Turbulent transport and plasma flow in the Reversed Field Pinch

V. Antoni,R. Cavazzana, E. Martines, G. Serianni, E. Spada, M. Spolaore, N. Vianello ,J. Drake, H. Bergsåker, M. Cecconello and the RFX and Extrap-T2R teams

1.Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, C.so Stati Uniti 4, I-35126 Padova, Italy

2. Division of Fusion Plasma Physics (Association Euratom/VR), Alfvén Laboratory, Royal Institute of Technology, SE10044, Stockholm, Sweden

Generation of Sheared Poloidal Flows by Electrostatic and Magnetic Reynolds Stress in the Boundary Plasma of HT-7 Tokamak

G.S.Xu, B.N.Wan and J.Li

Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, P.R.China,

Forewords

Sheared flows play a key role in explaining the transition to enhanced confinement regimes in magnetically confined fusion plasmas .

Finding the generation mechanism of sheared flows is crucial to understand the confinement transition and for developing techniques to suppress turbulence and reduce transport.

Turbulence studies in different configurations can contribute to general advance by comparative analysis

In this contribution a comparative study of ExB flow generation in the edge region of a tokamak (HT-7) and a RFP (EXTRAP-T2R) and the latest results on edge turbulent transport and its control in RFPs are reported

Outline

Introduction: Experiments and main differencies between RFP and Tokamak

Part I : ExB flow generation in Tokamak HT-7 and RFP experiment EXTRAP T2R

Part II: Turbulent transport and its control in RFP experiments RFX and EXTRAP T2R

Similarities between tokamaks and RFPs

New tools for turbulence control

HT-7 experiment

HT-7 is a superconducting tokamak : R=1.22, a=0.27m

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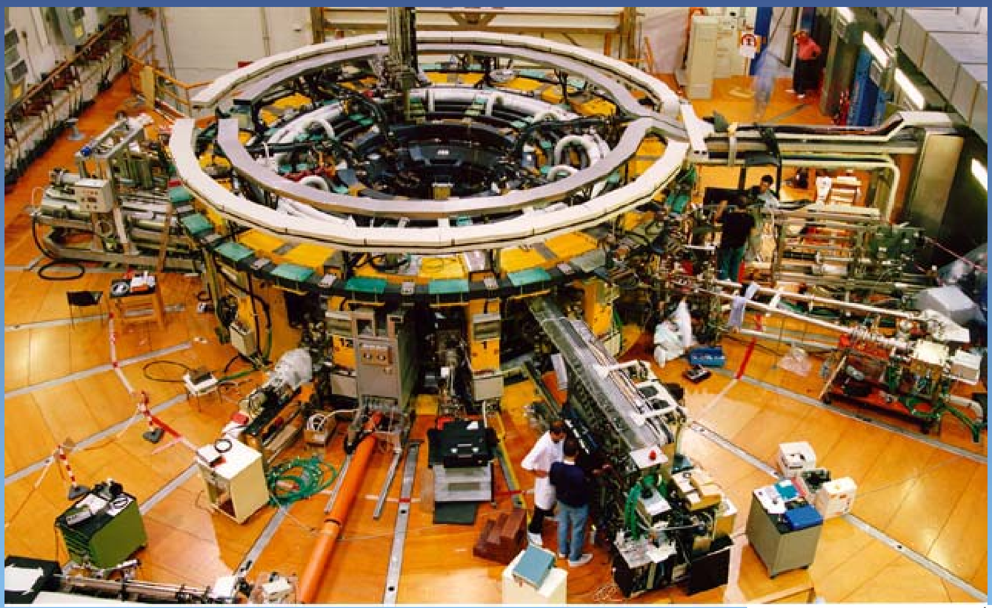
Data here reported refer to ohmic regime

Low β, ohmic regime in D, I ~120 kA, B_{ϕ} ~ 2T q_{edge} ~ 4.9

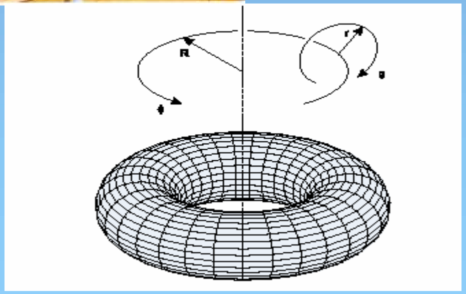
b/B ~ 10^{-4}

RFP Experiments

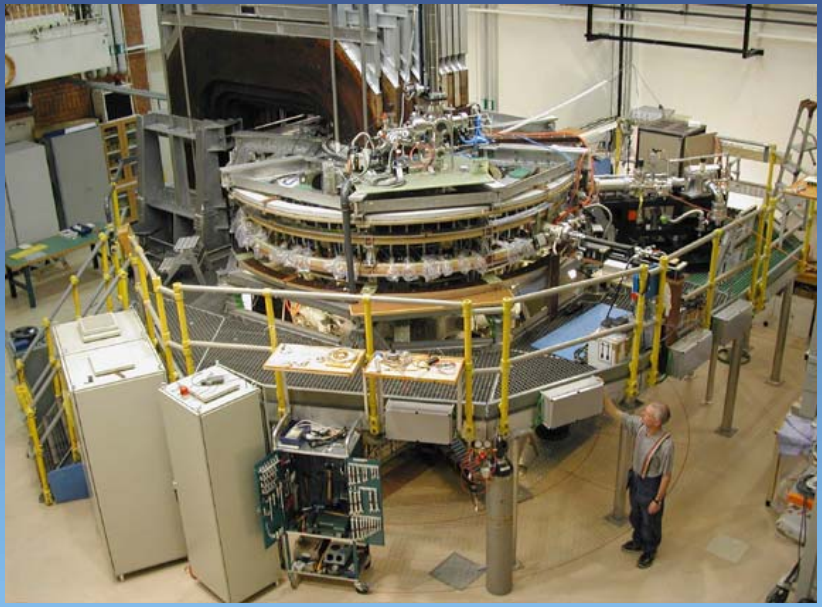
RFX
(Consorzio RFX - Padua)



