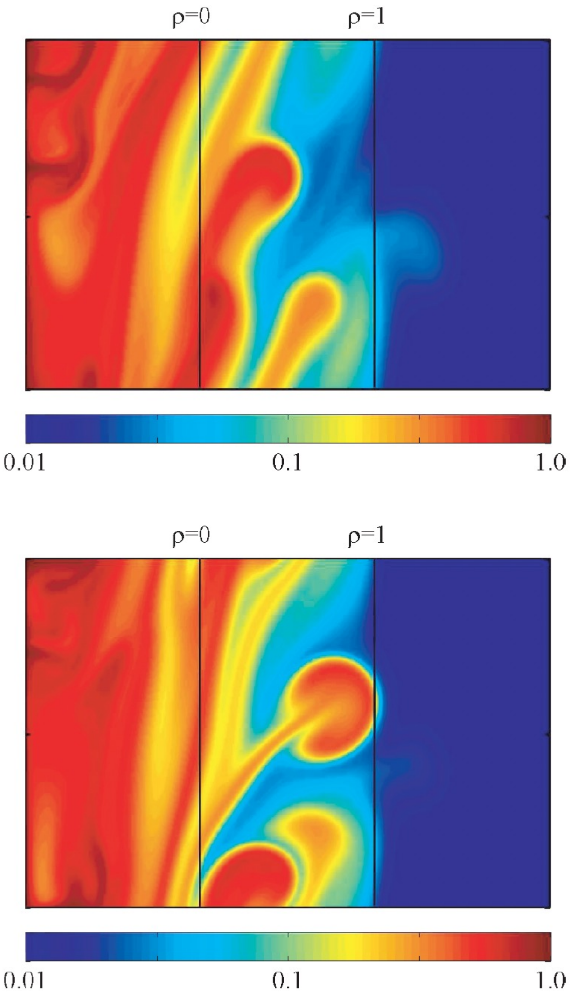


O. E. GARCIA Blob Transport in the Plasma Edge: a Review

Plasma turbulence

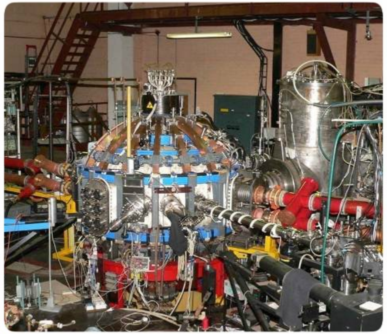
Galina Avdeeva

2023 Intro to fusion energy and plasma physics course

June 2023

About me

CXRS diagnostic

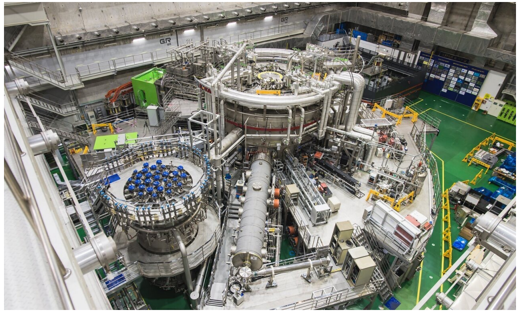


Globus-M spherical tokamak

St.Petersburg Polytechnic University
+
Ioffe Institute

Russia, Saint Petersburg

Modeling of SMBI

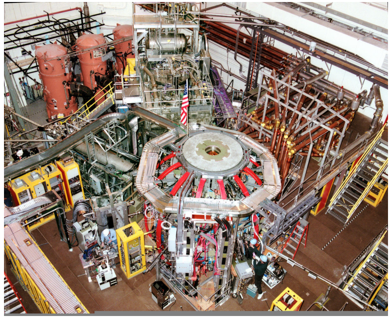


KSTAR tokamak

Denmark Technical University
+
KAIST and NFRI

Denmark + South Korea

Integrated modeling



NSTX tokamak

General Atomics
+
PPPL

USA

Topics in this talk

- What is turbulence?
- Mechanisms that can drive and suppress turbulence in a tokamak
- Ways to explore turbulence in fusion plasma

What is turbulence?

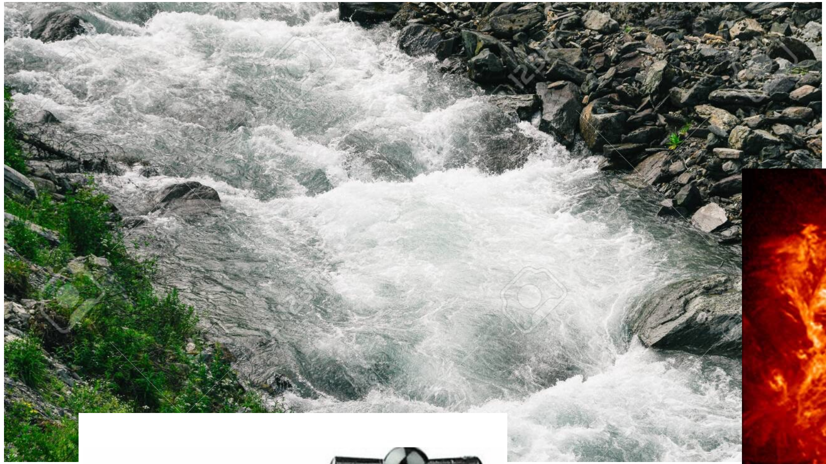
Turbulence or **turbulent flow** is fluid motion characterized by chaotic changes in pressure and flow velocity

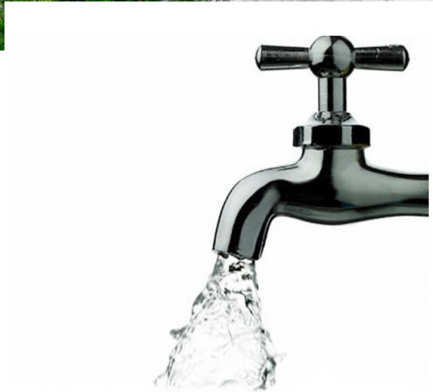
[Batchelor, G. (2000). Introduction to Fluid Mechanics]

