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TSVV13 Stellarator Turbulence Simulation: Progress, status and plans

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Motivation

- The understanding of turbulence in stellarators has been traditionally behind tokamaks' due to::
  - The computational cost of handling 3D magnetic geometries.
  - The limitations of the flux tube approach for stellarators.
- At the time TSVV13 was proposed, certain aspects of turbulence remained largely unexplored: impurity transport; particle transport; electromagnetic turbulence; and the interplay between neoclassical (NC) and gyrokinetic (GK) physics.

Key deliverables

- Set of stellarator gyrokinetic codes verified against each other, validated against stellarator and 3D tokamak experiments.
- Assess the relative weight of neoclassical and turbulent transport.
- Address the interaction between neoclassical and gyrokinetic turbulence.
- Develop reduced models.

TSVV13 team and codes

Member or code	Research Unit	Period	Commitment (PM/year)
José M. García-Regaña	CIEMAT	2024-2025	12
Edilberto Sánchez	CIEMAT	2024-2025	6
José Luis Velasco	CIEMAT	2024-2025	6
Alejandro Bañón-Navarro	MPG (IPP-Garching)	2024-2025	6
Alessandro Zocco	MPG (IPP-Greifswald)	2024-2025	6
Jörg Riemann	MPG (IPP-Greifswald)	2024-2025	6
Michael Barnes	CCFE (Uni. Oxford)	2024-2025	6
John Omotani	CCFE (Uni. Oxford)	2024-2025	6
Josefine H. E. Proll	DIFFER (Uni. Eindhoven)	2024/2025	3/0
Paul Mulholland	DIFFER (Uni. Eindhoven)	2024/2025	3/3
Maikel Morren	DIFFER (Uni. Eindhoven)	2024/2025	0/3
Unallocated	t.b.d.	2024/2025	0/6
ACH Tasks			
EUTERPE	ACH-MPG	2024/2025	5/12*
stella	ACH-CIEMAT	2024/2025	6/6*
Hanne Thienpondt	TSVV13 support ACH-CIEMAT	2024/2025	0/2*
Total resources			**71/80**

Team composition and 2025 resource planning as of November 2024

Code	Main characteristics
`GENE`	δf gyrokinetic code, flux tube for stellarator geometry, electromagnetic, **coupled to `KNOSOS+TANGO`**, incl. collisions.
`GENE-3D`	δf gyrokinetic code, flux tube (FT), full flux surface (FFS) and radially global (RG), **electromagnetic, coupled to `KNOSOS+TANGO`**, incl. collisions.
`stella`	δf gyrokinetic code, flux tube and **full flux surface, electromagnetic, incl. collisions. radially global version for tokamak geometry**, coupled to neoclassical code `SFINCS`.
`EUTERPE`	δf gyrokinetic code, radially global code (annulus choice possible), electromagnetic, incl. collisions. Neoclassical simulations enabled.
`KNOSOS`	δf neoclassical code, **coupled to GENE and GENE-3D through TANGO** transport solver.

Developed within the TSVV13

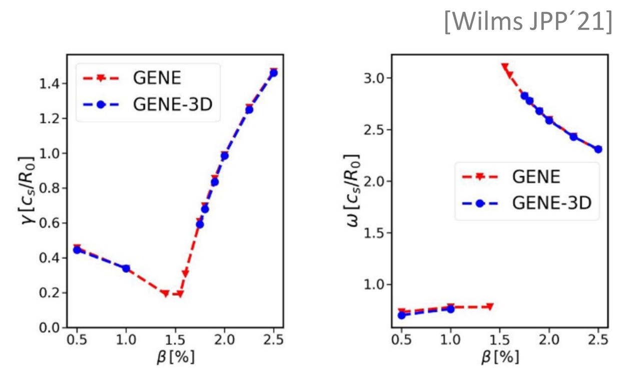
External experts: M. J. Pueschel (DIFFER), Ralf Kleiber and K. Aleynikova (IPP-Greifswald), Felix Wilms (IPP-Garching).
Ph.D. students: H. Thienpondt and F. Javier Escoto (CIEMAT), Linda Podavini (IPP-Greifswald), Don Fernando and Hugo Cu-Castillo (IPP-Garching), Georgia Acton (U. Oxford).

