Momentum transport in RFX-mod

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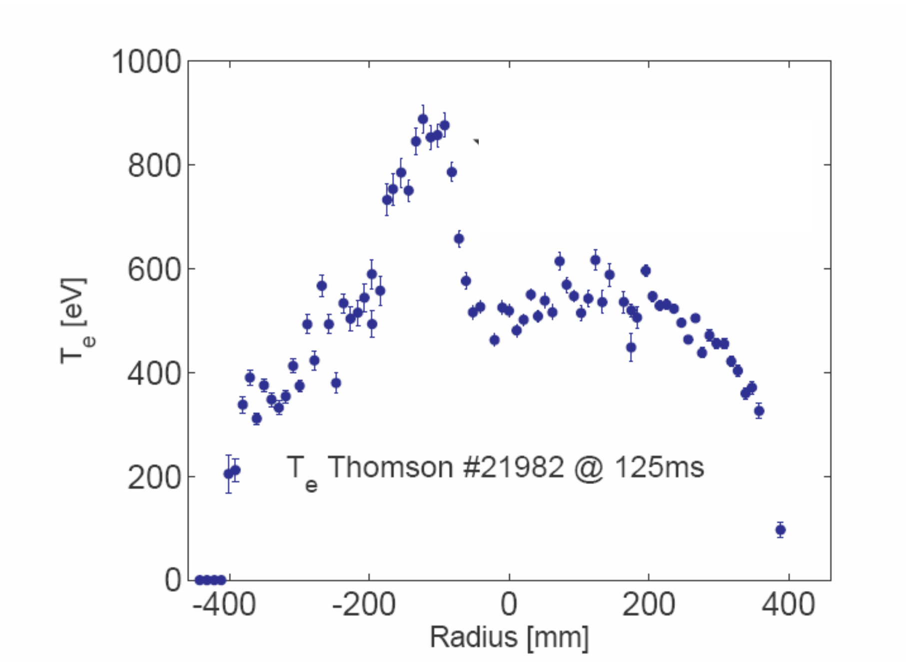
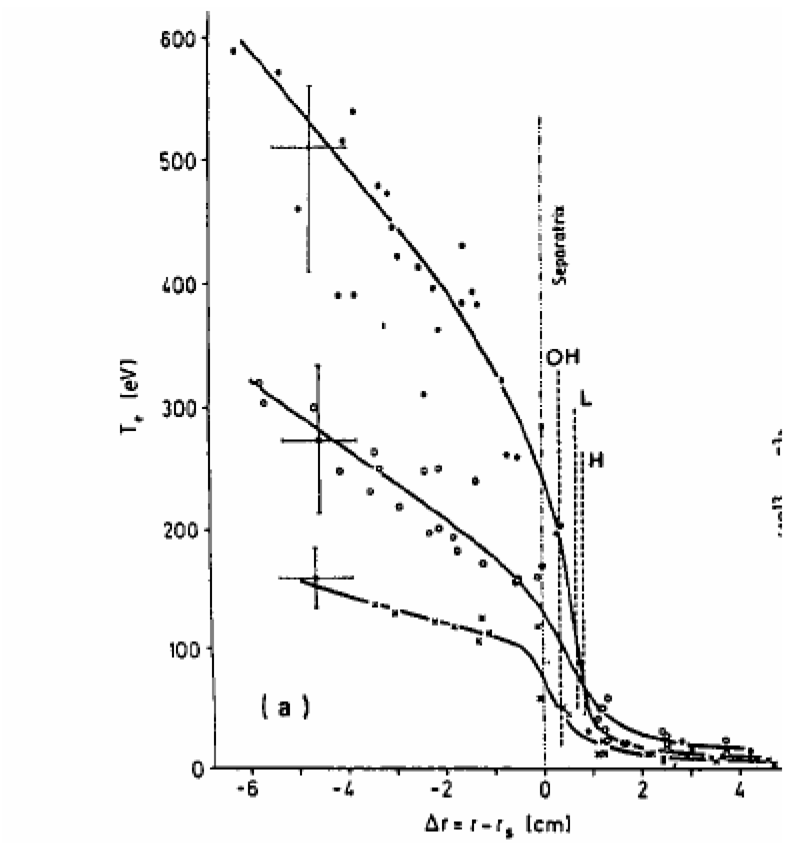
Reference papers

- **Experimental results in this talk have been taken from the following papers:**
  - *N. Vianello et al., PRL 94 135001 (2005)*
  - *N. Vianello et al., NF 45, 761, (2005)*
  - *N. Vianello et al., PPCF 48, S193 (2006)*
  - *V. Antoni et al., PPCF 47, B13 (2005)*
  - *N. Vianello et al., 2006 EPS conference, paper P. 5-085*

Edge region in fusion plasmas

- The edge region in fusion plasmas plays a crucial role for energy and particle confinement
  - **H-mode pedestal in tokamaks**
  - **Edge gradients in the RFP**





Role of turbulence

- Turbulence is responsible for anomalous transport.
- When turbulence is suppressed, regimes with enhanced confinement are obtained.
- *Example: magnetic turbulence in the RFP plasma core (OPCD)*

Magnetic turbulence and self-organization in the RFP

- Magnetic turbulence causes anomalous transport in the RFP plasma core, but at the same time drives the dynamo electric field, which sustains and heats the plasma.

- *Self-organization between two competing processes*.

