EUROfusion

TSVV1 "L-/H-transition and pedestal physics" – Update and Future plans

E-TASC Thrust 1 meeting
June 21, 2022

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
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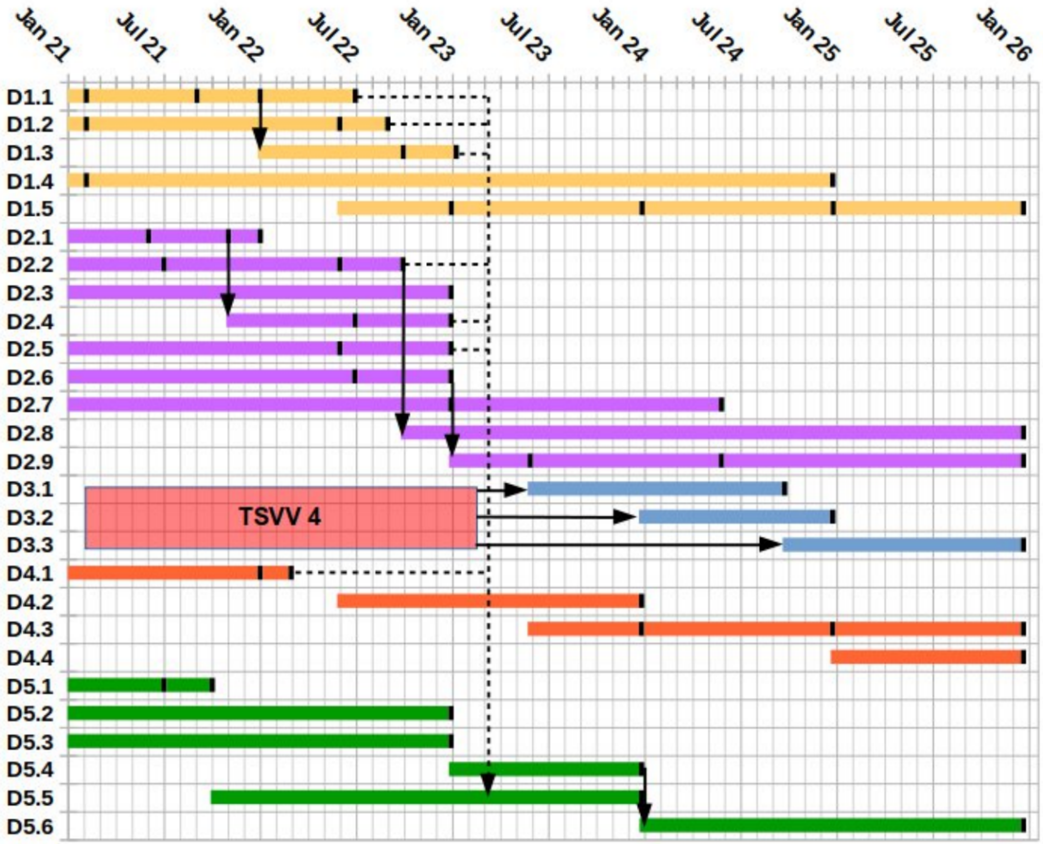
**left project in / end of 2021*
***permanent guests – no official project commitment*

Outlook

- Brief project plan reminder
- Targets 2022 & Selected Scientific highlights
- Summary

Workplan (as originally proposed)



Validated local & global GK simulations of ion-/elect.-scale, & multi-scale turbulent transport in the H-, QH-, I-, and L-mode edge: IPP, SPC, CEA, DIFFER (GENE, ORB5, GYSELA)

Extensions to relevant macroscopic (MHD-like) instabilities (CCFE, IPP) and radial electric field development: also CEA, SPC (ion orbit losses, fluid codes, eventually GK)

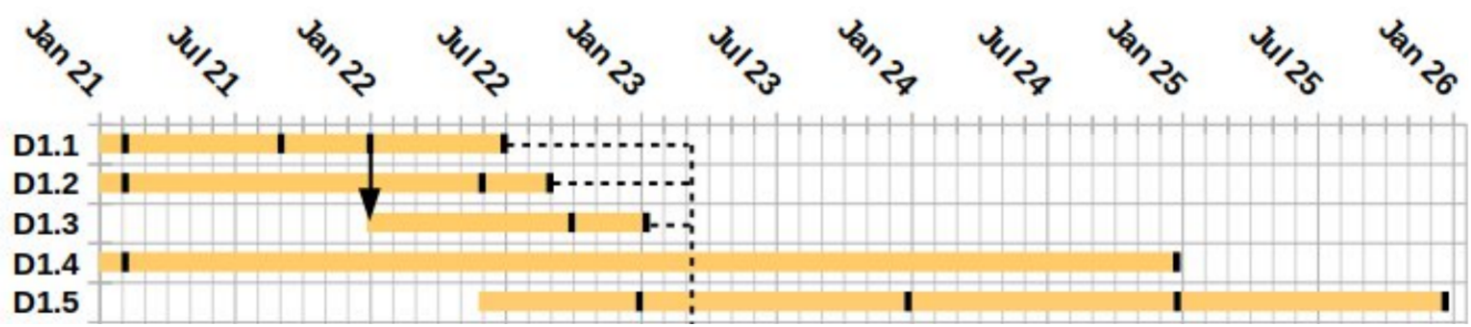
Consistent application of new Task 4 edge GK code: various partner 2022+

An interpretative and predictive capability of L-H transitions: from fluid codes (SOLEDGE2X, GBS) to TSVV4 code

Reduced transport models for the pedestal on the basis of GK simulations, involving electron-/ion-scale, and MHD-like instabilities: IPP, DIFFER (heuristic models to coupled QuaLiKiz profile predictions)

D1 targets for validated local & global GK sims

- **D1.1: Level of realism by first gyrokinetic validation (delta-f, local) studies discussed, further need for more comprehensive simulations (global, multi-scale) and physics scenarios assessed (08/2022)**
- **D1.2: ITB physics studied and key elements that could be transferred to edge transport barriers identified (09/2022)**
- **D1.3: Assessment of the level of realism confirmed by advanced delta-f validation studies (e.g., global, multi-scale) (12/2022)**
- **D1.4: Level of realism found in full-f simulations and coherency/agreement of the comparisons assessed (2024)**
- **D1.5: Extension of previous studies, e.g., by covering new scenarios and/or diagnostics (2025)**



D1 goals for validated local & global GK sims

- **Main goal / idea (in line with E-TASC call):**

  Analyse degree to which gyrokinetic codes (GENE, ORB5, GYSELA) can reproduce edge/pedestal turbulence in a number of scenarios (deliverable addresses 1st iteration);
  requires

  → reliable profile information & magnetic equilibria
  → at least power balance and as much fluctuation diagnostics as available

- **Side product:**

  Gradient-driven simulations usually performed with input variations within uncertainties to optimize match with observables; some parameter scans needed to characterize turbulence types

