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On the physics of shear flows in 3-D geometry

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The paradigm of sheared electric field suppression of turbulence

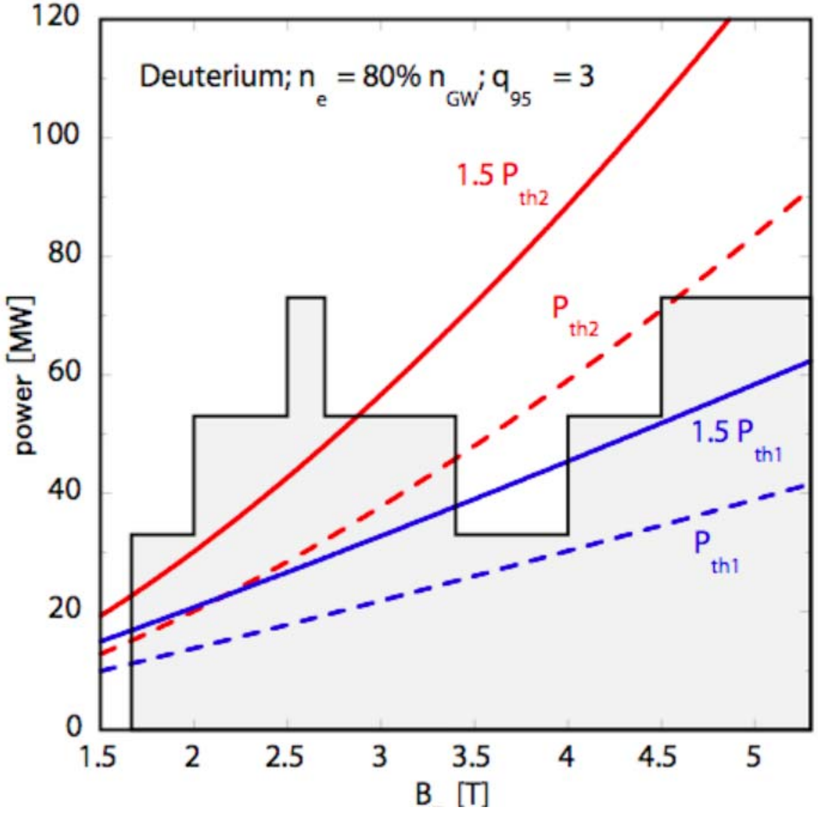
Different physics-based models have been proposed to explain the development of (edge) sheared flows and transport barriers, including:

- **Role of equilibrium flows**
- **Role of turbulence driven flows.**
- **The transport barrier width based on orbit ion losses (edge)**
- **Role of edge localized neutral particle sources (edge)**
- **Role of SOL boundary conditions (edge)**

Test underlying physics (theory / experiment):

•**Identify the (experimental) finger-print of theoretical models**

Sheared flows physics:
a key (open) issue in next step devices



An specific problem for ITER is the need to achieve and test H-mode performance before moving to the active phase.

But large uncertainties are still present in the empirical description of the L-H power transition with significant implications in the overall research programme of next step magnetic confinement devices (e.g. ITER).

This is reflecting the lack of basic understanding of the physics underlying the development of edge transport barriers and sheared flows.

Outline

Multi-scale physics mechanisms and plasma bifurcations

Transport barriers and sheared flows:

Evidence of multi-scale physics and L-H transition (TJ-II)

Multi-scale physics and confinement (TJ-II / LHD)

Energy transfer (zonal flows): 3-D physics

Conclusions

Why sheared flows driven by turbulence?: the role of multi-scale physics

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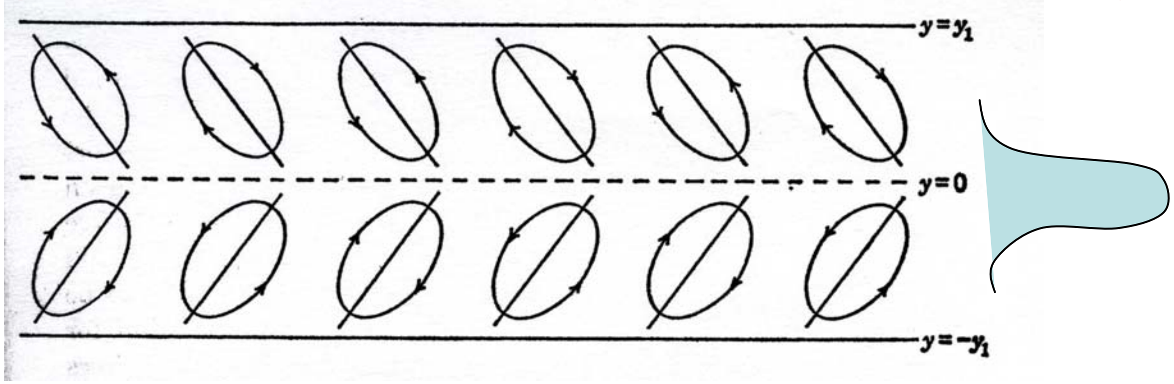
Flow having a momentum transport into the central portion of the channel: The essential features are the elliptical circulations and the systematic tilts of their major axes.



Key ingredients:

- The eddies which transport momentum contrary to the gradient of mean flow must have a supply of eddy kinetic energy.
- Symmetry breaking (e.g. Eddy tilting…….)
- Turbulent “irregulaties”
- The mean flow must be subject to some form of braking action so as not to increase without limit (e.g. positive viscosity). But, also this braking should be low enough to allow flow development.

e.g. Poloidal rotation driven by turbulence

Turbulent anisotropy

Flujo DC

$$\frac{\partial \langle \tilde{v}_r \, \tilde{v}_\theta \rangle}{\partial r} = \mu V_\theta$$

Turbulent irregularities

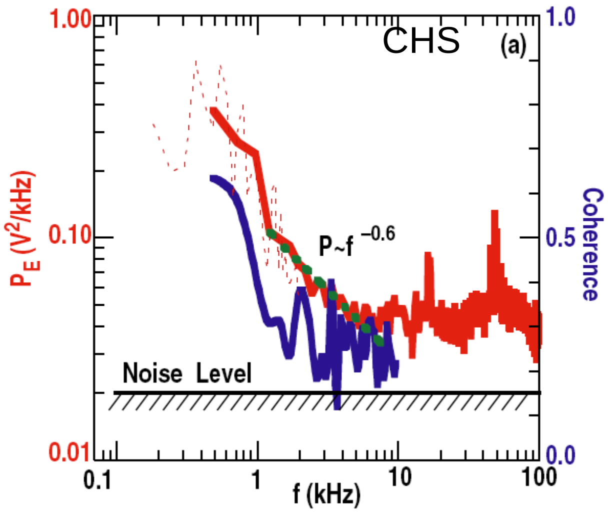
Positive viscosity (e.g. Neoclasical,…)

