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Stellarator turbulence simulation in Europe: a tour of its latest achievements

J. M. García Regaña (CIEMAT)

In collaboration with the TSVV13 (*Stellarator Turbulence Simulation*) team

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Laboratorio Nacional de Fusión
Ciemat
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK
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TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY
CCFE CULHAM CENTRE FOR FUSION ENERGY

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Outline

I. Transport channels in magnetically confined plasmas

II. Where does turbulence simulation in stellarators stand?

III. TSVV13 Project: Stellarator Turbulence Simulation

  - ❑ Verification (and code development)
  - ❑ Theory and Simulation
  - ❑ Validation

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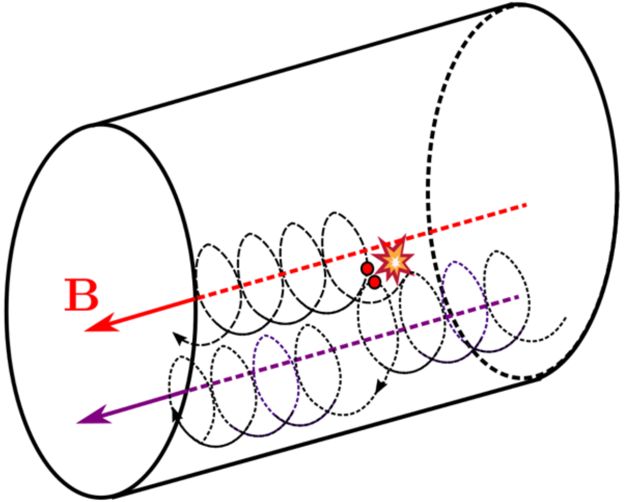
Magnetic confinement fusion: basis and classical losses

- **Nuclear fusion plasmas** are composed of **charged particles**: hydrogen nuclei, electrons and impurity ions (C, Fe, W, He, …).
- In a **uniform** magnetic field with **straight field lines**, charged particles follow helixes around the guiding center with gyro-frequency Ω_s and (Larmor) radius ρ_s.
- In **strongly magnetized plasmas** ($\rho_s^* = \rho_s/L \ll 1$, with L the system size) particles are confined in the absence of collisions.

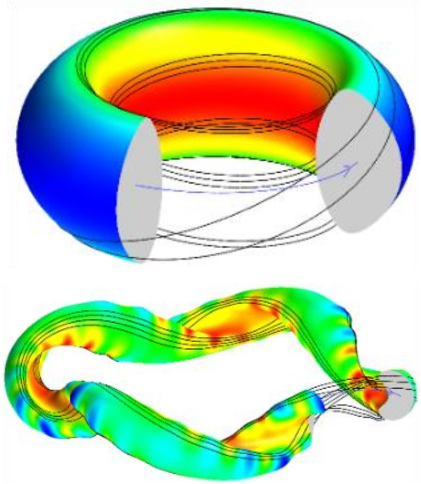


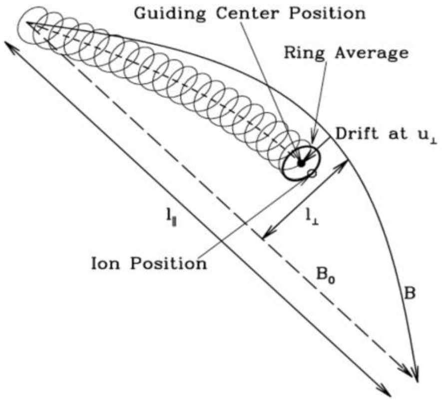
- Coulomb **collisions** between particles modify their velocity and, consequently, their guiding center position.
- ⇒ cross-field transport of particles, heat and momentum (**classical transport**)

Toroidicity, drifts and neoclassical transport

- Most present day magnetically confinement devices display a **toroidal magnetic geometry**.
- The gyro-motion follows a **guiding center** orbit that drifts w.r.t. the magnetic field line.

$$\mathbf{u}_\perp = \frac{m_s}{Z_s e}\frac{v_\parallel^2 + \mu B}{B^3}\mathbf{B}\times\nabla B + \frac{\mathbf{E}\times\mathbf{B}}{B^2}$$



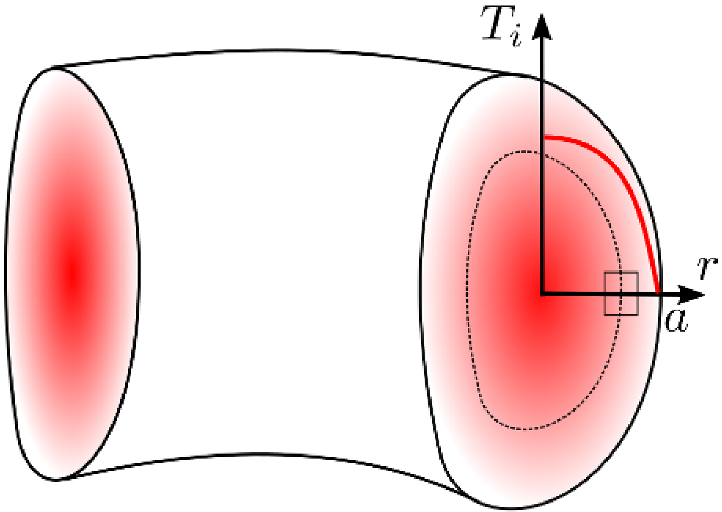


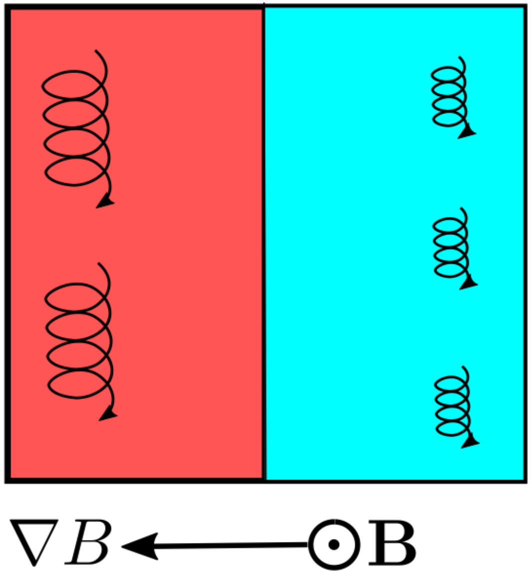
- **Curvature** and **inhomogeneity** of $\boldsymbol{B}$ along with $\boldsymbol{E}\times\boldsymbol{B}$ **drift** (of $\boldsymbol{E}$ and $\boldsymbol{B}$ varying in length scales $L \ll \rho_s$) and Coulomb collisions.

⇒ Cross-field transport of particles, heat and momentum, unfavourable in stellarators at low collisionality (**neoclassical transport**).

⇒ Stellarator **optimization** of neoclassical transport, e.g. **Wendelstein 7-X** (W7-X, IPP, Germany).

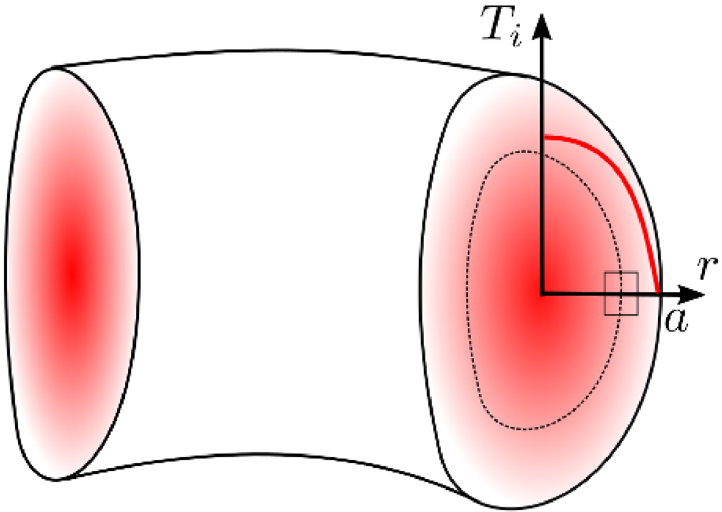
Microinstabilities and turbulence losses

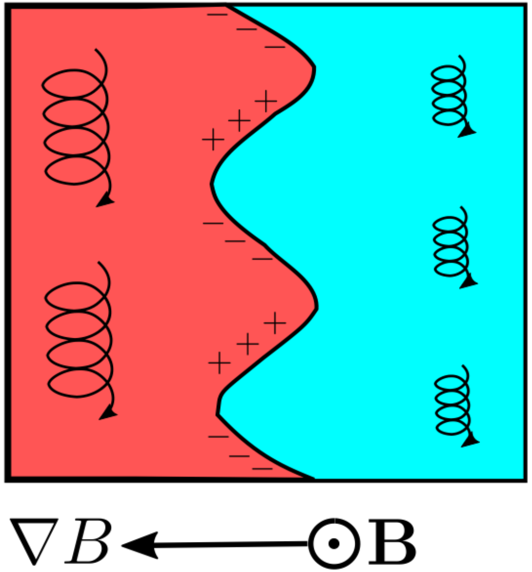




- High energy (hot) particles drift faster than (cold) lower energy particles.