$R = 2$ m
$a = 0.46$ m

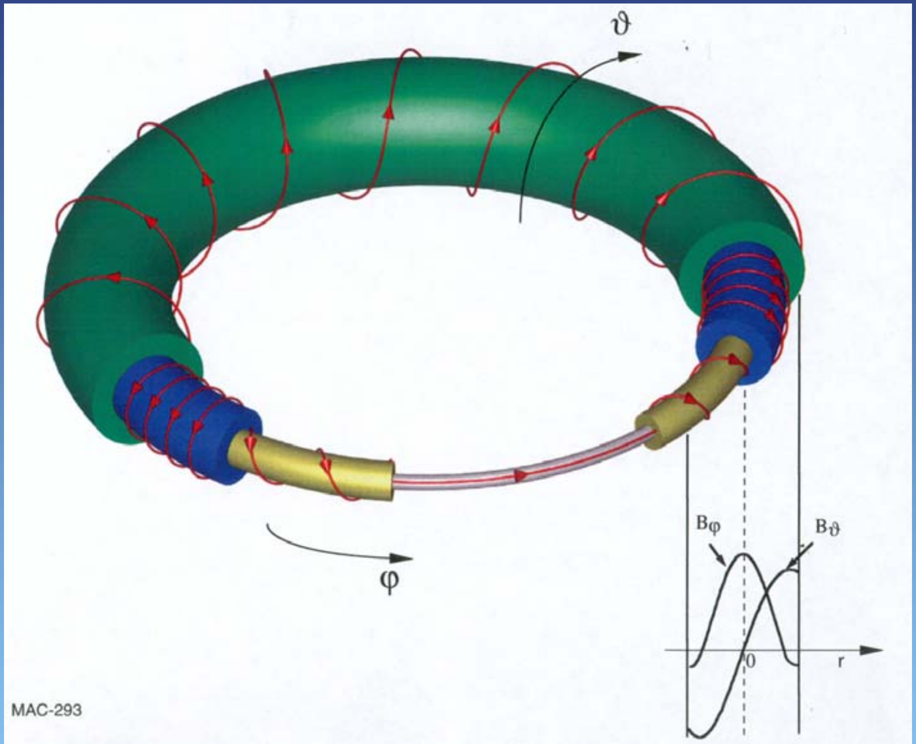


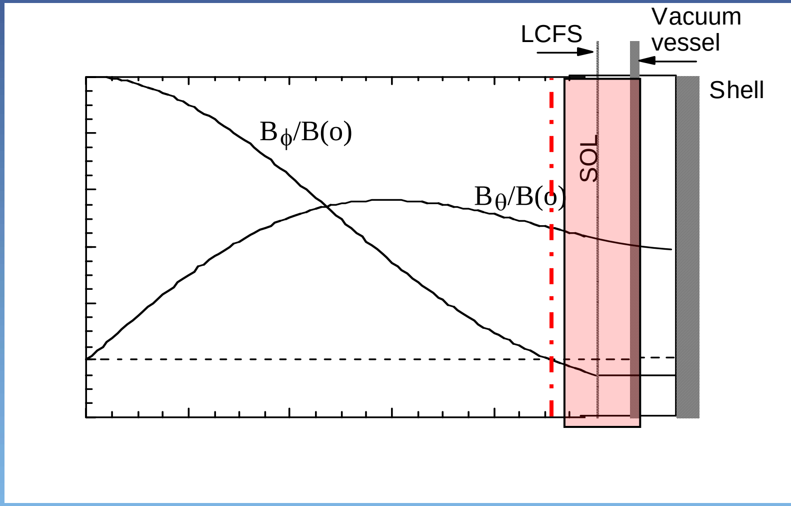
T2R
(KTH - Stockholm)



$R = 1.24$ m
$a = 0.183$ m

RFP configuration: main differences with tokamaks





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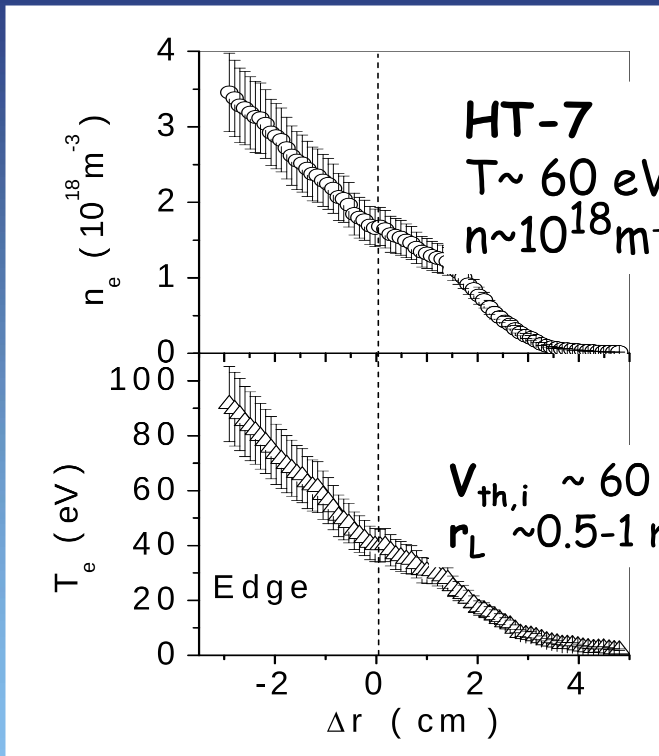
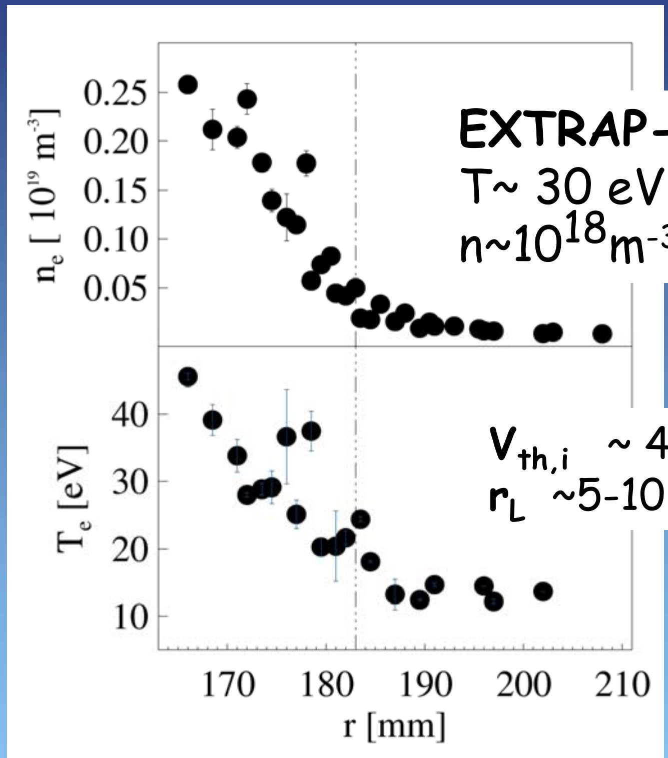
Main differencies with tokamak configuration:
Mainly originated by internal currents
Sustained against resistive diffusion by dynamo mechanism driven by tearing modes
High magnetic fluctuation (b/B >1%)

Edge parameters in EXTRAP-T2R and HT 7



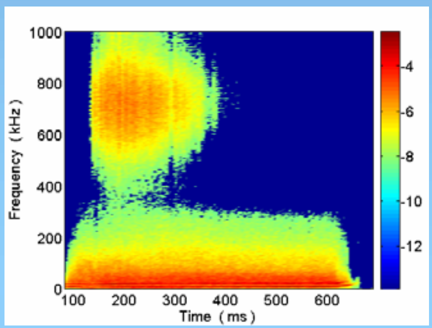
HT-7
T~ 60 eV
n~10^{18}m^{-3}

$V_{th,i}$ ~ 60 Km/s
r_L ~0.5-1 mm



EXTRAP-T2R
T~ 30 eV
n~10^{18}m^{-3}

$V_{th,i}$ ~ 40 Km/s
r_L ~5-10 mm



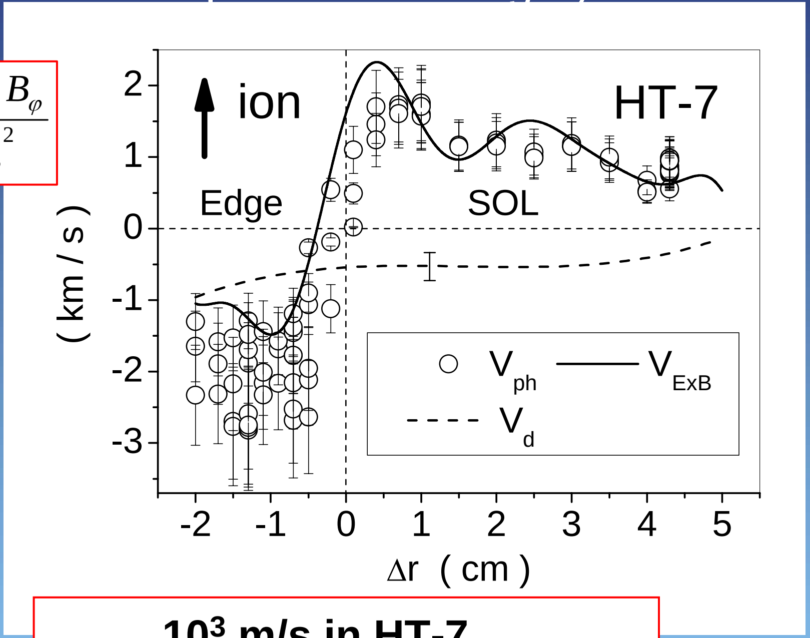
High frequency & ETG-like in HT-7 (see poster EX/84Rb Saturday morning)

