The Abdus Salam
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3 - 14 October 2011

Role of Self-generated Zonal Flows

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II. Role of Self-generated Zonal Flows

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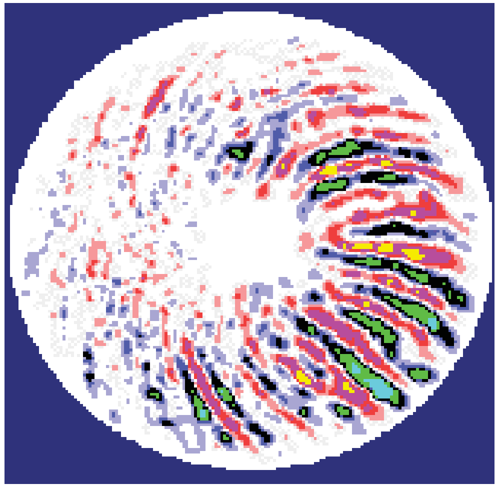
Joint ITER-IAEA-ICTP Advanced Workshop on “Fusion and Plasma Physics”,
Trieste, Italy Oct, 2011

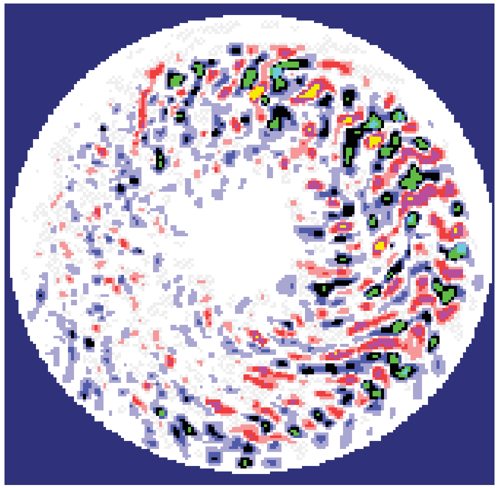
Sheared Zonal Flow Regulates Turbulent Eddy Size and Transport

[Lin, Hahm, Lee et al., Science 1998]

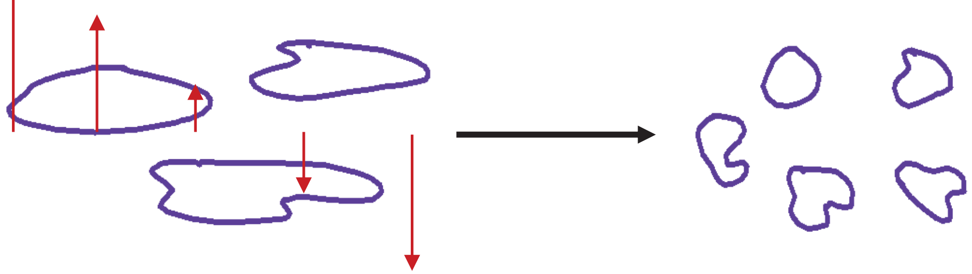
No flow



With flow



. Self-generated ExB zonal flow reduces radial size of eddies



. Breakup of radially elongated structures reduces transport

- Externally driven ExB Shear Flows were used before for the direct control of the turbulence

Role of E x B Shear in Reducing Turbulence

- Flow shear decorrelation in cylinder [Biglari-Diamond-Terry, Phys. Fluids-B '90]

$$\omega_E > \Delta\omega_T$$

- Turbulence quenching in gyrofluid simulation [Waltz-Kerbel-Milovich, Phys. Plasmas '94]

$$\omega_E > \gamma_{lin}$$

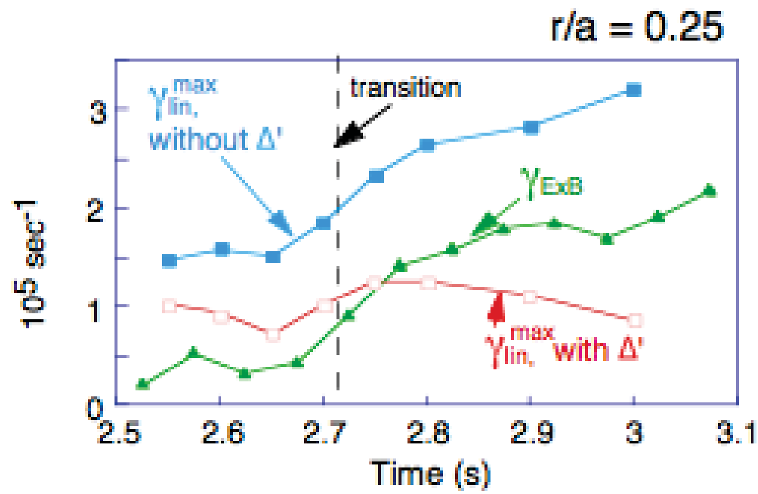
- ExB Shearing Rate in **General Toroidal Geometry** [Hahm-Burrell, Phys. Plasmas '95]

$$\omega_E = \frac{\Delta r_0}{\Delta_{\ell\perp}} \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial\psi}\left(\frac{E_r}{RB_\theta}\right)$$

- Made possible by developments of Experimental Diagnostics for E_r and B_θ (Motional Stark Effects, Charge Exchange Recombination Spectroscopy, …)
- Useful Rule of Thumb for Indication of the importance of ExB shear

- Widely used for experimental results analysis (TFTR, DIII-D, JET, JT60-U, AUG, TEXTOR, NSTX, MAST, LHD, W7-AS,…) with linear growth calculations via various gyrokinetic codes.

E. Synakowski et al., Phys. Plasmas '97 ----->



$E \times B$ Shearing Rate in Toroidal Geometry

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Hahm and Burrell, Phys. Plasmas **2**, 1648 (1995)

$$\omega_E = \frac{\Delta r_0}{\Delta l_\perp} \frac{(RB_\theta)^2}{B} \left| \frac{\partial}{\partial \psi} \left(\frac{E_r^{(0)}}{RB_\theta} \right) \right|$$

- $\frac{\partial}{\partial \psi}\left(\frac{E_r^{(0)}}{RB_\theta}\right)$:
  From u_θ and ∇P_i:(TFTR ERS, H-mode)
  or from u_ϕ (DIII-D NCS, VH; JET OS, RS...)

- $\frac{(RB_\theta)^2}{B}$:In-out Asymmetry
  Evidence from DIII-D, Pronounced for STs
  Rettig Stambaugh

- $\frac{\Delta r_0}{\Delta l_\perp}$:Eddy shape dependence
  Typically assumed to be 1
  Stronger shearing for radially elongated eddy

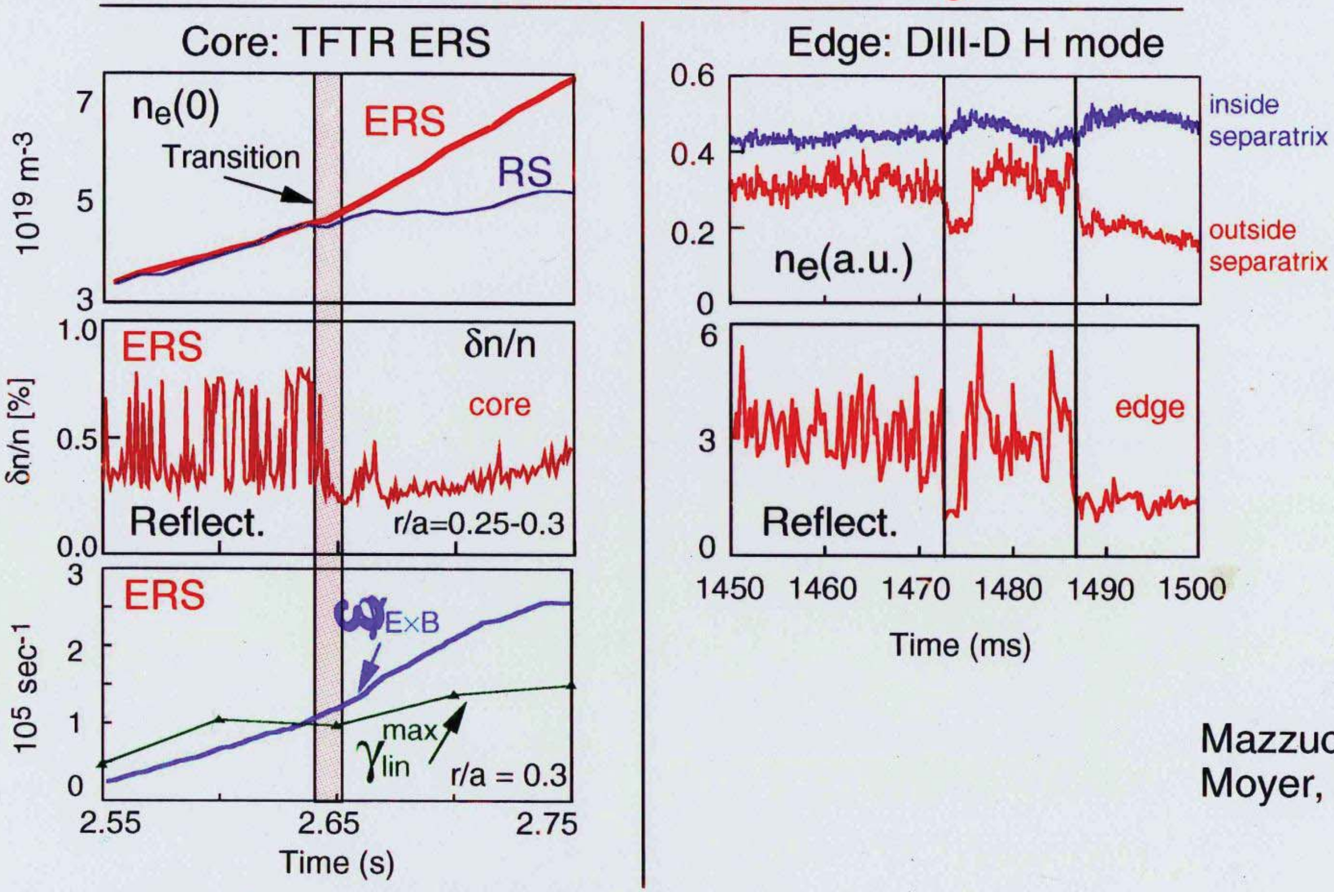
E x B Flow Shear is well-known to reduce Turbulence and Turbulence-driver Transport :