Microinstabilities and turbulence losses





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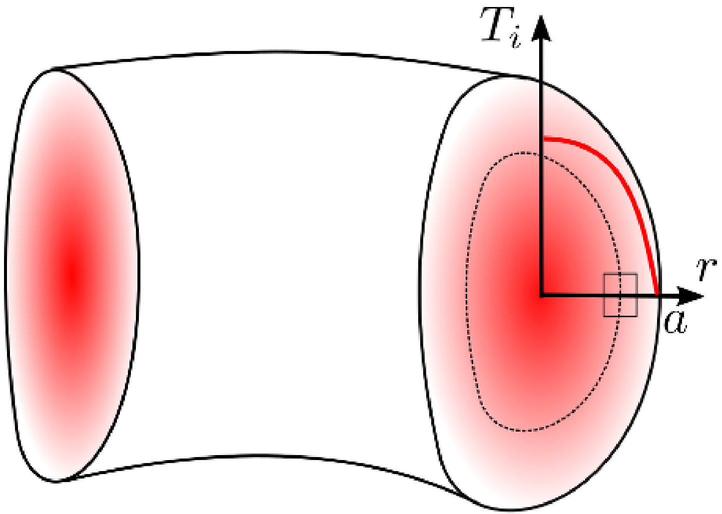
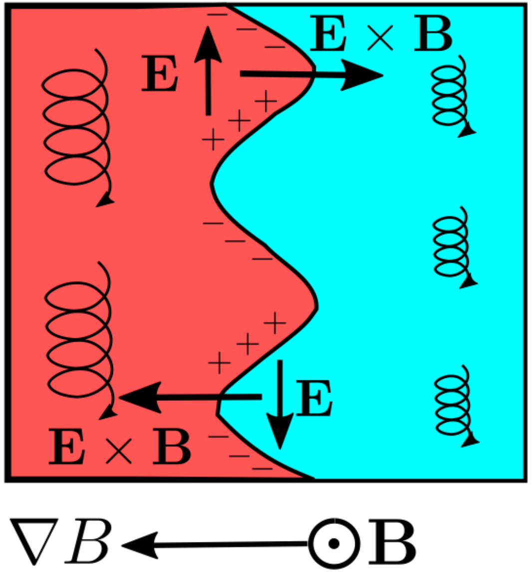
- If we **perturb** the system, **quasi-neutrality** breaks ⇒ electric field and $E \times B$ drift arises.

Microinstabilities and turbulence losses





- High energy (hot) particles drift faster than (cold) lower energy particles.
- If we **perturb** the system, **quasi-neutrality** breaks ⇒ electric field and $E \times B$ drift arises.
- $E \times B$ drift enhances the perturbation ⇒ **instability**.

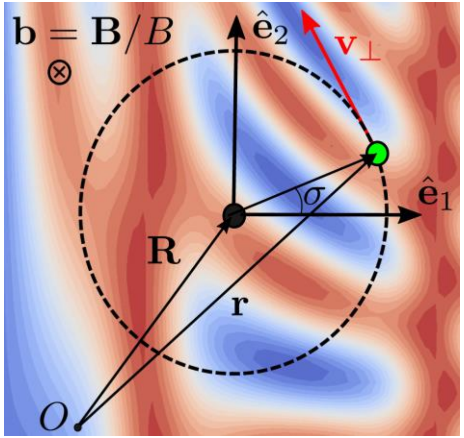
❑ Plasma micro-instabilities are excited in **unfavourable curvature** regions.

⇒ Turtulent fluctuations of the $\boldsymbol{E}$ and $\boldsymbol{B}$.

⇒ **Cross-field transport** of particles, heat and momentum (**turbulent transport**).

Gyrokinetic theory

- **Theoretical framework** to describe microturbulence **from first principles** [Catto'78, Frieman'82], solving the Vlasov-Maxwell system of equations.
- In **strongly magnetized plasmas**, with frequency $\omega \ll \Omega_s$, characteristic size such that $k_\perp \rho_s$ and $k_{||}/k_\perp \sim O(\rho_s^*)$.
- **Average out the fast gyro-phase** dependence (**6D → 5D**) retaining the **finite gyro-radius effect**.
- Splitting of the distribution function of the species, $f_s = f_{Ms} + \delta f_s$, Vlasov equation for $g_s \equiv \langle \delta f_s \rangle_\mathbf{R}$ becomes:



$$\partial_t g_s + \left(\overbrace{v_{||}\mathbf{b}\cdot\nabla}^{\text{Parallel stream.}} - \overbrace{\mu\mathbf{b}\cdot\nabla B\partial_{v_{||}}}^{\text{Magnetic mirror}} \right) g_s + \overbrace{\mathbf{v}_{Ms}}^{\nabla B-\text{drifts}} \cdot \left(\nabla_\perp g + \frac{Z_s e}{T_s}\nabla_\perp \langle\varphi\rangle_\mathbf{R} F_{Ms} \right)$$

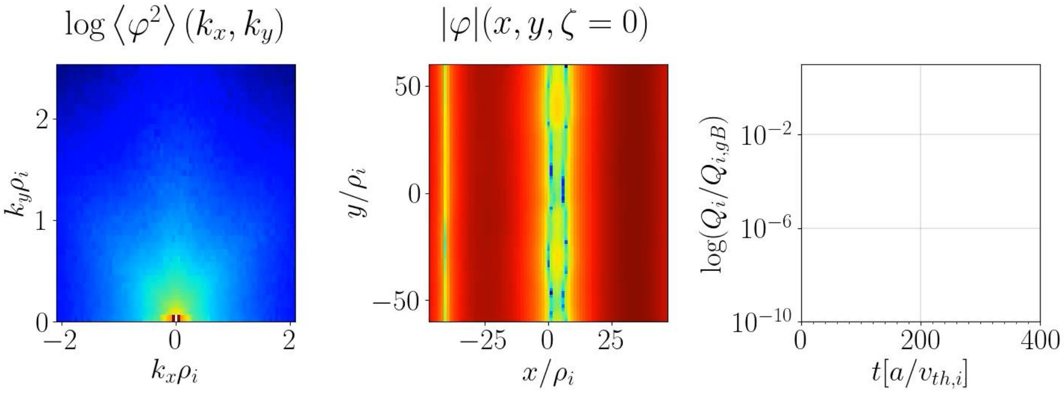
$$+ \underbrace{\frac{Z_s e v_{||}}{T_s}\mathbf{b}\cdot\nabla\langle\varphi\rangle_\mathbf{R}}_{\text{Electrostatic trapp.}} F_{Ms} + \underbrace{\langle\mathbf{v}_\mathrm{E}\rangle_\mathbf{R}\cdot\nabla_\perp g}_{E\times B\text{ non-linearity}} + \underbrace{\langle\mathbf{v}_\mathrm{E}\rangle_\mathbf{R}\cdot\nabla\big|_E F_{Ms}}_{E\times B\text{ drift + plasma gradients}} = 0$$

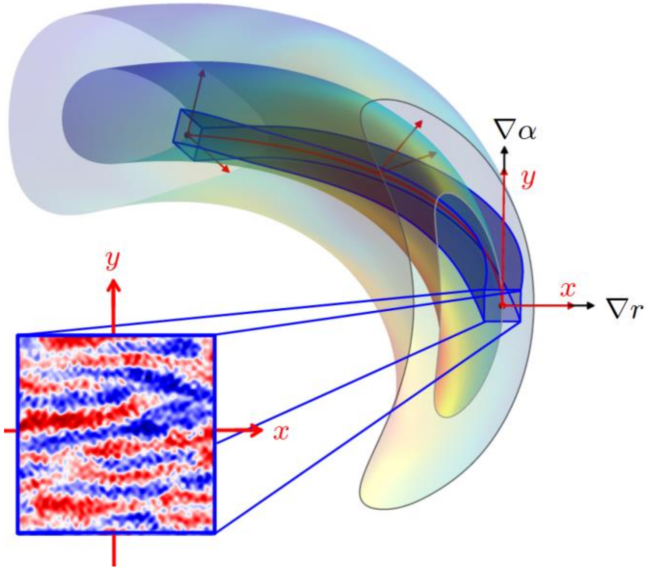
Gyrokinetic theory: turbulence in a flux tube

- Much **shorter wavelength** in the **perpendicular direction than in the parallel direction** (z), $k_{||}/k_{\perp} \sim O(\rho_s^*)$ ⇒ spectral treatment in the radial (x) and binormal (y) directions.

$$g_s(x, y, z, v_{||}, \mu, t) = \sum_{k_x, k_y} \hat{g}_{s,k_x,k_y}(z, v_{||}, \mu, t) \exp\left(ik_x + ik_y\right)$$

- Simulation domain: **a box surrounding a magnetic field** line several Larmor radii in x and y, **a flux tube**.