Multi-scale physics and L-H transition models: *a new way of thinking to test models*

Models (ExB shear)	Multi-scale physics driving	Multi-scale physics damping
Turbulence driven flows Stabler-Dominguez 1993 Diamond-Carreras 1994 Guzdar 2001	•Free-energy sources (gradients) •**Radial electric fields** (symmetry breaking)	Collisionality (temperature, atomic physics,magnetic topology,.)
Ion-orbit based models Shaing-Crume 1989 Itoh-Itoh 1988	•Ion orbit losses (momentum source)	**Radial electric fields** (reducing particle transport) Collisionality
Stringer spin-up Hassam et al., 1991 Stringer 1969	•Free energy sources •Poloidal asymmetries	**Radial electric fields** (reducing asymmetries in anomalous transport)
Equilibrium flows		

the importance of understanding the interplay between of radial electric field and (toroidal) multi-scale physics

Improving diagnostics for multi-scale mechanisms: trigger of new physics



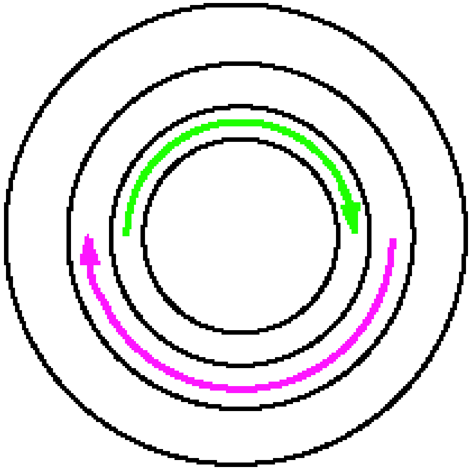
Fujisawa et al., Phys. Rev. Lett 93 (2004) 165002.

Using a unique experimental set-up (two HIBP systems separated toroidally 90 degrees in the CHS stellarator, it has been shown that:

1) The electric field fluctuation f < 10 kHz shows long-range correlation and reflects the activity of low frequency oscillations.

2) Low frequency fluctuations has a phase shift close to zero.

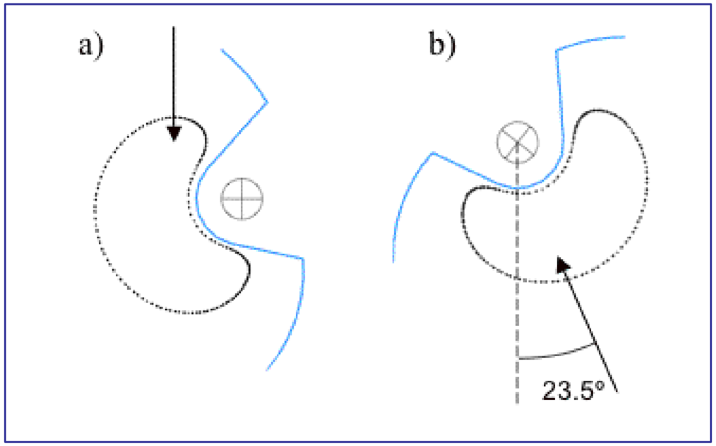
These results are consistent with zonal flows with n=0 and m = 0, providing the most clear evidence of zonal flows in fusion plasmas.



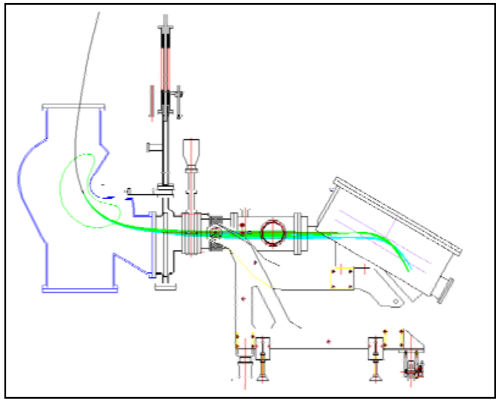
Zonal flows (stable modes driven by turbulence that regulate turbulent transport by shearing apart the turbulent eddies) is an important ingredient of transport in fusuion plasmas.

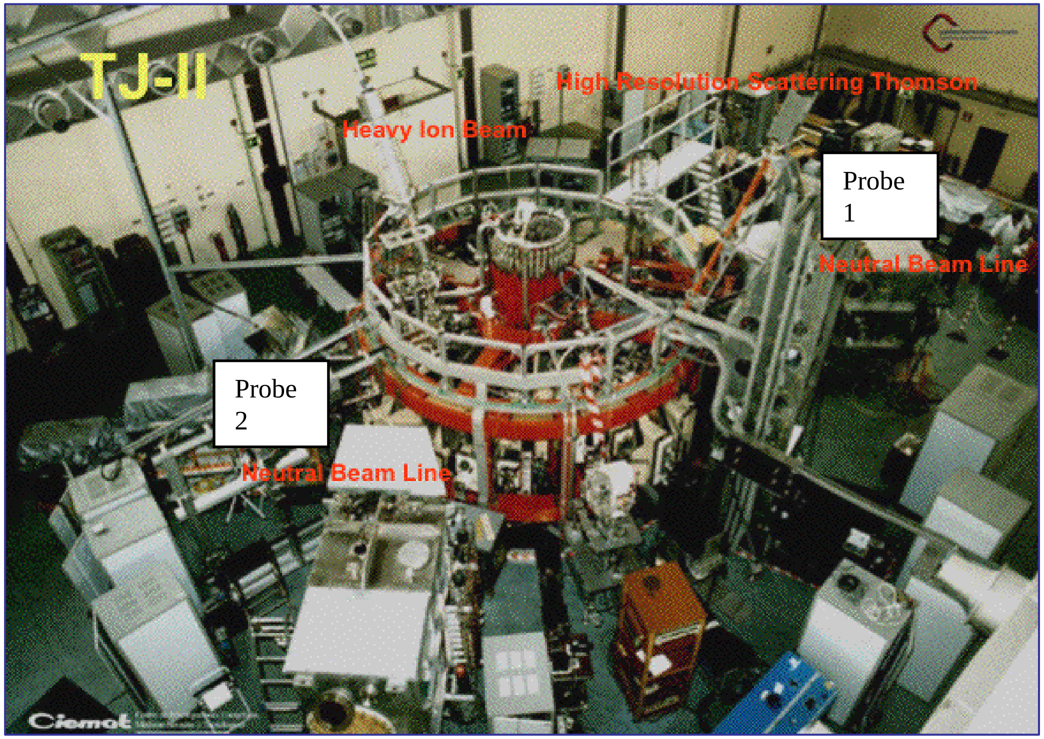
Diagnostic development (for long range correlation studies) in the TJ-II stellarator