Theoretically it can occur via

- Reduction in fluctuation amplitude
- Reduction in radial correlation length (eddy size)
- Elimination of large Transport Events
- Shift I cross phase between transported quantity (δn, δTi, ……)

  and transporter ($\delta v_r = \left(\frac{c}{B} \hat{b} \times \nabla \delta\phi \right) \cdot \hat{e}_r$)

Density fluctuations are reduced across confinement bifurcations in both the core and the edge



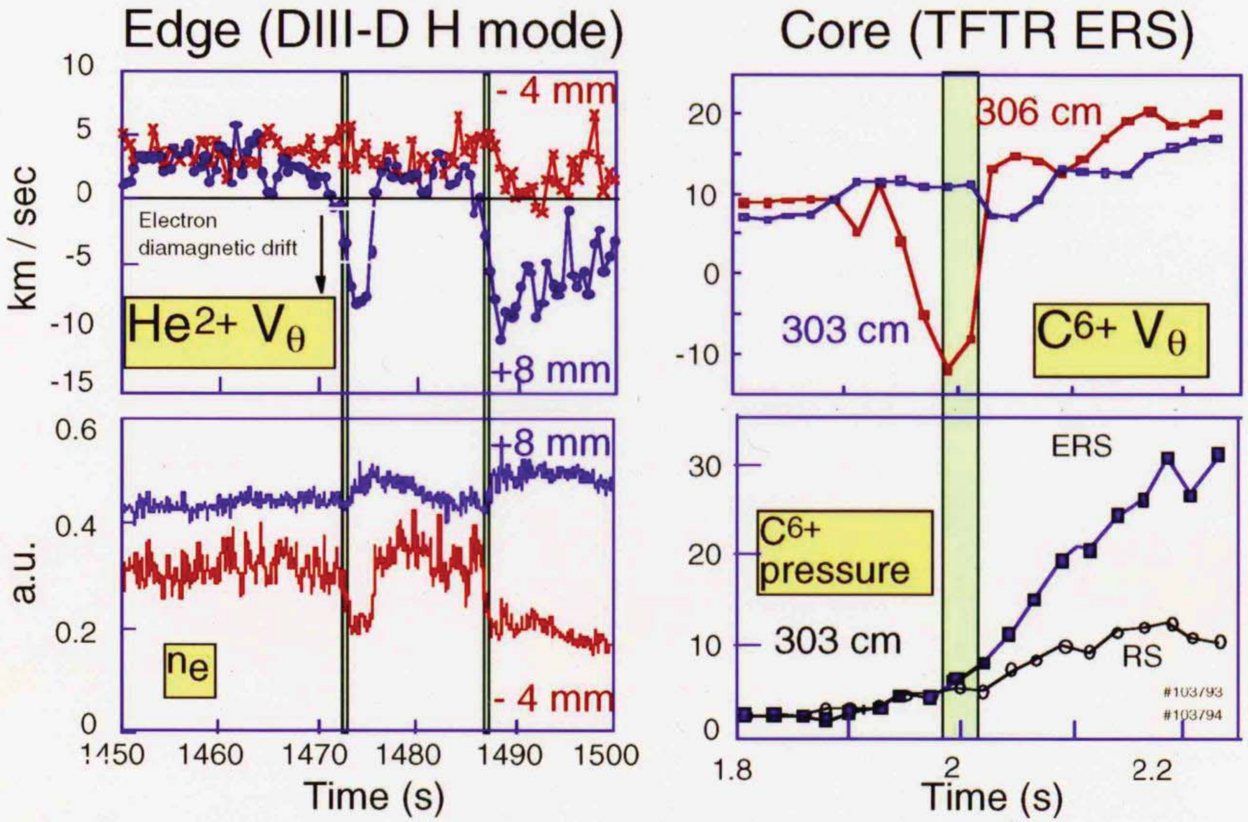
Mazzucato, 1996
Moyer, 1995

- In core, $\omega_{ExB}/\gamma_{lin}$ *increases* with rising ∇p
  ⇒ positive feedback
- Closeness of shearing and growth rates at transtion should be treated with caution

• BDT : $\Delta\omega_T$

≈ factor of 2 from Gyrofluid simulation

E_r shear layer bifurcation starts before confinement improvement in the TFTR ERS core and DIII-D edge



For both: large negative $\Delta V_\theta \Rightarrow$ large negative ΔE_r

∇p eventually dominates E_r in force balance

$\omega_{E\times B}/\gamma_{lin}^{max} \sim 10$ at peak ΔV_θ for ERS

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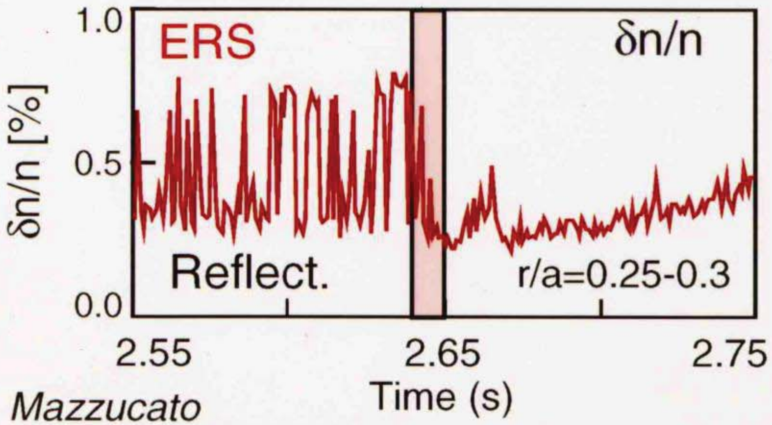
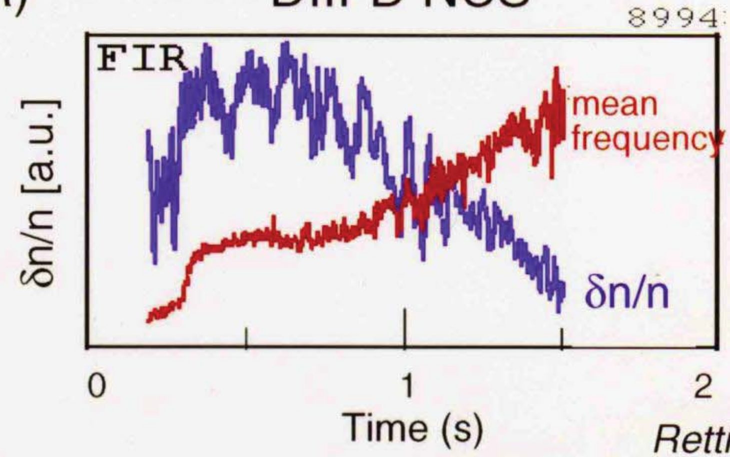
Core transport and fluctuation reduction can have very different time scales

Fast	Slow
High power ERS Core (TFTR)	DIII-D NCS



Mazzucato



Rettig

- Difference in time scale may be due to fast boostrap with ∇p-dominated bifurcation vs. competition between ∇p and V_ϕ in DIII-D case
- DIII-D: fluctuation, transport reduction during time when V_ϕ shear is slowly increasing
- TFTR: fluctuation, transport change is “single step” in character