Courtesy of H. Thienpondt

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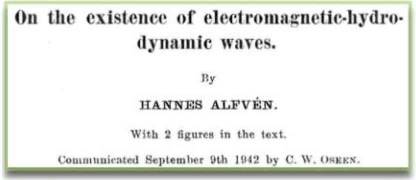
Plasma theory and simulation across its fields: Magnetohydrodinamics (MHD)

- Prediction of **Alfvén waves**. Advent of Magnetohydrodynamics [Alfvén Nature´1941].
- **Ideal MHD code VMEC** for stellarator equilibria [Hirshman PF´1986].
- Instabilities at the edge of tokamaks using **nonlinear MHD models and** numerous **extensions** [Hoezl NF´2021].



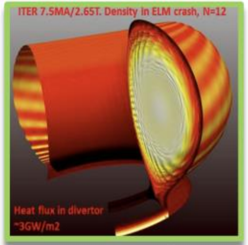
On the existence of electromagnetic-hydrodynamic waves.

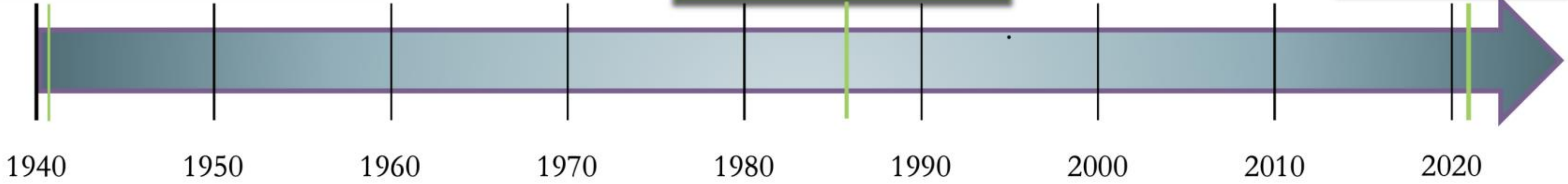
By

HANNES ALFVÉN.

With 2 figures in the text.

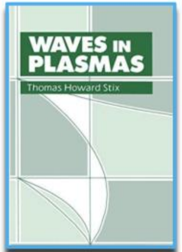
Communicated September 9th 1942 by C. W. Oseen.

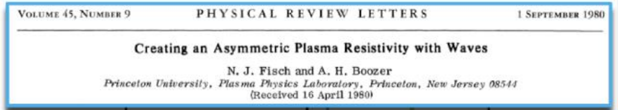




Plasma theory and simulation across its fields: Kinetic Theory of plasma waves

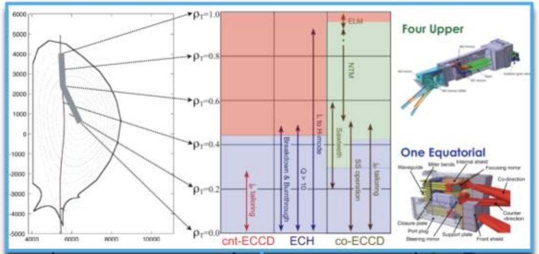
- ❑ Comprehensive description of the propagation of **waves in magnetized plasmas** [T. H. Stix´1961].
- ❑ Kinetic description of **non-inductive current** driven by cyclotron waves (ECCD) [Fisch PRL´1980].
- ❑ Utilization of these **waves for heating, ECCD, control of MHD** instabilities in tokamaks and stellarators, e.g. [Lang NF´13].

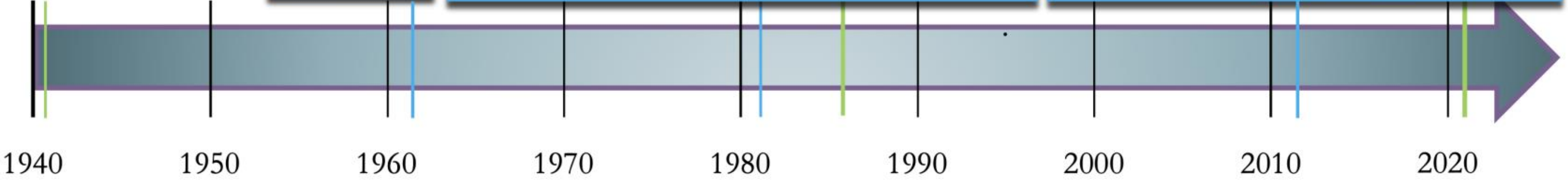



VOLUME 45, NUMBER 9 PHYSICAL REVIEW LETTERS 1 SEPTEMBER 1980

Creating an Asymmetric Plasma Resistivity with Waves

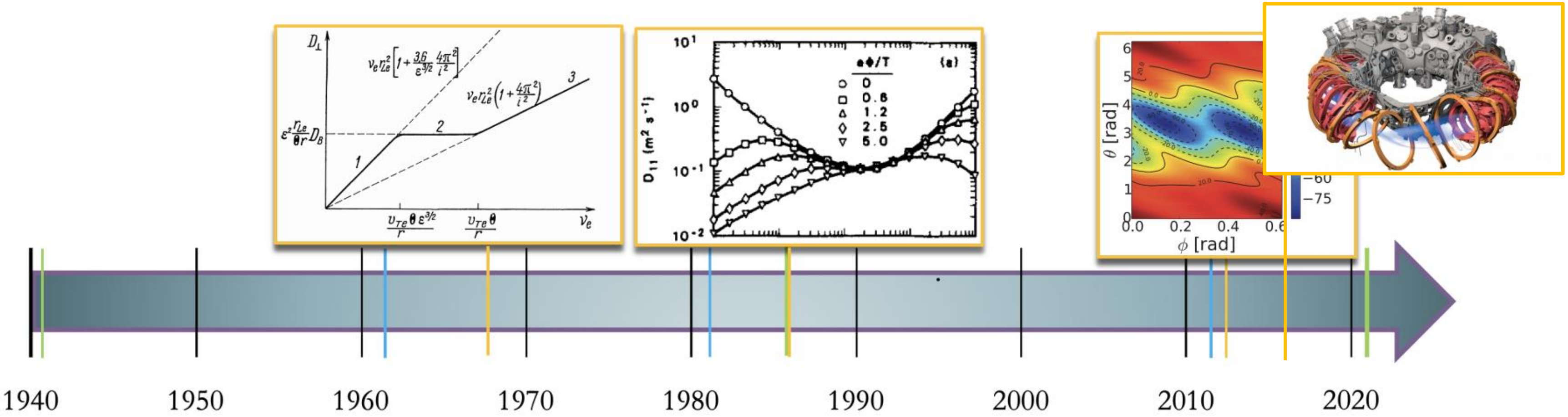
N. J. Fisch and A. H. Boozer
Princeton University, Plasma Physics Laboratory, Princeton, New Jersey 08544
(Received 16 April 1980)





