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TSVV13: Stellarator Turbulence Simulation

J. M. García Regaña (PI) on behalf of the TSVV13 Team

EUROfusion Science Meeting on Status of TSVV projects
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Laboratorio Nacional de Fusión
Ciemat
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
UNIVERSITY OF OXFORD
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY
CCFE CULHAM CENTRE FOR FUSION ENERGY

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Motivation: transport channels in neoclassically optimized stellarators and the TSVV13

	Physical Origin	Relevance for tokamaks	Relevance for stellarators
Classical transport	Collisions	Typically negligible	Typically negligible
Neoclassical Transport	Collisions + inhomogeneity of $\boldsymbol{B}$	Small	Large in non-optimized stellarators
Turbulent transport	Collective fluctuations	Dominant	Relevant in **neoclassically optimized stellarators**

- **First** large **neoclassically optimized stellarator**, Wendelstein 7-X (W7-X), **in operation since 2015**.
- Before, **only GENE** [Jenko PoP´00] and **EUTERPE** [Kornilov PoP´04] regularly carried out gyrokinetic simulations in W7-X, mostly linear and electrostatic.
- W7-X began its **exploitation with a notable deficiency in resources** to thoroughly comprehend its microturbulence.
- The **TSVV13** has assembled these resources, incorporating new gyrokinetic codes, stella [Barnes JCP´19] and GENE-3D [Mauer JCP´20], along with developers and users.

TSVV#13 Stellarator Turbulence Simulation: Overview

Background

- The understanding of turbulence in stellarators is **limited** in comparison with tokamaks, due to
  - the **computational cost** of handling 3D magnetic geometries;
  - the **limitations** of the flux tube approach for stellarators.
- In particular, some aspects of turbulence remain (electromagnetic turbulence, interplay between neoclassical (NC) and gyrokinetic (GK) physics) remain **practically unexplored**.

Project

- 9 milestones and 15 SMART deliverables to cover by 2025 the 5 key deliverables:
- **1) Stellarator GK codes verified** against each other and **2) validated** against stellarator and 3D tokamak experiments, **3) able to address the interaction between NC and GK** turbulence and **4)** to **assess relative weight of NC and turb. transport**. **5) Develop reduced models**.

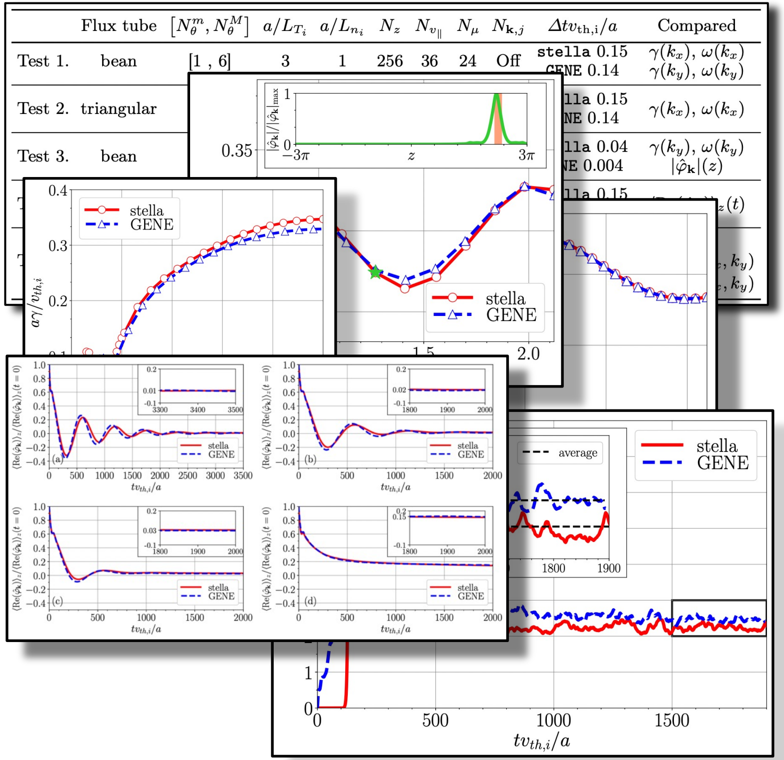
Team (CIEMAT, CCFE, MPG, DIFFER)

- **9 leading experts** in GK theory and simulation, developers and users of the main European stellarator GK codes + a NC code: **stella, GENE, EUTERPE, GENE-3D, KNOSOS**.
- **J.M. García-Regaña (PI), E. Sánchez, J. L. Velasco (CIEMAT), M. Barnes, J. Omotani (CCFE/U. Oxford), A. Bañón Navarro, J. Riemann, A. Zocco (MPG), J. Proll (DIFFER) + External Experts: M. J. Pueschel (DIFFER), R. Kleiber (MPG) … + PhD students.**
- **Former members: F. I. Parra, D. St.-Onge (Oxford), J. Alcusón (MPG).**

TSVV#13: Stellarator Turbulence Simulation

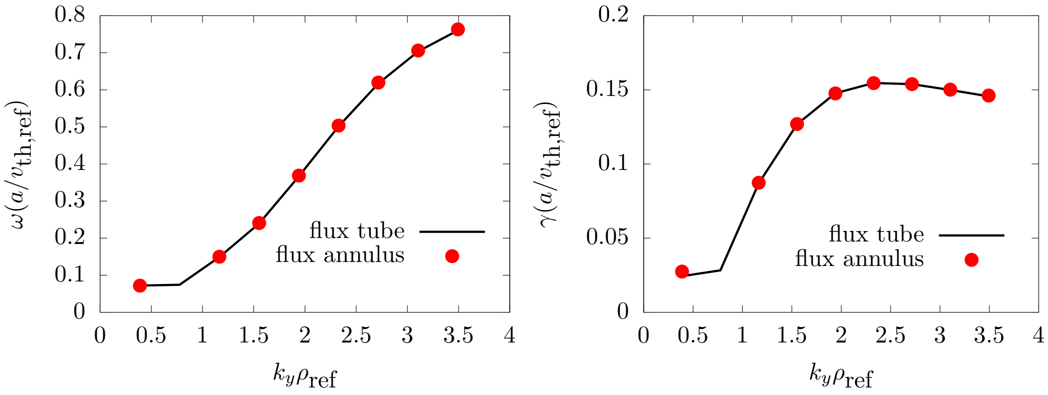
Verification (and code development)

- **stella**: δf flux tube, electrostatic, collisionless, multispecies, gyrokinetic code for 3D geometry [Barnes JCP´19].
- **Operator splitting** and **implicit treatment** of **parallel streaming term** ⇒ efficient treatment of kinetic electrons (larger time-step allowed) in multispecies simulations.
- A set of stellarator test cases for cross-code verification *à la Cyclone Base Case (CBC)* delivered for the **benchmark of stella against GENE**. All data, incl. configuration and resolution details in [González-Jerez JPP´22].
- So far, **GENE, stella, GX** [Mandel submitted´23], **EUTERPE** have used some, if not all, of these test cases.

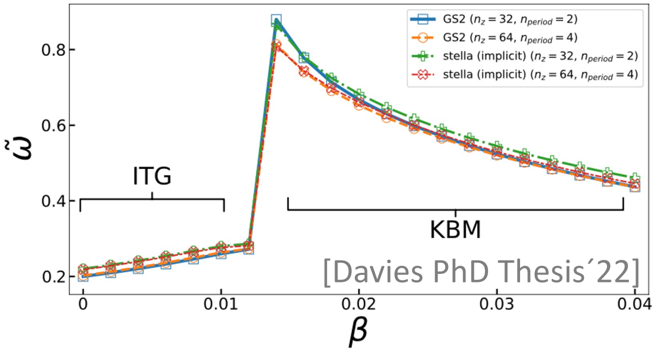


- **stella**: δf flux tube, **full flux surface (FFS), electromagnetic (EM), collisional,** gyrokinetic code for 3D geo., w/ neoclassical terms.
- **Full flux Surface** (FFS) or flux annulus version has been developed (fully functional but still doing nonlinear tests).
- Spectral in plane normal to mean magnetic field.

W7-X, $\rho = 0.5$, kin.e⁻ [Acton EFTC´23]

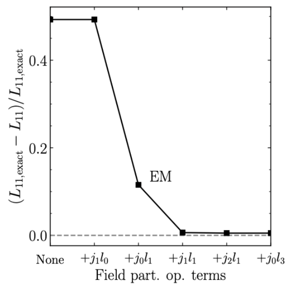


- Implicit implementation of **electromagnetic (EM) terms**.



[Davies PhD Thesis´22]

- Linearized (GK) Landau **collision operator**.



[von Boetticher PhD Thesis´22]

stella: a mixed implicit-explicit δf gyrokinetic code for general geometry

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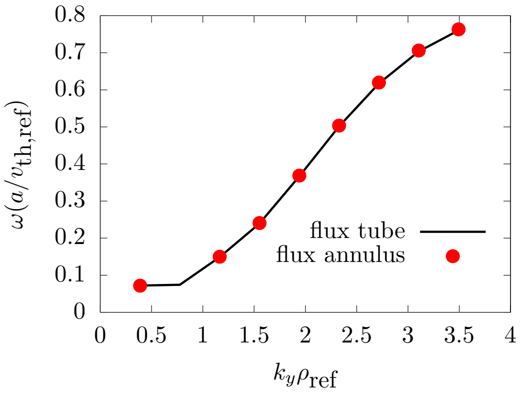
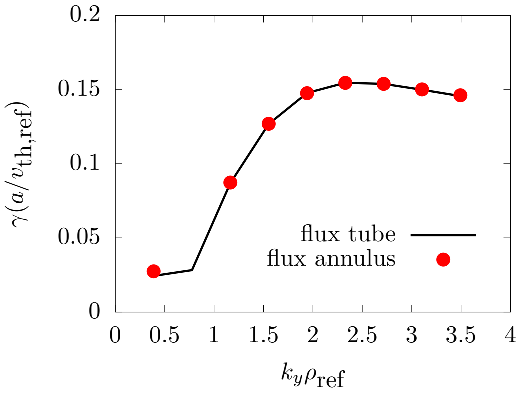
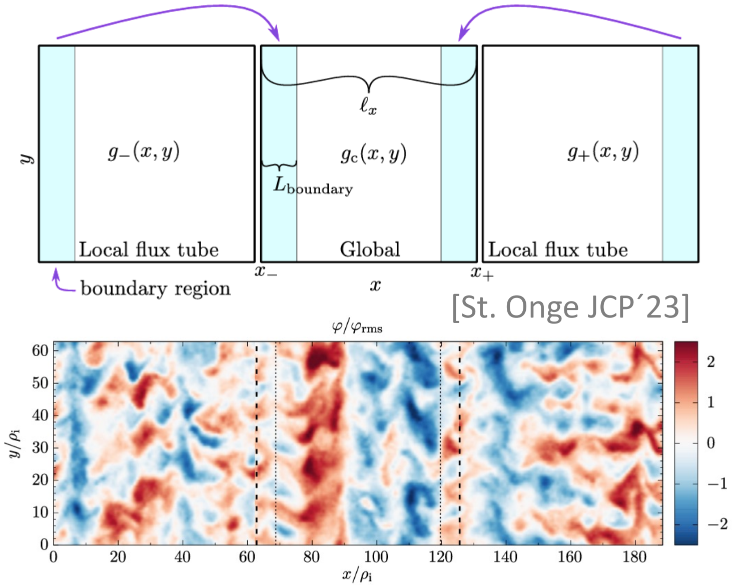




