Experimental Achievements on Plasma Confinement and Turbulence

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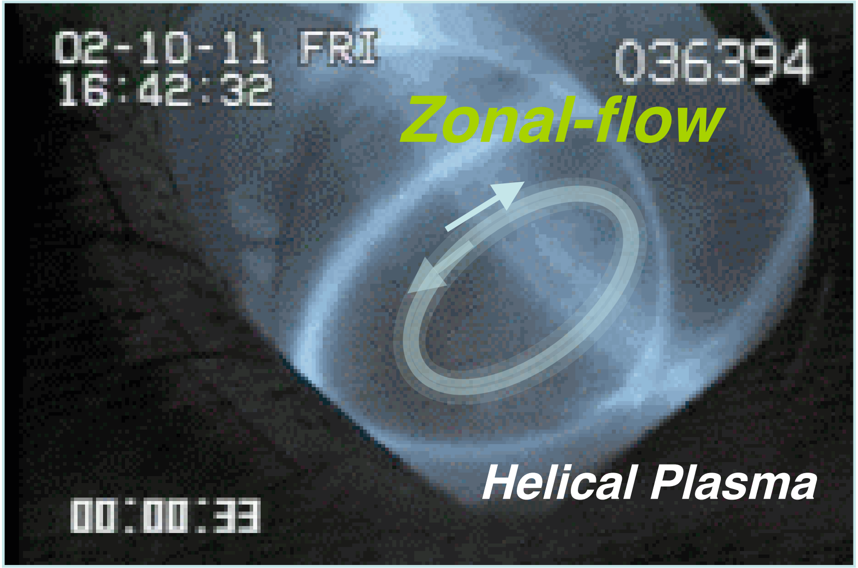
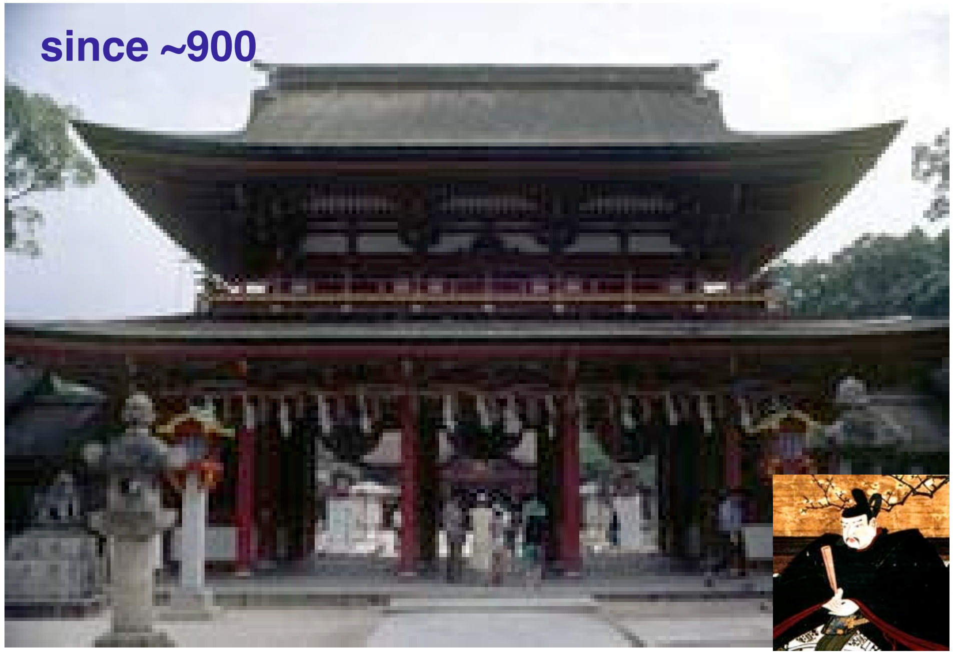




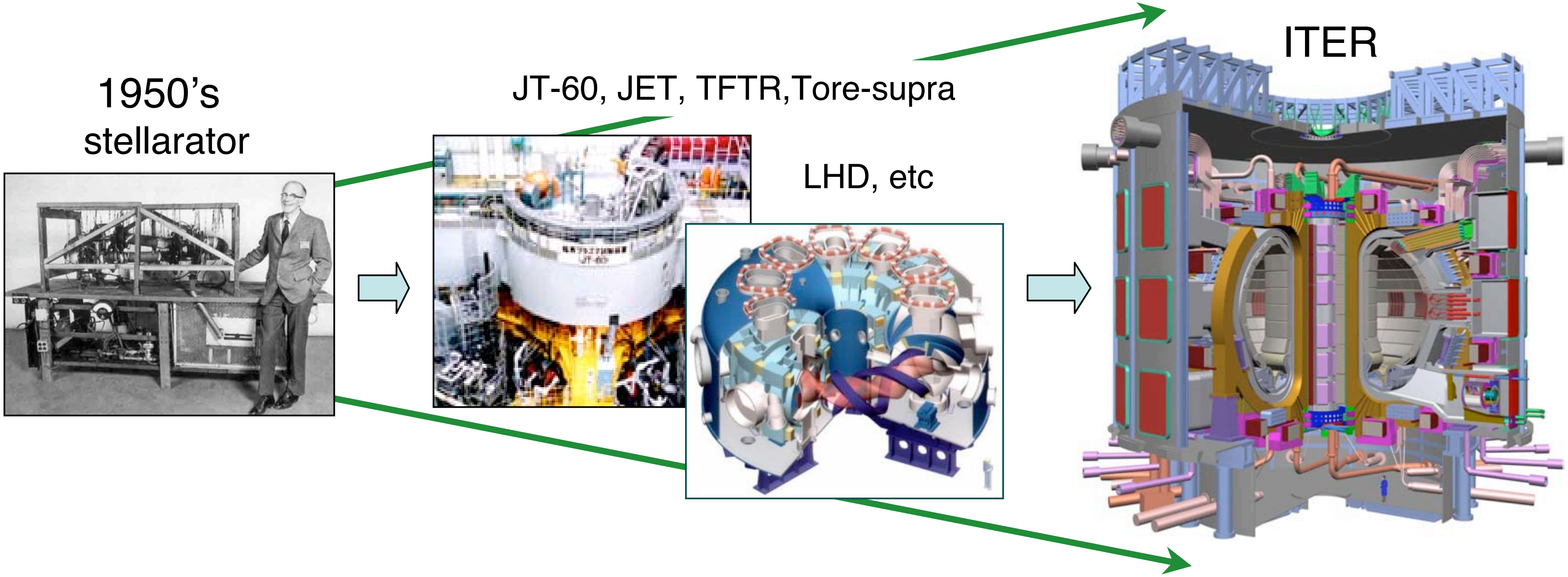
ITER- Summer School 2008 in Fukuoka Japan