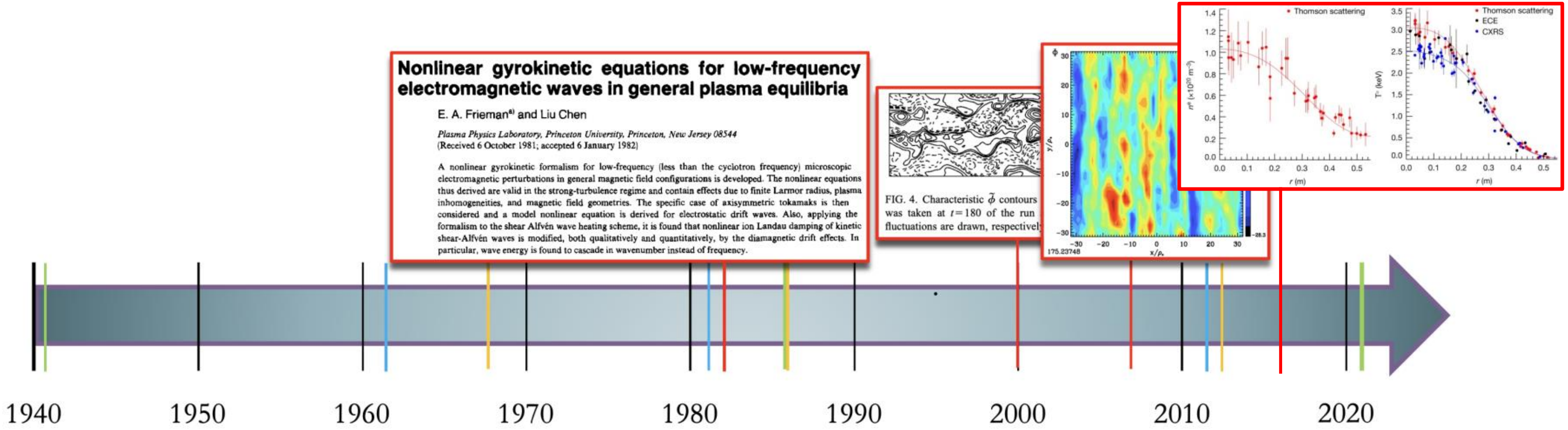
Plasma theory and simulation across its fields: Neoclassical theory and transport

- **Transport** associated with **particle drifts** in toroidal geometry [Galeev & Sagdeev JETP´1968].
- Development of the **standard neoclassical code DKES** (Drift Kinetic Equation Solver) [Hirshman PF´86].
- Obtaining the **complete neoclassical field** with DKES+EUTERPE for impurity particle transport [García-Regaña NF´17].
- Construction of first large stellarator optimized for neoclassical transport: Wendelstein 7-X (2015).



Plasma theory and simulation across its fields: gyrokinetic theory and turbulent transport

- ❑ Linear [Catto PP´78] and non-linear [Frieman PoP´82] **formulations of gyrokinetic equations**.
- ❑ Applications of **gyrokinetic codes** (GS2 and GENE) for **tokamak** turbulence studies [Jenko PoP´00].
- ❑ **Non-linear** simulations of ITG **turbulence** for **stellarators** with GENE [Xathopoulos PRL´07].
- ❑ **Record** triple product **in W7-X** ($n_i T_i \tau_E > 5.3 \times 10^{19}\ \mathrm{m}^{-3}$) in **reduced turbulence** scenarios [Beidler Nature´21].



Nonlinear gyrokinetic equations for low-frequency electromagnetic waves in general plasma equilibria

E. A. Frieman[a] and Liu Chen

Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544
(Received 6 October 1981; accepted 6 January 1982)

A nonlinear gyrokinetic formalism for low-frequency (less than the cyclotron frequency) microscopic electromagnetic perturbations in general magnetic field configurations is developed. The nonlinear equations thus derived are valid in the strong-turbulence regime and contain effects due to finite Larmor radius, plasma inhomogeneities, and magnetic field geometries. The specific case of axisymmetric tokamaks is then considered and a model nonlinear equation is derived for electrostatic drift waves. Also, applying the formalism to the shear Alfvén wave heating scheme, it is found that nonlinear ion Landau damping of kinetic shear-Alfvén waves is modified, both qualitatively and quantitatively, by the diamagnetic drift effects. In particular, wave energy is found to cascade in wavenumber instead of frequency.

FIG. 4. Characteristic $\tilde{\phi}$ contours
was taken at $t = 180$ of the run
fluctuations are drawn, respectivel

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- ❑ Problems in MHD theory, kinetic theory of waves, or neoclassical theory are approached with a **high degree of sophistication and refinement of these theories**.
- ❑ **Gyrokinetic theory and its simulation** with numerical codes are in a **much earlier stage** of development, particularly for stellarators.

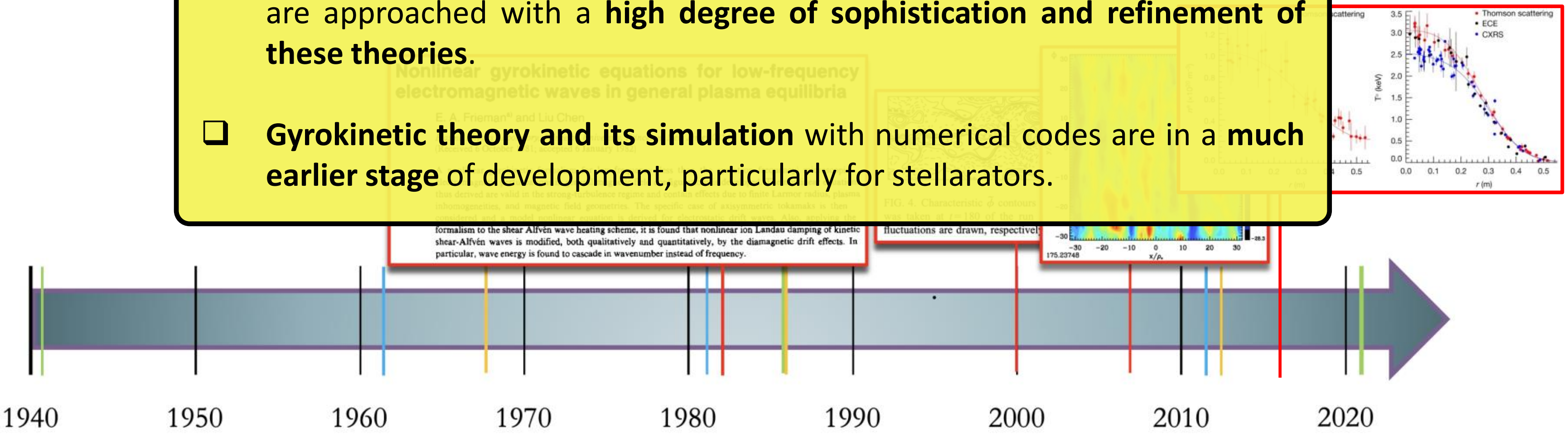

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FIG. 4. Characteristic ϕ contours ... fluctuations are drawn, respectively

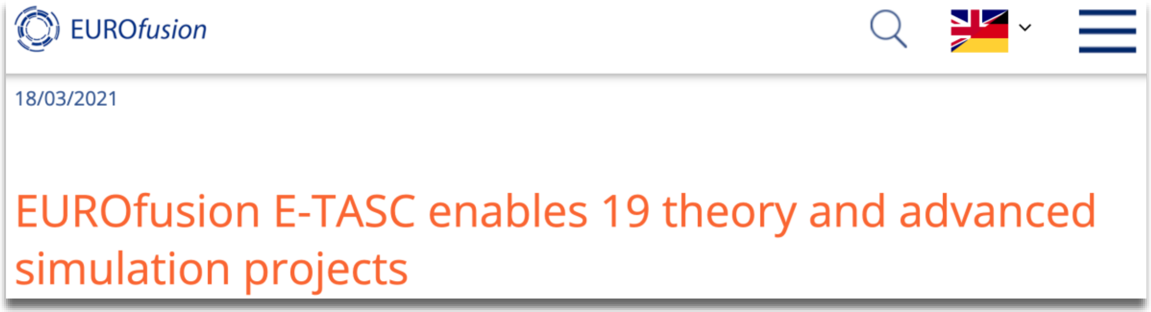
Transport channels and losses in tokamaks and stellarators

	Physical Origin	Relevance for tokamaks	Relevance for stellarators
Classical transport	Collisions	Typically negligible	Typically negligible
Neoclassical Transport	Collisions + inhomogeneity and curvature 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.

Theory and simulation in the context of EUROfusion: E-TASC

E-TASC : EUROfusion-Theory and Advanced Simulation Coordination.
TSVV : Theory, Simulation, Verification and Validation.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18/03/2021

EUROfusion E-TASC enables 19 theory and advanced simulation projects

6 out of 14 TSVV Projects consider development and exploitation of gyrokinetic codes as main tasks.

- ☐ TSVV01: Physics of the L-H Transition and Pedestals (PI: Tobias Görler, IPP).
- ☐ TSVV02: Physics Properties of Strongly Shaped Configurations (PI: Justin Ball, EPFL)
- ☐ TSVV04: Plasma Particle/Heat Exhaust: Gyrokinetic/Kinetic Edge Codes (PI: Daniel Told, IPP)
- ☐ TSVV10:Physics of Burning Plasmas (PI: Oleksiy Mishchenko, IPP).
- ☐ TSVV12: Stellarator Optimization (PI: Per Helander IPP).
- ☐ **TSVV13: Stellarator Turbulence Simulation (IP: Jose Manuel Garcia-Regaña, CIEMAT).**

TSVV13 Stellarator Turbulence Simulation in one slide

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 remain **practically unexplored** (impurity transport, electromagnetic turbulence, interplay between neoclassical (NC) and gyrokinetic (GK) physics).

