Control of Turbulent Transport in Fusion Plasmas

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Objectives for 2D global ITG turbulence simulations in various magnetic configurations:

- bifurcation in turbulence properties and transport during the transition from monotonic to reversed q-profile;
- control of the quality of the ITB and bursty transport through the current profile shaping:
  - (a) effect of low-order value of minimum safety factor at shear reversal radius;
  - (b) effect of the curvature of q-profile;
- dependence of turbulent diffusivity on magnetic shear

Objectives for 3D RBM simulations:

- effect of large imposed ExB rotation shear on turbulence properties;
- ExB shear stabilization of turbulent transport *(scaling with magnetic field and ExB shear, bifurcation, power threshold)*
- dynamics of transport barrier and confinement in the presence of large ExB shear

Asssumptions

- Resistive ballooning model
- Electrostatic fluctuations
- Fixed flux
- q profile monotonic between the rational surfaces $q = 2$ and $q = 3$
- $E \times B$ rotation shear externally imposed
- No self–generated $E \times B$ flow : the Reynold stress is artificially suppressed.

Model for Resistive Ballooning Modes (RBM)

The normalized model concists of a pressure and vorticity equation :

$$\frac{\partial}{\partial t}(\Delta_\perp \phi) + \{\phi, \Delta_\perp \phi\} = -\Delta_\parallel \phi - Gp + \nu \Delta_\perp^2 \phi - \alpha \Delta_\perp (\phi - \phi_0),$$

$$\frac{\partial p}{\partial t} + \{\phi, p\} = \chi_\parallel \Delta_\parallel p + \chi_\perp \Delta_\perp p + S_0,$$

where p, ϕ are the complete pressure and potential fields.

Note that the term $-\alpha \Delta_\perp (\phi - \phi_0)$ stands for the imposed $E \times B$ flow : it physically represent a friction term.

Radial Geometry of the 3D Model

Heat transport equation:

$$\partial_t \langle p \rangle = -\partial_r \left(\Gamma_{\text{turb}} + \Gamma_{\text{coll}} \right) + S$$

Statistically stationary state:

$$\Gamma_{\text{turb}} + \Gamma_{\text{coll}} = \int_{r_{\text{min}}}^{r} S dr'$$

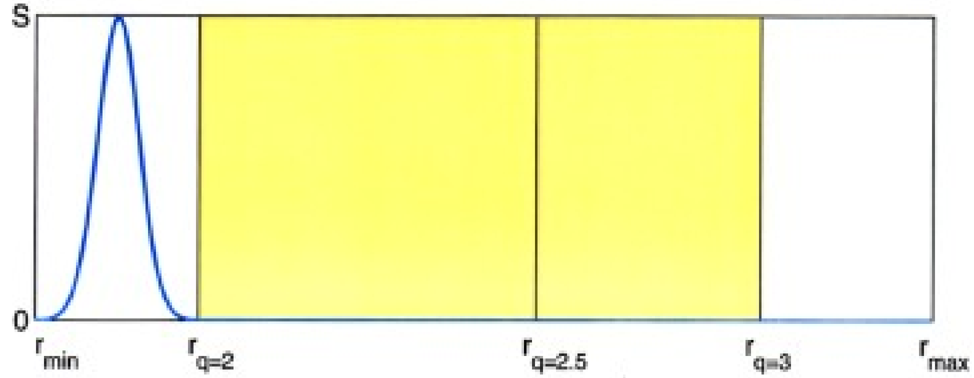
Impose local ExB shear:

$\Rightarrow \Gamma_{\text{turb}} \searrow$

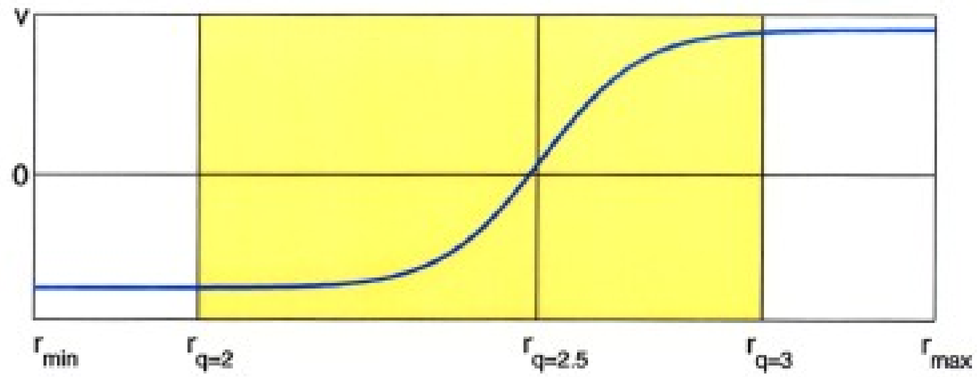
$\Rightarrow \Gamma_{\text{coll}} = -\chi_{\text{coll}} \partial_r \langle p \rangle \nearrow$

$\Rightarrow |\partial_r \langle p \rangle| \nearrow$

$\Rightarrow$ transport barrier

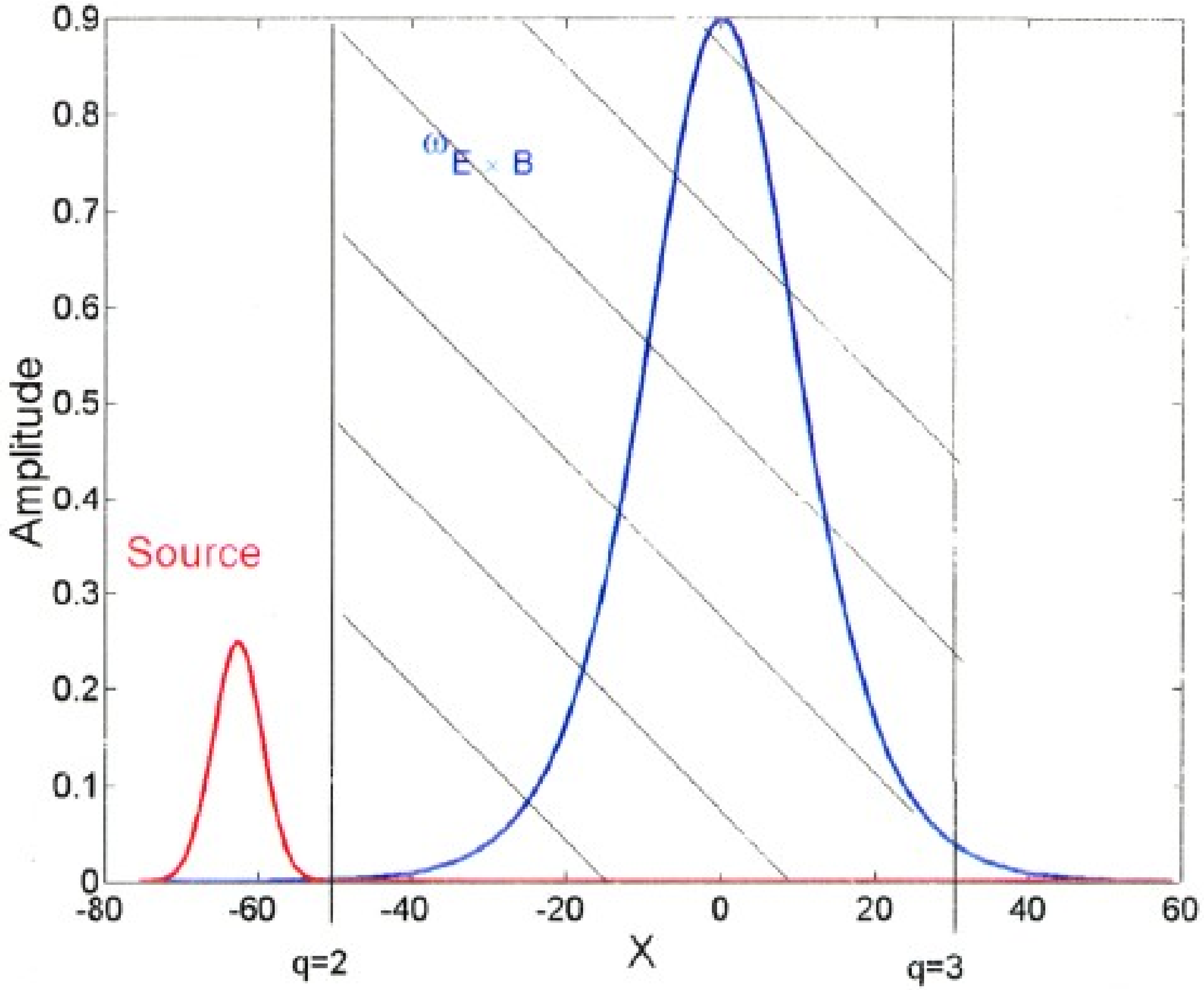


source profile



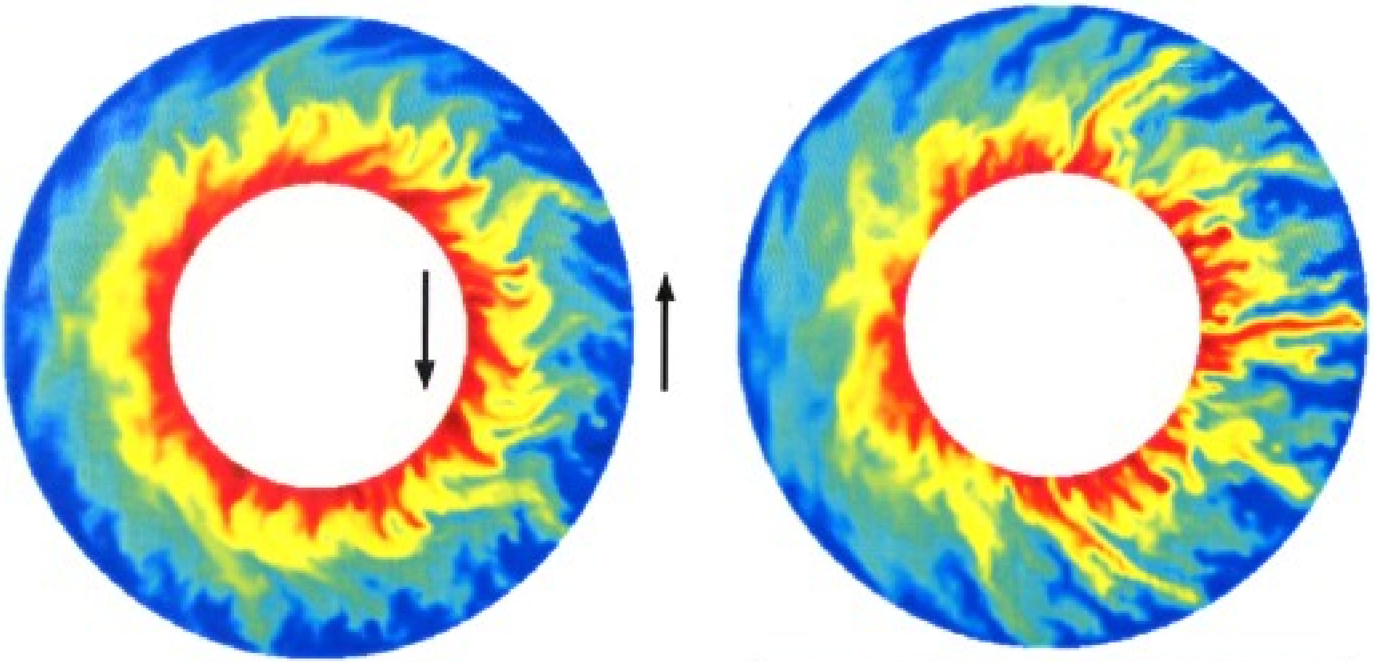
poloidal flow profile

The normalized shearing parameter $\omega_{E\times B}$ has a Gaussian radial profile and its amplitude, α has been varied from 0 (shearless case) to 0.9.



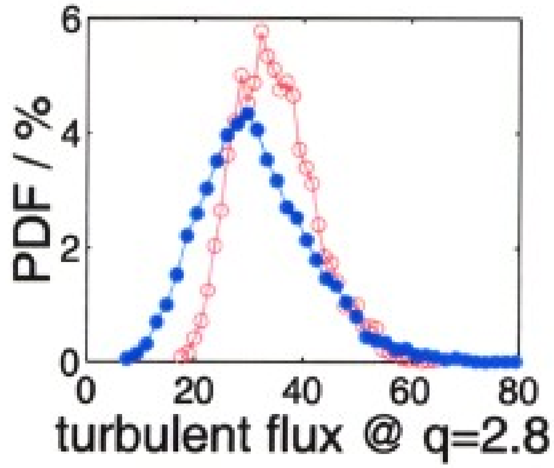
Turbulent transport: radially propagating events, zonal flows → more rapidly fluct., lower amplitude bursts