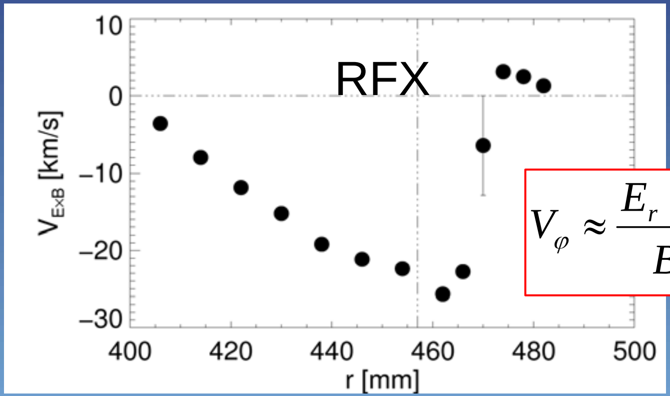
Electrostatic turbulence in both experiments has broadband features with fluctuation levels $\delta T/T$~ 30% $\delta n/n$~50% and $\delta\phi/T$~ 100% in RFPs and comparable values in HT-7

ExB flow in HT -7 and RFPs

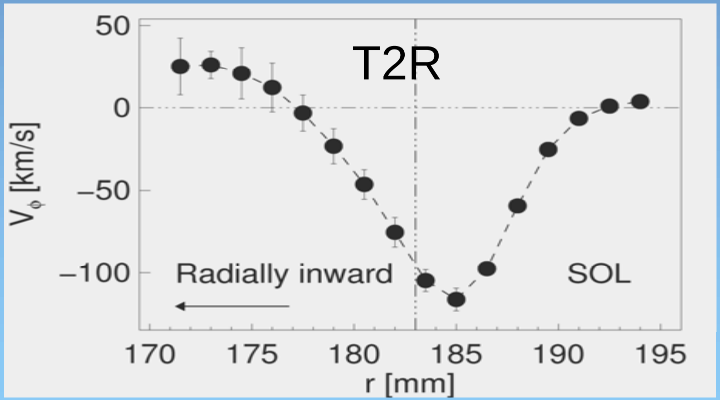
In all three experiments a highly sheared ExB flow is observed

$$V_\theta \approx \frac{E_r \times B_\varphi}{B_\varphi^{\ 2}}$$





$$V_\varphi \approx \frac{E_r \times B_\theta}{B_\theta^{\ 2}}$$



$v_{ExB} \sim$ 10^3 m/s in HT-7, 10^4 m/s in RFX, 10^5 m/s in EXTRAP T2R

$\omega_s \sim$ 10^5 s^{-1} in HT-7, 10^6 s^{-1} in RFX, 10^7 s^{-1} in EXTRAP T2R

$$\omega_s = \frac{\partial}{\partial r} V_{ExB} \approx \frac{E_r \times B_{edge}}{B_{edge}^{\ 2}}$$

The spontaneous ExB shear results marginal for turbulence suppression

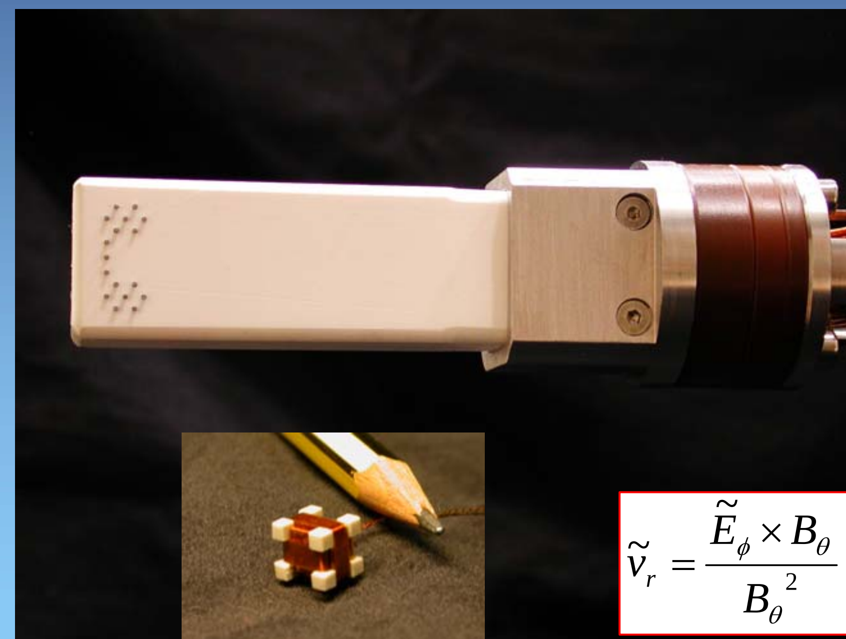
V. Antoni et al., Phys. Rev. Lett. 80, 4185 (1998).   G.S Xu et al., Phys. Rev. Lett. 91, 125001 (2003).

Reynolds Stress measurement

The (gradient of) Reynolds stress is believed to play an important role in the momentum balance.

The radial profile of the complete Reynolds Stress has been measured by arrays of Langmuir and magnetic probes in HT-7 and EXTRAP-T2R

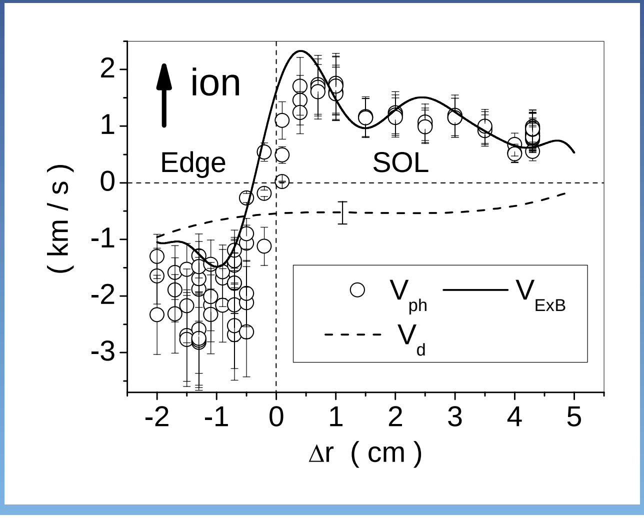
$$\tilde{v}_r = \frac{\tilde{E}_\theta \times B_\phi}{B_\phi^{\;2}}$$