Project

- 9 milestones and 15 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, K. Aleynikova (MPG).

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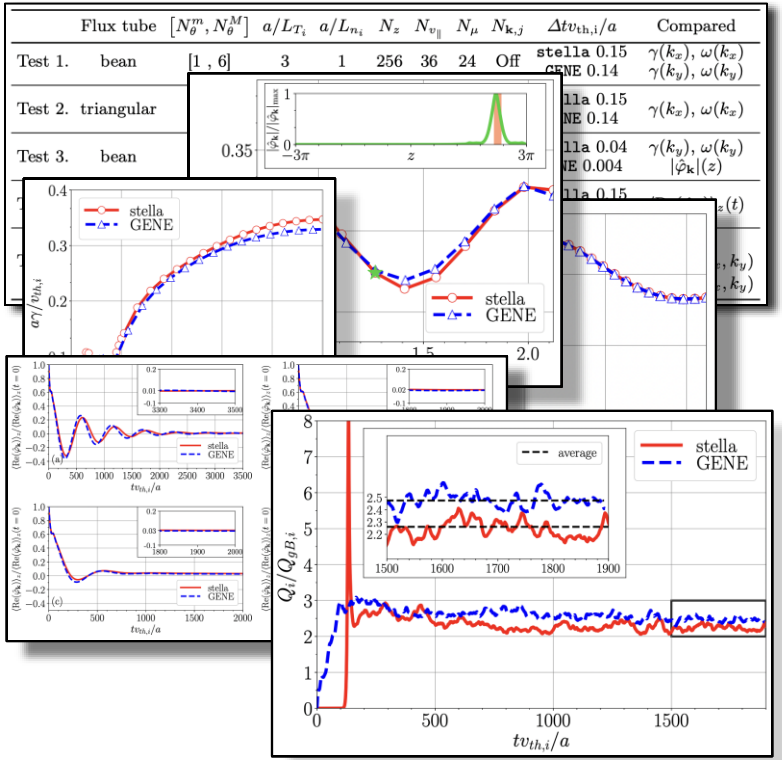
stella: a mixed implicit-explicit δf gyrokinetic code for general geometry

- **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].

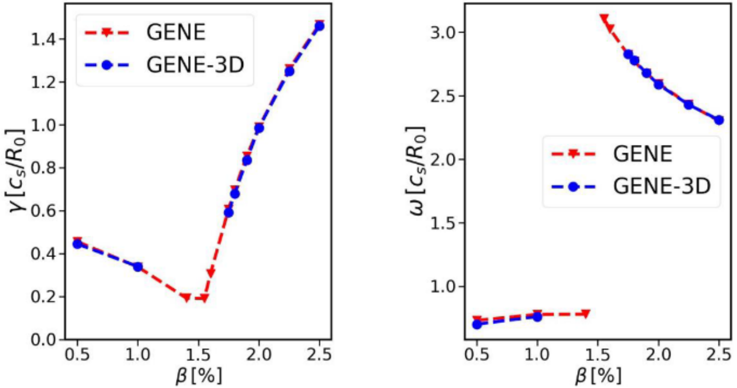
- So far, **GENE, stella, GX** [Mandel submitted´23], **EUTERPE** have used some, if not all, of these test cases.



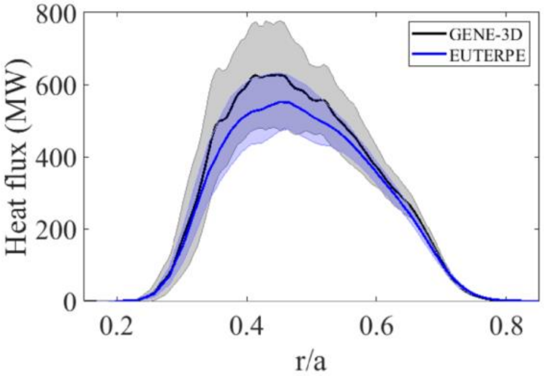
	Flux tube	$[N_\theta^m, N_\theta^M]$	a/L_{T_i}	a/L_{n_i}	N_z	$N_{v_\parallel}$	N_μ	$N_{\mathbf{k},j}$	$\Delta t v_{\mathrm{th},i}/a$	Compared
Test 1.	bean	[1 , 6]	3	1	256	36	24	Off	stella 0.15 GENE 0.14	$\gamma(k_x)$, $\omega(k_x)$ $\gamma(k_y)$, $\omega(k_y)$
Test 2.	triangular								lla 0.15 NE 0.14	$\gamma(k_x)$, $\omega(k_x)$
Test 3.	bean								lla 0.04 NE 0.004	$\gamma(k_y)$, $\omega(k_y)$ $\lvert\hat{\varphi}_{\mathbf{k}}\rvert(z)$

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]:



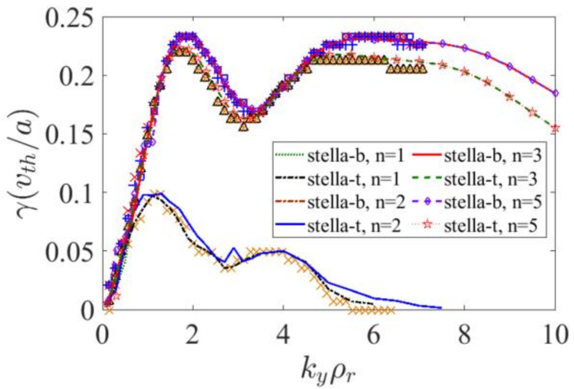
- **RG version benchmarked** for linear and nonlinear simulations against **EUTERPE** in stellarator geometry [Sánchez NF´22].

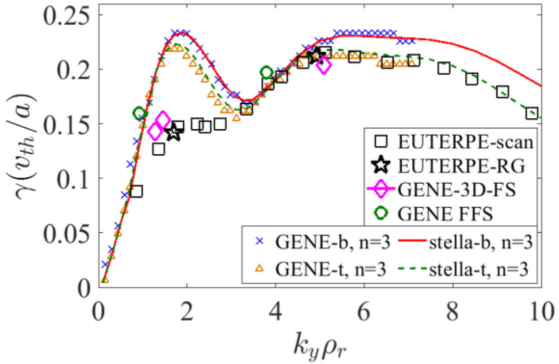


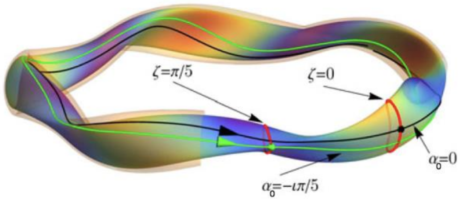
- **Good agreement** between codes.
- **Weaker turbulence localization** in nonlinear simulations than in linear simulations.
- **Weak effect of the neoclassical radial electric field** (E_r) on heat fluxes and turbulent fluctuations localization.

GENE/GENE-3D/stella/EUTERPE cross code comparison for linear simulations

- **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).







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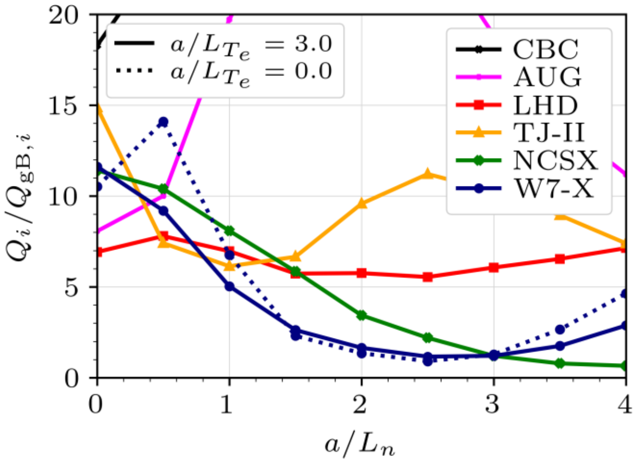
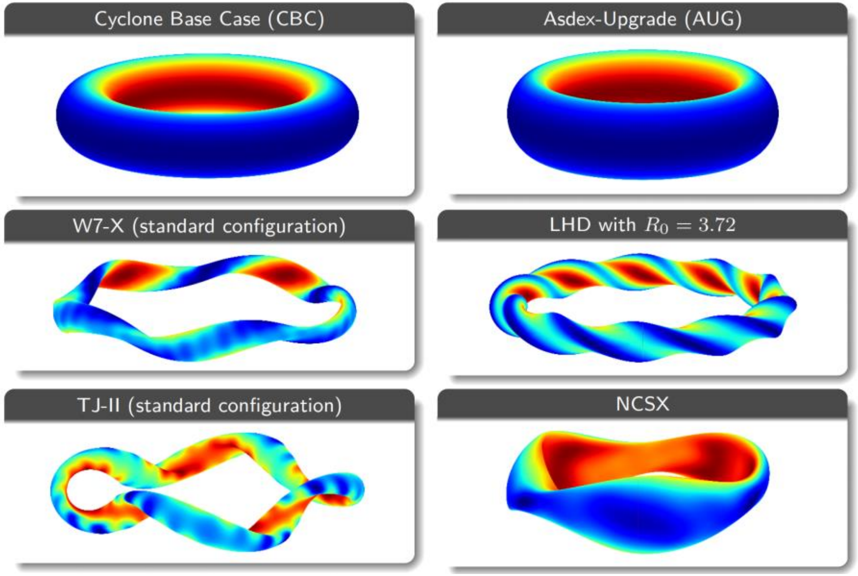
Cross-device comparison of electrostatic instabilities and turbulence