Langmuir/Mach Probes

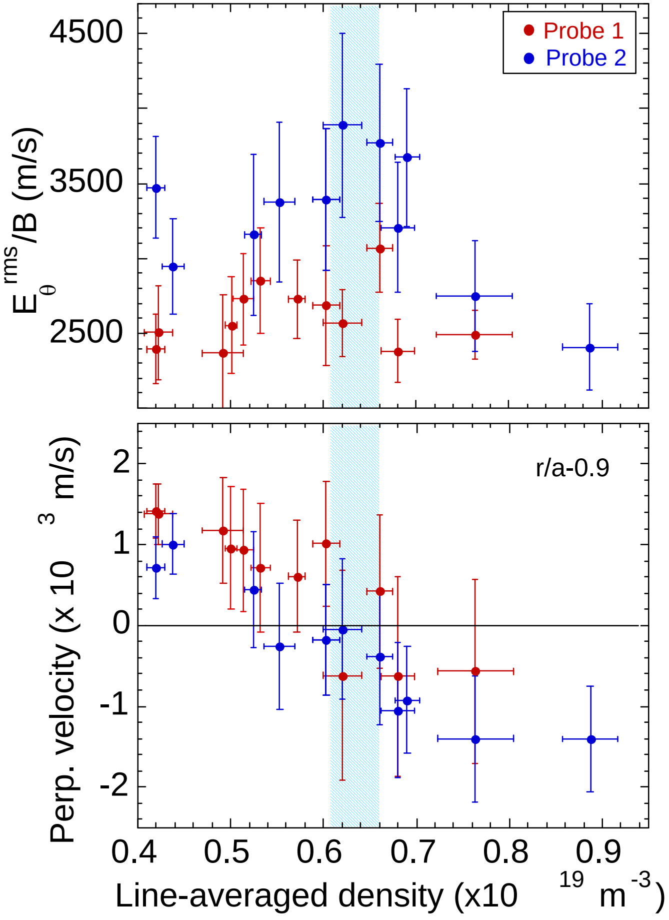


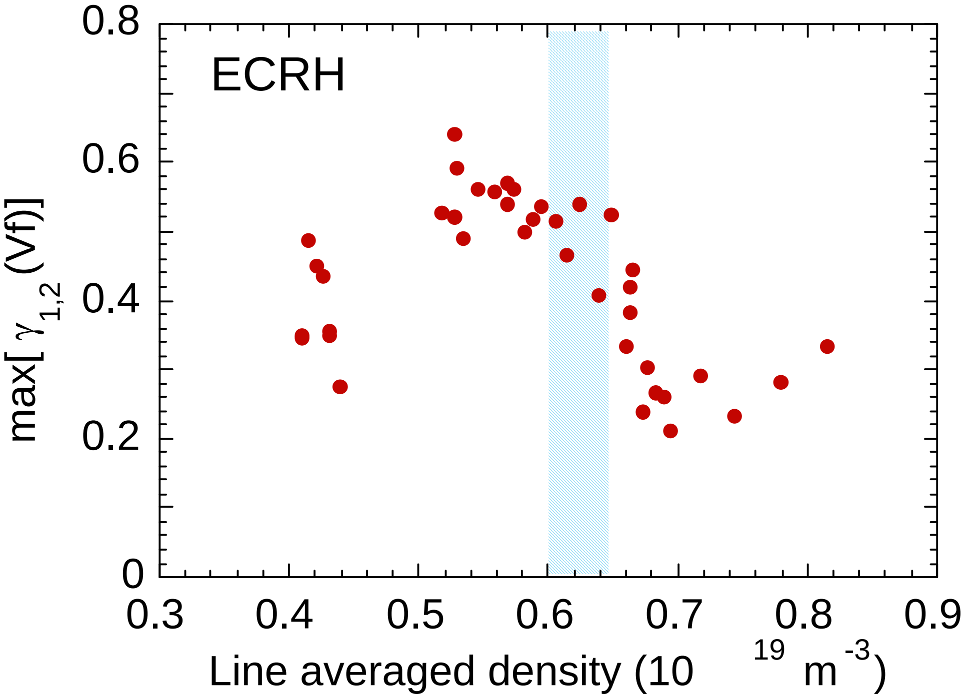
HIBP (Kurchatov / Kharkov collaboration)





