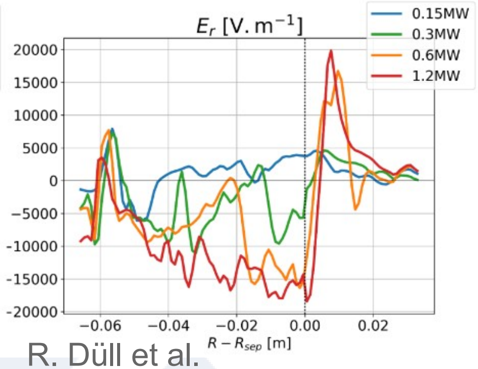
ASTRA-TGLF



N. Bonanomi et al.

E_r well in fast red. models

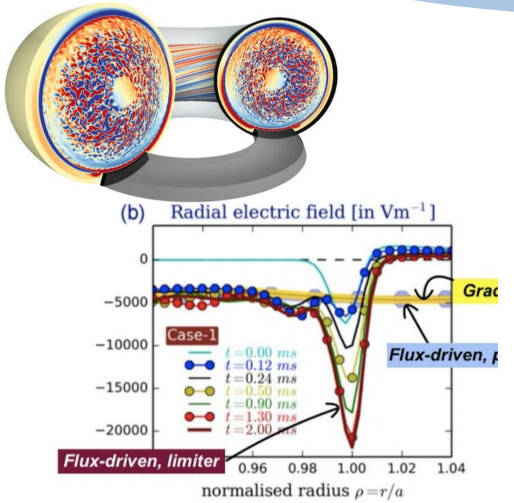
SOLEDGE-3X



R. Düll et al.

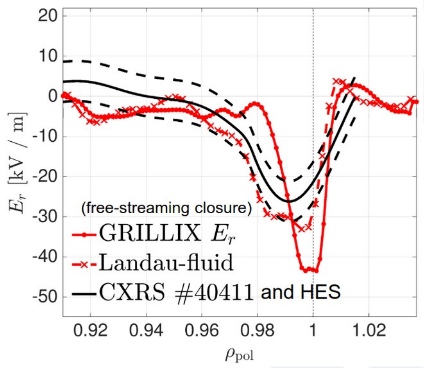
high to low fidelity

GYSELA



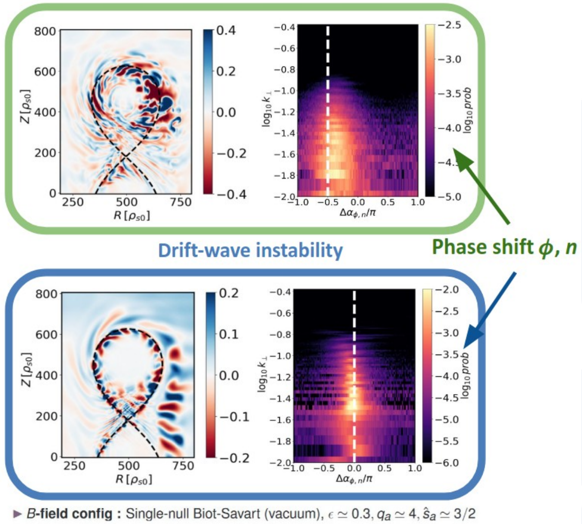
Dif-Pradalier, Comm. Phys, 2022

GRILLIX



W. Zholobenko et al.

GBS



$$P_{th}^{phys} \sim n^{0.83} B_T^{0.65} a R_0^{0.72} A^{-0.49} q^{-0.34}$$

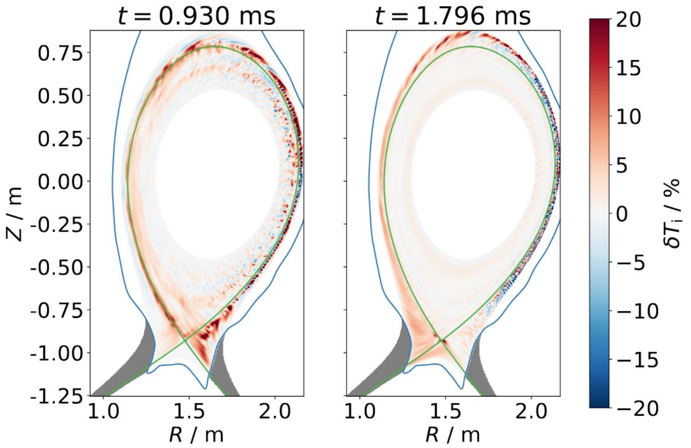
$$T_c^{th} \sim n^{-0.73} B_t^{1.30} A^{-0.064} q^{-1.46} R_0^{-0.34}$$

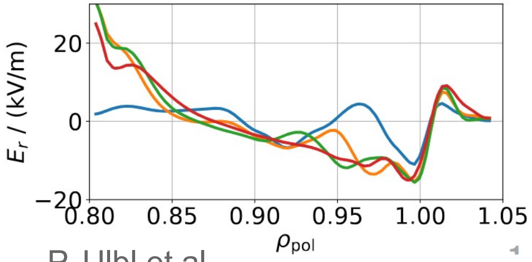
B. De Lucca et al.

Fluid-based scalings, characterisations, and fast phase transitions in power ramps

E_r development & towards L-H transition (flux-driven)

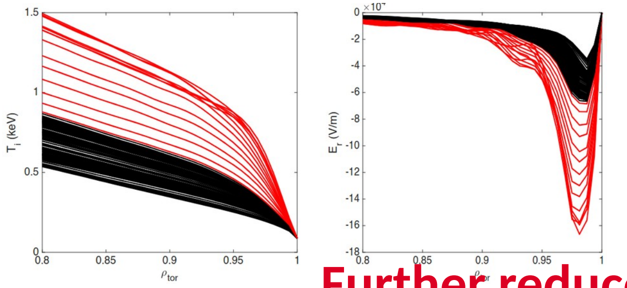
GENE-X





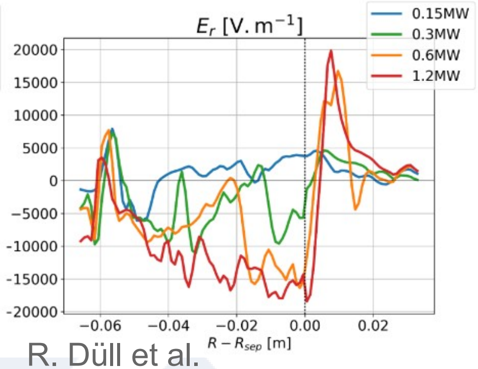
P. Ulbl et al.

ASTRA-TGLF



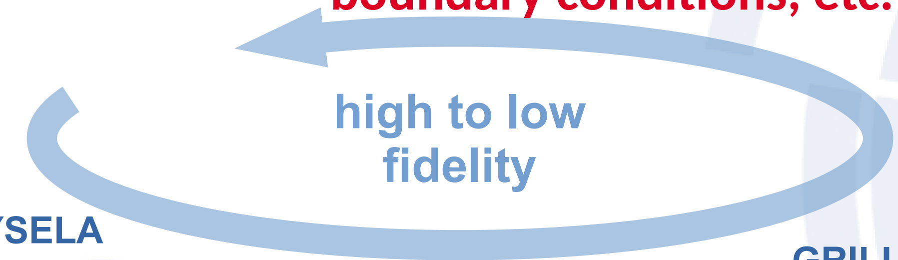
N. Bonanomi et al.

SOLEDGE-3X

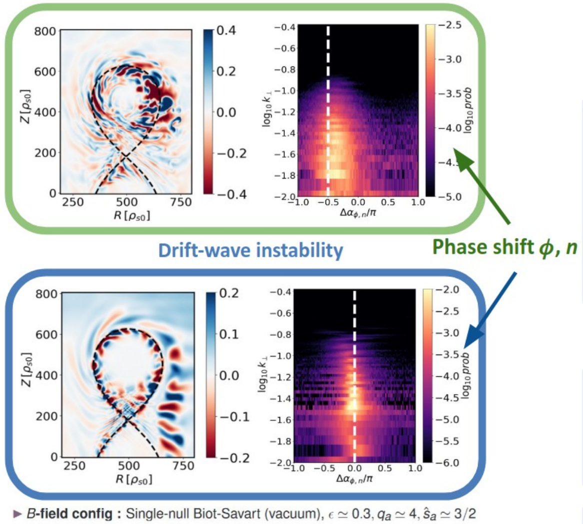


R. Düll et al.

Further reduced models, boundary conditions, etc.



GBS



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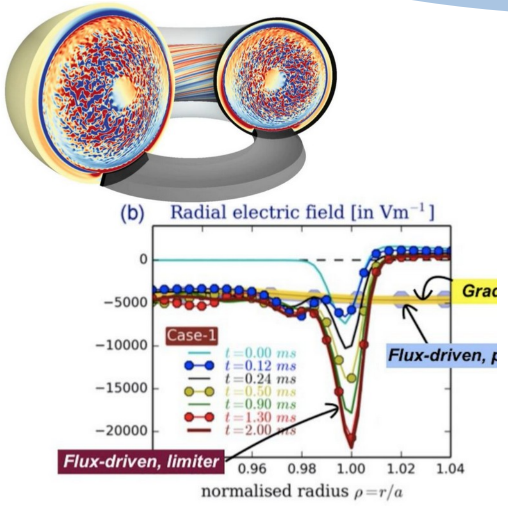
$$T_c^{th} \sim n^{-0.73} B_t^{1.30} A^{-0.064} q^{-1.46} R_0^{-0.34}$$

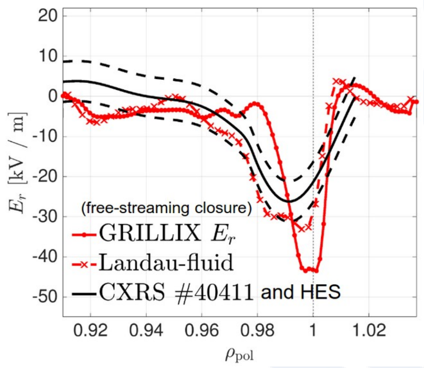
B. De Lucca et al.