- Tokamak extension to allow radial profile variation following [Parra&Barnes PPCF´15].
- **Local flux tubes** determine boundary conditions of *main* (**global**) **flux tube**.



[St. Onge JCP´23]

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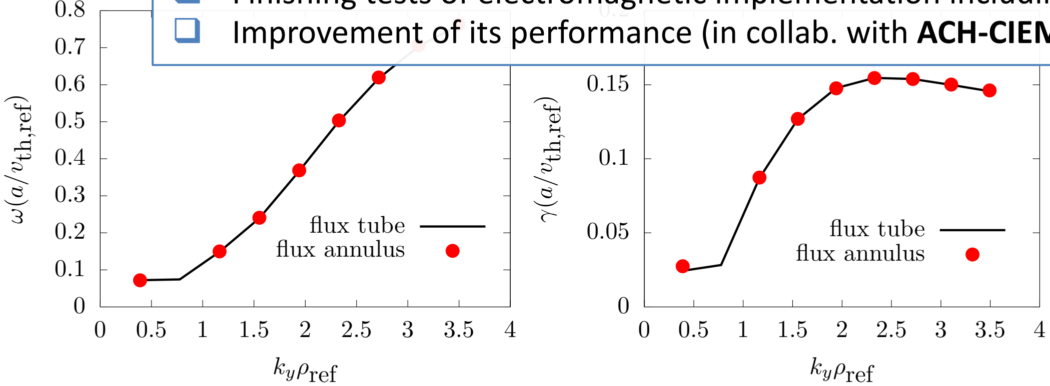

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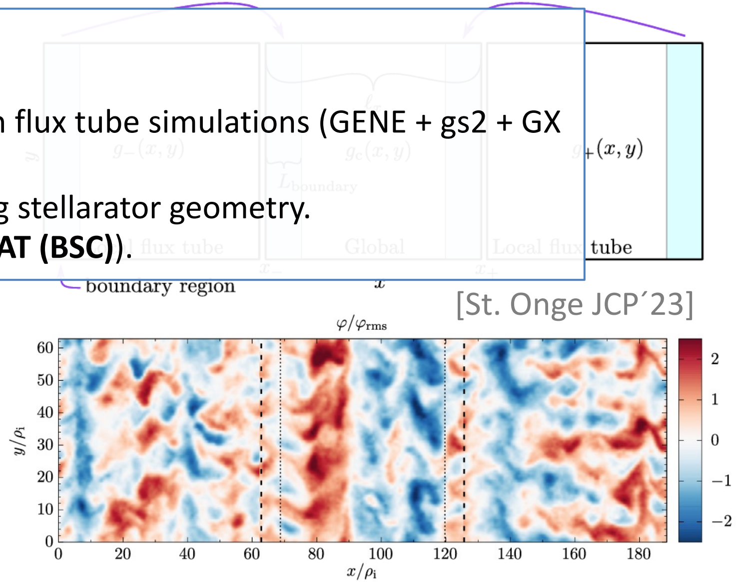
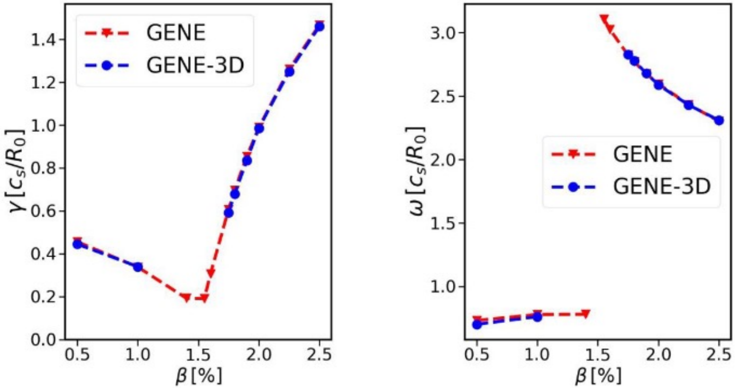


[St. Onge JCP´23]

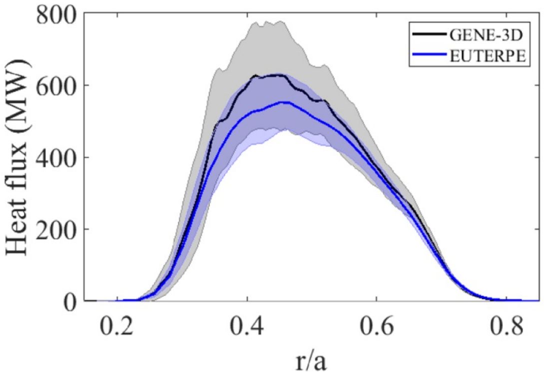
Next steps:
- Finishing linear/nonlinear tests of FFS implementation.
- Benchmarking FFS code against GENE-3D and compare with flux tube simulations (GENE + gs2 + GX + stella).
- Finishing tests of electromagnetic implementation including stellarator geometry.
- Improvement of its performance (in collab. with **ACH-CIEMAT (BSC)**).

GENE-3D: a global gyrokinetic code for stellarators

- **GENE-3D** [Maurer JCP´20]: Eulerian, field-aligned coordinates, δf, EM, collisional, multispecies, it handles **fully 3D geometries** (coupled to GVEC).
- It can run in flux tube, full flux suface (FFS) and radially global domains (RG).
- **RG version benchmarked** against the radially global version of GENE for tokamak geometry, both linearly and nonlinearly [Wilms JPP'21]:



- **RG version benchmarked** for linear and nonlinear simulations against **EUTERPE** in stellarator geometry [Sánchez NF´22].



- **Good agreement** between codes.
- **Weaker turbulence localization** in nonlinear simulations than in linear simulations.
- **Weak effect of the neoclassical radial electric field** (E_r) on heat fluxes and turbulent fluctuations localization.

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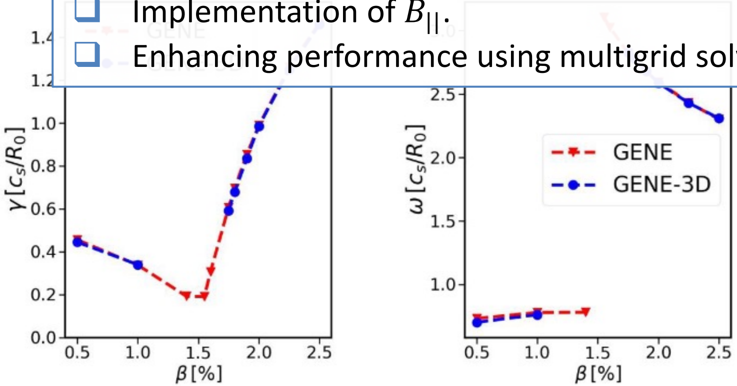

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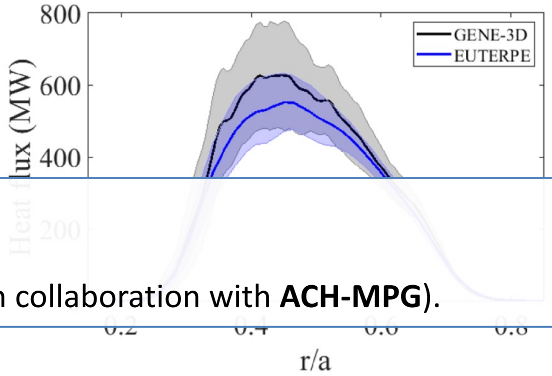
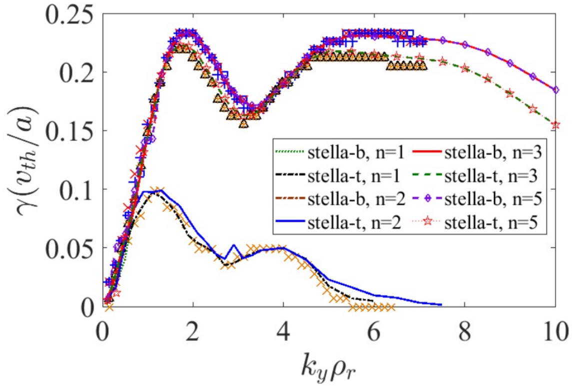


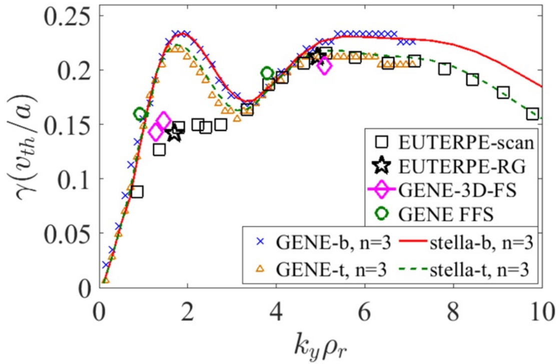
Next steps:

- Implementation of $B_{||}$.
- Enhancing performance using multigrid solver (ongoing, in collaboration with **ACH-MPG**).