  → provides first insights into parametric dependencies

  → simulation data may be used to guide diagnostics development

- **Future extensions once validation achieved:**

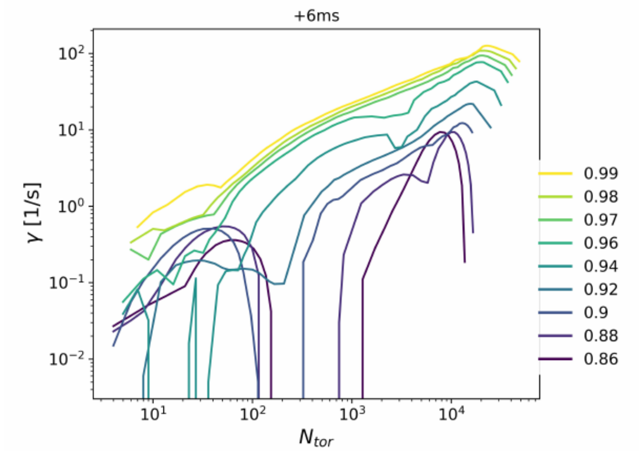
  → more scenarios

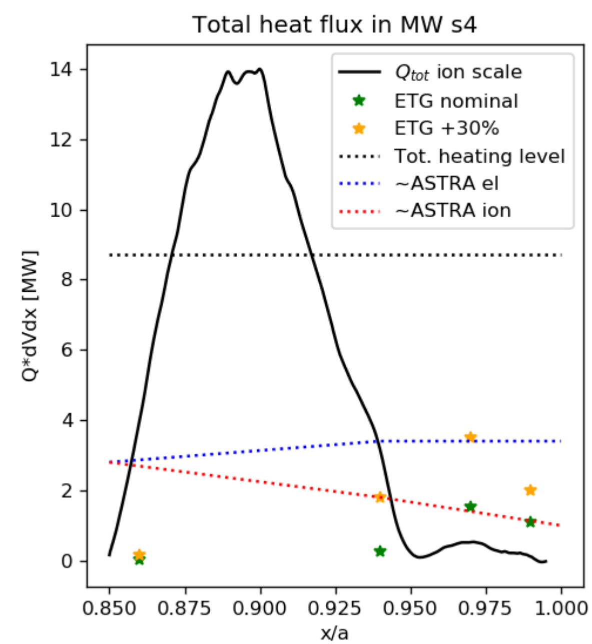
  → focus on parametric dependencies

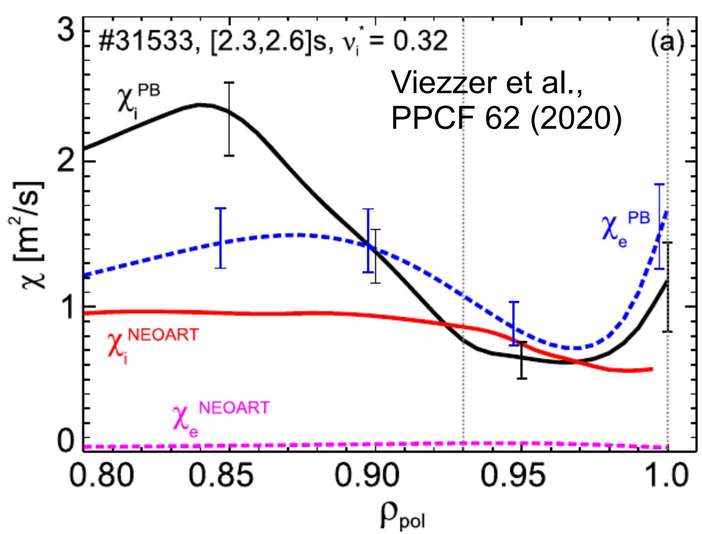
D1: Example – ELMy H-mode pedestal

Gyrokinetic study of an AUG H-mode ELM-cycle
here: post-ELM [L. Leppin et al., priv. comm. (2022)]

- **Linearly,** MTM at lowest ky, TEM, weak ETG at high ky at pedestal top; TEM/ETG hybrids at pedestal foot; closer to KBM threshold (but not exceeded)
- **Nonlinearly,** global ion-scale & local electron-scale sims offer qualitative explanation for exp. findings of diverse pedestal physics
  - strong ion-scale TEM transport at pedestal top, stabilized in steep gradient region (profile effect), electron-scale (ETG) transport at pedestal foot





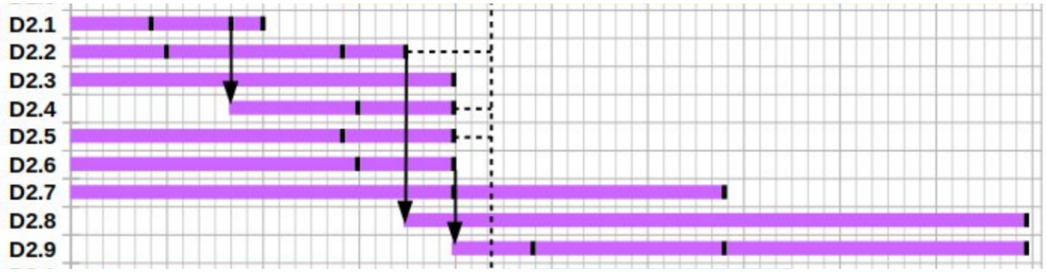


D1: Examples of launched/planned studies

- AUG H-mode pedestal ELM cycle [M Cavedon et al., PPCF'17, Viezzer et al., IAEA'18]
- AUG L-mode edge validation:
  - new outer-core validation performed in H-D isotope scan [P. Molina, T. Görler et al., EU-US TTF'21, PoP to be subm. (2022)], first simulations at ρ_{tor}~0.92
  - outer-core validation AUG turbulence reference discharge [K. Höfler, APS'21; C. Lechte, IRW'22,] → extensions to edge requires new exp. contact person
- JET Hybrid pedestal study launched (up to first EM global GK sims)
- AUG L-, H-mode & QCE discharge pedestal microinstability study comparing w/ and w/o gas puffing
- ITB scenario: first step, <u>idealized</u> setup – low magnetic shear studies
- Linear scans for JET parameters for QuaLiKiz comparison (→ D5), Micro-tearing mode studies (→ D5)
- TCV-inspired positive/negative triangularity plasma comparison with ORB5
- Further AUG edge/pedestal studies by N. Bonanomi (permanent guest)
- JET high/low power pedestal characterization by B. Chapman (permanent guest)

D2: MHD extensions & E_r development

- **D2.1/2.4: Simulation & analysis of the radial electric field development due to ion orbit losses in a fluid turbulence code with comparisons to SOLPS & assessments of ion orbit loss model (12/2021), interfacing to GK code (12/2022)**
- D2.2: GK simulations with MHD-terms added in at least one gyrokinetic code (2022); based on the outcome, coupling between MHD-dynamics and drift-mode physics and further refinements explored (2025)
- **D2.3: Development of full-f HAGIS code (12/2022)** & subsequent neoclassic bootstrap current studies in support of GK simulations (2024)
- **D2.5: Report from global fluid & GK (full-f) simulations on the relative impact of separate ingredients playing a role in the electric field formation (ripple, turbulence, neutrals, limiter, ion orbit losses …) (12/2022)**
- **D2.6: EM fluctuations and neutrals in GBS (12/2022)** and large parameter scan (injected power, shaping, etc) conducted on Er development (2025)



D2 goals for validated local & global GK sims

- **Main goals / ideas here:**

  Ion orbit losses possibly important feature for E_r well → improve coverage of this effect (still hardly considered in turbulence codes)

  Improve fluid codes (GBS) to cover and study (SOLEDGE3X) more physics

  Prepare HAGIS for full-f neoclassic bootstrap current calculations (first steps performed)

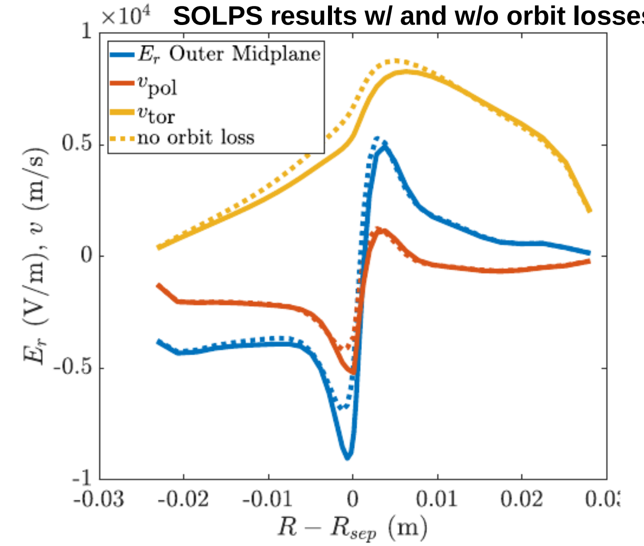
  Extend GK codes, e.g., to better include kink physics (on-going)