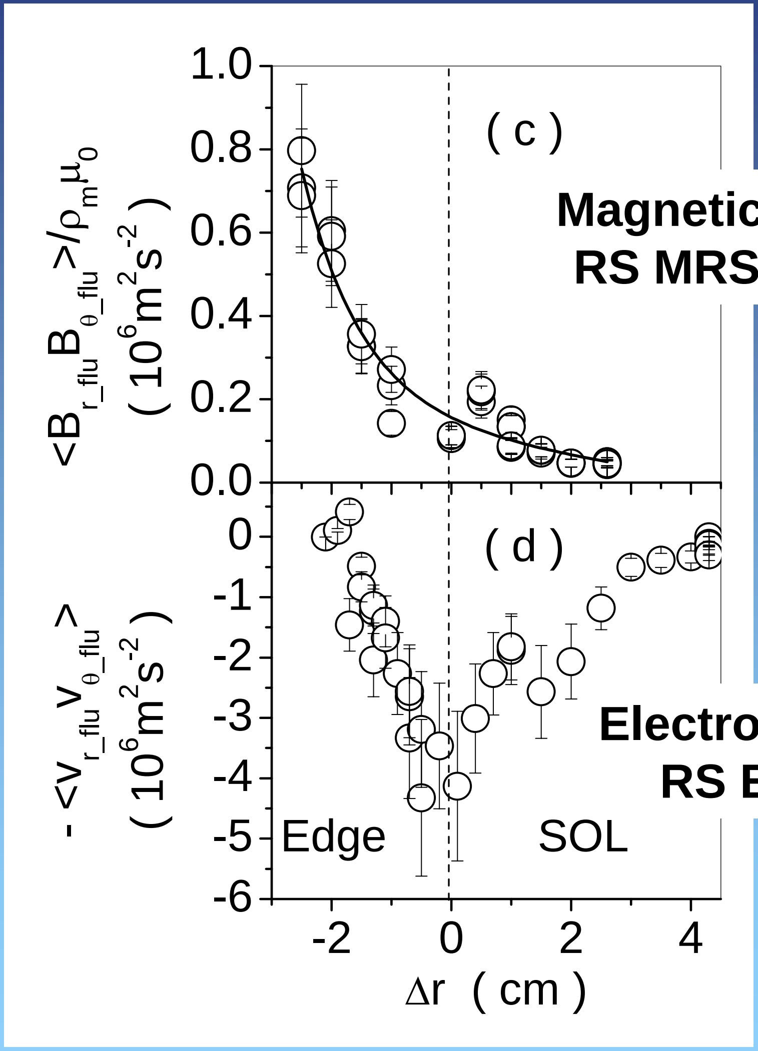
$$\tilde{v}_r = \frac{\tilde{E}_\phi \times B_\theta}{B_\theta^{\;2}}$$

Reynolds Stress (RS) profile in HT-7

$$RS = -<\tilde{v}_r \tilde{v}_\theta> + <\frac{\tilde{b}_r \tilde{b}_\theta}{\rho \mu_0}>$$



- High RS grad where high EXB flow grad
- Average MRS < ERS and ERS grad accounts for most of RS grad
- RS grad changes sign at the LCFS (consistent with fluctuation opposite radial propagation **see poster EX/84Rb Saturday morning**)

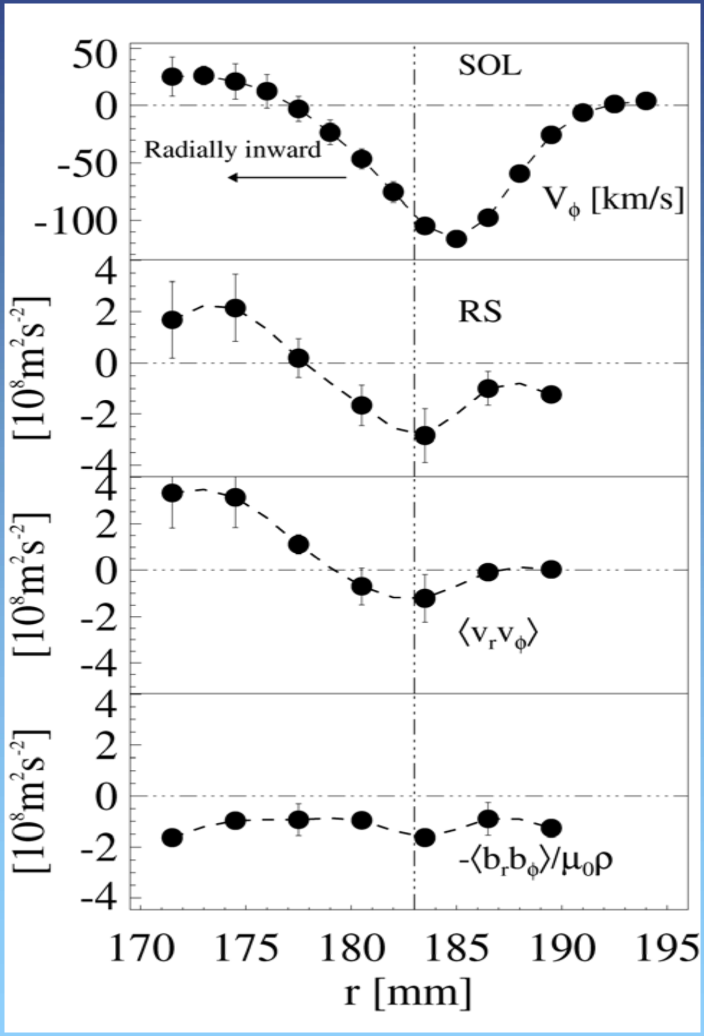


Magnetic RS MRS

Electrostatic RS ERS

Reynolds Stress profile in EXTRAP-T2R

$$RS = -\langle \tilde{v}_r \tilde{v}_\phi \rangle + \frac{\langle \tilde{b}_r \tilde{b}_\phi \rangle}{\bar{\rho}\mu_0}$$



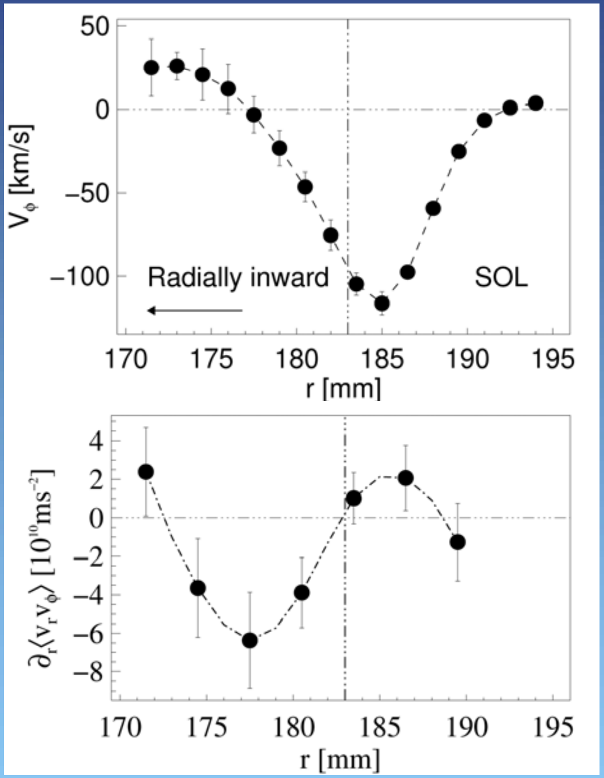
RS exhibits a strong radial gradient where velocity is highly sheared

MRS and ERS are comparable

The RS gradient is mostly due to electrostatic component, so that electrostatic RS drives the ExB shear

Comparison of Reynolds stress profiles

Also in EXTRAP-T2R the RS grad changes sign at the LCFS



In both experiments MRS grad < ERS grad (contributes to 15% in HT-7 and 20% in T2R)