- **Good agreement** between codes.
- **Weaker turbulence localization** in nonlinear simulations than in linear simulations.
- **Weak effect of the neoclassical radial electric field** (E_r) on heat fluxes and turbulent fluctuations localization.

- **Verification** of codes **beyond flux tube** geometry and impact of the domain considered in linear simulations.
- Comparison of **all gyrokinetic codes with participation** in the TSVV13: **stella**, **GENE** (run in FT and FFS domains), **GENE-3D** (run in FFS and RG domains) and **EUTERPE** (run in RG domain)
- Linear simulations of **ITG instabilities** (adiabatic electrons) and **zonal flow relaxation**, in the LHD and W7-X stellarators.
- **FT results converge to each other and to FFS and RG** simulations with **increasing FT** length (dependence on configuration).



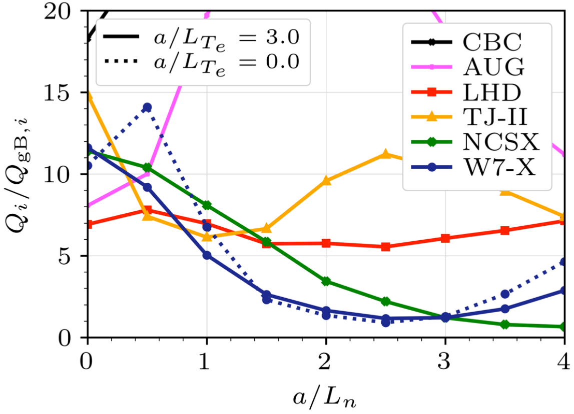


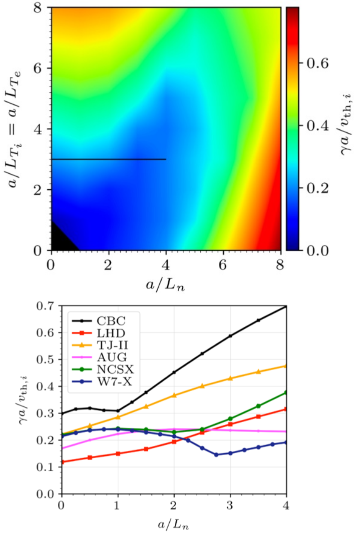
TSVV#13: Stellarator Turbulence Simulation

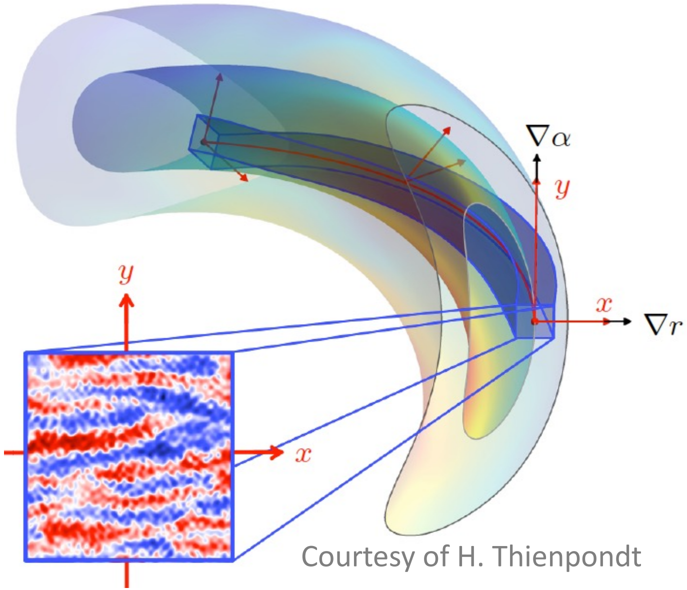
Theory and Simulation

Cross-device comparison of electrostatic instabilities and turbulence

- Comprehensive **cross-device comparison** and characterization of linear stability and nonlinear heat fluxes [Thienpondt ISHW´22, in progress´23].







Courtesy of H. Thienpondt

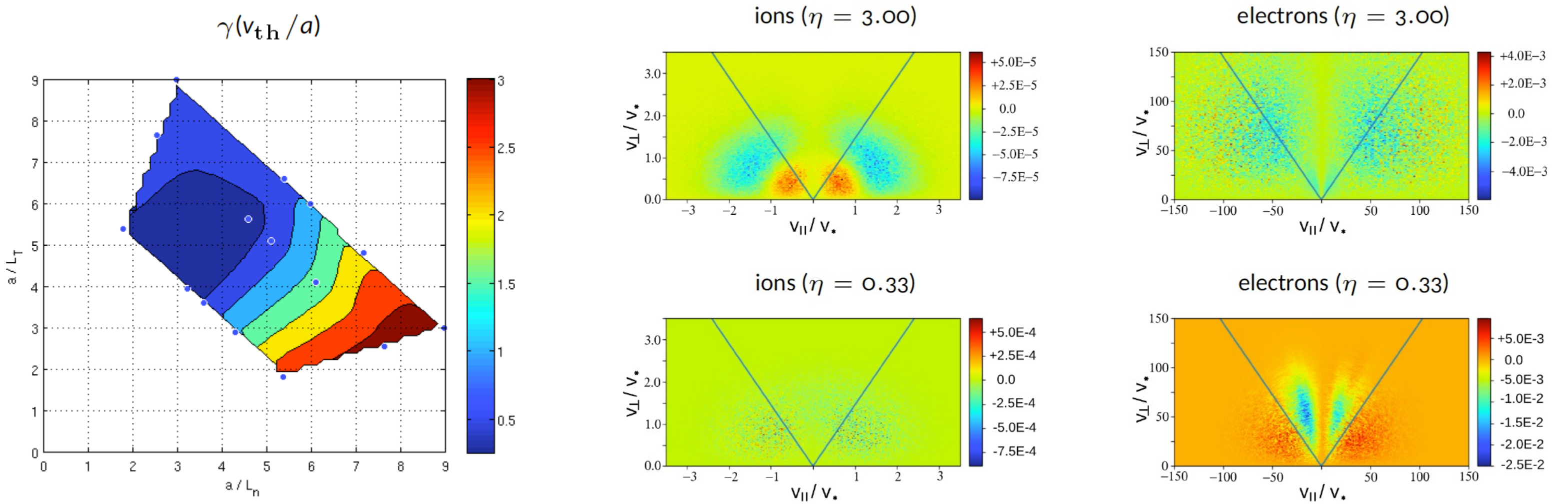
- W7-X and NCSX benefit from the **increase of the density gradient** to access **low turbulent heat levels**. Linear simulations do not correlate well, in general, with nonlinear fluxes.

Next steps:

- Including **new optimized stellarators**.
- Exploring various functional forms dependent on **linear parameters to predict nonlinear heat fluxes** from linear information.

Global simulations of electrostatic stability in W7-X

- **Stability** studies with **global simulations** (EUTERPE) for W7-X requires full profiles.
- **Pressure preserving scheme** has scanned $\eta = T'/n'$ in the range [0.33, 0.3] considering experimentally achievable profiles and consistent VMEC equilibria.
- **Local maxima of** γ found for $k_\perp \rho_i \approx 2$ found for a broad regions of the parameter space.
- **Diagnostics** to characterize the source of the instabilities in phase space.



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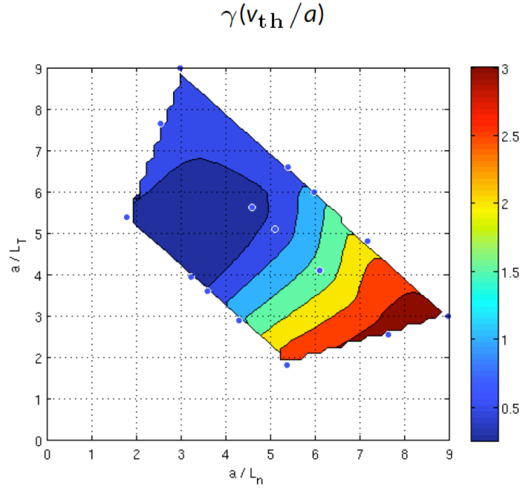
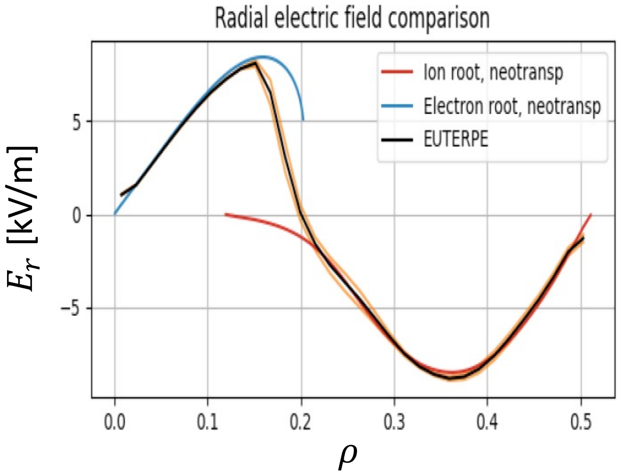
Next steps:

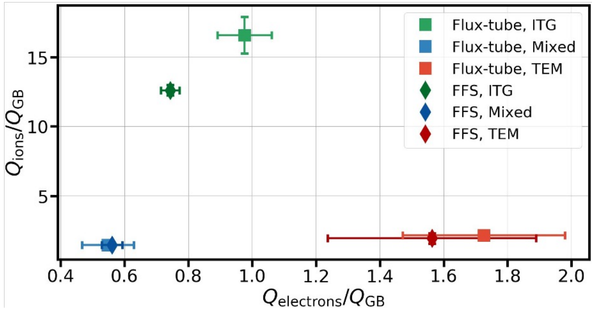
- Including effect of E_r, obtained from RG neoclassical simulation (new in EUTERPE), i-e root transition.
- Enhancing performance using multigrid solver (2023/24 ACH task, carried out by **ACH-MPG**)