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



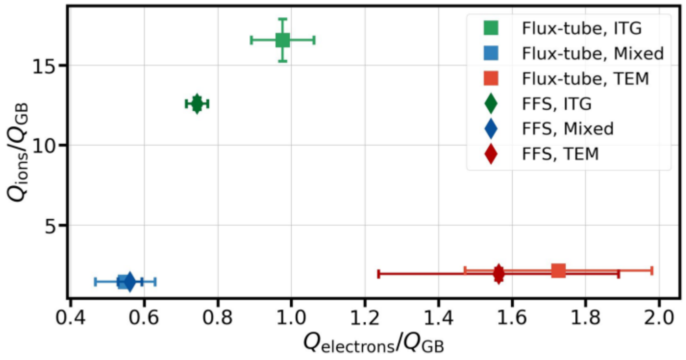


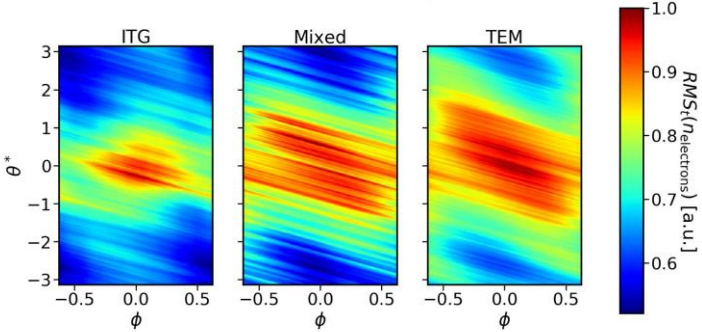
- W7-X and NCSX benefit from the **increase of the density gradient** to access **low turbulent heat levels**.
- Linear simulations do not correlate well, in general, with nonlinear fluxes.

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

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

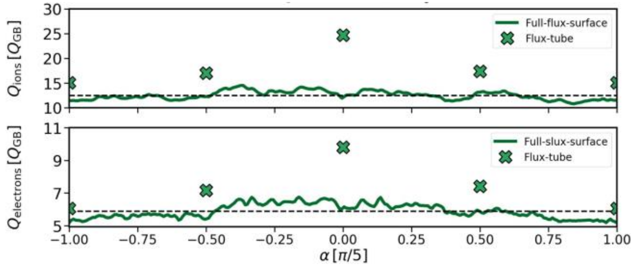
- What is **the impact of the domain** choice in non-linear simulations? [Wilms JPP´23]





- **Full-flux-surface** simulations **confirm** the **stabilisation** of turbulence in Wendelstein 7-X through $\boldsymbol{a/L_n}$ by local simulations [Alcusón PPCF´21].

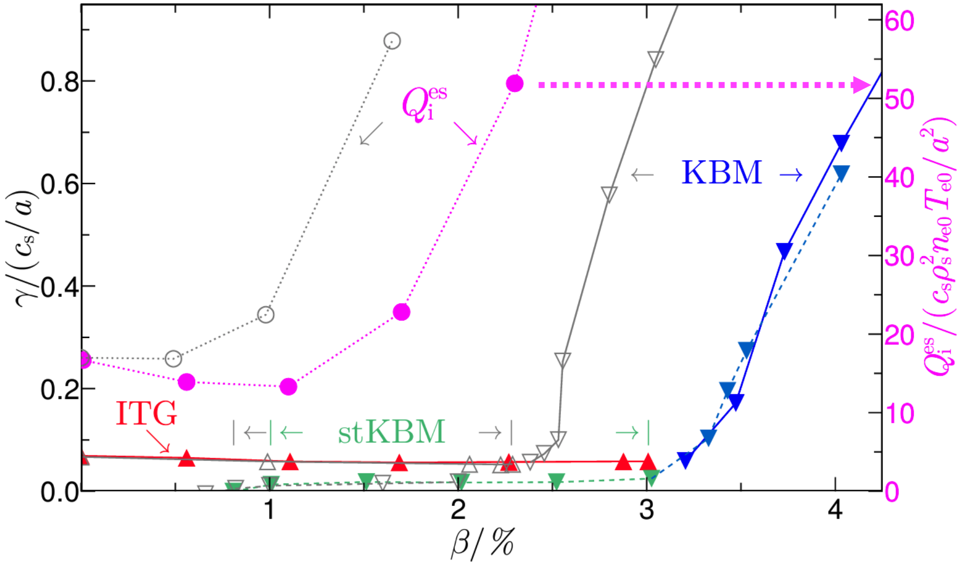
- Significant differences between flux-tube and full-flux-surface results for some parameters (kin. electrons with and finite a/L_{T_e})



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

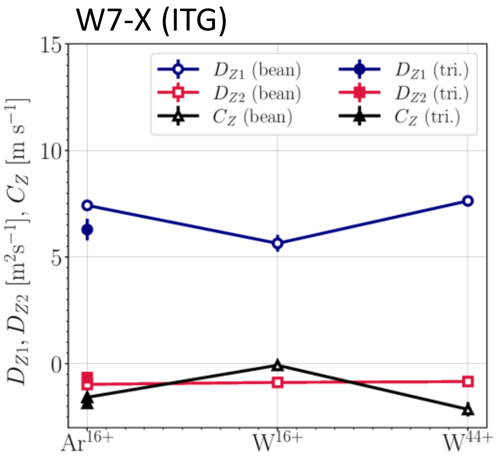
Electromagnetic simulations in Wendelstein 7-X

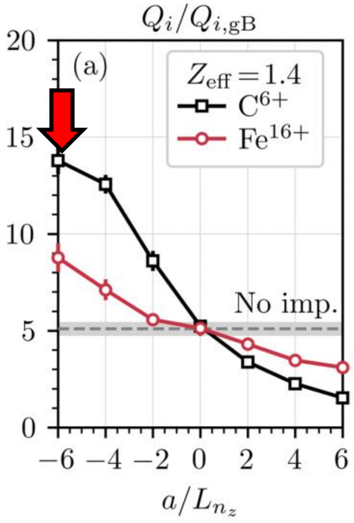
- **How does β (normalized plasma pressure) modify electrostatic picture?**
- Heat fluxes decrease slightly for $0 < \beta < 1\%$.
- A rapid heat-flux increase for $\beta \geq 1\%$, of up to a factor 4 [Mulholland PRL´23].
- Increase correlates with the presence of subdominant electromagnetic instabilities (KBM).



Impurity transport and turbulence in the presence of impurities

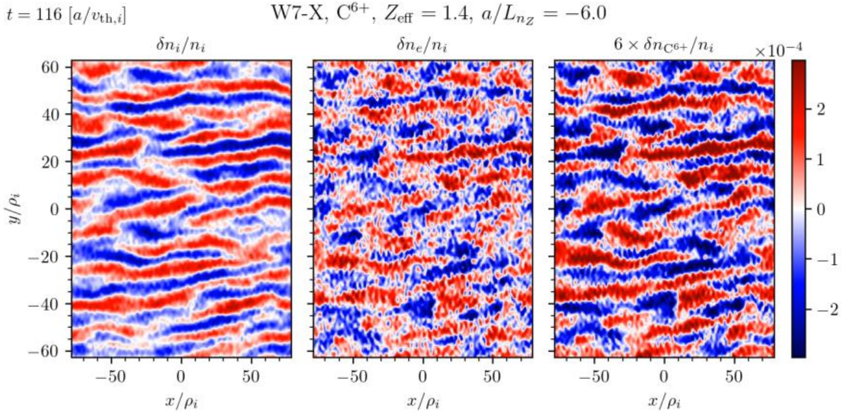
- Assessment of **turbulent impurity transport** under different turbulence type in W7-X.