GYSELA



Dif-Pradalier, Comm. Phys, 2022

GRILLIX



W. Zholobenko et al.

Missing physics: Neutrals, electron scale contributions, improved sheath models ...

Work on physics models (neutrals, ion-orbit-loss impact, ...)

Summary & Action Items recommended to TSVV-A and others

Turbulence characterisation for L-,I-,H-,EDA-H-modes: KBM proximity, ETG relevance, ExB/magnetic shear impact, impurities, ITB insights, validation	**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, IOL assessments, 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 flux-driven Edge/SOL ↔ E_r studies in comparison to exp. • 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 ▪ extend KBM reduced models, ...

Project activities / outreach

- **Meetings (51 in total):**

  Regular video meetings, see https://indico.euro-fusion.org/category/274/

  Annual Progress workshops (incl. WPTE, TSVV-4 representatives & further GK pedestal experts)
  - 2021: https://indico.euro-fusion.org/even/1213
  - 2022: https://indico.euro-fusion.org/event/2166/
  - 2023: https://indico.euro-fusion.org/event/2647/
  - 2024: https://indico.euro-fusion.org/event/3110/
  - 2025: https://indico.euro-fusion.org/event/3550/

- **External communication:**

  TSVV-01 wiki - https://wiki.euro-fusion.org/wiki/TSVV-01

  incl. project reports & proposals, project presentations at thrust or WP meetings, list of publications

  As discussed within thrust 1, **invited WPTE GK edge/pedestal researchers** to annual workshop to establish/facilitate mutual information flow.

  Links to other TSVVs via **staff overlap** and **mutual invitation of PIs** to meetings (esp., TSVV-04)

TSVV1 code coordination / ACH support

- **TSVV-01 code coordinator for “GENE”**
  - ACH MPG support for the on-going GPU porting / stream-lining highly appreciated
  - similarly, ACH IPPLM support for imasification (so far, code inputs) very valuable
  - GENE ported to EUROfusion gateway
  - EUROfusion standard software entries extended, respectively, and wrt. to V&V; GENE/GENE-X workshop / tutorial conducted in Jan 2026

- **Further ACH support requested by TSVV1 acknowledged:**
  - EPFL – GPU porting support for ORB5
  - EPFL - Community visualization tools
  - IPPLM - Imasification of TSVV1 codes (e.g., above)
  - VTT – in-situ diagnostics (first, GYSELA), e.g., anomaly detection

List of publications

Year	Author(s)	Title	Journal / Meeting	Pinboard ID / link
2021	H. Bufferand, ..., G.L. Falchetto et al.	Progress in edge plasma turbulence modelling hierarchy of models from 2D transport application to 3D fluid simulations in realistic tokamak geometry	Nuclear Fusion 61, 116052 (2021)	29527,29530
2022	G. Di Giannatale et al.	Triangularity effects on global flux-driven gyrokinetic simulations	J. Phys.: Conf. Ser. 2397 012002 (2022)	N/A
2022	P.D. Donnel et al.	Electron-cyclotron resonance heating and current drive source for flux-driven gyrokinetic simulations of tokamaks	Plasma Phys. Control. Fusion 66, 095008 (2022)	31366
2022	M. Giacomin et al.	Turbulent transport regimes in the tokamak boundary and operational limits	Physics of Plasmas 29, 062303 (2022)	31742
2022	M. Giacomin et al.	First-principles density limit scaling in tokamaks based on edge turbulent transport and implications for ITER	Physical Review Letters 128, 185003 (2022)	30417
2022	M. Giacomin et al.	The GBS code for the self-consistent simulation of plasma turbulence and kinetic neutral dynamics in the tokamak boundary	Journal of Computational Physics 463, 111294 (2022)	29830
2022	G. Snoep et al.	Improved flux-surface parameterization through constrained nonlinear optimization	Physics of Plasmas 30, 063906 (2023)	33548
2022	K. Stimmel et al.	Gyrokinetic analysis of an argon-seeded EDA H-mode in ASDEX Upgrade	Journal of Plasma Physics 88, 905880315 (2022)	30860
2022	R. Varennes et al.	Synergy of Turbulent Momentum Drive and Magnetic Braking	Physical Review Letters 128, 255002 (2022)	30988
2023	J. Cazabonne et al.	Experimental and numerical investigations of electron transport enhancement by electron-cyclotron plasma-wave interaction in tokamaks	Plasma Physics and Controlled Fusion 65, 104001 (2023)	33940
2023	M. Hamed et al.	On the impact of electric field fluctuations on microtearing turbulence	Physics of Plasmas 30, 042303 (2023)	32658
2023	L.A. Leppin et al.	Complex structure of turbulence across the ASDEX Upgrade pedestal	Journal of Plasma Physics 89, 905890605 (2023)	34774
2023	K. Lim et al.	Effects of triangularity on plasma turbulence and the SOL-width scaling in L-mode diverted tokamak configurations	Plasma Phys. Control. Fusion 65, 085006 (2023)	34216
2023	T. Luda di Cortemiglia et al.	Validation of IMEP on C-Mod and JET-ILW ELMy H-mode plasmas	Plasma Phys. Control. Fusion 65, 034001 (2023)	33197
2023	B.F. McMillan	Relationship between drift-kinetics, gyro-kinetics, and MHD in the long-wavelength limit	Journal of Plasma Physics 89, 905890115 (2023)	32547
2023	G. Snoep et al.	Improved flux-surface parameterization through constrained nonlinear optimization	Phys. Plasmas 30, 063906 (2023)	33548
2023	R. Varennes et al.	Impact of magnetic ripple on neoclassical equilibrium in gyrokinetic simulations	Plasma Phys. Control. Fusion 65, 035016 (2023)	32320
2023	A. Volcokas et al.	Ultra Long Turbulent Eddies, Magnetic Topology, and the Triggering of Internal Transport Barriers in Tokamaks	Nucl. Fusion 63, 014003 (2023)	32945
2024	T. Jitsuk et al.	Turbulent Multi-Scale Interactions between Tearing Modes, Trapped-Electron Modes and Zonal Flows	to be submitted to Physical Review Letters (2024)	39125
2024	L.A. Leppin	Turbulence simulations of the high confinement mode pedestal in tokamak fusion experiments, PhD thesis	Technische Universität München (2024)	NA
2024	K. Lim et al.	Predictive power-sharing scaling law in double-null L-mode plasmas	Nuclear Fusion 64, 106057 (2024)	37643
2024	G. Snoep et al.	Characterization of reduced-order turbulence models in the L-mode pedestal-forming region in JET	submitted to Nuclear Fusion (2024)	38013
2024	R. Varennes et al.	Safety factor influence on the edge E×B velocity establishment in tokamak plasmas	Plasma Phys. Control. Fusion 66, 025003 (2024)	36124
2024	A. Volcokas et al.	Numerical study of turbulent eddy self-interaction in tokamaks with low magnetic shear. Part I: Linear simulations	Plasma Phys. Control. Fusion 67 015001 (2025)	37753
2024	A. Volcokas et al.	Numerical study of turbulent eddy self-interaction in tokamaks with low magnetic shear. Part II: Nonlinear simulations Paper	Plasma Phys. Control. Fusion 67 015002 (2025)	37753
2024	W. Zholobenko et al.	Tokamak edge-SOL turbulence in H-mode conditions simulated with a global, electromagnetic, transcollisional drift-fluid model	Nuclear Fusion 64 106066 (2024)	36998
2025	J. Ball et al.	Intrinsic momentum transport driven by almost-rational surfaces in tokamak plasmas	submitted to Physical Review Letters	40126
2025	B. De Lucca et al.	Conservative formulation of the drift-reduced fluid plasma model	J. Plasma Phys. accepted (2025)	41042
2025	M. Dicorato et al.	Turbulent transport in the pedestal of small-ELMs regimes at JET	21st European Fusion Theory Conference, Aix-en-Provence (23-26 September 2025)	40645
2025	G. Dif-Pradalier et al.	Turbulence drive and causal generation of vorticity in edge fusion plasmas	Reviews of Modern Plasma Physics 9, 23 (2025)	40725
2025	G. Di Giannatale et al.	Global electromagnetic gyrokinetic simulations of internal transport barriers in reversed-shear tokamaks	Plasma Phys. Control. Fusion 67, 075008 (2025)	39236
2025	PD. Donnel et al.	An adaptive quasi-neutrality solver for full-F flux-driven gyrokinetic simulations of tokamak plasmas in presence of poloidal asymmetries	Open Plasma Science 1, 5 (2025)	40642
2025	R. Düll et al.	An electromagnetic model in SOLEDGE3X for edge plasma turbulence simulations in tokamak	Journal of Computational Physics 536, 114052 (2025)	39056
2025	B.J. Frei et al.	First-Principles Explanation of the Drift Configuration Dependence of the Radial Electric Field and High-Confinement Access in Tokamaks	to be submitted to Physical Review Letters	41503
2025	L.A. Leppin et al.	Gyrokinetic analysis of the JET hybrid H-mode pedestal	Phys. Plasmas 32, 102508 (2025)	37711
2025	O.P. Panico et al.	On the importance of flux-driven turbulence regime to address tokamak plasma edge dynamics	Journal of Plasma Physics 91, E26 (2025)	39091
2025	F. Sheffield et al.	Implementation of a long-wavelength model for parallel magnetic fluctuations in the global GENE code	Plasma Phys. Control. Fusion 67, 015028 (2025)	38854
2025	F. Sheffield et al.	On ion-frequency electron temperature gradient modes	Phys. Plasmas 32, 122301 (2025)	40990
2025	G. Snoep et al.	Efficient gyrokinetic eigenmode solving using dynamic mode decomposition	submitted to Physics of Plasma	40049
2025	A. Volcokas et al.	Turbulence-Induced Safety Factor Profile Flattening at Rational Surfaces in Tokamaks with Low Magnetic Shear	Plasma Phys. Control. Fusion 67, 125008 (2025)	39461
2025	A. Volcokas et al.	Turbulence-Generated Stepped Safety Factor Profiles in Tokamaks with Low Magnetic Shear	Phys. Rev. E 112, L043201 (2025)	39821
2025	A. Volcokas	Gyrokinetic investigation of plasma turbulence self-organization at low magnetic shear in tokamaks	PhD thesis, EPFL (2025)	N/A
2025	W. Zholobenko et al.	Fast turbulence phase transition in a flux-driven global edge-SOL simulation	Physical Review Letters accepted (2026)	40766