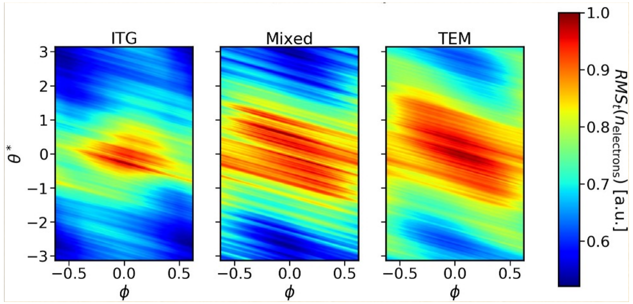




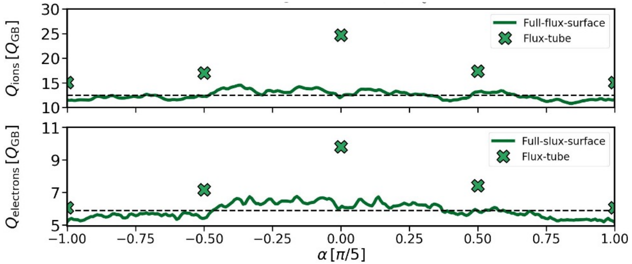
Impact of the domain choice in non-linear electrostatic simulations with GENE-3D

- What is **the impact of the domain** choice in non-linear simulations? [Wilms JPP´23]





- **Full-flux-surface** simulations **confirm** the **stabilisation** of turbulence in Wendelstein 7-X through a/L_n by local simulations [Alcusón PPCF´21].
- Significant differences between flux-tube and full-flux-surface results for some parameters



- **Turbulence** is only **weakly localised** on surface → extended nature could ease experimental measurements of fluctuation levels.

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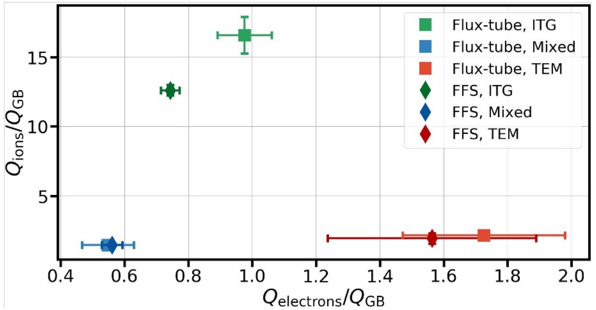

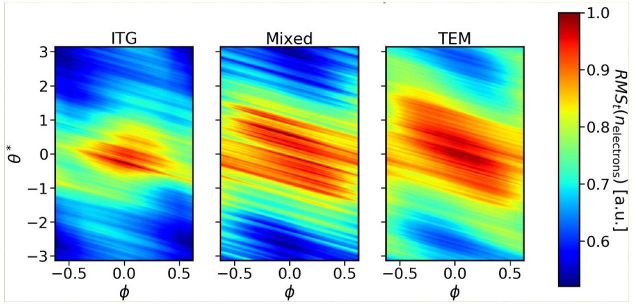

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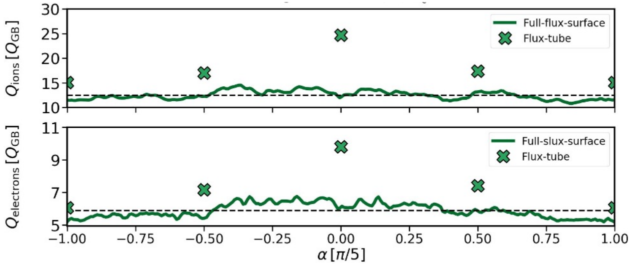
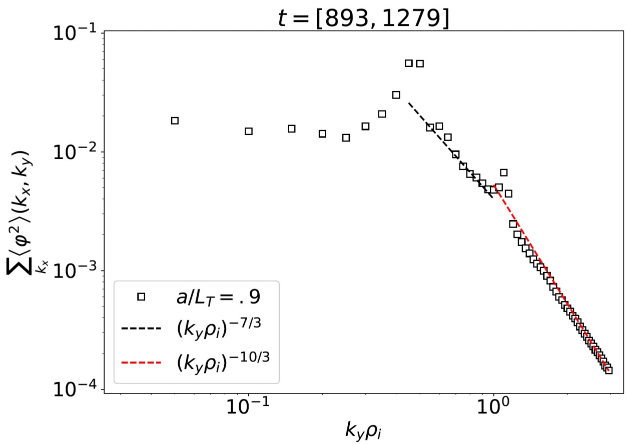


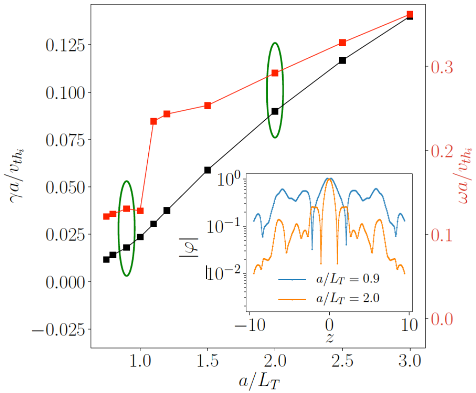
- **Turbulence** is only **weakly localised** on surface → extended nature could ease experimental measurements of fluctuation levels.

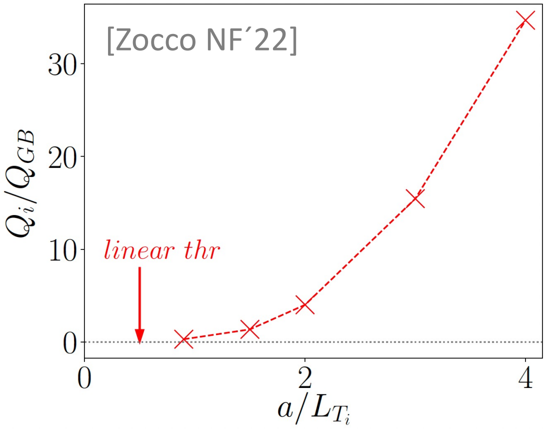
Next step:
- Investigate when **global effects** are important.

Electrostatic turbulence close to marginality in Wendelstein 7-X

- Electrostatic ITG turbulence with moderate to **nearly marginal temperature gradient**, $a/L_T = \{0.9, 2.0\}$, critical gradients has been studied.
- Close to marginality, **extended linearly unstable modes** are dominant, even in the presence of kinetic electrons.
- **No observed Dimits shift**, as turbulence becomes more radially localized and less prone to zonal *EXB* shearing stabilization.







- The power laws $(k_y\rho_i)^{-7/3}$ and $(k_y\rho_i)^{-10/3}$ are observed at the wavelengths at which they should be observed, $k_y\rho_i \lesssim 1$ and $k_y\rho_i \gtrsim 1$ [Barnes PRL´11].

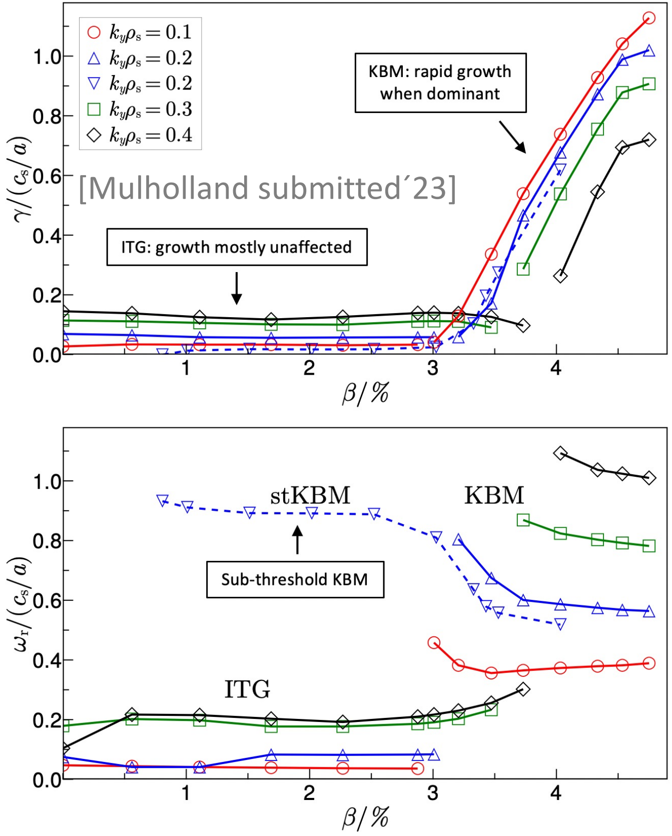
Electromagnetic simulations in Wendelstein 7-X

- <u>How does high β modify electrostatic picture?</u>

Linear GENE simulations

- **Dominant** (solid lines) and **sub-dominant** (dashed lines) instabilities have been characterized for a β scan at different wavelengths (k_y).
- **GENE eigenvalue solver** reveals **many subdominant unstable modes** with $\gamma < \gamma_{max}$ at each wavenumber.
- **Subdominant KBM (stKBM) threshold revealed**: $\beta_{crit}^{stKBM} \approx 1\%$.
- **stKBM** unstable far **below MHD** ballooning **limit** ($\beta_{crit}^{MHD} \approx 3\%$).

