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An update on recent results of turbulence simulation in stellarators

J. M. García-Regaña on behalf of the TSVV13 (*Stellarator Turbulence Simulation*) team

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Motivation for TSVV#13: Stellarator turbulence simulation

- The understanding of turbulence in stellarators is **limited** in comparison with tokamaks (**computational cost** of handling 3D magnetic geometries and **limitations** of the flux tube).
- Some aspects of turbulence remain **practically unexplored** (**impurity transport**, **bulk particle transport**, **electromagnetic turbulence**, interplay between neoclassical (NC) and gyrokinetic (GK) physics).

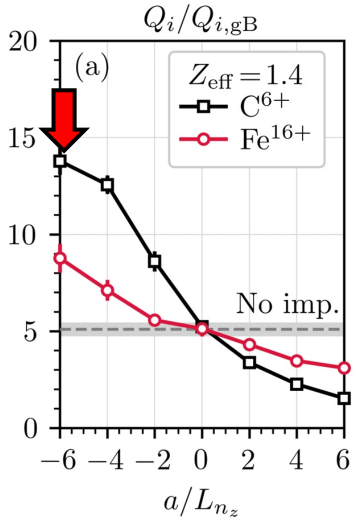
TSVV13 team: J.M. García-Regaña (P.I.), E. Sánchez, J. L. Velasco (CIEMAT), M. Barnes, J. Omotani (CCFE/U. Oxford), A. Bañón Navarro, J. Riemann, A. Zocco (IPP-Greifswald), P. Mulholland (DIFFER/TU/e).

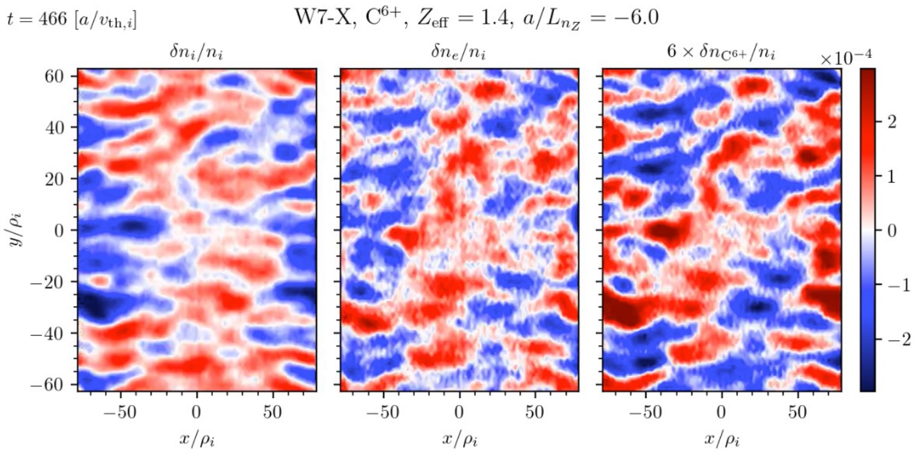
+ External Experts: I. Calvo (CIEMAT), M. J. Pueschel, (DIFFER/TU/e), F. Wilms, R. Kleiber, K. Aleynikova, J. H. E. Proll (IPP).

+ PhD students: H. Thienpondt, L. Podavini, G. Acton, M. Morren, F. J. Escoto, D. Fernando, M. Morren).

***TSVV = Theory, simulation, validation and verification**

- Investigation of the **impact of impurities on turbulent transport** characterized in W7-X and, for comparison, in LHD and ITER [García-Regaña PRL´24].
- The **impact of impurities** on heat fluxes correlates with **impurity density gradient**.
- Hollow impurity density* ⇒ **heat flux enhancement** and strong coupling between species.