Long range correlations and sheared flow physics



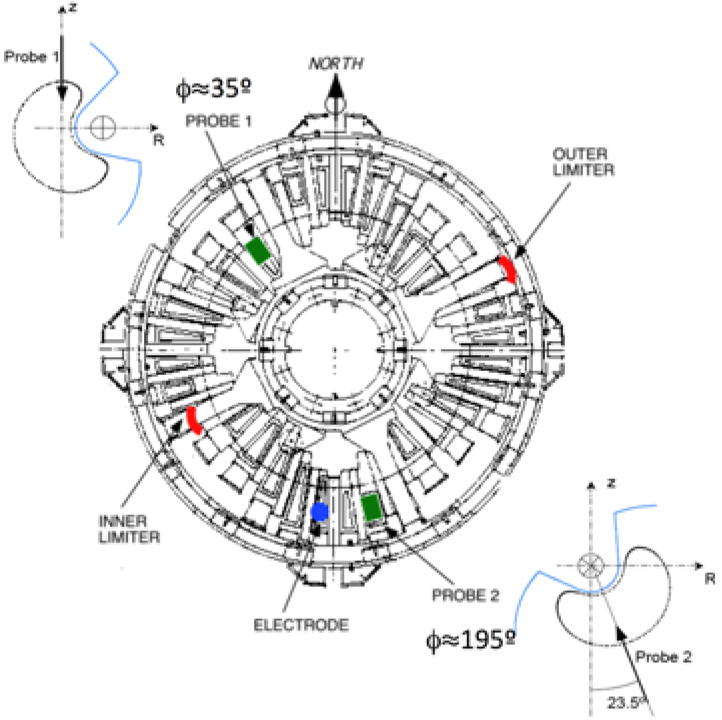


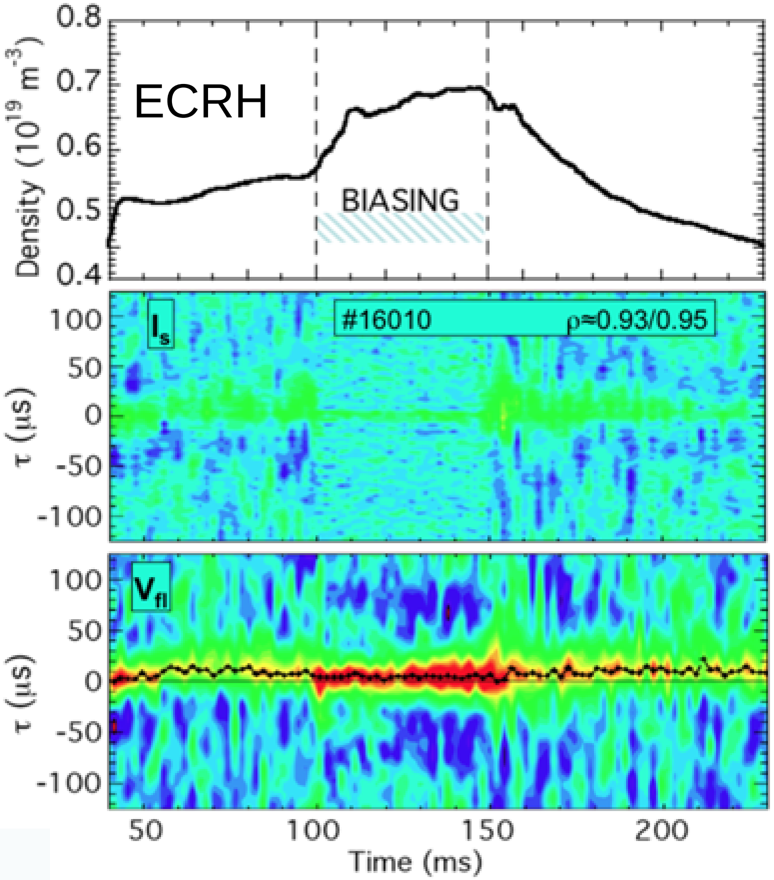
$$\gamma_{xy}(\tau) = \frac{E\{[x(t+\tau)-\bar{x}][y(t)-\bar{y}]\}}{\sqrt{E\{[x(t)-\bar{x}]^2\}.E\{[y(t)-\bar{y}]^2\}}}$$

M. A. Pedrosa et al. Phys. Rev. Lett. **100** (2008) 215003

Evidence of long-range correlations (multi-scale physics) which are amplified during the development of edge shear flows (low density regime).

Multi-scale physics during externally (biasing) driven bifurcations



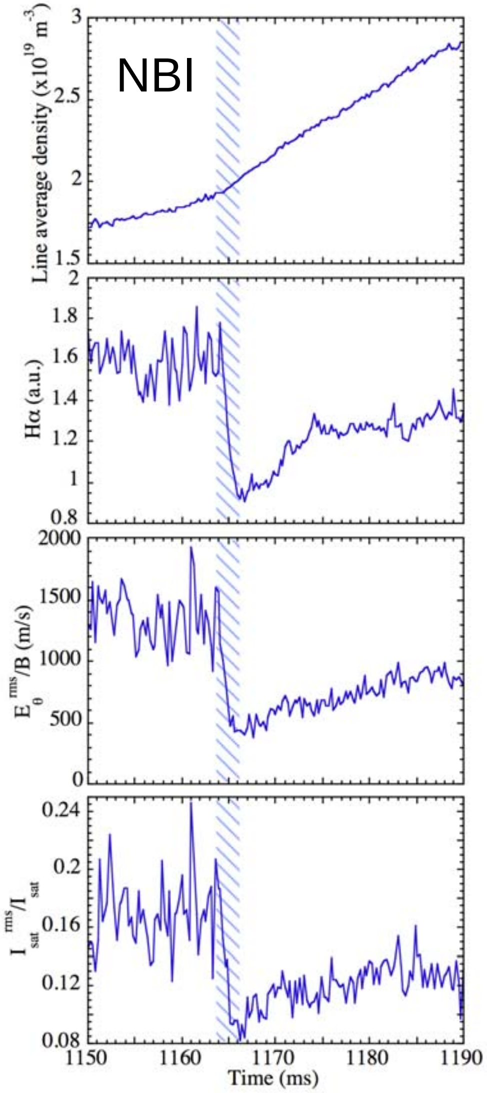


M. A. Pedrosa et al. Phys. Rev. Lett. **100** (2008) 215003

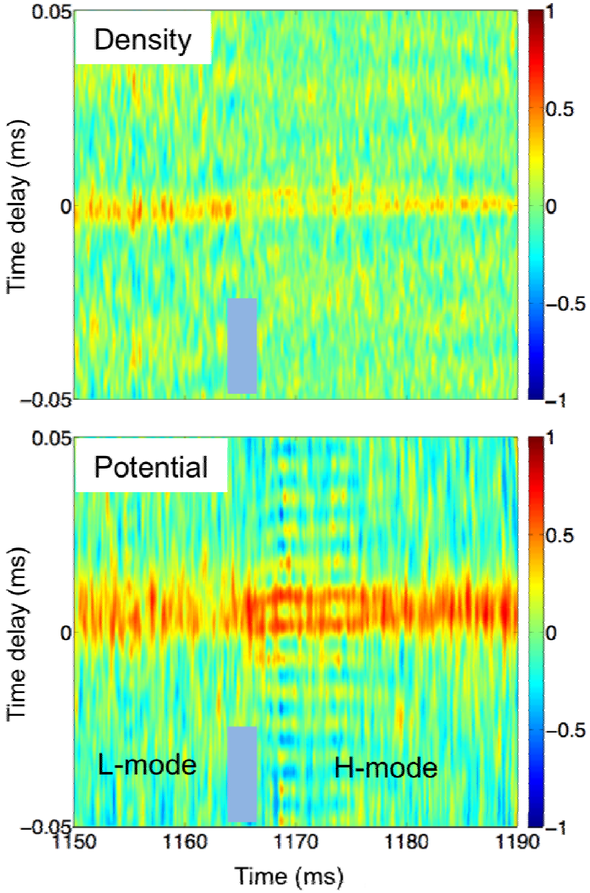
Long range cross-correlation (frequencies < 30 kHz) increases during during biasing induced

