Plasma turbulence in magnetic confinement fusion devices

Maurizio Giacomin

Department of Physics and Astronomy, University of Padua, Padua, Italy.
Consorzio RFX, Padua, Italy.

Synergies Between Astrophysical, Space, Laboratory, and Fusion Plasma Physics
11-29 May 2026, Nordita, Stockholm, Sweden.

CONSORZIO RFX
Ricerca Formazione Innovazione

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

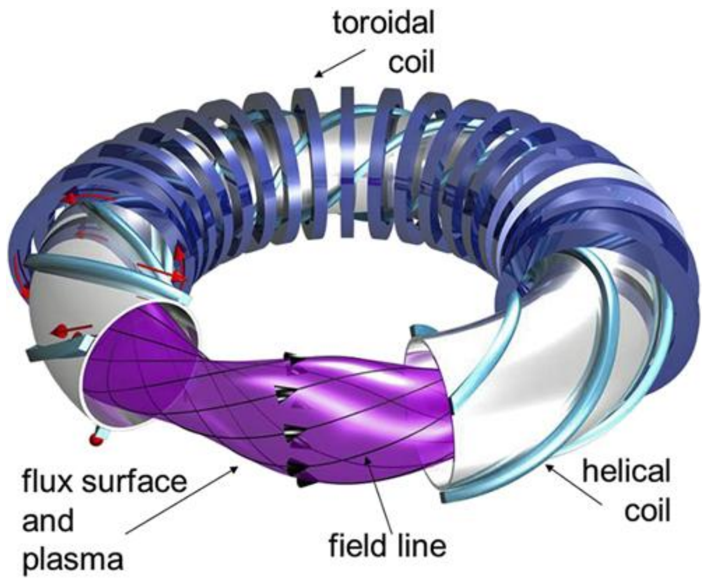
Email: maurizio.giacomin@unipd.it

Disclaimer

Turbulence in magnetic confinement fusion plasmas is a vast topic. Here, I will focus mostly on the modelling side and experimental validation.

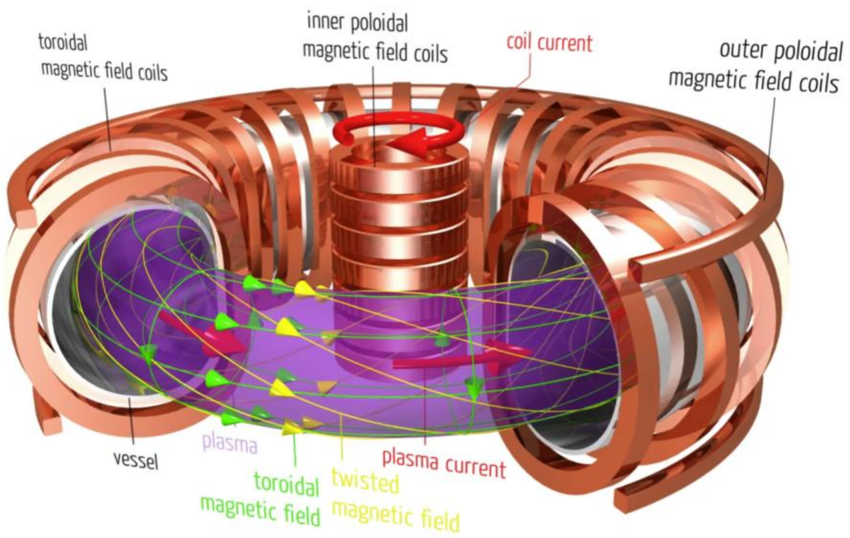
Magnetic confinement plasma devices

STELLARATOR



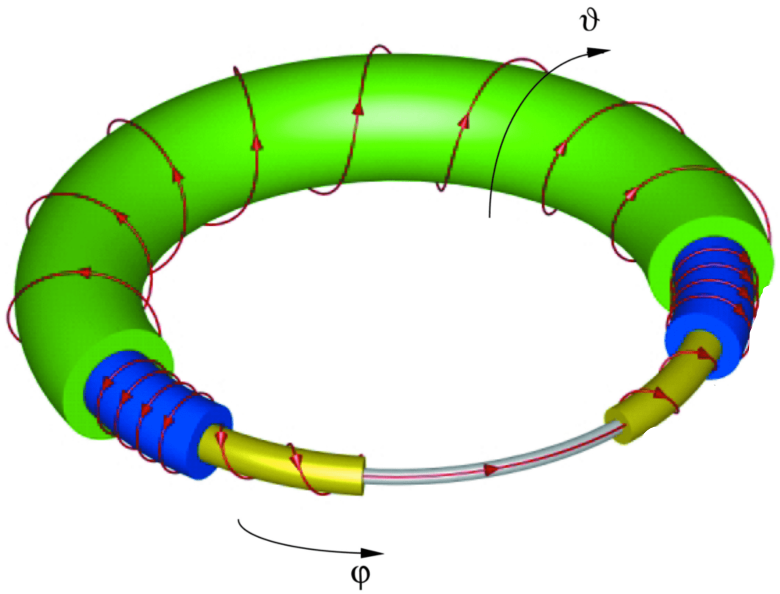
Credit: Cambridge University

TOKAMAK



Credit: Princeton University

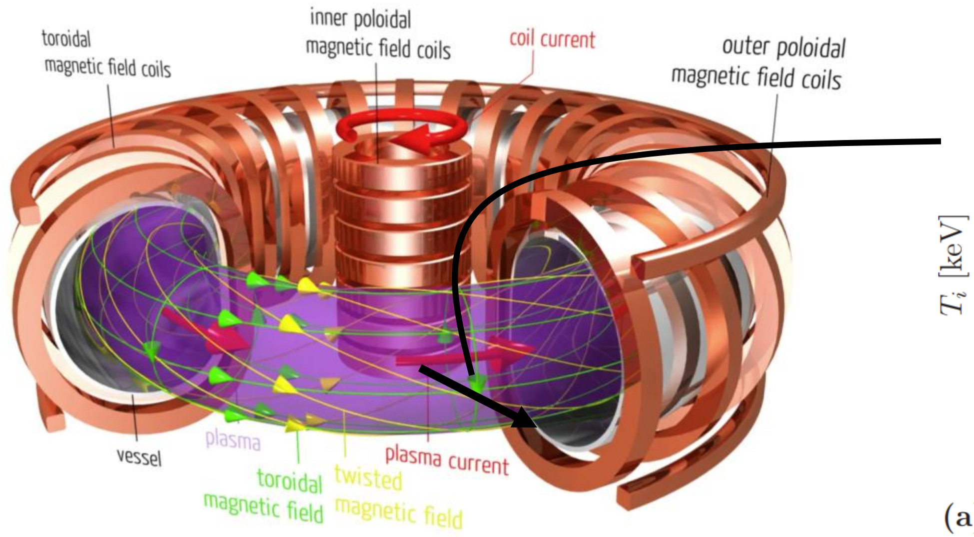
Reversed Field Pinch (RFP)



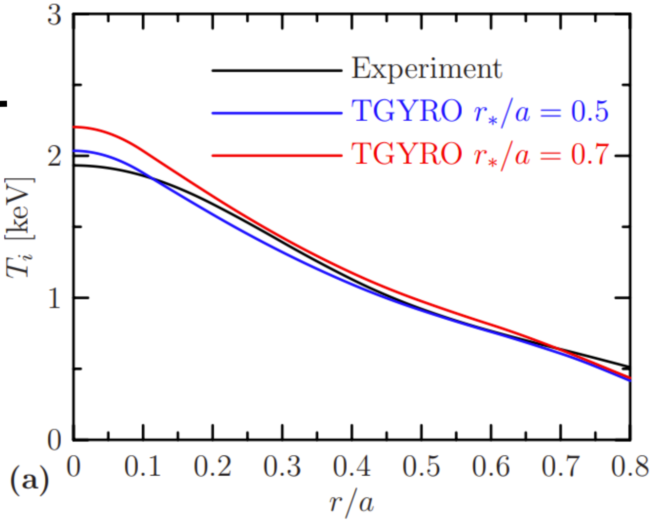
Credit: Consorzio RFX

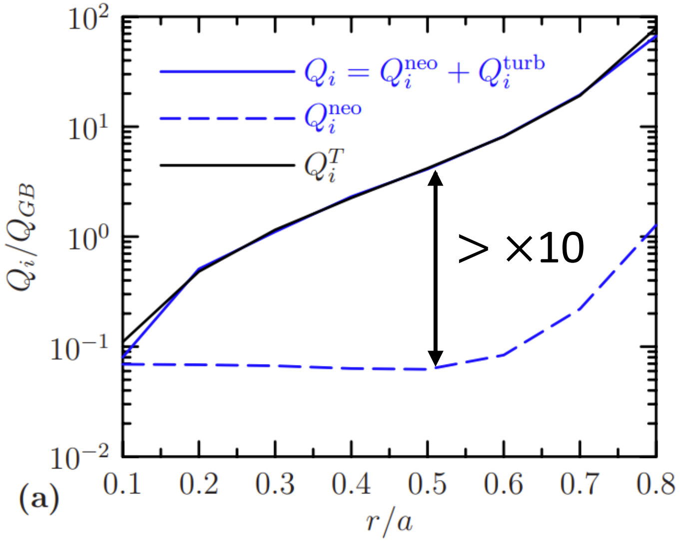
Plasma current

Why do we care about turbulence?



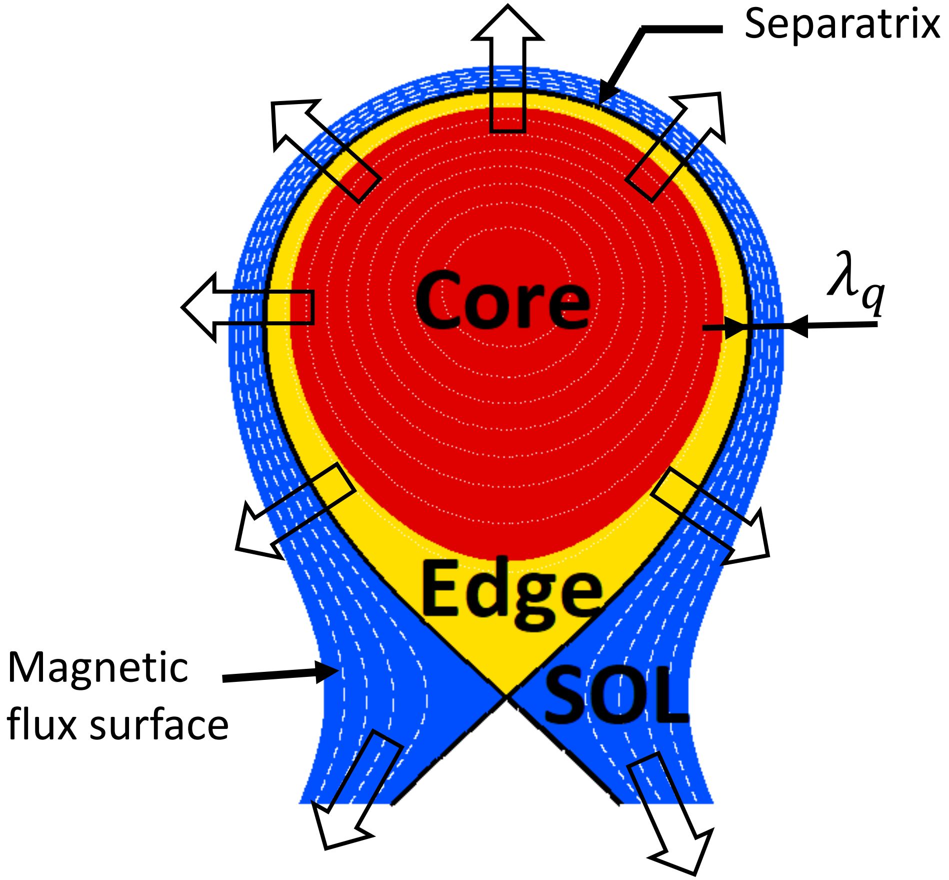
Candy et al. Phys. Plasmas 16 (2009)

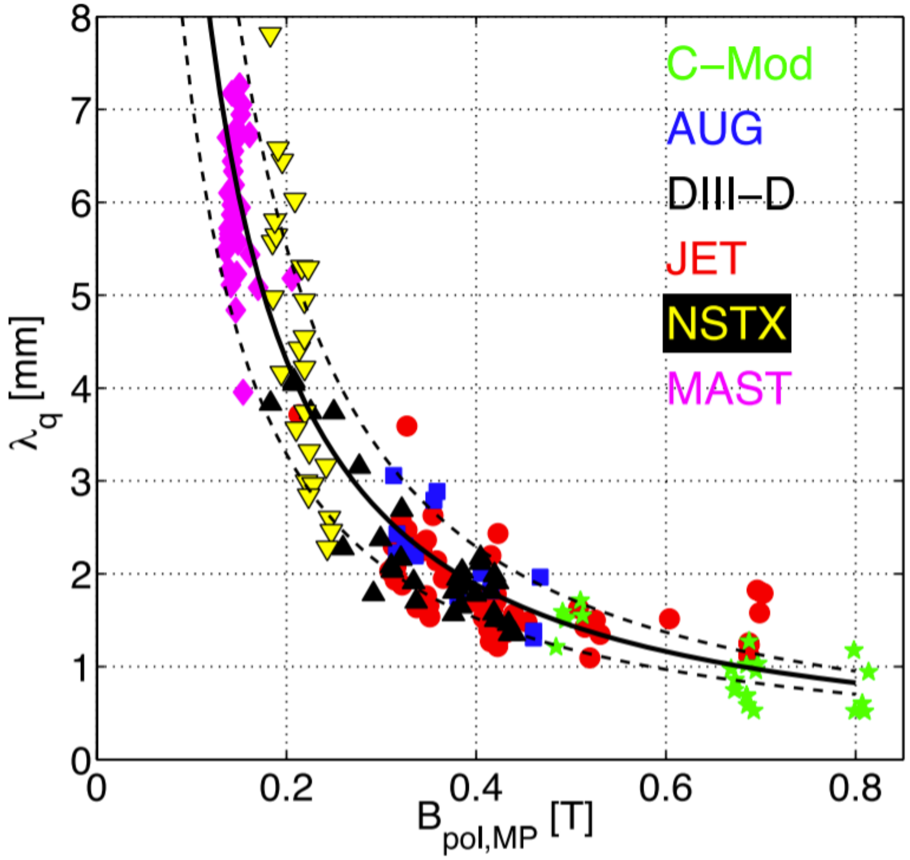




- Turbulent transport limits the energy confinement.
- Temperature profiles much steeper without turbulence.
- Smaller device to get the same fusion performance.

Is turbulence always a bad thing?