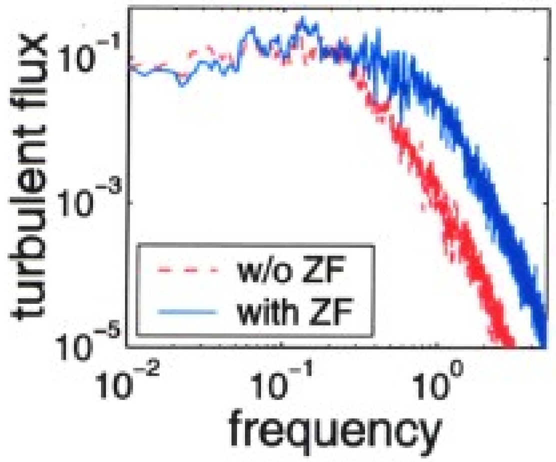
snapshots of pressure in poloidal plane



with self consistent mean & zonal flows

flows suppressed → more large bursts

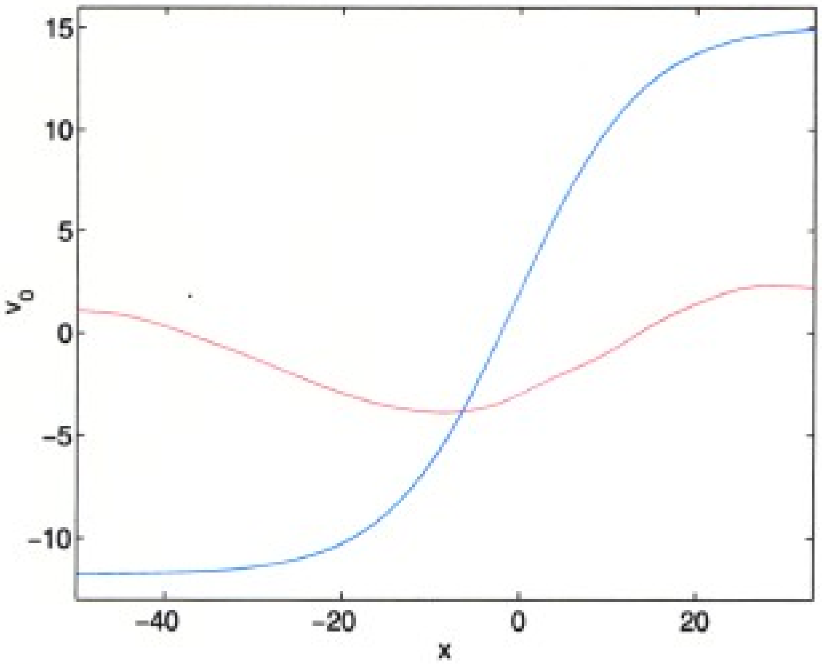




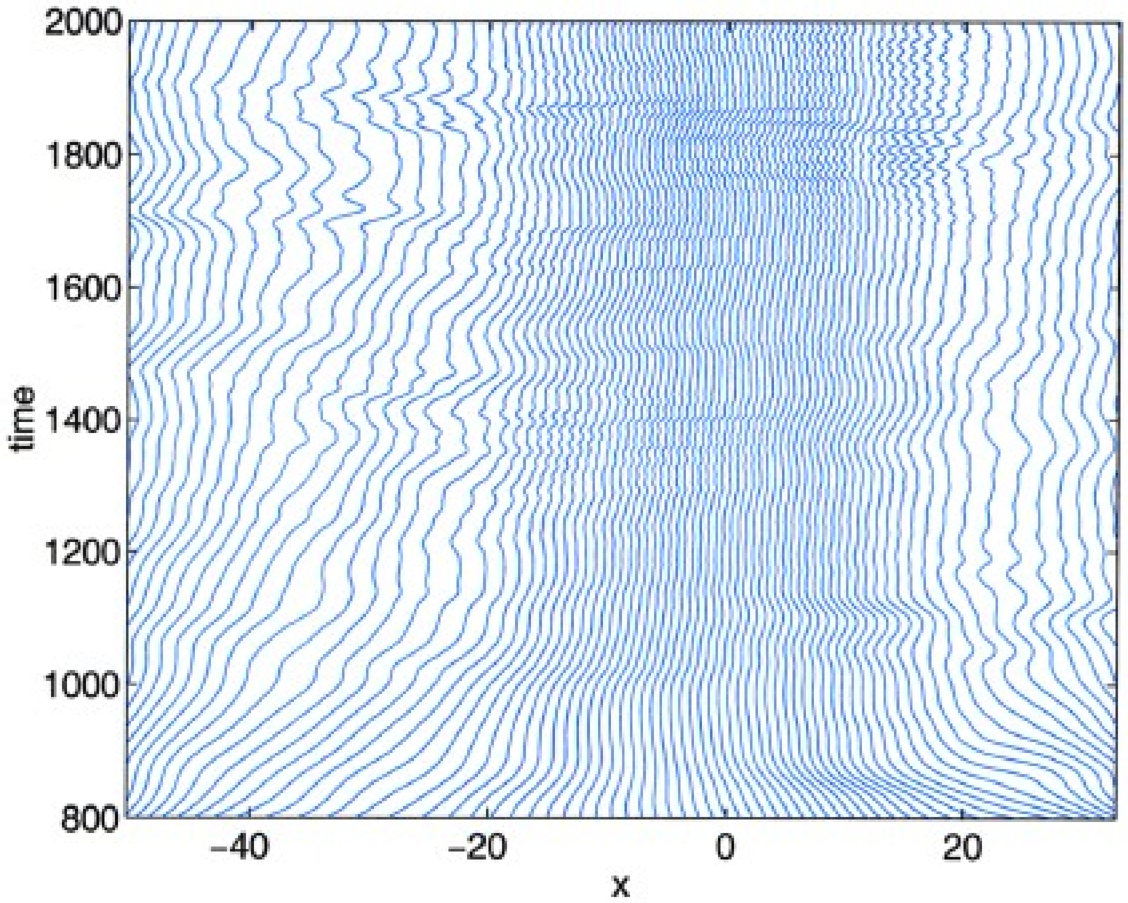
Dynamics of Bursts in Transport Barriers

- What occurs to large scale transport events in presence of a transport barrier?
- Hahm–Diamond 95, Newman et al. 96: change in the dynamics of avalanches.
- Speculation: a strong shear flow should limit the extension of a streamer.

Fully developed turbulence
+ Externally imposed strong shear flow (1)