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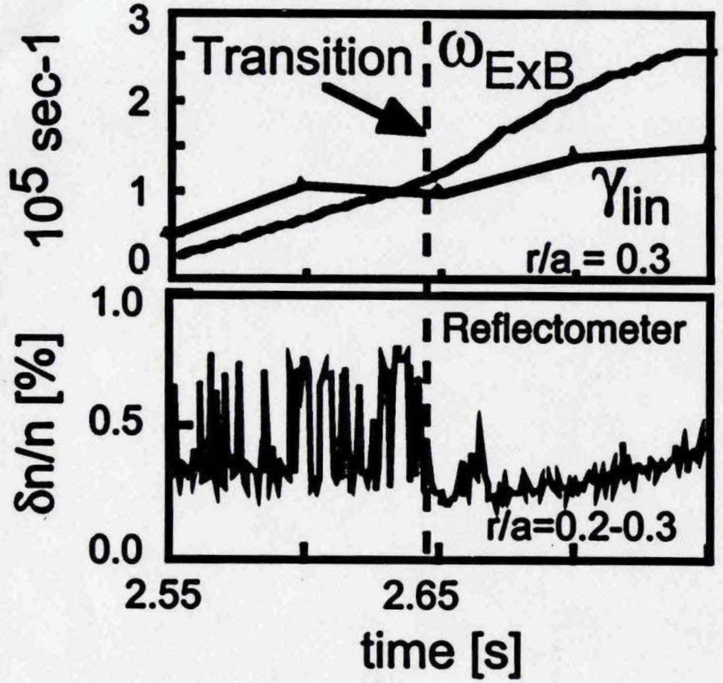
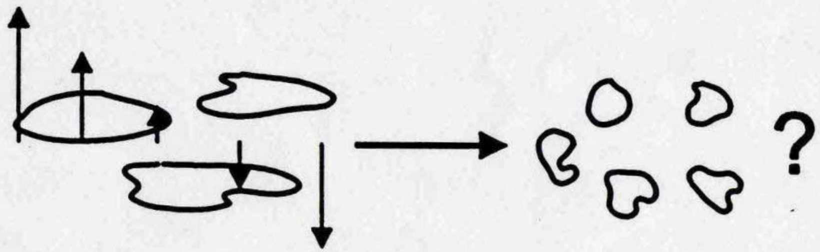
Transition to Enhanced Confinement Regime is Correlated with Suppression of Core Fluctuations in TFTR



- Theory predicts fluctuation suppression when rate of shearing (ω_{ExB}) exceeds rate of growth (γ_{lin})
- Outstanding issue: Is suppression accompanied by radial decorrelation?



- Similar suppression observed on JET (X-mode reflectometer) and DIII-D (FIR Scattering)

Hahm, Burrell, Phys. Plas. 1995, E. Mazzucato et al., PRL 1996.

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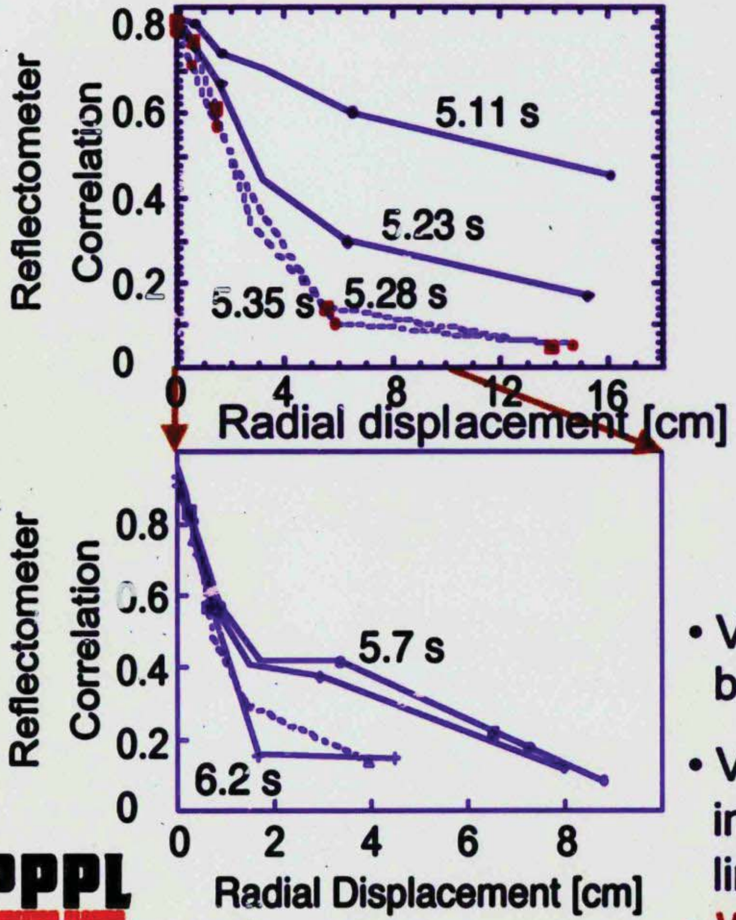
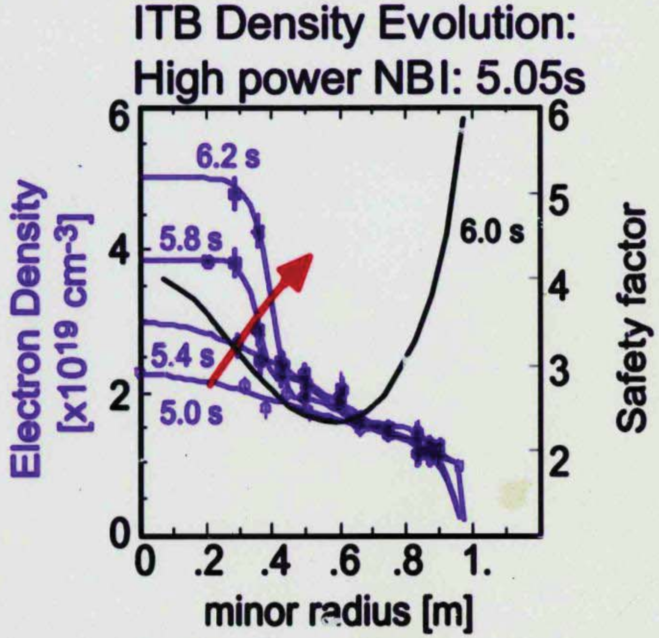
Dramatic Reduction of Radial Correlation Length in ITB of JT-60U: Are We at The Limit of Our Spatial Resolution?

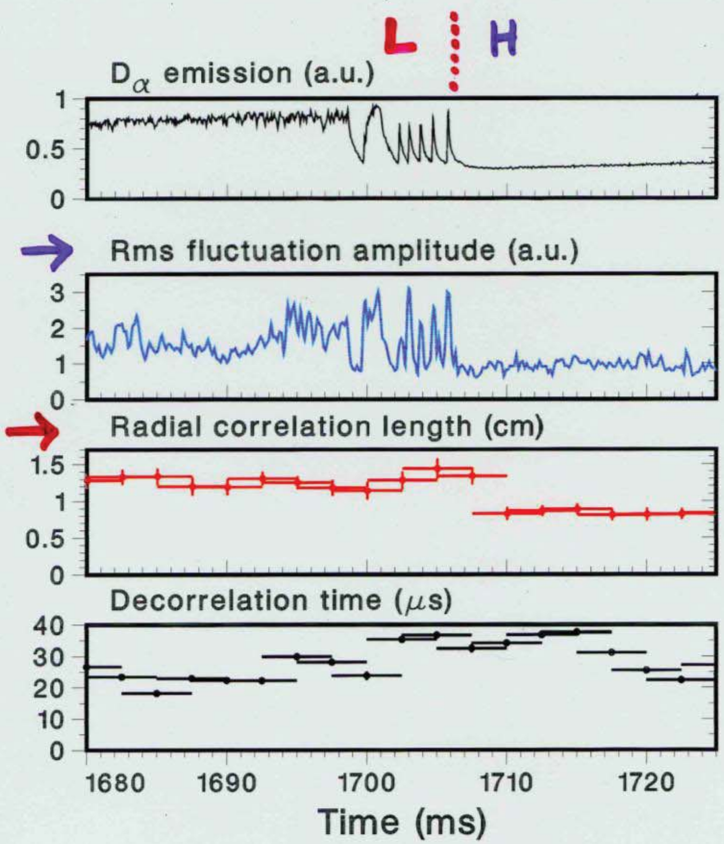




- Very long correlation lengths before ITB formation: L_r/ρ_i>>1 !
- Very short correlation lengths inside ITB: close to resolution limit?
- Weak change in fluctuation level

- PCI Measurements at DIII-D Edge show that δn and Δr decrease at L-H transition

Coda, Porkolab & Burrell : Phys. Lett. A. 2000.