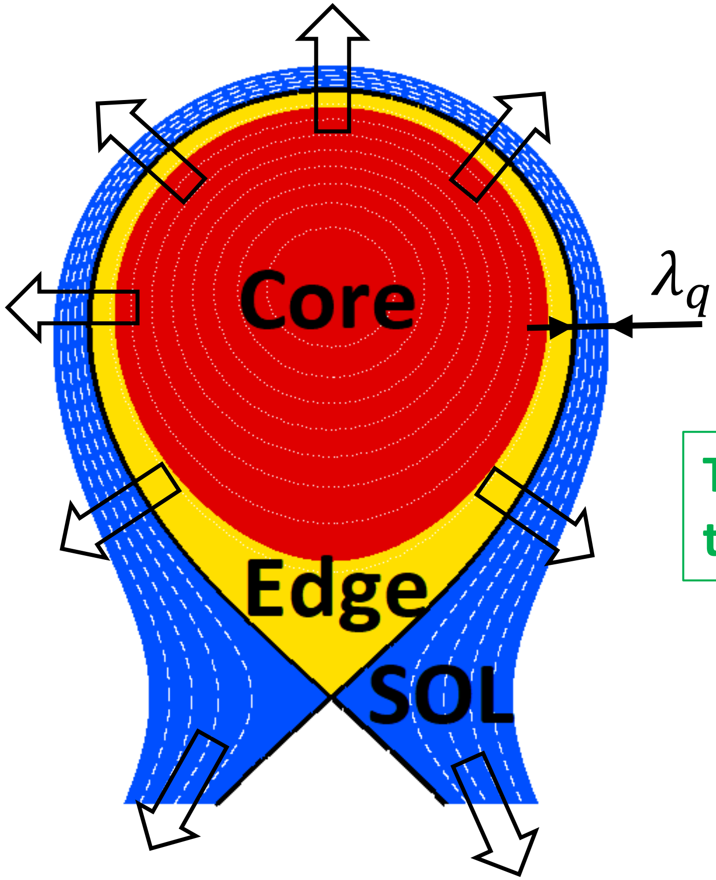




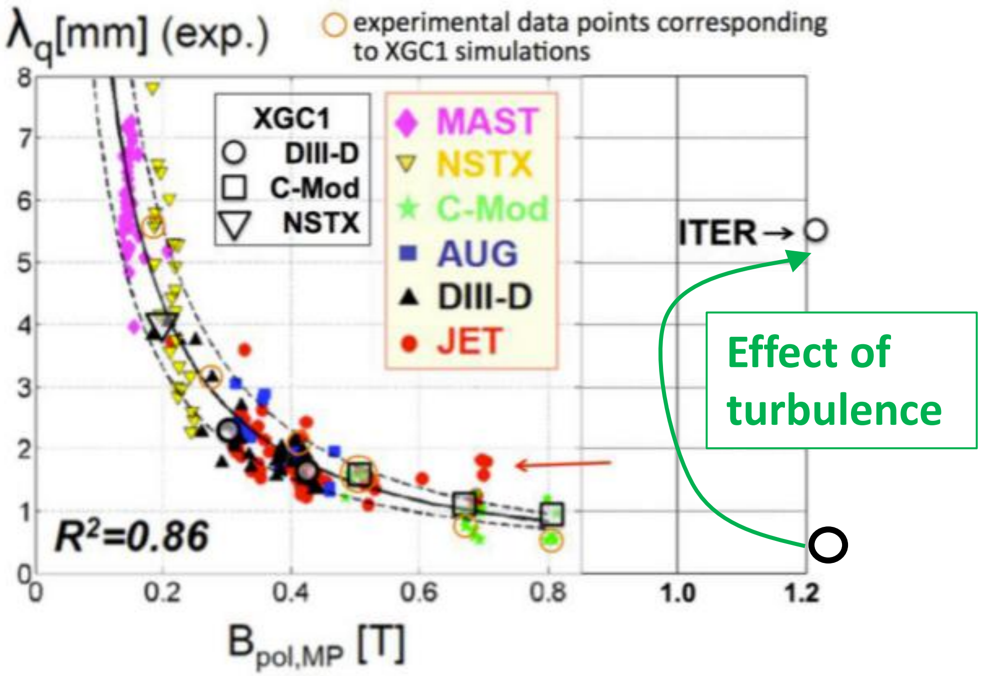
The SOL width determines the peak heat flux to the target

Eich et al. Nucl. Fusion 53 (2013)

Is turbulence always a bad thing?



Turbulence may widen the SOL width of ITER!



Effect of turbulence

The SOL width determines the peak heat flux to the target

Chang et al. Nucl. Fusion 57 (2017)

Turbulence plays a pivotal role in fusion plasmas

A deep understanding of turbulence dynamics in fusion plasmas is crucial for fusion performance (confinement) and material survival!

Outline

- A bit of history
  - From phenomenological theories to advanced simulations
  - The advent of gyrokinetic theory
- Applications to tokamak plasmas
  - Turbulent transport and confinement
  - Scrape-off layer turbulence
- Applications to non-axisymmetric magnetic fields
  - Boundary turbulence in reversed field pinch plasmas
- Open challenges (plasma turbulence)
  - The scrape-off layer width in future magnetic confinement fusion devices
  - The role of fast particles (alphas)

From phenomenological theories to advanced numerical simulations

Braginskii. Transport Processes in a Plasma. Reviews of Plasma Physics, 1

$$\frac{\partial n_e}{\partial t} + \operatorname{div}(n_e \mathbf{V}_e) = 0,$$

$$\frac{\partial n_i}{\partial t} + \operatorname{div}(n_i \mathbf{V}_i) = 0,$$

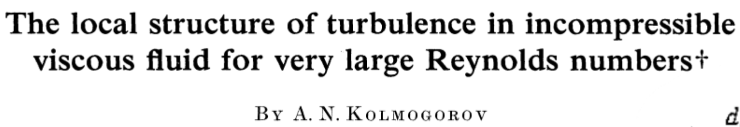
$$m_e n_e \frac{d_e V_{e\alpha}}{dt} = -\frac{\partial p_e}{\partial x_\alpha} - \frac{\partial \pi_{e\alpha\beta}}{\partial x_\beta} - e n_e \left(E_\alpha + \frac{1}{c}[\mathbf{V}_e \mathbf{B}]_\alpha\right) + R_\alpha,$$

$$m_i n_i \frac{d_i V_{i\alpha}}{dt} = -\frac{\partial p_i}{\partial x_\alpha} - \frac{\partial \pi_{i\alpha\beta}}{\partial x_\beta} + Zen_i \left(E_\alpha + \frac{1}{c}[\mathbf{V}_i \mathbf{B}]_\alpha\right) - R_\alpha,$$

$$\frac{3}{2} n_e \frac{d_e T_e}{dt} + p_e \operatorname{div} \mathbf{V}_e = -\operatorname{div} \mathbf{q}_e - \pi_{e\alpha\beta} \frac{\partial V_{e\alpha}}{\partial x_\beta} + Q_e,$$

$$\frac{3}{2} n_i \frac{d_i T_i}{dt} + p_i \operatorname{div} \mathbf{V}_i = -\operatorname{div} \mathbf{q}_i - \pi_{i\alpha\beta} \frac{\partial V_{i\alpha}}{\partial x_\beta} + Q_i.$$

Kolmogorov. Dokl. Akad. Nauk SSSR 30 (1941) 301



The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers†

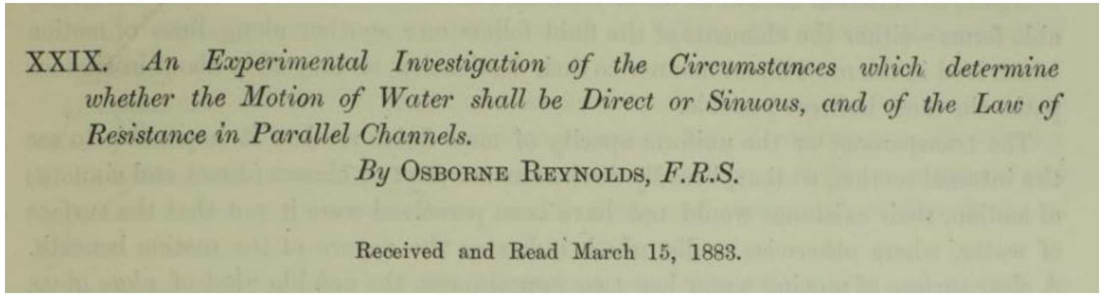
By A. N. Kolmogorov

1941

1965

1883

Reynolds. Philos. Trans. R. Soc. A 174 (1883) 935



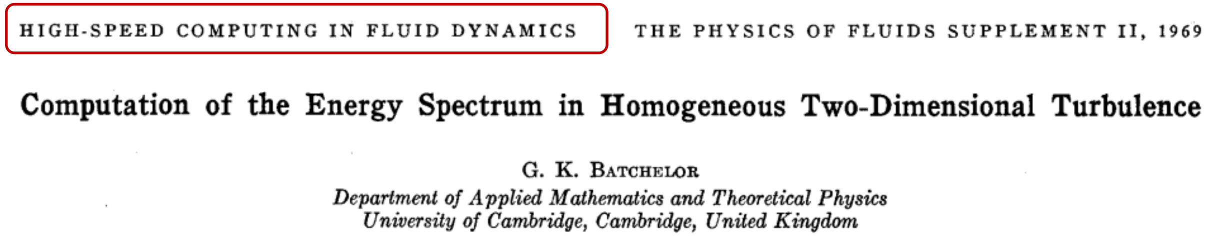
XXIX. *An Experimental Investigation of the Circumstances which determine whether the Motion of Water shall be Direct or Sinuous, and of the Law of Resistance in Parallel Channels.*

By Osborne Reynolds, *F.R.S.*

Received and Read March 15, 1883.

1969

Batchelor. Phys. Fluids 12, II-233–II-239 (1969)



HIGH-SPEED COMPUTING IN FLUID DYNAMICS

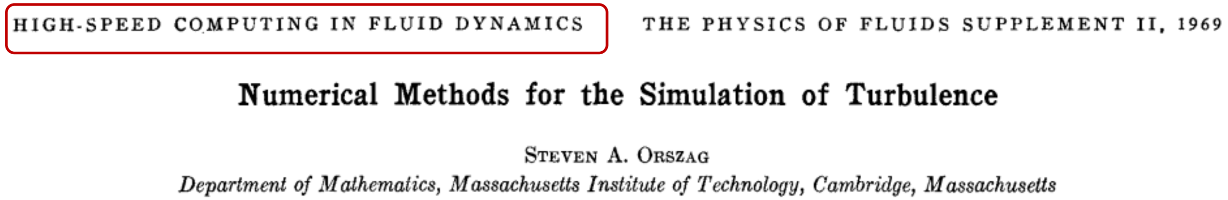
THE PHYSICS OF FLUIDS SUPPLEMENT II, 1969

Computation of the Energy Spectrum in Homogeneous Two-Dimensional Turbulence

G. K. Batchelor

Department of Applied Mathematics and Theoretical Physics
University of Cambridge, Cambridge, United Kingdom

Orszag. Phys. Fluids 12, II-250–II-257 (1969)



HIGH-SPEED COMPUTING IN FLUID DYNAMICS

THE PHYSICS OF FLUIDS SUPPLEMENT II, 1969

Numerical Methods for the Simulation of Turbulence

Steven A. Orszag

Department of Mathematics, Massachusetts Institute of Technology, Cambridge, Massachusetts

From phenomenological theories to advanced numerical simulations

The advent of the gyrokinetic theory

Frieman et al. Phys. Fluids 9, 1475–1482 (1966)
Taylor & Hastie Plasma Physics 10 (1968)
Catto. Plasma Physics 20 (1978)
Frieman & Chen Phys. Fluids 25 (1982)
Hahm. Physics of Fluids, 31 (1988)
A. Brizard. Physics of Fluids B, 1 (1989)

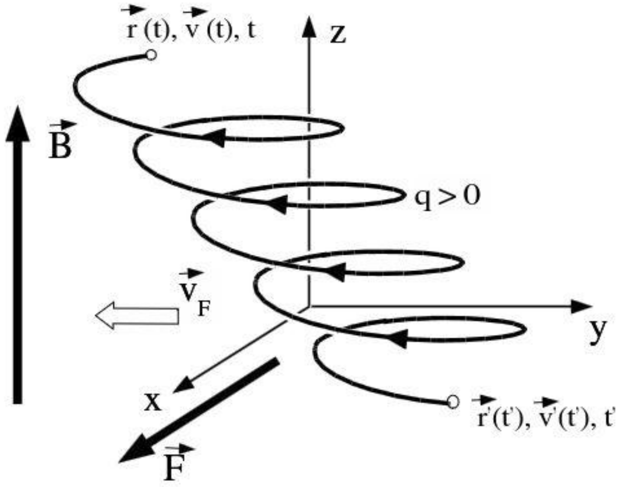
The era of drift-reduced models

Diamond et al. Phys. Fluids 28, 1116–1125 (1985)
Scott et al. Phys. Fluids 28, 275–277 (1985)
Biskamp et al. Phys. Rev. Lett. 76 (1996)
Zeiler et al. Physics of Plasmas 4 (1997)
Rogers & Drake. Phys. Rev. Lett. 79 (1997)

Nonlinear gyrokinetic simulations

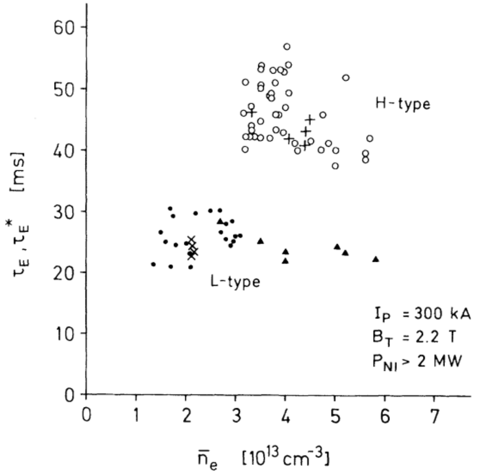
Jenko et al. Phys. Plasmas 7 (2000)
W. Dorland et al. Phys. Rev. Lett. 85 (2000)

1970s 1980s 1990s 2000s



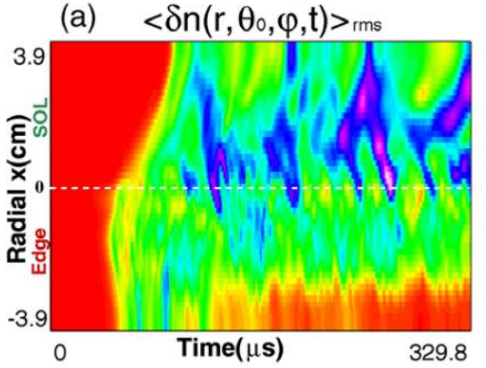
H-mode discovery

Wagner et al. Phys. Rev. Lett. 49 (1982)