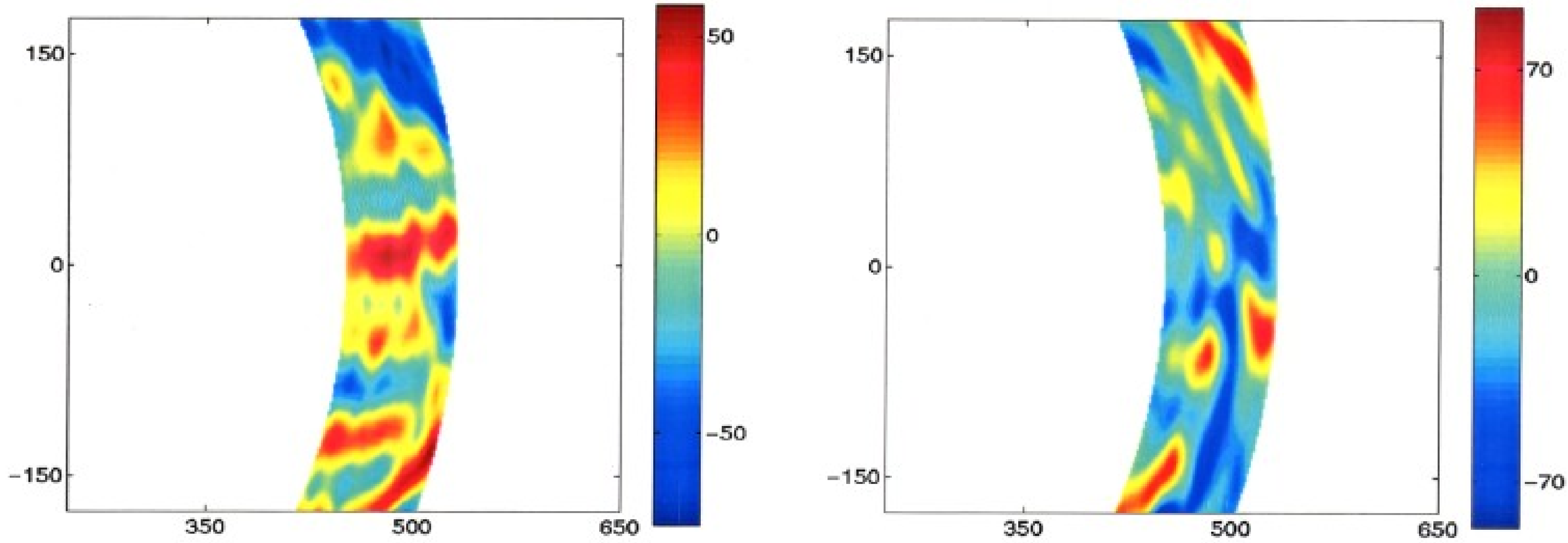
profile of rotation



flux surface averaged pressure

Strong shear flow breaks up large convection cells

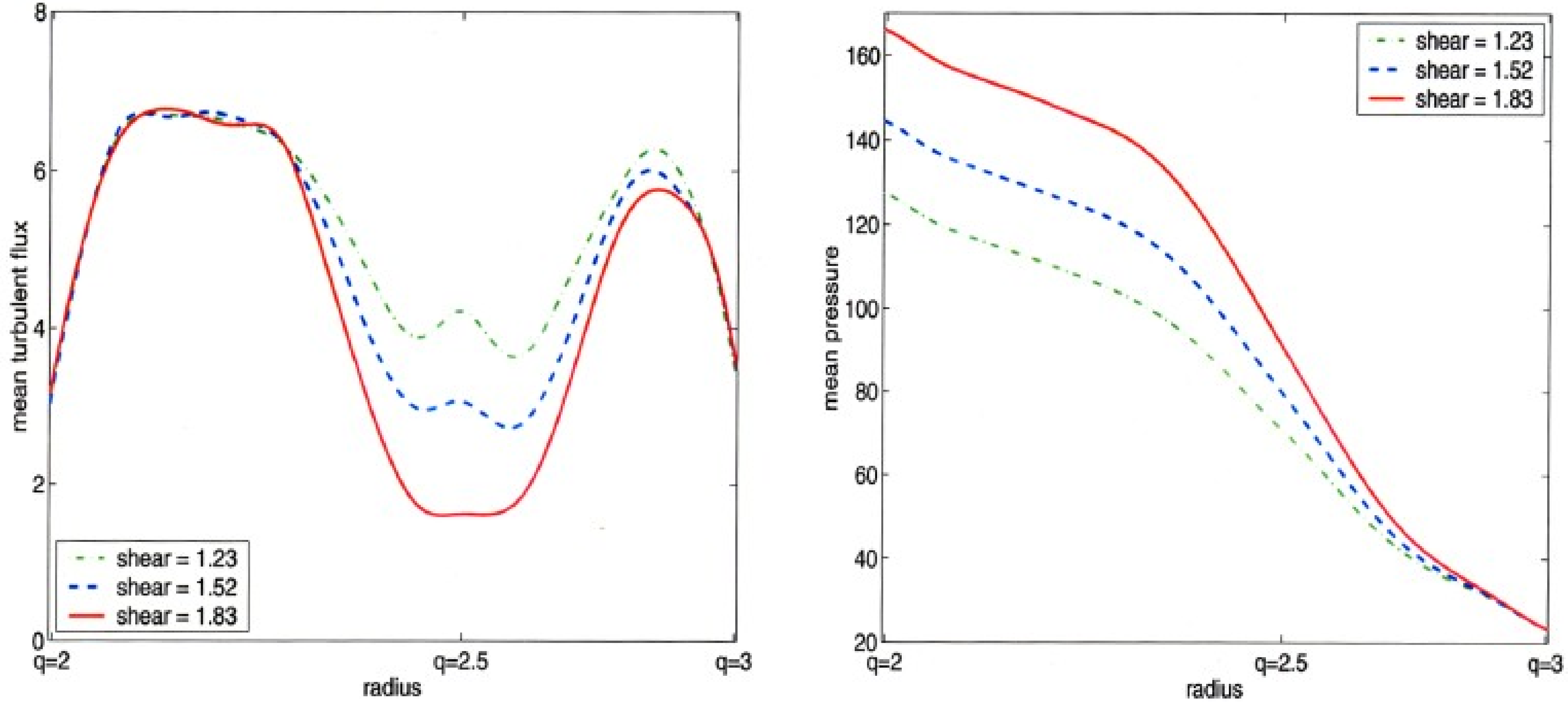
maps of potential in poloidal plane



without shear flow

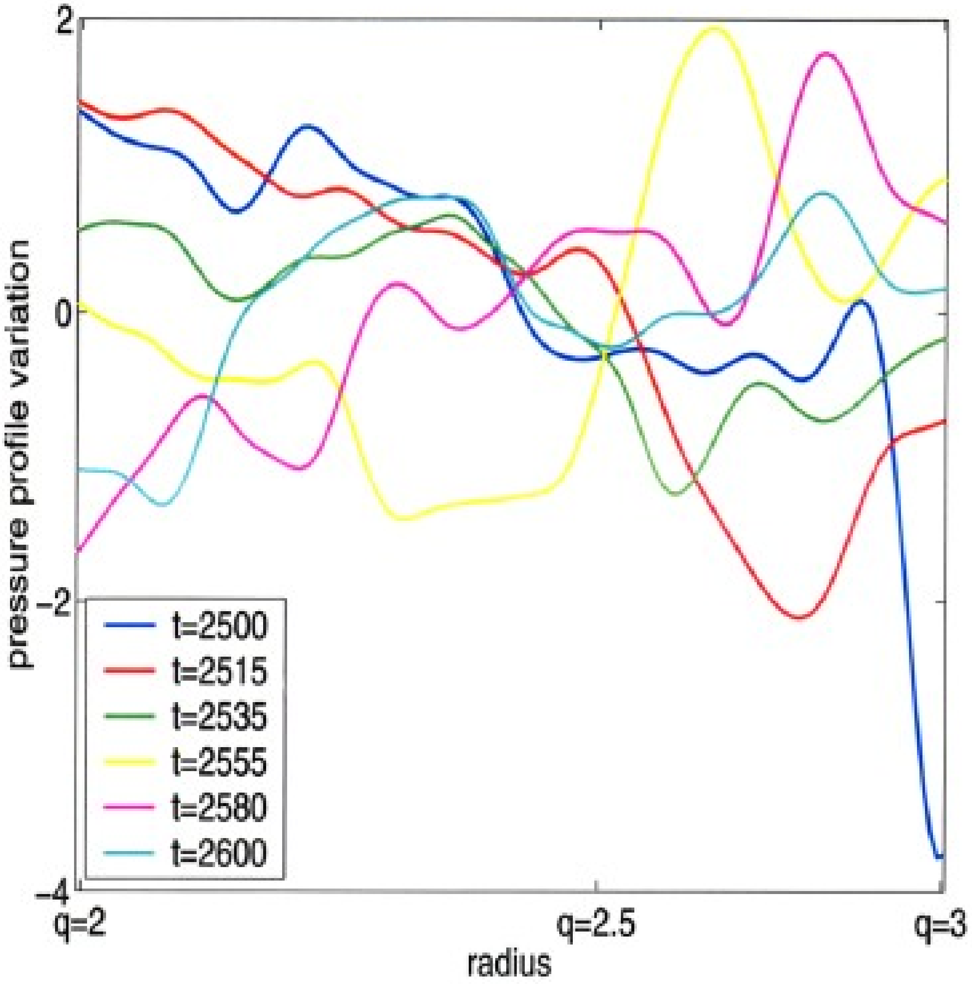
with shear flow

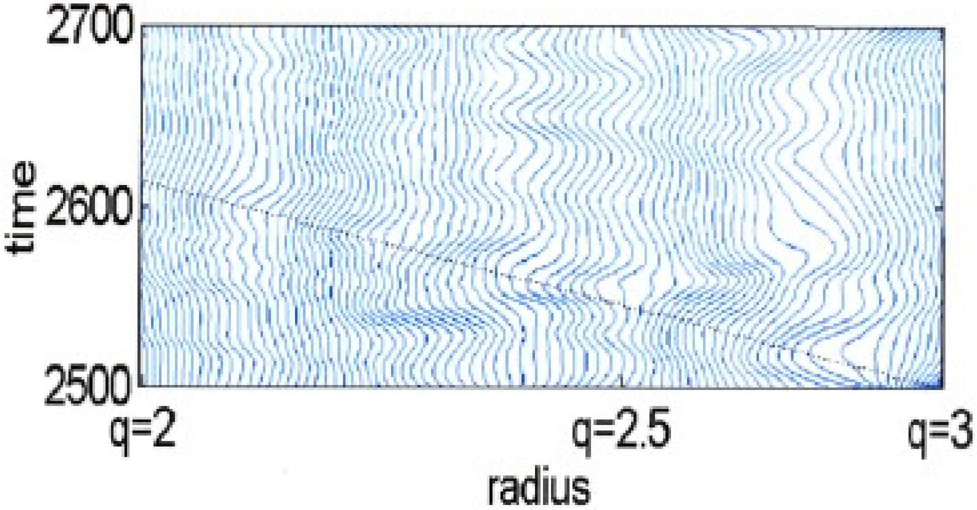
Time averaged profiles



Turbulent flux reduces and pressure gradient increases in the velocity shear layer with increasing shear.

Penetration of a pressure perturbation (w/o barrier)





Low pressure blop propagates radially inwards with $v_{blob} \approx 370 \frac{m}{s}$.

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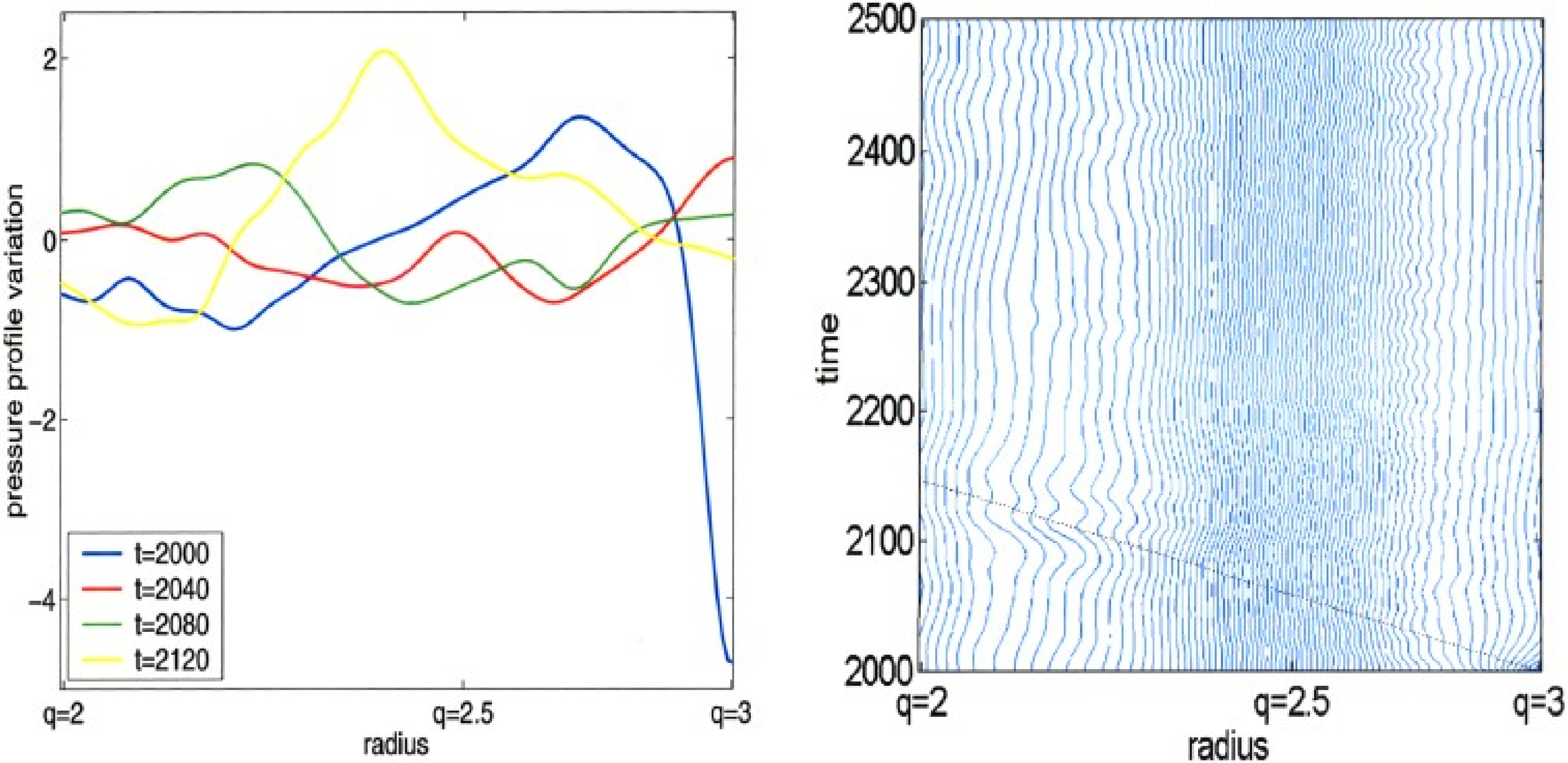
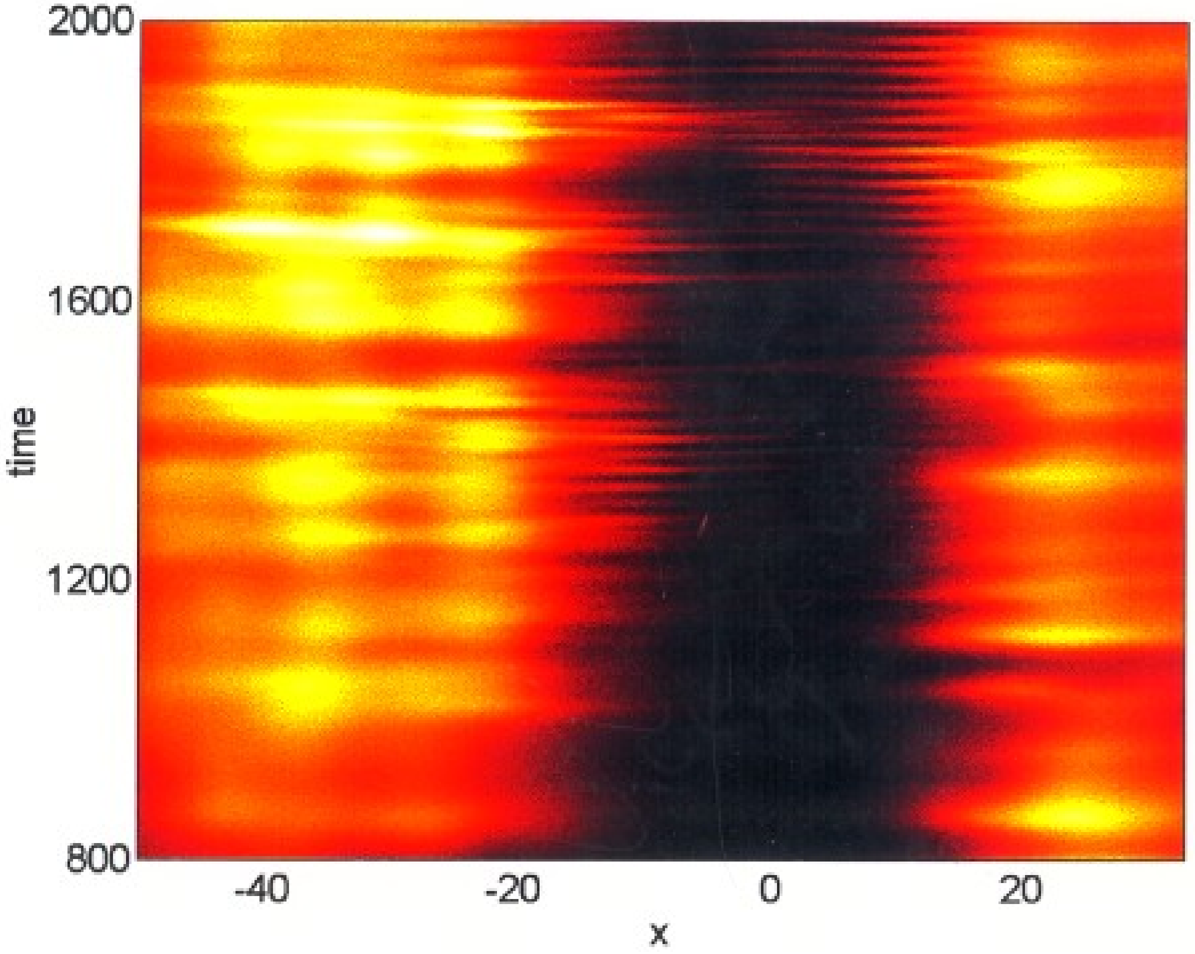
Penetration of a pressure perturbation (with barrier)



Low pressure blop induces perturbation on inner side of barrier, $v_{bl} \approx 260\frac{m}{s}$.

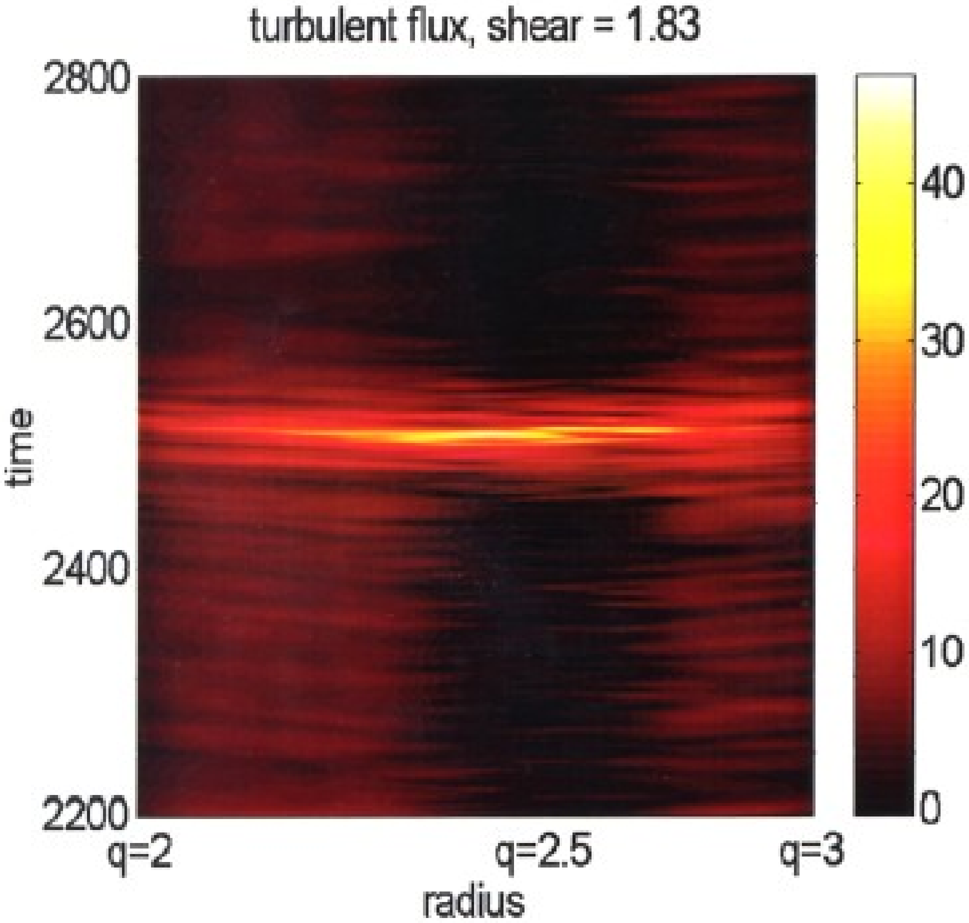
Transport Barrier in RB (cont.)