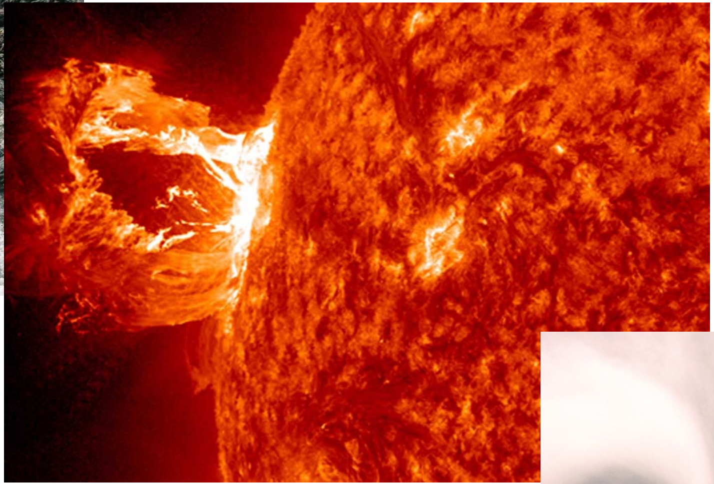
Irregular, unsteady, swirly

The turbulent flow by Leonardo da Vinci

Turbulence is commonly observed in everyday life





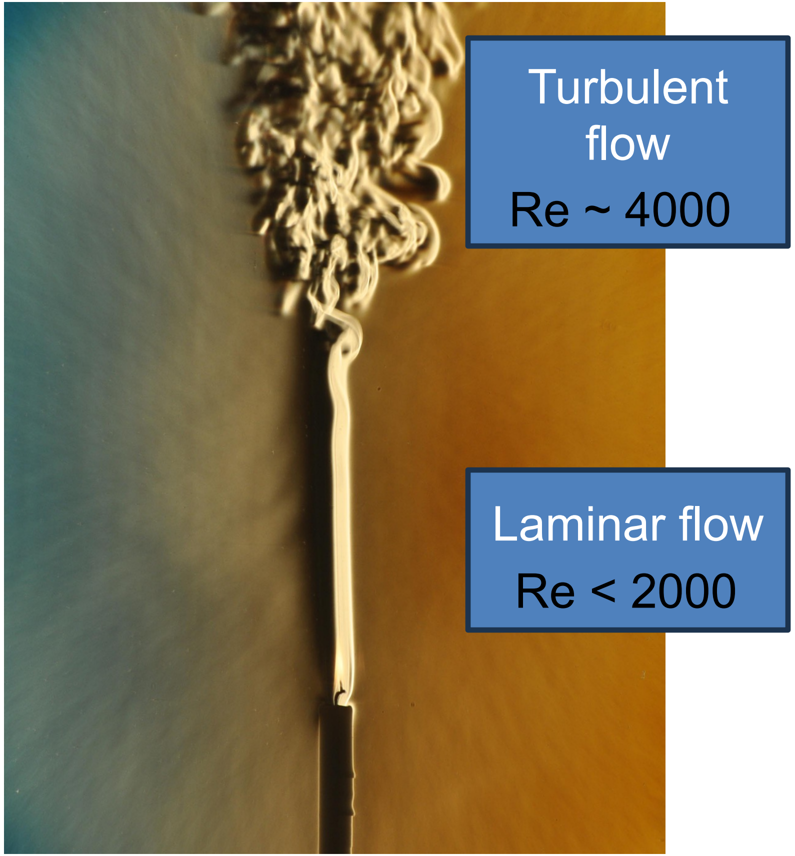


Turbulence is caused by excessive energy

Reynolds number – measure between kinetic energy and viscous damping

$$Re = \frac{ud}{\nu}$$

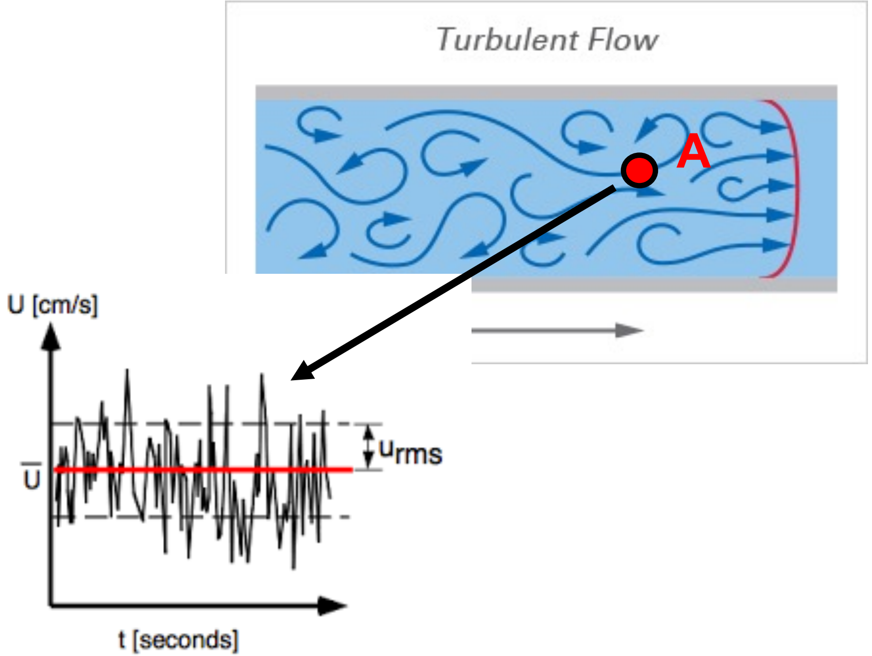
u – macroscopic velocity of the fluid
d – characteristic length
ν – kinematic viscosity of the fluid



Turbulence is characterized by the following features:

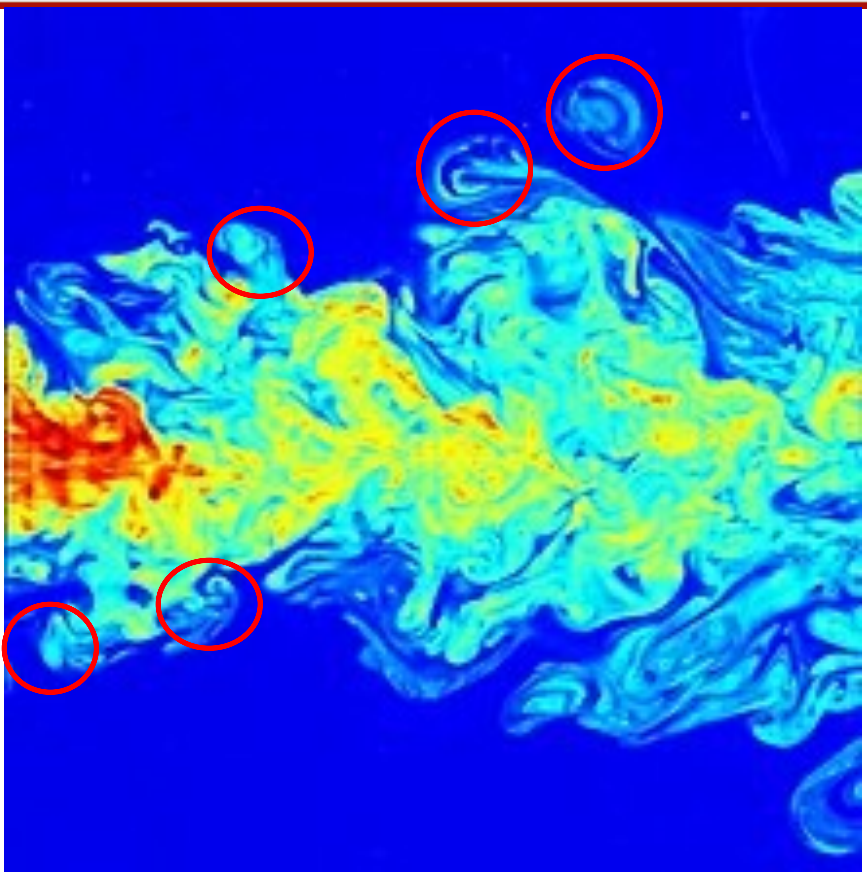
- irregularity

should be treated statistically



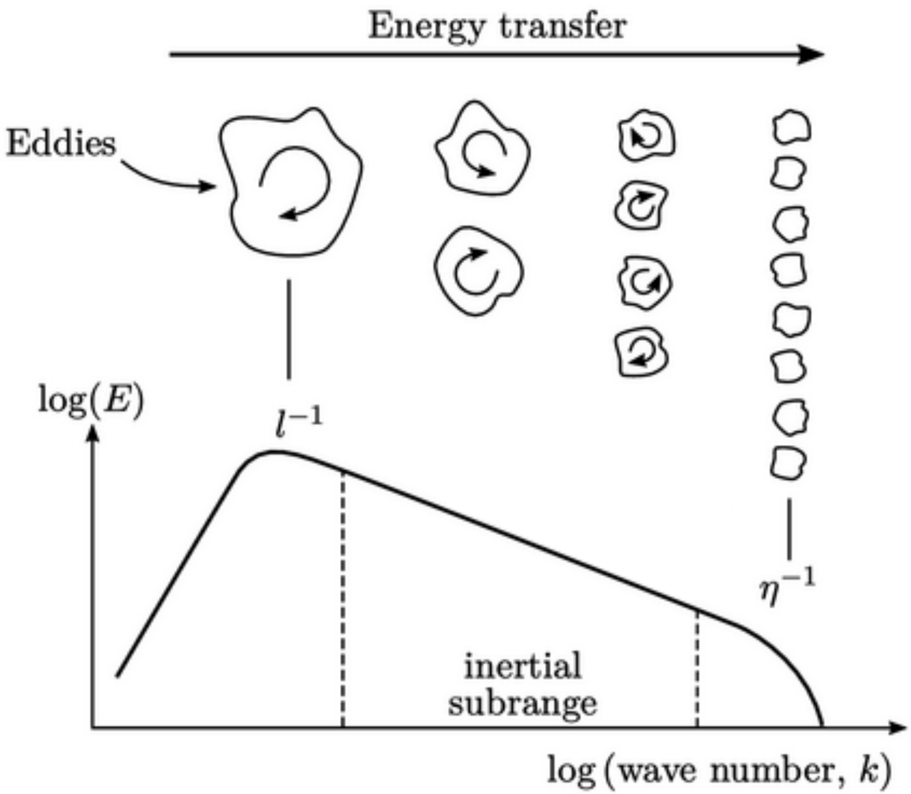
Turbulence is characterized by the following features:

- irregularity
- eddies of many different length scales



Turbulence is characterized by the following features:

- irregularity
- eddies of many different length scales
- energy dissipation through an “energy cascade”



Turbulence in fusion plasma (tokamak)