Code progress status

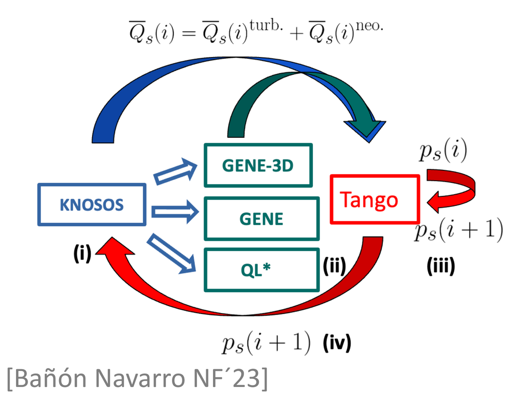
			SOFTWARE ENGINEERING				INTERFACES			VVUQ				DISSEMINATION		DOCUMENTATION		USER SUPPORT	
CODE	TSVV No	ACH support started	1. Version control implemented	2. Software engineering standards	3. Coding standards established	4. Performance optimization on HPC systems	1. User-friendly interface	2. Post-processing and visualisation tools	3. Interface to the IMAS Data Dictionary	1. Specific plans for code verification	2. Code verification studies accomplished	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-3D	13	Started	Completed	In Progress	In Progress	In Progress	In Progress	Completed	Not started	Completed	Completed	Completed	In Progress	Not started	Completed	In Progress	In Progress	Completed	Completed
STELLA	13	Started	Completed	In Progress	In Progress	In Progress	In Progress	Completed	Not started	Completed	Completed	Completed	Completed	Not started	Completed	Completed	In Progress	Completed	Not started

Code development and verification

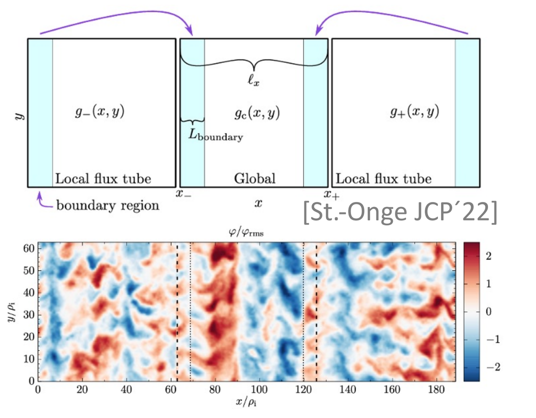
- Code development, a central task in the project's early stages, is now at a highly advanced stage.



Comparison between the electromagnetic versions of GENE and GENE-3D in flux tube geometry.

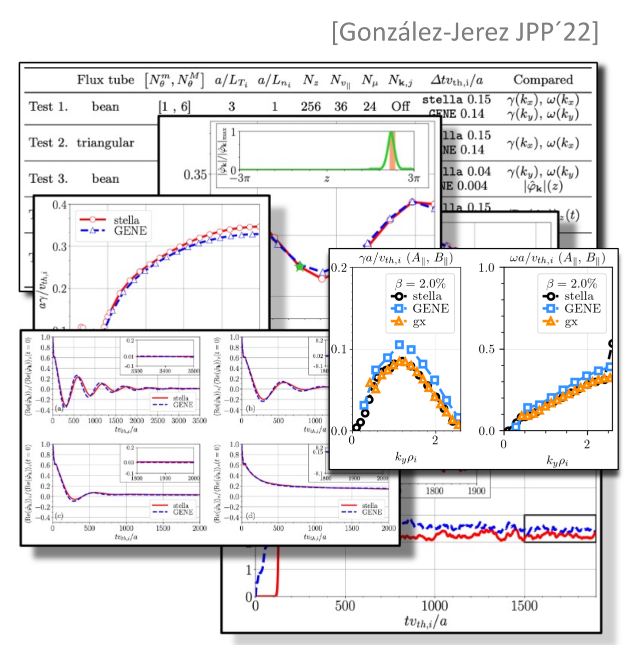


Interaction loop between the transport solver `Tango` with `KNOSOS` for neoclassical transport and various options for turbulent transport.