Publications since 05/2021:

- Papers & Theses submitted / published: **43**
- Conference Contributions: **41**

Full list including conferences at
https://wiki.euro-fusion.org/wiki/TSVV-01

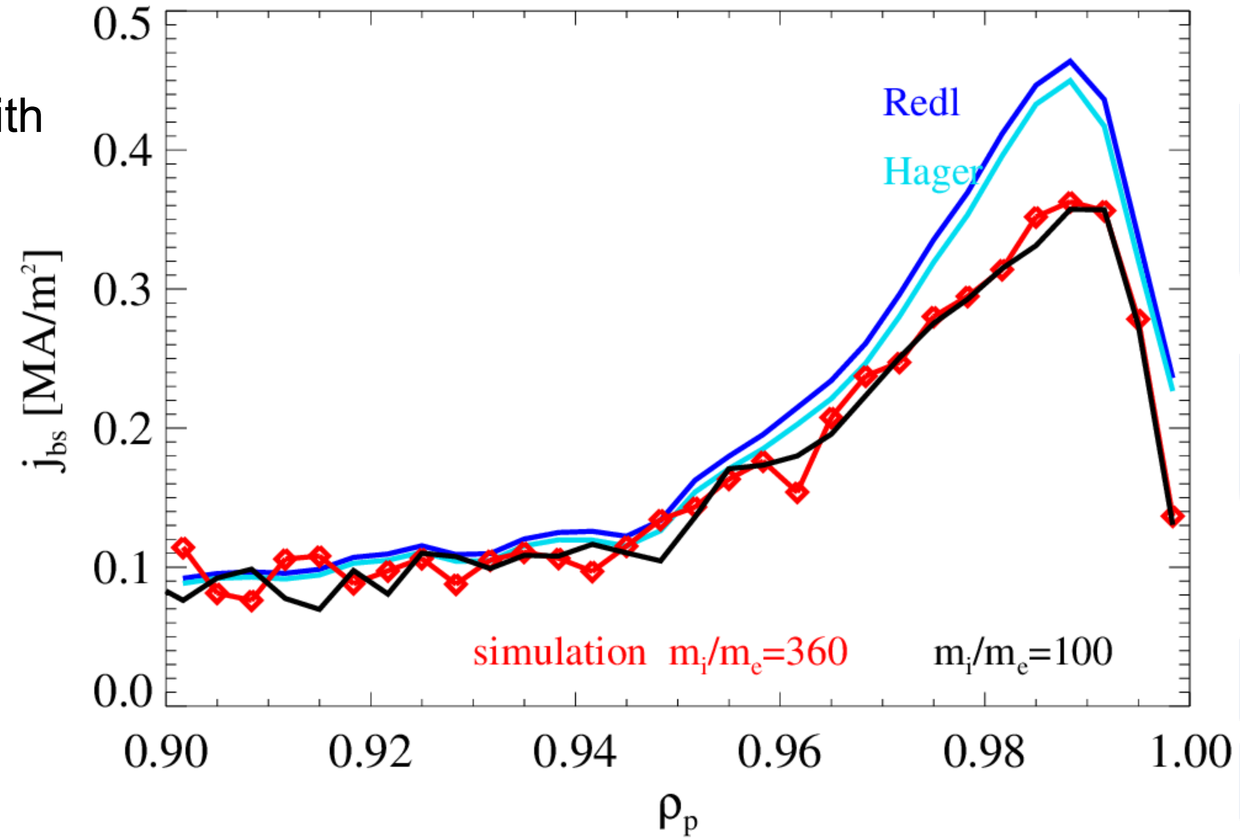
Thank you for your attention!

Appendix

Bootstrap current studies with new full-f HAGIS code

- **Improved collision operator for full-f HAGIS** simulations implemented
- Effect of collisions is calculated in the frame moving with the field particles
- **New nonlinear versus linear collision operator:** additional terms due to the heat flux
- Corrections for momentum/energy conservation proportional to theoretical rates are smaller than for linearized operator
- Reduced mass ratio (360, 100) in bootstrap current gives same results and is effective in reducing the numerical noise

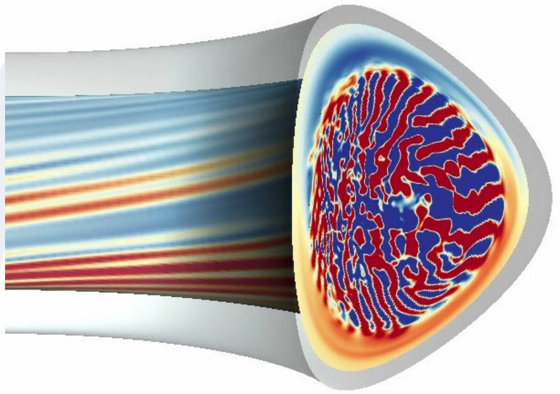
Comparison of neoclassical bootstrap current from full-f HAGIS & analytic expressions by [Redl et al., PoP (2021) and Hager et al., PoP (2016)]



Courtesy: A. Bergmann

A new quasi-neutrality solver for GYSELA

A **new quasi-neutrality (QN)** solver has been developed for GYSELA. The features of this new solver are:



- **Valid for any axisymetric geometry** → allows **shaping** studies
- Include 3 models for electrons (full kinetic, adiabatic, trapped kinetic), LWA & **Padé** (novelty in GYSELA) versions of the polarization
- Possess a **polarisation density** that **evolves in time** and can **display poloidal asymmetries**. Expected to be needed to simulate the edge / Scrape-off Layer [R. M. Churchill, POP 2015]
- Even in the simplest case, updating of the time-dependent coefficients has a major impact on the turbulence. Compromise between refreshing rate and numerical costs required.

A corresponding publication is work in progress [P. Donnel et al., OSS submitted (2025)]

Objective: obtain a spontaneous L-H transition in a gyrokinetic code

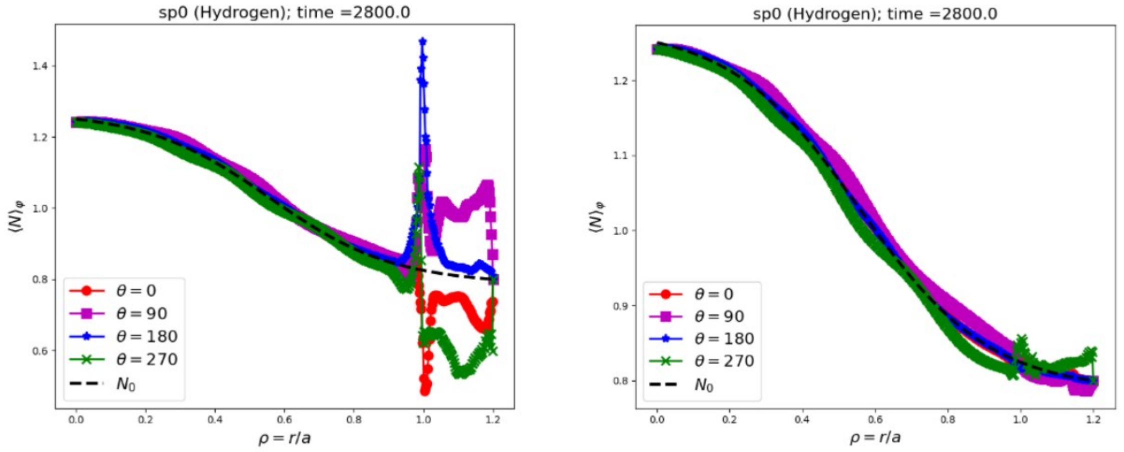
Status in GYSELA

What physics is a priori needed?

- Poloidally localised boundary conditions (limiter or divertor) — [G. Dif-Pradalier 2022, Donnel 2025]
- Flux driven (power scan & self organisation of profiles)
- Electromagnetic fluctuations (for saturation of pedestal) — [PhD C. Gillot 2017-2020, PhD R. Bigué 2023-2026]

What physics might be needed?

- Neutrals (in particular particle source)
- Sheath boundary condition
- Electron scale turbulence
- More finite Larmor effects due to large gradients (kinetic corrections, FLR effects in collisions…)



(a) No update (b) With update

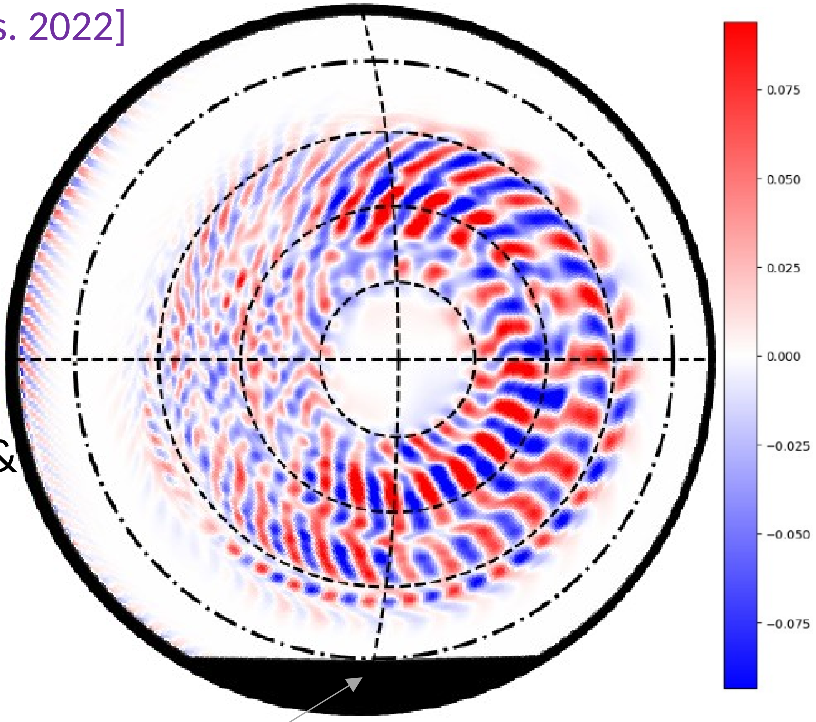
GYSELA: simple modelling of limiter BC with kinetic electrons