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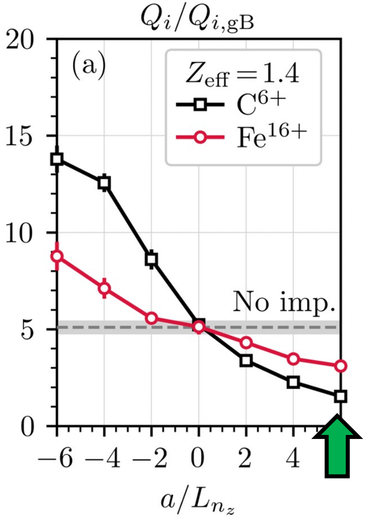

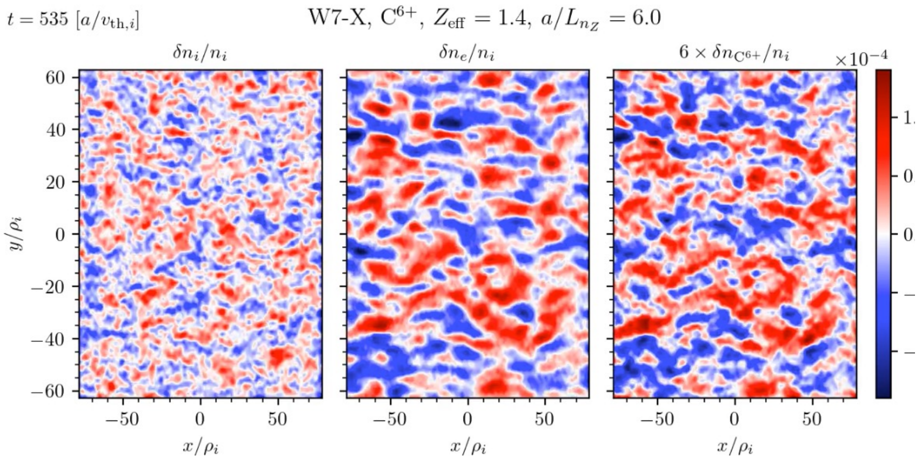

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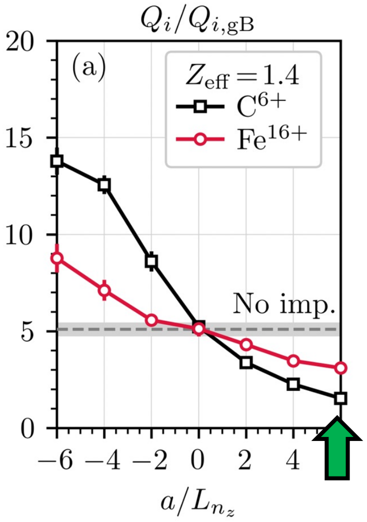

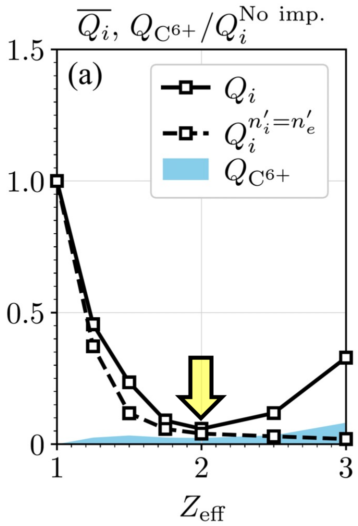

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Turbulence in the presence of impurities [García-Regaña PRL´24]

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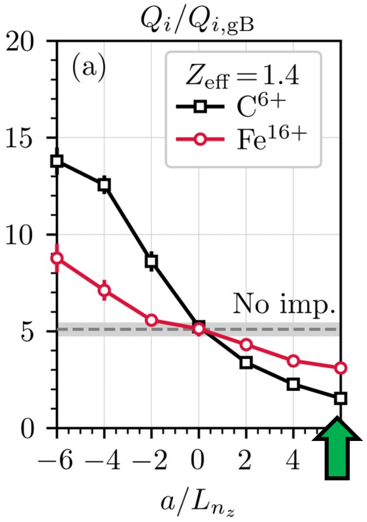