- The goal: find the conditions where the plasma keeps the magnetic turbulence self-organized threshold as low as possible

- In the RFP:
  - *Naturally, via low-chaos helical states (Single Helicity)*
  - *Driving the dynamo field by external means (current drive)*

Electrostatic turbulence

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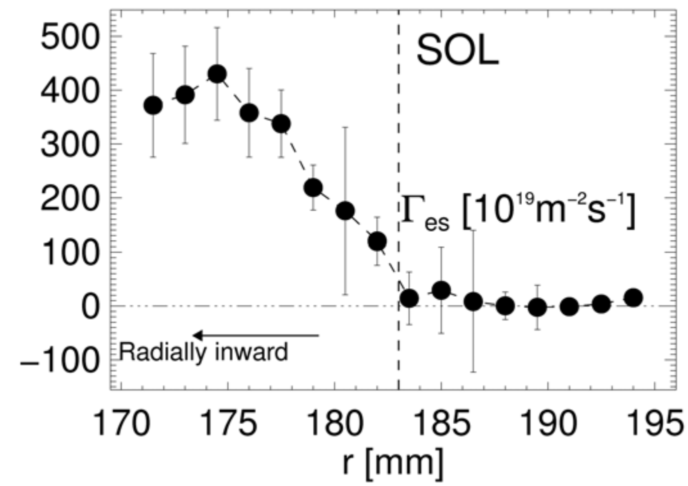
transport

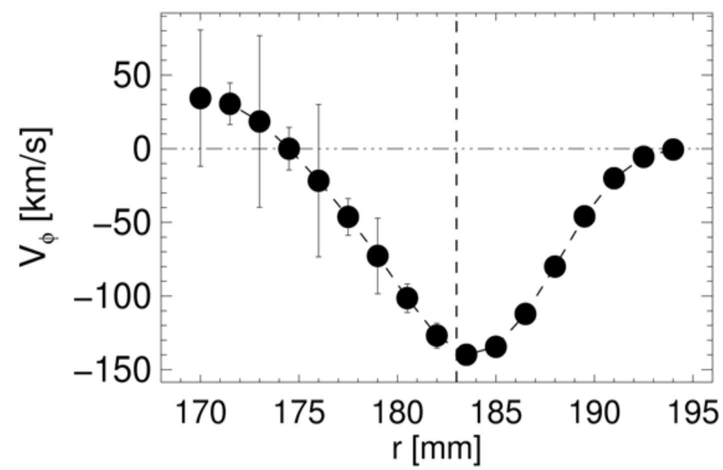
SELF-ORGANIZED LINK

Sheared flow

Anomalous transport



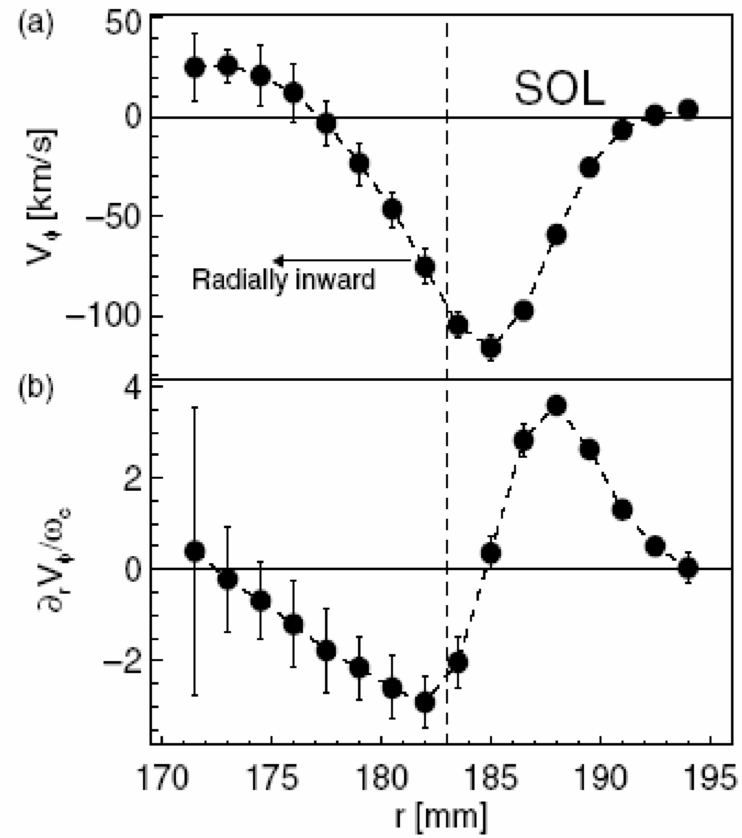
Turbulence suppression
and improved transport