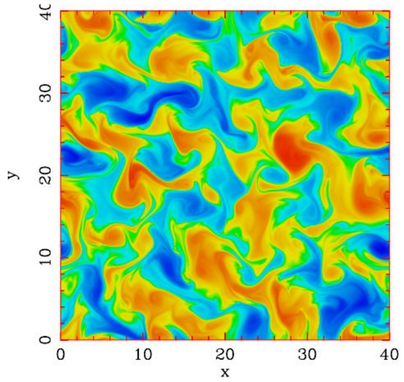


Nonlinear two-fluid simulations

Xu et al. New J. Phys. 4 (2002)



Naulin New J. Phys. 4 (2002)



From phenomenological theories to advanced numerical simulations

Teraflops

Two-fluid tokamak simulations
Local gyrokinetic simulations
Global δf GK simulations

Petaflops

Two-fluid stellarator simulations
Fluid + neutrals simulations
Global δf GK simulations
Global full-f GK simulations (core)

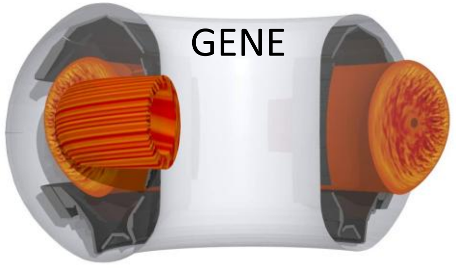
Exaflops

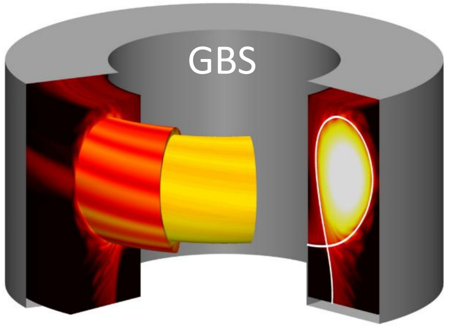
Global full-f GK simulations of the whole device
Two-fluid simulations with neutrals, impurities, …

Artificial Intelligence

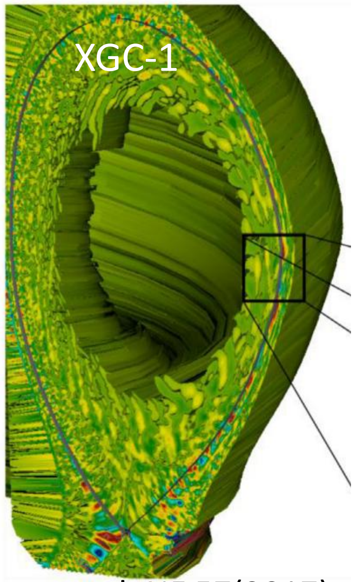
Surrogate models for turbulence
Digital twins
Advanced tools for data analysis
…

2010s 2020s 2030s

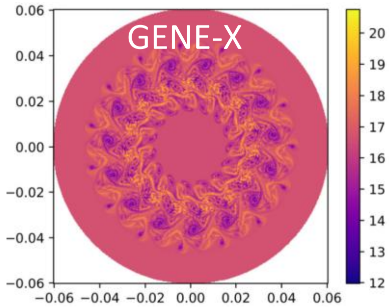




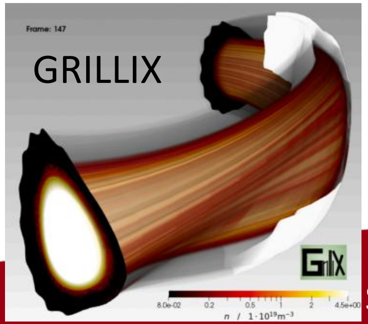
Giacomin et al. JCP 463 (2022)



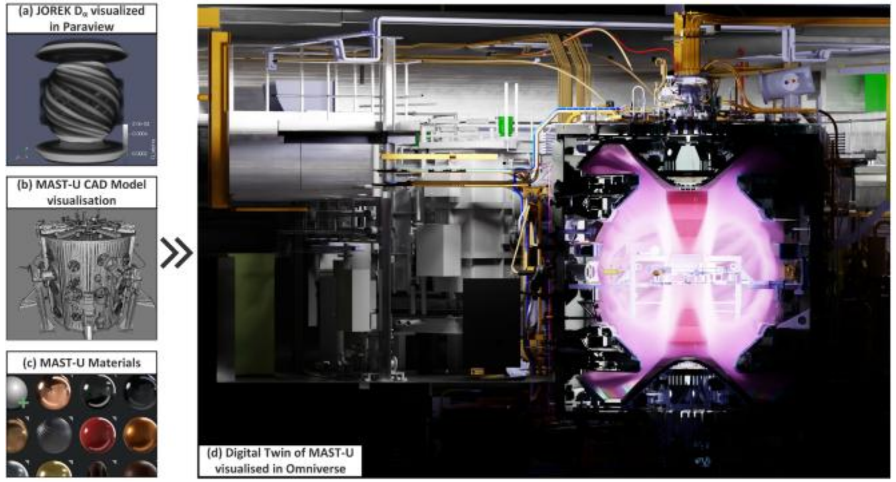
Chang et al. NF 57(2017)



Michels et al. CPC 264 (2021)



Stegmeir et al. CPC 318 (2026)



N. Bathia et al. AIP Advances 15 (2025)

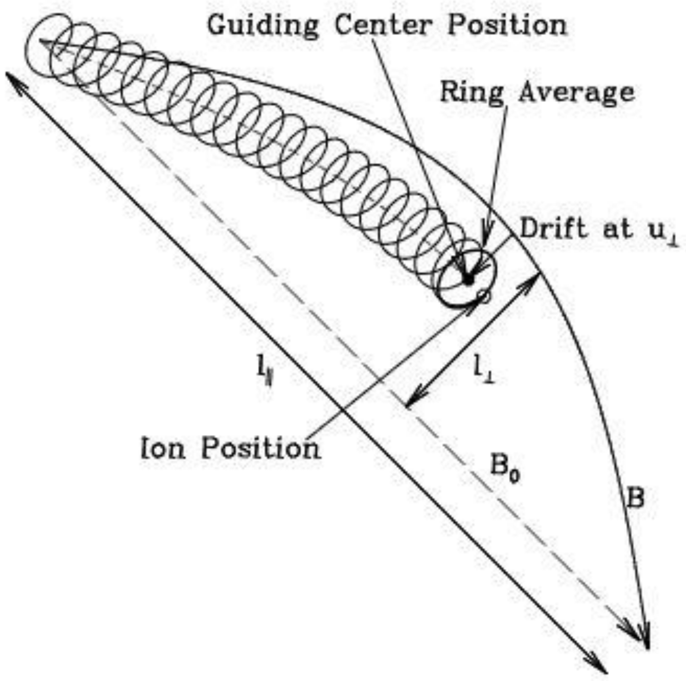
The advent of gyrokinetics: a change of paradigm

- Plasma dynamics described by the kinetic equation

$$\frac{\partial f_s}{\partial t} + \vec{u}\cdot\frac{\partial f_s}{\partial \vec{x}} + \frac{q_s}{m_s}\left(\vec{E} + \vec{u}\times\vec{B}\right)\cdot\frac{\partial f_s}{\partial \vec{u}} = C(f_s)$$

- The Vlasov equation retains fast time scales, associated with cyclotron and plasma frequencies, and small spatial scales, associated with the Debye length.
- Turbulence in fusion plasma develops on longer time scales and larger spatial scales.
- Gyrokinetic ordering:
  - Slow temporal variation with respect to gyromotion: $\omega/\Omega \ll 1$
  - Large separation between macroscopic scale and Larmor radius: $\rho/L \ll 1$
  - Strong anisotropy: $k_\parallel/k_\perp \ll 1$
- A major speedup:
  - Remove plasma frequency: $\omega_{pe}/\Omega_i \sim m_i/m_e$
  - Remove Debye length scale: $(\rho_i/\lambda_{De})^3 \sim (m_i/m_e)^{3/2}$
  - Average over fast ion gyration: $\Omega_i/\omega \sim 1/\rho_*$
  - Field-aligned coordinates: $L_\parallel/L_\perp \sim 1/\rho_*$

$$\left.\begin{array}{l}\times 10^3\\ \times 10^5\\ \times 10^3\\ \times 10^3\end{array}\right\}\times 10^{14}$$

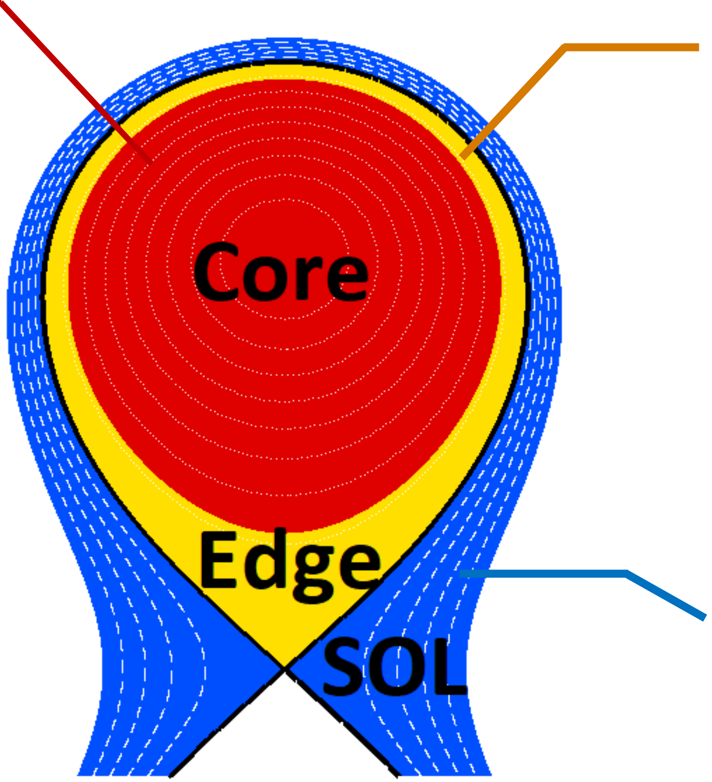


This factor enabled kinetic simulations in realistic magnetic confinement fusion device geometry!

Outline

- A bit of history
  - From phenomenological theories to advanced simulations
  - The advent of gyrokinetic theory
- Applications to tokamak plasmas
  - Turbulent transport and confinement
  - Scrape-off layer turbulence
- Applications to non-axisymmetric magnetic fields
  - Boundary turbulence in reversed field pinch plasmas
- Open challenges (plasma turbulence)
  - The scrape-off layer width in future magnetic confinement fusion devices
  - The role of fast particles (alphas)

Turbulence simulations in fusion plasmas



Low collisionality: turbulence dynamics is described with gyrokinetic models

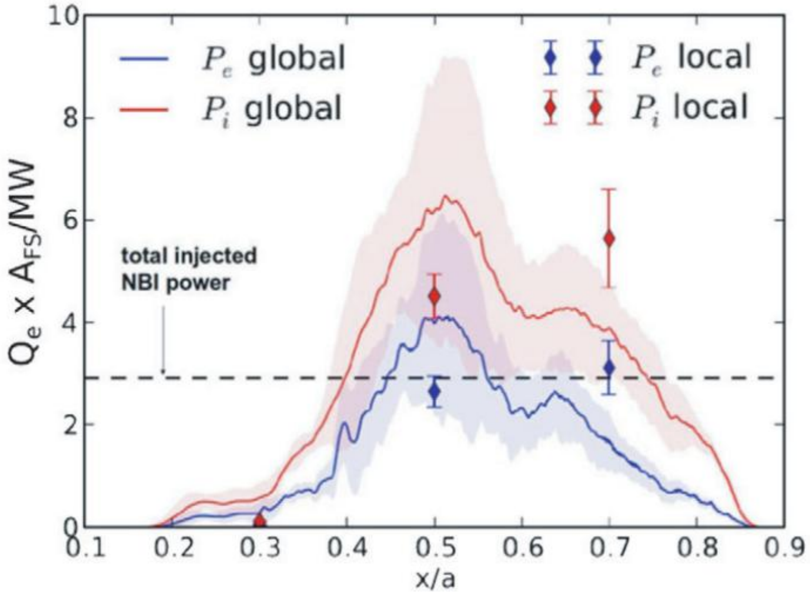
Difficult region: large gradients, intermediate collisionality, edge-localized modes, etc.

High collisionality: turbulence dynamics is often described with two-fluid models. GK boundary codes are recent

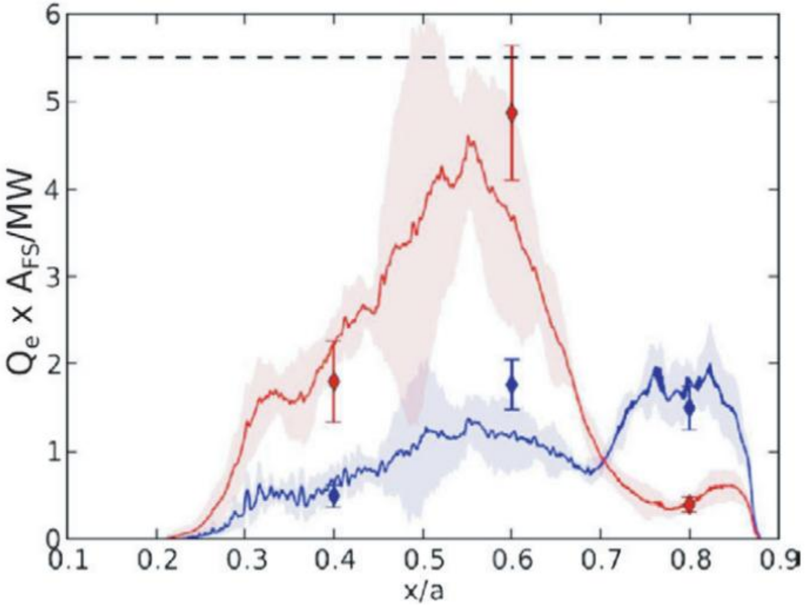
Global vs local

- Local gyrokinetic: "δf" ($\delta f / F_0 \ll 1$), $\rho_* = \rho_L / L \ll 1$, radial variation of parameters are neglected (i.e., both n_0 and dn_0/dr are constant), domain periodic in the radial direction.
- Global gyrokinetic: "δf" or full-f ($f = F_0 + \delta f$), radial profile variation, need of boundary conditions in the radial direction.