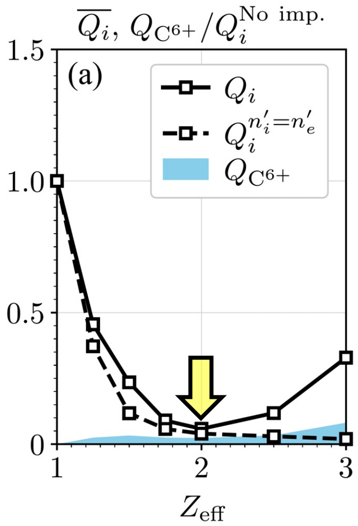

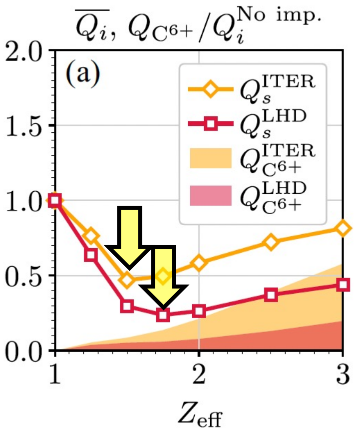

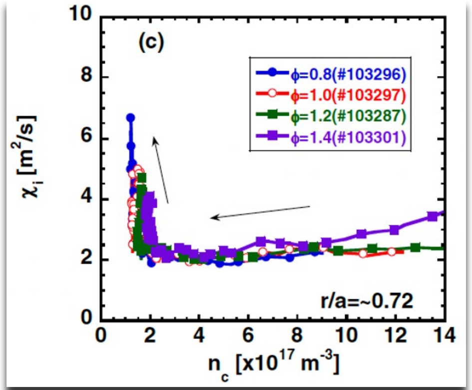

[Osakabe PPCF´14]

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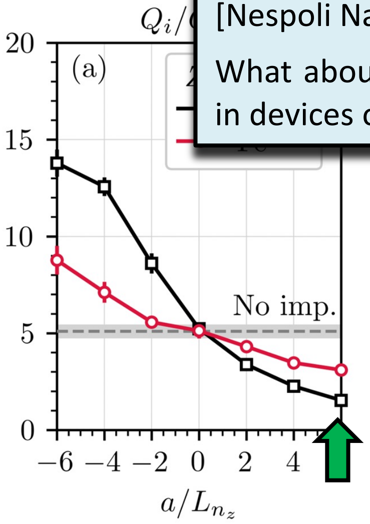
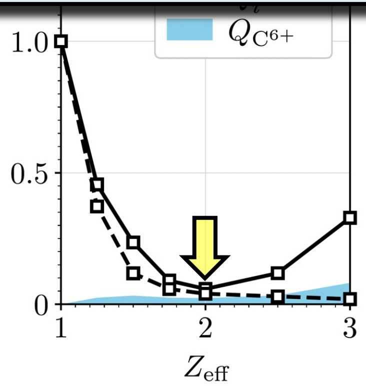
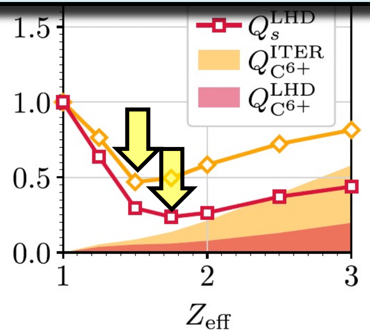
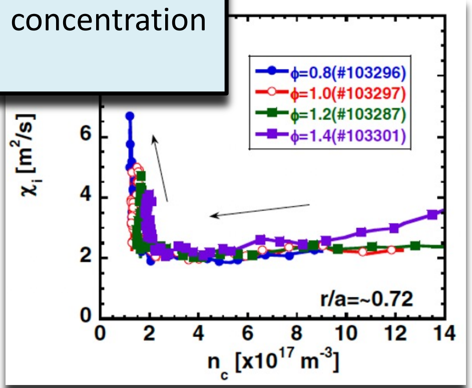
Impurity driven turbulence reduction has been reported in experiments, see e.g. [Nespoli Nat. Phys´22, Osakabe PPCF´14, etc].

What about turbulence enhancement? What about the optimal impurity concentration in devices other than LHD?