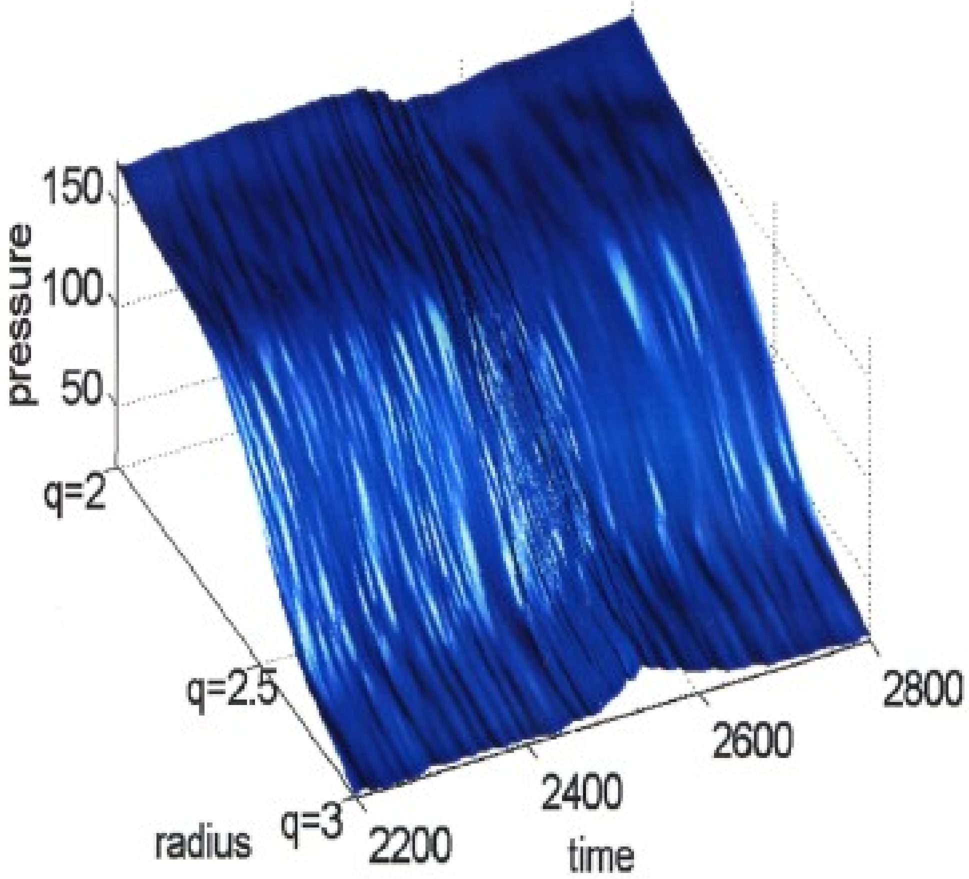
- Suggests an effect of velocity shear on the propagation of a streamer
- Some events cross barrier: open question.



turbulent flux versus radius and time
min = -0.1 (black), max = 3.8 (white)

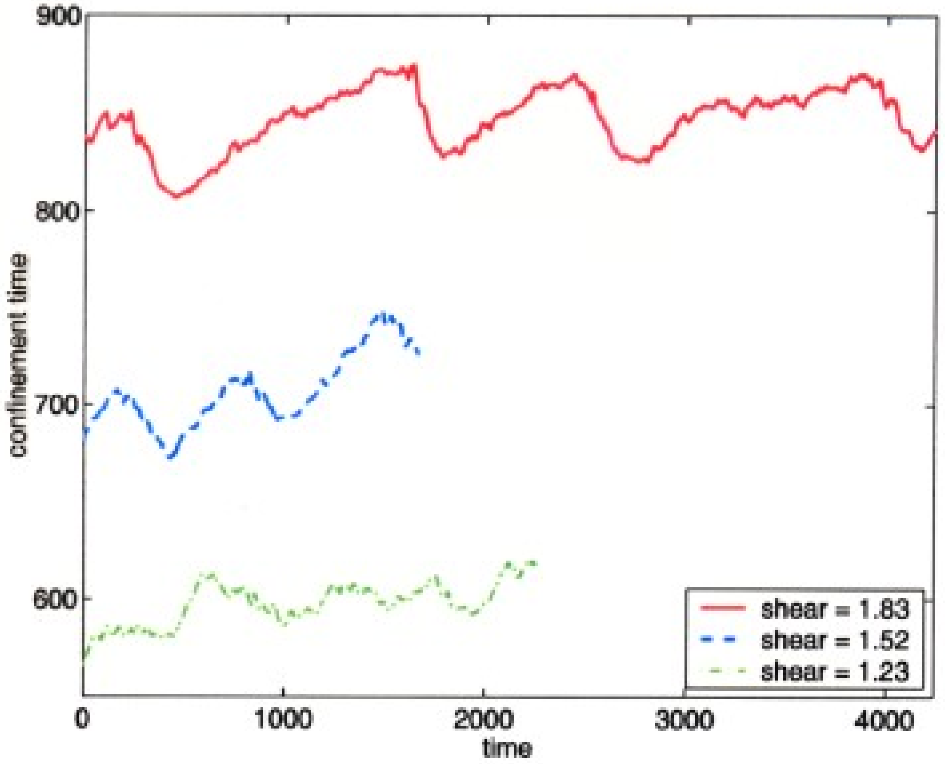
Barrier relaxation

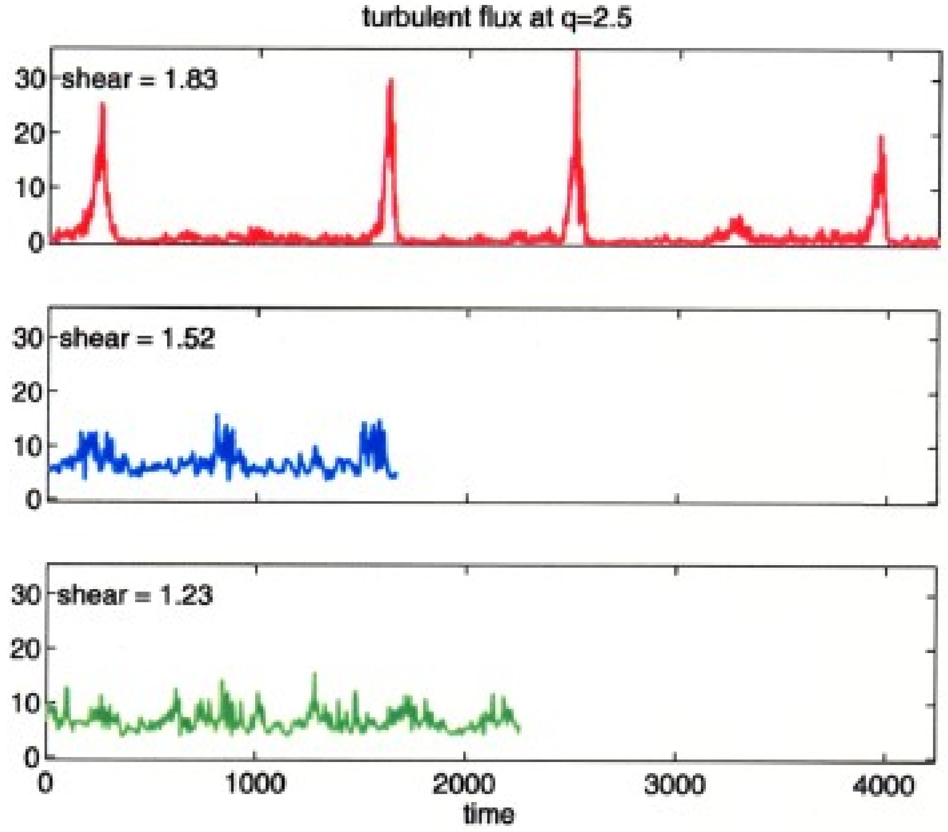




Erosion of the barrier by succession of several large bursts.

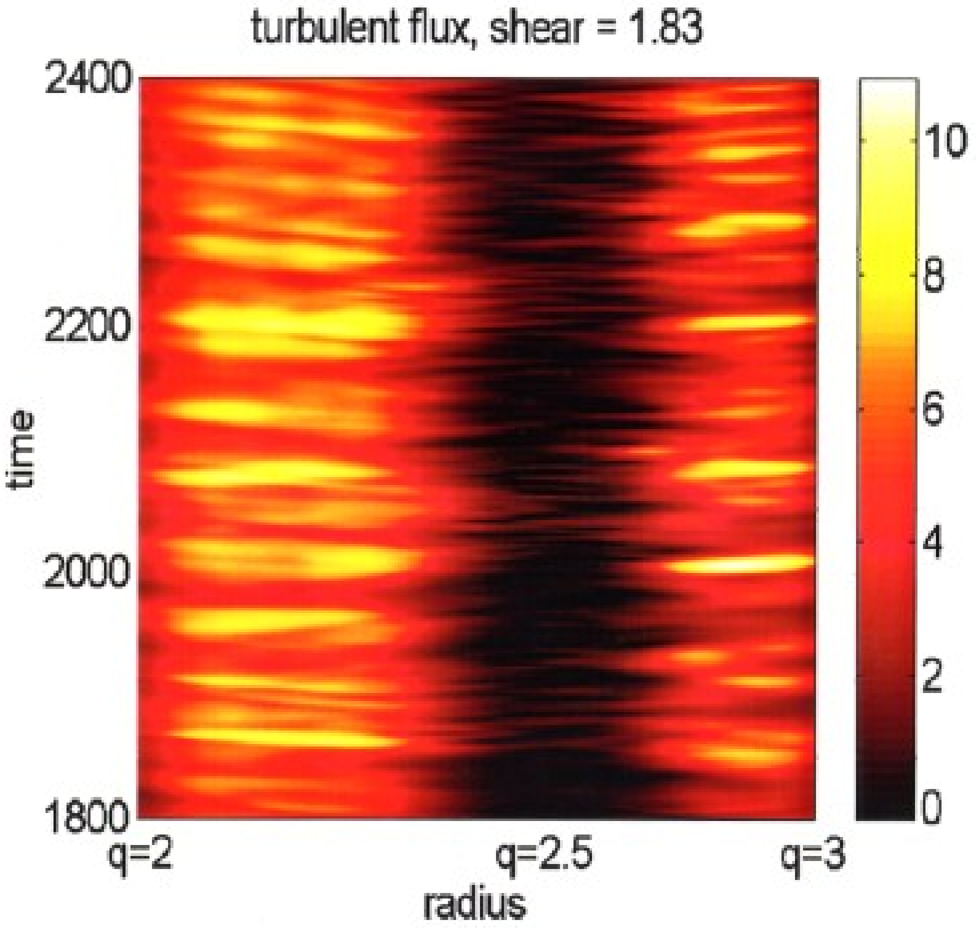
Dynamique de la barrière I

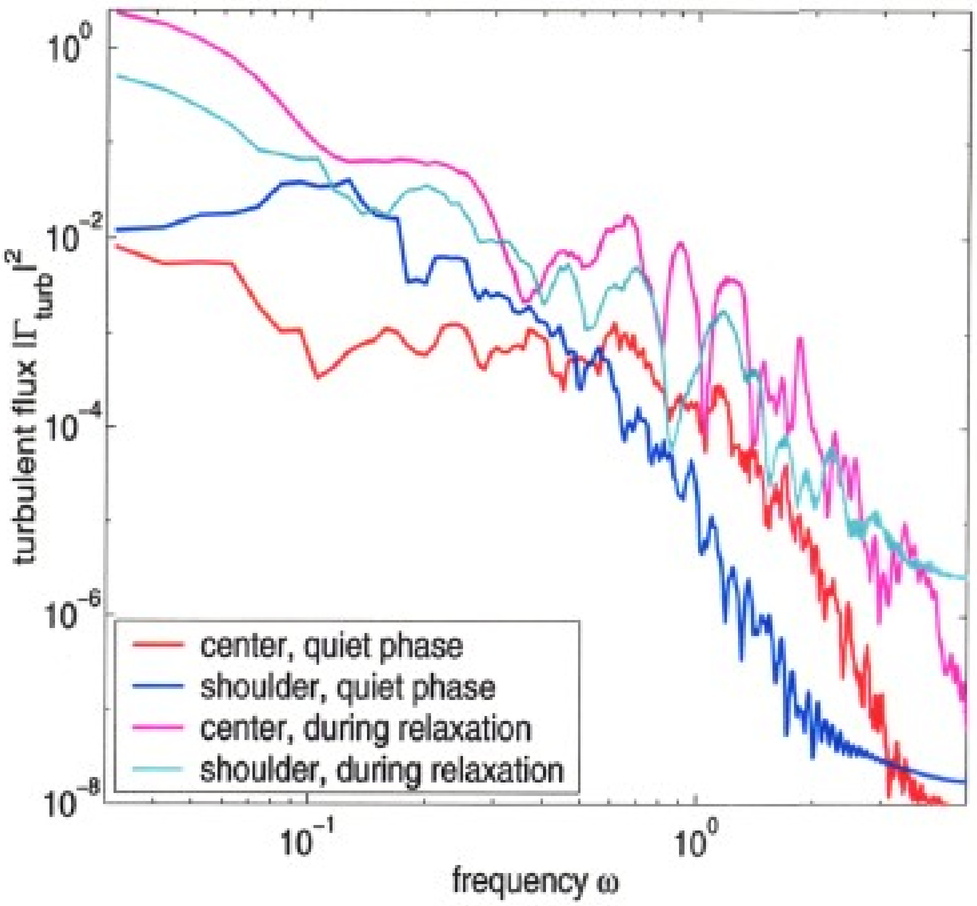




- Cisaillement de vitesse fort $\longrightarrow$ oscillations de relaxation de la barrière.
- Pression $\uparrow$ pendant $t \sim \tau_{conf}$ $\leftrightarrow$ phase quiescente, suivie d'un événement de relaxation.