Self-organization for electrostatic turbulence

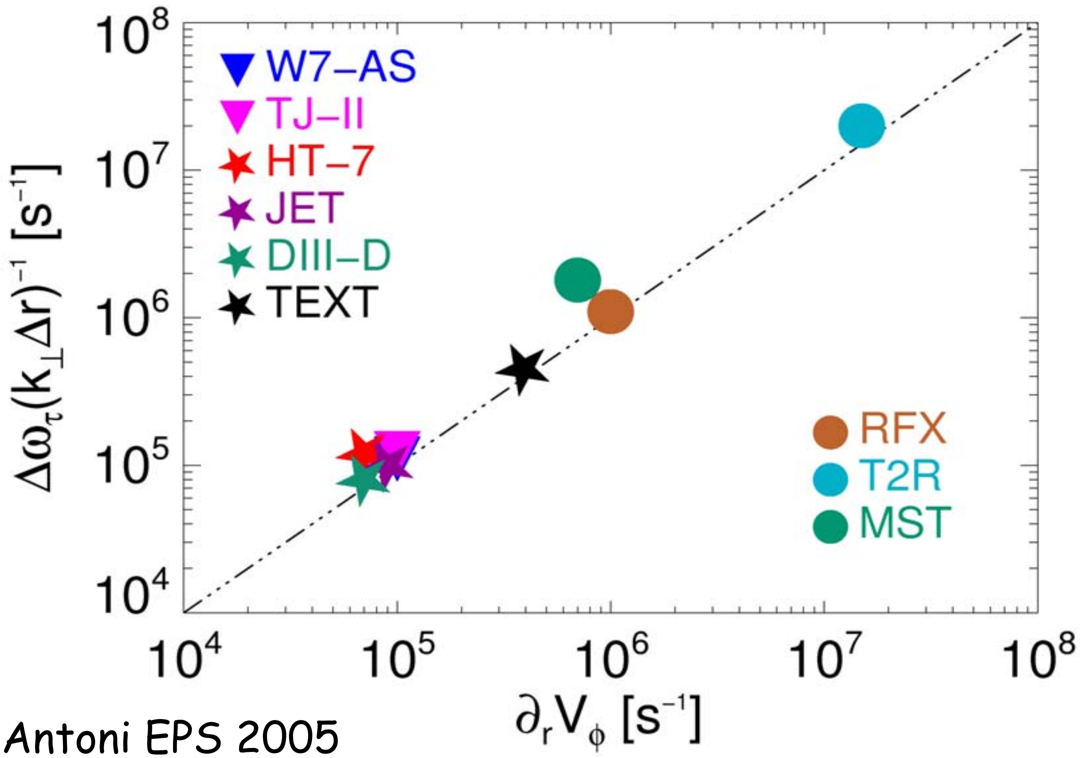
- Spontaneous self-organization by which turbulent energy goes into sheared flow energy
- Turbulence self-organizes to drive stabilizing sheared flows
- Coupling between small scales of turbulence and large scales of *E* x *B* flow

EXTRAP T2R



Self-organization for electrostatic turbulence: universal process

- The spontaneous shear is marginal according to turbulence decorrelation criteria (BDT), which says that turbulence can be radially decorrelated if the shearing frequency ω_s is larger than the ambient turbulent spectrum width $\Delta\omega_t$



V.Antoni EPS 2005

$$\Delta r_t \frac{\partial V_\varphi}{\partial r} \geq \frac{\Delta\omega_t}{k_\perp}$$

Momentum conservation equation

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$$mn\left(\frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla\right)\mathbf{V} = -\nabla p + \mu\left[\nabla^2\mathbf{V} + \frac{1}{3}\nabla(\nabla\cdot\mathbf{V})\right] + \mathbf{J}\times\mathbf{B} + \mathbf{F}^{\mathrm{nf}}$$

- For a constant density incompressible plasma

$$\left(\frac{\partial}{\partial t} + \mathbf{V}\cdot\nabla\right)\mathbf{V} = -\nabla\mathbf{p} + \mathbf{J}\times\mathbf{B} + \nu\nabla^2\mathbf{V}$$

$$\frac{\mathbf{B}}{\sqrt{\rho\mu_0}} \rightarrow \mathbf{B} \qquad \frac{\mathbf{J}}{\sqrt{\rho/\mu_0}} \rightarrow \mathbf{J} \qquad \frac{p}{\rho} \rightarrow p \qquad \mathbf{J} = \nabla\times\mathbf{B}$$

Momentum conservation equation - 2

$$\mathbf{V} = \overline{\mathbf{V}} + \tilde{\mathbf{v}} \qquad \mathbf{B} = \overline{\mathbf{B}} + \tilde{\mathbf{b}}$$

- Ensemble averaging:

$$\frac{\partial \overline{V}_i}{\partial t} + \partial_r \left[\langle \tilde{v}_r \tilde{v}_i \rangle - \langle \tilde{b}_r \tilde{b}_i \rangle \right] + \partial_r \left[\overline{V}_r \overline{V}_i - \overline{B}_r \overline{B}_i \right] =$$
$$\partial_i \left[\overline{p} + \frac{\overline{B}^2}{2} + \frac{\langle \tilde{\mathbf{b}}^2 \rangle}{2} \right] + \nu \nabla^2 \overline{V}_i$$

- Assumptions: axisymmetry, no toroidal effects, no curvature, i.e.:

$$\frac{\partial}{\partial \phi} = \frac{\partial}{\partial \theta} = 0 \qquad \frac{1}{r} \ll \frac{\partial}{\partial r}$$

$$\frac{\partial \overline{V}_\phi}{\partial t} + \frac{\partial}{\partial r} \left[\langle \tilde{v}_r \tilde{v}_\phi \rangle - \langle \tilde{b}_r \tilde{b}_\phi \rangle \right] = \frac{\partial}{\partial r} (\overline{B}_r \overline{B}_\phi - \overline{V}_r \overline{V}_\phi) + \nu \nabla^2 \overline{V}_\phi$$