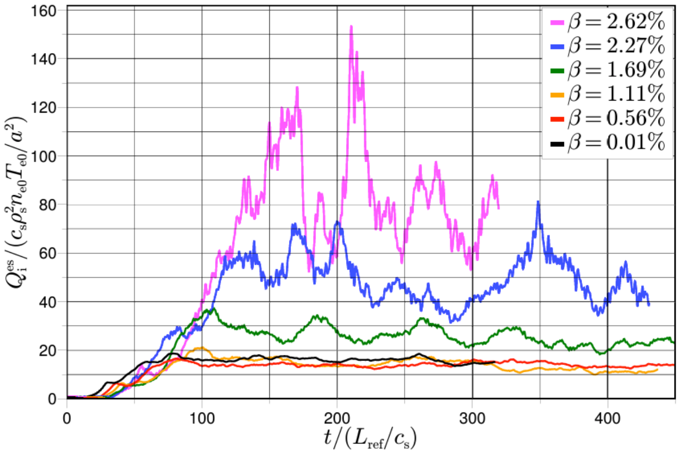






[Osakabe PPCF´14]

- **How does β impact turbulent heat fluxes?**
- Ion heat flux roughly unaffected below $\beta \sim 1.5$ %
- Ion heat flux abruptly increases by a factor ≈ 4 in the range $\beta \sim 1.5 \to 2.5$ % [Mulholland PRL´23].
- Increase correlates with the presence of subdominant electromagnetic instabilities (KBM).
- Simulations with vanishing temperature gradient.



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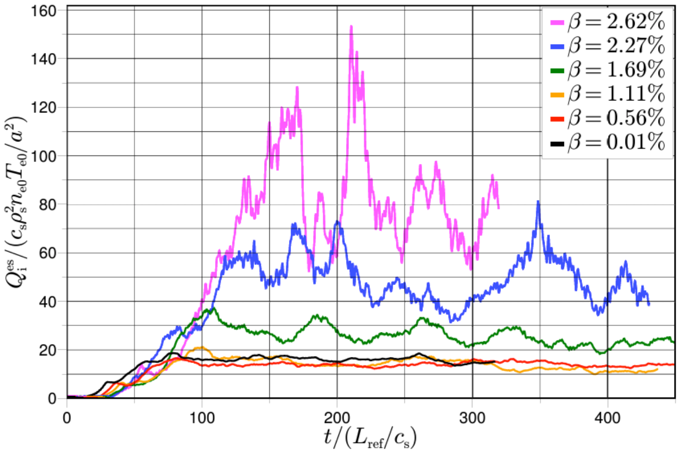
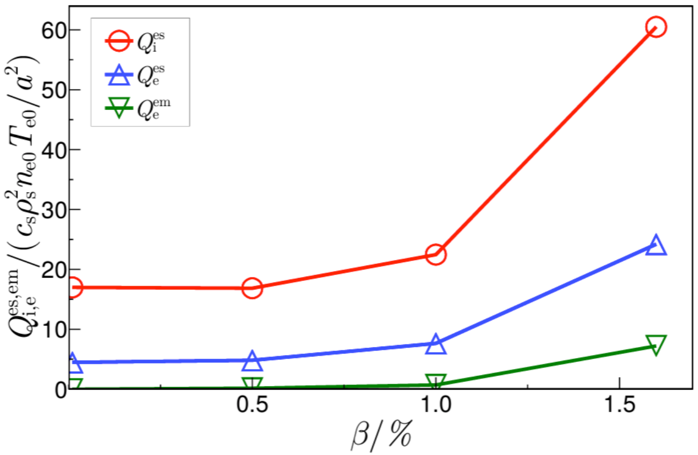


- Adding a small ammount of electron temperature gradient, $a/L_{T_e} = 1.75$, displaces the abrupt increase of heat losses to an even lower $\beta \sim 1.0$ % [Mulholland submitted´24].



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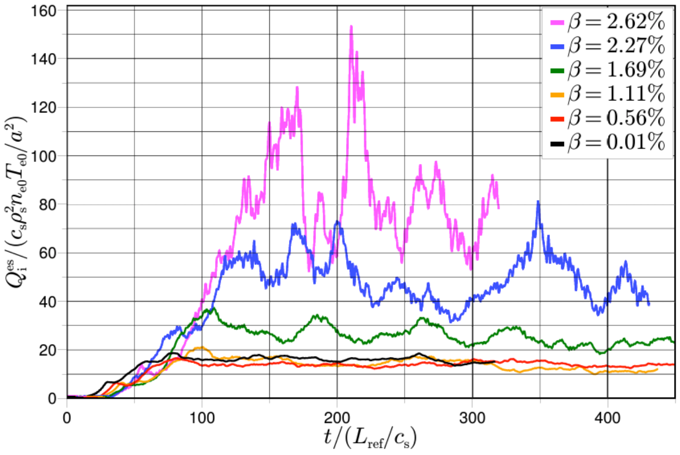