ASDEX-Upgrade ($\boldsymbol{\rho_* \simeq 0.0027}$)



JET ($\boldsymbol{\rho_* \simeq 0.0014}$)

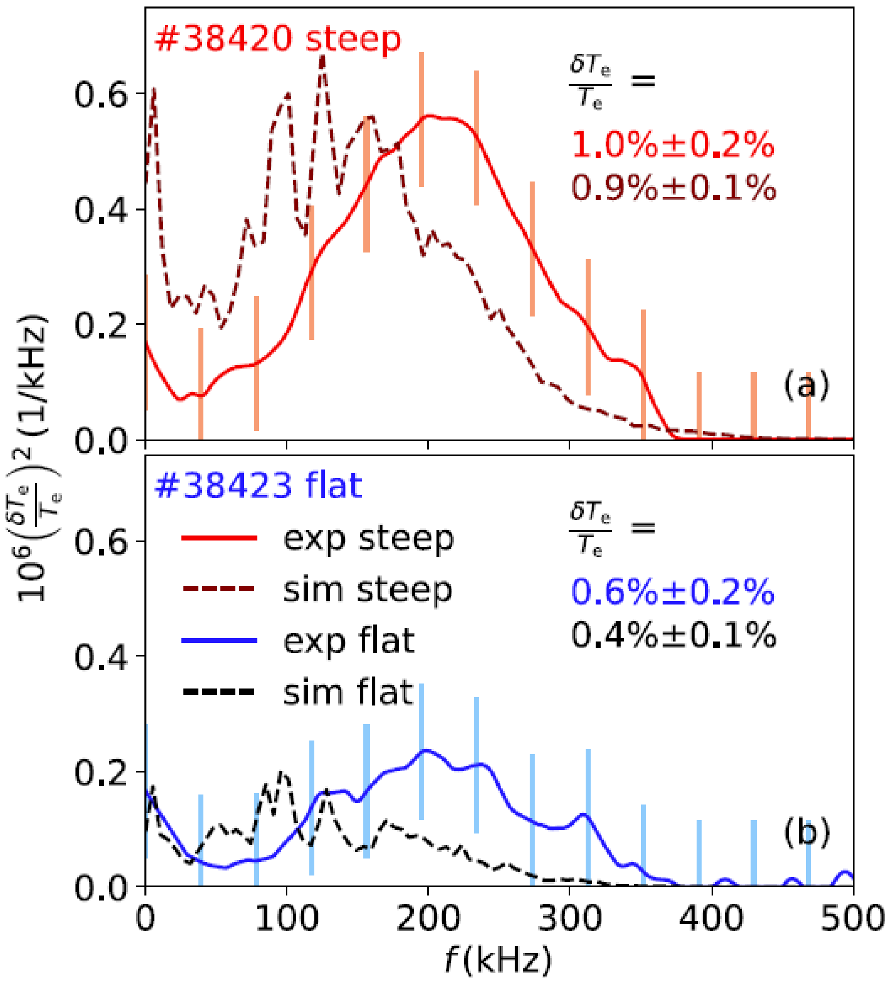


Jenko et al. Nucl. Fusion 53 (2013)

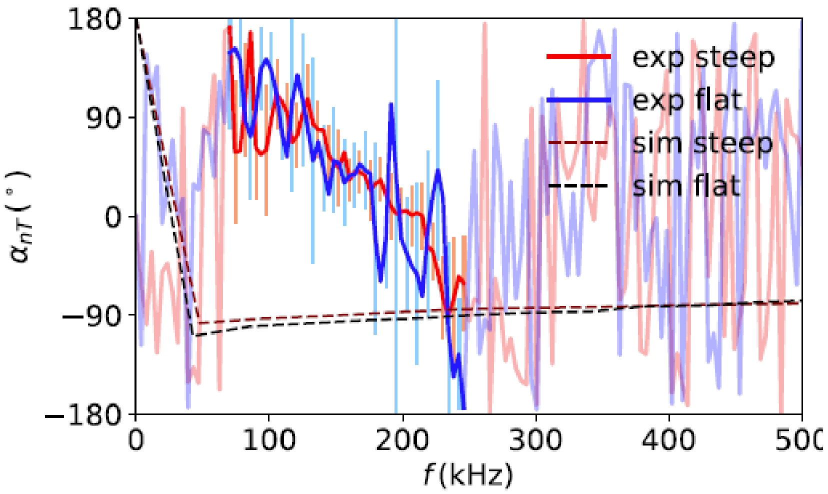
Local gyrokinetic usually sufficient ($\rho_* \ll 1$), but energetic particle modes and tearing modes enhance global effects.

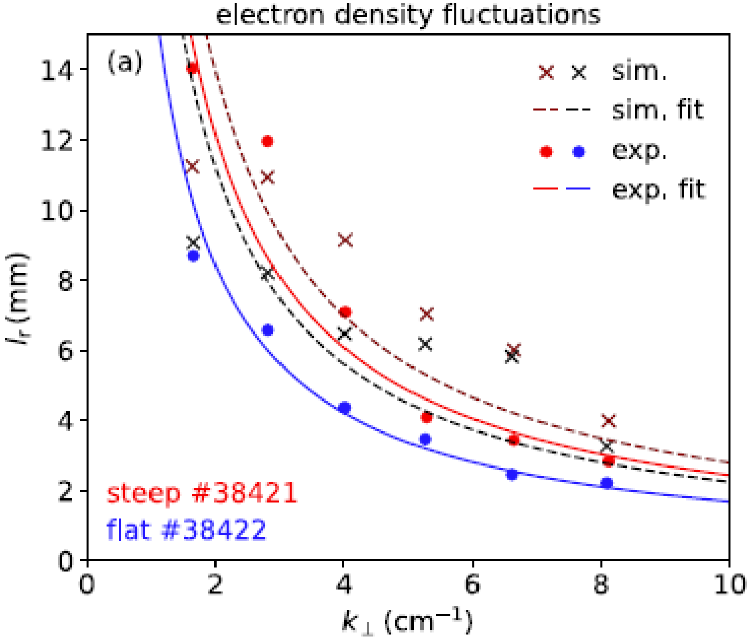
Experimental validation (not only fluxes!)

Fluctuation amplitude



Cross-phase between δT_e and δn_e





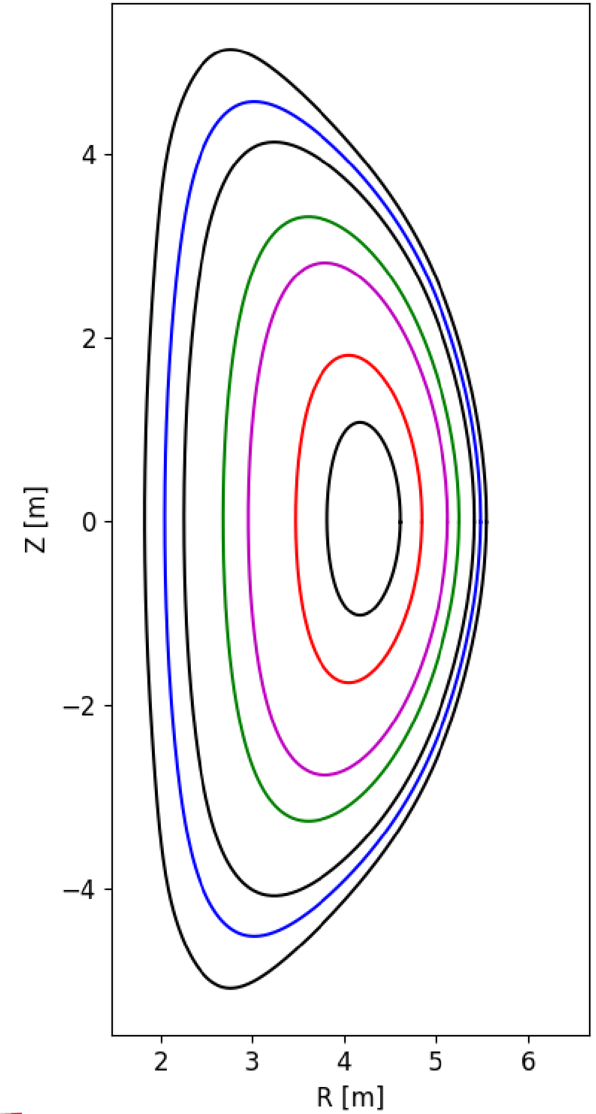
Radial correlation length

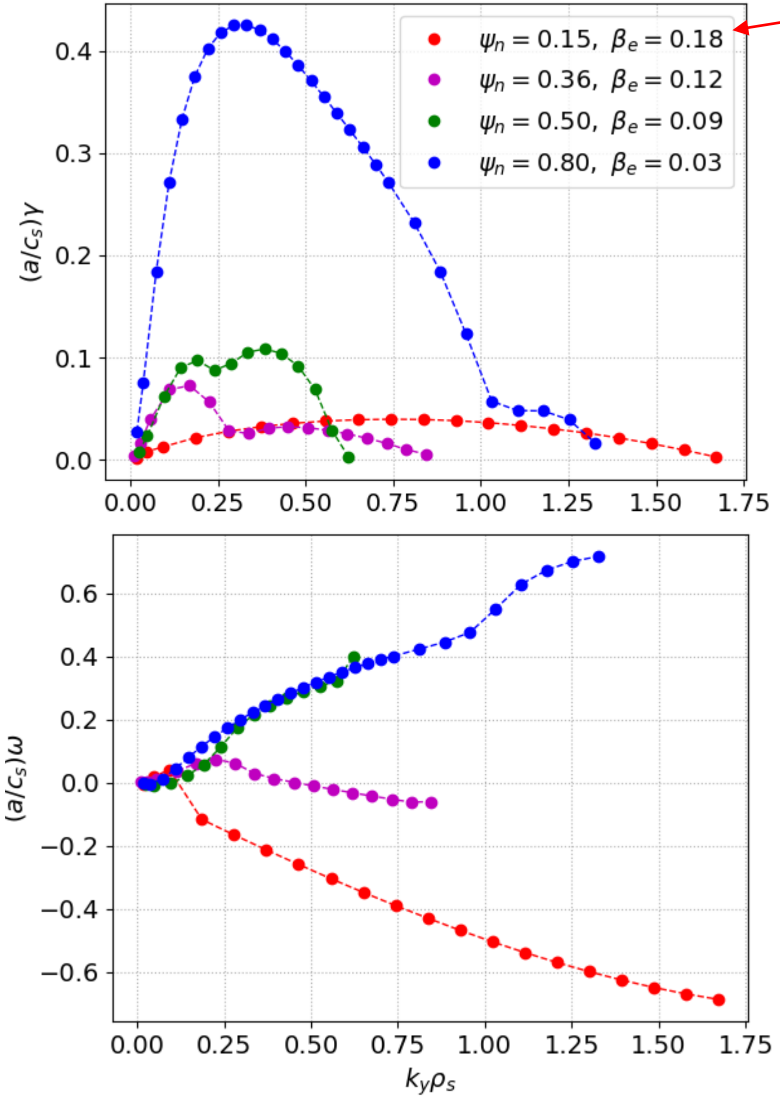
Laboratory plasmas offer a great framework for model validation!

Höfler et al. Nature Communications 16 (2025)

An extremely high-β case in fusion plasma

A proposed scenario for the Spherical Tokamak for Energy Production (STEP)





$\beta \simeq 40\ \%$

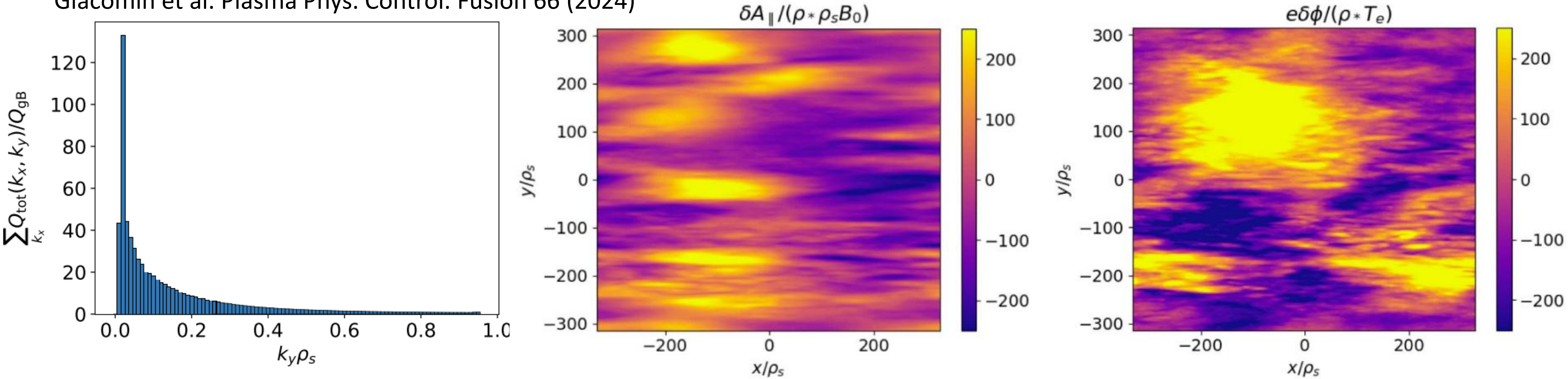
- An ambitious UK project to demonstrate technological feasibility of fusion power plant by 2040.
- Based on the high-β spherical tokamak concept.
- Gyrokinetic analysis of a proposed plasma scenario (flat-top) shows electromagnetic microinstability (kinetic ballooning modes and microtearing modes).
- Typical microinstabilities in high-β fusion plasmas (but not only).