- Limiter boundary condition (r,θ) with **adiabatic electrons** [G. Dif-Pradalier, Comm. Phys. 2022]
  - Penalisation of f_i towards f_{target} at low temperature → heat sink
  - Modified adiabatic electron response in the scrape-off layer

- Generalisation with **kinetic electrons** [P. Donnel, Open Plasma Science 2025]
  - Penalisation of f_i & f_e towards f_{target} → heat & particle sink @ constant charge
  - Trapped Kinetic Electrons in the core, Full Kinetic Electrons in the SOL
  - Refined calculation of polarisation density → accounting for time evolution & poloidal inhomogeneity is key

Debye-sheath physics not implemented yet

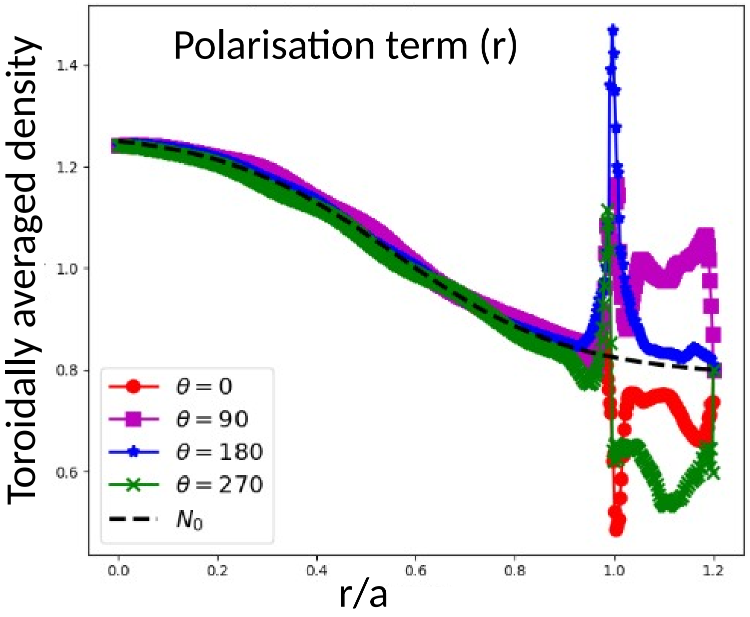
Fluctuations of electric potential ϕ

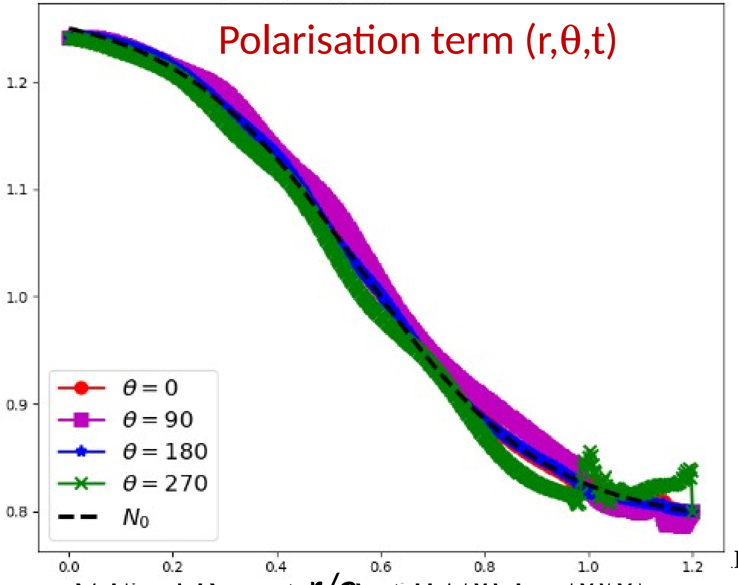


$$\frac{d\bar{f}_s}{dt} = -\mathcal{M}_{\lim.}(r,\theta)\,\nu_s\left(\bar{f}_s - \bar{f}_{s,target}\right)$$

$$-\nabla_\perp \cdot \left(\frac{m_i \langle \bar{n}_i \rangle_\varphi}{\langle B \rangle_\varphi^2} \nabla_\perp \phi\right) = \sum_s e_s \delta \bar{n}_s$$

Function of (r,θ,t)





GYSELA – q (or I_p) impact on flows & turbulence

- **Turbulence** & **collisions** : simplified conservation equation → **antagonistic contributions** @equil.

$$\partial_t V_E = \underbrace{-\nabla \cdot \Pi_\theta}_{\text{Turbulent source}} \underbrace{- \nu_{col}^{\theta}(V_E - V_{E,col})}_{\text{Neoclassical sink}} \rightarrow V_{E,eq} = V_{E,col} - \frac{\nabla \cdot \Pi_\theta}{\nu_{col}^{\theta}}$$

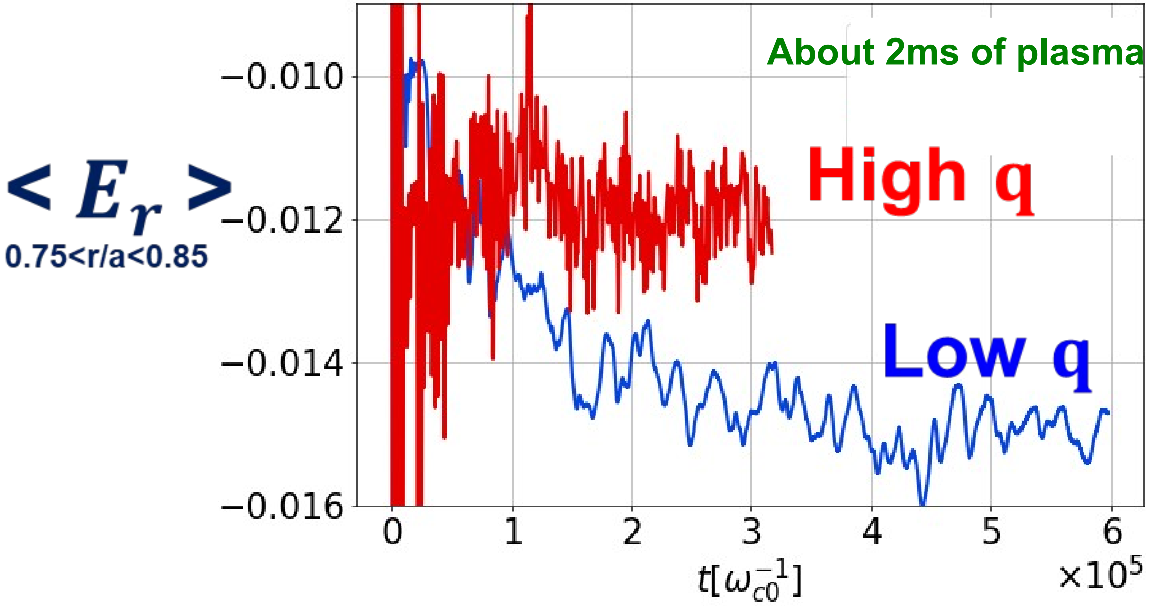
$\nabla \cdot \Pi_\theta \propto q^{1/2}$

$\nu_{col}^{\theta} \propto q^2$

$V_{E,col} \propto q^0$

decreases with q !

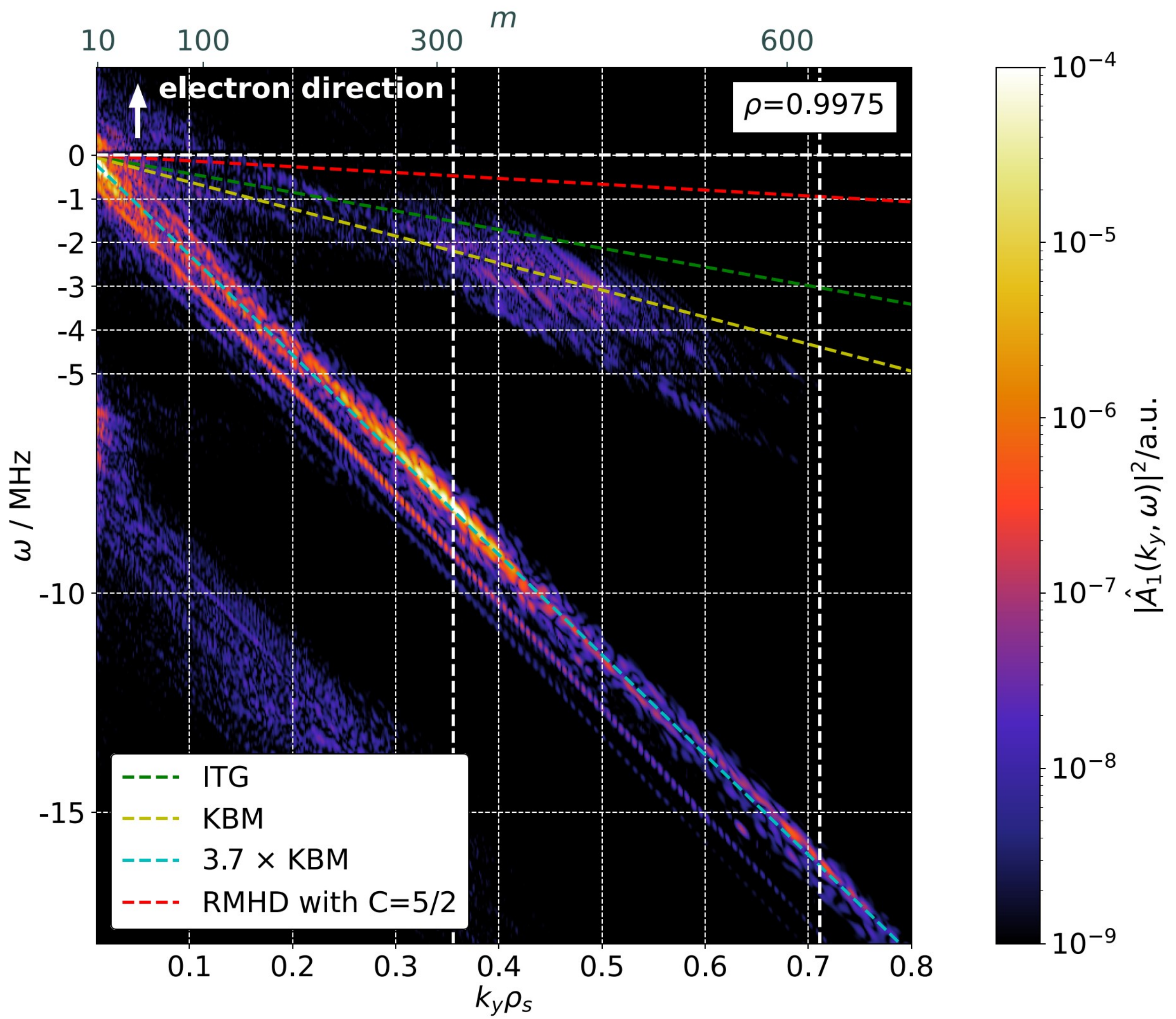
[G. Dif-Pradalier et al., PRL (2009)]