Multi-scale physics mechanisms are amplified by electric fields

Multi-scale physics during spontaneous (L-H) transition

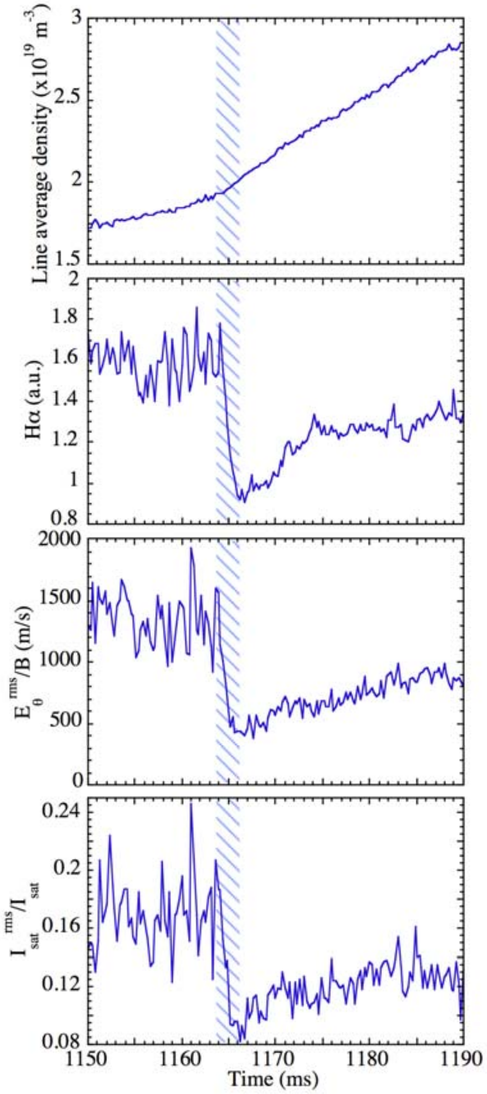


TJ-II team, November 2008

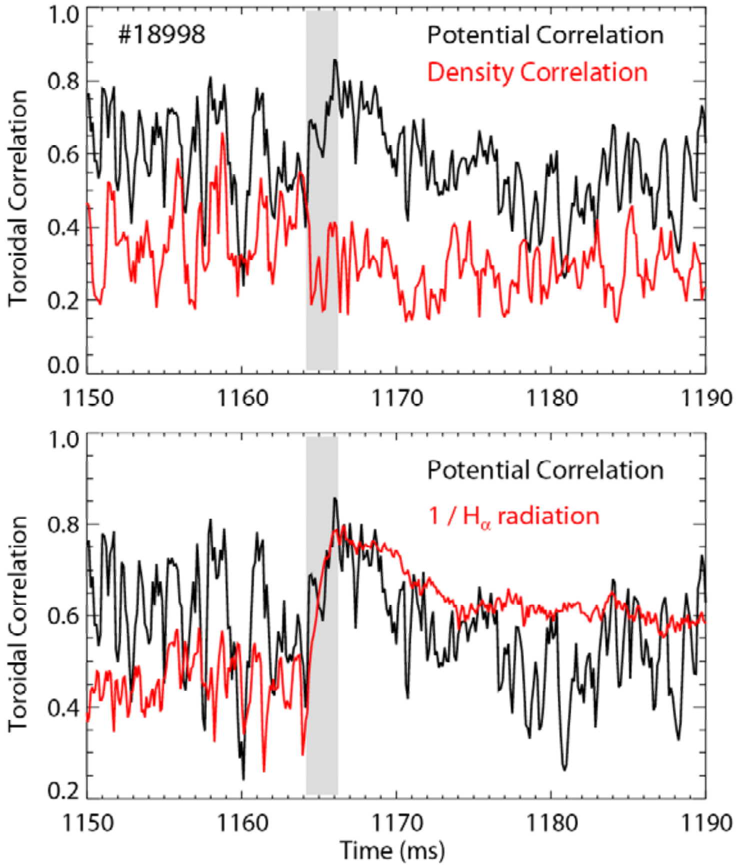


Multi-scale mechanisms (long-range correlations) as a new experimental fingerprint of the plasma behaviour during transport bifurcations