Goal: measure Reynolds stress

Maxwell stress

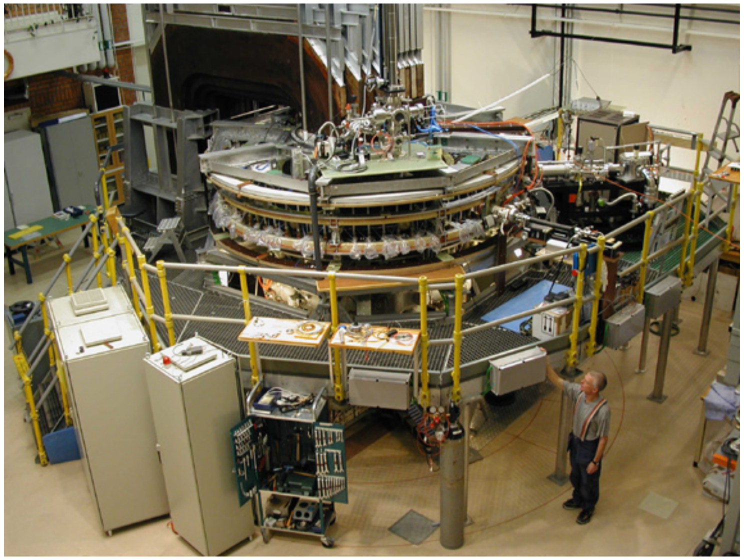
$$\frac{\partial \overline{V}_\phi}{\partial t} + \frac{\partial}{\partial r}\left[\langle \tilde{v}_r \tilde{v}_\phi \rangle - \langle \tilde{b}_r \tilde{b}_\phi \rangle\right] = \frac{\partial}{\partial r}\left(\overline{B}_r \overline{B}_\phi - \overline{V}_r \overline{V}_\phi\right) + \nu \nabla^2 \overline{V}_\phi$$

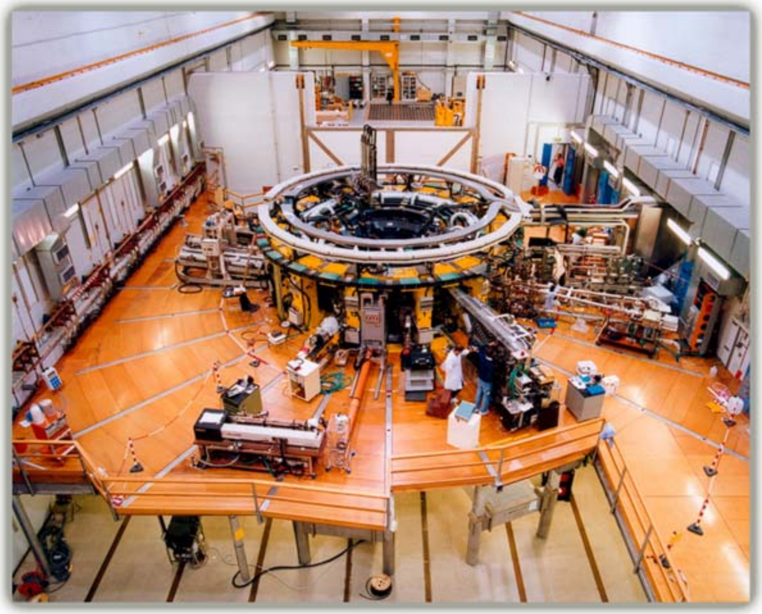
Electrostatic Reynolds stress

- Velocity fluctuations have been approximated by *E* x *B* drift velocity fluctuation
  - (*E* x *B* toroidal in a RFP)
- Works on parallel flow on-going

Devices used for this study

- **EXTRAP T2R** (Stockholm, Sweden)
  - R = 1.24 m, a = 0.183 m
  - Ip~60 kA, ne~1x10^{19} m^{-3}





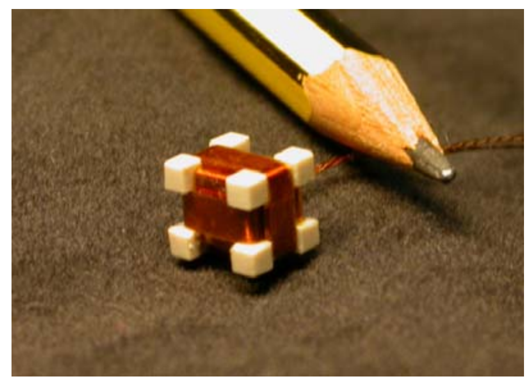
- **RFX-mod** (Padova, Italy)
  - R = 2.0 m, a = 0.457 m
  - Ip~1.2 MA, ne~1-8x10^{19} m^{-3}

Diagnostics for Maxwell and Reynolds stresses

- *Different probes used in the two experiments, but based on the same principle.*

In RFX-mod:

- **Two 2D arrays of electrostatic pins:**
  - 5 (toroidal) x 8 (radial)
  - Δr=6mm - $\Delta\varphi$=6mm - pin Φ=3 mm
- **Two arrays of 7 (B_r,B_θ,B_φ) magnetic probes:**
  - size: 7mm X 6mm X 8mm
  - Δr=6mm
  - **5 MHz** sampling rate.