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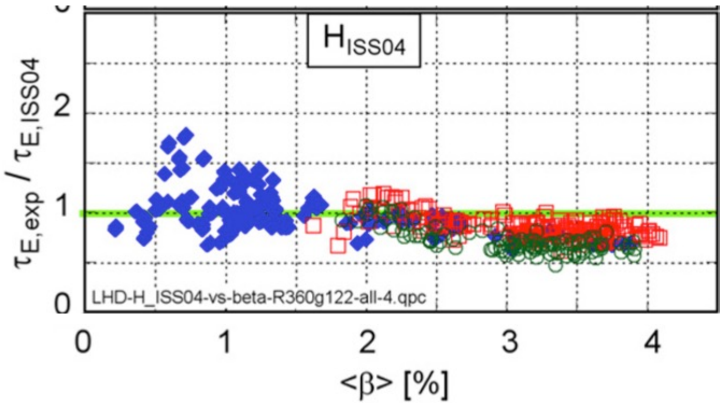
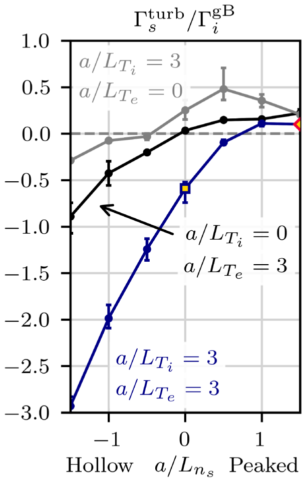
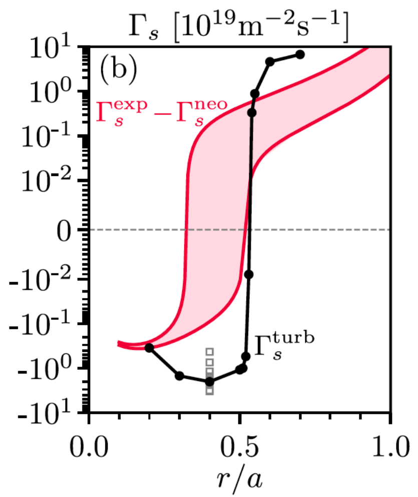
Is W7-X confinement on the verge of degrading its performance with β (like τ_E degradation reported for LHD [Weller NF´09])?

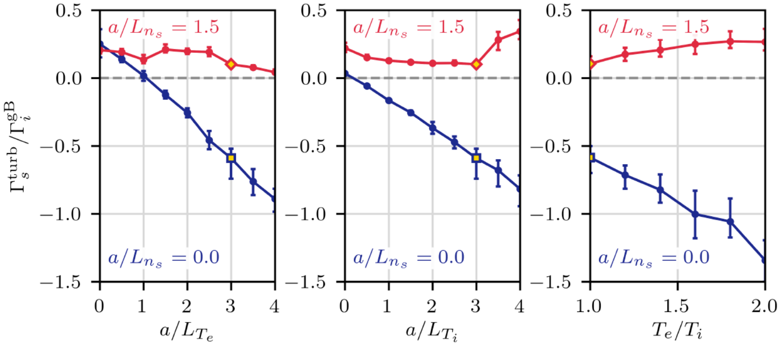
[Weller NF´09]



- 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.