- Complex $\frac{\nabla \cdot \Pi_{turb}}{\nu_{col}}$ dependencies recovered, ITG turbulence
- Qualitative **trend with experiment**
- Quantitatively: miss **TEM & boundary-induced instabilities**
  → $\nabla \cdot \Pi_\theta$ likely higher

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

Kinetic ballooning modes (KBMs) in the pedestal with GRILLIX



These same GRILLIX simulations show a **critical role of magnetic fluctuations** in the H-mode pedestal:

- **Magnetic flutter** in Ohm‘s law **stabilises drift-Alfvén turbulence**
- In the **upper pedestal half, transport is neo-classical**
- At the **pedestal foot, transport is electromagnetic**, with a large coherence between magnetic fluctuations & parallel heat flows along them
- Mode propagates in ion diamagnetic direction (excludes MTM), and frequency is 4 x flux-tube GK ideal (collisionless) KBM: deviation due to geometry or resistivity?

Quite clearly a kinetic ballooning mode

W. Zholobenko *et al.*, (2024)

D4 Example: Edge plasma turbulence phase space in global flux-driven EM 3D 2-fluid GBS sims

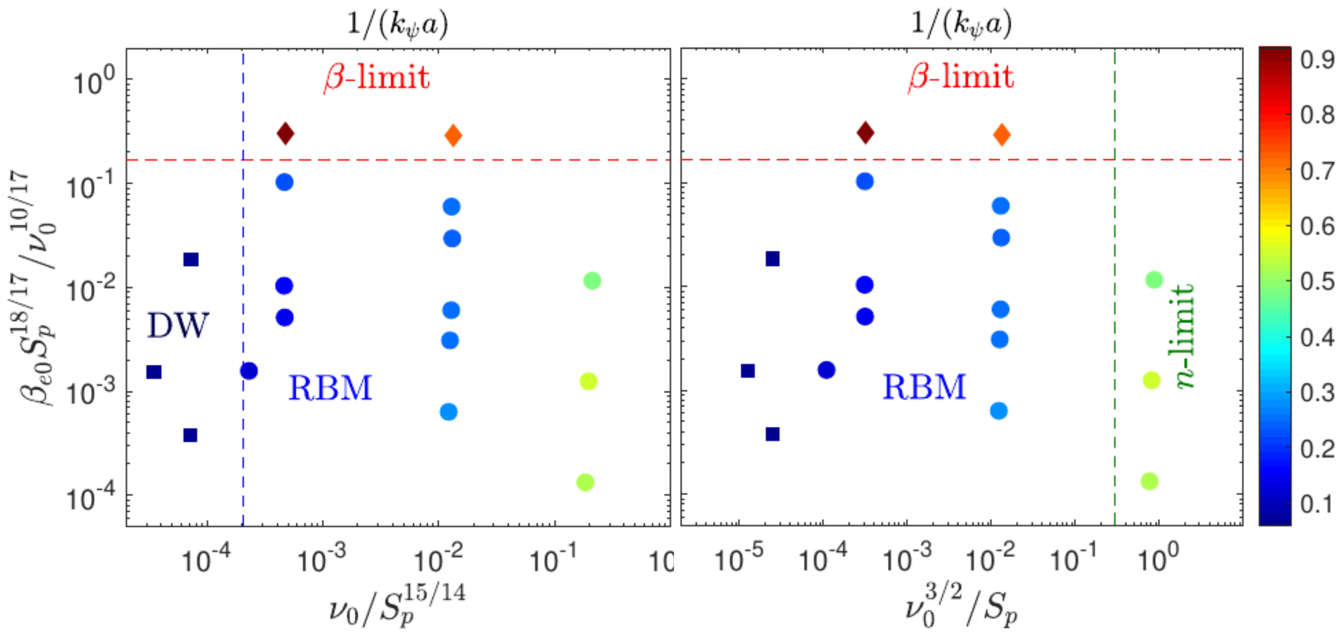
- **Four turbulence regimes identified** scanning **resistivity ν_0, heat source S_p** and **plasma β** with upgraded GBS code w/o Boussinesq approx. [M. Giacomin, P. Ricci, PoP 29, 062303 (2022)]:

(i) intermediate ν_0, S_p, β: resistive ballooning modes (RBM) (~ standard tokamak L-mode)

(ii) low ν_0, large S_p, intermediate β: reduced transport, mainly drift-wave (DW) instability (~ high density H-mode)

(iii) high ν_0: extremely large turbulent transport regime, RBM (~ L-mode density limit crossing)

(iv) large β regime (~ crossing of the β limit): ideal ballooning instability, large scale modes leading to a total loss of plasma and heat

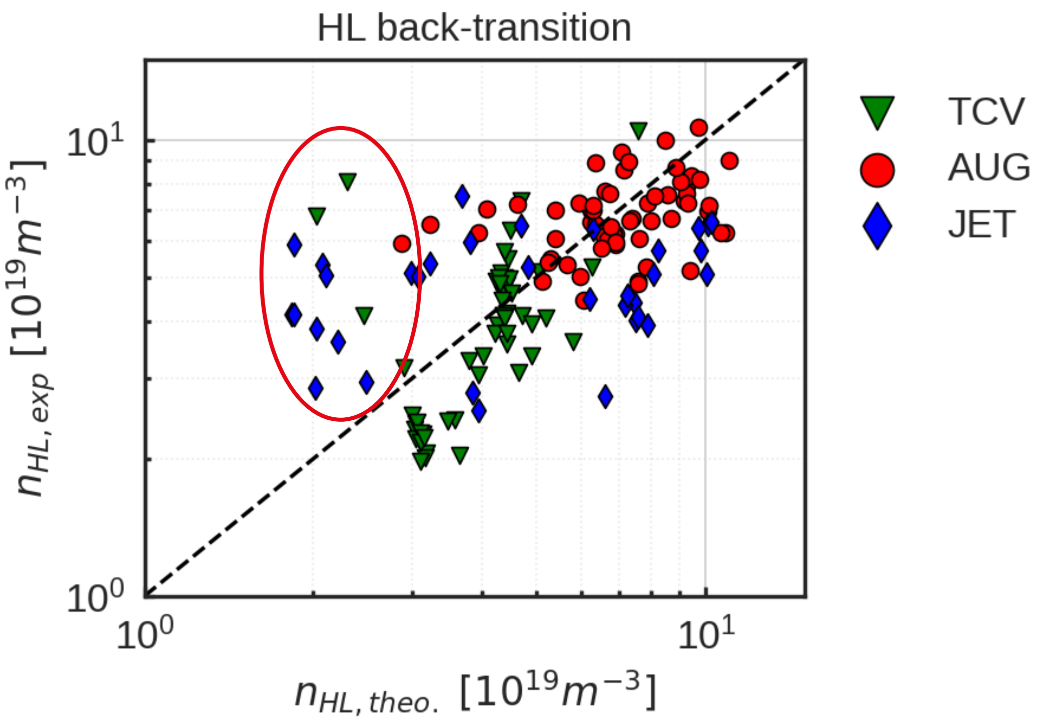


- DW-to-RBM transition ~H-mode density limit
- Boussinesq approx. strong effect at low ν_0

→ ample motivation to compare scalings with exp. and gyrokinetic results

Validation of the HL back transition scaling law against multimachine dataset

$$n'_{\mathrm{HDL}} \sim C_{\mathrm{geo}}^{-15/37} A^{8/37} P_{\mathrm{SOL}}^{19/37} a^{-19/37} q^{-36/37} R_0^{-22/37} B_T^{15/37}$$



A theory-based scaling law for the **H-mode density limit (HDL)** was previously investigated, and its validation against multi-machine datasets is currently underway.

A few discharges show discrepancies, which can be attributed to **(i)** experimental error, **(ii)** assumptions in the scaling law, or **(iii)** other physics at play, such as EM effects.