Linear growth rates and real frequencies



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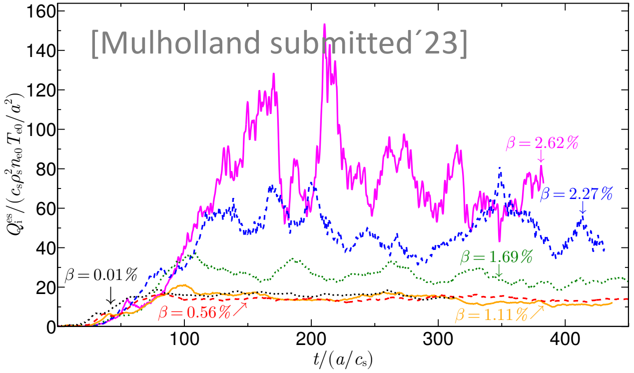
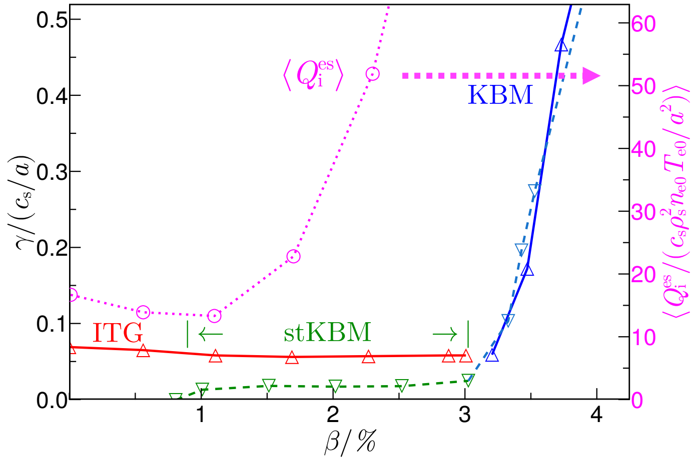
Nonlinear GENE simulations

- Heat fluxes decrease slightly for $0 < \beta < 1\%$.
- Rapid heat-flux increase for $\beta \geq \beta_{crit}^{stKBM} \approx 1\%$
- **stKBM** is highly excited in turbulence (NL projections) [Mulholland submitted´23].





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Linear GENE simulations

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- GENE eigenvalue solver reveals many subdominant unstalbe modes with $\gamma < \gamma_{max}$ at each wavenumber.
- Subdominant stKBM (stKBM) also been revealed: $\beta_{crit}^{stKBM} \approx 1\%$
- stKBM unstable far below MHD ballooning limit ($\beta_{crit} \approx 3\%$).

Next steps:

- Studying the impact of $\hat{s}$ and horizontal shift on stKBM properties.
- Characterizing the configuration dependence on β.
- Verification against GENE-3D.
- Application of reduced models (quasilinear) for quick prediction of heat fluxes.

Nonlinear GENE simulations

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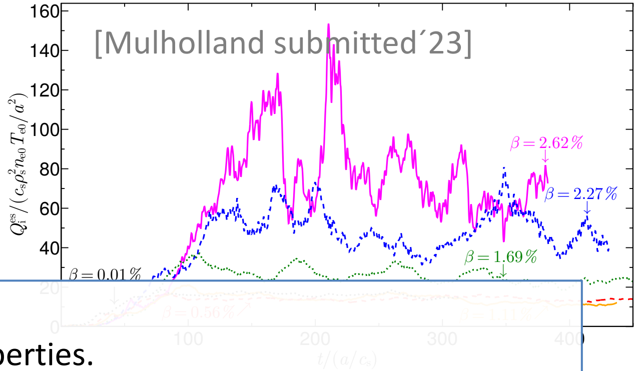
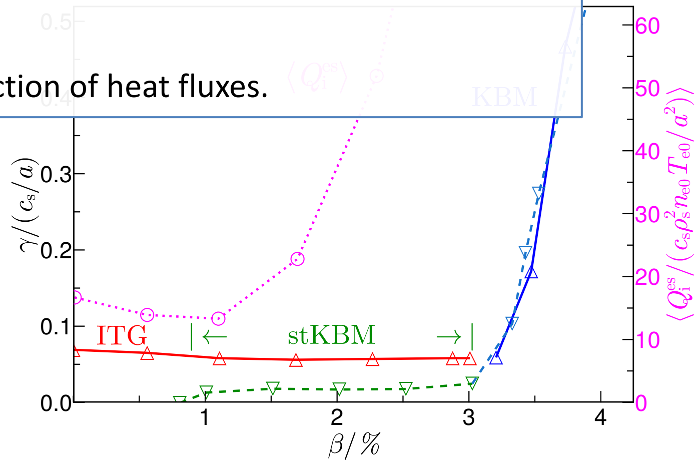
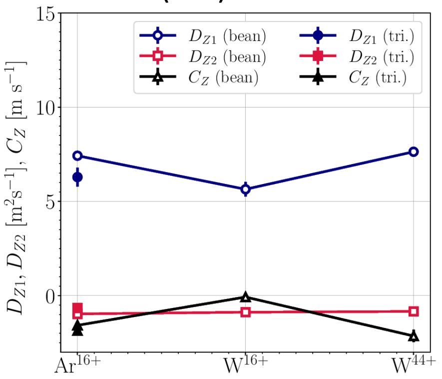




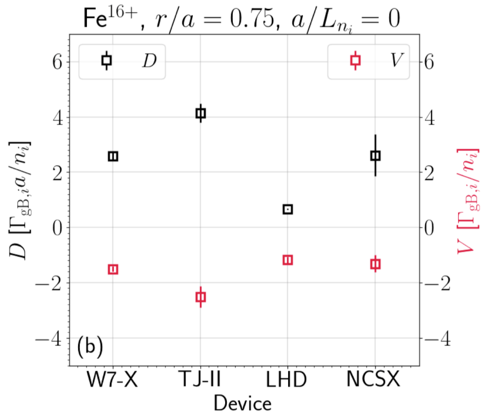
Impurity transport and turbulence in the presence of impurities

- Assessment of **turbulent impurity transport** under different turbulence type and comparison across devices.

W7-X (ITG)



[García-Regaña JPP´21].



[García-Regaña NF´21].

- ITG (resp. TEM) turbulence yield curvature pinch (resp. **anti-pinch**) convective contribution. Both turbulence type yield **inward thermo-diffusive** contributions. Weak dependency on the device observed for ordinary difussion.

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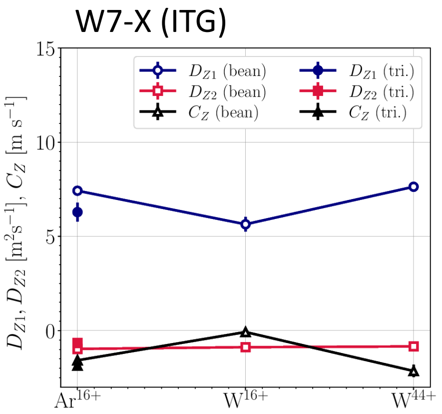
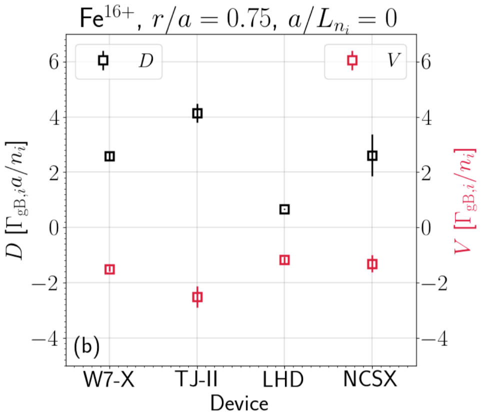


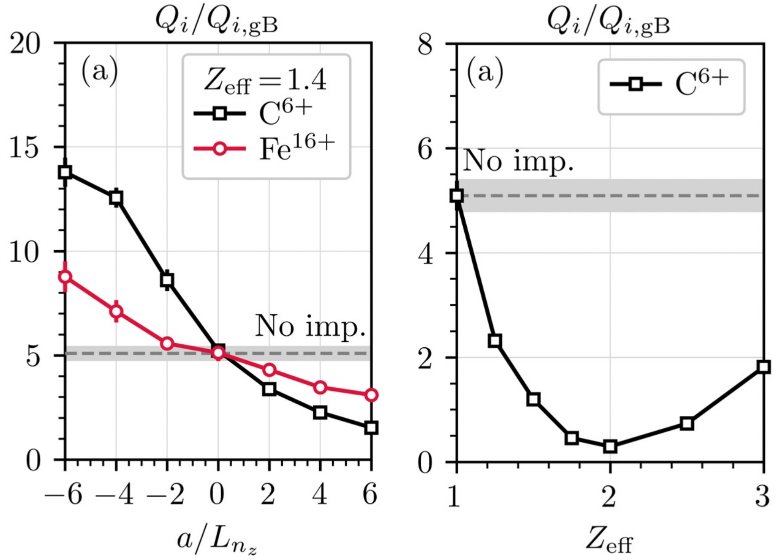
[García-Regaña JPP´21].



[García-Regaña NF´21].

- ITG (resp. TEM) turbulence yield curvature pinch (resp. **anti-pinch**) convective contribution. Both turbulence type yield **inward thermo-diffusive** contributions. Weak dependency on the device observed for ordinary difussion.

- Investigation of the **impact of impurities on turbulent transport** characterized in W7-X.



- Impurities can substantially **enhance or reduce turbulent heat losses**. **Optimal content** of impurities found [García-Regaña submitted´23].