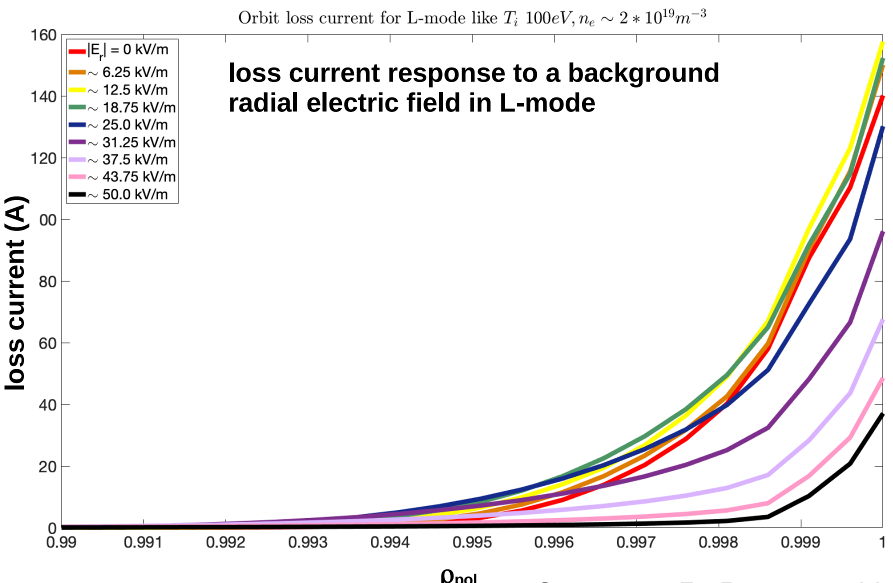
  Ultimately, study radial electric field development with fluid and GK codes → insights into parametric dependencies (may involve less physics than D1)

D2.1/2.4: Ion-orbit loss model

- **Steady-state ion-orbit loss & SOLPS coupling**
  - E_r affected by ion-orbit losses
  - Poloidal asymmetries are less strongly forced
- **Stand-alone orbit loss model with emphasis on clear documentation**
  - largely implemented in GRILLIX (fluid code) with A. Stegmeir; first sims performed
  - shall be ready for TSVV1 (and other) codes hereafter
- **Model accuracy greatly improved** velocity-space coordinates corresponding to losses evolve over a loss trajectory

SOLPS results w/ and w/o orbit losses



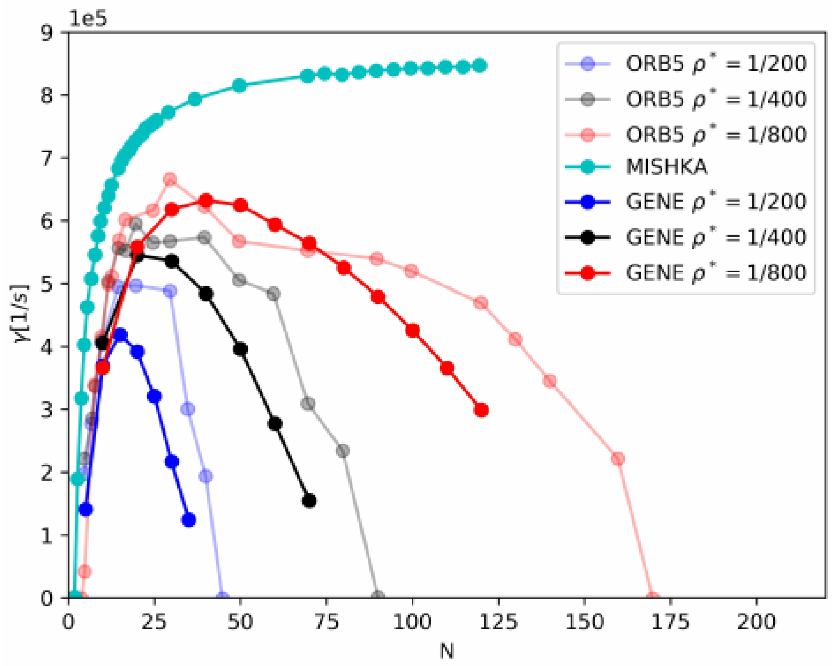


Courtesy: R. Brzozowski

D2.2: GK/MHD comparisons & extensions

- **GENE joined GK-MHD (ORB5/MISHKA) comparison**

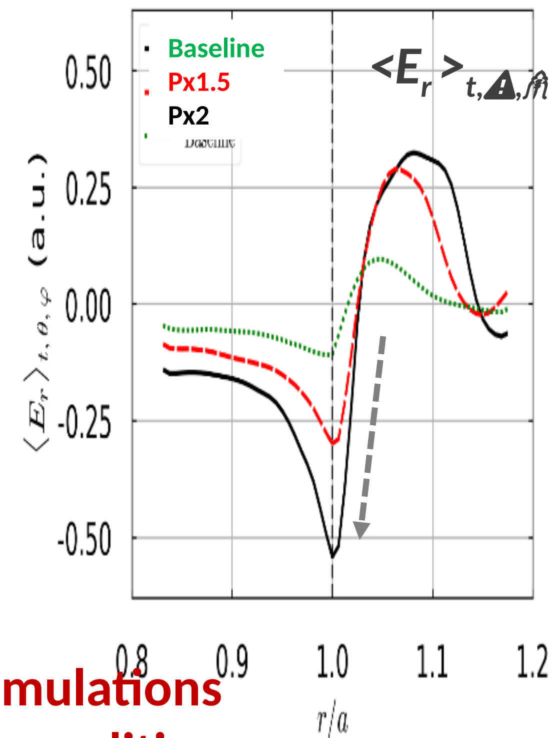
- **One important ingredient to improve agreement a low-n: kink physics**
  - 2D parallel current density implemented in ORB5 during TSVV pilot phase;
    further test/refinements on-going
  - Implementation of a shifted Maxwellian for kink physics work-in-progress in GENE (together with US co-workers)

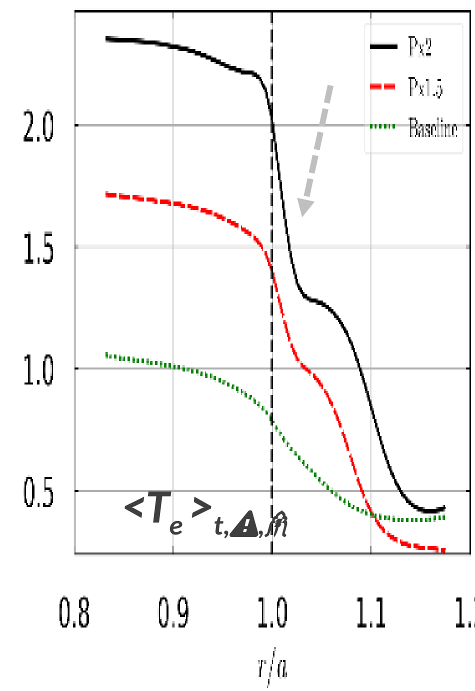


- **Theory background and discussion of MHD&GK relations and To Do's:**
  B. McMillan, to be submitted to JPP'22

D2: ETASC TSVV- PILOT Physics of the L-H transition & pedestal

TSVV1 pilot:
TOKAM3X power scan
in circular limited COMPASS-like param.
Falchetto et al EPS 2021





quasi-stationary state few ms.