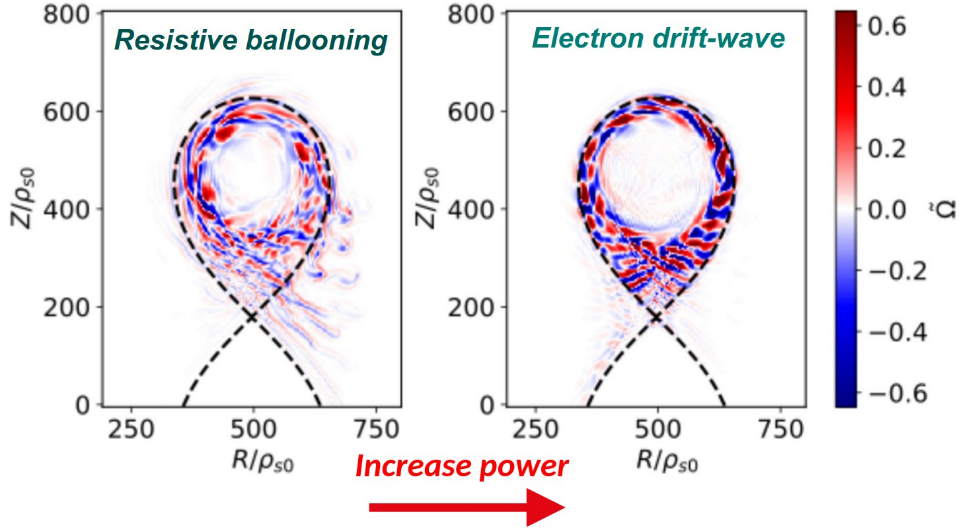
K. Lim *et al.*, (2024)

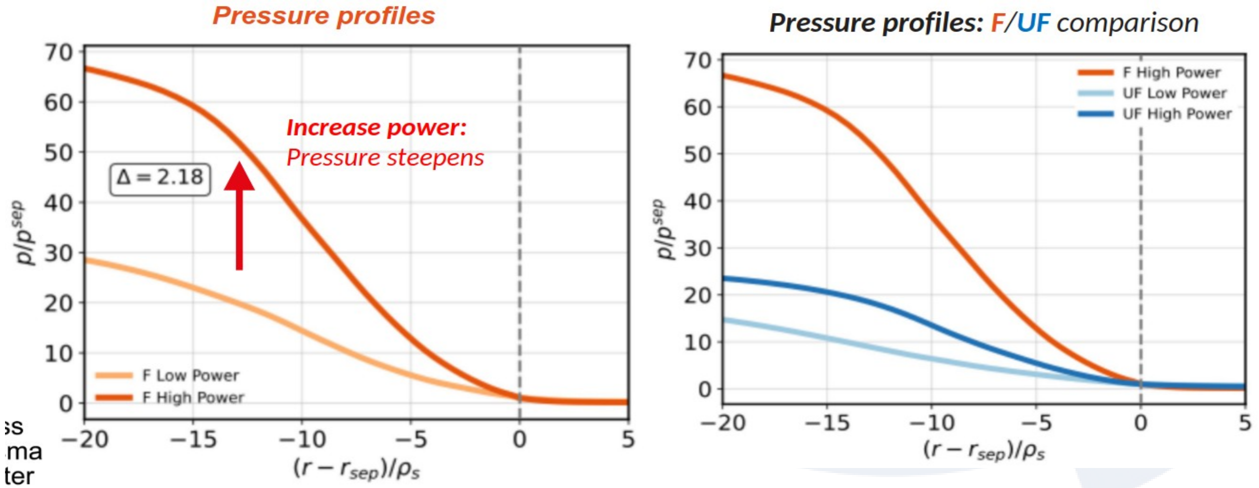
GBS – Unfavorable vs. Favorable Comparisons

Increasing T_e (decreasing collisionality) in GBS → transition resistive-ballooning driven to electron drift-wave turbulence

Favorable case: pressure profiles steepen & turbulence suppressed
- Distance from separatrix order of ρ_s
- Quantity to discern transport barriers: turbulent heat diffusivity
- L-mode, no steep edge-gradient: expect turbulent diffusivity to increase as separatrix approached
- Clear transition: turbulent diffusivity profile flattens and ∼ 2–3 × reduction

Unfavorable case, no clear transition
- Pressure profile increases only slightly
- Turbulent diffusivity profile: Unfavourable case remains close to L-mode transport level
- Difference between F/UF does not require kinetic effects (e.g. ion-orbit-losses)



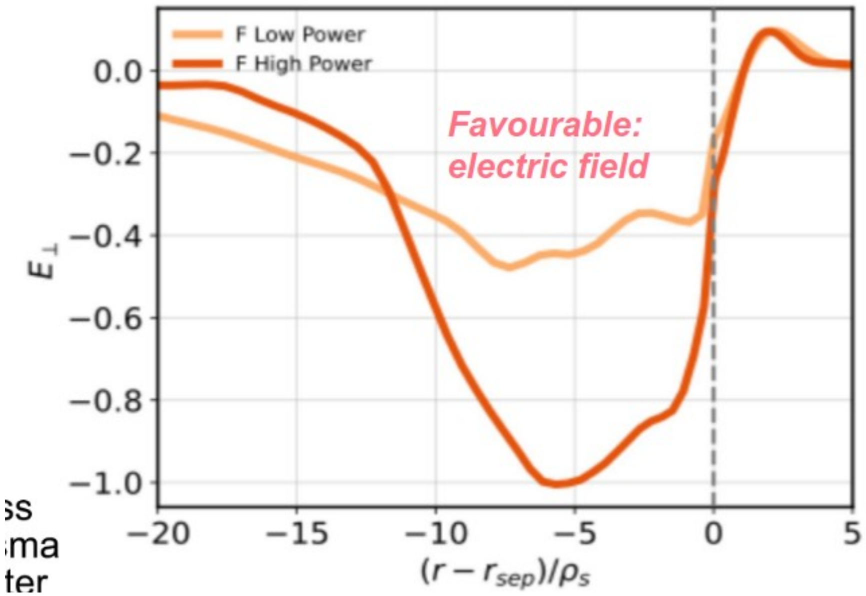


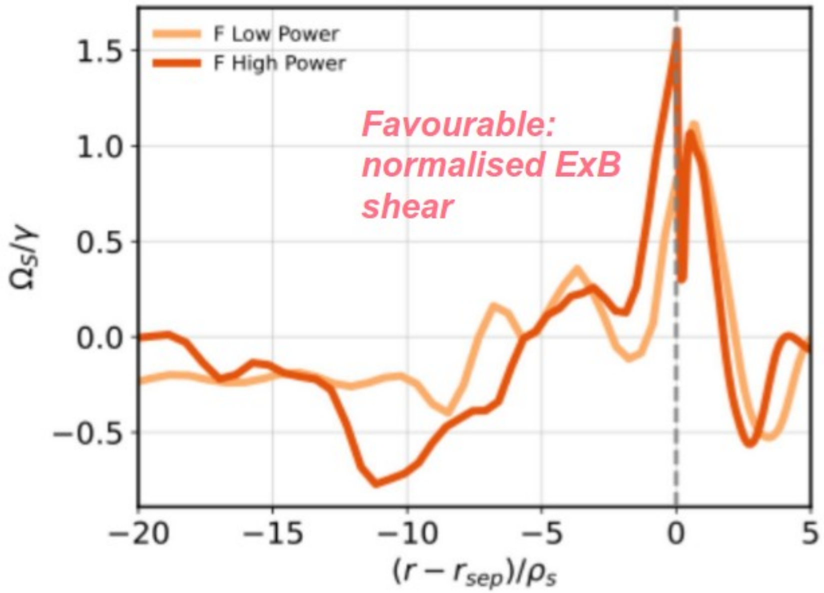
[B. De Lucca *et al.*, (2025)]

GBS – Unfavorable vs. Favorable Comparisons

E× B shear suppresses turbulence when shear rate ΩS approaches nonlinear decorrelation time (∼ growth rate) [Terry, Rev. Mod. Phys, 2000]

- Most common explanation given for L-H transition [Kim & Diamond PRL, 2003]
- Simulation results: Electric-field well deepens but small difference in normalized shear rate
- Further analysis required: E× B shear alone cannot explain transition in Favorable
- Drift-wave turbulence is suppressed by finite plasma β (electromagnetic effects)





[B. De Lucca *et al.*, (2025)]

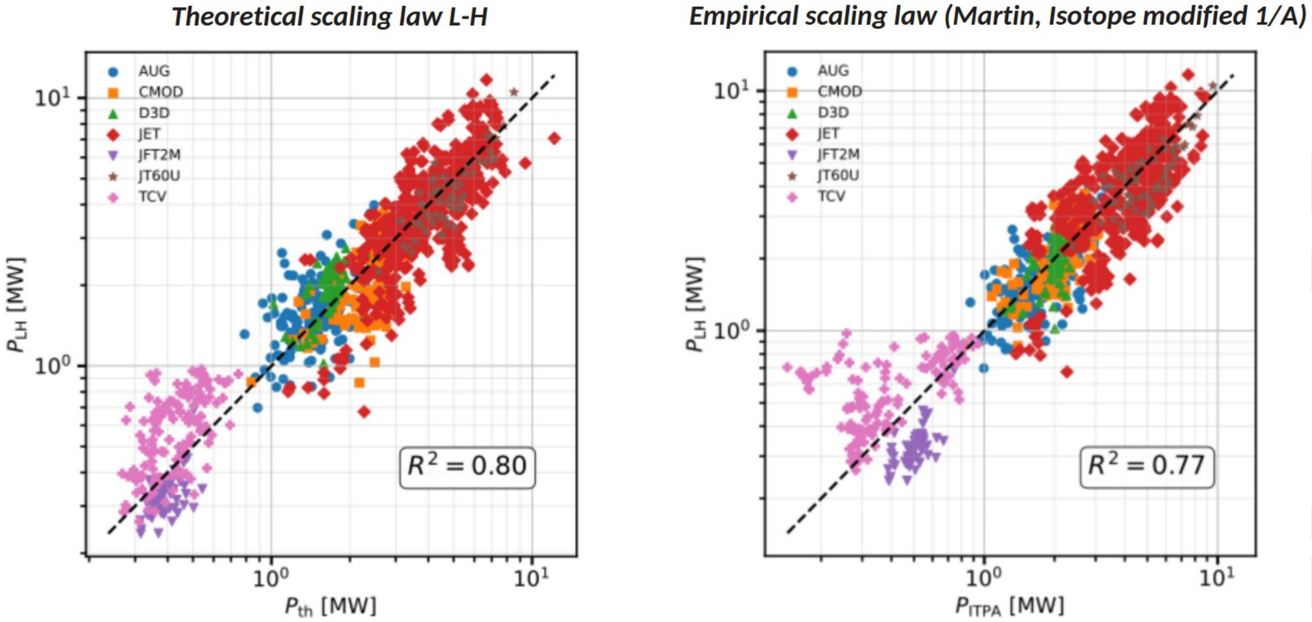
GBS – Unfavorable vs. Favorable comparisons

Electromagnetic suppression of DW proportional to edge pressure gradient: spontaneous pedestal