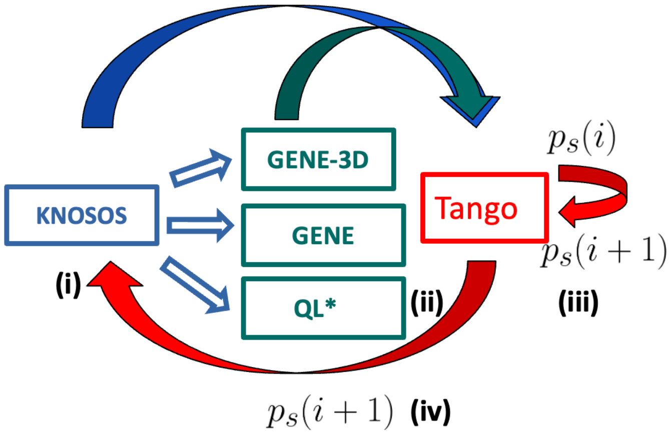
TSVV#13: Stellarator Turbulence Simulation

Validation

Tango/GENE-3D/KNOSOS: A high-fidelity framework for predicting plasma profiles

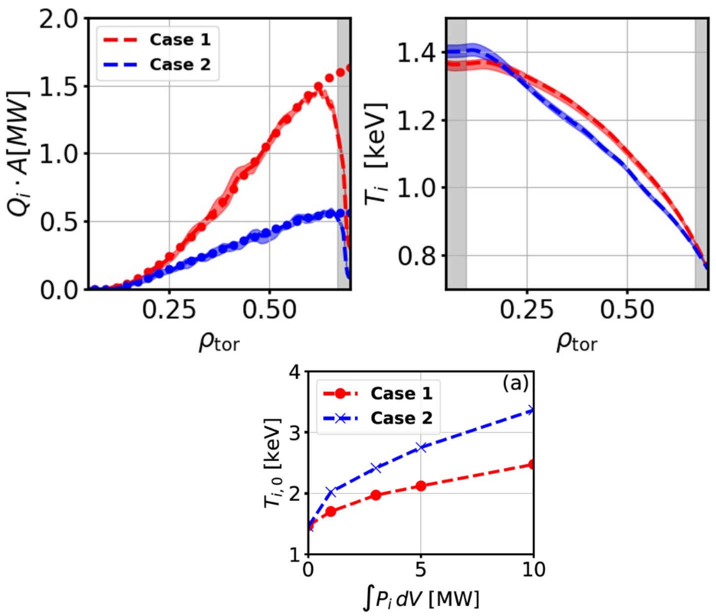
- **First principles multiple-time scale approach**: it simulates turbulence and transport only on their **natural time scales.**

$$\overline{Q}_s(i) = \overline{Q}_s(i)^{\text{turb.}} + \overline{Q}_s(i)^{\text{neo.}}$$



- **KNOSOS** [Velasco JCP´21] → neoclassical fluxes
- **GENE/GENE-3D/Models** → turbulent fluxes.

- Applied to standard ERCH W7-X scenarios [Banón Navarro NF´23].
- Different ion heating result in **the same on-axis T_i**.
- The model **reproduces** the experimentally observed T_i clamping [Beurkens NF´21].



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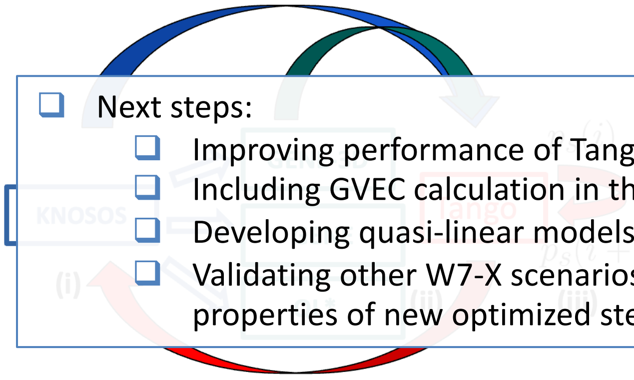

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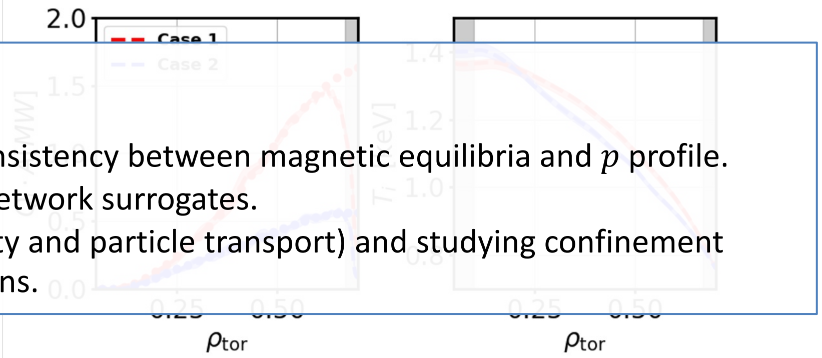
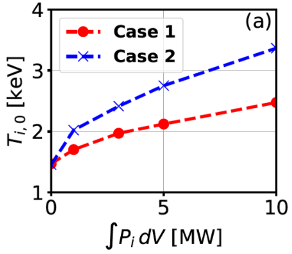
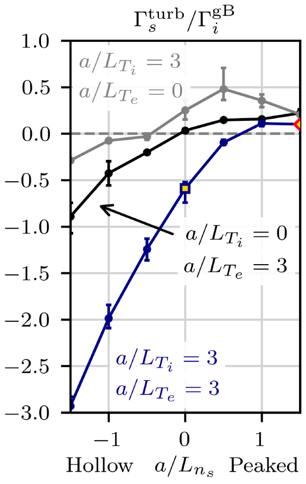


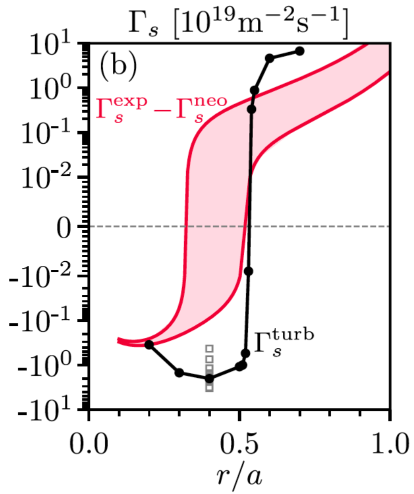
- Next steps:
  - Improving performance of Tango.
  - Including GVEC calculation in the loop for consistency between magnetic equilibria and p profile.
  - Developing quasi-linear models and neural network surrogates.
  - Validating other W7-X scenarios (incl. impurity and particle transport) and studying confinement properties of new optimized stellarator designs.

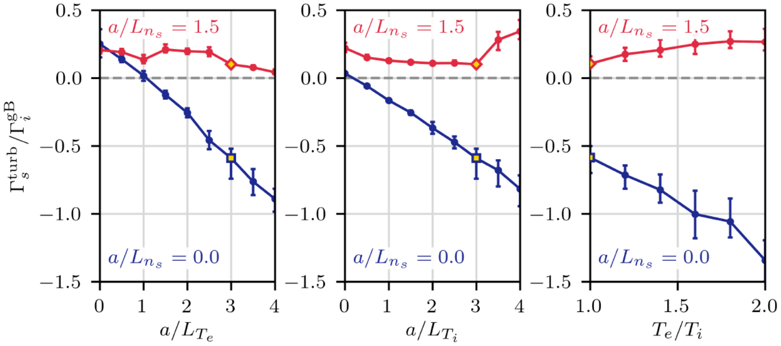


Turbulent particle transport in stellarators

- In neoclassically dominated plasmas, **theory predics strongly hollow density profiles in stellarators**, that are, in general, not observed.
- **Particle transport** studied for W7-X combining gyrokinetic stella simulations, KNOSOS neoclassical simulations and 1D neutral model [Thienpondt PRR´23].
- Turbulence driven by finite a/L_{T_e} and a/L_{T_i} **produces a particle pinch.** In W7-X, that pinch ⇒ absence of core density depletion.







- The **parametric dependence** has been characterized in detail.

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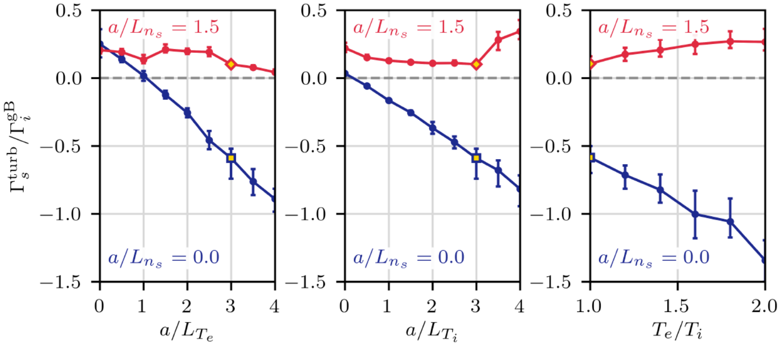
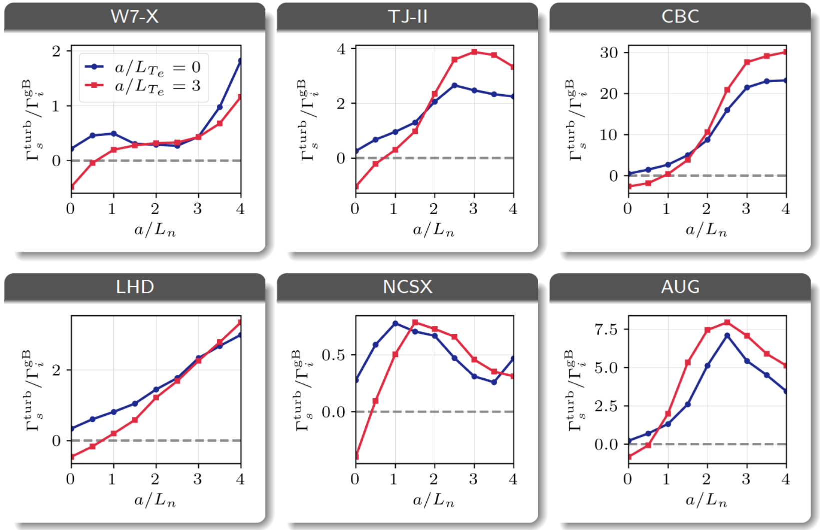
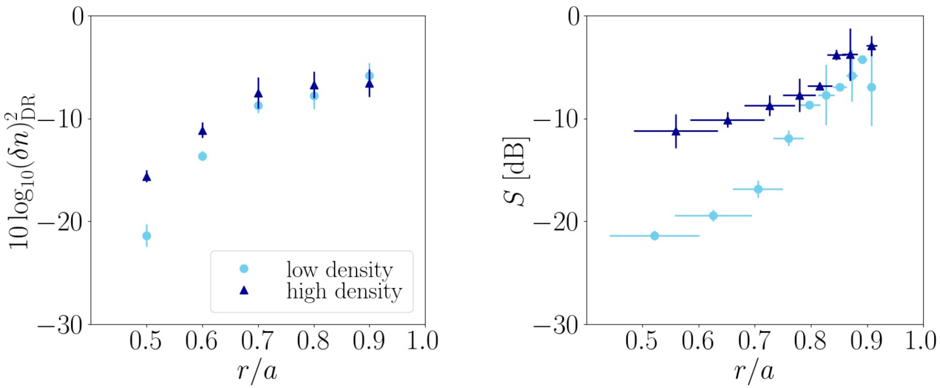




- The **parametric dependence** has been characterized in detail.
- The presence of the turbulent pinch, is found **in all devices analyzed so far**.