Turbulence are driven by instabilities

- Many instabilities in fusion plasma

  - Alfvén eigenmodes
  - Ballooning instability
  - Drift wave instability
  - Edge Localized Modes
  - Electron Temperature Gradient instability
  - Flute instability
  - Geodesic Acoustic Mode (GAM)
  - Interchange instability
  - Ion Temperature Gradient instability
  - Kink instability
  - Sausage instability
  - Tearing mode instability, see also Magnetic island
  - Whistler mode

http://fusionwiki.ciemat.es/wiki/Plasma_instability

Turbulence are driven by instabilities

- Many instabilities in fusion plasma

  - Alfvén eigenmodes
  - Ballooning instability
  - Drift wave instability

Pressure driven instabilities

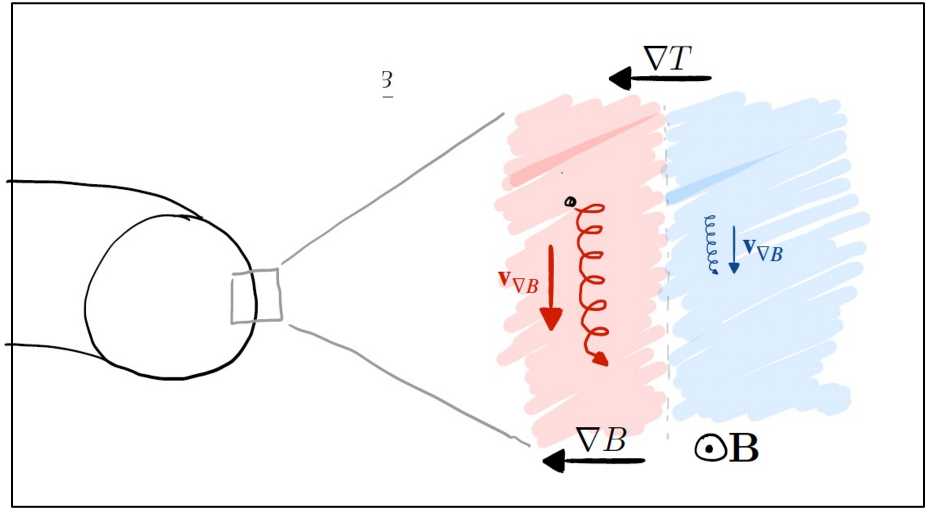
  - Ion Temperature Gradient instability
  - Kink instability
  - Sausage instability
  - Tearing mode instability, see also Magnetic island
  - Whistler mode

http://fusionwiki.ciemat.es/wiki/Plasma_instability

Mechanism of the pressure driven instabilities in a tokamak configuration

- Drift in a curved magnetic field

$$\mathbf{v}_{\nabla B} = \frac{\frac{1}{2}mv_\perp^2}{qB}\frac{\mathbf{B}\times\nabla B}{B^2} \approx \frac{T}{qB}\frac{\mathbf{B}\times\nabla B}{B^2}$$



Courtesy: Manaure Francisquez

Mechanism of the pressure driven instabilities in tokamak configuration

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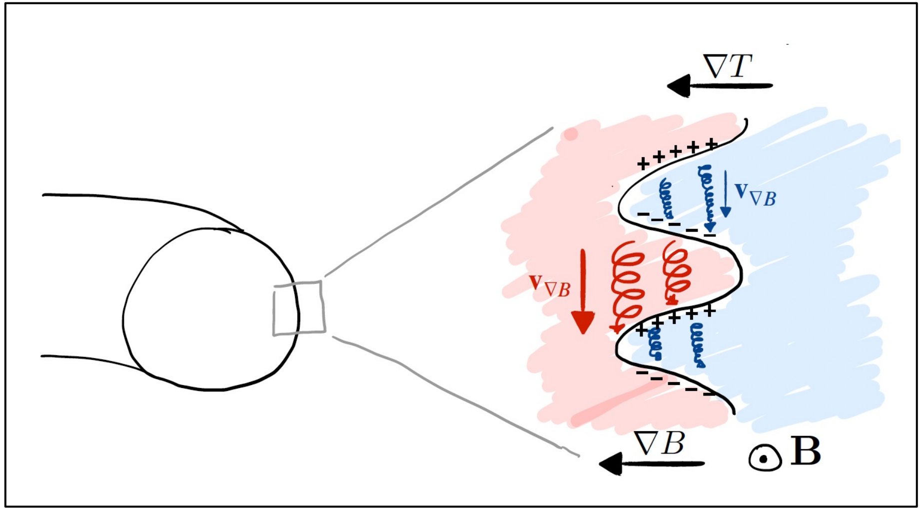
- Charge separation



Courtesy: Manaure Francisquez

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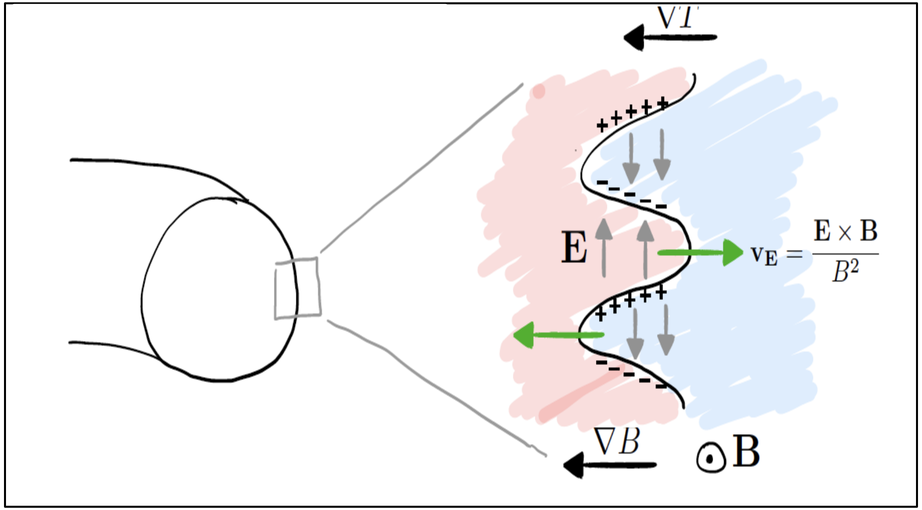
- Charge separation

- Electric field



Courtesy: Manaure Francisquez

Mechanism of the pressure driven instabilities in tokamak configuration

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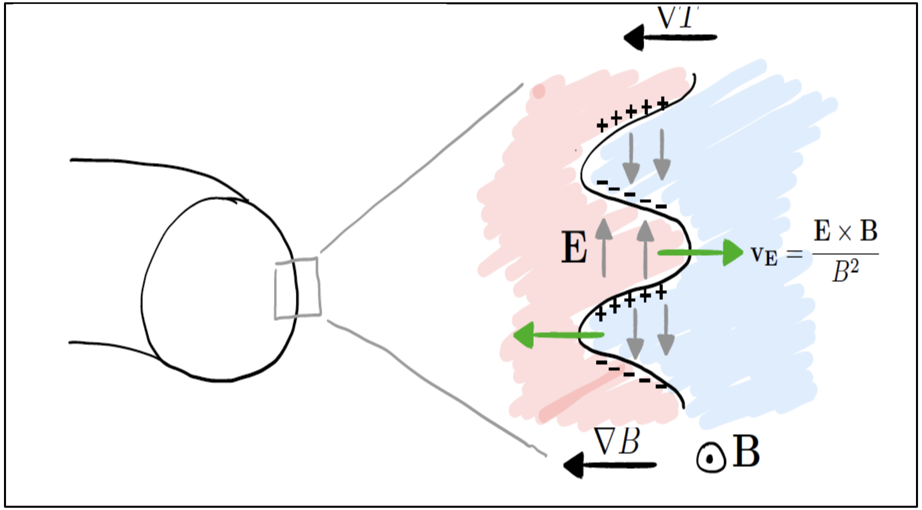
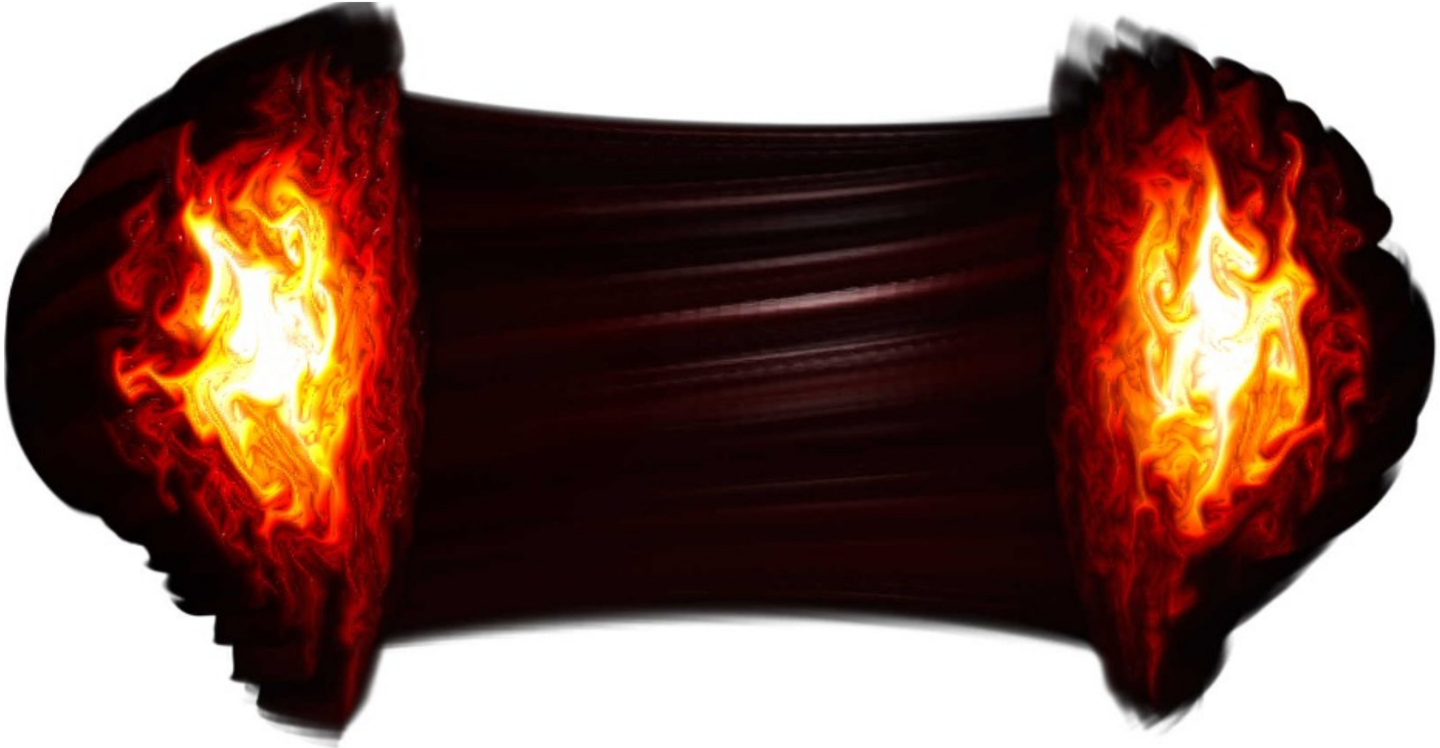
- Charge separation
- Electric field
- ExB drift