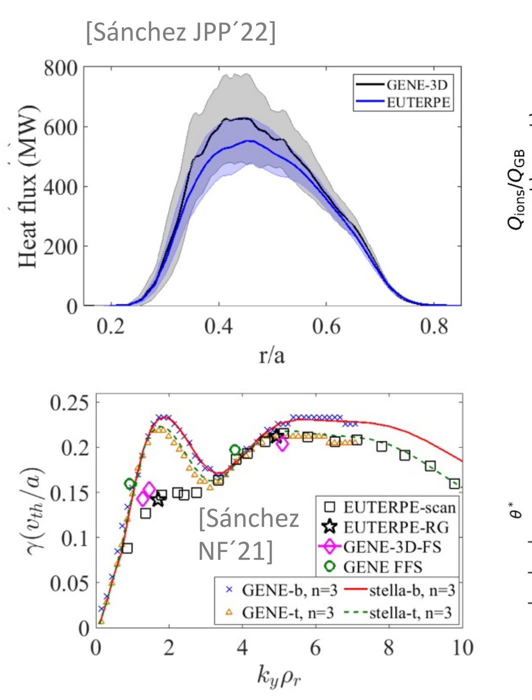


Multiple-flux-tube method in `stella` for two local and independent flux-tube simulations feeding into the boundary region of a central, *global* tokamak simulation.

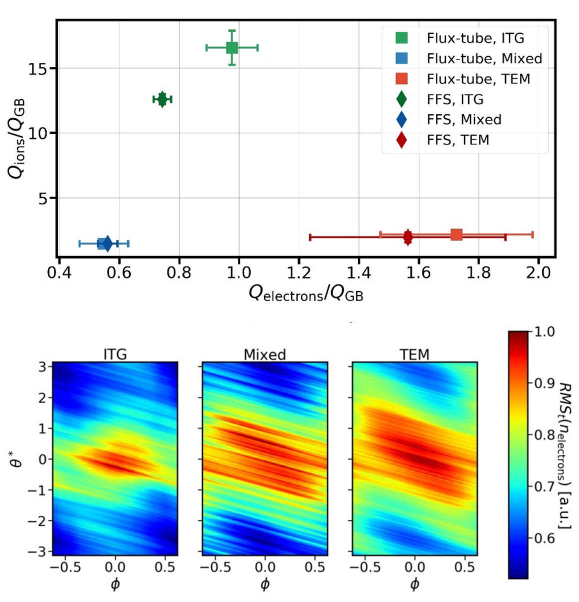
- Cross-code verification has been a continuous process from the beginning and remains ongoing as new code capabilities are enabled.



Stellarator-base-case proposed by for cross-code comparison in the W7-X high mirror configuration considering multiple instabilities and problem settings.



Comparison between `GENE-3D` and `EUTERPE` in radially global domain (top). Comparison between all GK codes within the TSVV13 for different domains (bottom).