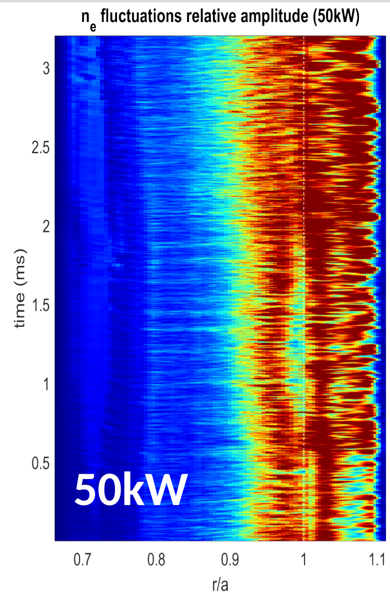
TSVV1 2021-2025
SOLEDGE3X 3D turbulence simulations in more realistic edge plasma conditions

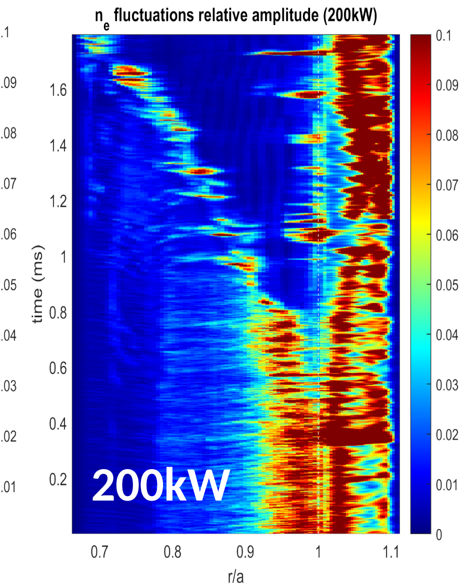
- **neoclassical viscosity**
- recycling **neutrals**
- realistic **divertor geometry** (WEST/TCV)
- **favorable (towards X-point) vs unfavorable magnetic drift direction** (WEST LSN vs USN)
- realistic collisionality

D2: Turbulent suppression near separatrix at high power

- Well developed turbulence at low power
  Avalanches cross the separatrix
- Reduction of fluctuation level around the separatrix at higher power
  "gap" propagates from separatrix inward
  Associated with higher shear
  Stationary zonal flows observed in the low turbulence region

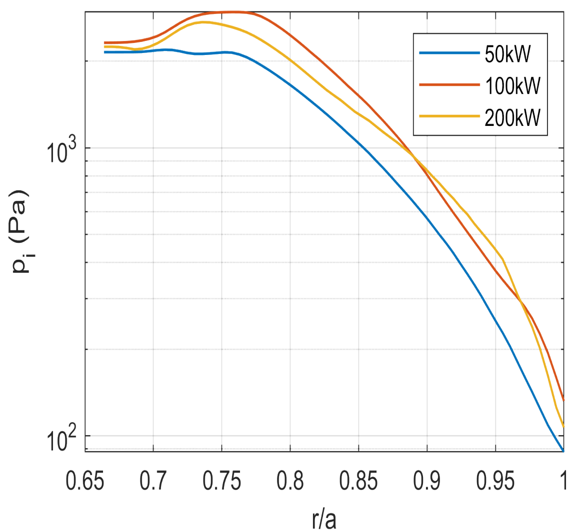
  Similar to [Giacomin, J. Plasma Phys., 2020]

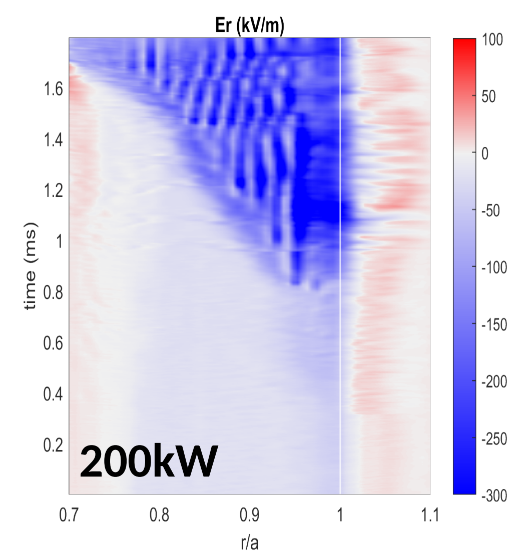




- 1ms after turbulence reduction, no clear steepening in pressure profile
  local steepening near separatrix
- E_r well recovered though **very high value**

missing a term to control plasma rotation? Ion viscosity effects
[Sigmar & Helander, Zholobenko et al., PPCF 2021]

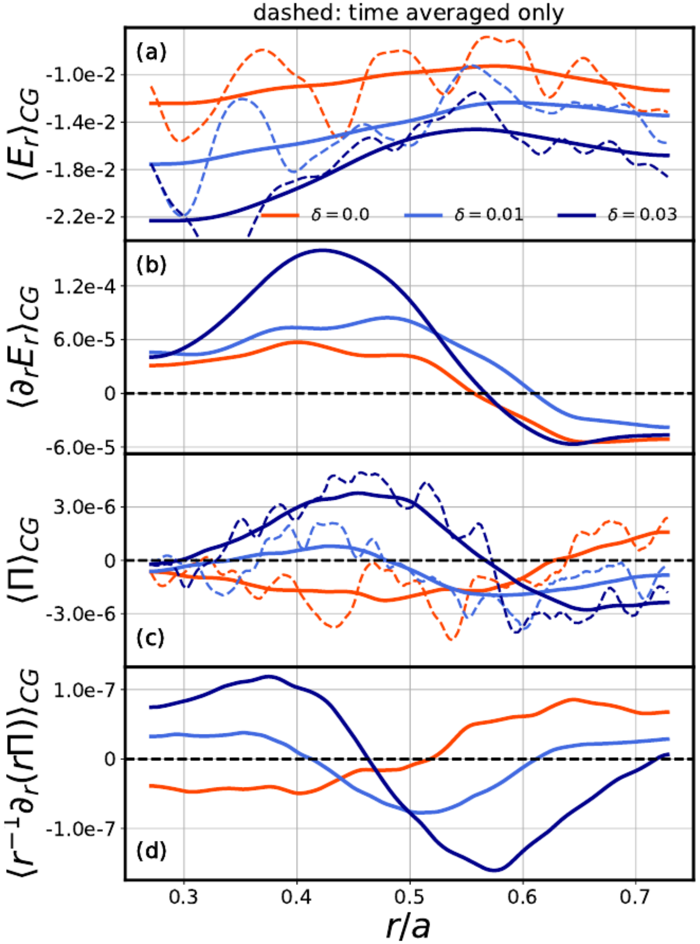




Courtesy H . Bufferand PET 2021

D2- Ripple effects in flux-driven global gyrokinetic GYSELA ITG-ae simulations

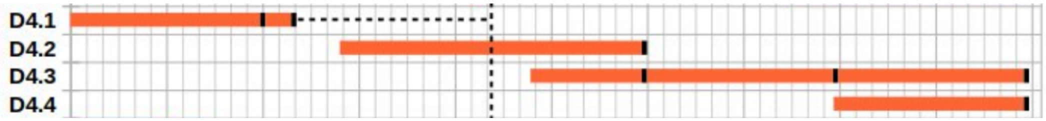
- **Capacity of ripples(*) to overcome turbulence as main flow drive revealed** [R. Varennes et al., PRL accepted (2022)]:
  - **reduced model** for ripple amplitude threshold for magnetic braking to overcome turbulence developed & validated
  - **toroidal velocity impact** of ripples by changing turbulent Reynolds stress through residual stress (E_r shear follows Reynolds stress variations)
  - neoclassical theory hence overestimates equilibrium toroidal velocity at realistic ripple amplitudes



(*) for simplicity at mid-radius, but exp. relevant in edge / pedestal regime

D4: interpretative & predictive capability of L-H transitions: from fluid codes to TSVV4 code

- **D4.1: Quantification of ITB momentum drive from rational vs. irrational surfaces and comparisons to plasma edge (04/2022)**
- Report on the SOLEDGE3X study of the effect of the direction of the magnetic drift and the level of realism of the edge conditions, with respect to experimental measurements (2023) → preparations, see D2
- **Predictive capabilities of the edge turbulence regime transitions based on a large scan of GBS simulations**, and validation with experimental results (2025) → preparations, see D2
- Assessment of comparison of fluid results with TSVV4 code (2025)



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)]:

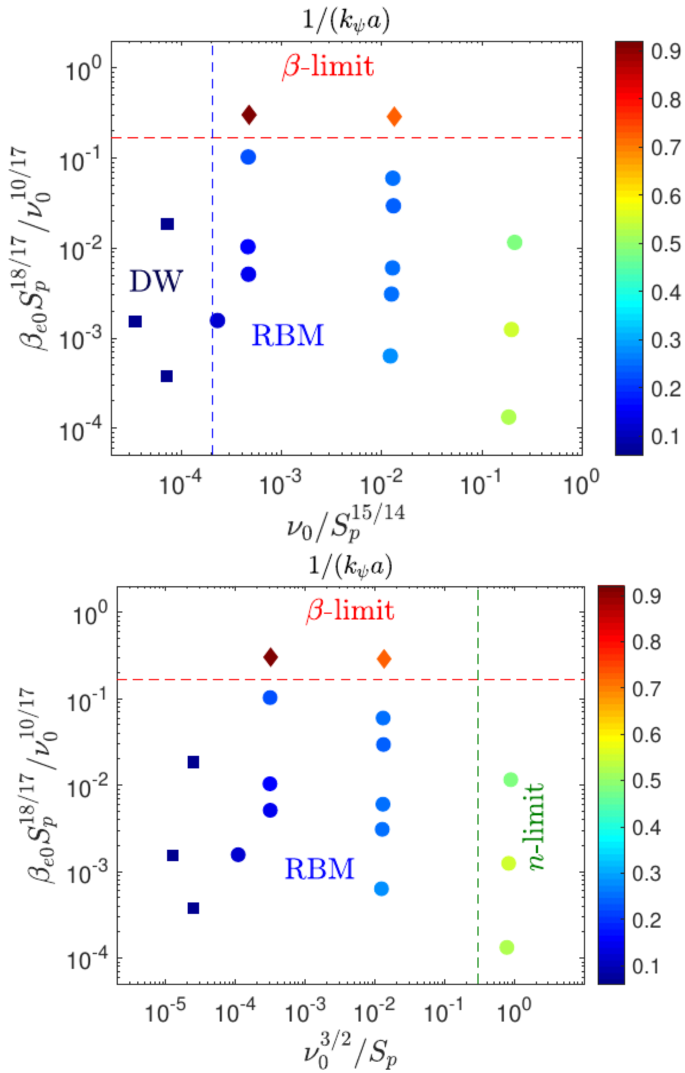
  (i) intermediate ν_0, S_p, β: resistive ballooning modes (RBM) (~ standard tokamak L-mode)

  (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)

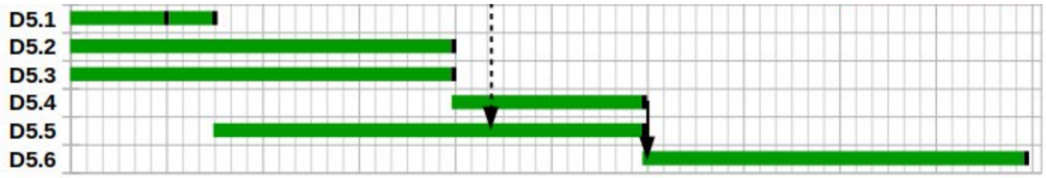
  (iv) large β regime (~ crossing of the β limit): ideal ballooning instability, large scale modes leading to a total loss of plasma and heat
- DW-to-RBM transition ~H-mode density limit
- Boussinesq approx. strong effect at low ν_0

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



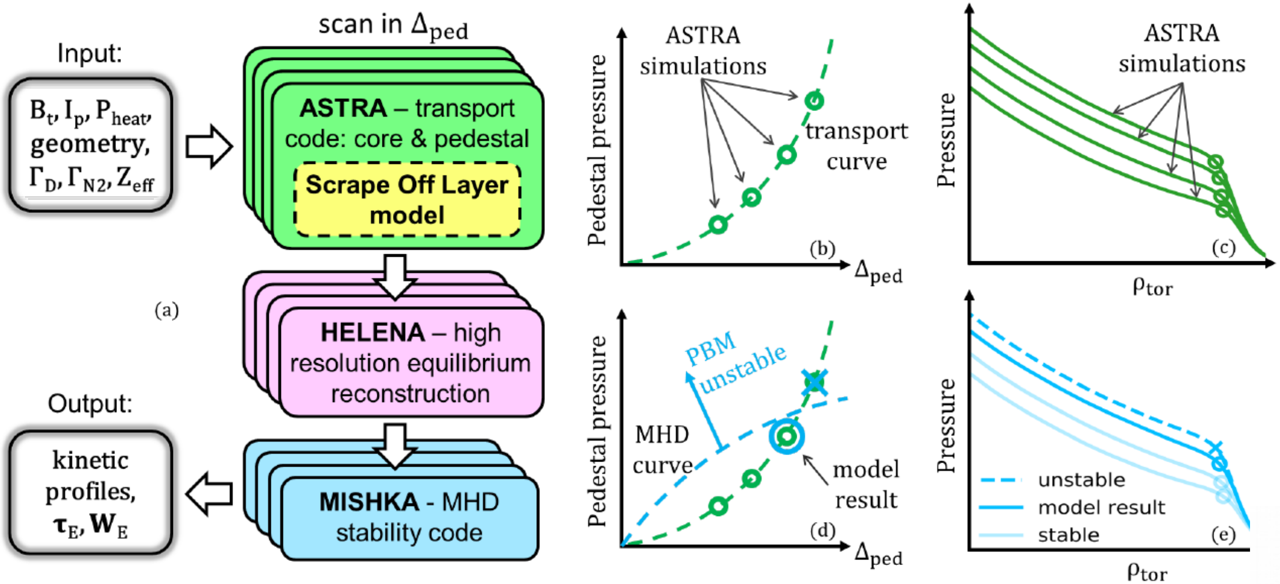
D5: Goals for red. transport model development for the pedestal on the basis of GK simulations

- **D5.1: Refined heuristic transport model ready for interfacing (12/2021)** and updated versions based on TSVV1 findings (2023, 2025)
- **D5.2: Core-edge coupled flux-driven integrated modelling (QuaLiKiz-based) for L-H transition studies implemented with available reduced physics models (2022+updates)**
- **D5.3: Reduced models for selected edge/pedestal modes (e.g., micro-tearing modes) developed (2022)** and validated (2023)



D5.1: Heuristic pedestal transport model

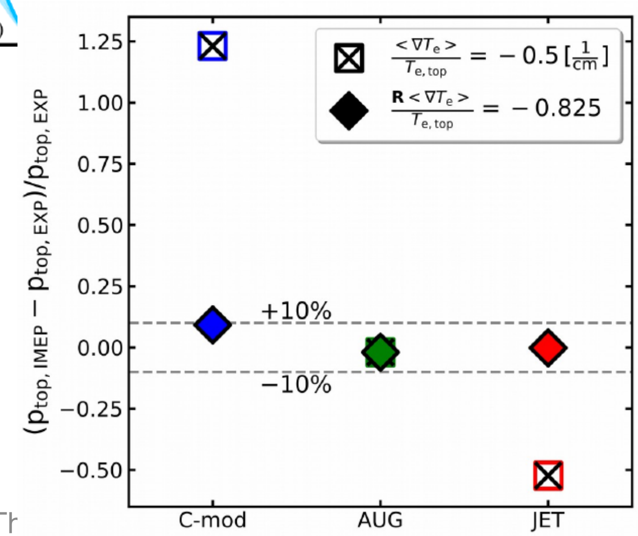
Integrated Model based on Engineering Parameters (IMEP)



[T. Luda *et al* 2020 *NF*]
[T. Luda *et al* 2021 *NF* (to be submitted)]

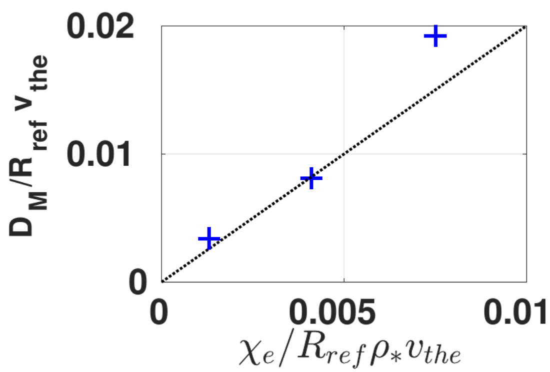
- **Model improvement: Rescale pedestal top condition with major radius R → nice agreement with 60 new JET discharges**
- **Refined model available within IMEP, IMAS interface established, tests imminent**