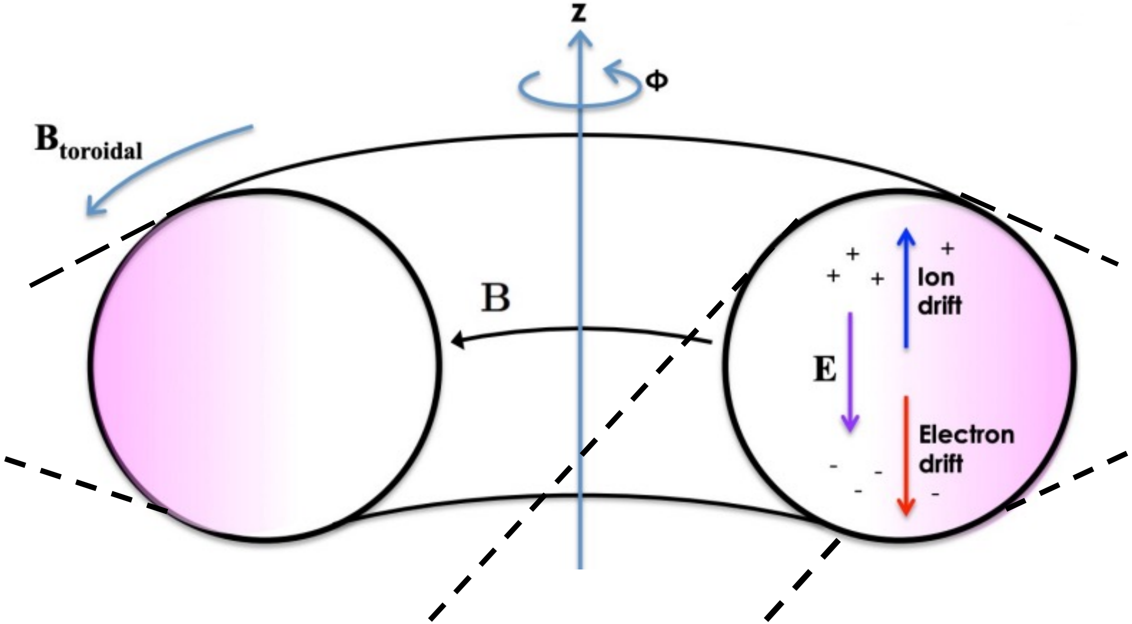
Courtesy: Manaure Francisquez

Turbulent transport is the main mechanism of plasma losses in fusion plasma



https://feltor-dev.github.io/showroom/ - Ion density

Instabilities can be suppressed by the 'good' magnetic curvature

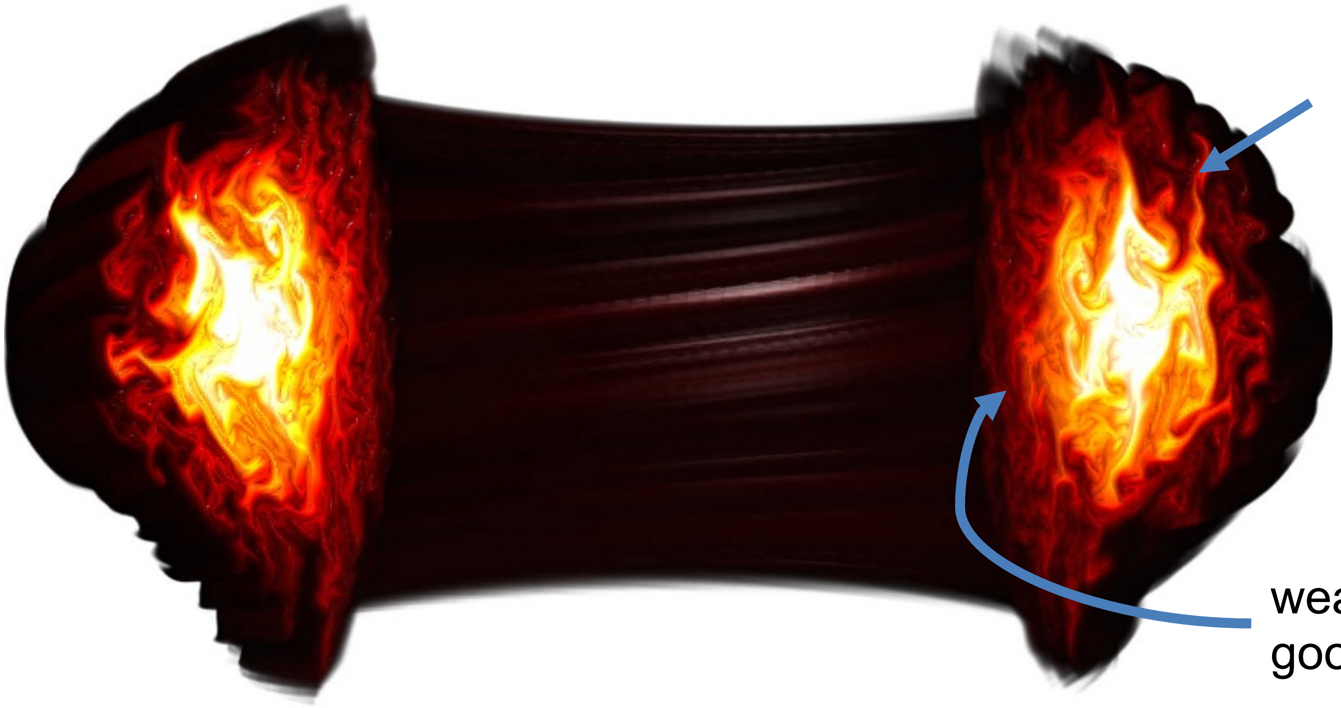


Bad curvature
Unstable region
$\nabla p \cdot \nabla B > 0$

Bad curvature
Unstable region
$\nabla p \cdot \nabla B > 0$

Good curvature
Stable region
$\nabla p \cdot \nabla B < 0$

Instabilities can be suppressed by the ‘good’ magnetic curvature



stronger fluctuations in the bad curvature region

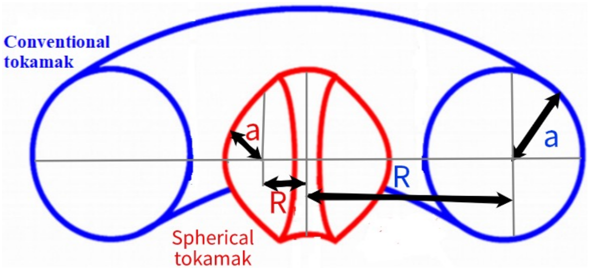
weaker fluctuations in the good curvature region