Reynolds and Maxwell stress in Extrap T2R

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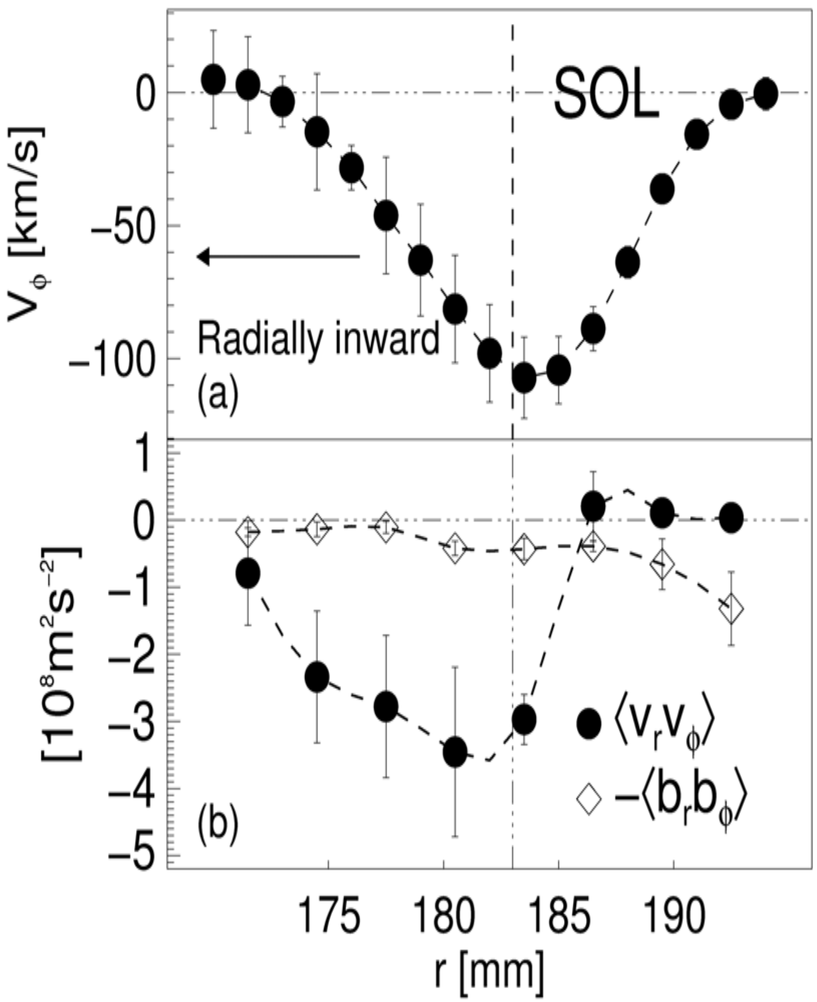
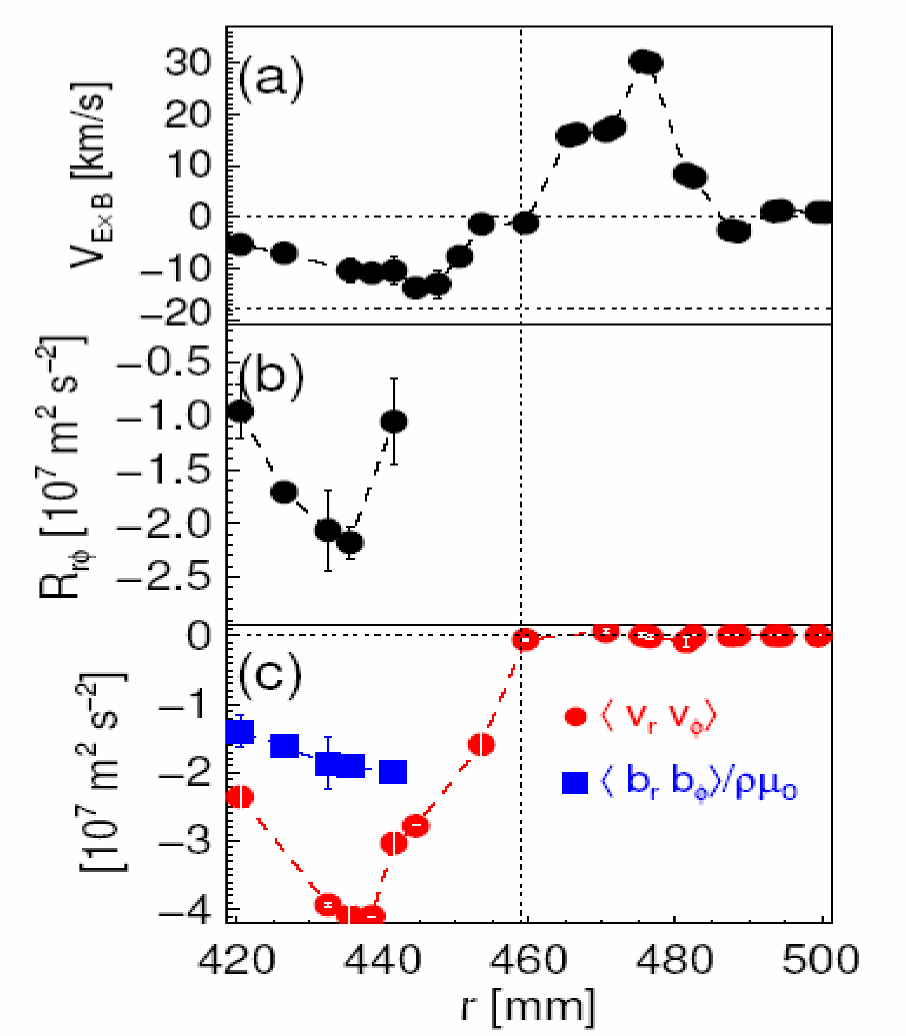


- **Electrostatic Reynolds** stress is larger than magnetic Maxwell stress
- **The gradient:**
  - is due to the electrostatic component
  - Is large in the region where the velocity is strongly sheared