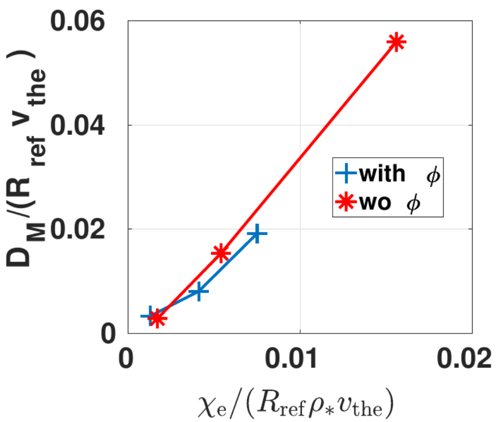
- **Old model:** $\chi_{e,ped}$ adjusted to $\frac{<\nabla T_e>}{T_{e,top}} = -0.5\ [1/cm]$
- Optimized to 50 AUG H-modes
- **Now tested on C-Mod & JET-ILW** ELMy H-mode phases → *major radius R relevance*



D5.2/5.3: QuaLiKiz-based modelling / reduced MTM model

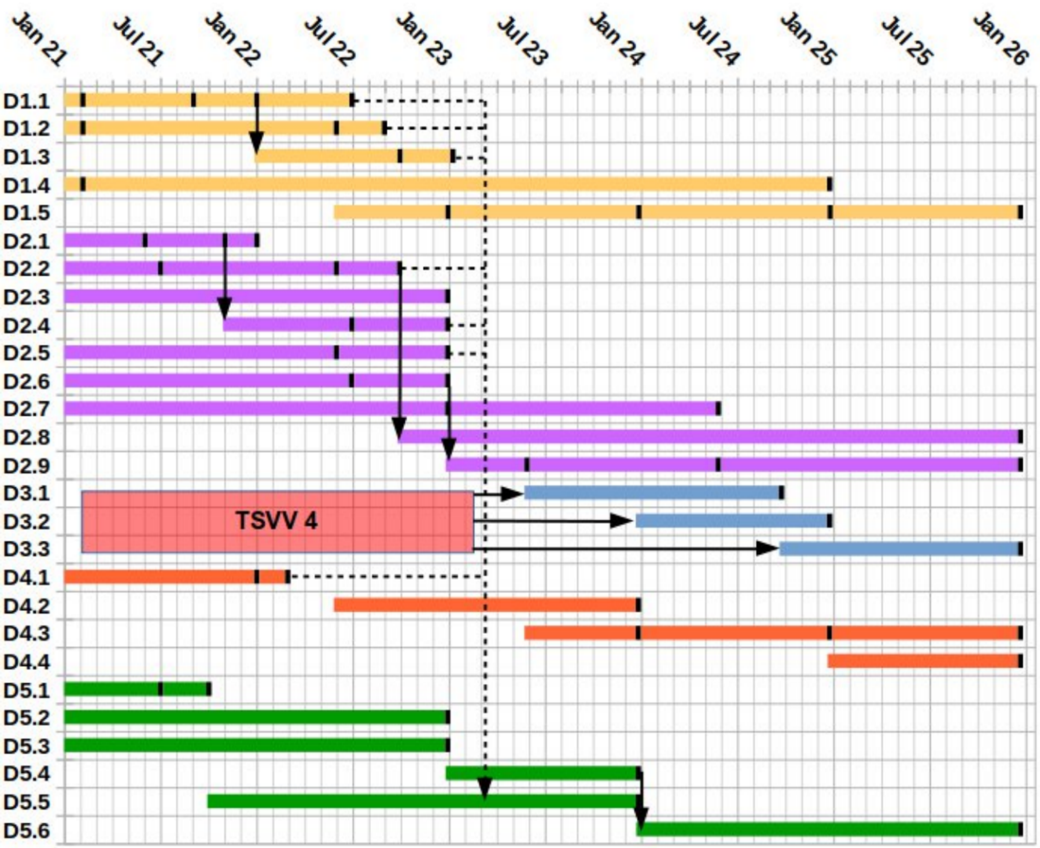
- **Core-edge coupled flux-driven integrated modelling (QuaLiKiz-based) for L-H transition studies implemented with available reduced physics models:**
  - high-dimensional micro-instability scan with GENE for QuaLiKiz tuning completed + possible deficiencies of reduced model identified
- **Reduced models for selected edge/pedestal modes**
  - Micro-tearing Modes: Further assessment of Rechester-Rosenbluth-based model $D_M = \tilde{b}_r^2 L_{\|} v_{th_e} = \pi q R \tilde{b}_r^2 v_{th_e}$ with $\tilde{b}_r = \left\langle \left(\frac{\tilde{B}_r}{B_{\rm eq}} \right)^2 \right\rangle^{1/2}$





  - ES potential & zonal flows identified as important NL effect explaining the remaining deviations of model and fully GK sims [M. Hamed, pinboard entry (06/2022)]

Summary



- Most 2022 milestones and deliverables progressing well (ion orbit losses affected by loss of key personnel)
- Interesting findings (pedestal transport structure, possible ripple impact, (fluid) turbulence characterization, reduced models)
- Regular monthly meetings + progress workshop planned for Sep. 26-27(-28), 2022