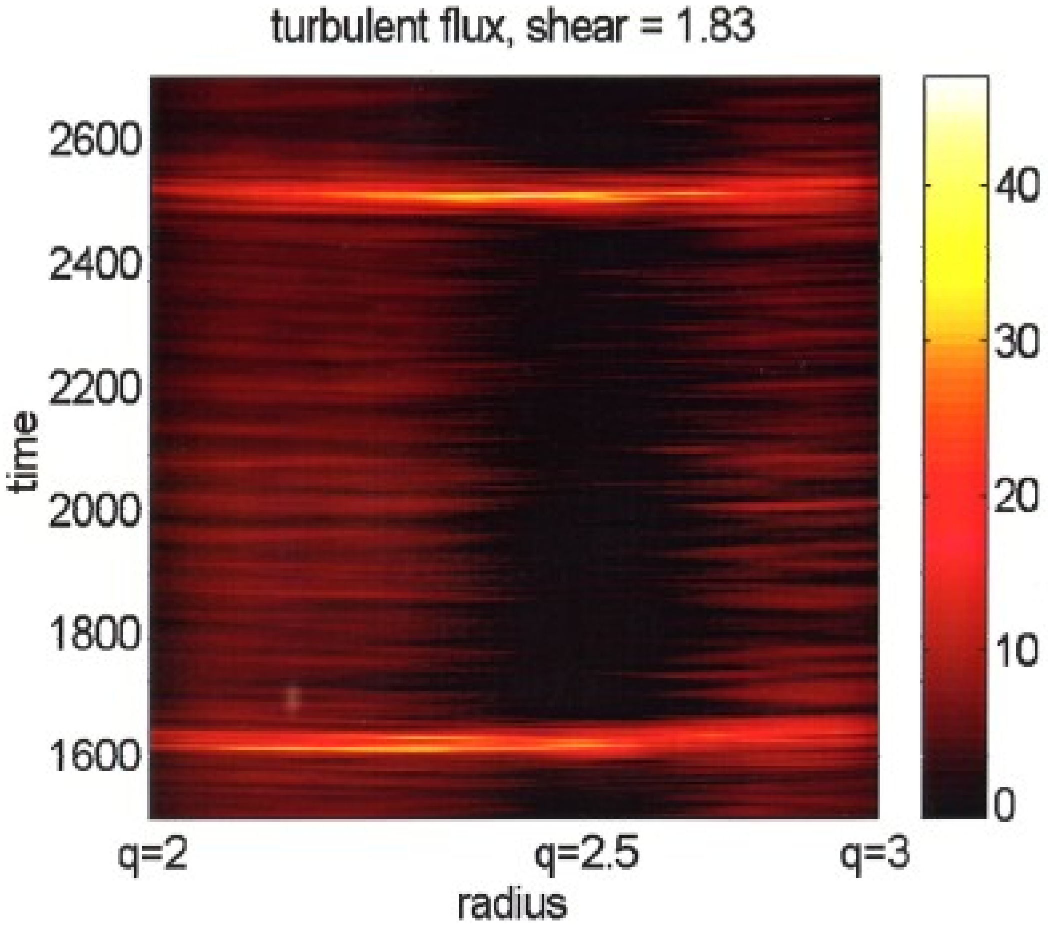
Burst dynamics during quiet phase

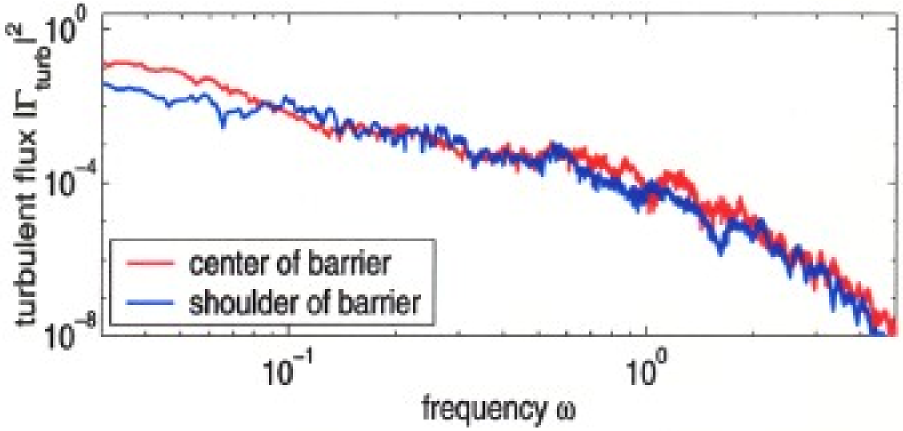


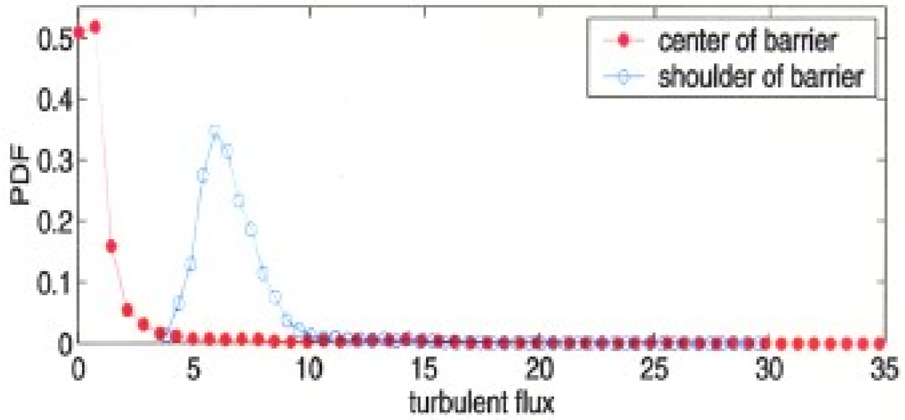


- Bursts are suppressed in the center of the barrier.
- Low frequency comp. are reduced, high frequency comp. are enhanced.

Barrier dynamics II

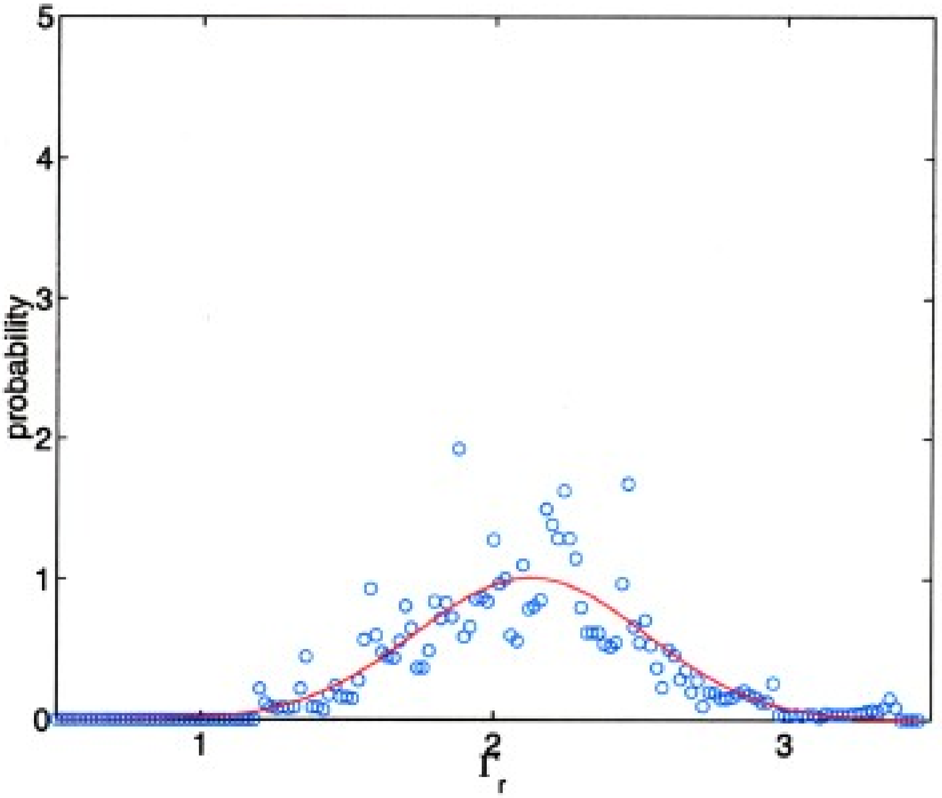




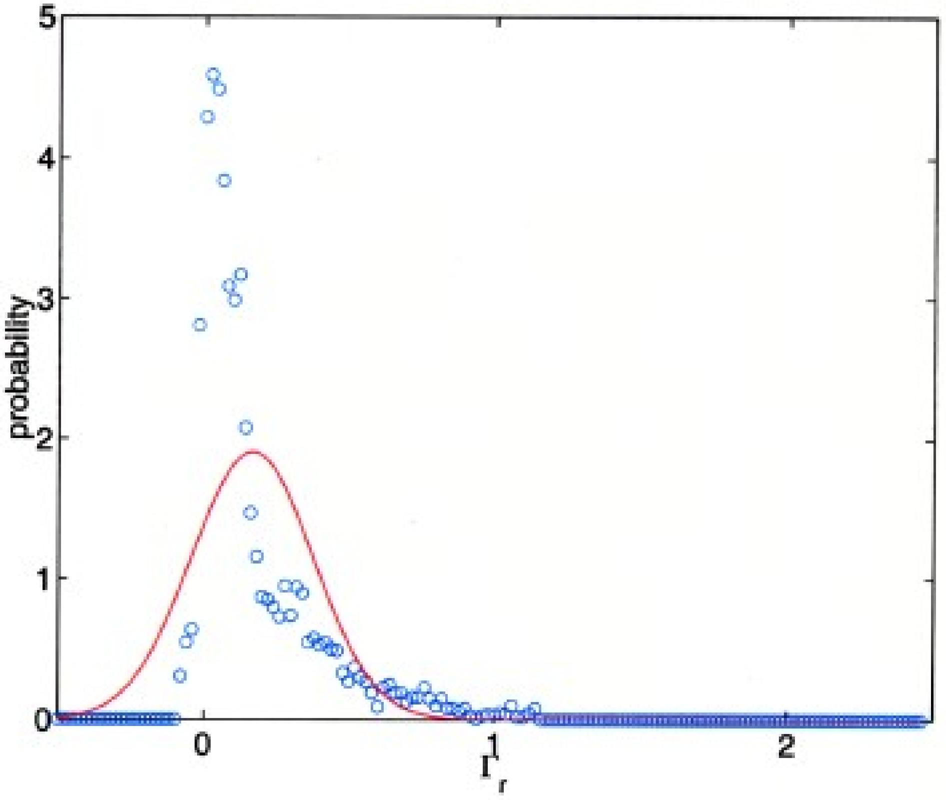


- Frequency spectra in center and at shoulder of barrier are similar.
- Turbulent flux PDF is peaked at low fluxes, highly asymmetric in center.

Probability distribution function of the radial flux



shoulder of barrier



center of barrier

Introduction

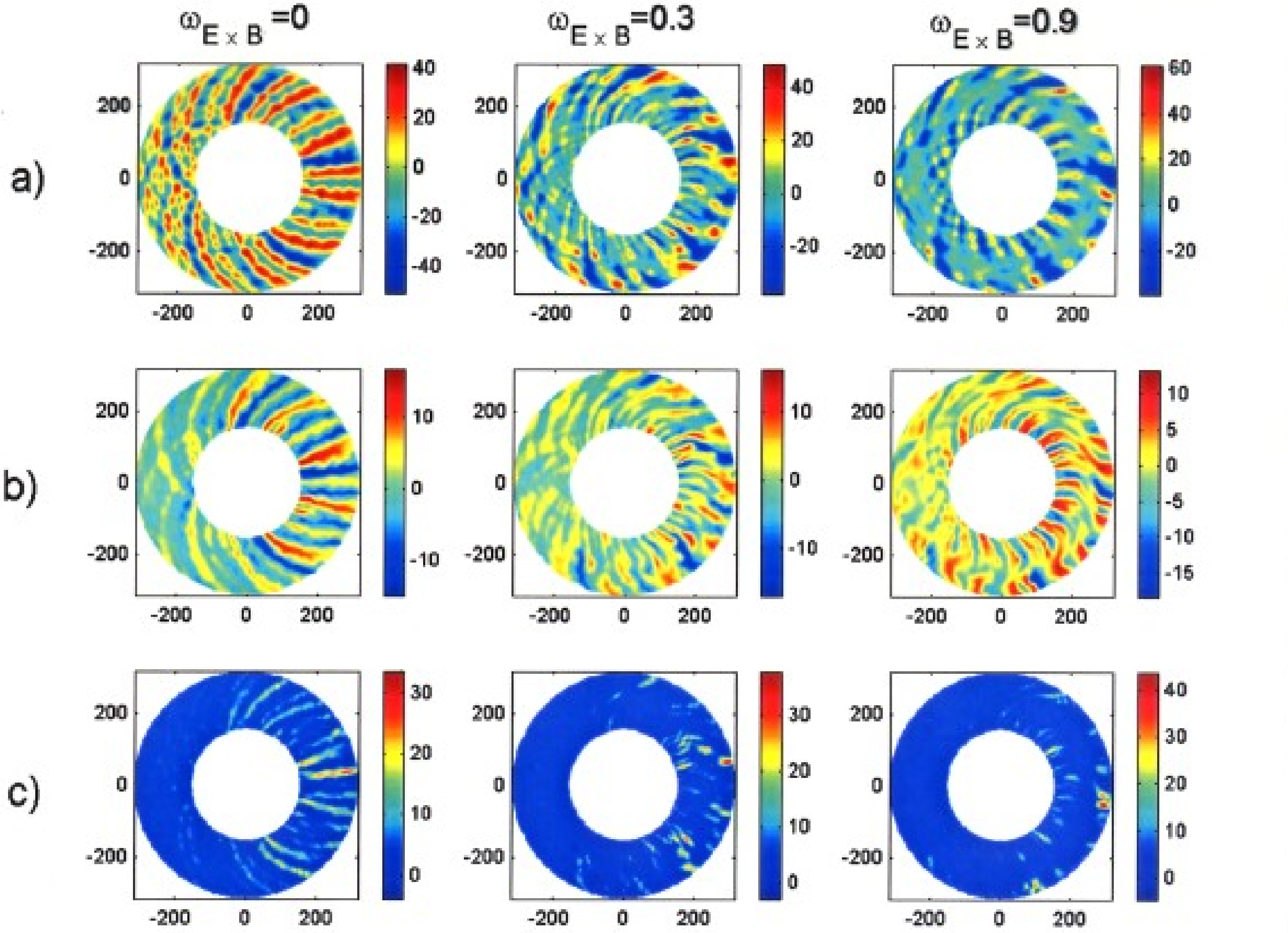
Motivation :

- $E \times B$ velocity shear $\Rightarrow$ transport and turbulence reduction (BDT, PoF 1990...Terry, RMP 2000)$\Rightarrow$ improved regime with transport barriers.
- Empirical model for $\chi = \chi(\rho^*, \nu^*, \beta)\ F(s, \nabla E_r)$: Form of $F(s, \nabla E_r)$?
- $E \times B$ velocity shear flow affects the fluctuations and their cross–phase (Carreras et al. PoP 1995; Ware et al. PPCF 1996; Ware et al. PoP 1998) .