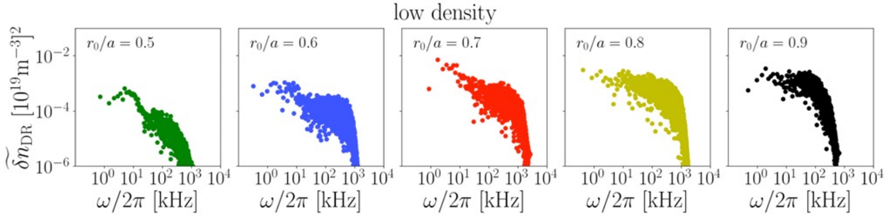
Comparison between stella simulations and Doppler Reflectometry measurements

- Confidence on our gyrokinetic codes is essential for the planning of experiments and their interpretation ⇒ **careful translation of our code output into measurable data.**

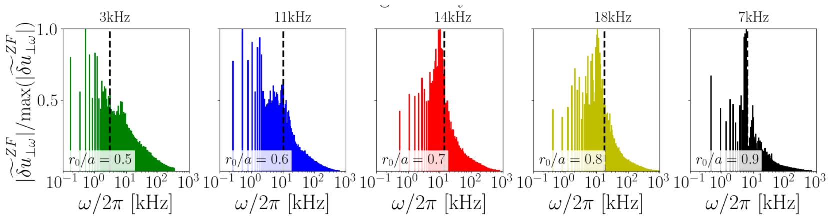


- **stella-Doppler Reflectometry** (DR) comparison $(\delta n)^2$ of OP1 plasmas for low and high density ECRH standard discharges [González-Jerez submitted´23].
- **Agreement between experimental and simulations**, and **DR/PCI** differences are explained by the measurement position in wavenumber space.

- **Frequency spectra** of the **density fluctuations** measured by the DR have been obtained.



- **Frequency spectra** of the **zonal flow components** has been brought forward for future comparison with dual DR system, run during past campaign.



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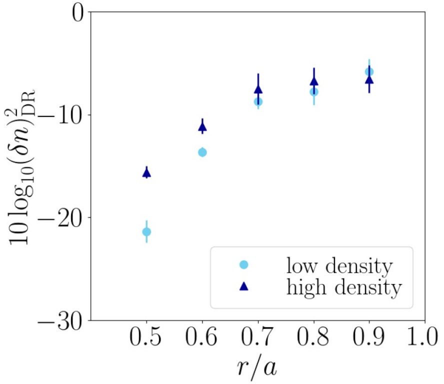

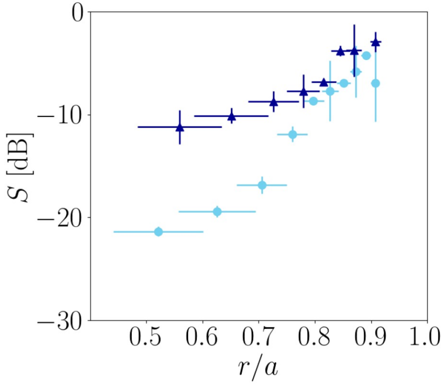

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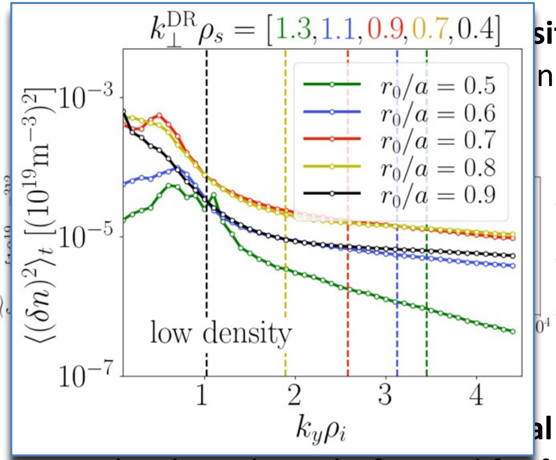

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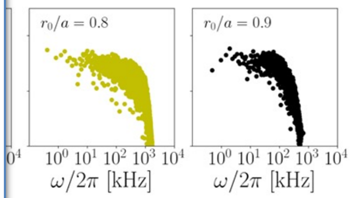

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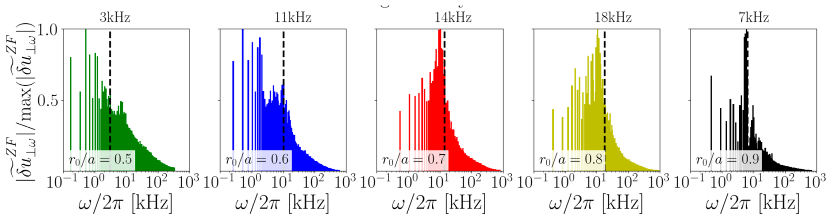

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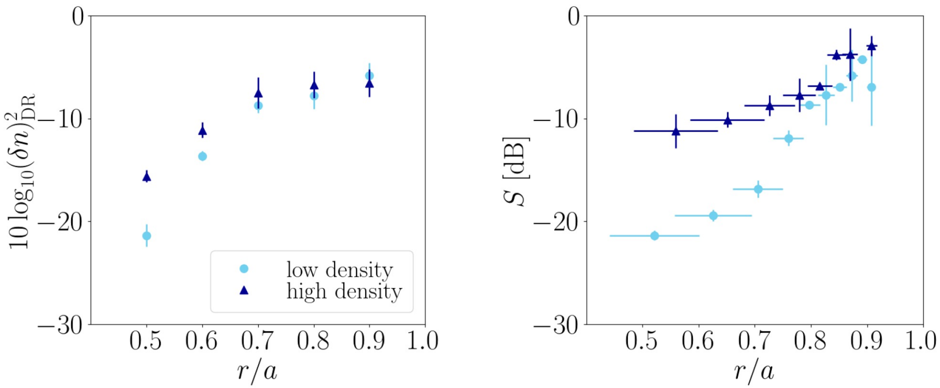

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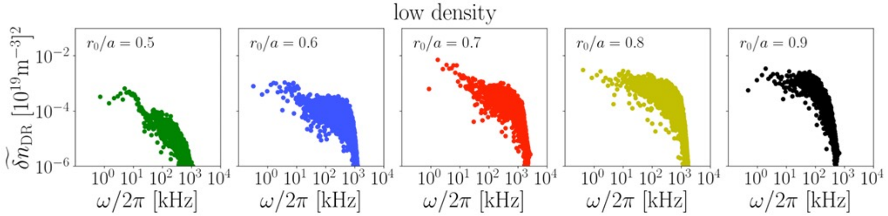

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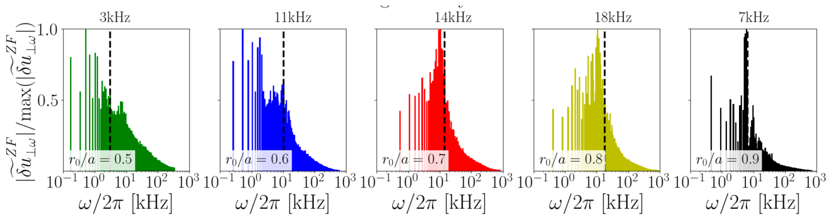

Next steps on validation and the TSVV13 presence in the W7-X OP2 campaign

Proposal name	Author	*Title*
ksena_006	P. Mulholland	*Stabilisation of KBMs with increasing magnetic shear*
rjose_002	J. M. García-Regaña	*Turbulent (de)stabilization driven by **non-trace impurities***
rjose_003	J. M. García-Regaña	*Assessment of the **relative weight** of the different transport channels (i.e. **neoclassical and turbulent**) on particle transport*
dinklage_013	A. Dinklage	*Database for the TSVV **code validation***
edis_003	E. Sánchez	*Experimental validation of theoretical expectations of **ZF properties***
gawe_020	G. Weir	***Shear stabilization** of ion-scale drift wave turbulence*
gawe_021	G. Weir	*Matching physics parameters and fluxes to nonlinear gyrokinetic calculations at the ion-scale*
tere_003	T. Estrada	*Systematic searching for **zonal flows** using dual V-band DR*
dacar_006	D. Carralero	*Full characterization of turbulence during **suppressed turbulence** scenarios*
Etc.	Etc.	*Etc.*

Summary of the TSVV13 progress

- The TSVV13 project has **united the efforts** of several codes (**stella, GENE-3D, EUTERPE, GENE and KNOSOS**) thereby enhancing the **capacity** to solve **high-impact problems in stellarator turbulence**.
- It has addressed numerous challenges, in the areas of **code development**, code **verification** and **validation** along with **theory**.

- The codes are in **continous development** and cross-**verification**.
- The **stability** properties in stellarators, in all their diversity of configurations, is **much better characterized** (sinergy with TSVV#12).
- Impact of the choice of reduced **domains**, w.r.t RG simulations, is much better **understood**.
- Bulk and impurity **particle transport** questions have been for the first time been **satisfactorily addressed**.
- **Transport simulations,** evolving profiles iteratively, have been **enabled**.
- **Electromagnetic simulations** have become routine (linked to TSVV#10 work).
- Etc.