Hierarchy of E × B Shear Effects

- Reduction in Transport comes from Amplitude Reduction (δn) or Radial Decorrelation (Δr)
- Together: DIII-D Edge [*Coda*], Gyrokinetic Simulation [*Lin*]
- Radial Decorrelation only in JT-60U Core [*Nazikian '98*]?
- Dramatic Form of Radial Decorrelation: via Elimination of **Transport Events**

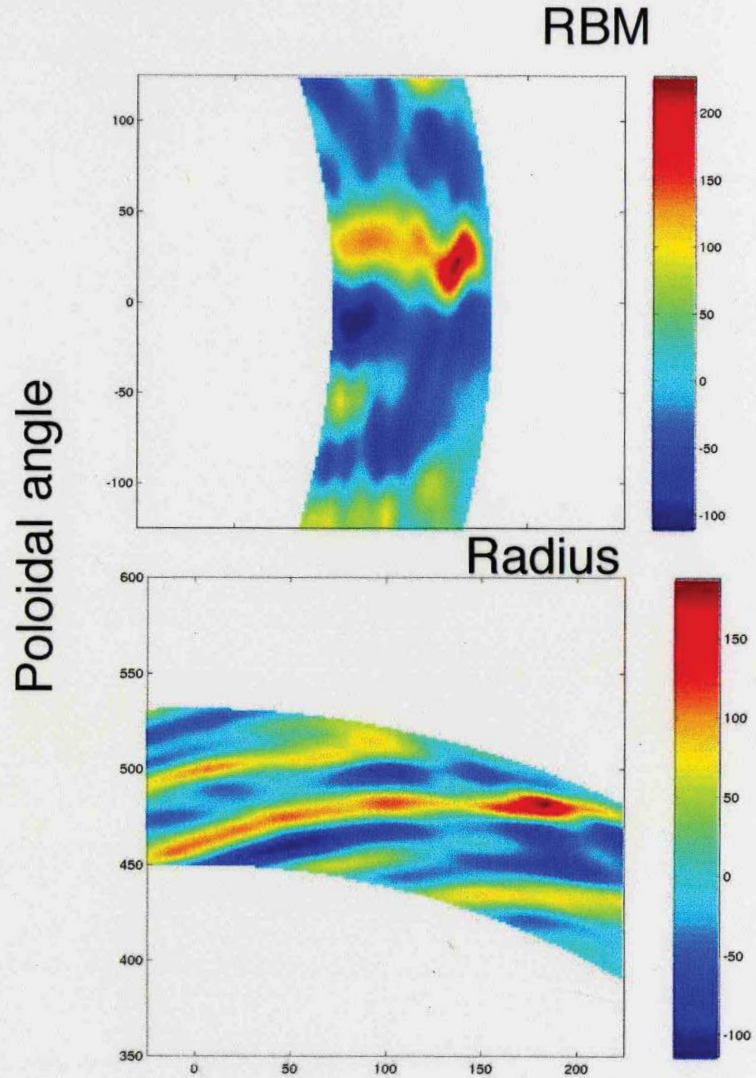
Mean Field Th (χ_i, D, ... :
↓
Statistical Approach
PDF { Γ, Q_i ... }
$\langle \tilde{Q}_i^2 \rangle - \langle \tilde{Q}_i \rangle^2$.
e.t.c.

- T_e evolution in DIII-D via ECE [*Politzer*]
- RBM and ITG Fluid Simulations [*Garbet, Beyer, Sarazin*]
- Gyrokinetic Simulation Data Analysis [*Nevins*]
- SOC Models [*Diamond-Hahm, Newman-Carreras*]

- Cross Phase Shift between δn (transportee) and $\delta \phi$ (v_r) (transporter) DIII-D Edge [*Boedo, Moyer*], Mode-specific Theory [*Terry, Ware*]

3D Structure of Streamers

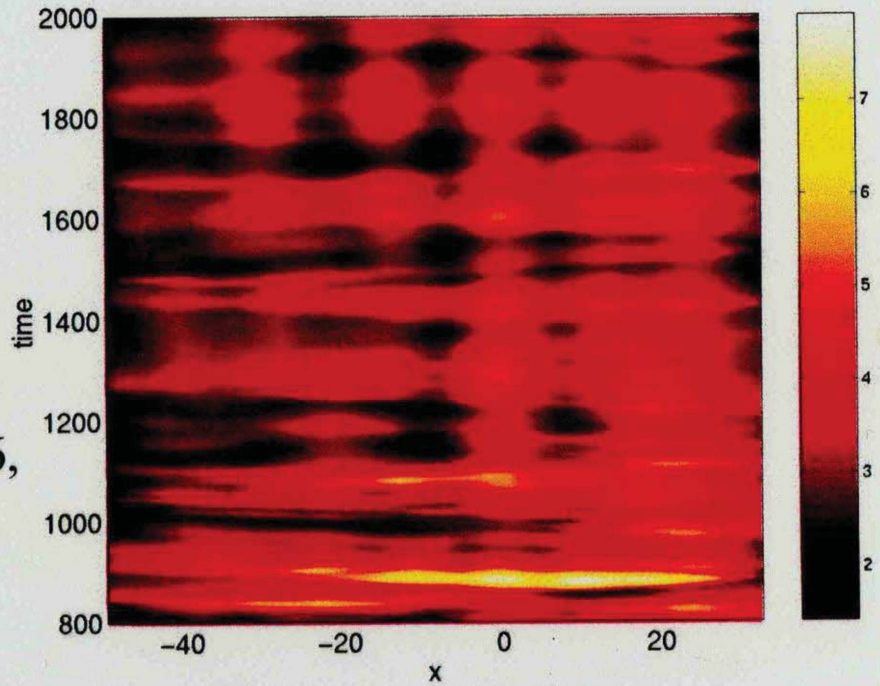
- Maps of the flux in poloidal planes.
- Elongated structures in the radial direction: **streamers**.
- Aligned with the direction of field lines.



Bursty Transport

- Diamond and Hahm 95: profile relaxations at all spatial and time scales (avalanches).
- Observed in many turbulence simulations (Carreras 96, Sarazin and Gendrih 98 Garbet and Waltz 98, Beyer et al. 99,...)

Beyer et al 99

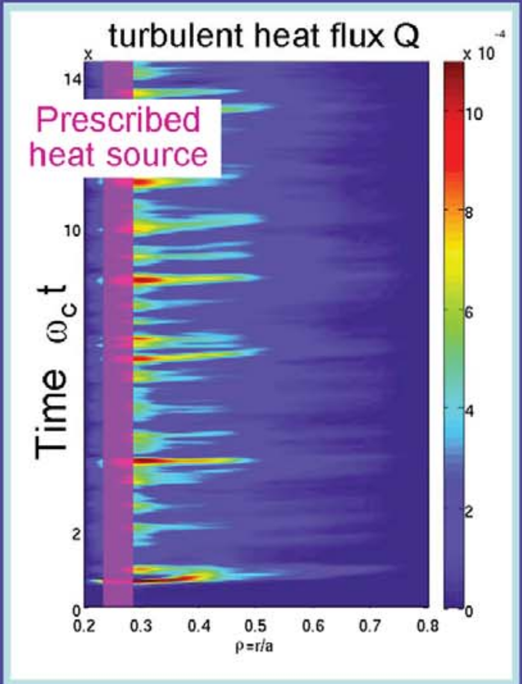


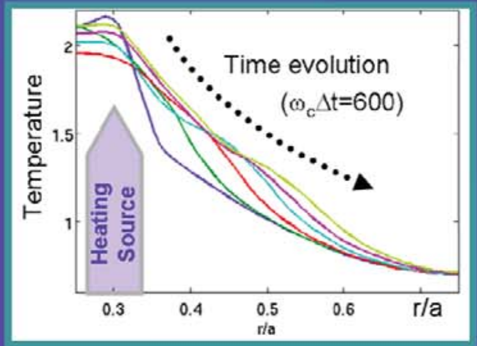
Flux vs. r and t

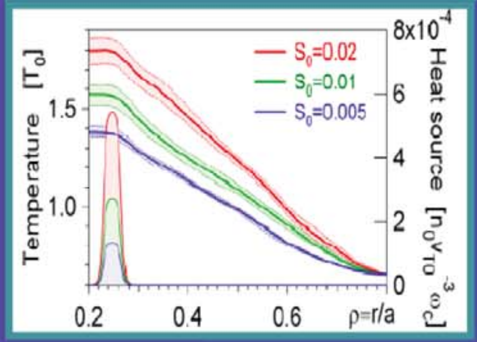
GYSELA 5D runs Forced-Flux Turbulence

- ❑ Avalanche-like transport
- ❑ Local profile relaxation
- ❑ Resilient temperature profile when heat flux increased