In both experiments RS gradient changes sign at the LCFS

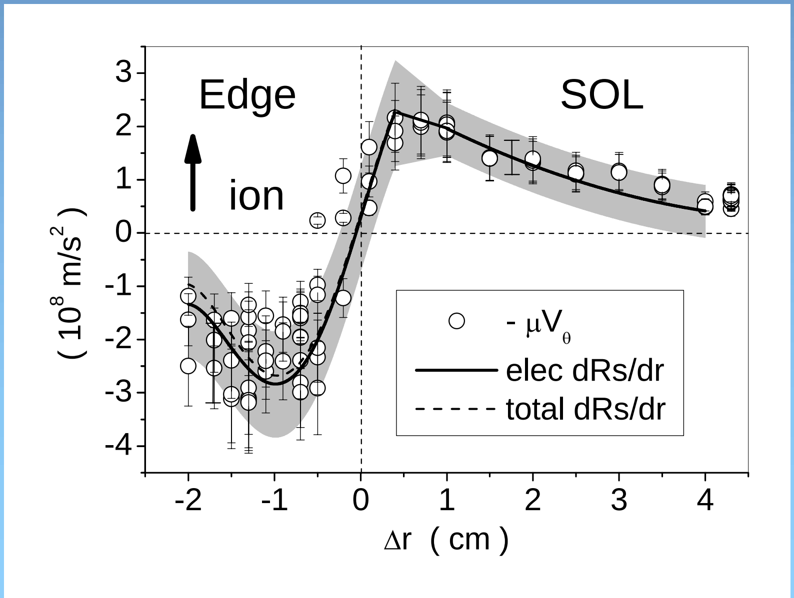
Viscous damping

In HT-7 the RS gradient has been balanced by neoclassical viscous damping

$$\frac{\partial}{\partial r}\left(- < \tilde{v}_r \tilde{v}_\theta > + < \frac{\tilde{b}_r \tilde{b}_\theta}{\rho \mu_0} > \right) - \mu V_\theta$$

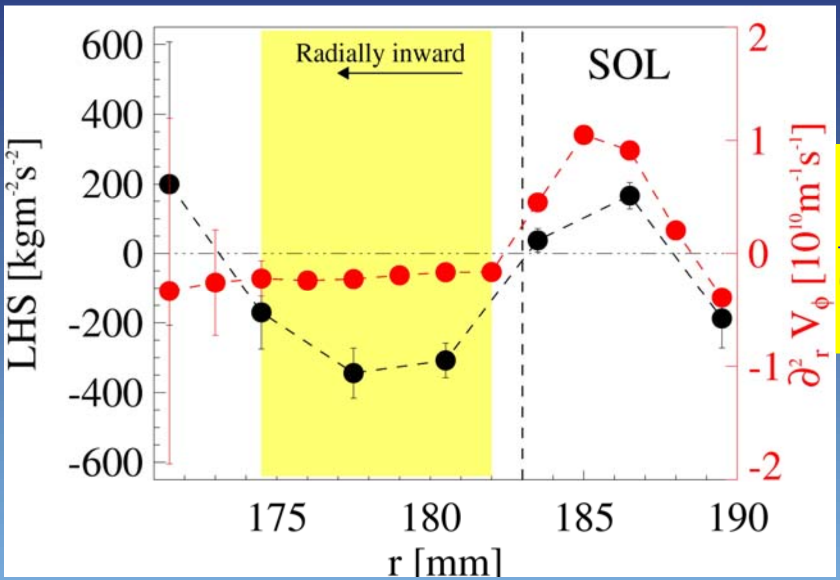
Where, according to Stix-model:

$$\mu V_\theta = \left(\frac{\sqrt{\pi}}{2} \frac{q V_{th}}{R_0} \exp\left(-U_{pm}^2\right) + \frac{1}{2} \frac{\nu_{ii} q^2}{1+U_{pm}^2} \right) \left(V_\theta - V_\theta^{Neo}\right) \quad , \quad \text{where} \quad U_{pm} = -\frac{E_r}{B_\theta V_{th}}$$



In HT-7 in stationary conditions the RS gradient results to be balanced by neoclassical viscous damping

Viscous damping

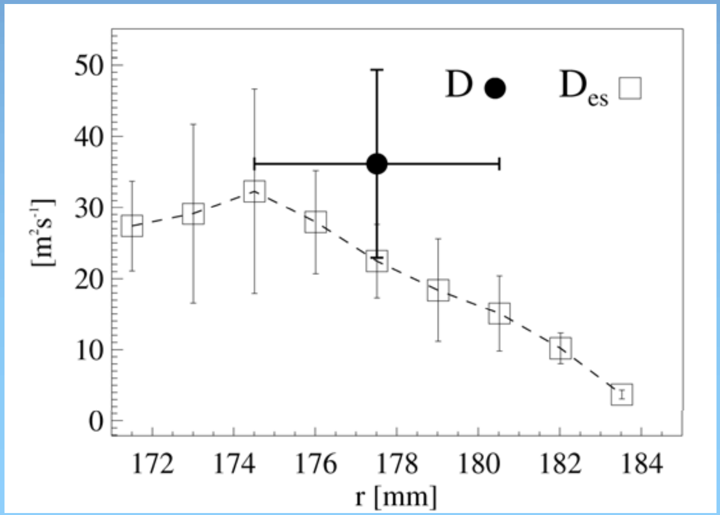


In RFP the terms entering in momentum balance equation have been measured

$$\frac{\partial}{\partial r}\left[\underbrace{-\bar{\rho}\left\langle\frac{\tilde{b}_r\tilde{b}_\phi}{\bar{\rho}\mu_0}-\tilde{v}_r\tilde{v}_\phi\right\rangle}_{A}+\underbrace{\langle\tilde{v}_r\tilde{v}_\phi\tilde{\rho}\rangle}_{B}\right]+\underbrace{m_i\Gamma_{es}\frac{\partial\overline{V}_\phi}{\partial r}}_{C}\approx\nu\frac{\partial^2\overline{V}_\phi}{\partial r^2}$$

Both LHS and RHS change sign across LCFS. From their ratio the perpendicular viscosity results

Experimental viscosity results much larger than classical one. Assuming **ν=ρD** the corresponding diffusivity results comparable to that caused by electrostatic turbulence ($D=\Gamma_{es}/\nabla n$).
Therefore momentum transport is anomalous and consistent with anomalous particle transport



Turbulence self regulation

In both experiments ExB velocity profile is the result of the balance between mainly electrostatic Reynolds Stress and viscous damping (neo classical viscous damping in HT-7 and anomalous viscosity in EXTRAP-T2R)

The ‘spontanoeus’ ExB velocity shear is marginal for turbulence suppression/ mitigation

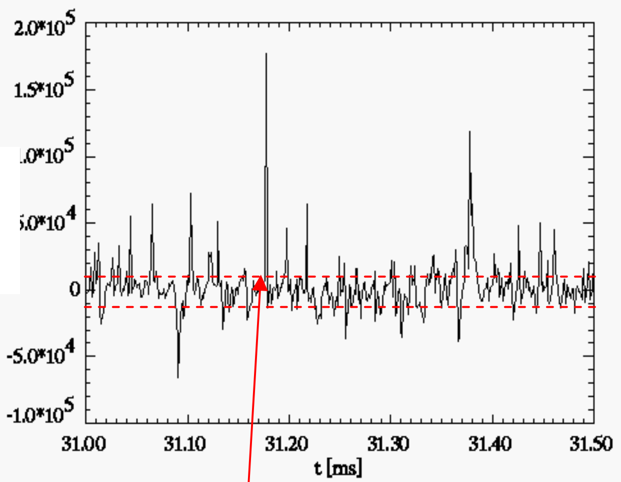
A turbulence self-regulation process is in action in the edge region of tokamaks (stellarators) and RFPs