Turbulent particle transport in stellarators [Thienpondt PRR´23]

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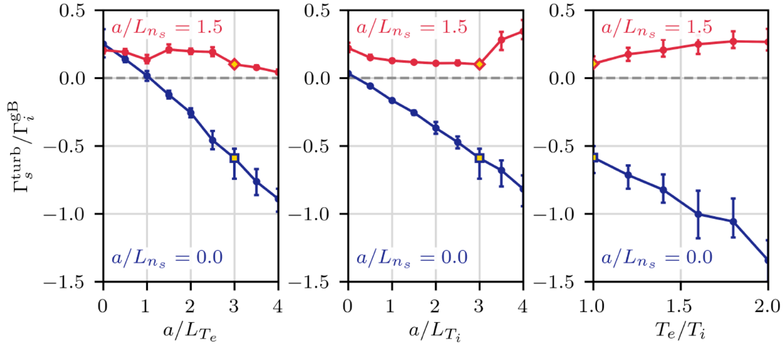
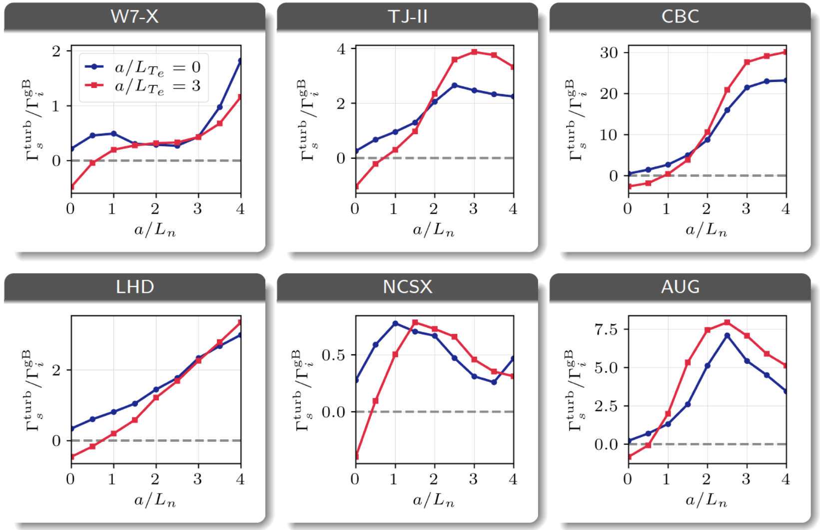




- The **parametric dependence** has been characterized in detail.

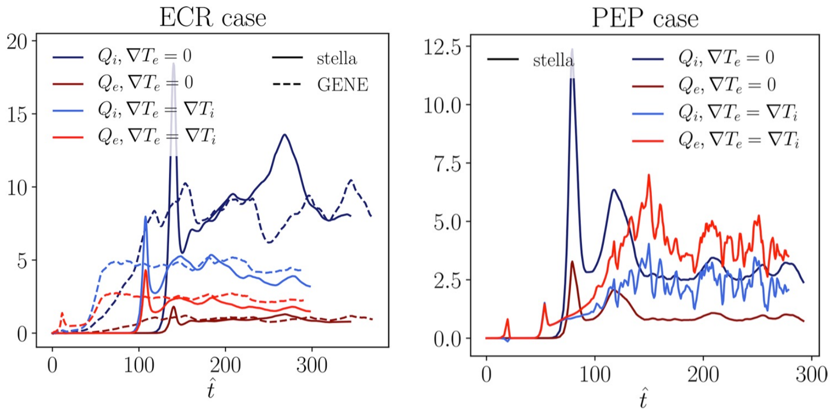
> Whereas each device exhibits a different shape $\Gamma(a/L_n)$, the presence of a **turbulent pinch** is found **in all devices analyzed so far** [Alonso NF´24].

Revisiting W7-X pellet-enhanced-performance (PEP) [Zocco PRR´24]

- Initial gyrokinetic studies of PEP W7-X plasmas [Xanthopoulos PRL´20] **neglected the role of the electron temperatura gradient**, setting $a/L_{T_e} = 0.0$.
- With recent stella simulations, PEP scenarios have been revisited retaining a/L_{T_e} and comparing the results against standard ECR shots.

TABLE II. Turbulent thermal diffusivities from STELLA in S.I. units.