- Flow-shear symmetry-breaking: unfavorable configuration more unstable to ballooning modes close to L-H boundary

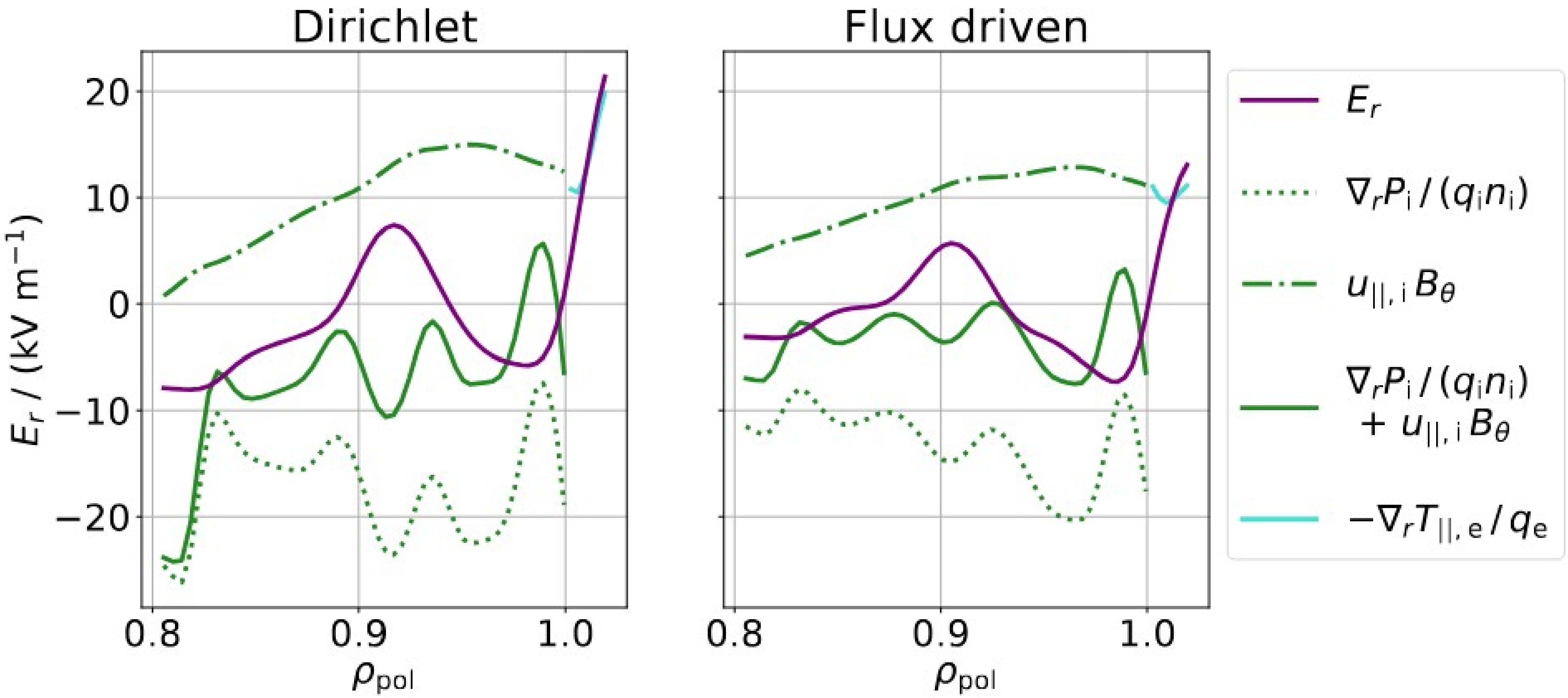
Theoretical scaling law derived from **quasi-linear theory** and power balance
→ Correct scale, zero fitted exponents, outperforms Martin scaling while satisfying Kadomtsev constraint exactly

$$P_{LH} = K(K_{dim} Z_{eff}^{9/17}\, n^{127/135}\, B_T^{11/17}\, a R_0^{110/153}\, \hat{s}^{20/153}\, q^{-52/153}\, A^{-55/153})$$



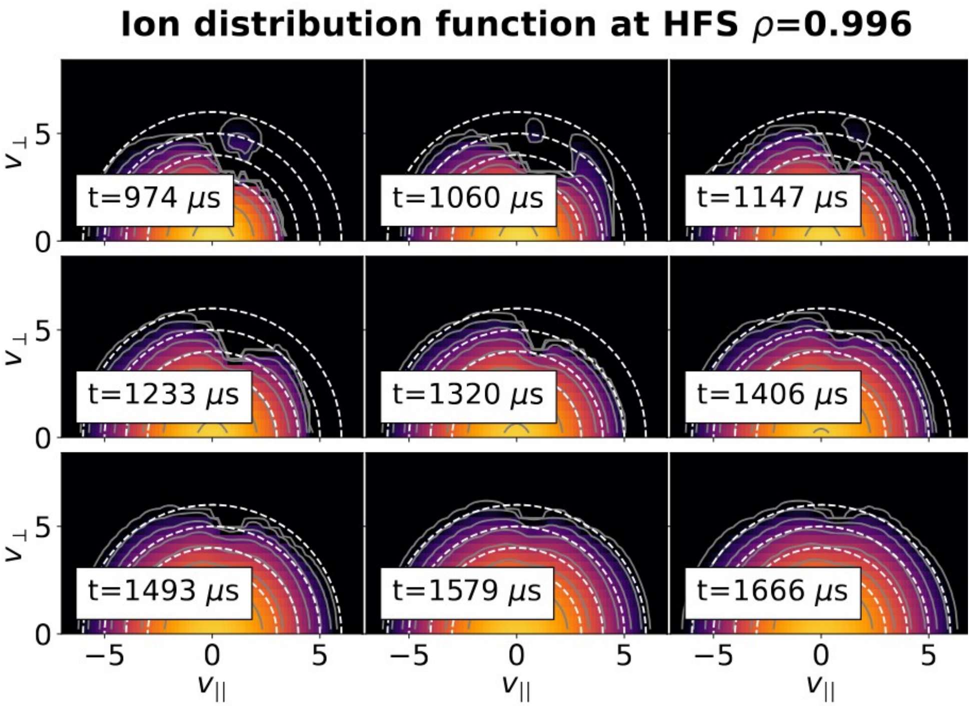
[B. De Lucca *et al.*, (2025)]

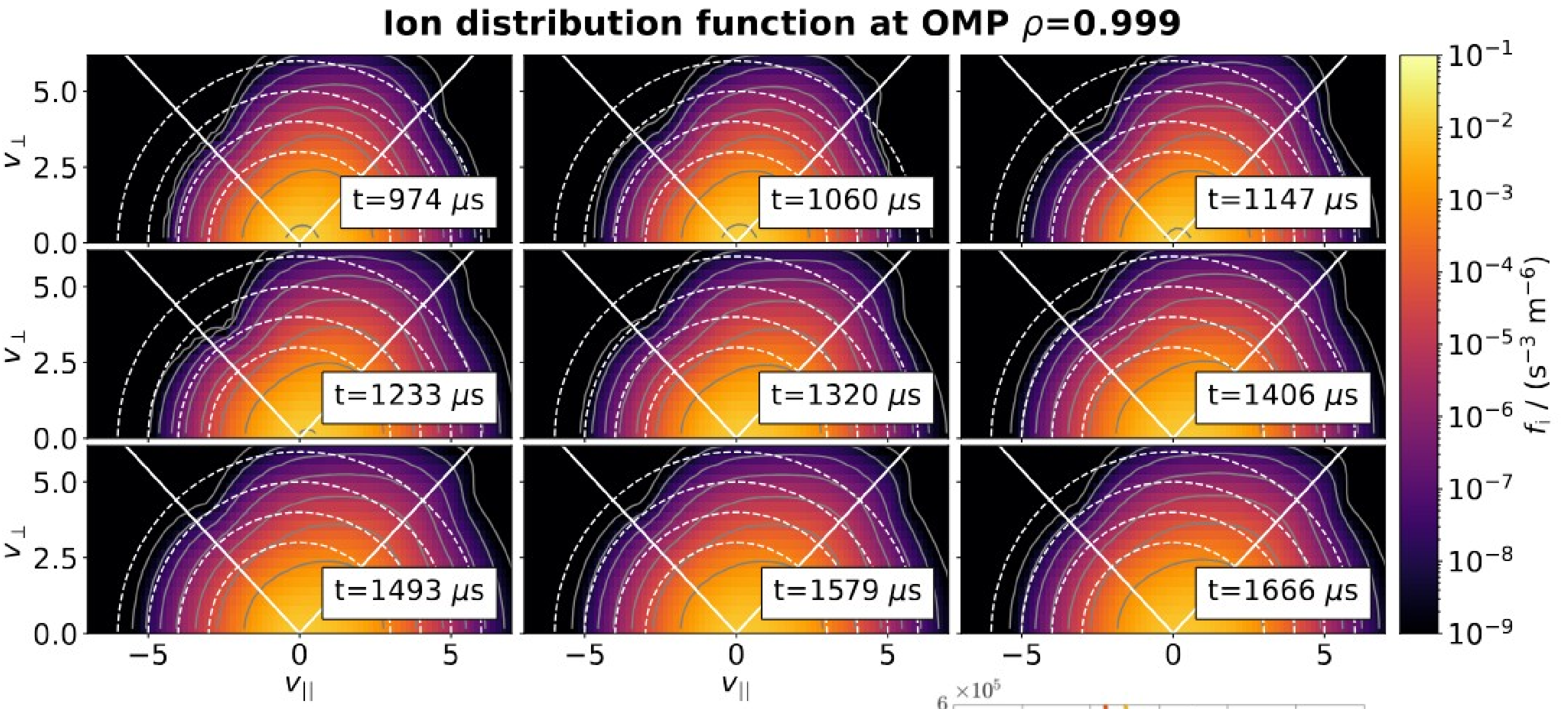
New boundary condition in GENE-X



Ulbl *et al.*, (2025)