Work :

- Effect of an externally imposed $E \times B$ velocity shear on turbulence and transport using the 3D global code for Resistive Ballooning Modes : RBM3D.

Transport Reduction by Rotation shear



a) Potential
b) Pressure
c) Turbulent flux

$\mathbf{E} \times \mathbf{B}$ rotation shear effect on transport

- Scaling of

$$\chi = -\frac{\Gamma}{\nabla p} = \chi(\rho^*, \nu^*, \beta)\ F(\nabla E_r)$$

- Scaling of the fluctuation level $< \tilde{v_r}^2 >^{1/2}, < \tilde{p}^2 >^{1/2}$ with shear

Cross–phase effect on transport

$$
\begin{aligned}
<\Gamma> &= <\tilde{v_r}\tilde{p}> \\
&= <\tilde{v_r}^2>^{1/2}<\tilde{p}^2>^{1/2} \; \frac{<\tilde{v_r}\tilde{p}>}{<\tilde{v_r}^2>^{1/2}<\tilde{p}^2>^{1/2}} \\
&= <\tilde{v_r}^2>^{1/2}<\tilde{p}^2>^{1/2} \; \cos\delta_{v_r p}
\end{aligned}
$$

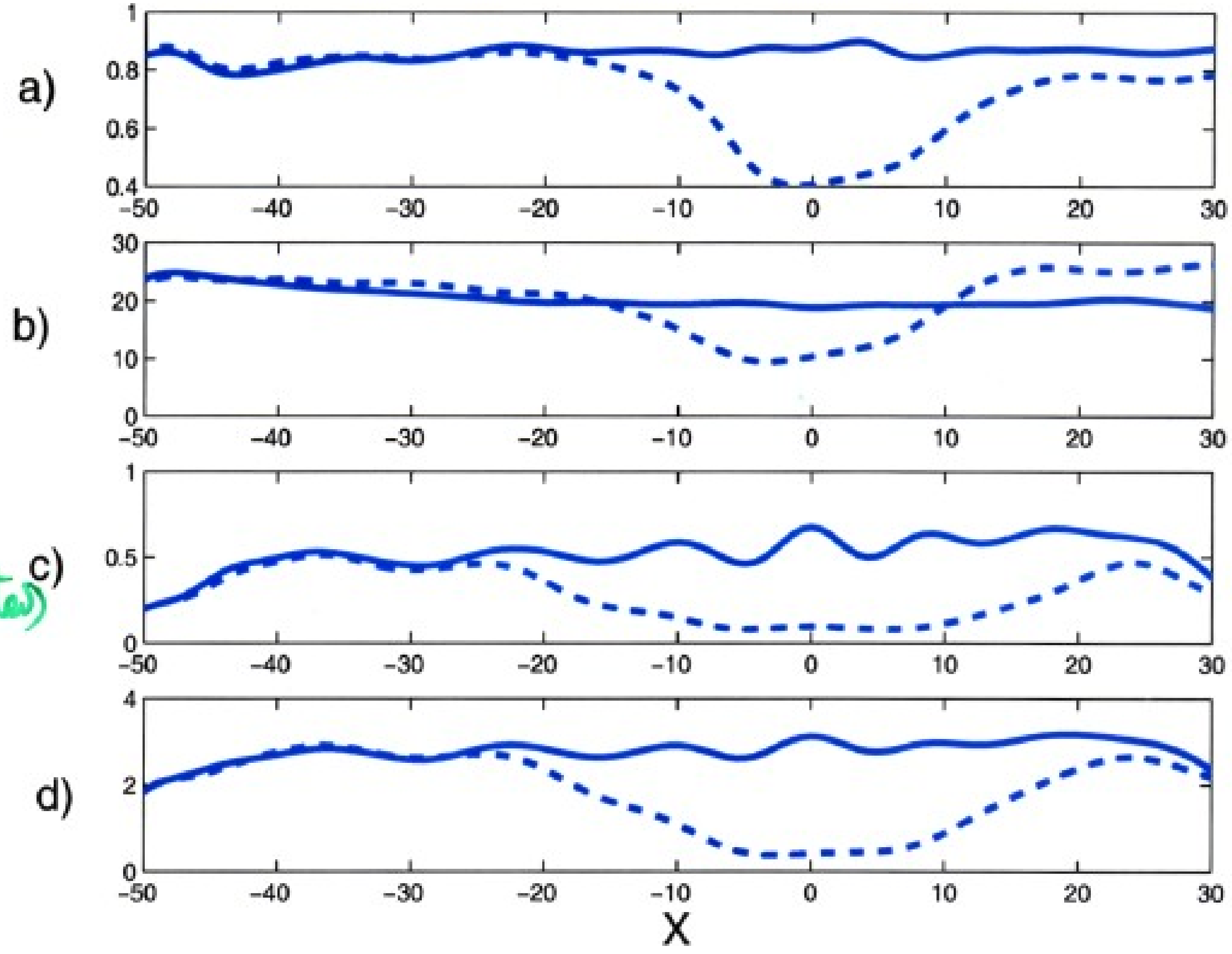
where $\cos\delta_{v_r p}$ stands for cross–phase cosine between $\tilde{v_r}$ et $\tilde{p}$. With $v_r = v_{E\times B}\cdot\mathbf{r} = -\partial_y\phi$, $E = -\nabla\phi$.

a) Cross–phase $\cos\delta_{v_r p}$

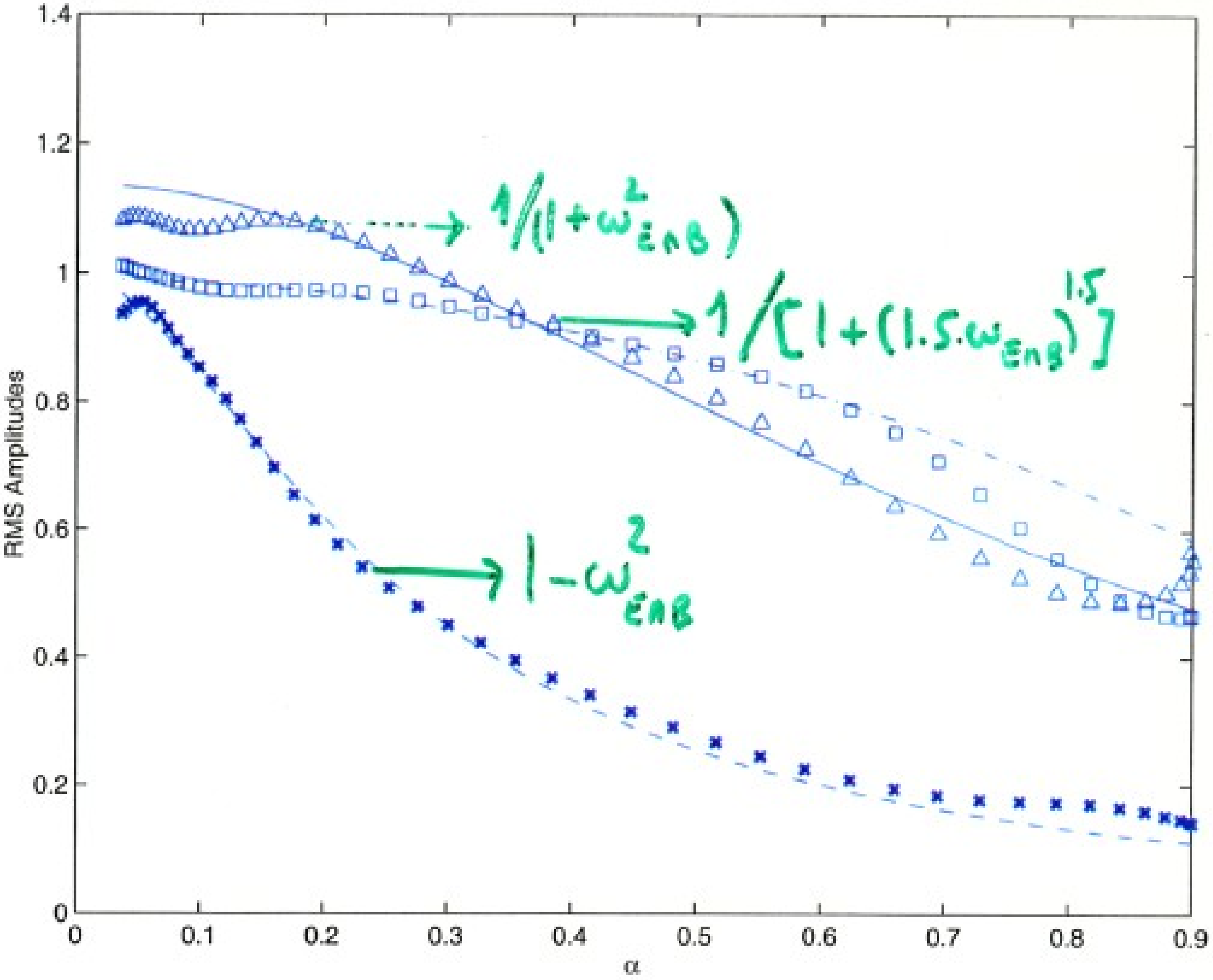
b) Pressure fluctuations

c) v_r fluctuations (More Affected)

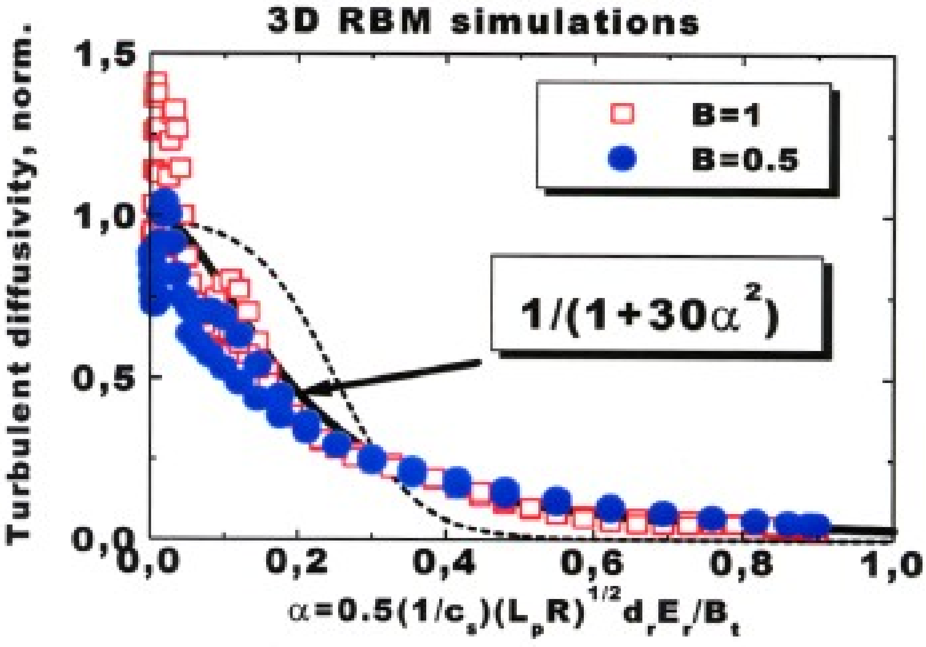
d) Turbulent flux profiles for the shearless case (solid lines) and strong rotation shear (dashed lines).



$\mathbf{E} \times \mathbf{B}$ shear scaling of fluctuation level for RMS pressure (triangles) radial velocity (crosses) cross–phase (squares) respectively fitted with solid, dashed and dotted lines



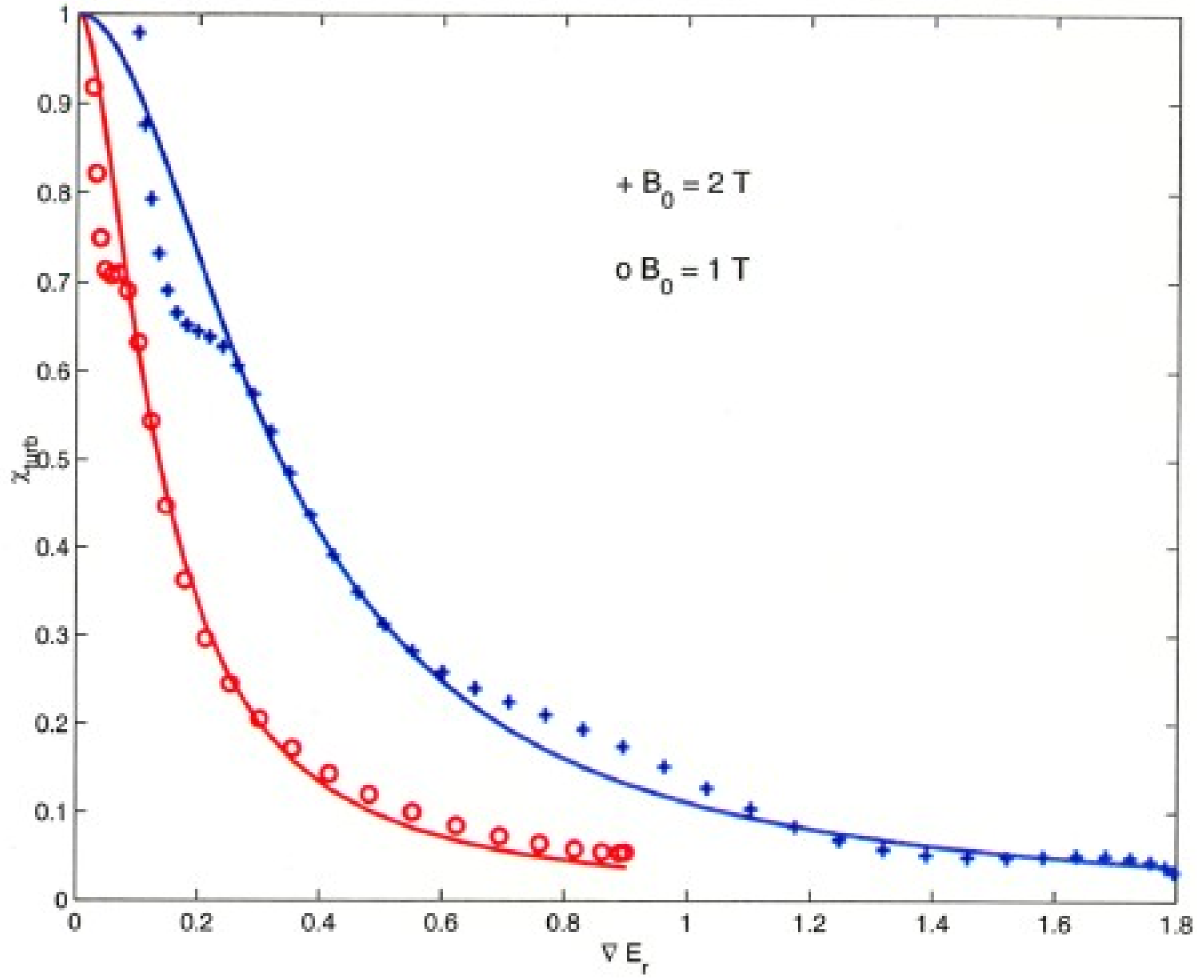
ExB rotation shear stabilization of RBM driven transport