Appendix
Further activities

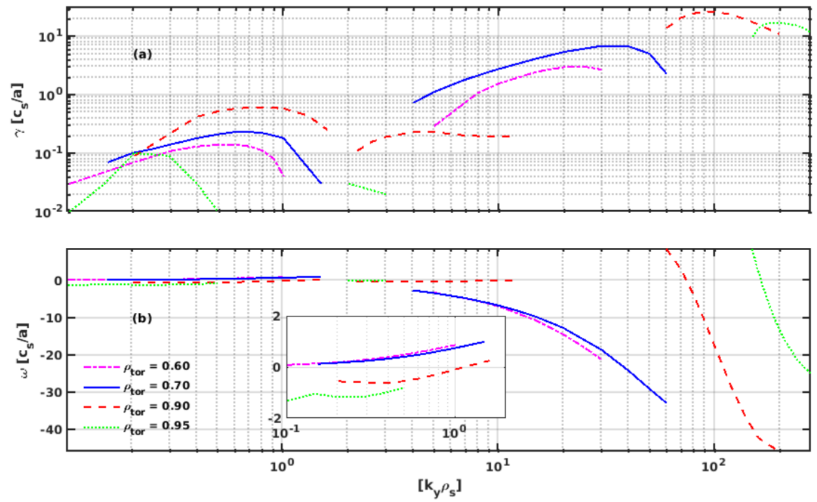
Publication list as of 03/2022

Year	Author(s)	Title	Journal / Meeting	Link/reference
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)	doi
2021	G.L. Falchetto	Interaction between a self-generated reversed radial electric field and turbulence in 3D global flux-driven fluid edge plasma simulations (poster)	47th Conference on Plasma Physics (EPS), Sitges, Spain, online, June 21-25, 2021	pinboard entry
2021	M. Giacomin	Theoretical interpretation of the density limit and comparison to experimental data (invited)	63rd Annual Meeting of the APS Division of Plasma Physics, Nov 8-12, 2021	abstract
2021	M. Hamed	A reduced model for microtearing instability and transport (oral)	47th Conference on Plasma Physics (EPS), Sitges, Spain, online, June 21-25, 2021	
2021	G. Snoep et al.	Validation of reduced-order turbulence modelling in L-mode near-edge (poster)	47th Conference on Plasma Physics (EPS), Sitges, Spain, online, June 21-25, 2021	pinboard entry
2021	G. Snoep et al.	Validation of reduced-order turbulence models in the tokamak L-mode near-edge (oral)	25th Joint EU-US Transport Task Force Meeting, Sept 6-10, 2021	
2021	G. Snoep et al.	Validation of reduced-order turbulence models in the tokamak L-mode near-edge (oral)	ITPA T&C Fall meeting 2021	
2021	L. Leppin et al.	Tackling turbulence in the plasma edge pedestal with a revised version of the GENE code (poster)	DPG SMuK Meeting, Germany, online, August 30 - September 03, 2021	pinboard entry
2021	K. Stimmel et al.	Gyrokinetic study of EDA H-mode with argon seeding in ASDEX Upgrade	Submitted to Physics of Plasmas (2021)	pinboard entry
2021	R. Varennes	Impact of non-axisymmetric magnetic field perturbations on flows (poster)	25th Joint EU-US Transport Task Force Meeting, Sept 6-10, 2021	
2021	R. Varennes et al.	Plasma rotation: when turbulent momentum drive opposes magnetic braking.	submitted to Phys. Rev. Lett. (2021)	pinboard entry
2022	P.D. Donnel et al.	Electron-cyclotron resonance heating and current drive source for flux-driven gyrokinetic simulations of tokamaks	submitted to Plasma Physics and Controlled Fusion (2022)	pinboard entry
2022	M. Giacomin et al.	Electromagnetic phase space of turbulent transport in the tokamak boundary	submitted to Nuclear Fusion (2022)	pinboard entry
2022	M. Hamed et al.	Microtearing turbulence and reduced transport model building in H-mode plasmas (poster)	Physics@Veldhoven Hybrid Conference, Jan 25-26, 2022	pinboard entry
2022	M. Hamed et al.	Microtearing turbulence and reduced transport model building in H-mode plasmas	48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 27th June 2022 - 1st July 2022	pinboard entry
2022	L.A. Leppin et al.	Tackling turbulence in the plasma edge with a revised version of the GENE code	DPG Spring Meeting 2022, Mainz, Germany, 28th March 2022 - 1st April 2022	pinboard entry
2022	L. Vermare et al.	Influence of safety factor on the radial electric field at the edge of tokamak plasmas	48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 27th June 2022 - 1st July 2022	pinboard entry
2022	R. Varennes et al.	Plasma rotation: when turbulent momentum drive opposes magnetic braking	48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 27th June 2022 - 1st July 2022	pinboard entry

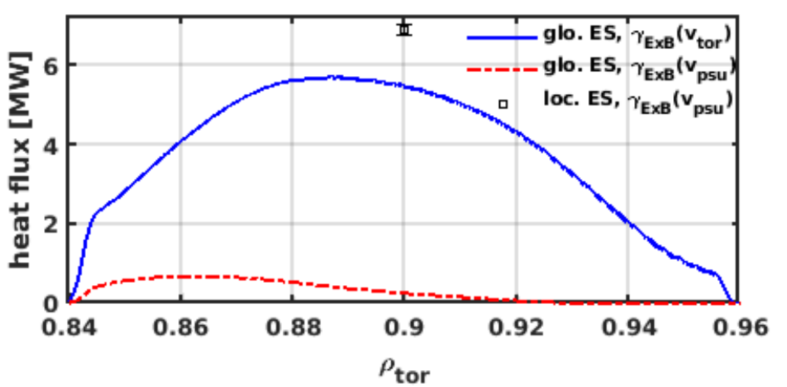
Evolving list at
https://wiki.euro-fusion.org/wiki/TSVV-01#Publications_.2F_Conference_presentations

D1: Example – EDA H-mode with Ar-seeding

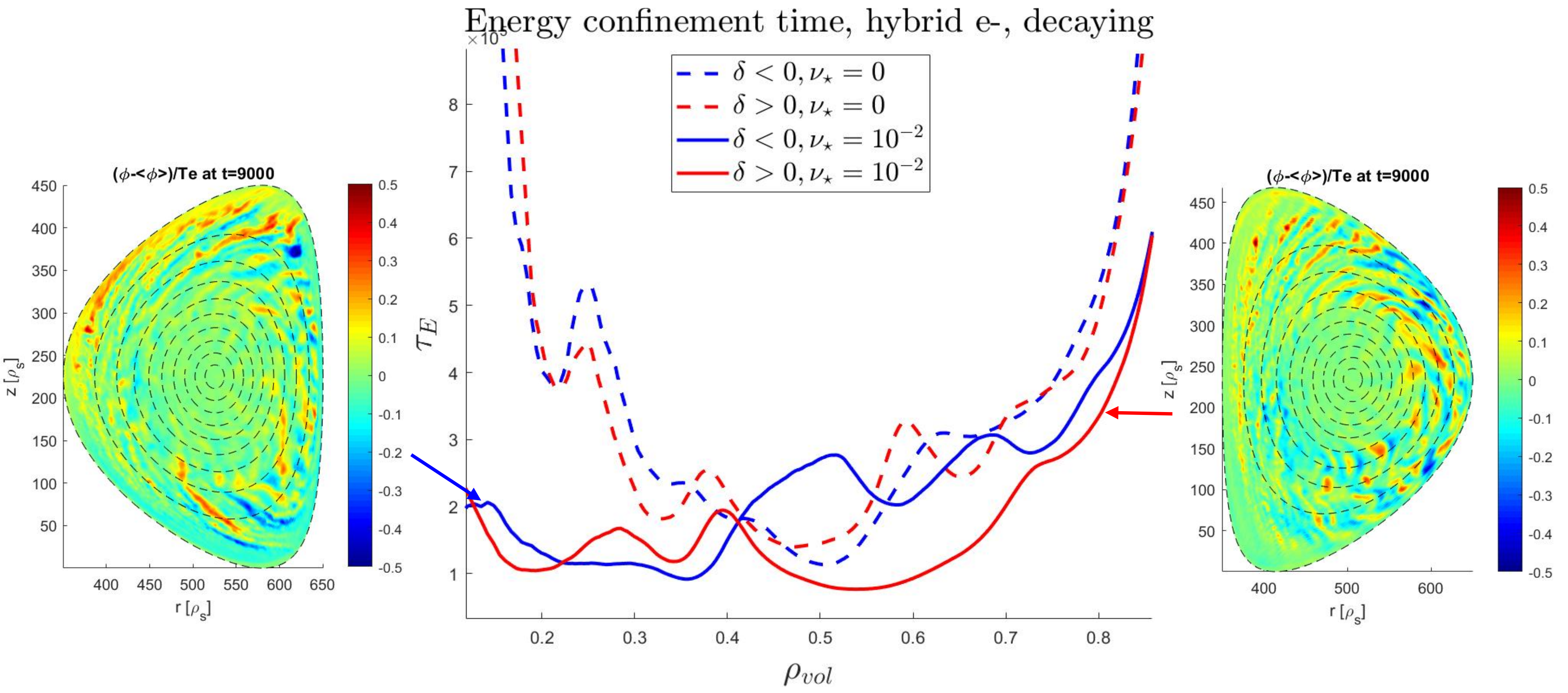
- **Gyrokinetic study of EDA H-mode with Ar-seeding on ASDEX Upgrade**
  [K. Stimmel et al., JPP accepted (2022)]
  - Pedestal top instabilities: MTM but also hybrid modes (drift direction changes) found at ion-scales; ETG at electron scales
  - Nonlinearly, ETGs negligible, ion-scale turbulence in the right ballpark with global simulations (EM still needs to be performed)
  - Quasi-linearity & frequency spectra assessed as well