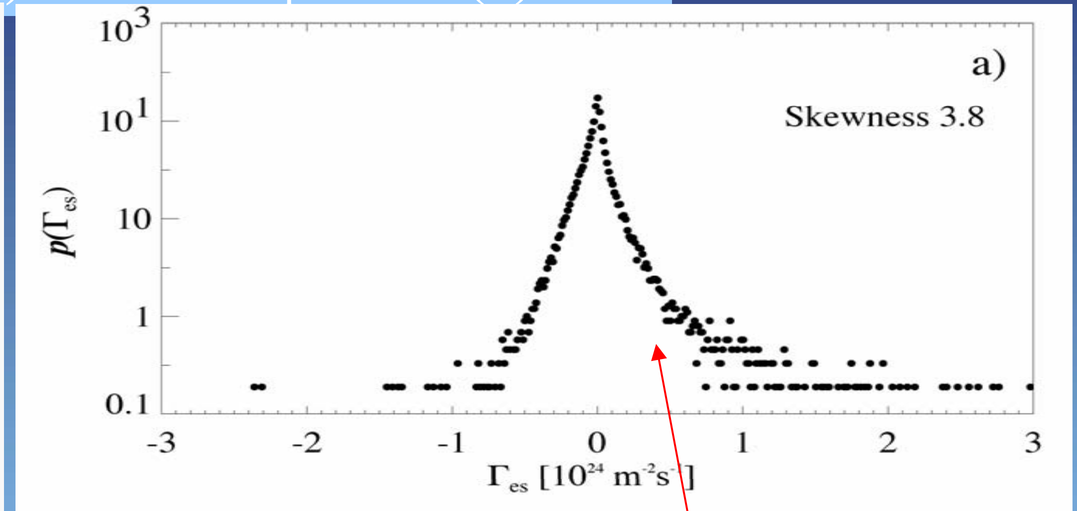
C. Hidalgo , OV/4-3

Bursts on electrostatic turbulence & particle flux

Bursts are observed in primary (n,T,ϕ) and derived quantities (Γ)

Γ [a.u.]

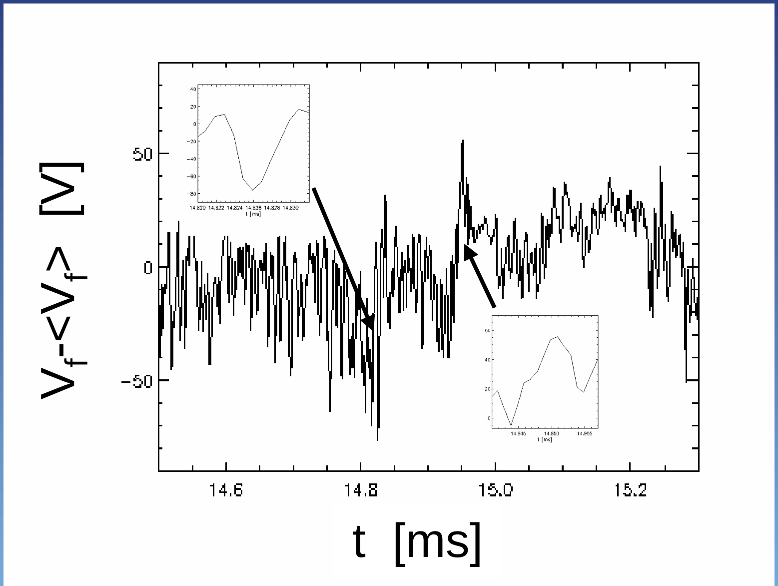


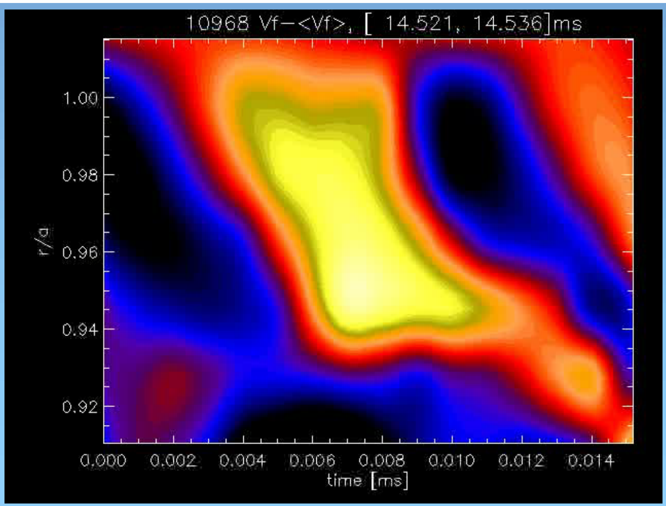


Bursts in radial particle flux Γ_{es} carry almost 50% of the particle flux (as in tokamaks and stellarators) ***V. Antoni et al. Phys Rev Lett , 87, 045001 (2001)***

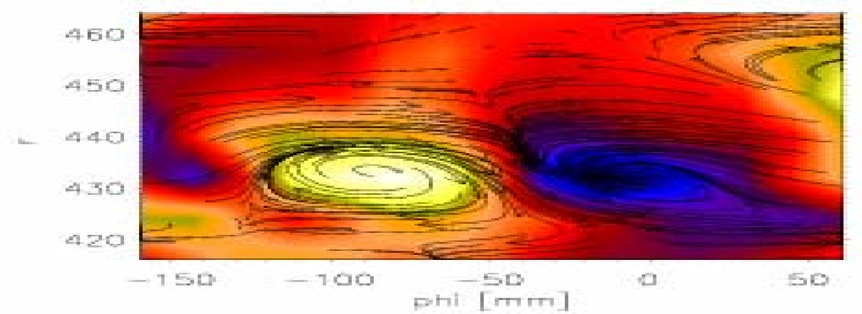
Bursts have been demonstrated to be intermittent events in RFPs, as the PDFs at different time scales are not self-similar with pronounced non-gaussian tails ***V. Carbone et al., Phys.Plasmas 7, 445 (2000)***

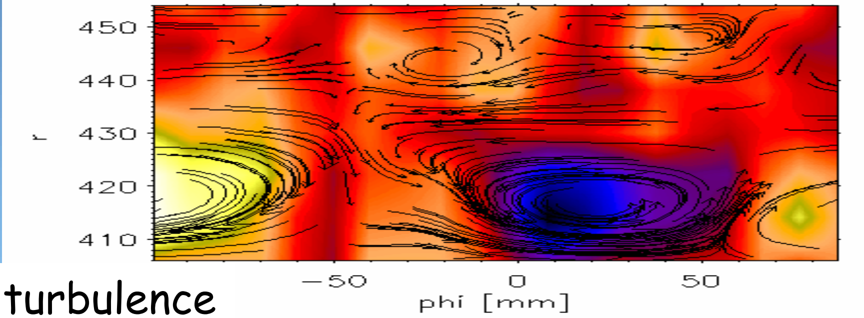
Bursts and vortices





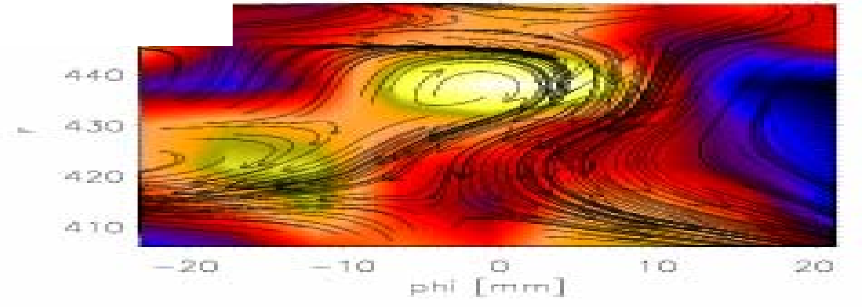
Bursts in V_f correspond to dipolar and monopolar vortices with opposite vorticity