Confinement degrades with power ~ $P^{-0.7}$, consistent with global scaling







Transport Scaling in Weak Turbulence Regime

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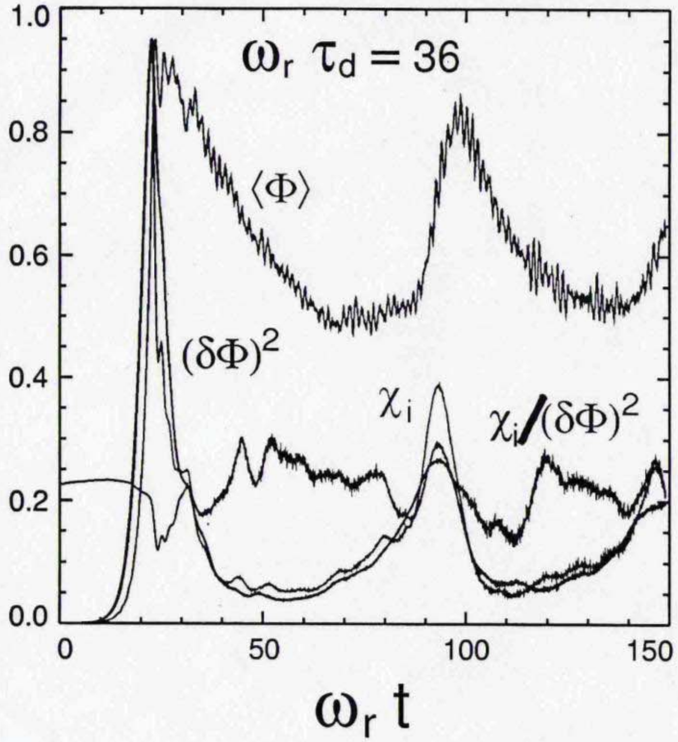
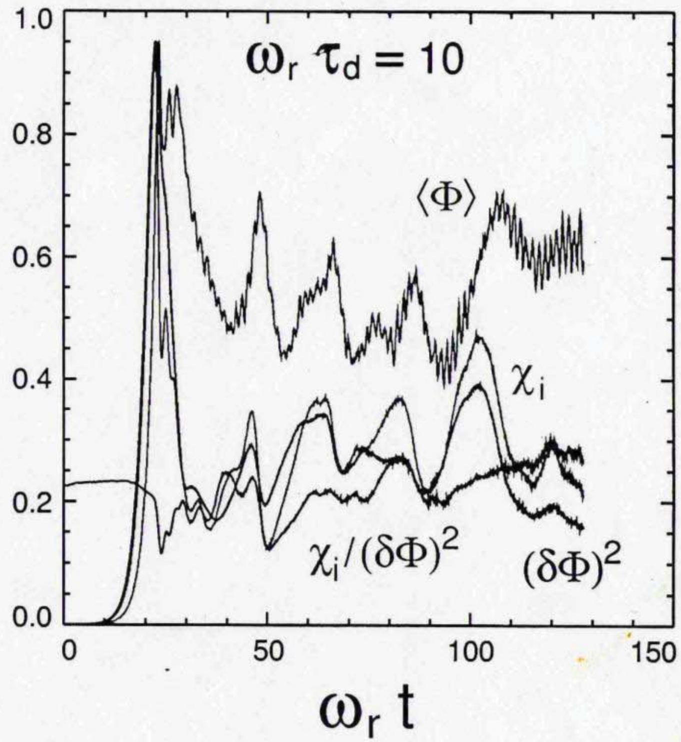




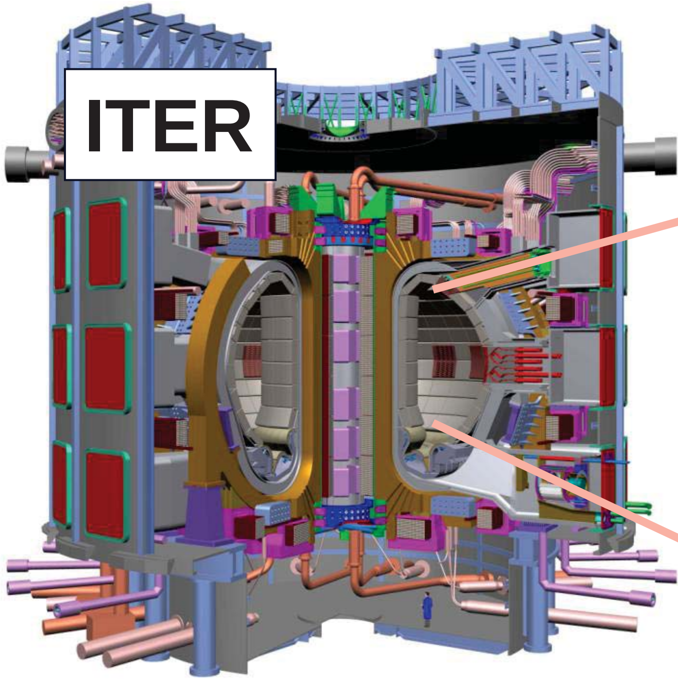
Use Falchetto.

- Scaling studies possible without changing profiles.
- $\chi_i \sim (\delta\Phi)^2$ observed for ν^* up to 8 times realistic value.

→ Change in cross phase btwn $\delta\Phi$, δT_i small.

What is a zonal flow?

Courtesy: K. Itoh, in made in Japan, edited in USA, and presented in Korea



ExB flows

$m=n=0$, k_r = finite

From GTS

Drift Waves

↓

Drift waves
+
Zonal flows

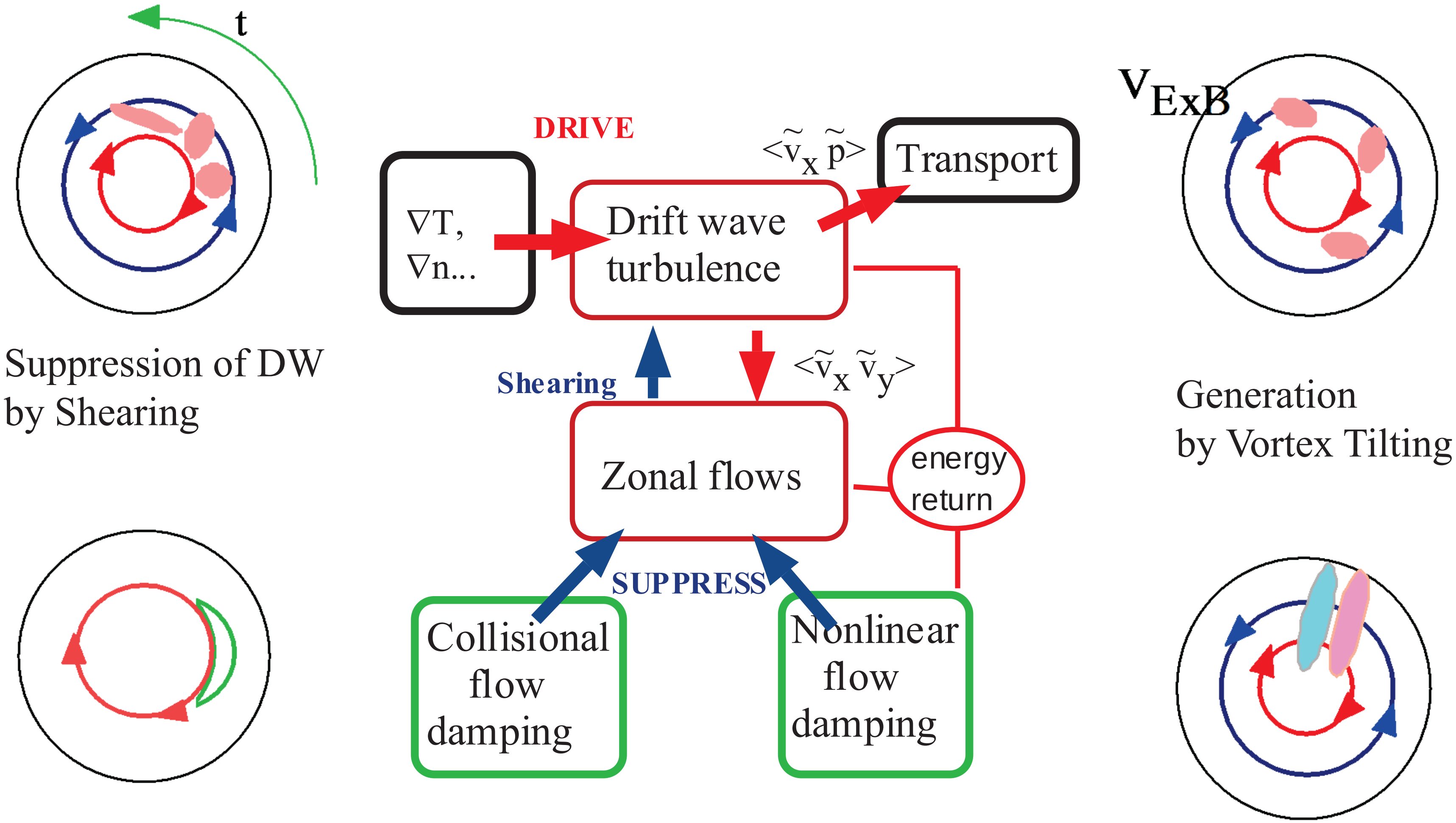
Paradigm Change

ZFs are "modes", but:

1. No direct radial transport
2. No linear instability
3. Turbulence driven

Basic Physics of a Zonal Flow

from Diamond,Itoh,Itoh, and Hahm, “Zonal Flows in Plasma-a Review” PPCF ‘05



Damping by Collisions

E x B Shearing by time-dependent Zonal Flow

[Hahm, Beer, Lin, et al., Phys. Plasmas '99]

- **Gyrofluid Simulations observed that instantaneous** $\omega_E(t) >> \gamma_{\mathrm{lin}}$ **while turbulence was at L-mode level and transport was anomalous.**

- **Effective E x B shearing rate has been analytically derived to take into account the time dependence of zonal flows**