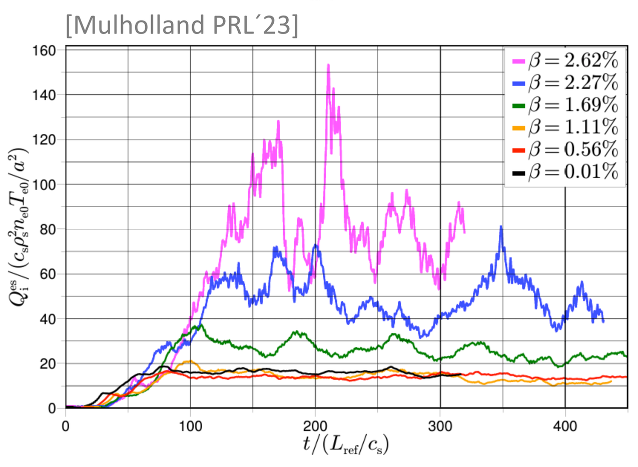


Comparison between flux tube (FT) and full flux surface (FFS) `GENE-3D` simulations for different type of instabilities

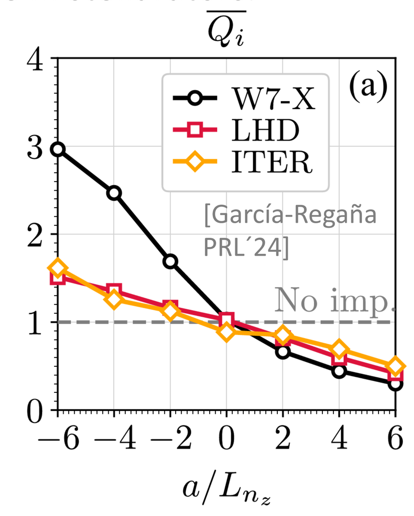
⇒ Well documented and comprehensive set of comparisons between gyrokinetic codes in 3D geometry (`GENE`, `GENE-3D`, `stella`, `EUTERPE`, `GX`, and `XGC` involved so far) has improved confidence in our codes and our understanding of the impact of the spatial domain (FT, FFS or RG domain).

Validation and theory

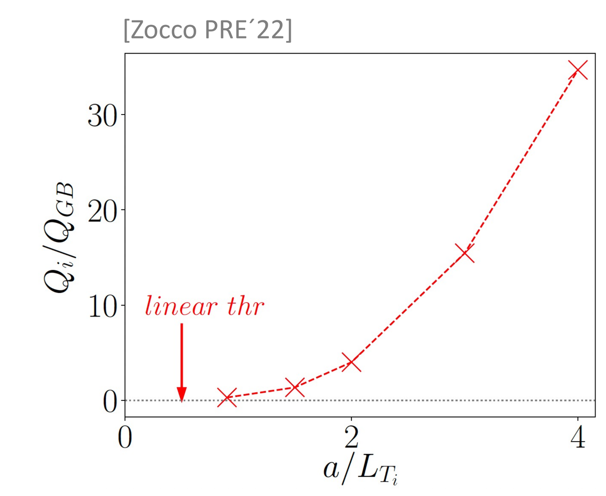
- The TSVV13 work on theory and validation have been strongly driven by aspects insufficiently addressed in the context of gyrokinetic turbulence in stellarators.



First scans of β in W7-X point out a strong increase of heat losses due to subthreshold Kinetic Ballooning Modes (stKBMs), threatening out scenario performance in future campaigns.

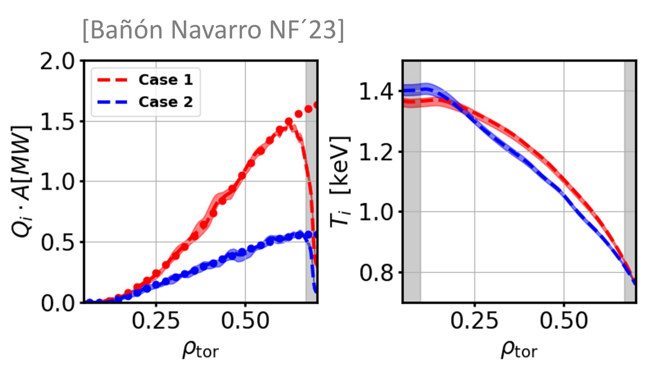


Impurities can contribute to the reduction or enhancement of heat losses. The main dependencies have been identified and are found largely universal.