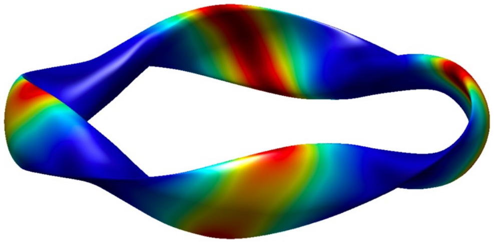
Units, m^2/s	$\nabla T_e = 0$	$\nabla T_e = \nabla T_i$
$\chi_i^{PEP}/\chi_i^{ECR}$	2.50/5.88	2.08/2.60
$\chi_e^{PEP}/\chi_e^{ECR}$	N.A.	3.60/1.19



- Simulations without a/L_{T_e} **artificially enhance** turbulence suppression due to density peaking.
- **Electron heat transport can dominate at the ion scale**.
- Turbulence suppression is linked to the **rapid growth of zonal flows**, especially with higher density gradients.

Turbulence in new configurations: CIEMAT-QI4 [García-Regaña subm.´24]

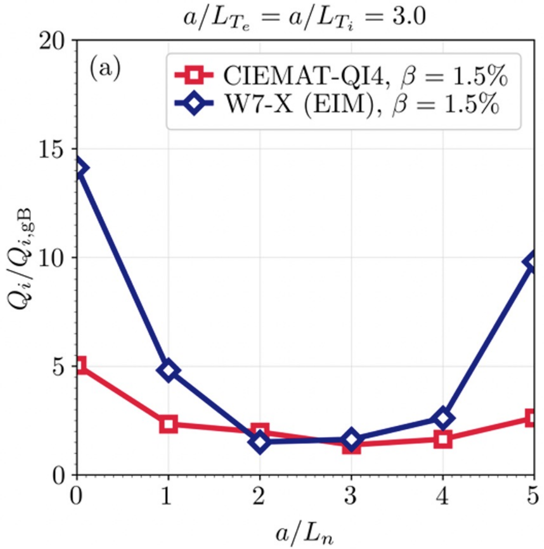
- 4-field-period configuration remarkably close to maximum-J property.
- Low effective ripple, $\varepsilon_{\mathrm{eff}}$(s=0.25)<0.5 % and small bootstrap current.
- Low shear profile with $\iota \sim 0.85 - 0.95$ at the edge.
- Ideal and ballooning MHD stable up to $\beta \sim 5\%$.
- Good fast-ion confinement at low β and excellent fast-ion confinement at high β.
- Reduced electrostatic turbulent transport [García-Regaña submitted´24].



[Sánchez NF´23]

Electrostatic turbulence in CIEMAT-QI4 [García-Regaña subm.´24]

- **At high density gradient** CIEMAT-QI4 is remarkably resilient to density gradient driven turbulent transport.
- **At intermediate density gradient** heat flux reduction is comparable to that W7-X.
- **At low density gradients**, low ion heat losses are observed for CIEMAT-QI4, which exhibits distinctively different zonal flow (ZF) behavior.