Reynolds and Maxwell stress in RFX-mod

- Results are consistent with those obtained in EXTRAP T2R



Time resolved measurements in RFX-mod

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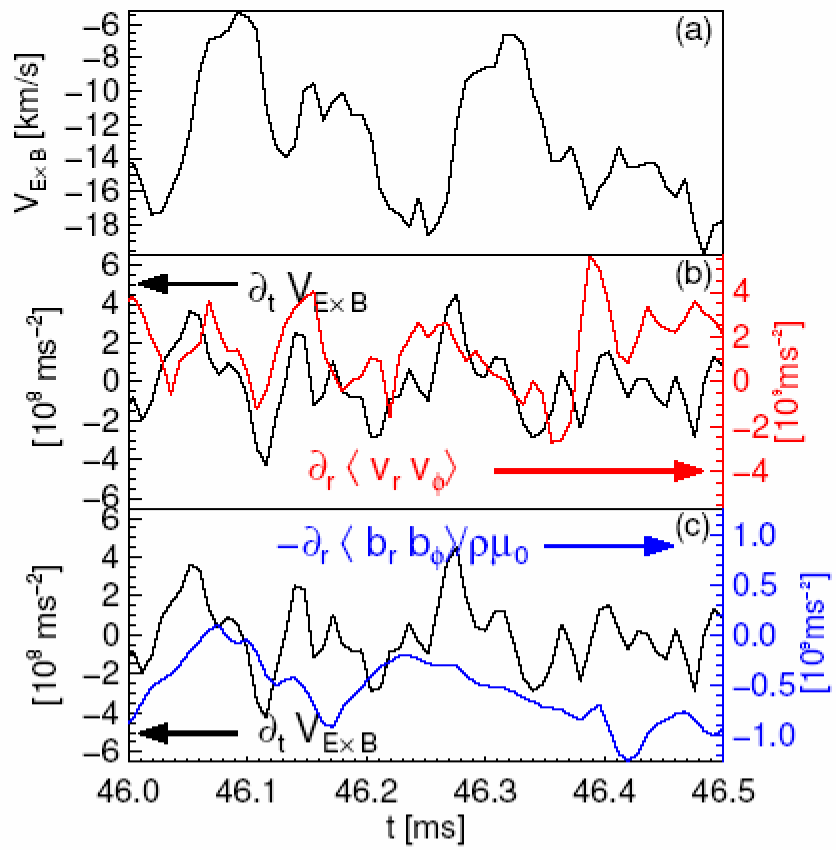
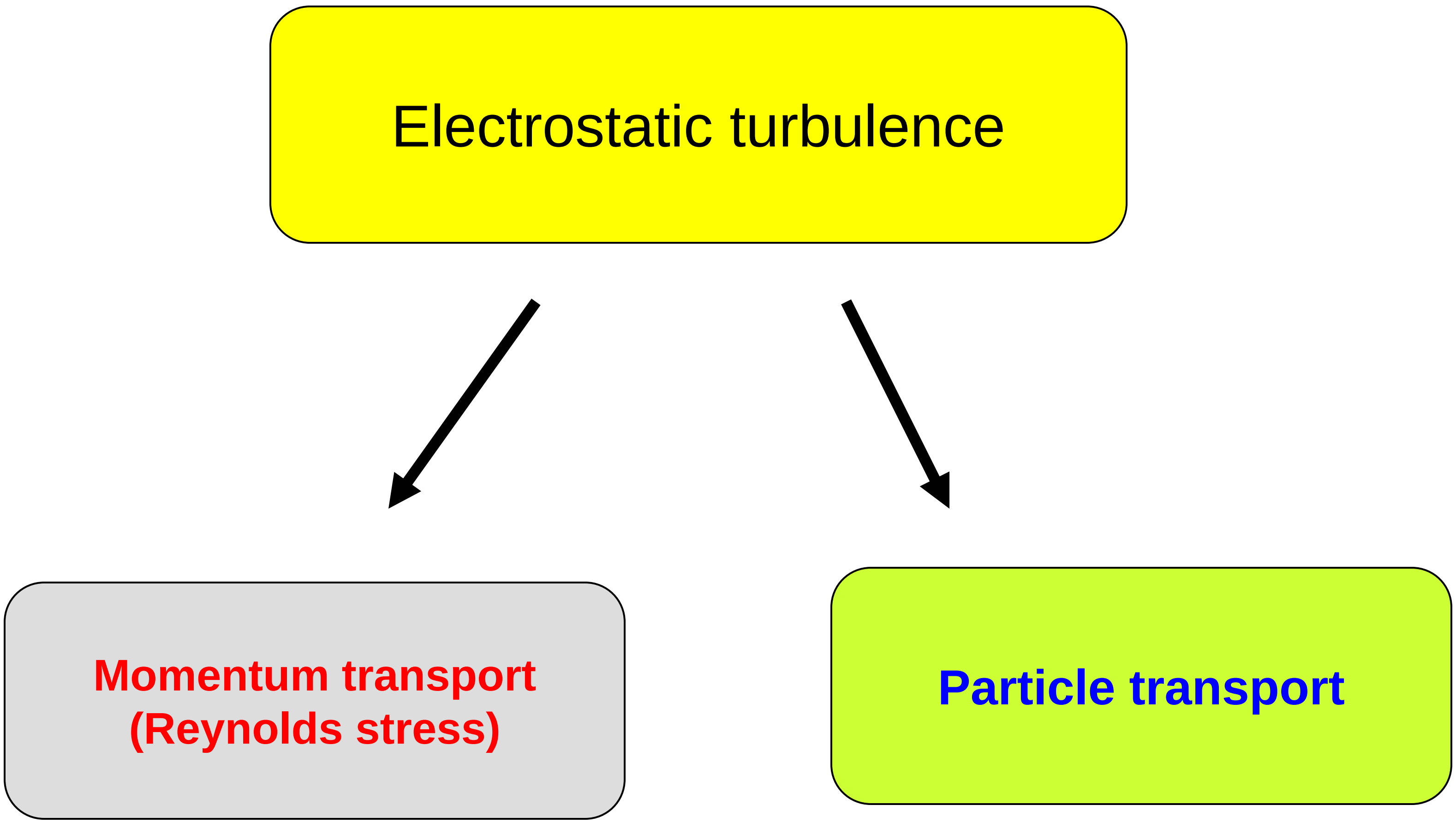
- Correlation between plasma acceleration and ERS gradient evident