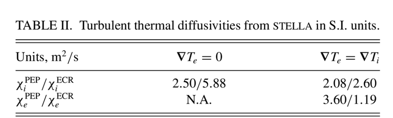


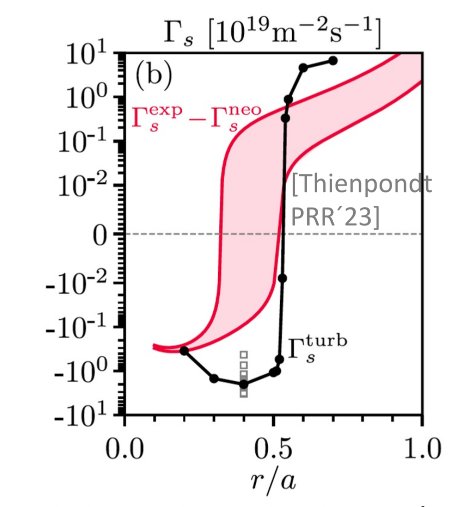
Parametric scans near marginality show the absence of Dimits shift in W7-X, which correlates with a less radially extended turbulent structures.

- Examining specific discharges has yielded significant validation achievements and shed light on long-standing issues.

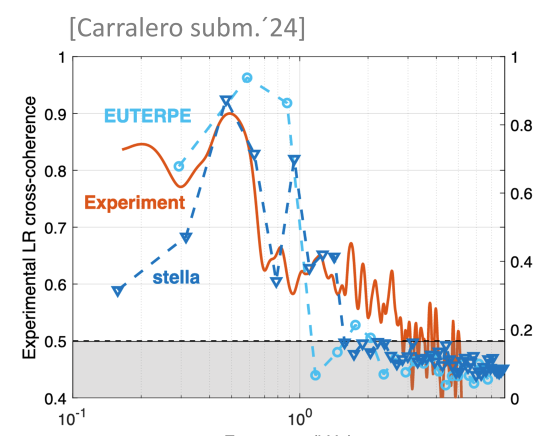


High-fidelity transport simulations, with the `Tango+GENE-3D+KNOSOS` suite, closely reproduce the ion temperature clamping observed at the core of W7-X standard ECRH plasmas.

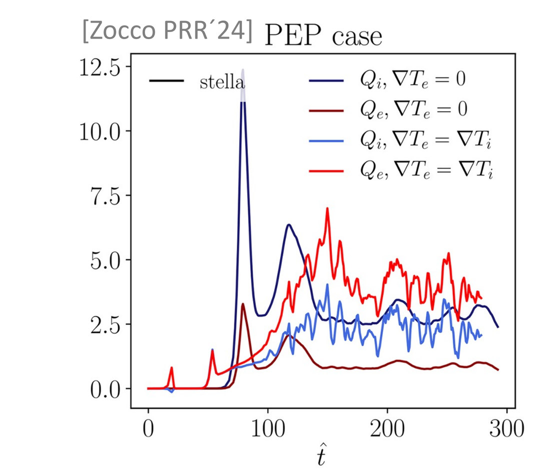




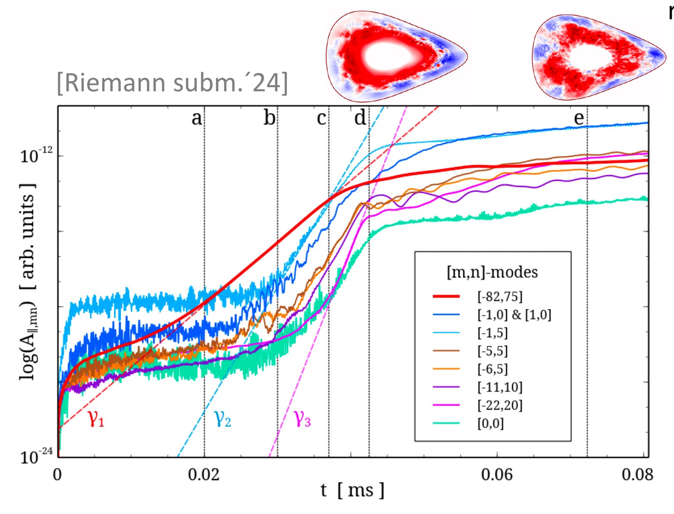
Turbulence driven by finite T_e' and T_i' yields, regardless of the device, a pinch that prevents the core density depletion predicted by neoclassical theory.