- Numerical predictions of strong **turbulent diffusion** and **lack of** clear **dependence** of transport coefficients on the **impurity species** in agreement with the experiment.

- Investigation of the **impact of impurities on turbulent transport** characterized in W7-X.
- The **impact of impurities** on heat fluxes correlates with **impurity density gradient**.
- Hollow impurity density ⇒ **heat flux enhancement**.



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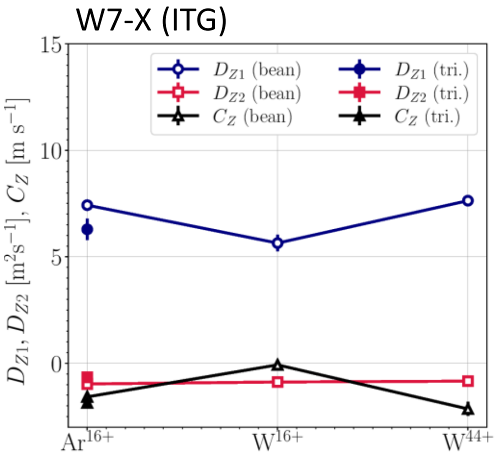
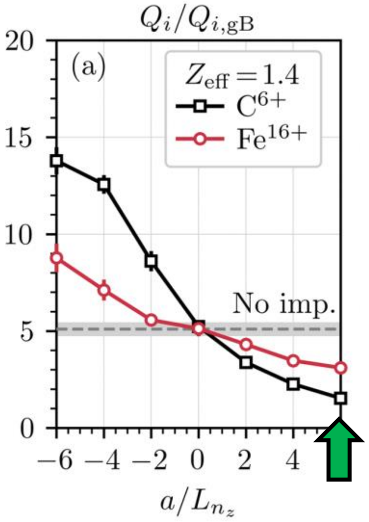
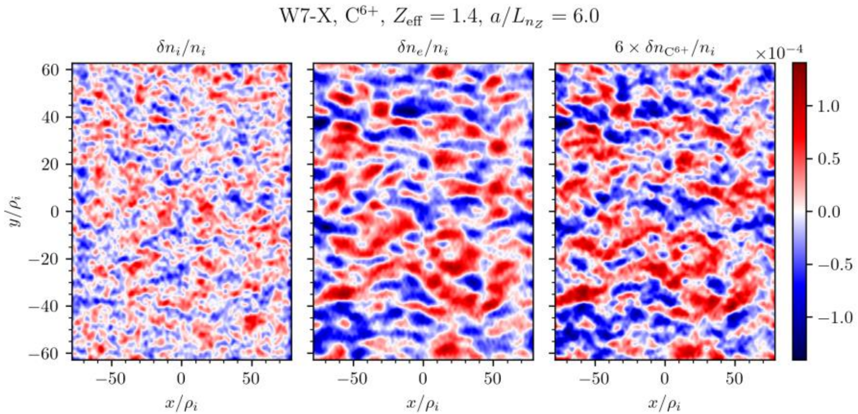




- Numerical predictions of turbulent diffusion and overall absence of dependence of transport coefficients on charge or mass of impurity in agreement with the experiment.

- Investigation of the **impact of impurities on turbulent transport** characterized in W7-X.
- The impact of impurities on heat fluxes correlates with impurity density gradient.
- Hollow impurity density ⇒ **heat flux reduction**.



Outline

I. Transport channels in magnetically confined plasmas

II. Where does turbulence simulation in stellarators stand?

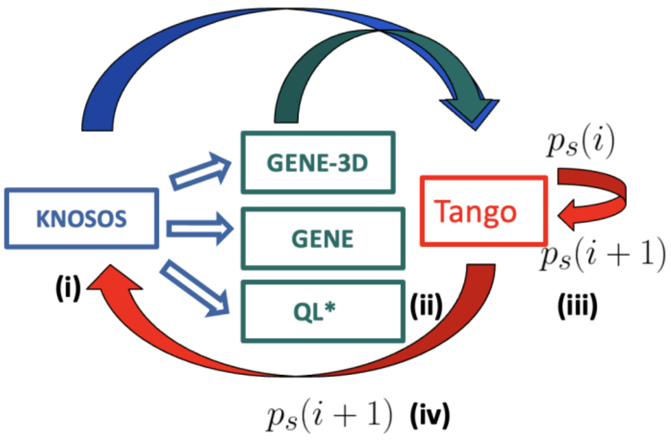
III. TSVV13 Project: Stellarator Turbulence Simulation

- ☐ Verification (and code development)
- ☐ Theory and Simulation
- ☐ Validation

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

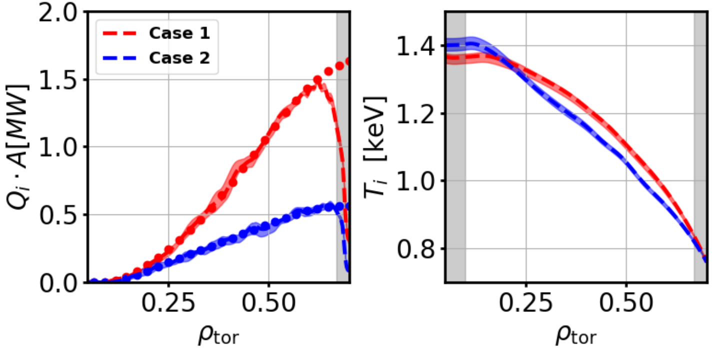
- **First principles multiple-time scale approach**: it simulates turbulence and transport only on their **natural time scales.**

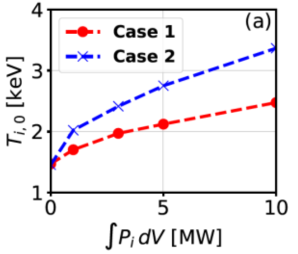
$$\overline{Q}_s(i) = \overline{Q}_s(i)^{\mathrm{turb.}} + \overline{Q}_s(i)^{\mathrm{neo.}}$$



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

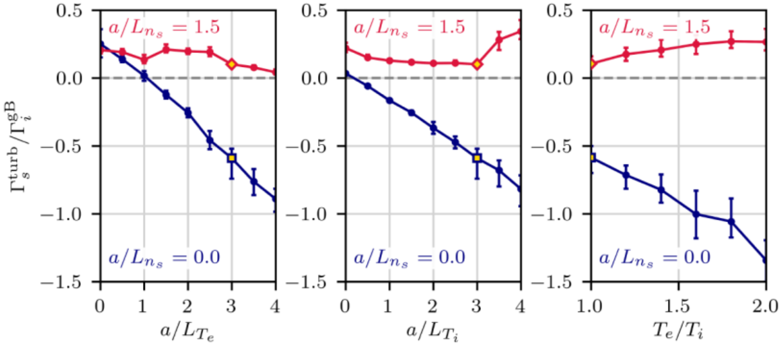
- Applied to standard ERCH W7-X scenarios [Banón Navarro NF´23].
- Different ion heating result in **the same on-axis T_i**.
- The model **reproduces** the experimentally observed T_i clamping [Beurkens NF´21].