Electrostatic turbulence plays a double role



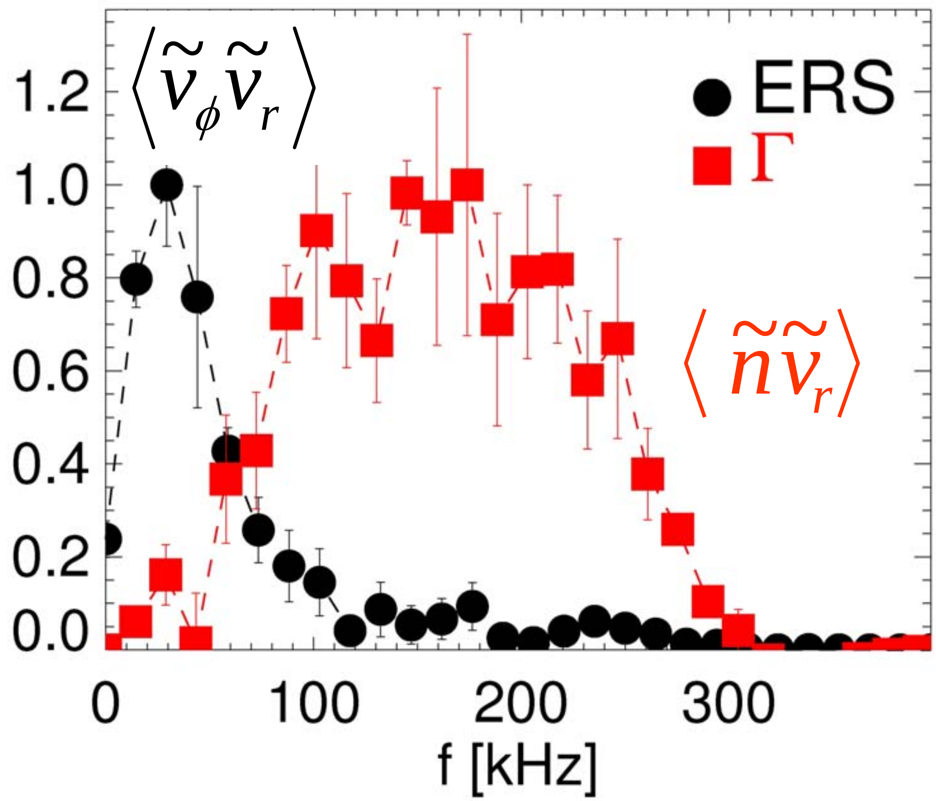
Different origin for the two mechanisms ?

The Fourier spectra of

- *electrostatic Reynolds stress*
- *particle flux*

peak at different frequencies

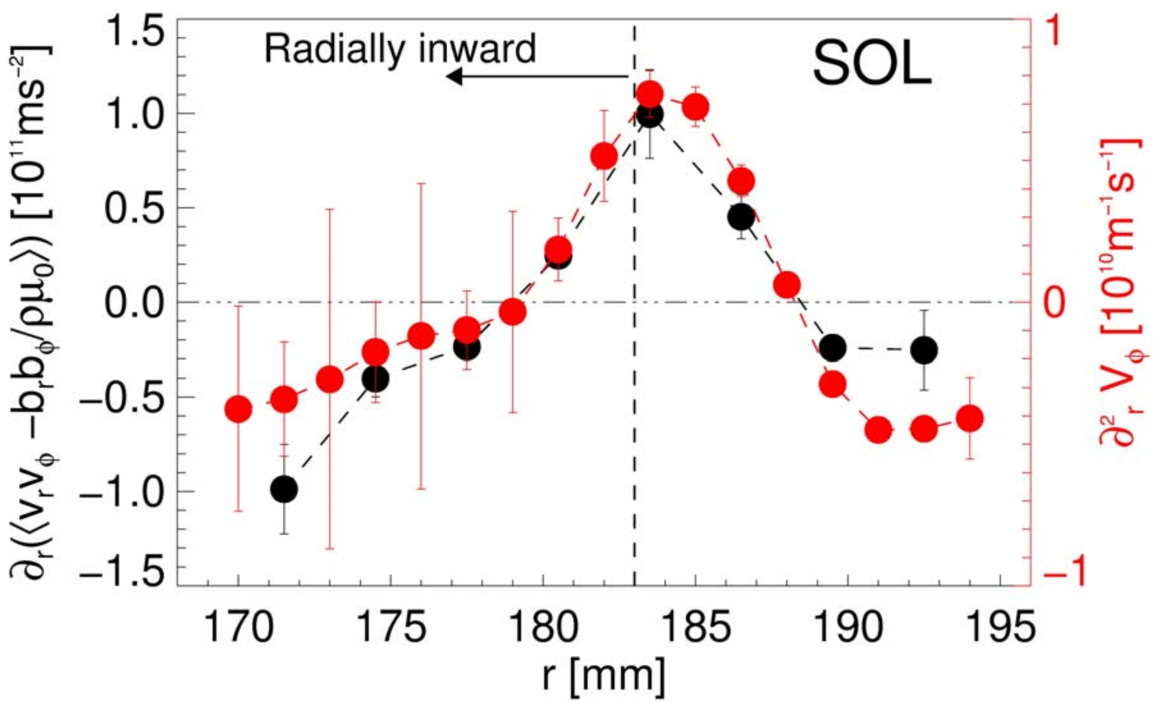
EXTRAP T2R



Momentum equation in stationary condition

$$\partial_t = 0 \qquad \overline{V}_r \approx 0 \qquad \overline{B}_r \approx 0$$

$$\frac{\partial}{\partial r}\left[\langle \tilde{v}_r \tilde{v}_\phi \rangle - \langle \tilde{b}_r \tilde{b}_\phi \rangle\right] = \nu \frac{\partial^2 \overline{V}_\phi}{\partial r^2}$$