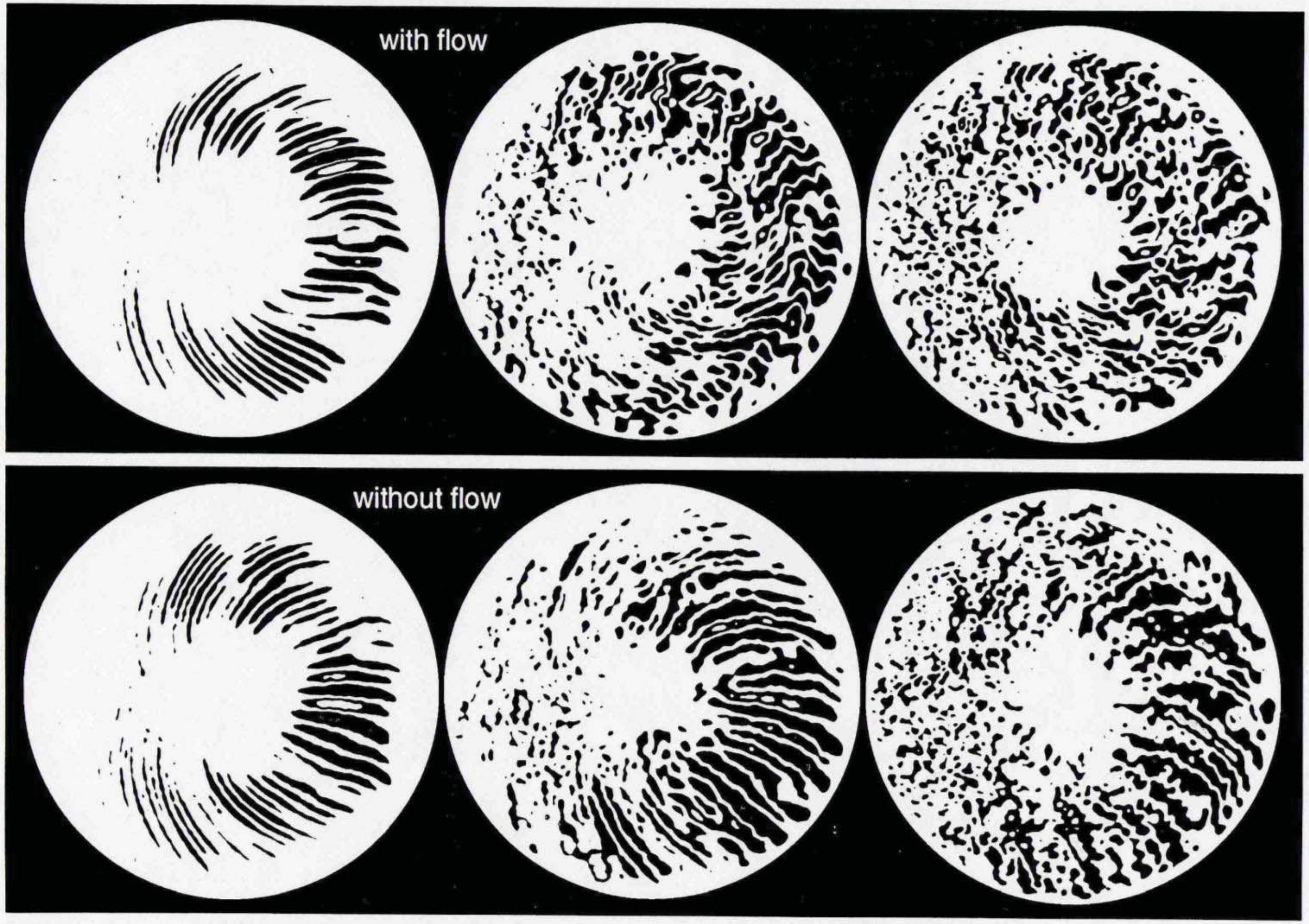
- **From Gyrofluid simulation data analysis, has been observed**: $\omega_E^{\mathrm{eff}} \sim \gamma_{\mathrm{lin}}$

-- Shearing due to high frequency comp. ZF is predicted to be ineffective for core turbulence.

- **Gyrokinetic simulations demonstrated broadening of k_r of ITG turbulence (a symptom of eddy breaking-up) due to zonal flows quantitatively.**

Radial Correlation Length &

Turbulence Generated E X B Flows Reduce Transport in Gyrokinetic Simulation



Broadening of k_r Spectrum by Zonal Flows

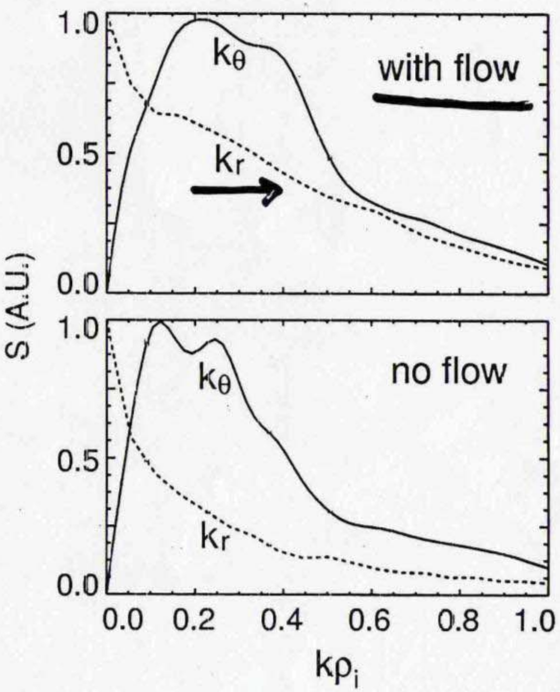
- Theory for $\mathbf{E} \times \mathbf{B}$ shear decorrelation of turbulence has been generalized to include time-dependence of zonal flows

  [*T. S. Hahm, M. A. Beer, Z. Lin, G. W. Hammett, W. W. Lee, and W. M. Tang, Phys. Plasmas, 1999*]

$$\left(\frac{\Delta r_0}{\Delta r}\right)^2 = 1 + \frac{\omega_{Eff}^2}{\Delta \omega_T^2}$$

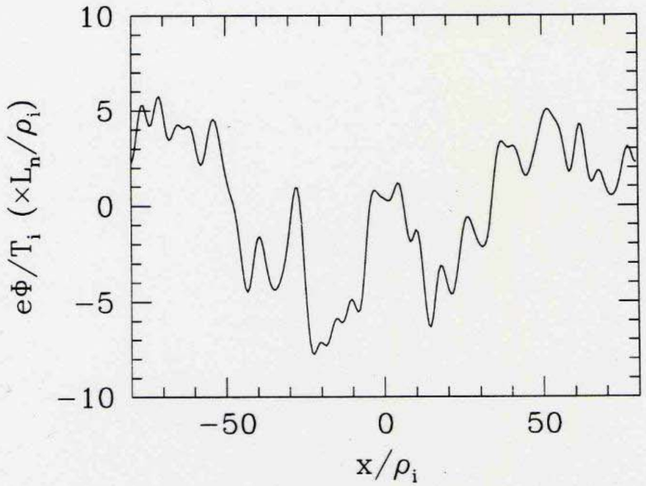
- Fast time-varying $\mathbf{E} \times \mathbf{B}$ flow is not effective in suppressing turbulence: flow pattern changes before eddies get distorted

$$\omega_{Eff} \simeq \omega_E^{(0)} \frac{\Delta \omega_T}{\sqrt{\Delta \omega_T^2 + 3\omega_f^2}}$$

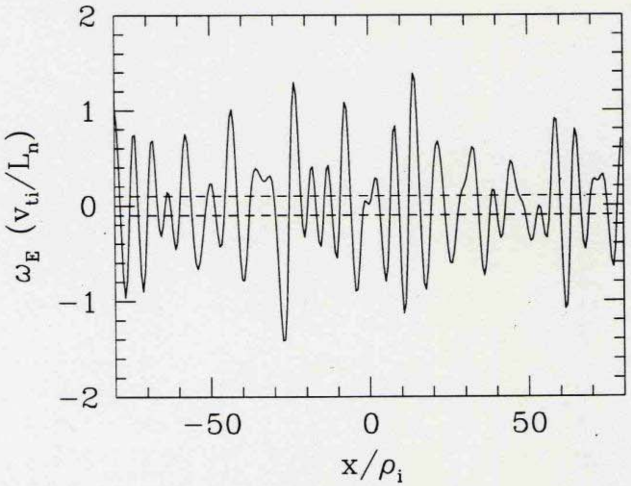


Shearing Rates from Gyrofluid Simulations

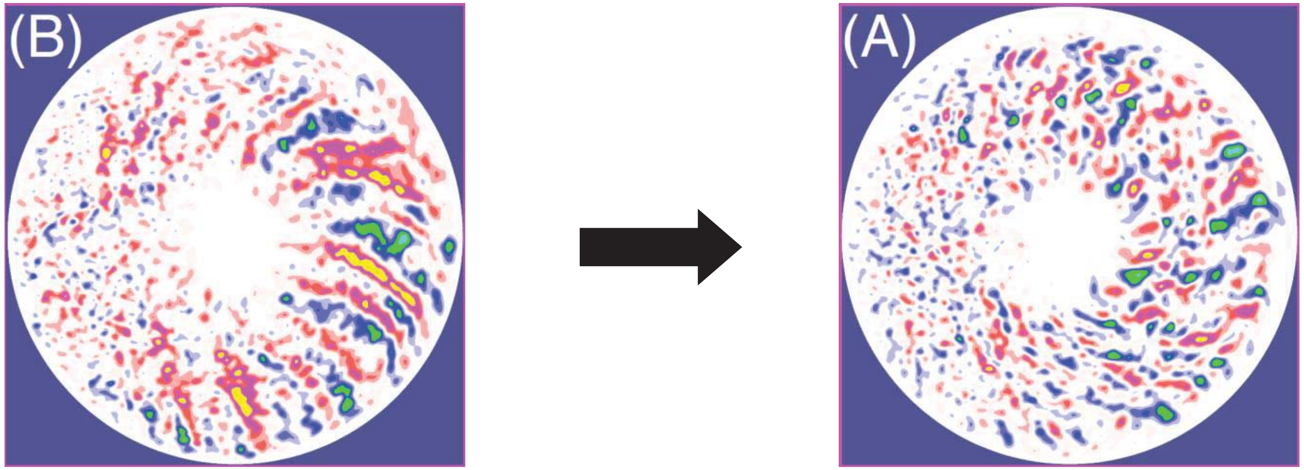
- Small-scale turbulence generated flow from gyrofluid simulation, instaneous potential:



- Instantaneous shearing rate, ω_E, is large, but dominated by high frequency and high k_x components.