Heat Transport [MW]			ρ_i-scale						ρ_e-scale	neo.	Q_{sum}	
			e.s. channel			e.m. channel						
radial position	ρ_i mod.	v_{prof}	ion	e^-	Ar	ion	e^-	Ar	ρ_e sum		sim.	exp.
$\rho_{tor} = 0.60$	–	v_{tor}	2.11	0.82	–	-0.03	0.02	–	0.06*	0.48	3.46±0.14	3.36
	$\omega_{Ti} - 15\%$	v_{tor}	0.83	0.34	–	-0.01	0.00	–			1.70±0.00	
$\rho_{tor} = 0.70$	–	v_{tor}	4.32	1.96	–	-0.05	0.03	–	0.14*	0.56	6.96±0.01	3.44
	$\omega_{Ti} - 15\%$	v_{tor}	2.38	1.14	–	-0.02	0.02	–			4.22±0.14	
	+ Ar prof. 2	v_{tor}	3.19	1.43	0.01	-0.04	0.02	0.00			5.31±0.14	
$\rho_{tor} = 0.90$	–	v_{tor}	12.68	23.36	–	-0.14	1.40	–	0.03	0.60	37.93±1.29	2.75
	–	v_{psu}	5.48	9.34	–	0.20	0.92	–			16.57±0.76	
	$\beta_e = 0$	v_{psu}	2.38	4.53	–	–	–	–			6.91±0.14	
$\rho_{tor} = 0.95$	–	v_{tor}	1.88	3.15	–	0.00	0.15	–	0.00	0.88	6.06±0.18	2.22
ρ_{tor} = 0.84 - 0.96	$\beta_e \sim 0$	v_{tor}	1.38	2.40	–	–	–	–	–	–	3.77	–
ρ_{tor} = 0.84 - 0.96	$\beta_e \sim 0$	v_{psu}	0.04	0.08	–	–	–	–	–	–	0.12	–



Hybrid electrons and collisions needed to qualitatively reproduce the improvement of confinement in δ<0 (TCV case)



Next steps : include ECRH [Donnel et al., PPCF 2021] source to have flux driven simulations → study the impact of boundary conditions on confinement

D2: Improved HAGIS code for NC predictions

- **Pedestal: steep density & temperature profiles, strong Er**
  higher collisionality
- **LH-TSVV pilot project: need for more accurate model for bootstrap current calculations shown**
- **Goal here:**
  - **Improve HAGIS collision model (mostly done in 2021) and run HAGIS as full-f code**
    (new initialisation procedure, procedure to stabilise the density and temperature profiles w/o turbulent transport in the simulation)

- *First step on-going/partially achieved: δf code with improved collisions and profile stabilisation*

D2: GBS extensions for global fluid sims

EPFL

Investigation of turbulent transport in the plasma boundary and formation of a transport barrier by using GBS simulations

M. Giacomin

Description	Status	Date
Improve the GBS fluid turbulence code to avoid the Boussinesq approximation and to include electromagnetic effects	The GBS code has been extended to include the electromagnetic effects and avoid the Boussinesq approximation	12/2021
Improve the GBS fluid turbulence code to include the interaction with neutrals	Work in progress. No major issue so far	12/2022
Using the GBS code, two-fluid simulations that include electromagnetic fluctuations, neutral physics and avoid the Boussinesq approximation	To be addressed	06/2023

Simulations that avoid the Boussinesq approximation and include electromagnetic effects are currently running

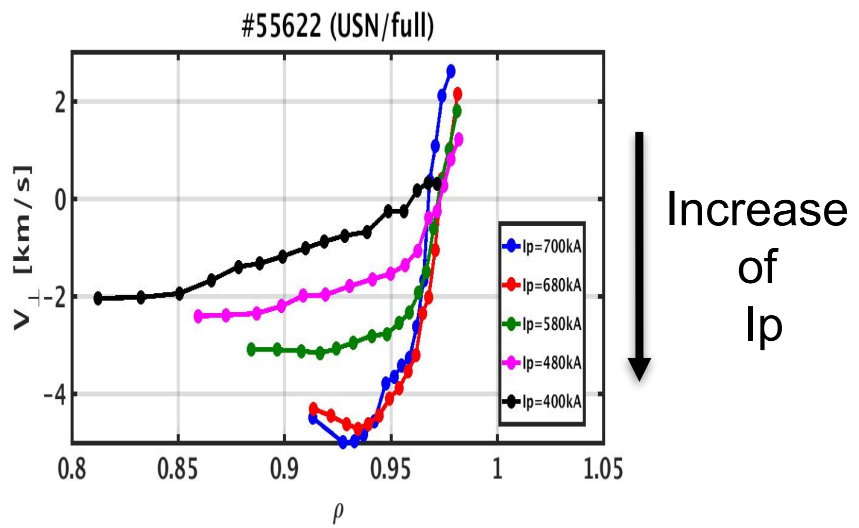
Swiss Plasma Center

D2: Full-f GK radial electric field studies

M2.9	Study the development of a radial electric field in response to key parameters such as injected power, collisionality and safety factor, using the GYSELA and ORB5 codes including simplified limiter/SOL - comparison with fluid code results	L. Vermare, X. Garbet, R. Varennes, P. Donnel	06/2022

- Evolution with the safety factor (through the plasma current)
- Experimental measurements on WEST plasmas
- Gyrokinetic simulations in progress …

<u>Experimental evidence of the influence of Ip in the Er profile</u>



D2: Full-f GK radial electric field studies II

D2.5	Report including statements on the relative impact of some separate ingredients playing a role in the radial electric field formation (orbit losses, ripple, turbulence, neutrals, limiter...)	report or paper submitted, conference contribution	X. Garbet, R. Varennes, L. Vermare, G. Falchetto, P. Donnel	12/2022

Impact of ripple on turbulence

Neoclassical predictions on toroidal velocity :

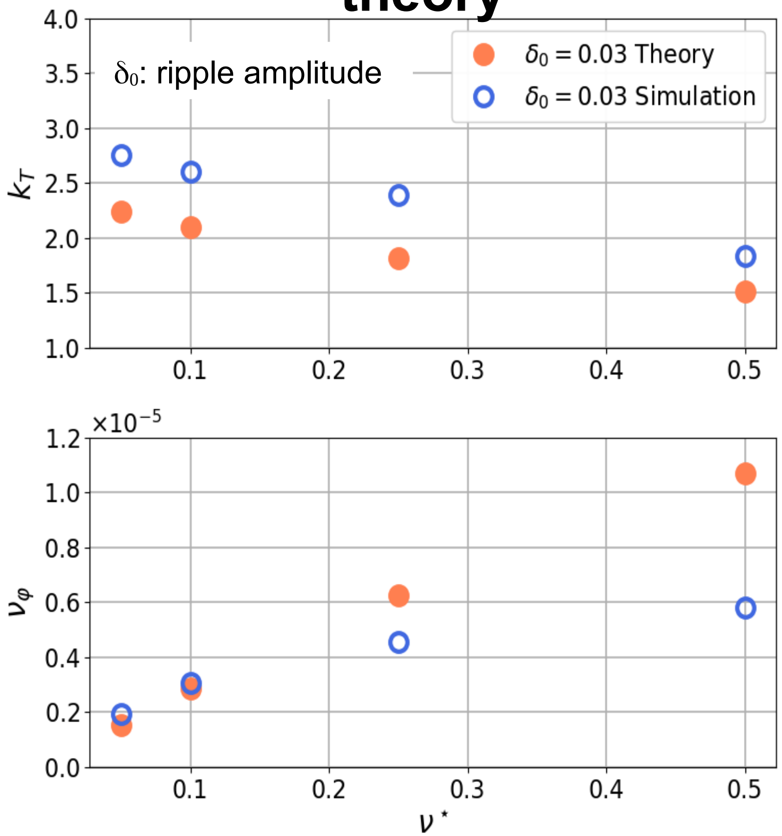
$$\frac{\partial V_T}{\partial t} = -\nu_\varphi \left(V_T - k_T \frac{\nabla T}{e B_P} \right)$$

Neoclassical friction

Thermal drive

Gyrokinetic code GYSELA compared successfully with neoclassical predictions

Comparison simulations / theory



D2: Full-f GK radial electric field studies III

D2.5	Report including statements on the relative impact of some separate ingredients playing a role in the radial electric field formation (orbit losses, ripple, turbulence, neutrals, limiter…)	report or paper submitted, conference contribution	X. Garbet, R. Varennes, L. Vermare, G. Falchetto, P. Donnel	12/2022

Gyrokinetic simulations : ripple activated on top of a turbulent statistical equilibrium

Gaussian ripple perturbation (maximum at mid-radius) to avoid mix-up with boundary conditions