Giacomin et al. J. Plasma Phys. 91 (2025)

High-β operation is beneficial for fusion performance but difficult to achieve

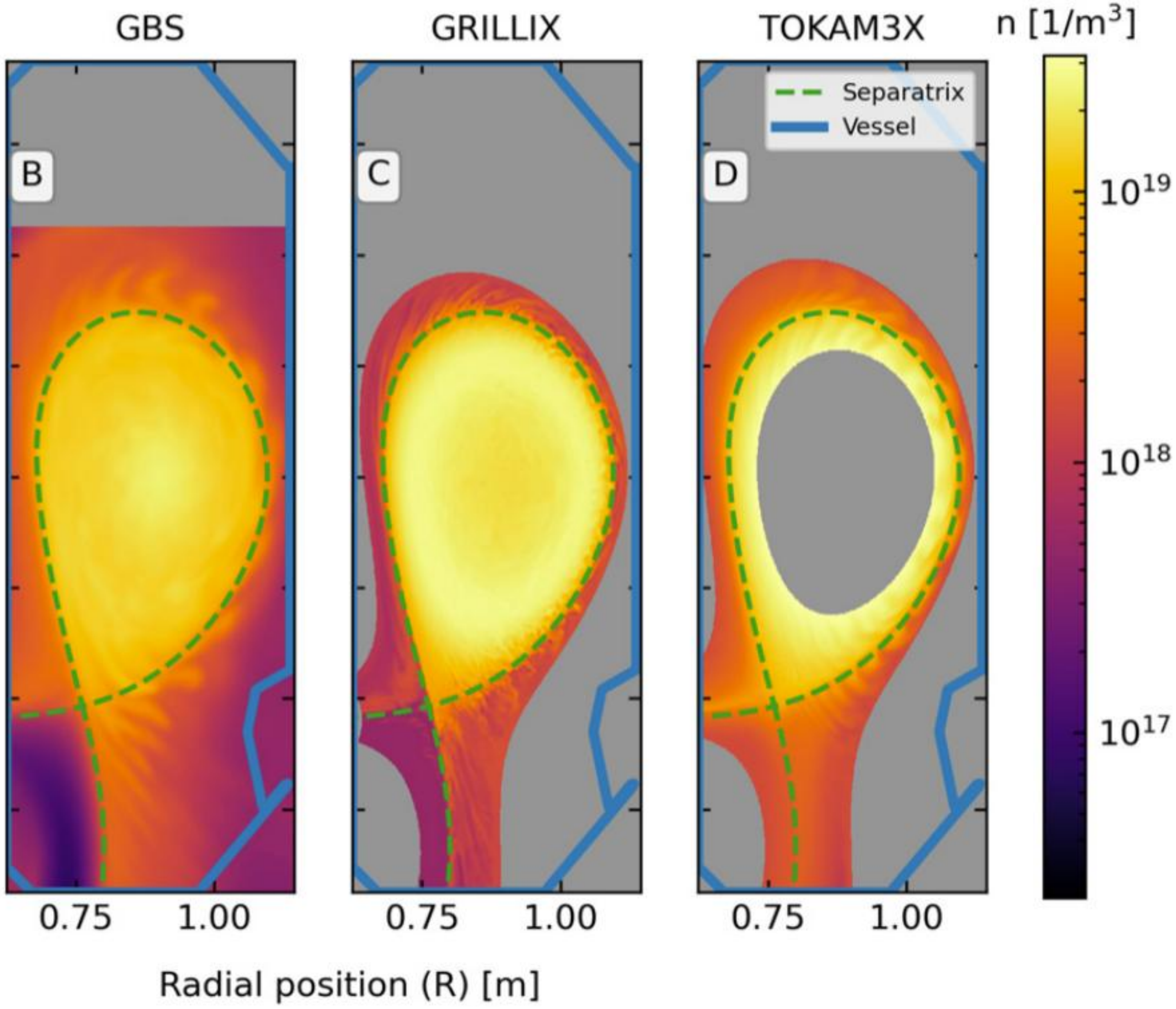
Large β values drive large scale magnetohydrodynamic instabilities as well as strong electromagnetic microinstabilities

Giacomin et al. Plasma Phys. Control. Fusion 66 (2024)

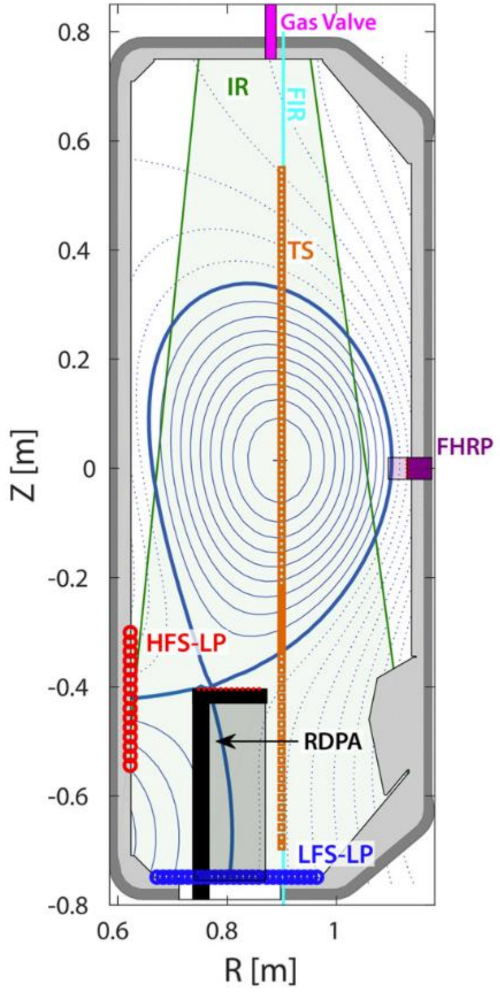


Analogy with velocity-space turbulent cascade in the Near-Sun Solar Wind [Pezzi et al. Phys. Plasmas 25 (2018); Larosa et al. Astrophys. J. Lett. 995 (2025)] under investigation [Larosa et al. in preparation]

Turbulence in the plasma boundary: cross-code comparison and validation

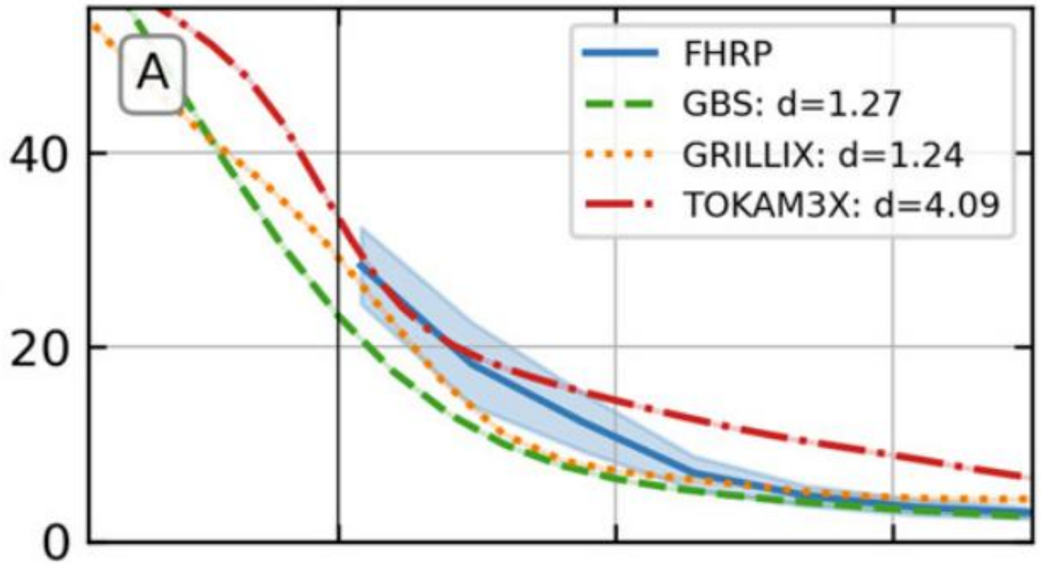


Oliveira et al. Nucl. Fusion 62 (2022)



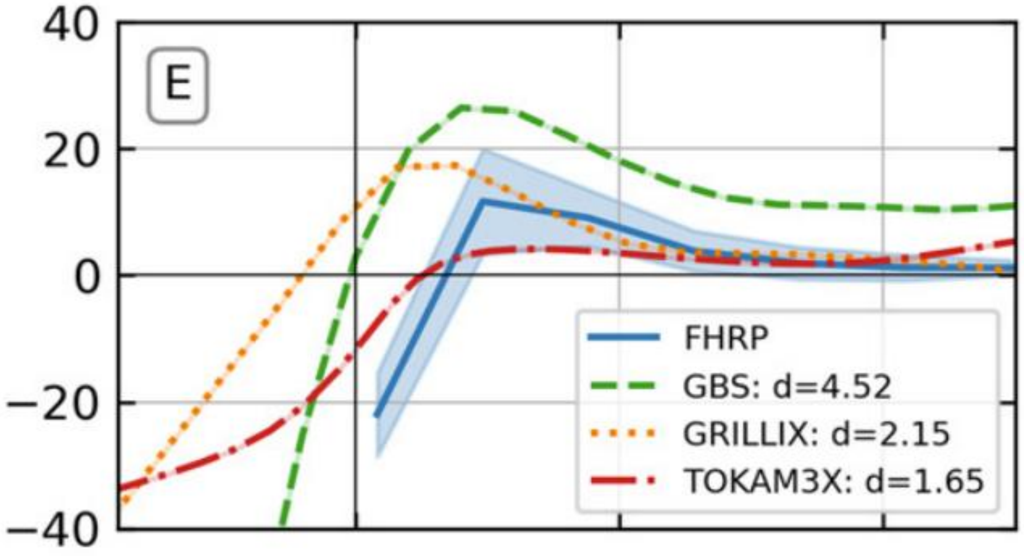
Turbulence in the plasma boundary: cross-code comparison and validation

J_{sat} **[kA/m²]**



$R - R_{sep}$ [cm]

V_f **[V]**



$R - R_{sep}$ [cm]

Reasonable agreement between code predictions and experimental data, but discrepancy across codes arises from different numeric and boundary conditions!

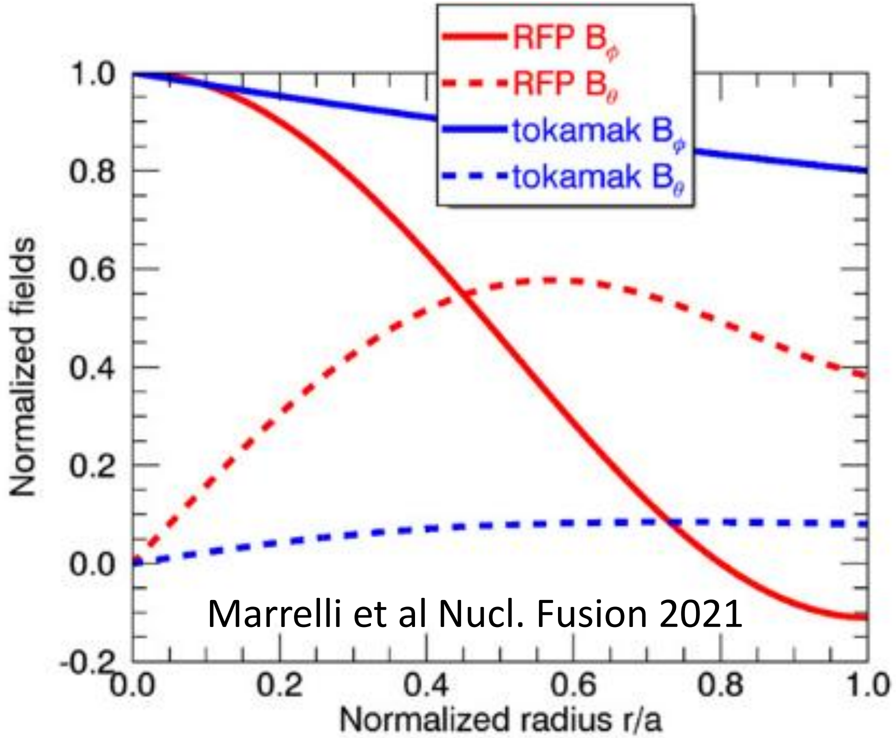
Oliveira et al. Nucl. Fusion 62 (2022)

Outline

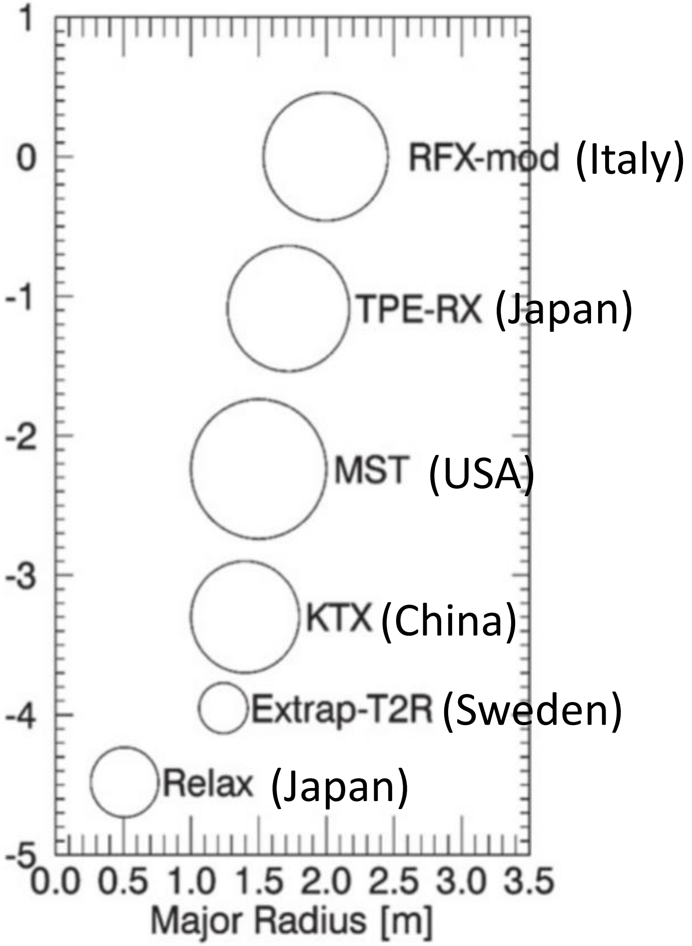
- A bit of history
  - From phenomenological theories to advanced simulations
  - The advent of gyrokinetic theory
- Applications to tokamak plasmas
  - Turbulent transport and confinement
  - Scrape-off layer turbulence
- Applications to non-axisymmetric magnetic fields
  - Boundary turbulence in reversed field pinch plasmas
- Open challenges (plasma turbulence)
  - The scrape-off layer width in future magnetic confinement fusion devices
  - The role of fast particles (alphas)

What is a Reversed Field Pinch (RFP)?

- Magnetically confined toroidal paramagnetic plasma.
- Self-organize plasma state: plasma currents generate most of the magnetic flux.
- Toroidal magnetic field reverses its direction at the plasma boundary.



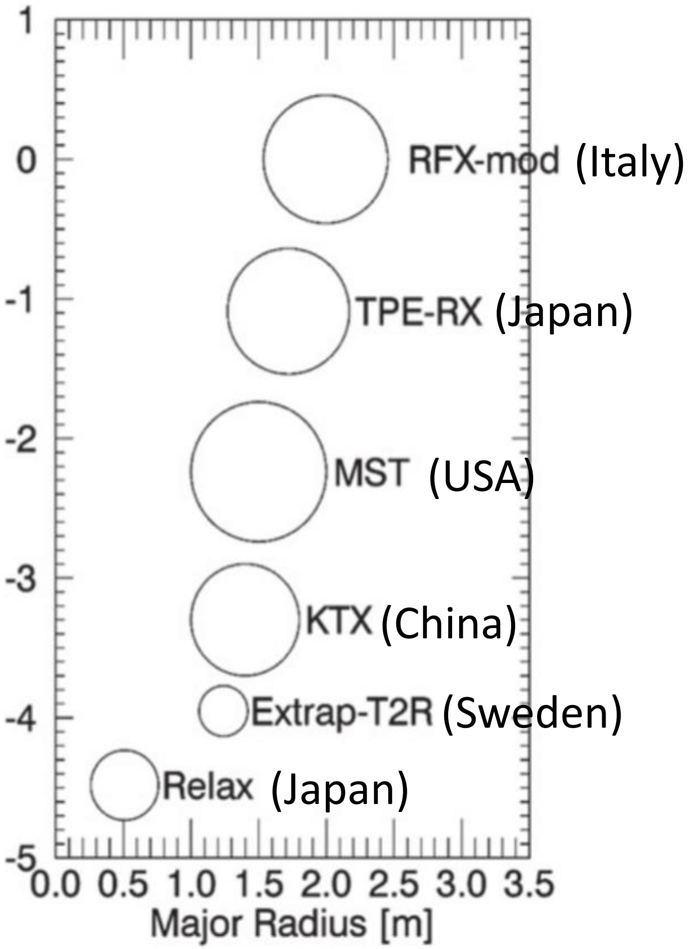
Marrelli et al Nucl. Fusion 2021



Marrelli et al Nucl. Fusion 2021

What is a Reversed Field Pinch (RFP)?