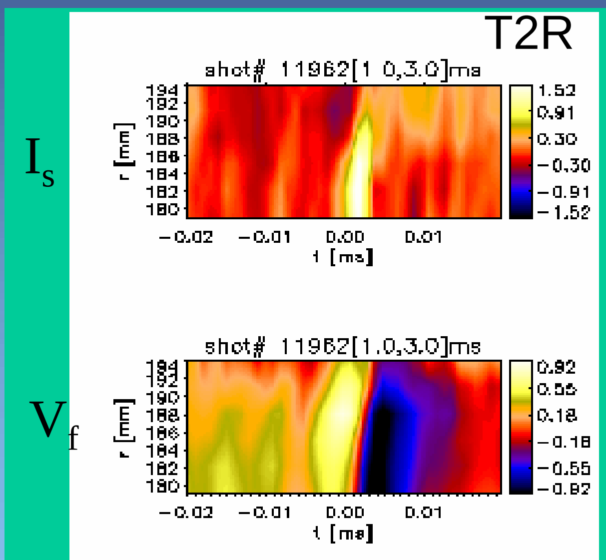
Hyp: Frozen turbulence

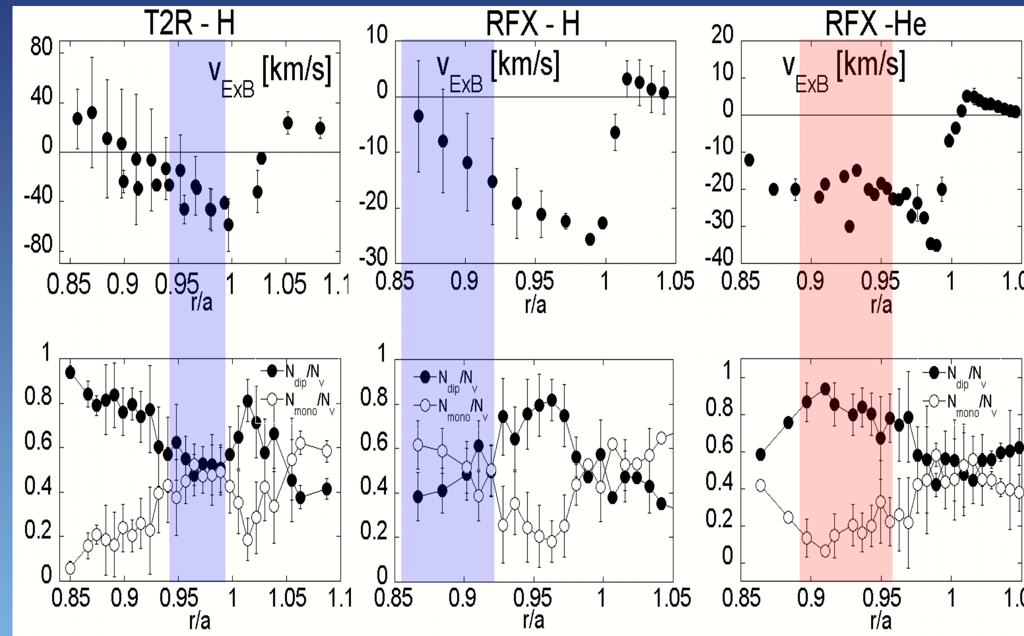
$\Delta z \approx \Delta t \, v_{ExB}$



Density blobs, vortices and ExB flow shear

Dipolar and monopolar population depends on ExB flow shear

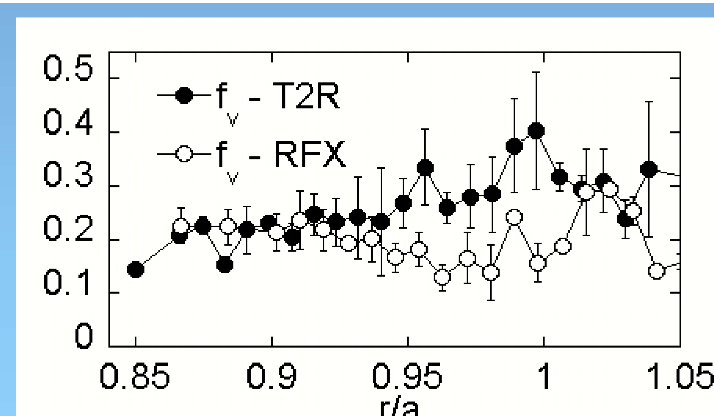




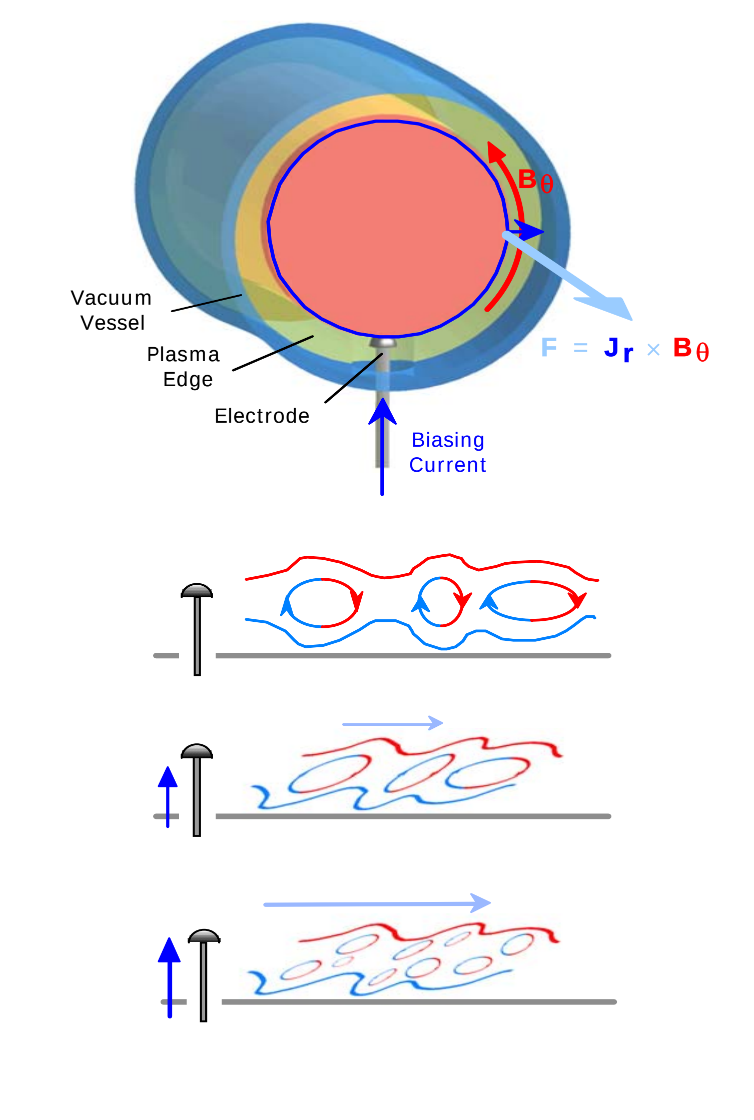
Vortices correspond to density blobs

Coherent structures occupies 20-30% of the the edge region and their interaction accounts for 50% of anomalous particle transport at the edge

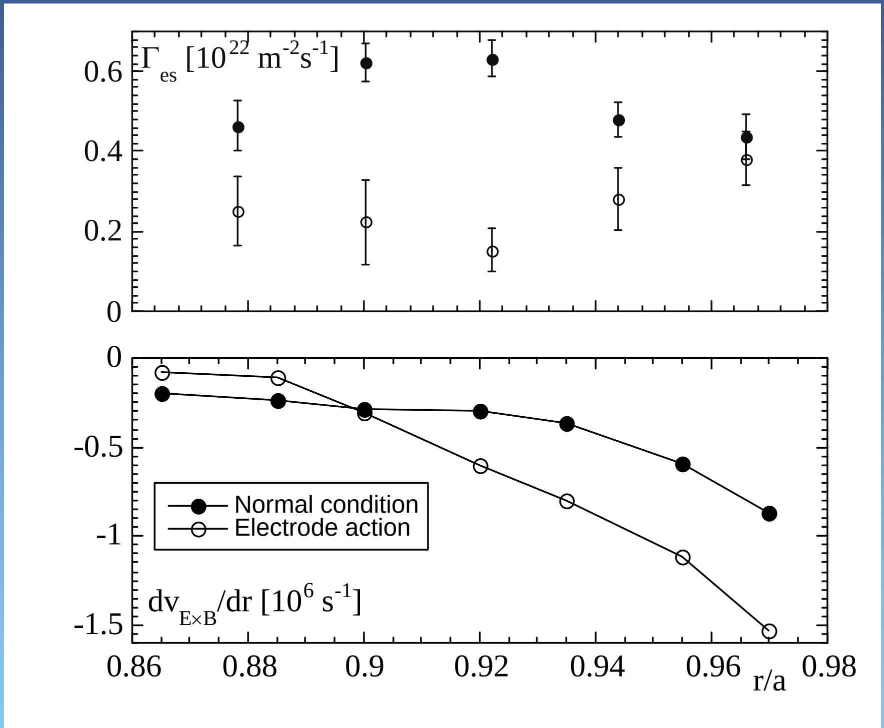
M.Spolaore et al., to appear in PRL (2004)