Duality of Flow Generation and Random Shearing of Eddys



$\omega_k >> \omega_{ZF}$ ➡ Drift Wave Action Density, $N_{\vec{k}}$, is conserved.

From $\omega_{DW} = \dfrac{k_\theta v_*}{1+k_\perp^{2'}\rho_s^2}$ shearing $\longrightarrow k_r^2 \nearrow \longrightarrow$ Drift Wave Energy:

$$E_k = N_k \omega_k \searrow$$

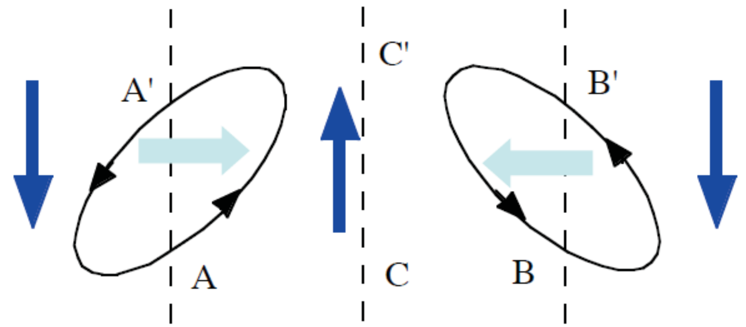
Since total energy conserved between ZF and Drift Wave,

Energy for ZF generation is extracted from DWs.

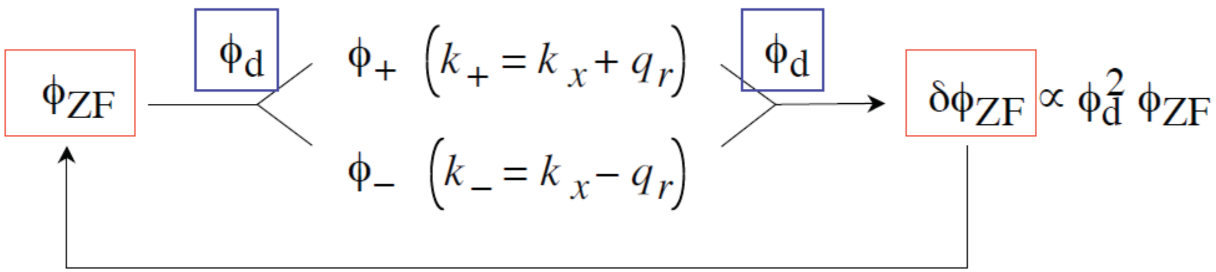
[Diamond et al., IAEA-FEC, 1994];

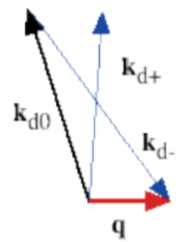
Generation Mechanism

(1) Tilt of convection cell by a sheared flow

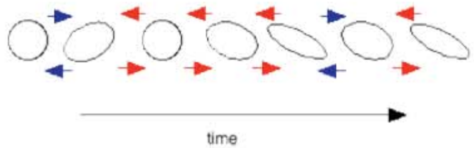
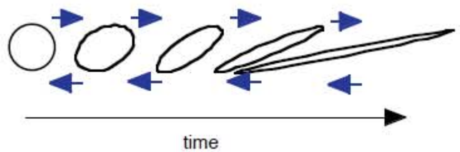


(2) Modulational Instability





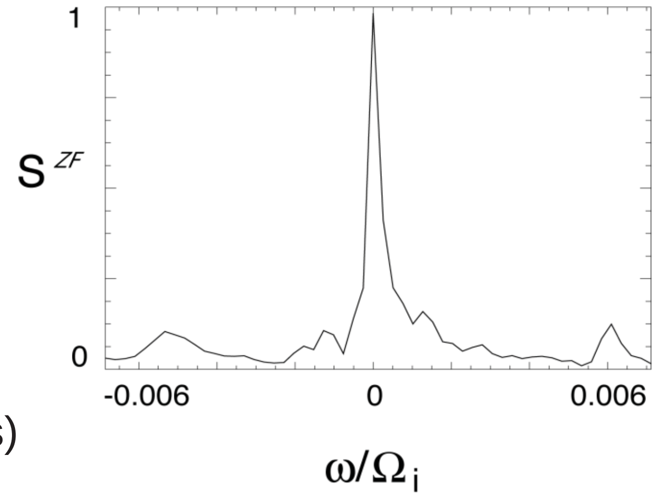
Distinction between ZF and Mean < E_r >

	Zonal Flows	Mean Field < E_r >
Time	can change on turbulence time scales	changes on transport time scales
Space	oscillating, complex pattern in radius $\sim 20\,\rho_i$	smoothly varying
Stretching behavior ***k*** of waves	diffusive $\langle \delta k^2 \rangle \propto t$ 	ballistic $\langle \delta k^2 \rangle = t^2 k^2 V_E'^2$ 
Drive	Turbulence	equilibrium ∇p, orbit loss, external torque, turbulence, etc.

Active research on synergy between them is underway.

Characterization of Zonal Flow Properties from Simulations Motivated Experimental Measurements

[Hahm, Burrell, Lin et al, Plasma Phys. Control. Fusion '00]



From Gyrokinetic Turbulence Code simulations:

- n=0, m=0, broad k_r, potential fluctuation
- Broad-band zero-freq Zonal Flows

& Geo-Acoustic side-bands

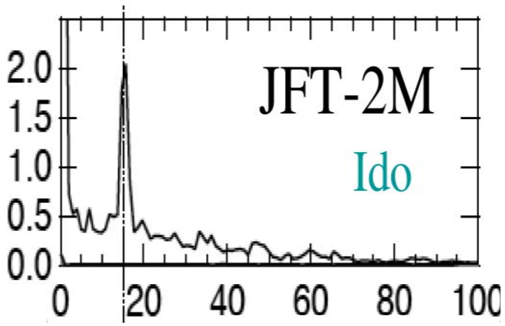
- Properties of associated density fluctuations

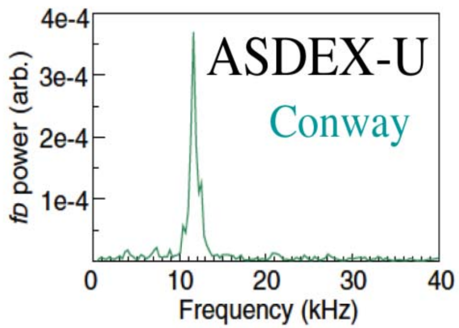
Experiments:

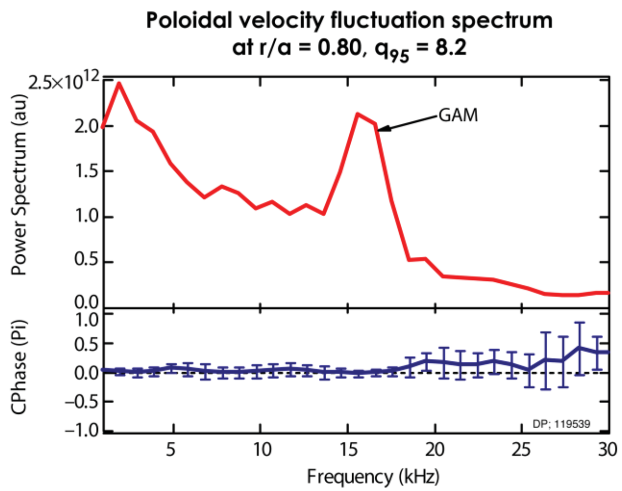
DIII-D(Beam Emission Spectroscopy, Langmuir Probes)

TEXT, JFT-2M, JIPPT-IIU (Heavy Ion Beam Probe),

AUG (Doppler Reflectometry)