Multi-scale physics during spontaneous (L-H) transition

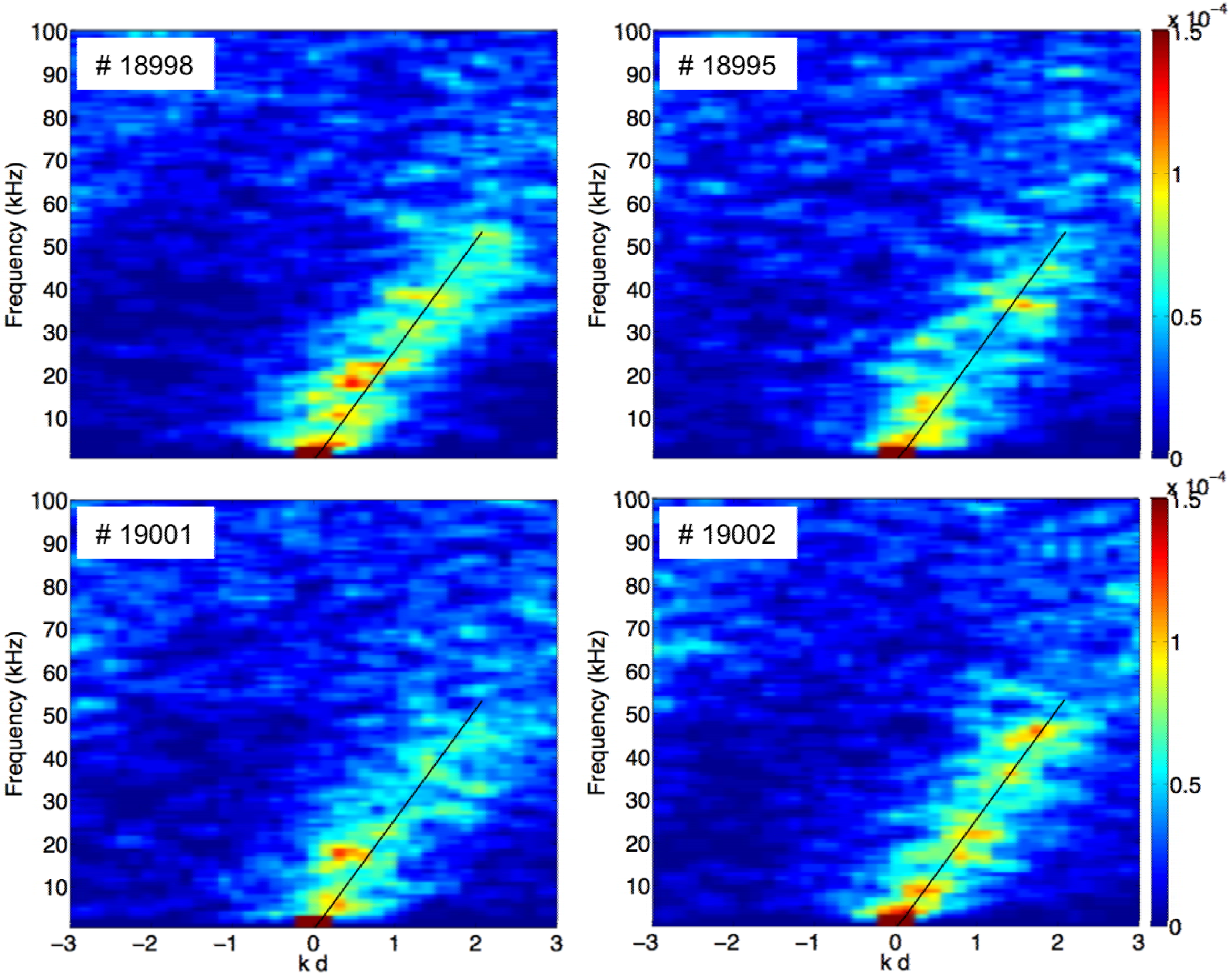


TJ-II team, November 2008

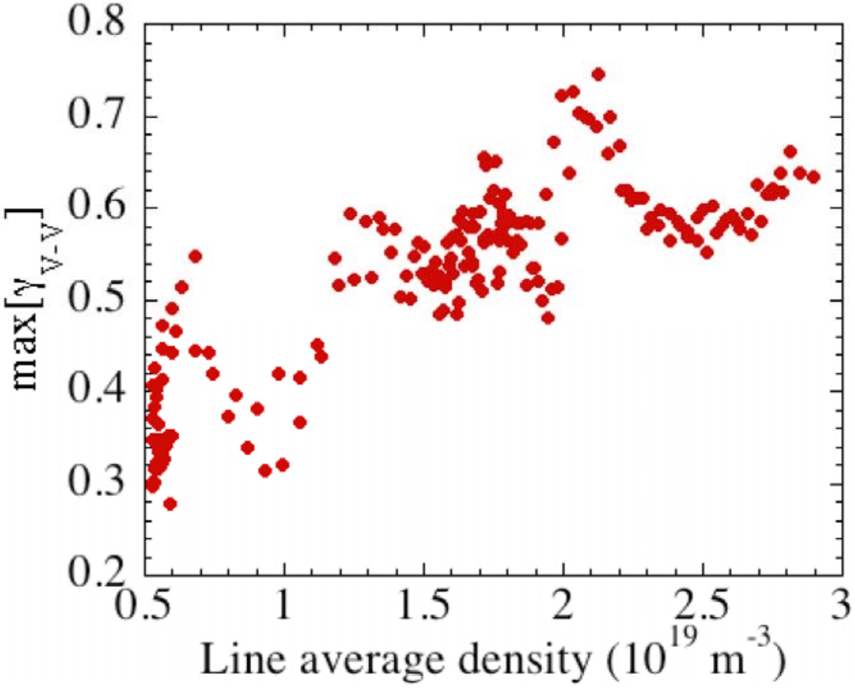


Multi-scale mechanisms (long-range correlations) as a new experimental fingerprint of the plasma behaviour during transport bifurcations

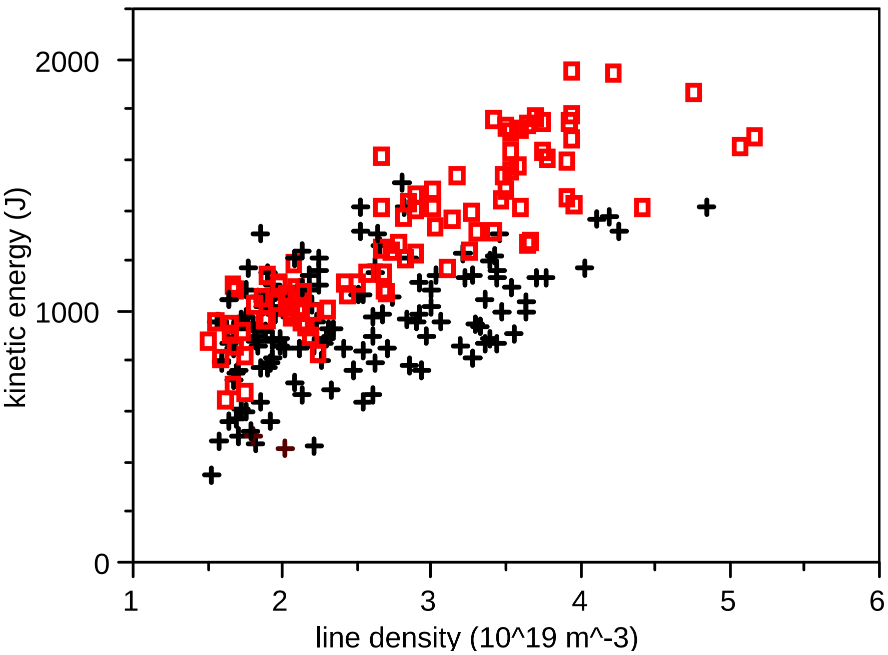
The S(k, w) function for long-range correlations (H-mode)