Turbulence control:edge biasing



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



V Antoni, et al. Plasma Phys. Control. Fusion **42** (2000)

Turbulence control: pulsed poloidal current drive

In T2R a transient (10-fold) increase of the toroidal ExB flow shear has been obtained during Pulsed Poloidal Current Drive

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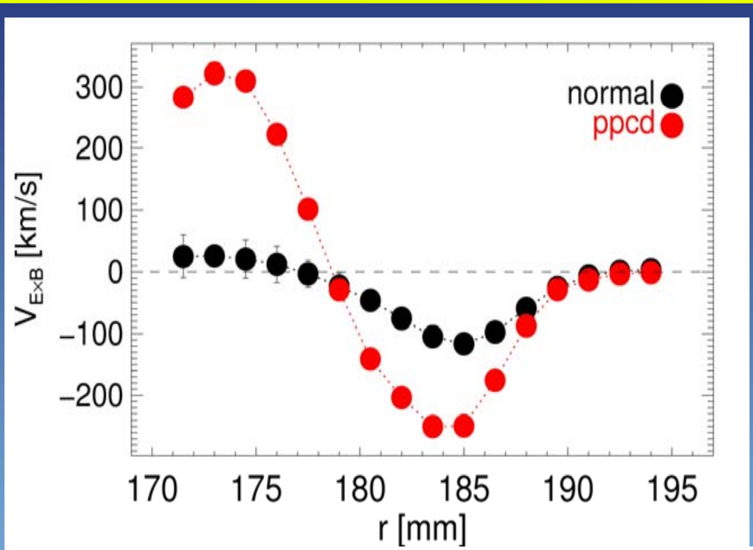
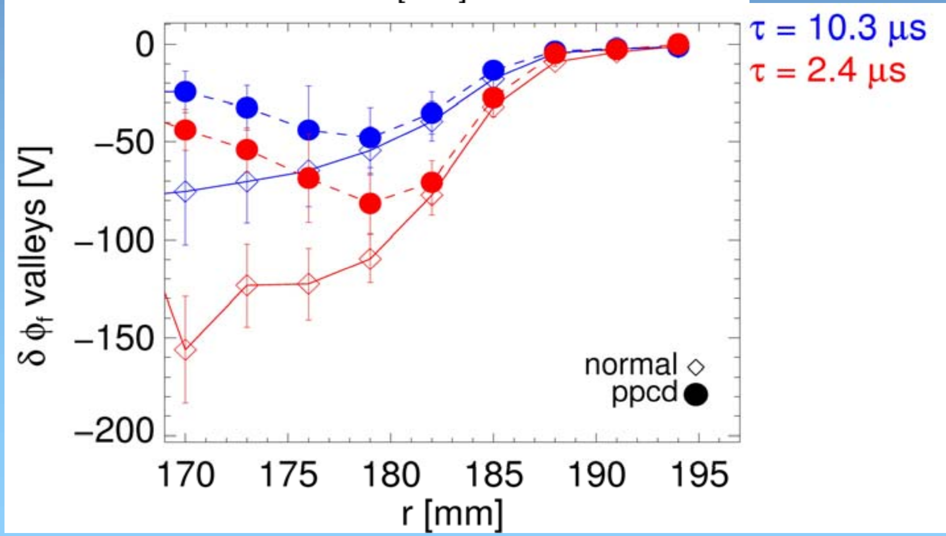


A reduction of the burst intensity is observed → strong reduction of structure's vorticity



New tools for MHD control & new diagnostics for turbulence measurements in RFX

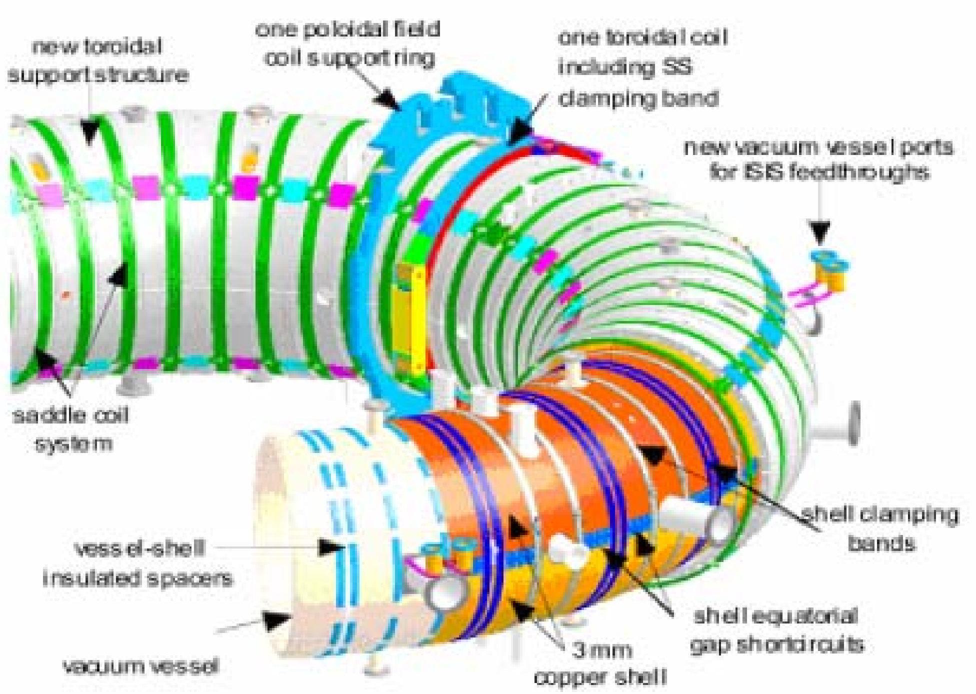
RFX plasma experiments will restart by the end of 2004, with new tools and diagnostics, among which:

-New system of 192 (4x48) saddle coils, individually fed by fast amplifiers

-New arrays of in-vessel magnetic and electric probes

-The new tools are expected to affect edge turbulence dynamics

More details at the poster
by F. Gnesotto FT P7-9 on Saturday



Conclusions

Several similarities in edge physics with Tokamaks and Stellarators: Particle flux is mainly driven by electrostatic turbulence and ExB shear increase is effective in turbulence transport decrease. Coherent structures emerge from the turbulent background and contribute to 50% of the particle transport.

The highly sheared ExB flow at the edge comes from a balance between Reynolds stress and viscous damping and a turbulence self-regulation process is in action.
Turbulence control experiments in RFPs show that externally induced high flow shear can reduce the transport due to background and coherent structures.

Because of these analogies, investigation of magnetic and electrostatic turbulence in RFP can contribute to general advance of fusion research. Studies on MHD control will be relevant also for Tokamaks operating under advanced confinement scenarios.