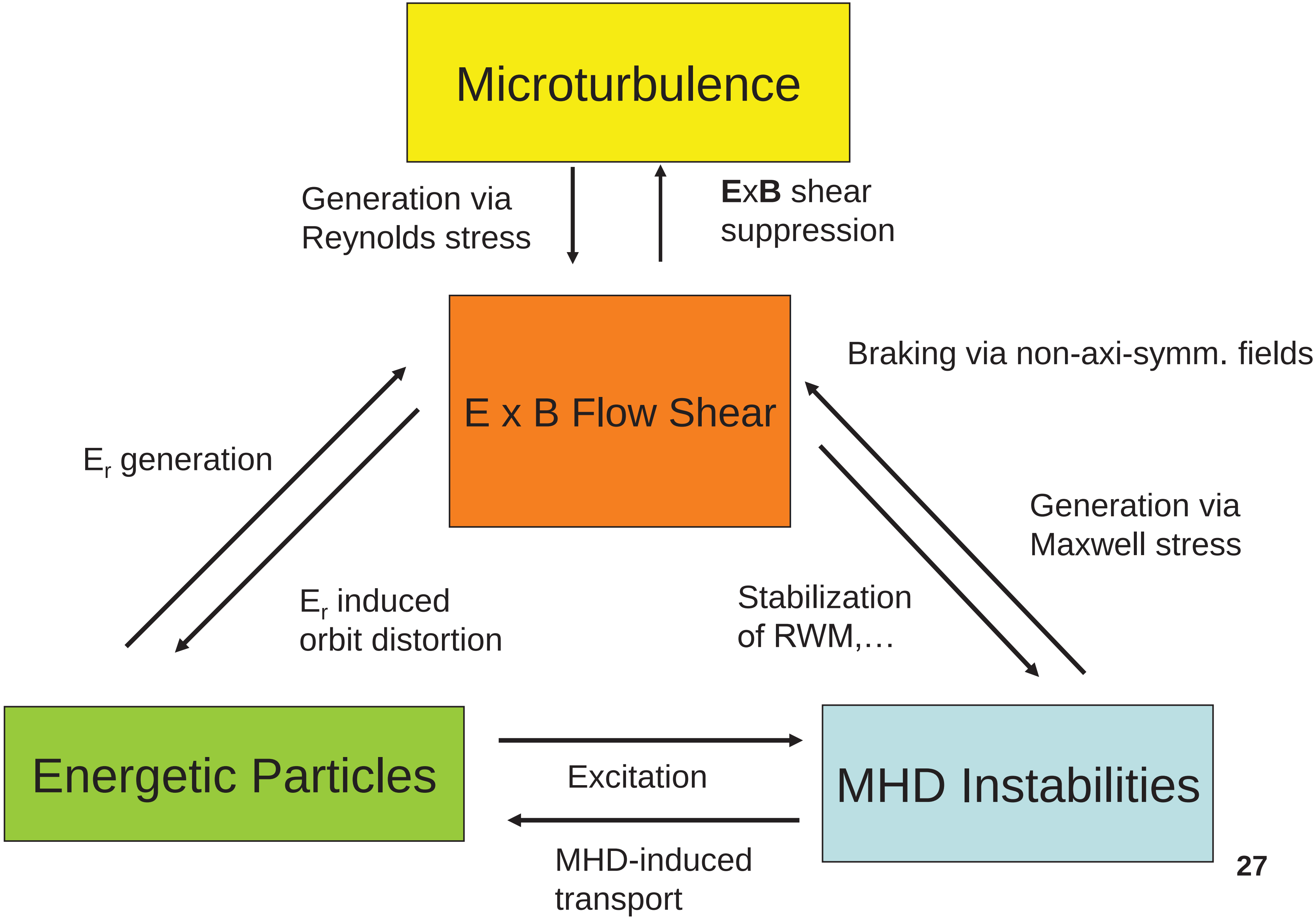






DIII-D Data from Gupta et al., PRL '05

E x B Flow Shear Plays a Central Role in Magnetic Confinement



Key Physics Mechanisms behind Size Scaling of Confinement

- **Global Toroidal ITG eigenmode**

[Horton-Choi-Tang, PF '81] [Cowley-Kulsrud-Sudan, PF B' 91]

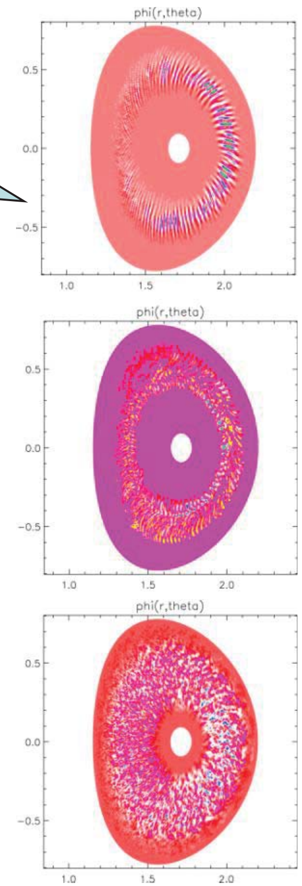
[Romanelli-Zonca, PF B' 93][Parker-Lee-Santoro, PRL'93]

Bohm Scaling ?

- **Self-regulation by Zonal Flows**:

[Cast of Thousands]
[Lin, Hahm, Lee et al., Science '98]
[Diamond, Itoh, Itoh and Hahm, Review in PPCF '05]

GyroBohm Scaling !



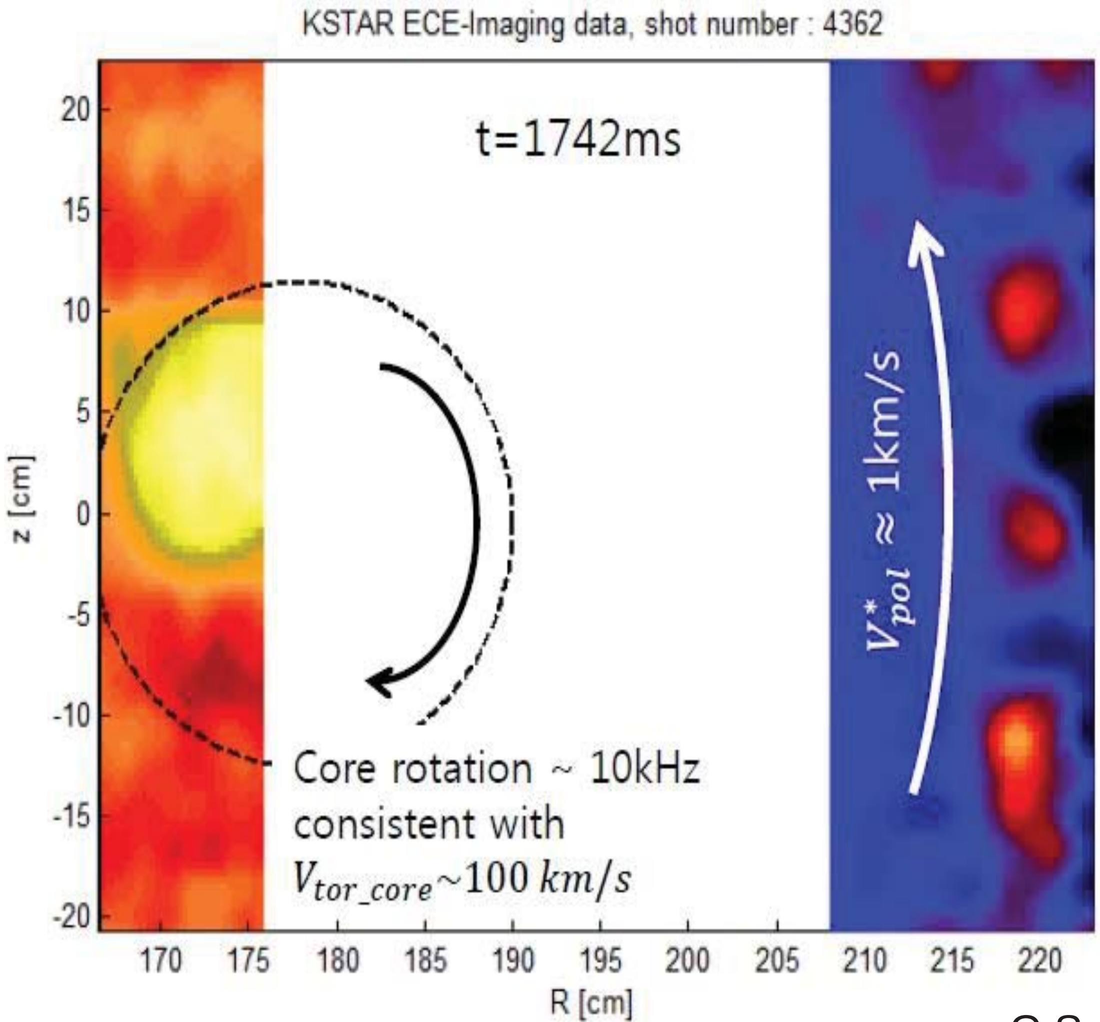
$t=150\ v_{ti}/L_T$

$t=210\ v_{ti}/L_T$

$t=1260\ v_{ti}/L_T$

Density fluctuations from a GTS simulation of a shaped plasma with typical DIII-D core parameters
[Wang, Hahm, Lee *et al.,* PoP `07]

Fluctuation Measurements provide useful info about rotation



G.S. Yun and H. Park
Private Communications [2011]

Summary

Zonal Flows

Huge Effect on Tokamak Confinement Scaling
with respect to Machine Size:

GyroBohm Scaling !

Not the End of Story …