Progress of the TSVV13 progress along its deliverables

Deliverable name	Short description	Progress
D-REF-CASES	Definition of a reference case for code verification and validation in stellarator geometry	100 %
D-TURB-ZTRANSP	Initial assessment of turbulent transport of impurities	100%
D-TURB-BULKTRANSP	Turbulent transport of the main ions and electrons in W7-X	In continuous progress
D-TURB-ZNONTRACE	Role of impurities in the turbulent heat losses	100 %
D-KBM-BASIC	Linear KBM simulations in W7-X equilibria	100%
D-TURB-WEIGHT	Assessment of the relative weight between turbulent and neoclassical transport	100 %
D-TURB-DOMAIN	Assessment of the effect of the spatial domain (global vs FFS) on turbulence	75 %
D-ADJ-THEORY	Development of time-dependent method for linear gyrokinetics	100 %
D-NUM-DIAG	Development of synthetic diagnostics	75 %

Progress of the TSVV13 progress along its milestones and key deliverables

Milestone name	Short description	Progress
M-GENE-3D-EM	Development of an electromagnetic version of GENE-3D	100 %
M-BENCHMARK-ES-GLOB	Benchmark between GENE-3D and EUTERPE for electrostatic turbulence with adiabatic electrons	100%
M-TRANSPORT-SUITE	Development of a transport suite that enables, with input from neoclassical and gyrokinetic codes, profile prediction and validation.	100 %
M-STELLA-COLL	Implementation of the full linearized collision operator in stella.	100%
M-STELLA-FFS	Development of a full-flux-surface (FFS) version of stella	75%
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More than 90 % of Marconi quota consumed in 5th and 6th cycles (≈50% of 7th cycle)
⇒ **180 M CPUhours**, approximately, spent by the TSVV#13.

Progress along key deliverables

Key deliverables:

1) ***Verified set of gyrokinetic stellarator codes*** *that self-consistently treat multiple particle species (enabling, in particular, studies of* ***turbulent impurity transport****) and whose simulation domains cover an* ***entire flux surface or a fully global domain****. Assessment on the* ***minimal simulation domain needed to correctly calculate turbulent fluxes and zonal flow dynamics in stellarators****. Synergies with the tokamak community are to be sought.*

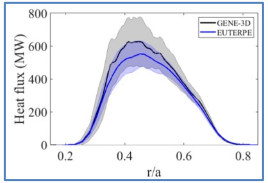
2) *Inclusion in (at least some of) these codes of the capability to use the* ***neoclassical equilibrium as background distribution for turbulence calculations****. Quantification of the modification of linear and nonlinear turbulence properties due to the neoclassical equilibrium.*

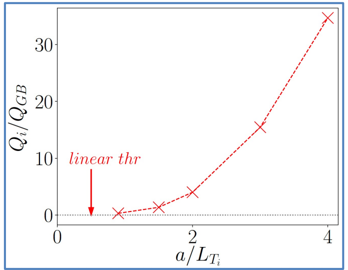
3) *Study of the* ***relative weight of the neoclassical and turbulent branches of radial transport in multispecies stellarator plasmas****, as a function of the species and the collisionality regime.*

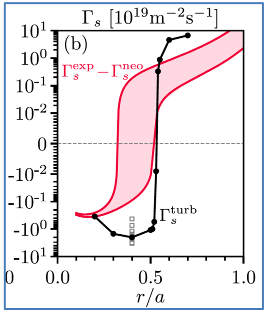
4) ***Validation of the codes for the calculation of turbulent fluxes in multispecies stellarator plasmas*** *and in tokamaks with broken axisymmetry. In stellarators,* ***explicit comparisons*** *should be provided between the total transport experimentally measured and the sum of the simulated neoclassical and turbulent components.*

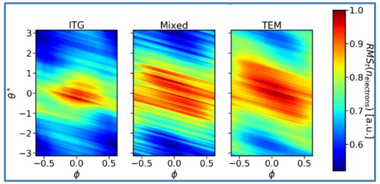
5) *Development of efficient reduced models (suitable for integration into stellarator optimization codes, see TSVV Task 12) capable of reliably predicting stellarator turbulent fluxes.*

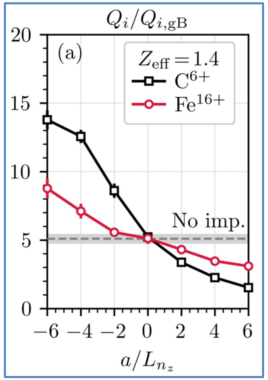
Substantial contributions / To be prioritized until 2025

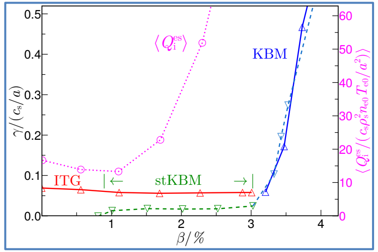


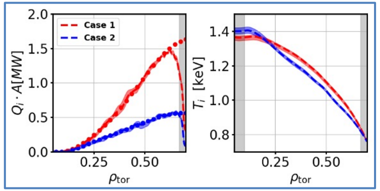










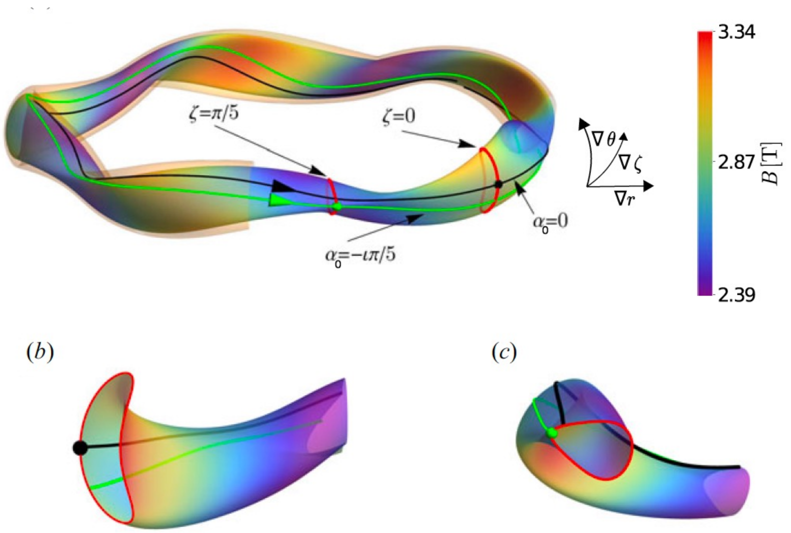


Backup slides

Status of the code progress towards the EUROfusion standard software

	TSVV CONTACT		Progress towards EUROfusion Standard Software																	
				SOFTWARE ENGINEERING				INTERFACES			VVUQ				DISSEMINATION		DOCUMENTATION		USER SUPPORT	
CODE	TSVV No	Contact Person	ACH support started	1. Version control implemented	2. Software engineering standards	3. Coding standards established	4. Performance optimization on HPC systems	1. User-friendly interface	2. Post-processing and visualisation tools	3. Interface to the IMAS Data Dictionary	1. Specific plans for code verification	2. Code verification studies mplished	3. Inter-code benchmarking accomplished	4. Code validation studies accomplished	1. Up-to-date release version on the Gateway	2. Trainings provided to code users	1. High-quality technical documentation	2. User manual available for download	1. Responsive support team	2. Tools for managing support requests
GENE	1	Tobias Görler	Started	Completed	Completed	Completed	In Progress	In Progress	In Progress	Not started	In Progress	Completed	Completed	In Progress	In Progress	Not started	In Progress	Completed	Completed	In Progress
EUTERPE	10	Ralf Kleiber	Started	Completed	In Progress	In Progress	Not started	In Progress	Completed	In Progress	In Progress	In Progress	In Progress	Completed	In Progress	Completed	In Progress	In Progress	Completed	Completed
KNOSOS	12	José Luis Velasco	Started	Completed	In Progress	Not started	In Progress	Not started	In Progress	Not started	Completed	In Progress	Completed	In Progress	Not started	Not started	In Progress	In Progress	Completed	Not started
GENE-3D	13	Alejandro Bañón-Navarro	Started	Completed	In Progress	In Progress	Not started	Not started	Completed	Not started	Not started	Completed	Not started	In Progress	Not started	Completed	In Progress	In Progress	Completed	Completed
STELLA	13	Michael Barnes	Started	Completed	In Progress	In Progress	In Progress	In Progress	In Progress	Not started	Completed	Completed	In Progress	In Progress	Not started	Completed	Completed	In Progress	Completed	Not started

Differences between flux tubes in a stellarator



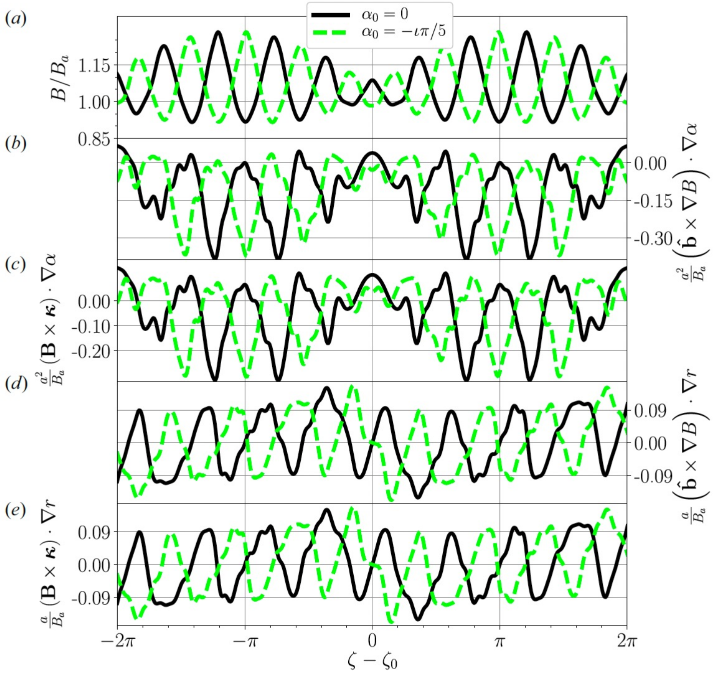


FIGURE 3. Normalized geometric quantities in the range $\zeta - \zeta_0 = [-2\pi, 2\pi]$ for the surface $r_0/a = 0.8$ along the field lines $\alpha_0 = 0$ (solid black line) and $\alpha_0 = -\iota\pi/5$ (dashed green line). The magnetic field strength is represented in (*a*); the projections of $\hat{\boldsymbol{b}} \times \nabla B$ and $\boldsymbol{B} \times \boldsymbol{\kappa}$ along the binormal direction are represented in (*b*,*c*), respectively; the projections of $\hat{\boldsymbol{b}} \times \nabla B$ and $\boldsymbol{B} \times \boldsymbol{\kappa}$ along the radial direction are represented in (*d*,*e*), respectively.