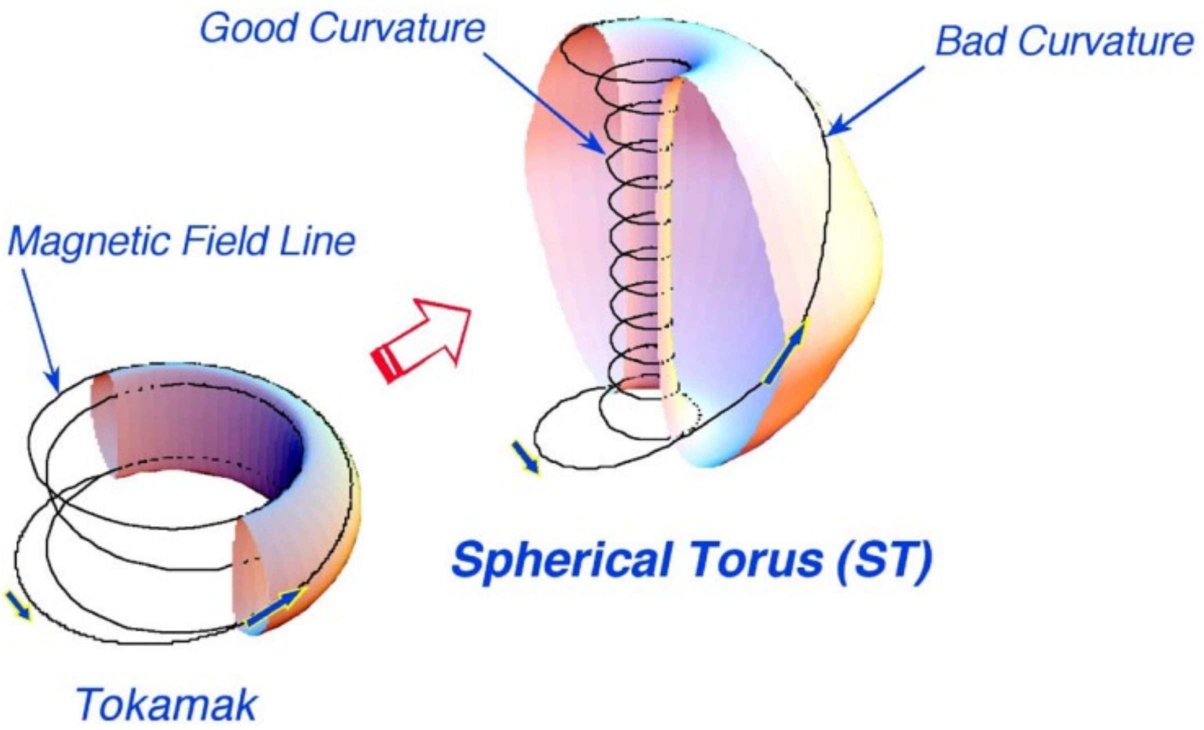
https://feltor-dev.github.io/showroom/ - Ion density

Low aspect ratio tokamaks have improved confinement

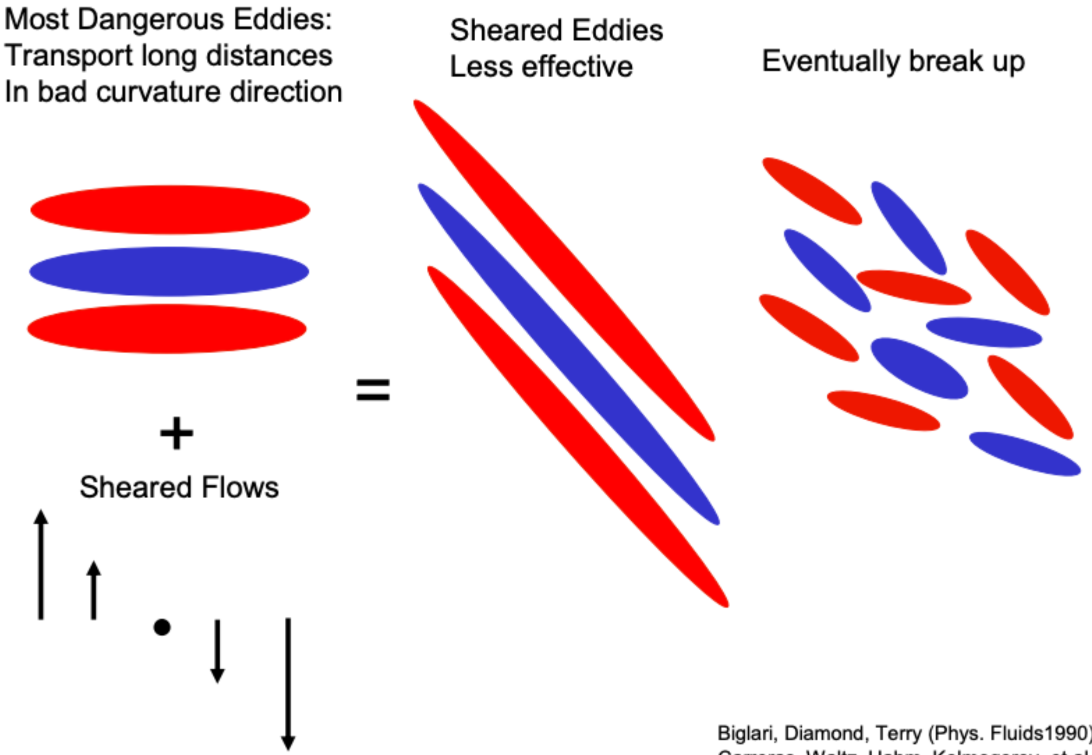
Aspect ratio A = R/a

Conventional tokamak
A > 2.5
Spherical tokamak
A < 2



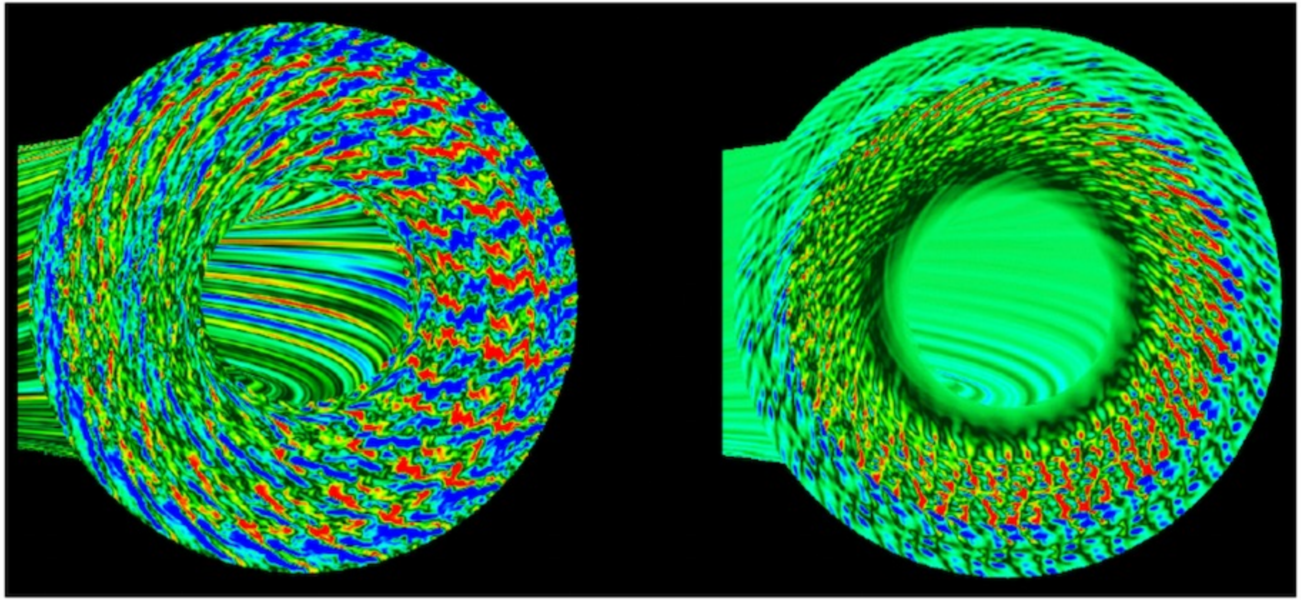


Sheared flows can reduce or completely suppress turbulence



Biglari, Diamond, Terry (Phys. Fluids1990),
Carreras, Waltz, Hahm, Kolmogorov, et al.