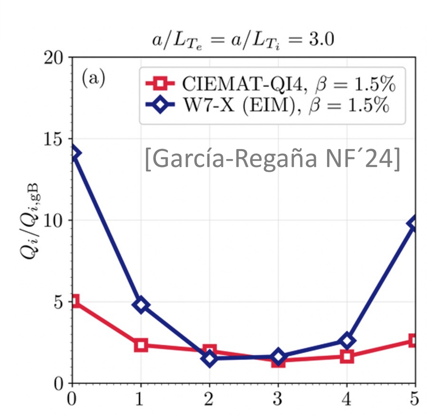
Synergies with WPW7X: from TSVV13, we have contributed to the validation of the first observation of zonal flows through Doppler reflectometry in W7-X.



Retaining T_e' results in a moderate Q_i reduction and even an increase in Q_e in pellet-enhanced-high performance (PEP) W7-X scenarios, questioning previous intrepretations that relied on the approximation $T_e' = 0$.



Synergies with TSVV10: the excitation of long-wavelength Alfvénic modes in W7-X stellarator driven by ITG turbulence using nonlinear electromagnetic radially global simulations has been addressed, observing growth rate ratios reminiscent of forced-driven zonal flow generation ($\gamma_1 : \gamma_2 : \gamma_3 = \gamma : 2\gamma : 3\gamma$).



Sinergies with TSVV12: In the TSVV13 the assessment of turbulent transport in existing configurations [Thienpondt subm. ´24] and newly designed stellarators, some with reduced electrostatic turbulence, has become routine.

Work in progress and perspectives for 2025 and beyond

- All key deliverables have been addressed to varying degrees. The initial focus on code development and verification has moved to a second phase more focused on theory and code validation.
- Efforts in code validation and theory will continue, with additional priorities and directions:

2024	2025	2026	2027 and beyond
	Studying the effect of 3D perturbations in tokamak turbulence (communicated to ITPA Transport and Confinement group)		
	Assessment of the effect of neoclassical ingredients on turbulent transport		
	Support of 2025 and 2026 W7-X campaigns (in line with the significant participation of TSVV13 members in the preparation of the experimental proposals)		
	Advancing the routine execution of EM simulations, with the goal of integrating them into an iterative transport solver. So far, ~90% of the work has considered electrostatic turbulence only.		
		Identify future milestones of the stellarator program in order to apply and expand the acquired knowledge. For example, high-Z impurity turbulent transport toward operation with a tungsten wall at W7-X	
			Addressing stellarator mutiscale turbulence simulations

- Additionally, the dissemination of the codes used in TSVV13 will continue in the coming years.

Summary

- In the framework of the TSVV13, substantial development and verification of the main European stellarator gyrokinetic codes (`stella, GENE-3D, EUTERPE, GENE`) has been achieved, enhancing the capacity and confidence to tackle high-impact stellarator turbulence problems.
- The advent of TSVV13 has significantly improved our understanding in several key areas: bulk and impurity particle transport in stellarators, the relative weight of turbulent and neoclassical transport and their interaction (in progress), predictive transport simulations accounting for turbulent transport have been enabled, the potential impact of electromagnetic effects on turbulence (yet to be thrououghly explored).
- The initial TSVV13 work plan has evolved and expanded towards new objectives and problems, to be addressed in the period 2025-2027 and beyond.

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