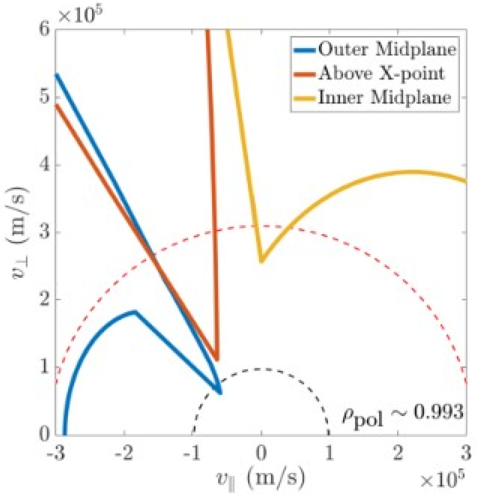
Near-separatrix velocity space analysis with GENE-X





Indications for ion orbit losses (IOL) close to separatrix:

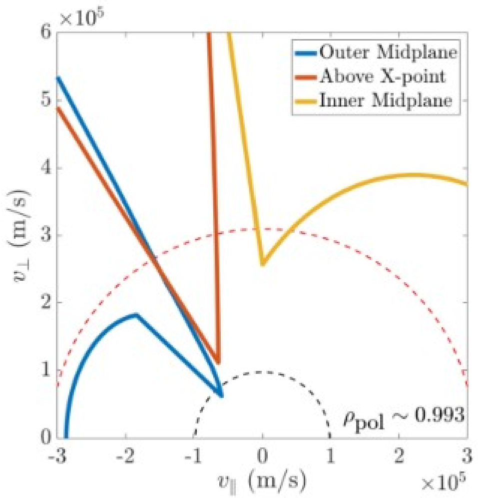
Shape of loss region at HFS differs to LFS **in line with theory**



[R. Brzozowski, PhD (2021)]

Ulbl *et al.*, (2024)

Steady-state Ion Orbit Loss model



Ion orbit loss source terms are added to current continuity

$$\nabla \cdot \boldsymbol{j} = \nabla \cdot \left(\tilde{\boldsymbol{j}}^{(\mathrm{dia})} + \boldsymbol{j}^{(\mathrm{vis})} + \boldsymbol{j}^{(\mathrm{in\text{-}gyro})} + \boldsymbol{j}_{\|} + \boldsymbol{j}^{(\mathrm{iol})} + \boldsymbol{j}^{(\mathrm{AN})} + \ldots \right) = 0$$

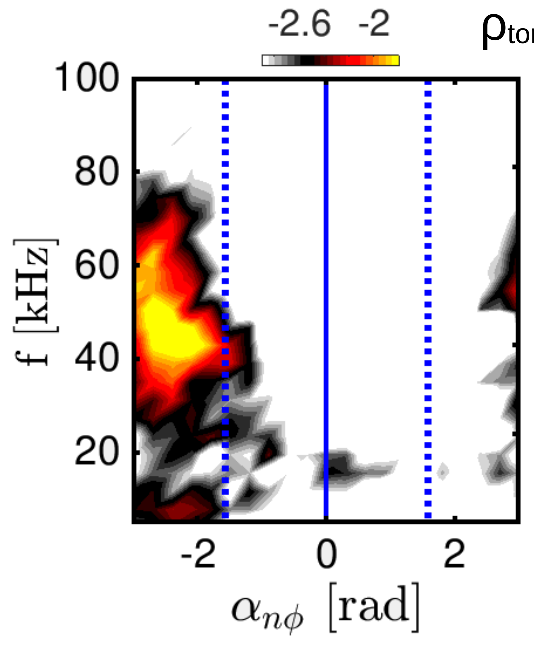
$$\nabla \cdot \boldsymbol{j}_{\text{c-less}} = Ze \int_S \left\langle \frac{dw}{dt} \right\rangle f dS$$
$$= \frac{Ze}{\sqrt{3}} \int_S \nu_\perp v \left(2\mathrm{erf}\left(\frac{\Delta\theta}{\sqrt{2\nu_\perp \tau_l}} \right) - 1 \right) |\cos(\alpha)| \, f dS$$

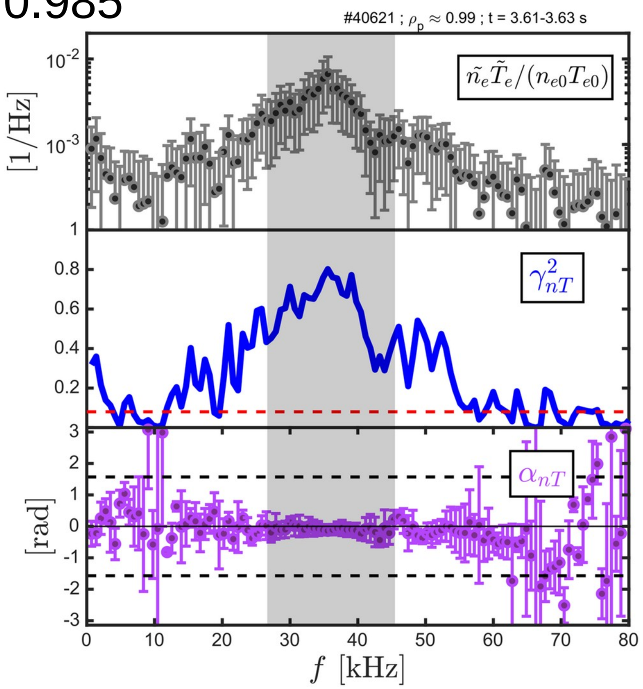
$$\nabla \cdot \boldsymbol{j}_{\mathrm{coll}} \approx \frac{Ze}{z - z_X} \int_{\Sigma_{\mathrm{coll}}} (v_{\nabla B} + v_C) \, f d^3 V$$
$$\approx \frac{m}{2RB(z - z_X)} \int_{\Sigma_{\mathrm{coll}}} v^2 \left(1 + \zeta^2\right) f d^3 v$$

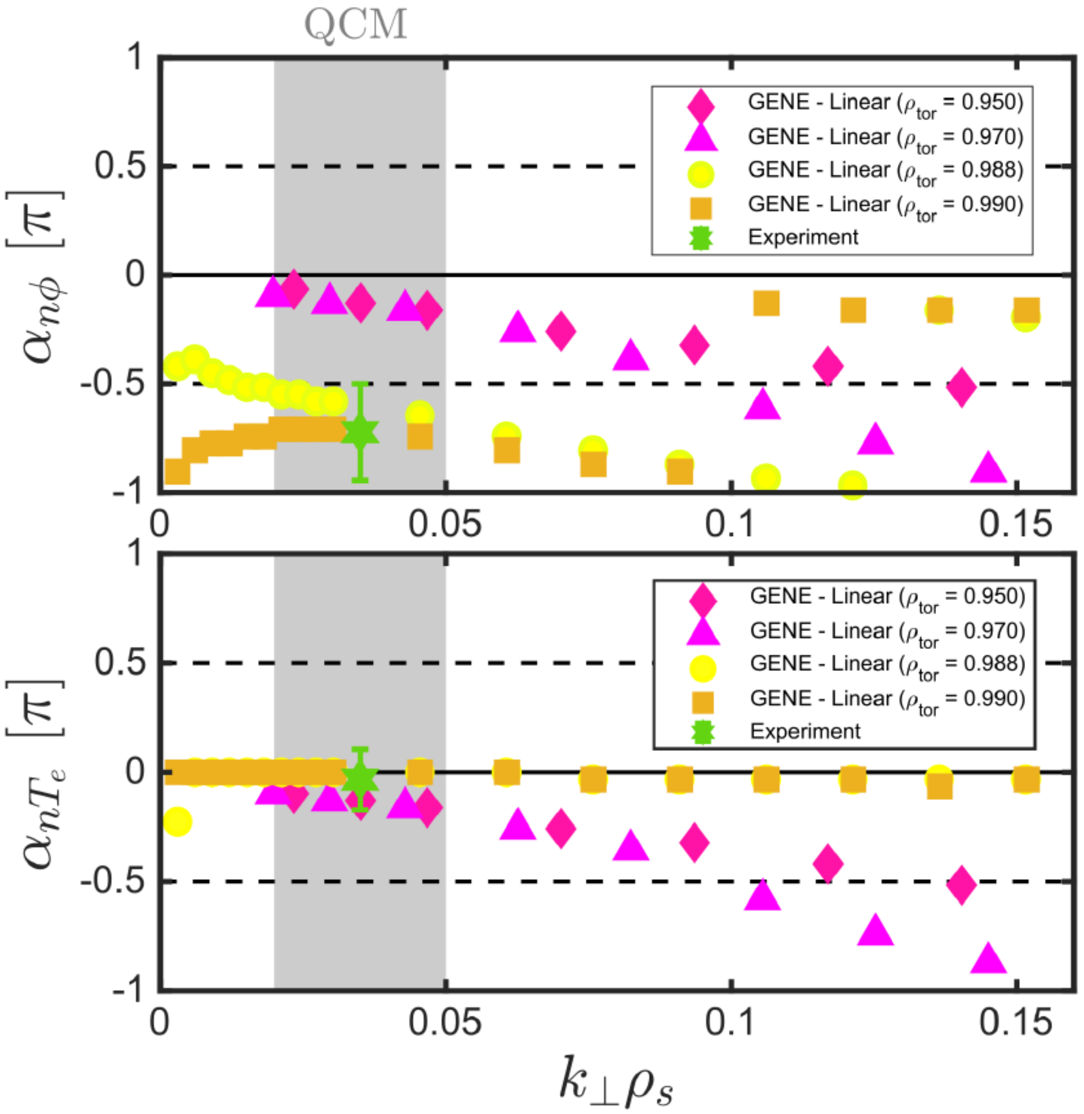
[R. Brzozowski, PhD (2021)]

AUG EDA-H mode 41374 characterization with GENE

ρ_{tor} ~ 0.985







Interesting observation:

KBM-type modes a pedestal foot ρ_{tor} ~ 0.98/0.99 display density / potential and density / electron temperature cross phases as measured in experiment for quasi-coherent mode

⇨ local near-separatrix physics spreading into pedestal?

⇨ subdominant mode in linear global simulations

T. Görler *et al.*, (2025)