Sheared flows can reduce or completely suppress turbulence

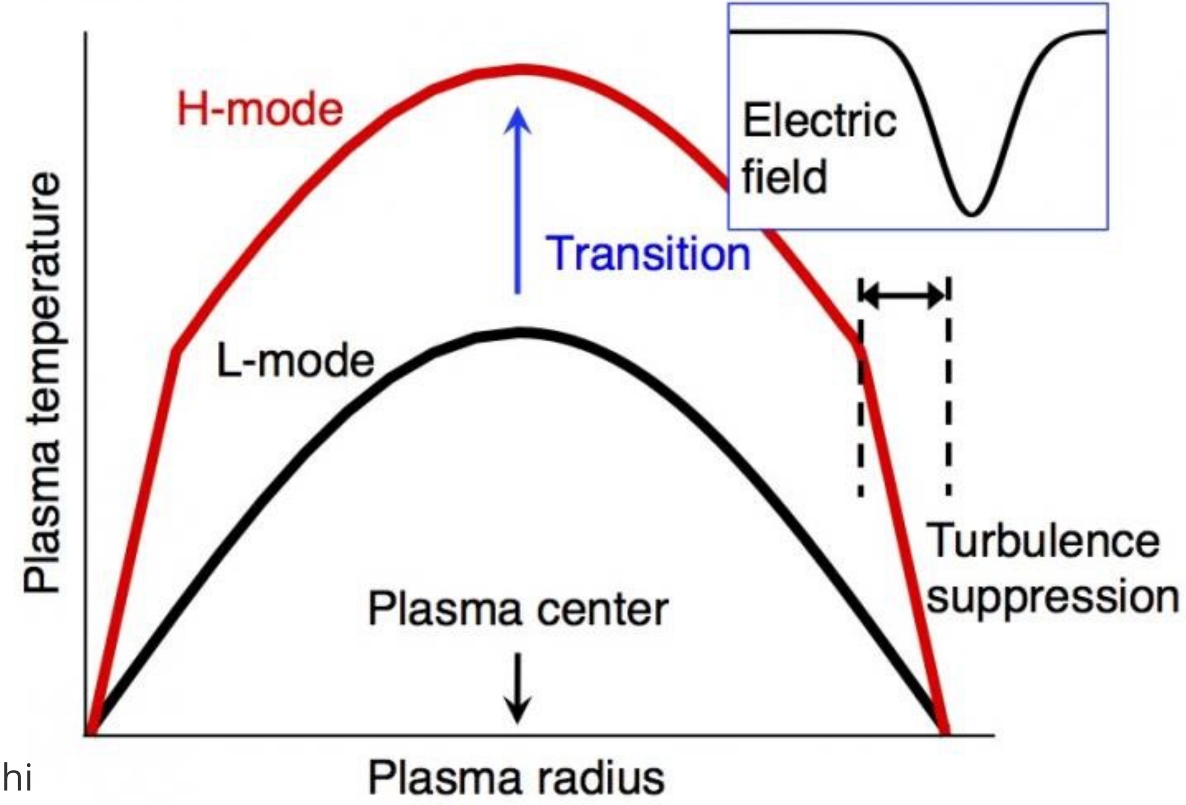


Dominant nonlinear interaction between turbulent eddies and ±θ-directed zonal flows.

Additional large scale sheared zonal flow (driven by beams, neoclassical) can completely suppress turbulence

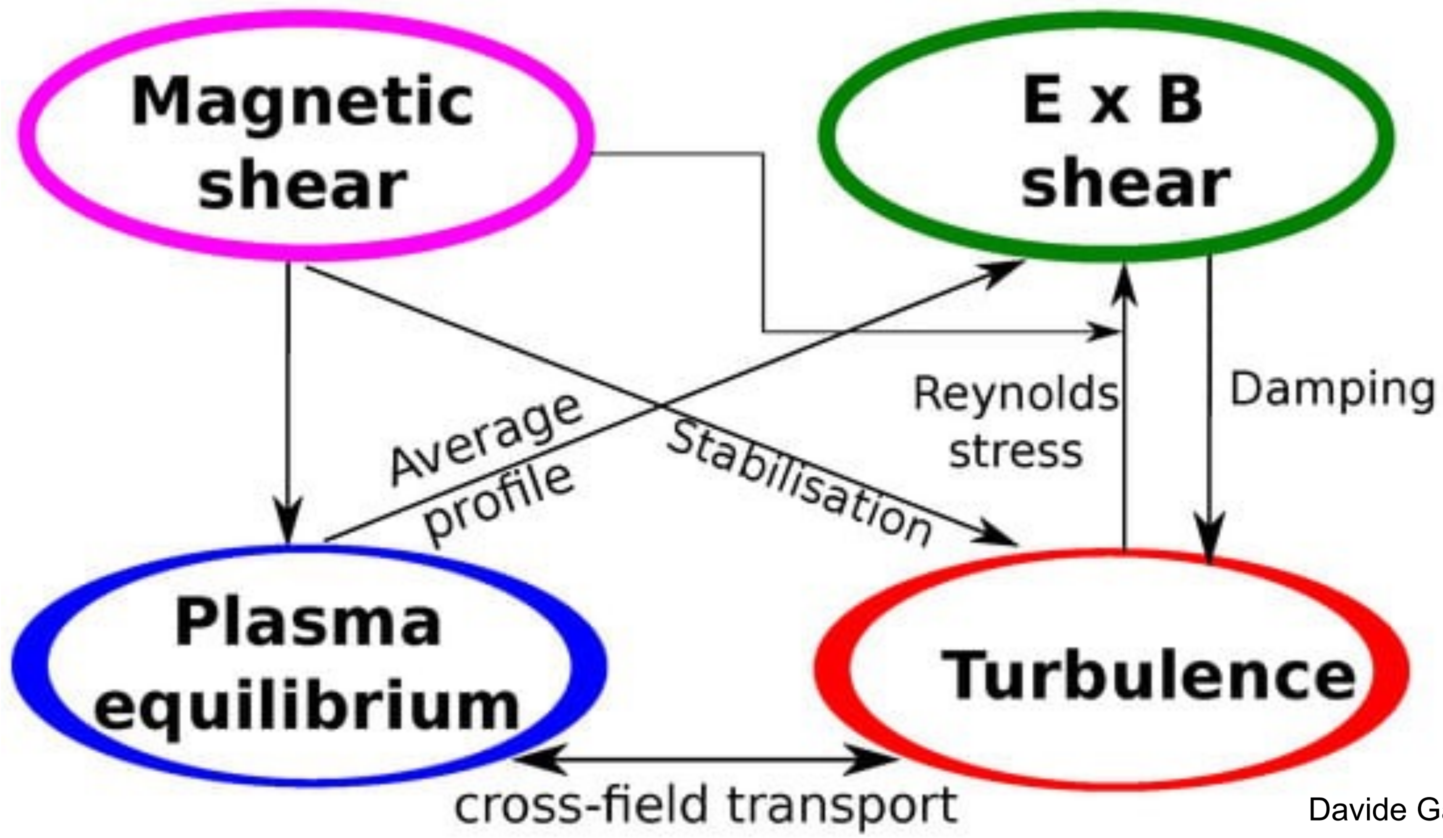
Waltz, Kerbel, Phys. Plasmas 1994 w/ Hammett, Beer, Dorland, Waltz Gyrofluid Eqs., Numerical Tokamak Project, DoE Computational Grand Challenge

Stabilization of turbulence improves plasma performance by formation of a transport barrier



CREDIT Tatsuya Kobayashi

Transport is complex and non-linear



Davide Galassi ; Fluids, 2019

Ways to explore turbulence in fusion plasma (tokamak)

Turbulence is frequently studied via numerical simulation

First principles → Kinetic description → Gyrokinetic description → Fluid modeling