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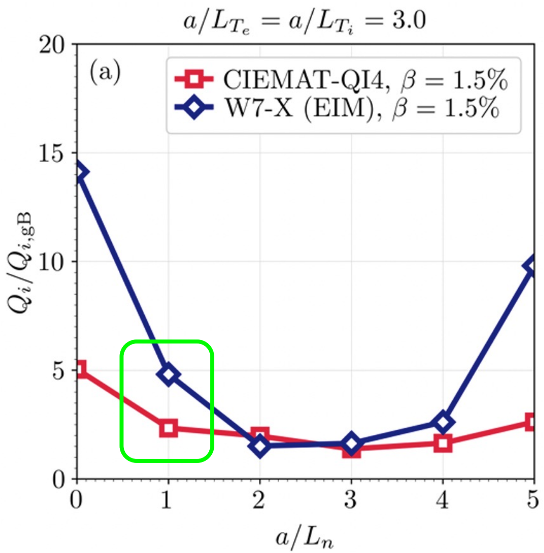
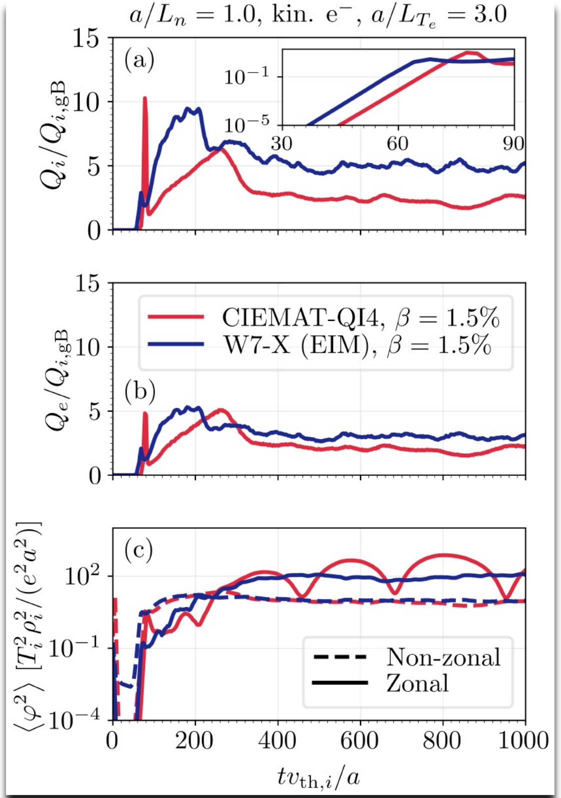
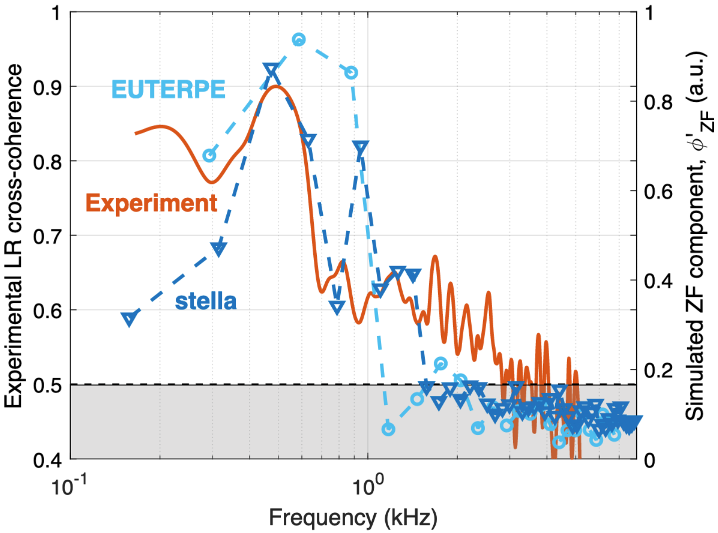
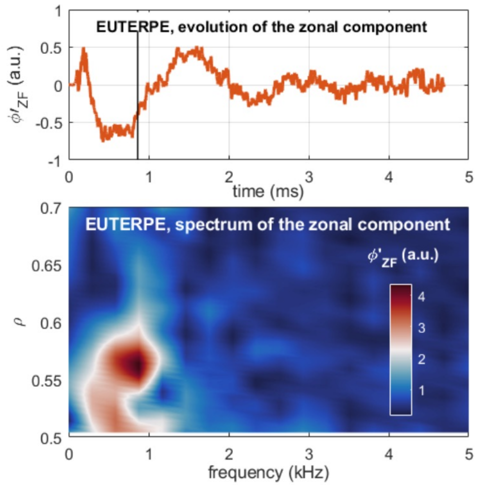




Direct experimental observation of zonal flows in W7-X [Carralero subm.´24]

- **First observations of zonal flows in W7-X** with toroidally separated twin Doppler reflectometers [Carralero EPS´24, submitted´24].
- Comparisons of nonlinear simulations, radially global simulations with EUTERPE and flux tube simulations with stella, **show robust agreement**.
- **Dominant frequency** and **radial location** of maximum correlation are predicted remarkably well.





Summary

Since the last CWGM edition, within TSVV13, we have made substantial progress in understanding:

- The **role of impurities** in turbulence.
- The **impact of plasma pressure** on the excitation of electromagnetic modes and the consequent increase in heat losses.
- Turbulent **particle transport** and its role in preventing particle core depletion.
- **Heat transport in high-performance plasmas.**
- **Turbulent transport in new configurations**.
- **and validating zonal flows** measurements for the first time in W7-X.
- And much more:

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.*

Additionally, participation of TSVV13 members in the upcoming W7-X campaigns is noteworthy.