It is possible to evaluate the kinematic viscosity

The viscosity is anomalous

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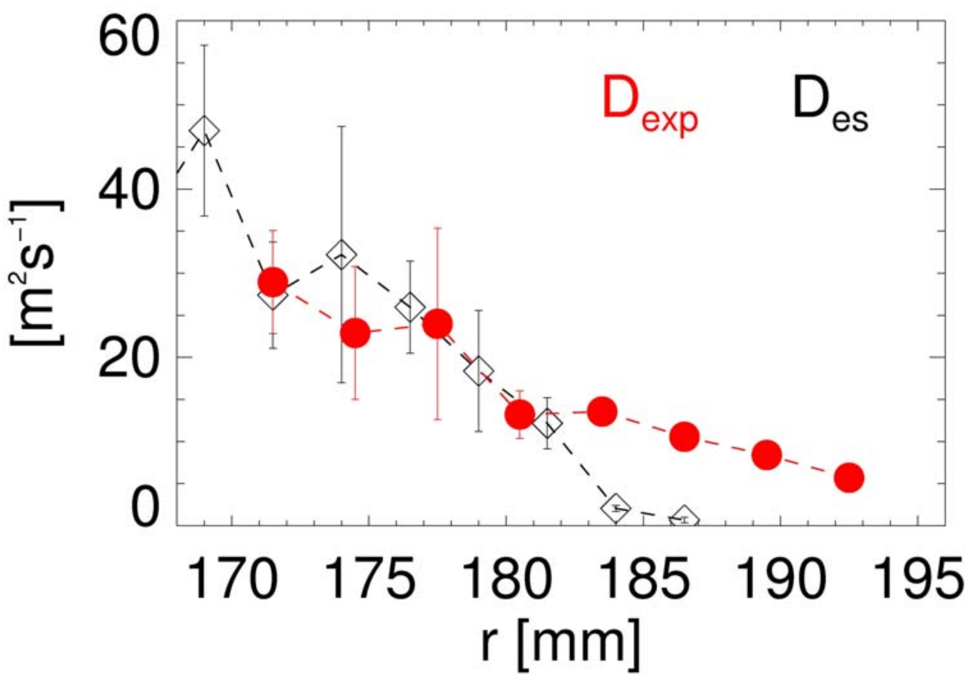
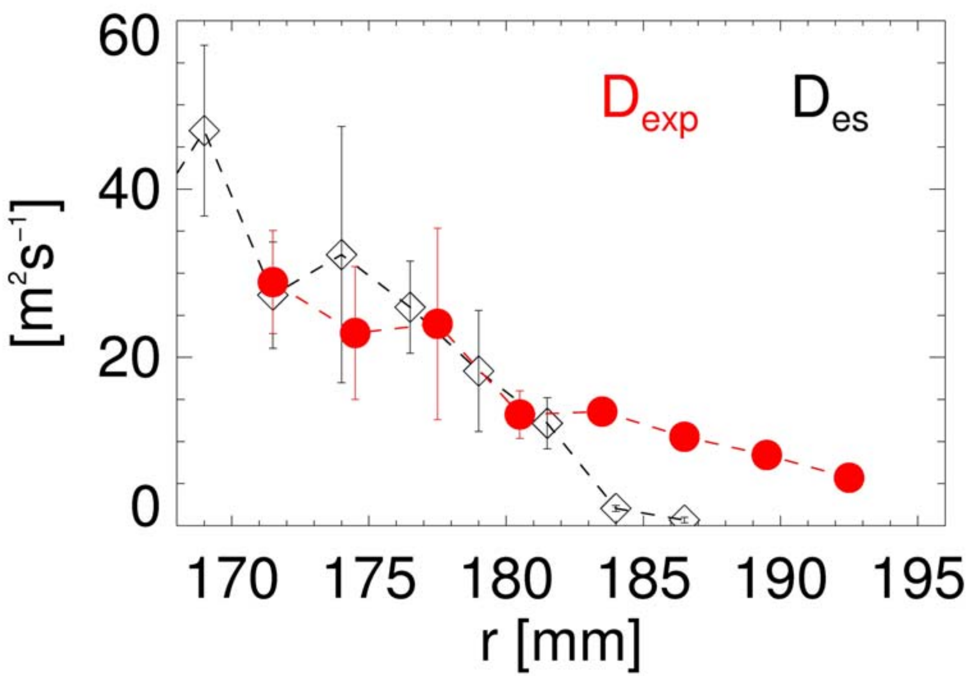


Experimental viscosity is more than 1 order of magnitude larger than classical

$$\nu \approx D_{exp} \approx D_{es} = \frac{\Gamma_{es}}{\nabla \cdot n}$$

Same order of magnitude of the effective diffusion caused by electrostatic particle flux

The viscosity is anomalous



Momentum transport is anomalous and viscosity consistent with anomalous particle transport

Electrostatic fluctuations:

flow driving *through ERS*

flow damping *through anomalous viscosity*

Conclusions

- Reynolds stress measured in RFP.
- Reynolds stress is mainly driven by electrostatic turbulence although ERS and MS have the same sign.
- Electrostatic turbulence is responsible for flow driving and flow damping
- Electrostatic part of RS is the main driving term of the flow shear
- Viscosity is anomalous and linked to turbulence
- More work on-going in RFX-mod
- For more info: *vianello@igi.cnr.it*