Simulation of each particle

Distribution function

Averaging over gyromotion

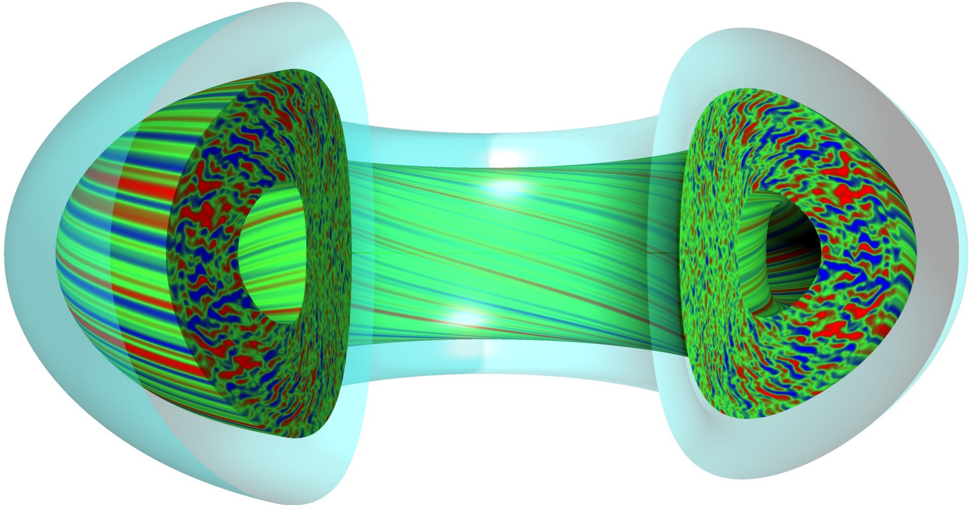
Plasma as a fluid

Decrease of complexity, accuracy, computational time →

Hybrid models

Reduced models

3D gyrokinetic modeling

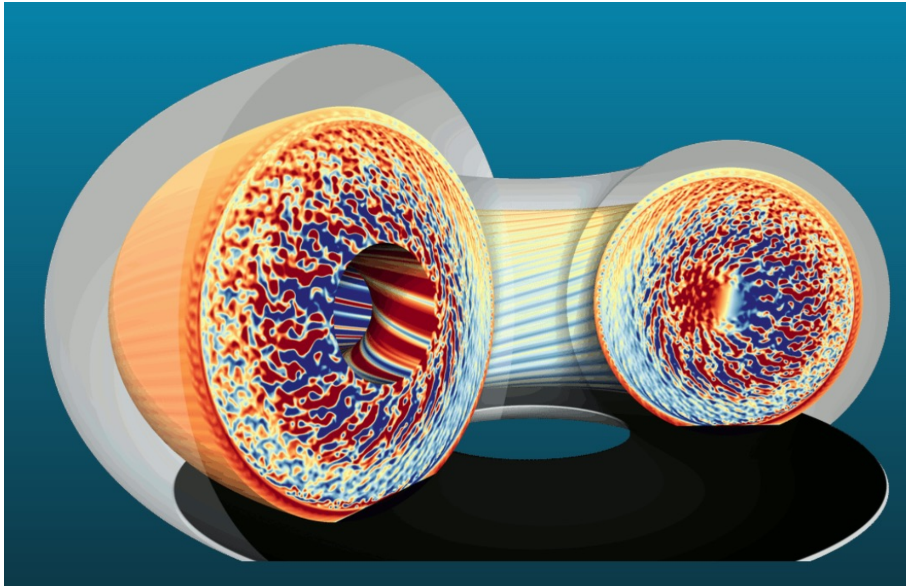


GYRO; General Atomics; USA

https://gafusion.github.io/doc/gyro.html

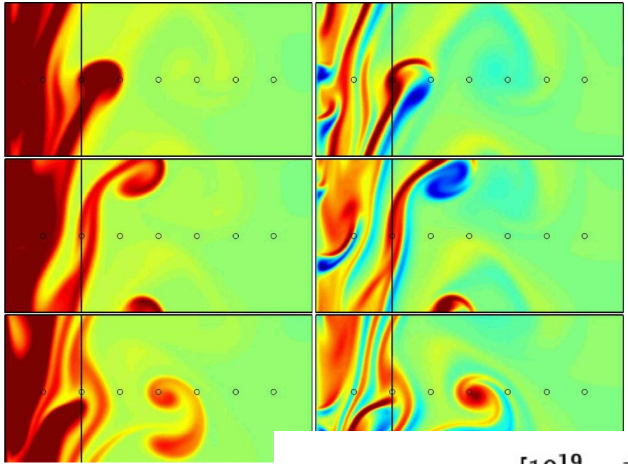
GYSELA-X; CEA/IRFM ; EU

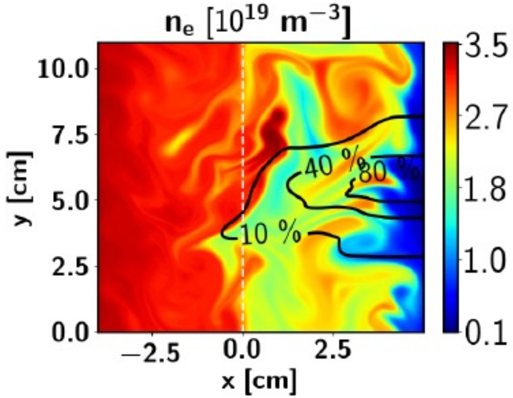
https://gyselax.github.io/



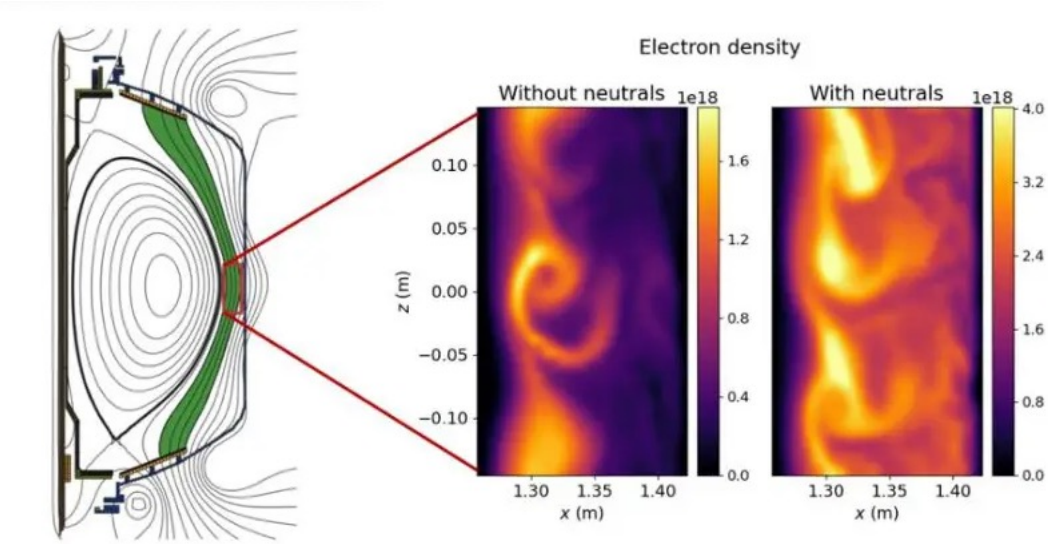
2D fluid modeling: plasma blobs formation and interactions with neutrals