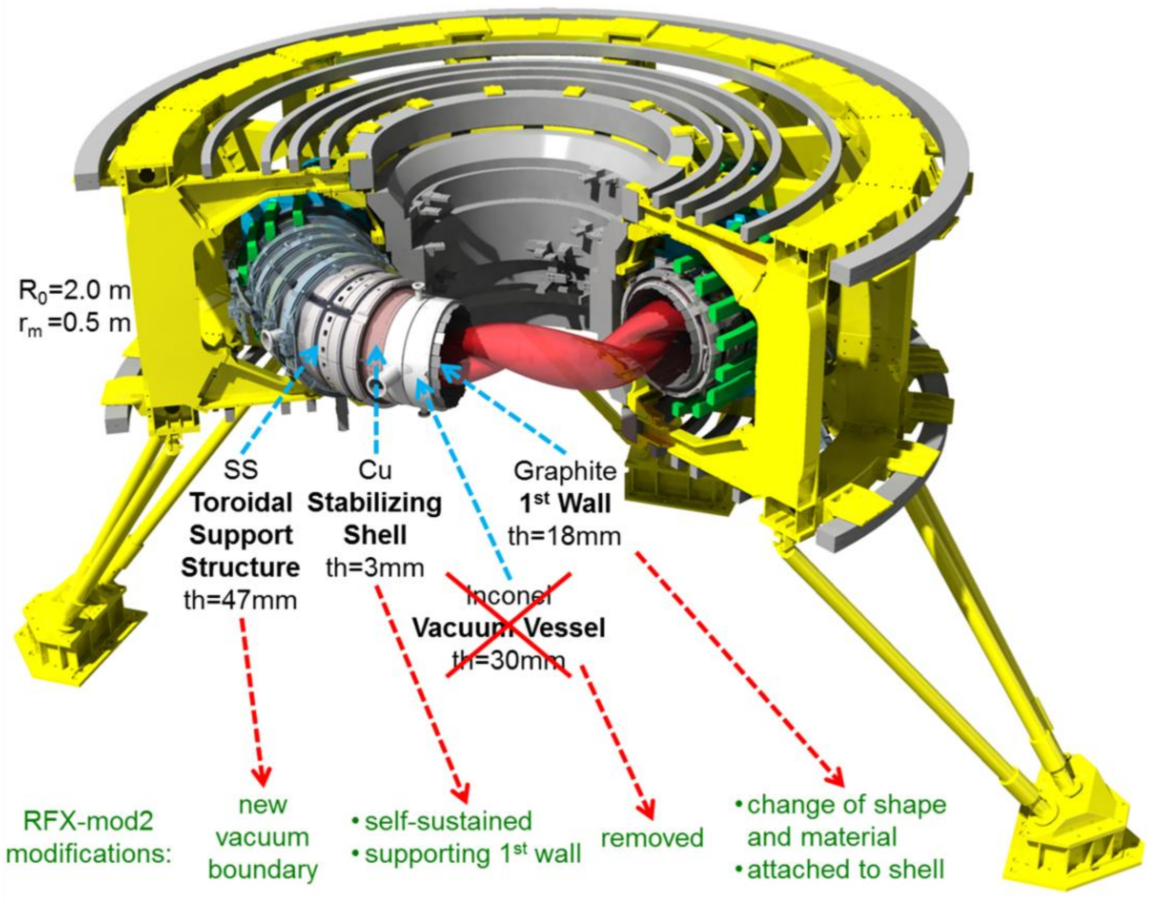
- Magnetically confined toroidal paramagnetic plasma.
- Self-organize plasma state: plasma currents generate most of the magnetic flux.
- Toroidal magnetic field reverses its direction at the plasma boundary.
- Fascinating plasma physics: magnetic reconnection, dynamo, relaxation events, turbulence and stochastic processes, etc.
- Large plasma current (Ohmic heating) and low magnetic field make RFP an interesting option for compact fusion reactors.



Marrelli et al Nucl. Fusion 2021

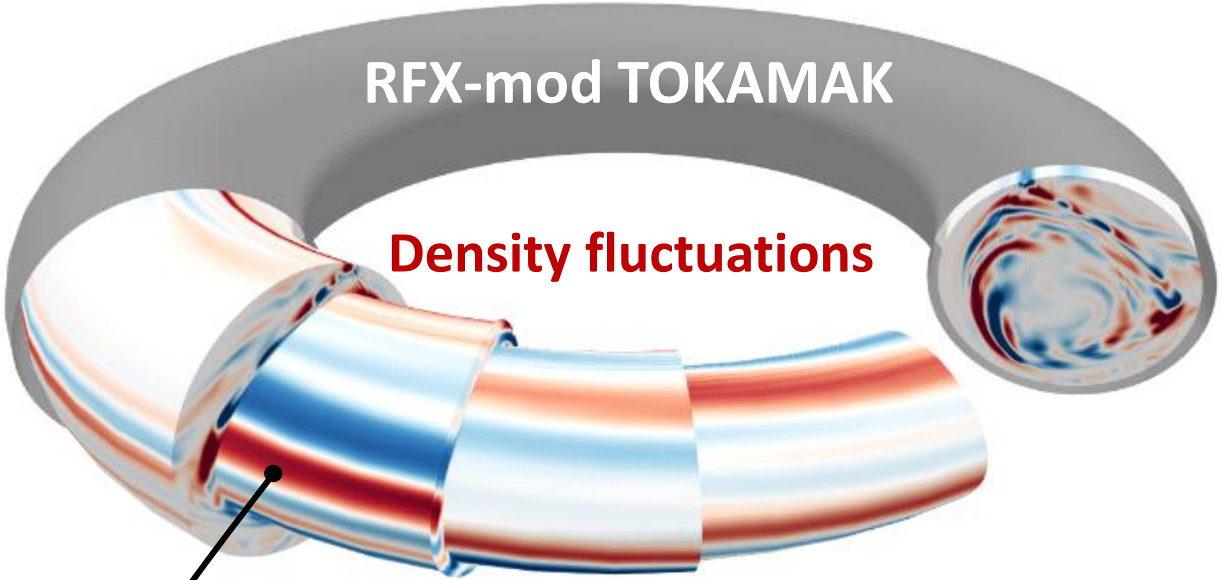
The RFX-mod(2) device

- RFX-mod is a magnetic confinement plasma toroidal device at Consorzio RFX (Padua, Italy).
- Major radius $R = 2$ m and minor radius $a = 0.46$ m.
- It operates both as RFP ($I_p = 2$ MA, quasi-single helicity [1]) and tokamak ($I_p \simeq 100$ kA, L-mode and H-mode [2]).
- After a significant machine upgrade, RFX-mod2 [3] is about to start operations in a few month time!
- New diagnostics are being installed to characterize boundary plasma turbulence [4].

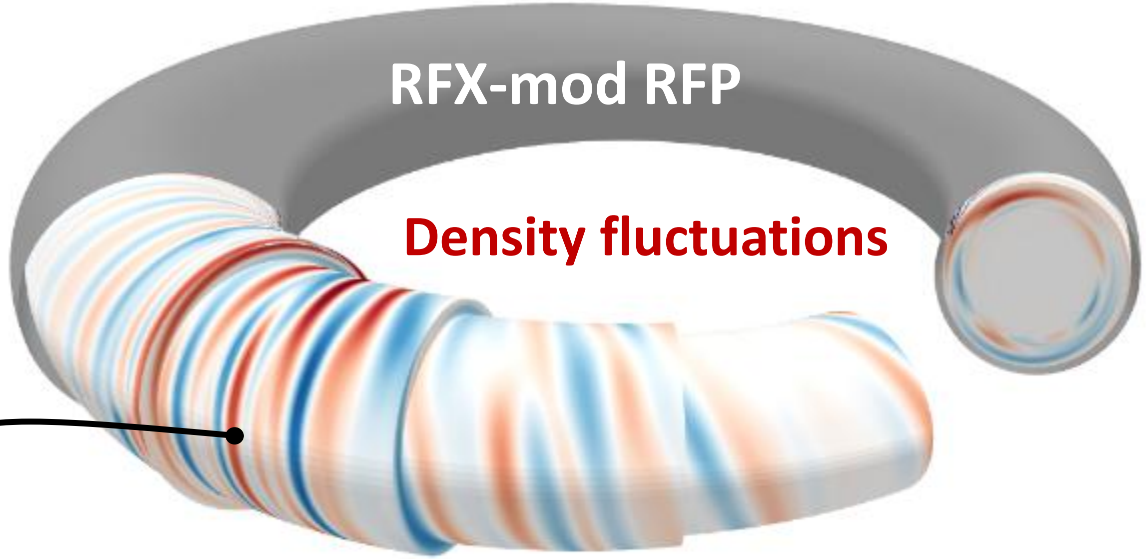


[1] Lorenzini et al Nat. Physics 2009.
[2] Spolaore et al 2017 Nucl. Fusion 57.
[3] Peruzzo et al 2023 Fusion Eng. Des. 194
[4] Carraro et al 2024 Nucl. Fusion 64.

Boundary turbulence simulation in RFX-mod



Same machine but different configuration

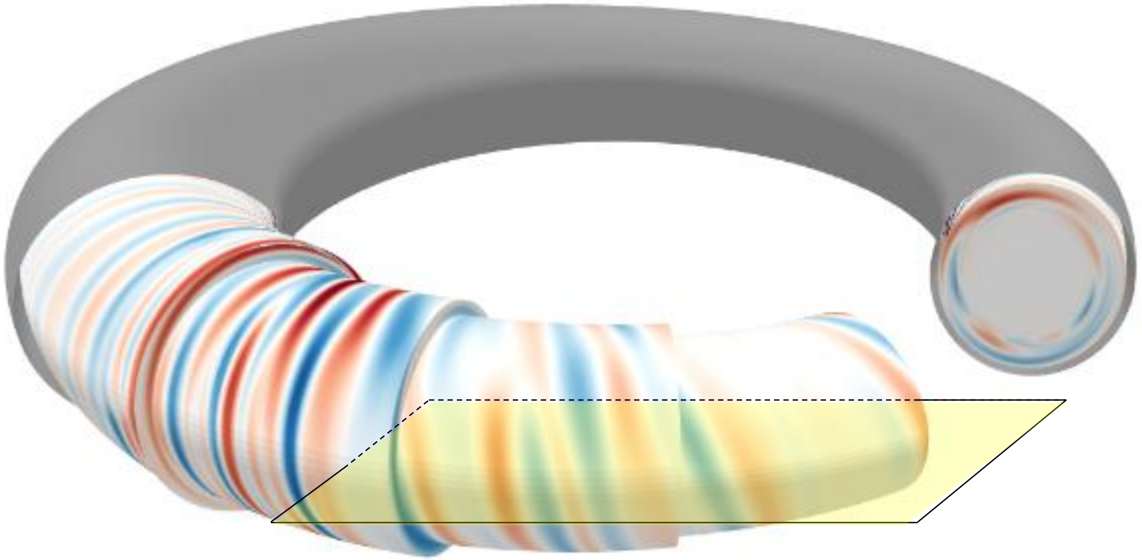


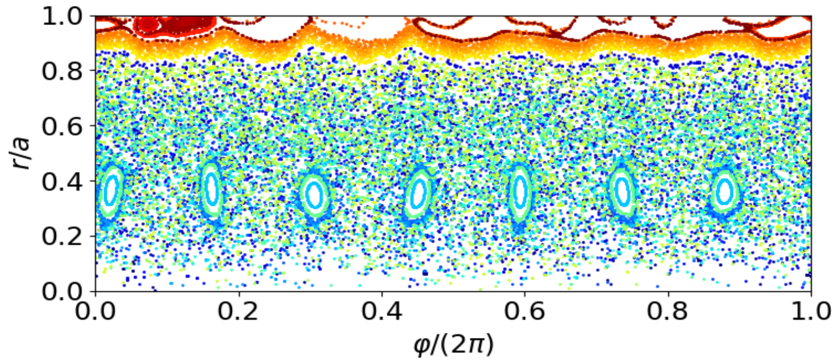
Turbulent eddies elongated along the magnetic field: toroidal in tokamak and poloidal in RFP

Giacomin et al. Commun. Phys. (2026)

Significant numerical challenges

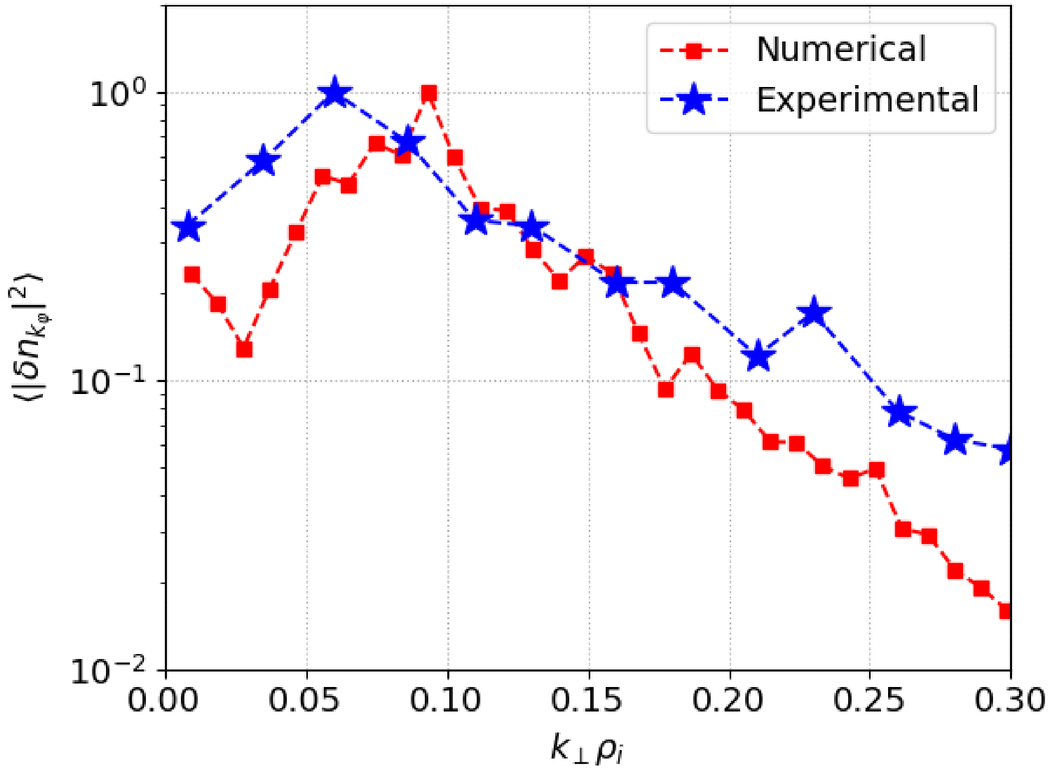
- The null of the toroidal magnetic field breaks the differential operator ordering used in many boundary turbulence code.
- Magnetic chaos disrupts conserved magnetic flux surfaces.
- Poisson and Ampère equations require three-dimensional solvers!
- High numerical resolution along all spatial directions.
- Much worse than turbulence simulations in stellarator plasmas.