No threshold in the ExB shear suppression of turbulent transport:

the thermal diffusivity is reduced even at low shear

Good Agreement with
Textor results
JACHNICHS et al, PPCF (00)



Turbulent diffusivity as a function of ∇E_r for $B_0 = 2T$ (+) and $B_0 = 1T$ (0). The solid lines are analytical fit :

$$F(\nabla E_r) = \frac{1}{1 + (\frac{\nabla E_r}{\nabla E_{r\,crit}})^2}$$

Model for ITG turbulence

$$d_t N_i - \nabla\left[\frac{N_i m_i}{e_i B^2}\left(\partial_t + (V_E + V_{pi})\nabla\Phi\right)\right] = -N_i \nabla_{//} V_{//i} + N_i (V_E + V_{pi})\frac{2\nabla B}{B} + S_n$$

$$N_i m_i d_t V_{//i} = -\nabla_{//} P_i - N_i e_i \nabla_{//}\Phi$$

$$d_t P_i = -\frac{5}{3} P_i \nabla_{//} V_{//i} + \frac{5}{3} P_i (V_E + V_{pi} + V_{Ti})\frac{2\nabla B}{B} + S_p$$

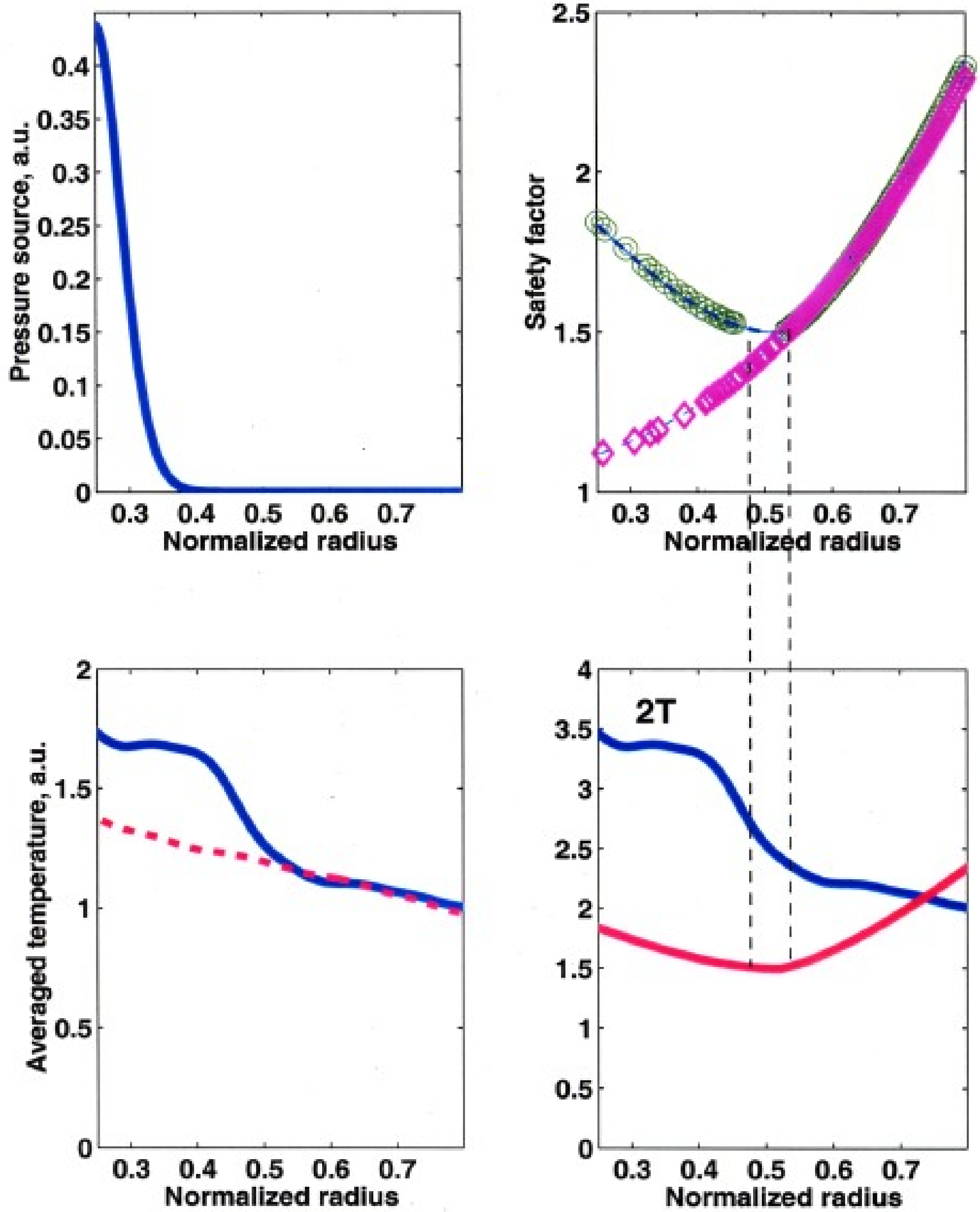
where $V_E = B\times\nabla\Phi/B^2$, $V_{pi} = B\times\nabla P_i/(N_i e_i B^2)$, $V_{Ti} = B\times\nabla T_i/(e_i B^2)$; $d_t = \partial_t + V_E\nabla$

Approach and assumptions:

- **self-consistent turbulence-transport simulations (flux-driven approach);**
- **Gaussian shape for heating power source located at r/a=0.25;**
- **flat density profile, Te ~ Ti ;**
- **adiabatic electrons;**
- **a dissipation has been added to ensure the convergence:**
  - **(a) collisional viscous dissipation + dissipation due to small scale fluctuations ($k_\perp \rho_i \geq 1$) (adjusted to reproduce a linear spectrum of growth rates calculated with a gyro-kinetic linear code);**
  - **(b) "Landau damping" – like dissipation;**
  - **(c) neoclassical friction**

The simulations have been performed with the 2D/3D TRB code [Garbet X., et al., Nucl. Fusion, 1999]

ITB formation with shear reversal

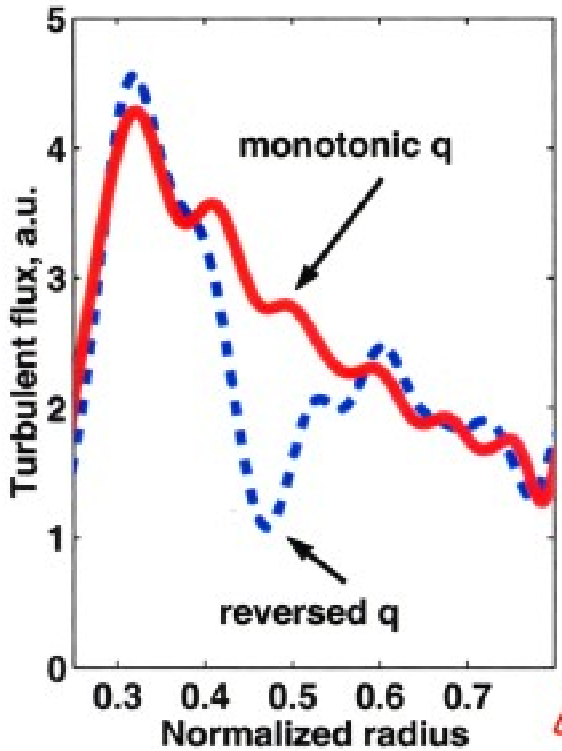


A gap in the radial position of rational surfaces at zero magnetic shear ($q_{min} = 3/2$) is observed

→ Reduction of Toroidal Coupling of neighboring modes

↔ Reduction of Turbulent Flux

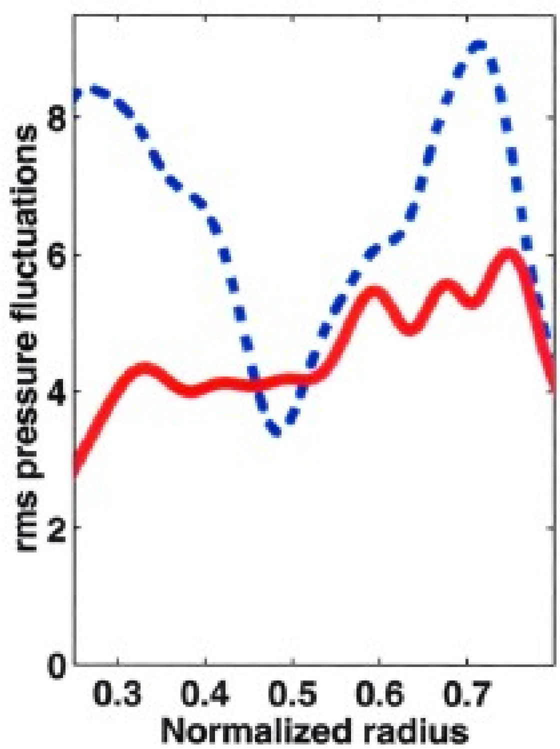
Turbulent flux and amplitudes with monotonic and reversed q-profile