Long range (toroidal) correlations and confinement



M.A. Pedrosa, B.A. Carreras et al., December 2008

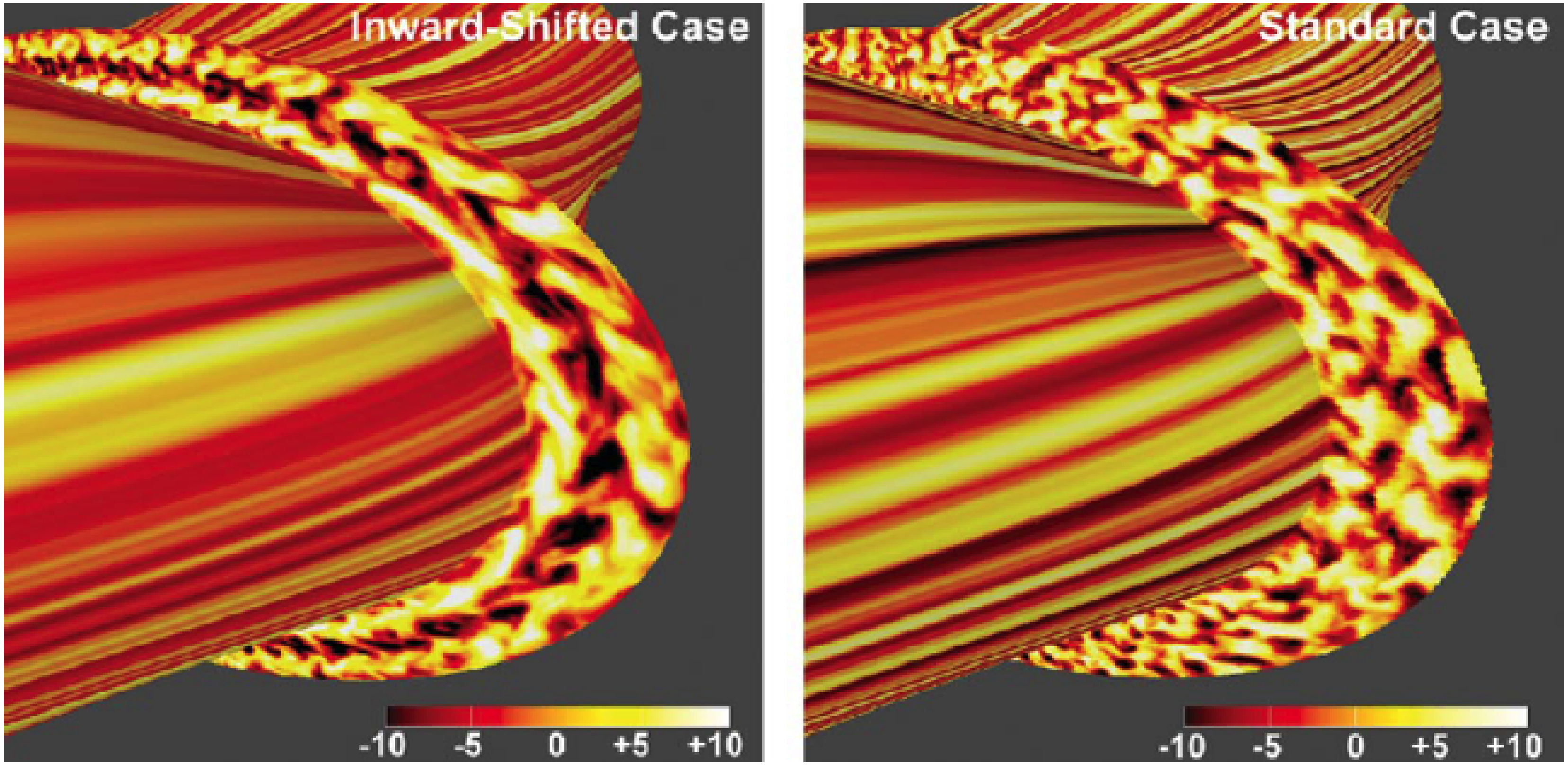


F. Tabarés et al., PPCF-2008 /
J. Sánchez et al., IAEA-2008

Both the degree of long range (toroidal) correlations and confinement increase with increasing plasma density in the TJ-II stellarator.

This correlation suggests the interplay between zonal flow enhancement and confinement in TJ-II.

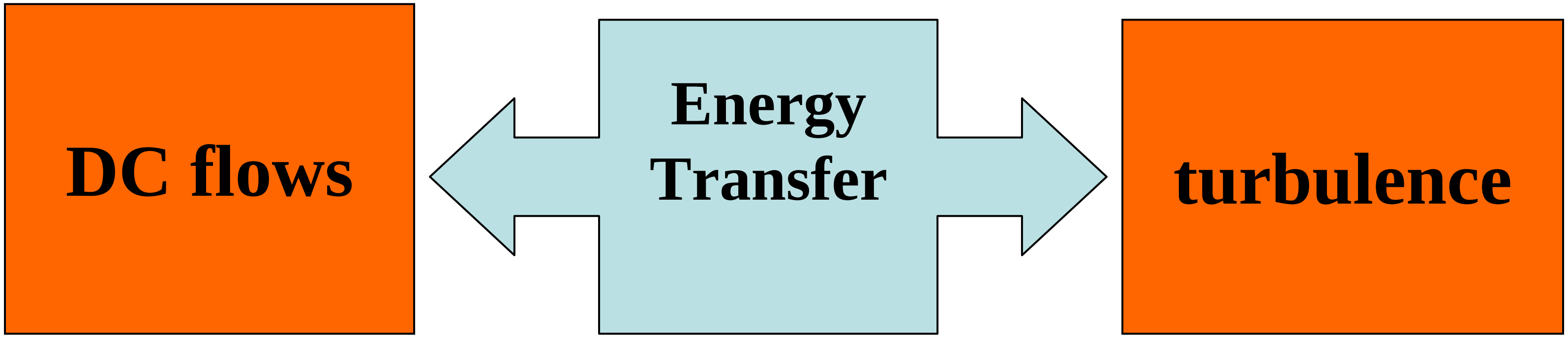
Interplay between flows driven by turbulence and neoclassical transport



In stellarator devices (LHD) zonal flows are enhanced in configurations with reduced neoclassical transport.

Watanabe et al., Phys. Rev. Lett 100 (2008) 195002.

Energy transfer computation



DC flows

Energy Transfer

turbulence

Equations for the mean flow (E) and turbulence (k) kinetic energy evolution

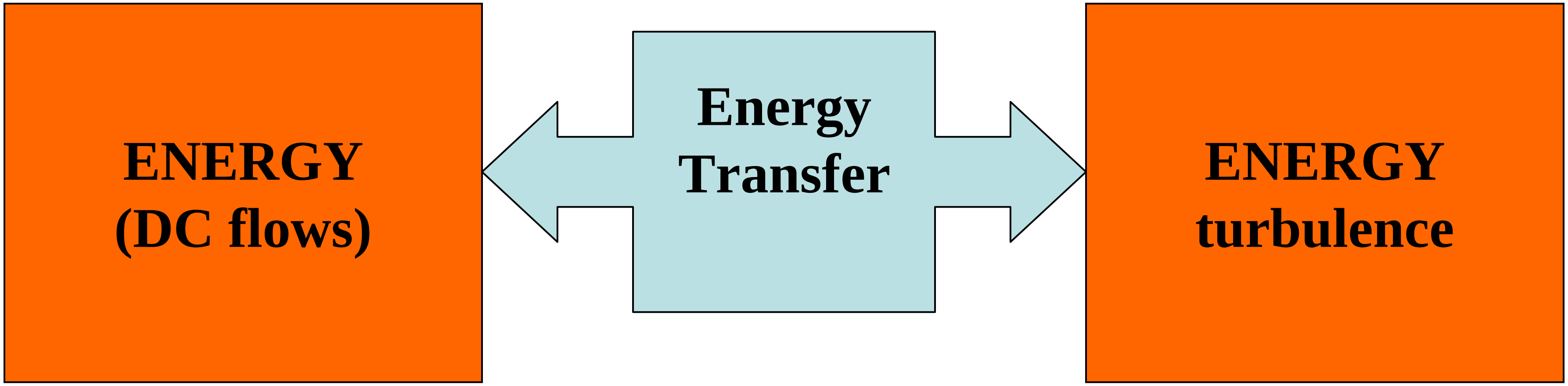
$$\left.\begin{aligned} \frac{dE}{dt} + \nabla \overline{T} &= -P - \overline{\varepsilon} \\ \frac{dk}{dt} + \nabla T' &= P - \varepsilon \end{aligned}\right\}$$

$$P \equiv - < v_i v_j > \frac{\partial < V_i >}{\partial x_j}$$

There are four terms in the k equation: the mean flow convection (dk/dt), the turbulent transport, the dissipation (ε) and the production (P).