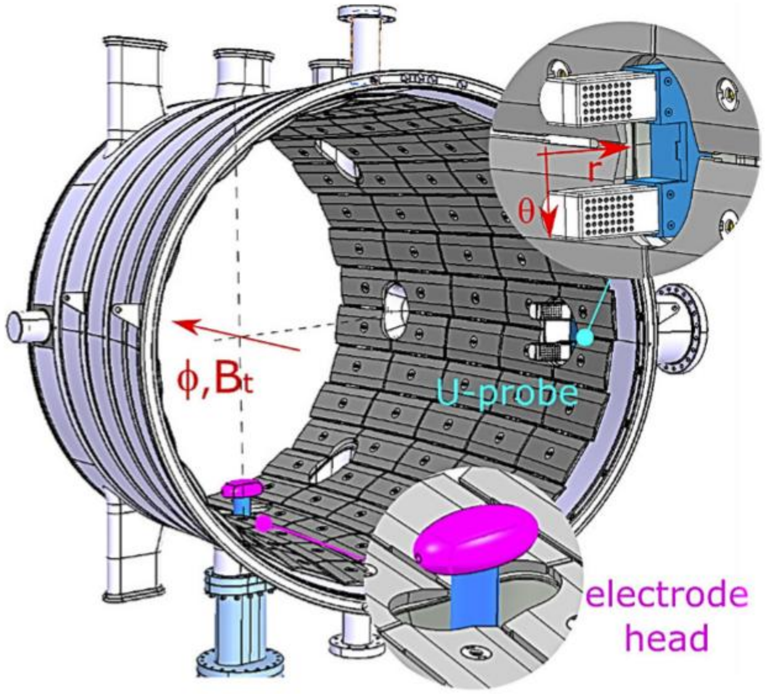
Validation against U-probe data

Experimental data from U-probe measurements
[C. Rea et al Nucl. Fusion 2015]



The maximum of the power density spectrum is reproduced quite well in the GBS simulation

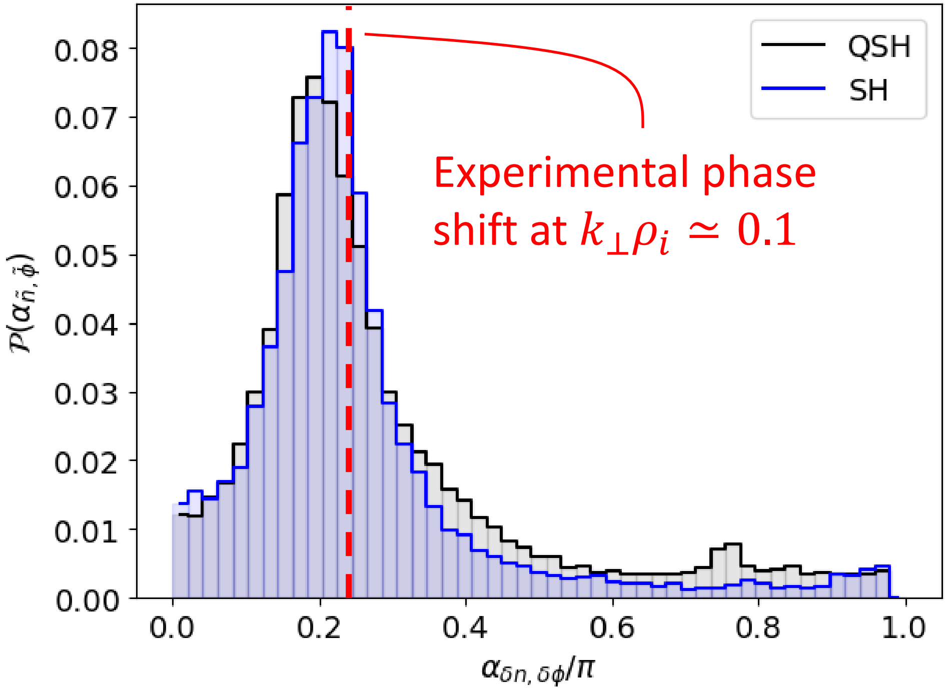
The U-probe is an insertable probe that includes 2D arrays of electrostatic and magnetic sensors.



Spolaore et al. Nucl. Fusion 2017

Validation against U-probe data

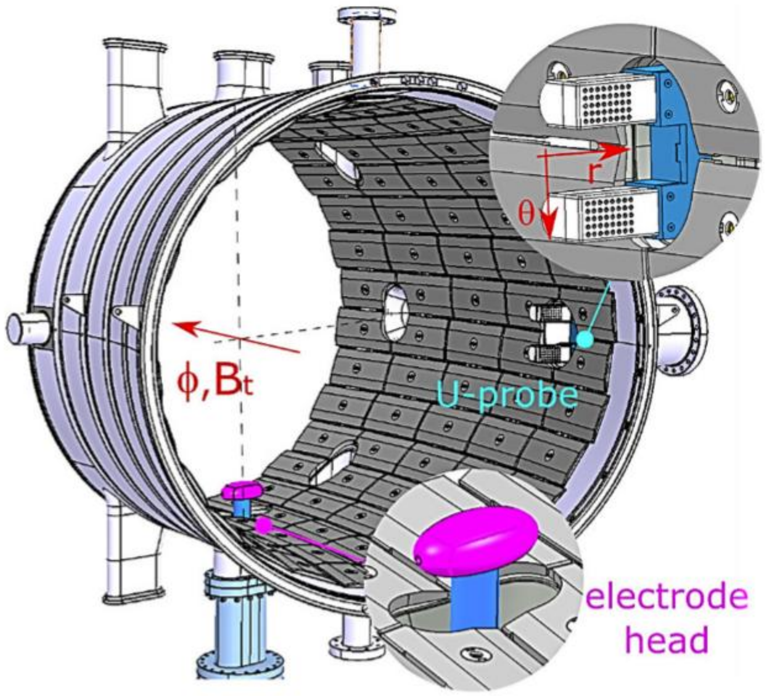
Probability distribution function of the phase shift $\alpha_{\tilde{n},\tilde{\phi}}$ between $\tilde{n}$ and $\tilde{\phi}$



Experimental phase shift at $k_\perp \rho_i \simeq 0.1$

The most probable phase shift value agrees well with experiments.

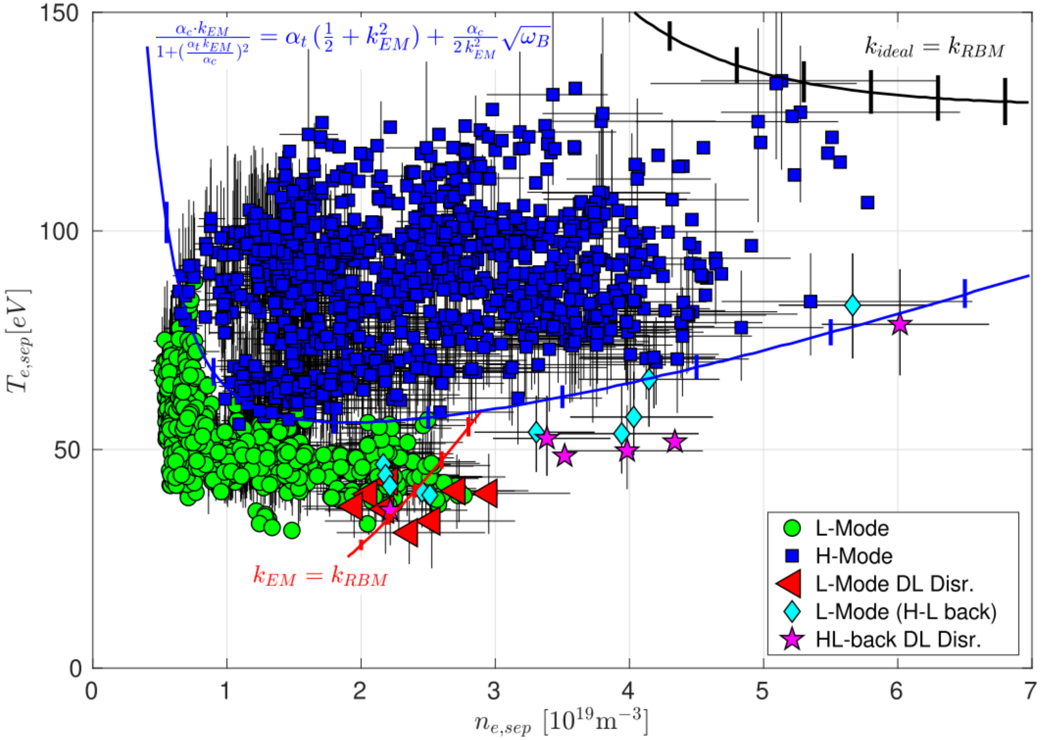
The U-probe is an insertable probe that includes 2D arrays of electrostatic and magnetic sensors.



Spolaore et al. Nucl. Fusion 2017

Not only simulations, but also analytical predictions

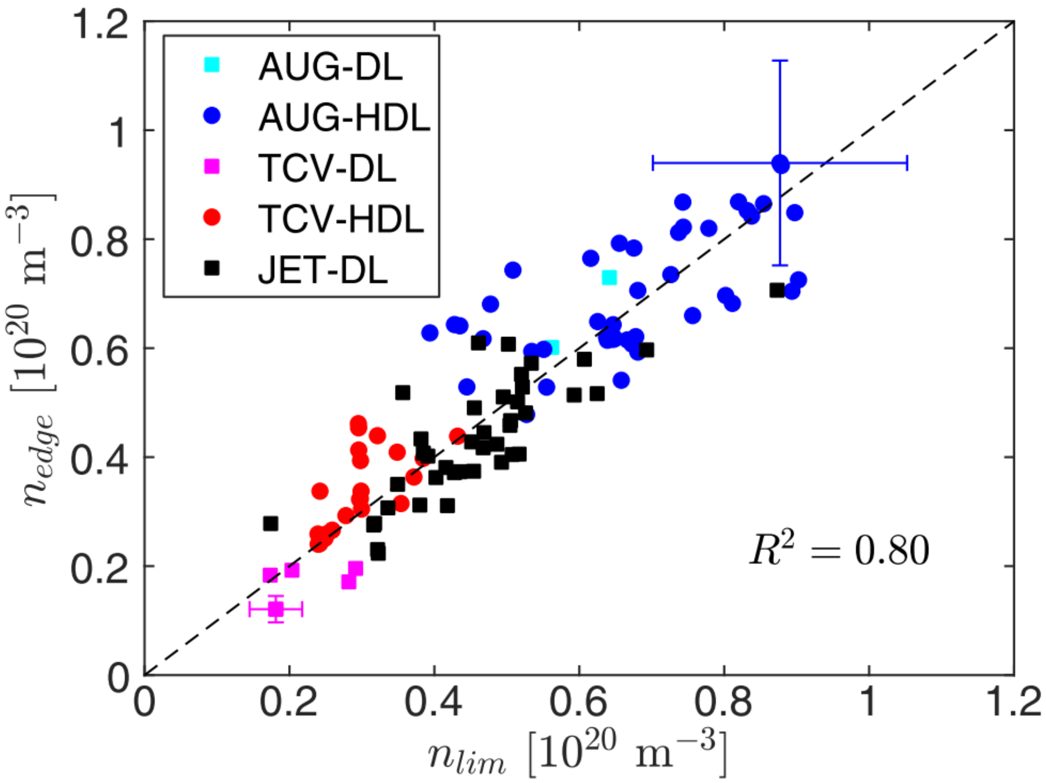
The separatrix operational space of ASDEX Upgrade



Eich et al. Nucl. Fusion 61 (2021)

Manz et al. Rev. Mod. Plasma Phys. 9 (2025)

Theory-based density limit scaling



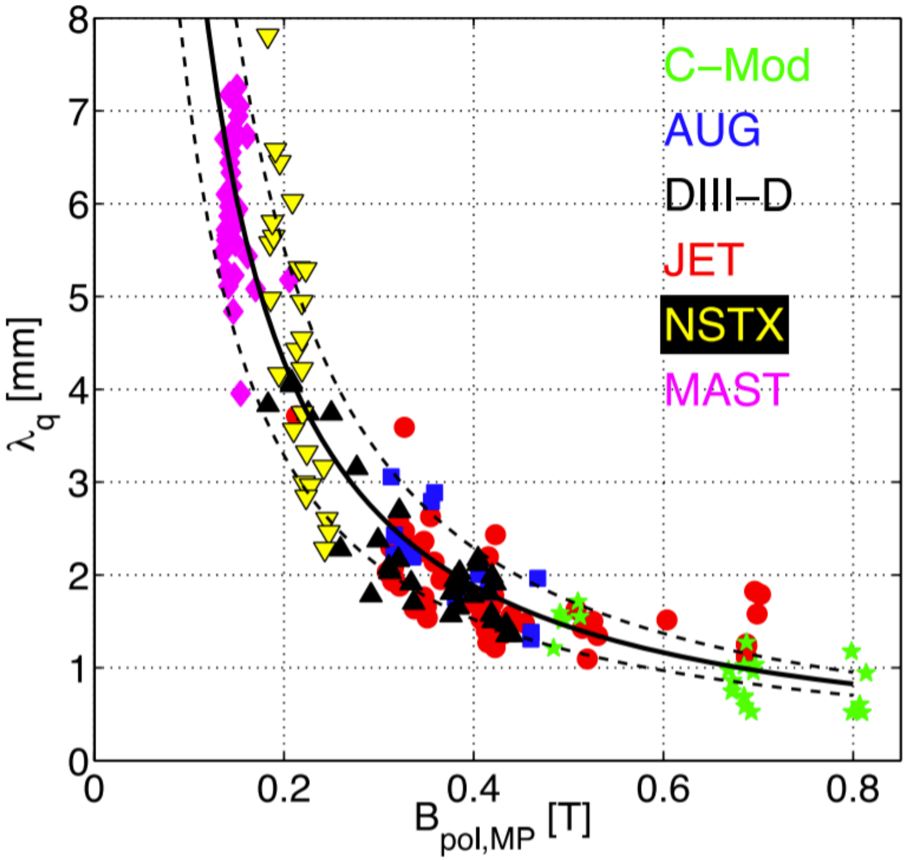
$$n_{\mathrm{lim}} \simeq 3.3 A^{1/6} a^{3/14} P_{\mathrm{SOL}}^{10/21} R^{-43/42} q^{-22/21} (1+\kappa^2)^{-1/3} B_T^{2/3}$$

Giacomin et al. Phys. Rev. Lett. 128 (2022)

Outline

- A bit of history
  - From phenomenological theories to advanced simulations
  - The advent of gyrokinetic theory
- Applications to tokamak plasmas
  - Turbulent transport and confinement
  - Scrape-off layer turbulence
- Applications to non-axisymmetric magnetic fields
  - Boundary turbulence in reversed field pinch plasmas
- Open challenges (plasma turbulence)
  - The scrape-off layer width in future magnetic confinement fusion devices
  - The role of fast particles (alphas)

The SOL width: a big unknown!