Credit: T. Bernard





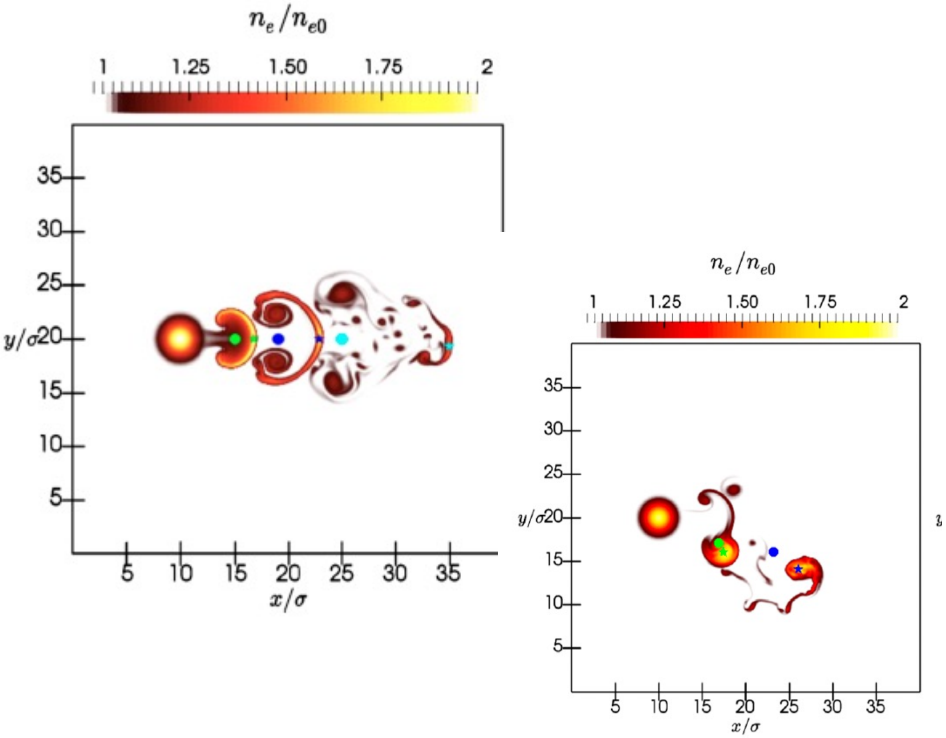
HESEL



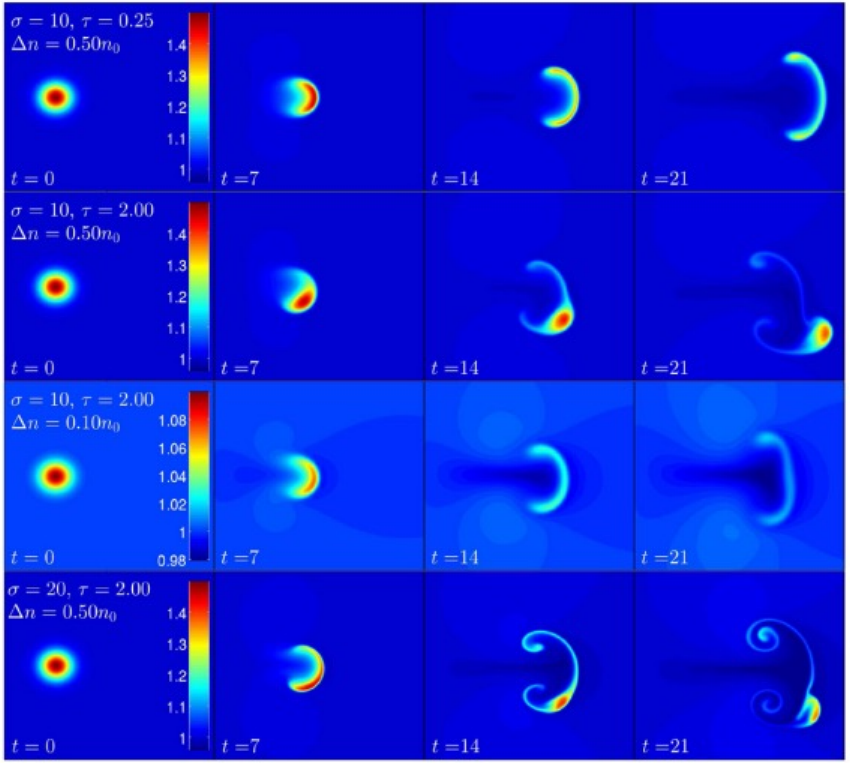
Gkeyll

Dynamics of plasma filaments under different conditions

M. Held et al 2016 Nucl. Fusion 56 126005



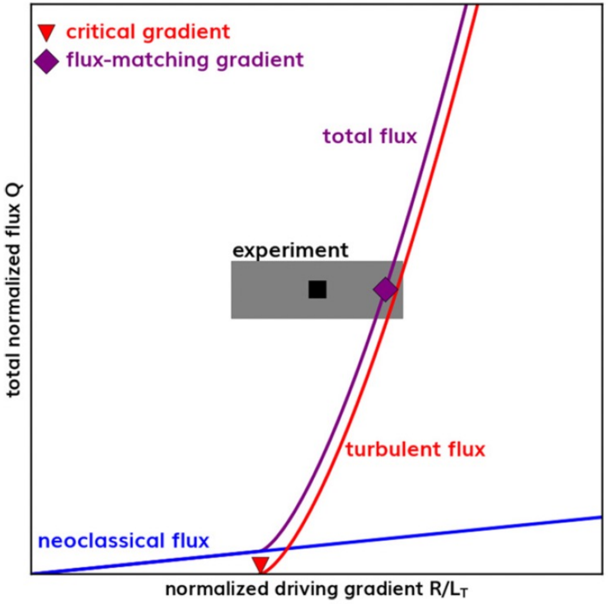
Jeppe Olsen et al 2016 Plasma Phys. Control. Fusion 58 044011



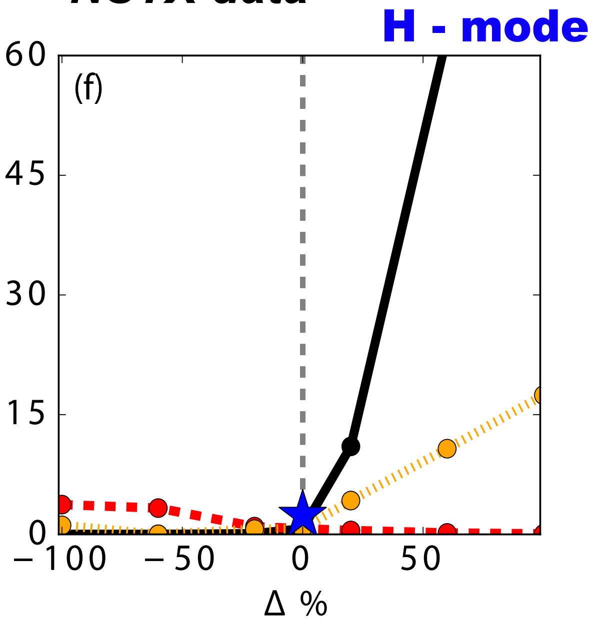
Local 1D modeling for validation with experimental data

C. Holland et al 2021 Nucl. Fusion 61 066033

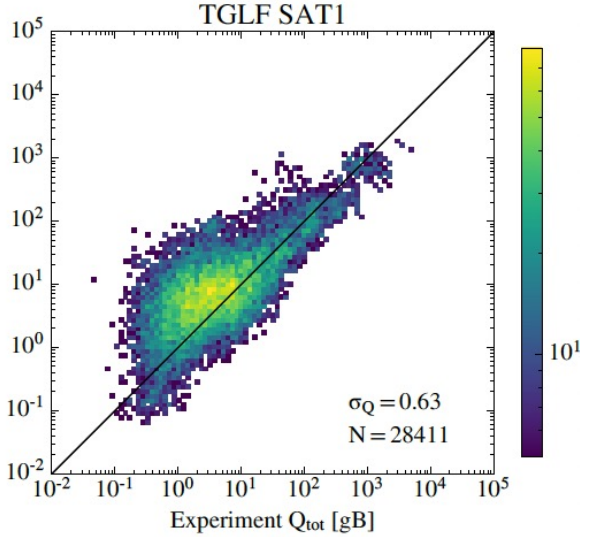
Tom F. Neiser/ US-EU TTF Meeting/ April 7th, 2022



Example of NSTX data

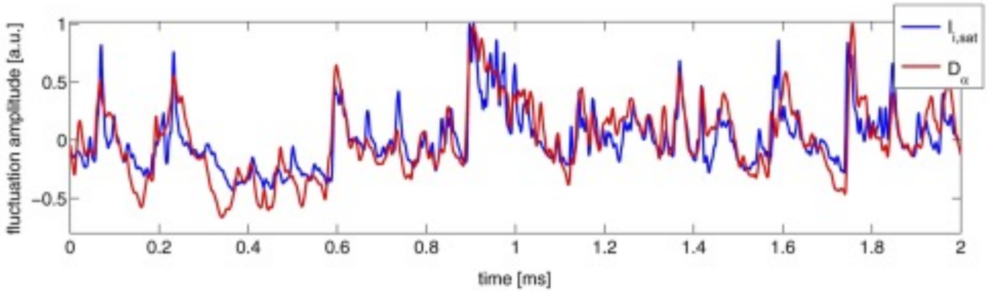


Large database validation

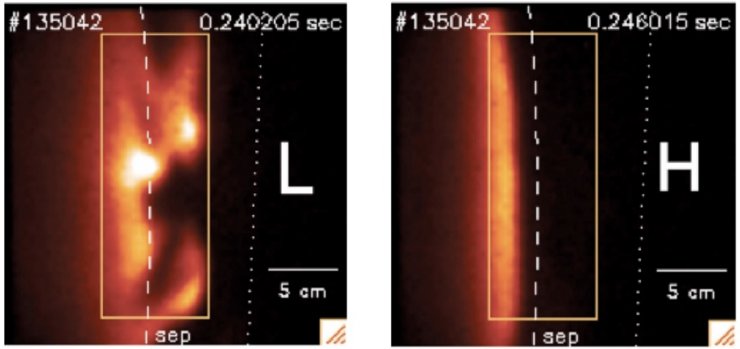


Plasma turbulence is observed experimentaly

Langmuir probe measurements

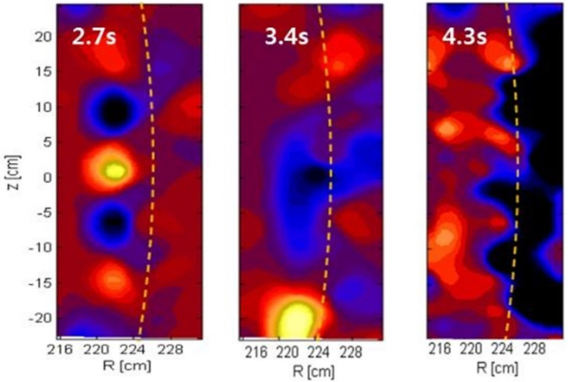


Gas puff imaging (GPI) diagnostic NSTX



S. J. Zweben et al., Review of scientific Instruments 88, 041101 (2017)

Electron cyclotron emission diagnostic KSTAR



https://www.iter.org/newsline/198/950

Summary

- Turbulent flow is irregular, unsteady, swirly
- Turbulent transport is the main mechanism of plasma losses in fusion plasma
- Turbulent transport can be mitigated

Understand:

- structure and dynamics of turbulence and induced transport

↓

Predict:

- scaling of different confinement regimes

↓

Control:

- plasma equilibrium and confinement, local turbulence control