It should be noted that the production term (P) appears with different sign both in the mean-kinetic-energy equation and turbulent-kinetic-energy equation

Zonal flows: 2-D or 3-D physics ?



ENERGY (DC flows)

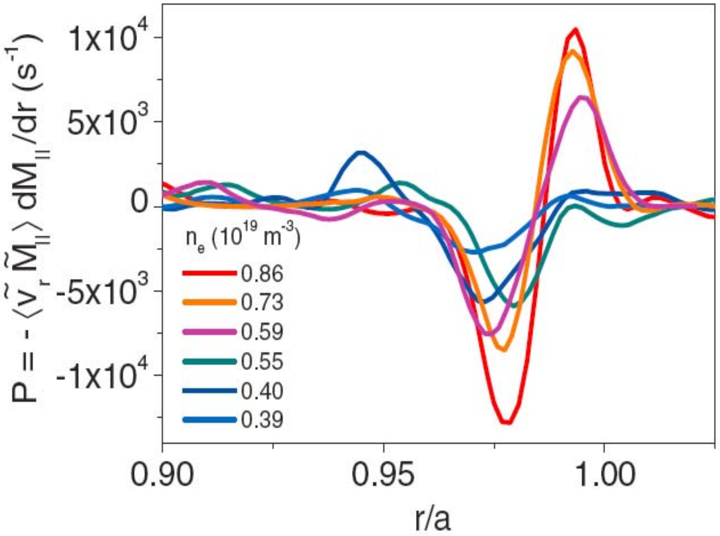
Energy Transfer

ENERGY turbulence

2-D $$P \approx -< v_\perp v_r > \frac{\partial V_\perp}{\partial r}$$

3-D $$P \approx -< v_\parallel v_r > \frac{\partial V_\parallel}{\partial r} - < v_\perp v_r > \frac{\partial V_\perp}{\partial r}$$

Quantifying the link between global (parallel) flows and turbulence: **energy transfer (TJ-II)**

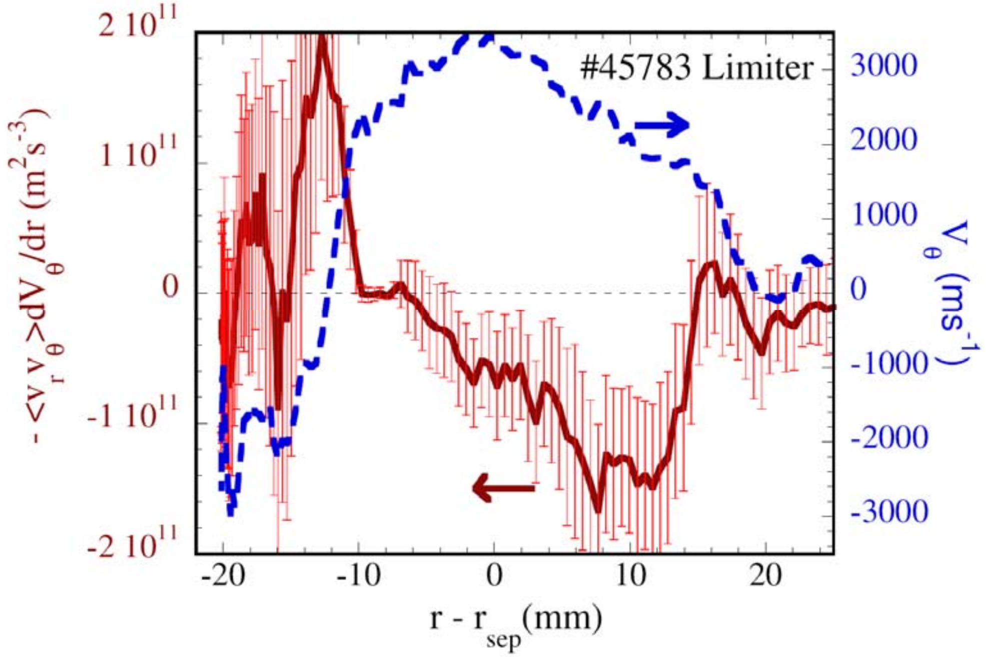


$$P \approx -< v_\parallel v_r > \frac{\partial V_\parallel}{\partial r}$$

Firts measurements of the production term (P) in the TJ-II stellarator show the importance of 3-D physics in the development of perpendicular sheared flows and the delopment of significat parallel turbulent forces.

B. Gonçalves et al., Phys. Rev. Lett. 96 (2006) 145001

Quantifying the link between global (perpendicular) flows and turbulence: **energy transfer (JET)**



$$P = < \tilde{v}_\perp \tilde{v}_r > \frac{\partial V_\perp}{\partial r}$$

It has been found that the energy transfer from DC flows to turbulence, directly related with the momentum flux (e.g.) and the radial gradient in the perpendicular flow, can be both positive and negative in the proximity of sheared flows.

These results show that turbulence can act as an energy sink and energy source for the mean flow near the shear layer, emphasizing the important role of turbulence to understand perpendicular dynamics in the plasma boundary region of fusion plasmas.

E. Sánchez et al., J. of Nuclear Materials 337 (2005) 296.

Conclusions

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There is evidence supporting the ExB shear paradigm in fusion plasmas. But the large uncertainties (e.g.) in the empirical description of the L-H transition power threshold, are reflecting the lack of basic understanding of the physics of sheared flows edge transport barriers.

Experimental findings show the importance of multi-scale physics mechanisms as a new finger print of the plasma behaviour during transport bifurcations providing a critical test for transition models.

Flows driven by turbulence (e.g. zonal flows) might explain such experimental observation, which would imply to consider the importance of 3-D effects on the energy transfer between flows and turbulence.

Comparative studies in different magnetic configurations (tokamak vs stellarators vs RFPs), diagnostic development and large-scale simulation are needed to assess the importance of multi-scale physics in the development of sheared flows.