Eich et al. Nucl. Fusion 53 (2013)

- Heuristic drift-based scaling law (ion neoclassical transport) [Goldston. Nucl. Fusion 52 (2011)]

$$\lambda_q \propto B_{pol}^{-1}$$

- Multi-machine regression led to [Eich et al. Nucl. Fusion 53 (2013)]

$$\lambda_q[\mathrm{mm}] = (0.63 \pm 0.08) B_{pol}^{-1.19\pm0.08}$$

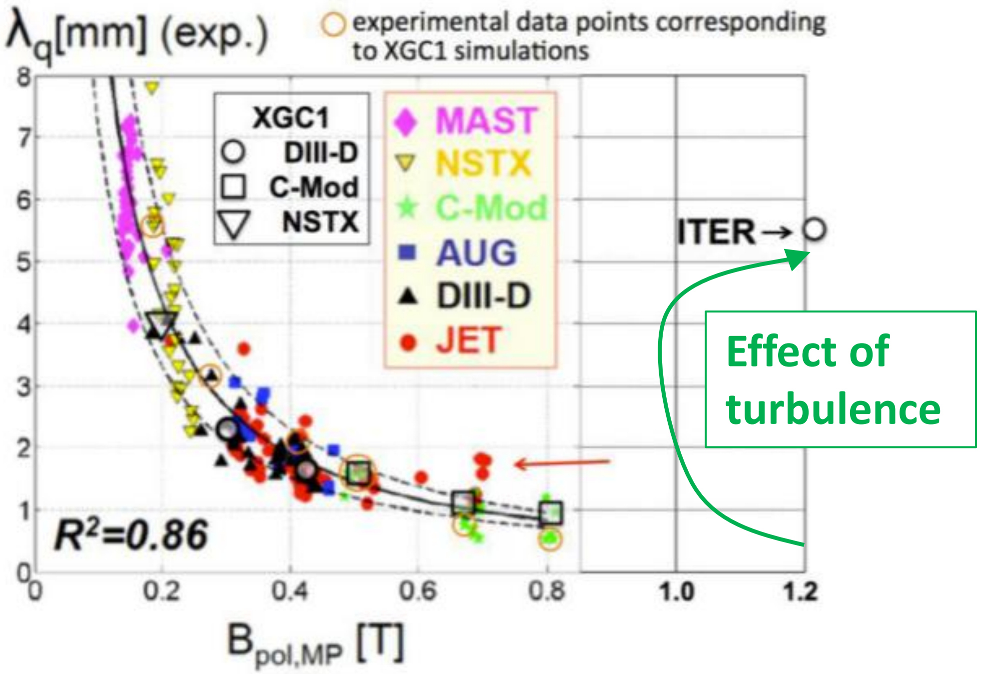
- Prediction for ITER ($I_p = 10$ MA): $\lambda_q \simeq 1$ mm

This is a huge concern for material survival!

The SOL width: a big unknown!

Strong motivation for high-fidelity SOL turbulent simulations of the ITER baseline scenario

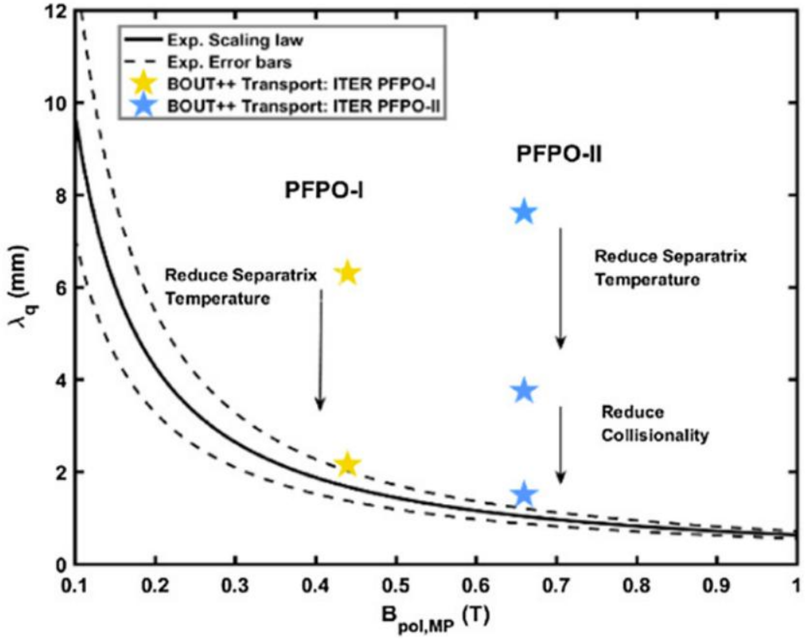
Gyrokinetic SOL simulation with the XGC1 code



Effect of turbulence

Chang et al. Nucl. Fusion 57 (2017)

Two-fluid SOL simulations with the BOUT++ code



Li et al. Nucl. Fusion 59 (2019)
He et al. Nucl. Fusion 62 (2022)

ITER prediction

$\lambda_q > 5$ **mm**

The SOL width: a big unknown!

Strong motivation for high-fidelity SOL turbulent simulations of the ITER baseline scenario

G

++ code

- Physical mechanism behind SOL width broadening predicted with the two approaches is different.
- Experimental evidence of turbulence SOL width broadening [Eich et al. 2020 Nucl. Fusion 60; Sun et al. Nucl. Fusion 63 (2023)].
- Topic still highly debated in the community.

ITER prediction
$\lambda_q > 5$ **mm**

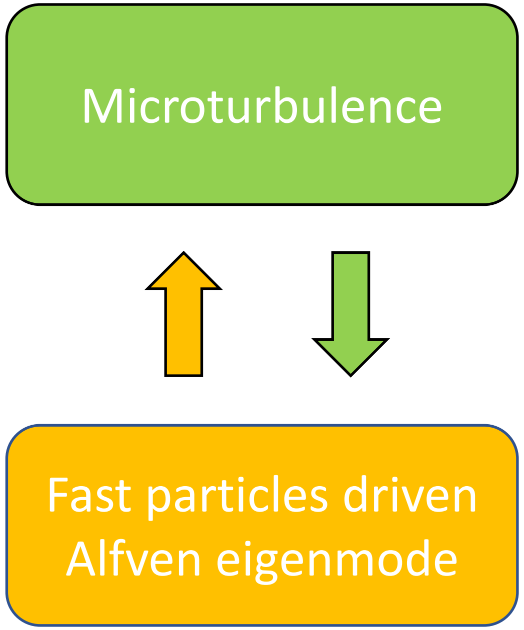
Chang et al. Nucl. Fusion 57 (2017)

Li et al. Nucl. Fusion 59 (2019)
He et al. Nucl. Fusion 62 (2022)

What is the role of fast alphas on turbulence?

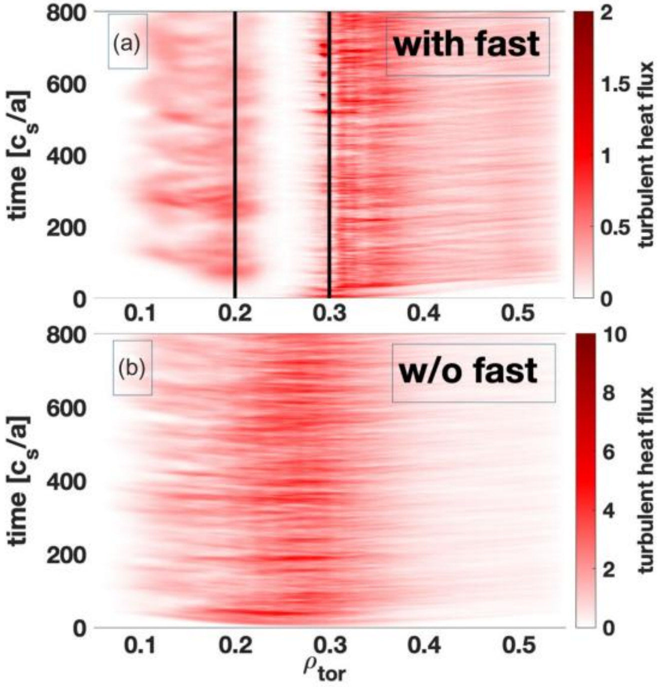
$$\mathrm{D} + \mathrm{T} \longrightarrow \alpha(3.5\,\mathrm{MeV}) + n(14\,\mathrm{MeV})$$

Fast α-particles generally stabilize microturbulence but introduce strong multiscale coupling via energetic-particle-driven modes.

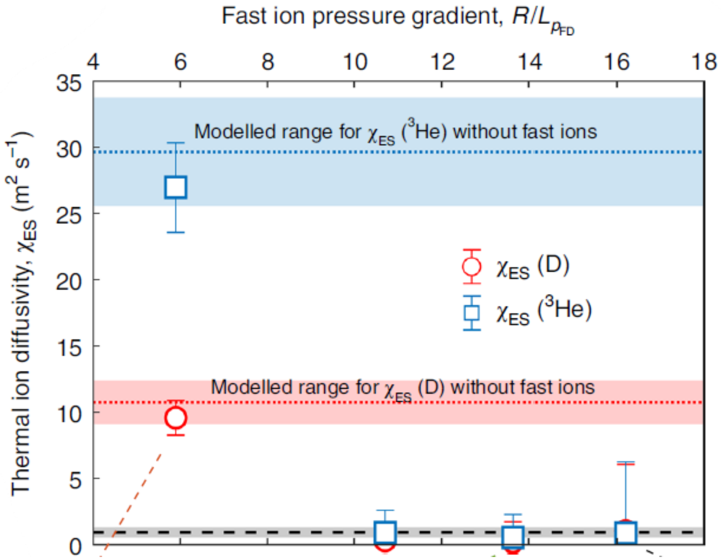


Microturbulence

Fast particles driven Alfven eigenmode



Di Siena et al. PRL 127 (2021)

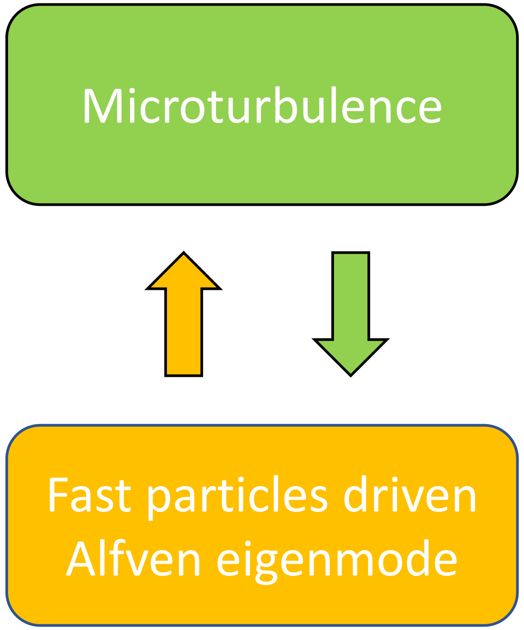


Mazzi et al. Nat. Physics 18 (2022)

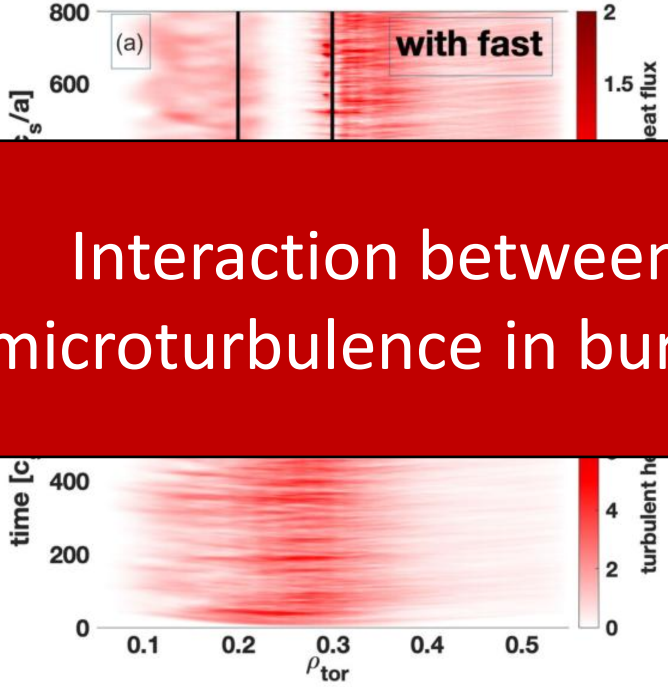
What is the role of fast alphas on turbulence?

$$\mathrm{D} + \mathrm{T} \longrightarrow \alpha(3.5\,\mathrm{MeV}) + n(14\,\mathrm{MeV})$$

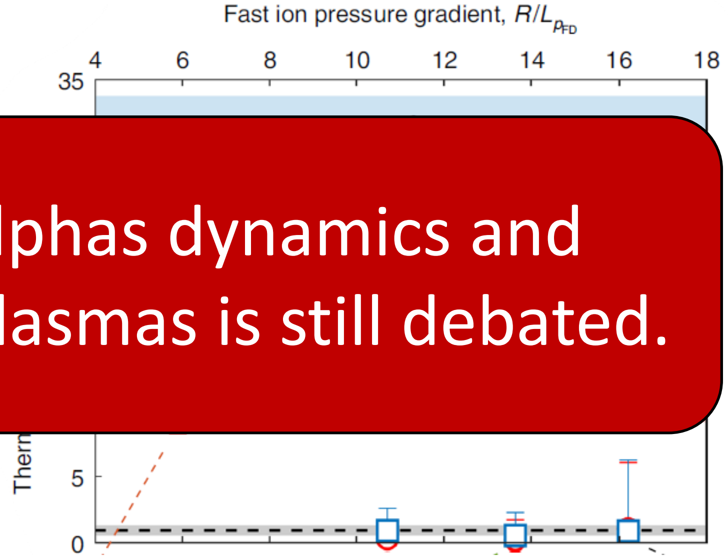
Fast α-particles generally stabilize microturbulence but introduce strong multiscale coupling via energetic-particle-driven modes.



Interaction between fast alphas dynamics and microturbulence in burning plasmas is still debated.



Di Siena et al. PRL 127 (2021)



Mazzi et al. Nat. Physics 18 (2022)

Turbulence in magnetic confinement fusion plasmas is a fascinating yet extremely convoluted topic, which has major consequences on the design and operation of future fusion power plants.

Thank you very much!