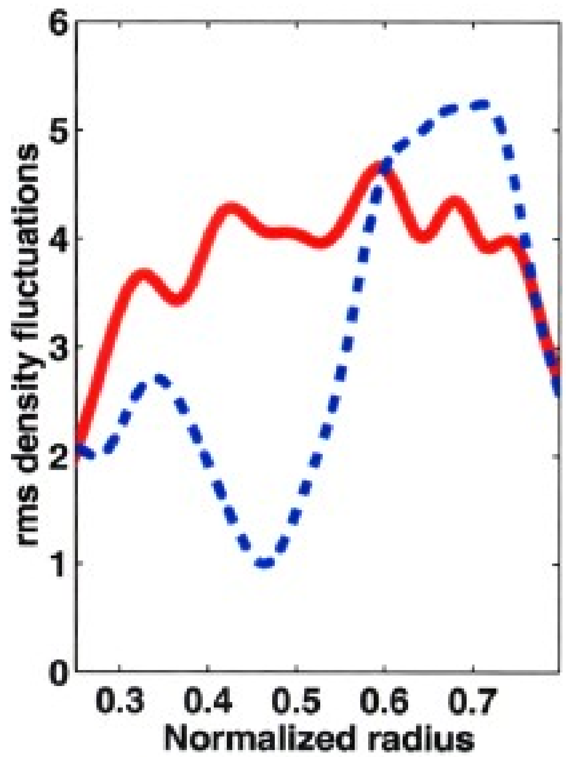


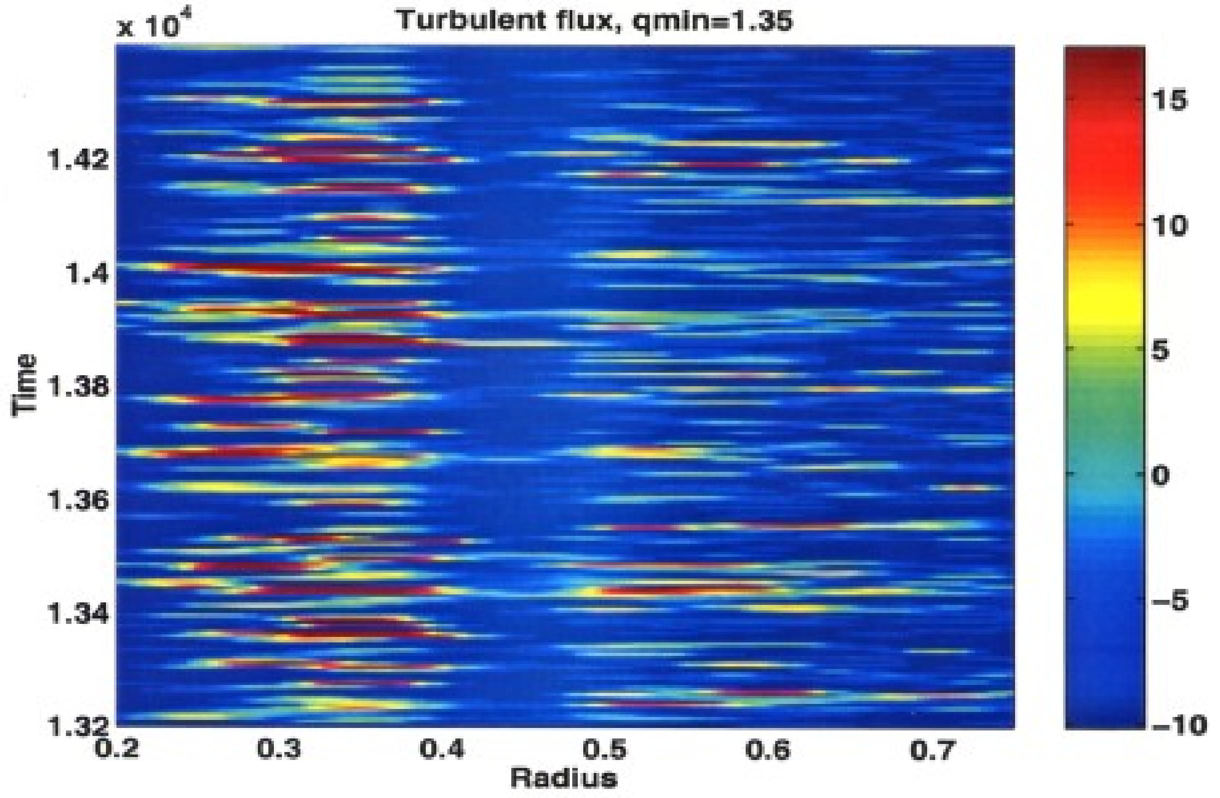
With the formation of ITB

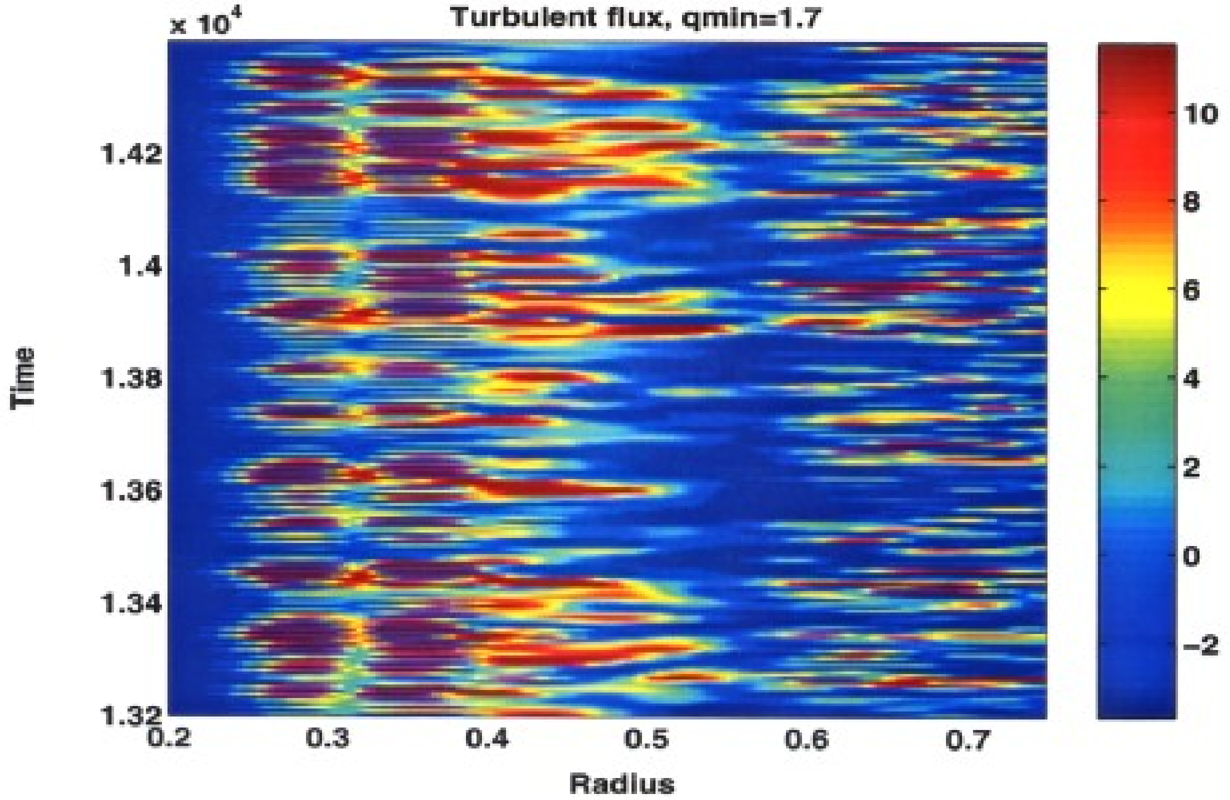
- pressure fluctuations are nearly unchanged in the region of reduced transport while they strongly increases outside !
- In contrast, the level of density fluctuations reduces at zero shear

→ To be compared later with RBM simulations.





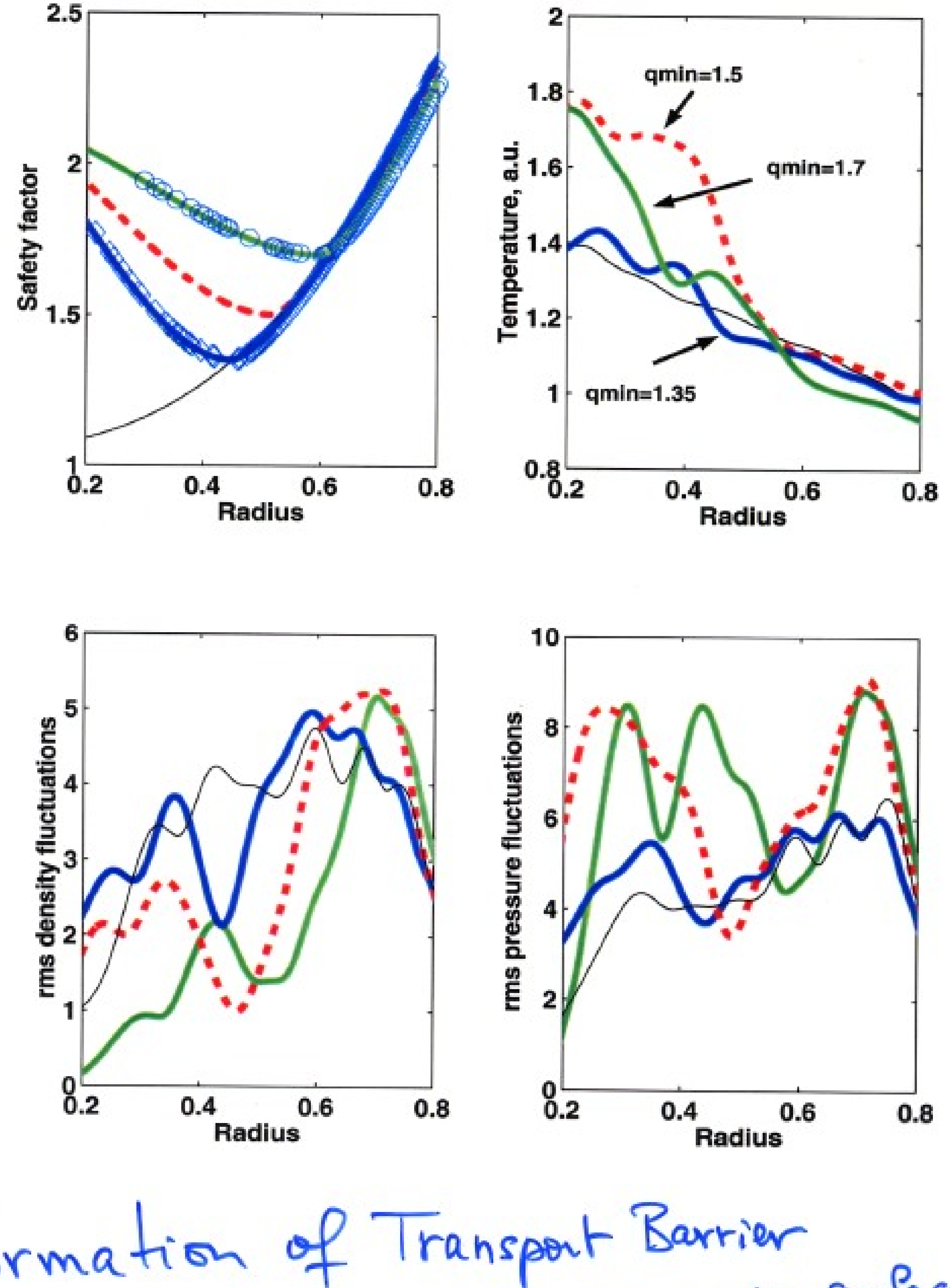

Turbulent flux, qmin=1.35
x 10^4
Time
Radius
1.32
1.34
1.36
1.38
1.4
1.42
0.2
0.3
0.4
0.5
0.6
0.7
15
10
5
0
−5
−10


Turbulent flux, qmin=1.7
x 10^4
Time
Radius
1.32
1.34
1.36
1.38
1.4
1.42
0.2
0.3
0.4
0.5
0.6
0.7
10
8
6
4
2
0
−2

We fix the heating source and change the q profile only.

Influence of Gap between neighboring rational surfaces

Effect of simple rational surfaces

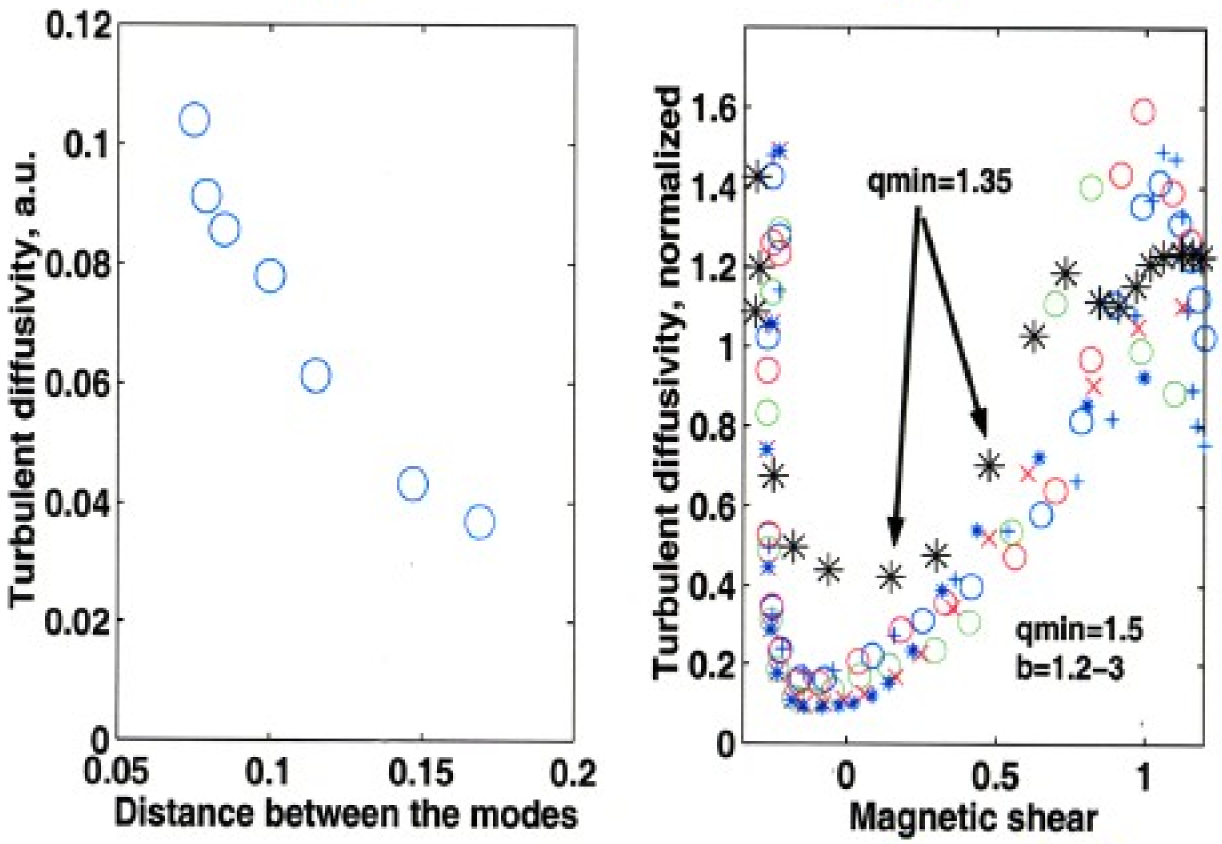


Formation of Transport Barrier

↪ Rarefaction of the resonant surfaces

Turbulent transport in different magnetic configurations

(a) (b)



(b) Simulations show two curves → $q_{min} = 3/2$ and ≠ curvature
→ $q_{min} = 1.35$

Most efficient suppression of turbulent transport takes place around zero magnetic shear.

In the negative shear region, transport ↗ due to ↗ in toroïdal coupling

Same mechanism holds for the positive region until $s_m = 1$

Further ↗ of s_m ⟹ small reduction of diffusivity

Conclusion

- The classical $E \times B$ shear stabilisation effect has been found on turbulent structures and transport with formation of transport barriers.
- The $E \times B$ rotation shear affects the fluctuations and their cross–phase. In agreement with experiments as Boedo et al., PPCF, 2000.
- Concerning the shear scaling suppression of the turbulent transport, we found $\chi = \chi(\rho^*, \nu^*, \beta)\ F(s, \nabla E_r)$, $F(\nabla E_r) = 1/(1 + (\nabla E_r^2))$. Simulations in good agreement with experiments (Jachmich et al., PPCF 2000; Czech. J. Phys. 1999).
- For fluctuation level, RMS of p and v_r scale as $f(\nabla E_r) = 1/(a + b * (\nabla E_r)^2)$ (Models of Zhang–Mahajan /Shaing et al.) but for the cross–phase as $f(\nabla E_r) = a - b * (\nabla E_r)^2$ (Ware et al. model.). These agree with experiments (Boedo et al. IAEA 2000).

Summary

- Turbulent transport is characterized by radial propagation of bursts.
- Imposed ExB shear and zero/negative magnetic shear produce a bifurcation in the plasma confinement and generate transport barrier.
- Dynamics of barrier: Quiet phases alternate with relaxation events.
- During quiet phases, bursts are suppressed in center of barrier.
- Relaxation events are successions of bursts with erosion of barrier.
- Pressure perturb. crosses barrier, consistent with ballistic propagation.
- Control of the ITB and large Scale Transport Events through the current profile shaping has been shown in ITG simulations.