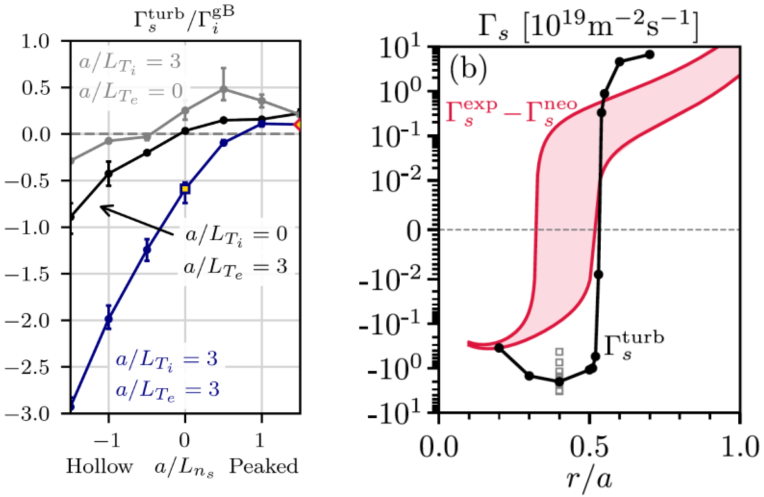




Turbulent particle transport in stellarators

- 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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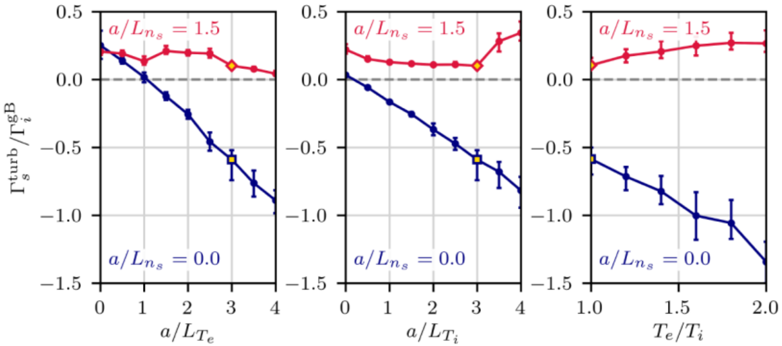
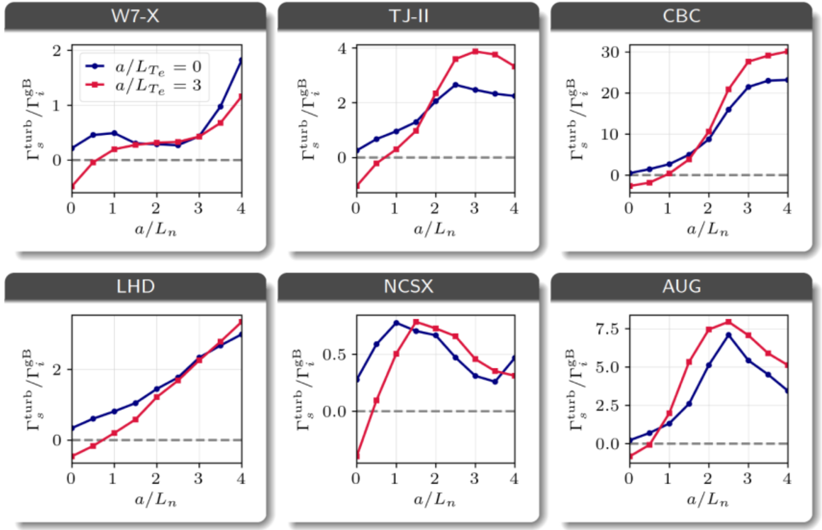
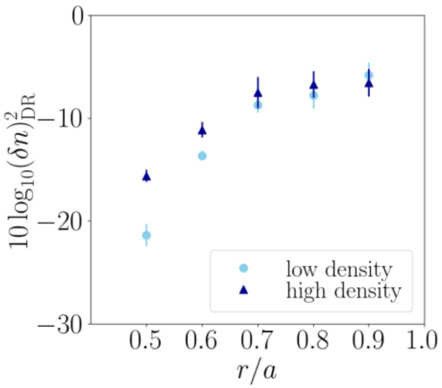


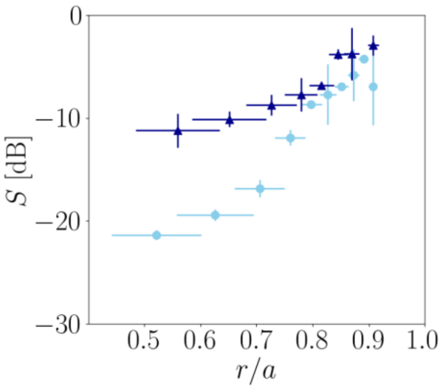


- The **parametric dependence** has been characterized in detail.
- The presence of the turbulent pinch, is found **in all devices analyzed so far**.

Comparison between stella simulations and Doppler Reflectometry measurements

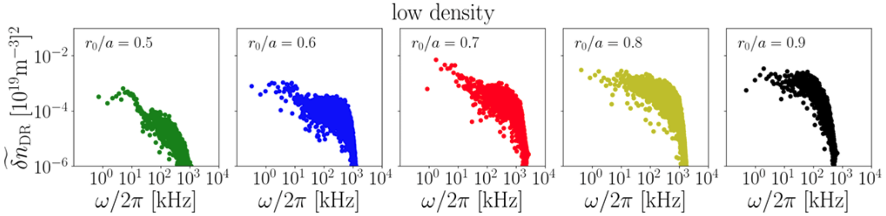
- Confidence on our gyrokinetic codes is essential for the planning of experiments and their interpretation ⇒ **careful translation of our code output into measurable data.**



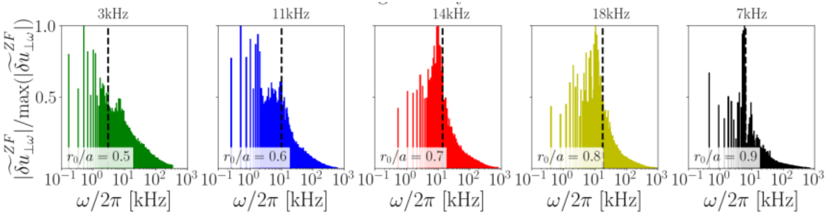


- **stella-Doppler Reflectometry** (DR) comparison $(\delta n)^2$ of OP1 plasmas for low and high density ECRH standard discharges [González-Jerez submitted´23].
- **Agreement between experimental and simulations**, and **DR/PCI** differences are explained by the measurement position in wavenumber space.

- **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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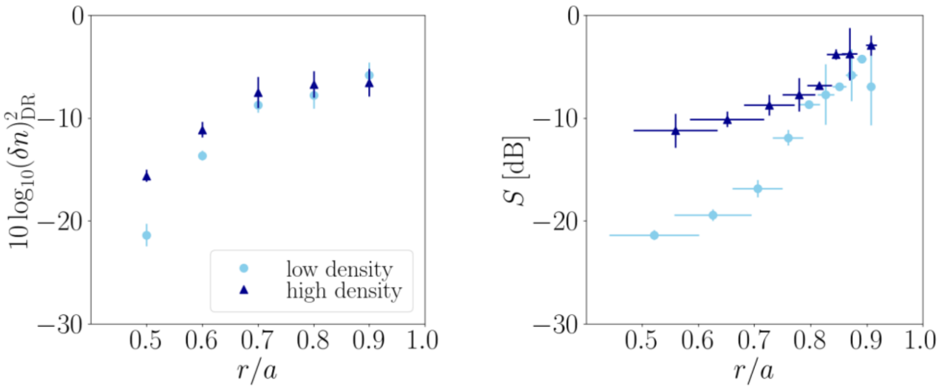

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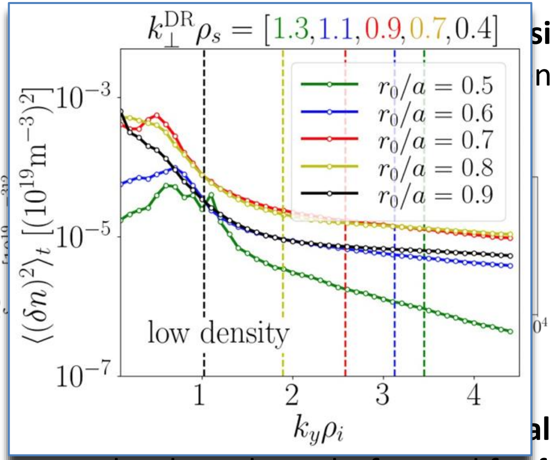

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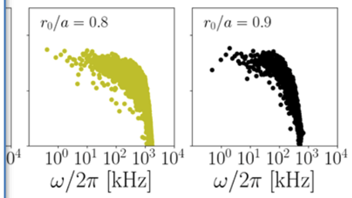

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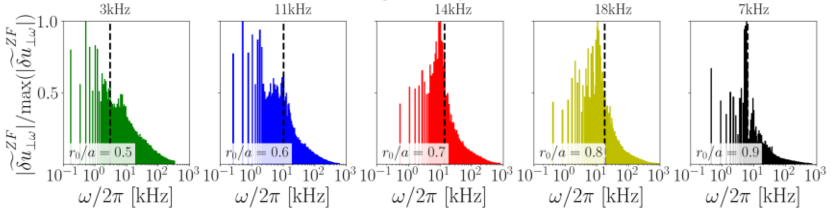

TSVV13 presence in the W7-X OP2 campaign

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

- ❑ **Stellarator turbulence simulation** was in a very **early state** of development and understanding, compared to its tokamaka couterpart and other fields.
- ❑ 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**.

  - ✓ Codes are in **continous development** and cross-**verification**.
  - ✓ **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 **satisfactorily addressed in W7-X.**
  - ✓ **Transport simulations,** evolving profiles iteratively, have been **enabled**.
  - ✓ **Electromagnetic simulations** have become routine (linked to TSVV#10).

- ❑ In computational terms, this effort has spent ≈**180 Million CPU hours** since its beginning.