Introduction

For more than 50 years efforts, the construction of ITER has begun.

$$\tau_{\mathrm{E}} \propto I^{0.96} B^{0.03} P^{-0.73} n^{0.40} M^{0.2} R^{1.83} \varepsilon^{-0.06} \kappa^{0.64}$$

Empirical scaling laws



1950's stellarator

JT-60, JET, TFTR,Tore-supra

LHD, etc

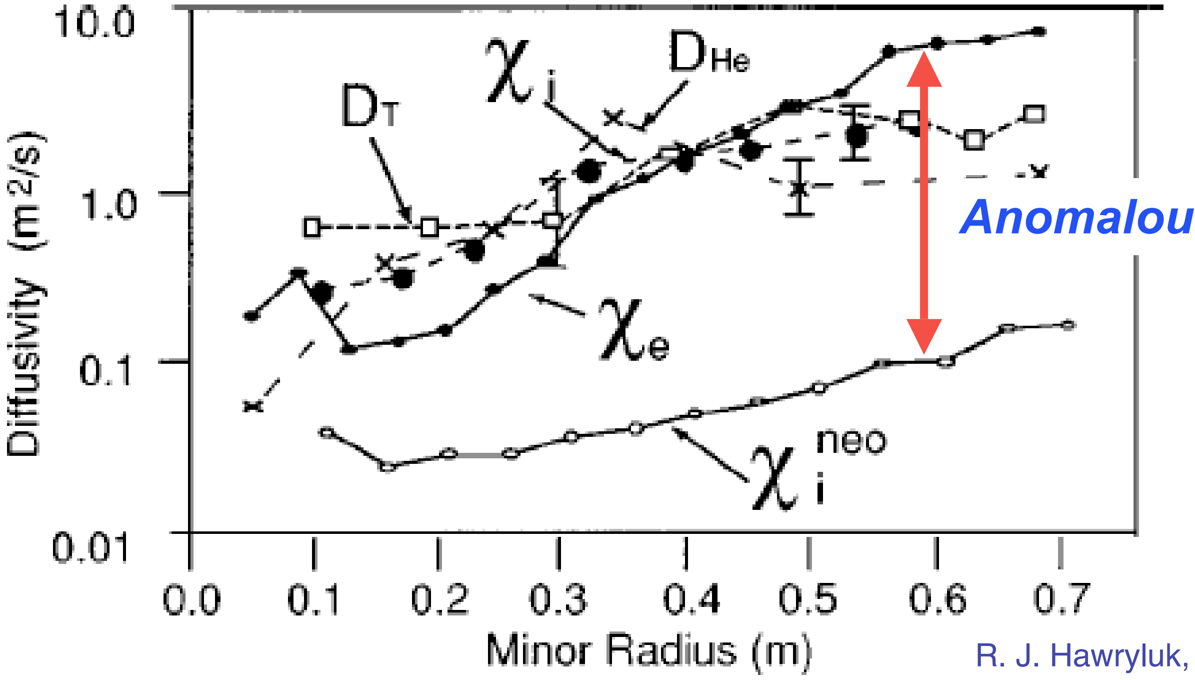
ITER

The understanding from **the first principle** should give us more confidence by providing more precise prediction of plasma performance for any given magnetic configurations

Anomalous Transport

TRANSPORT = COLLISIONAL+TURBULENCE
NEOCLASSICAL

TFTR



Anomalously large transport

R. J. Hawryluk, Phys. Plasmas **5** 1577 (1998)

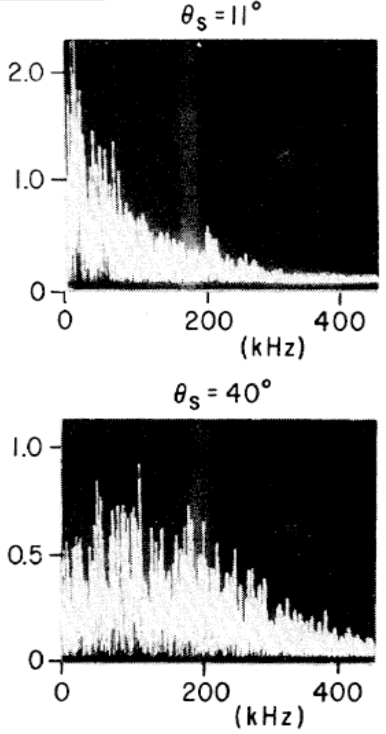
ANOMALOUS TRANSPORT can be ascribed to DRFIT WAVE TURBULENCE.

To understand the plasma transport is to study the turbulence

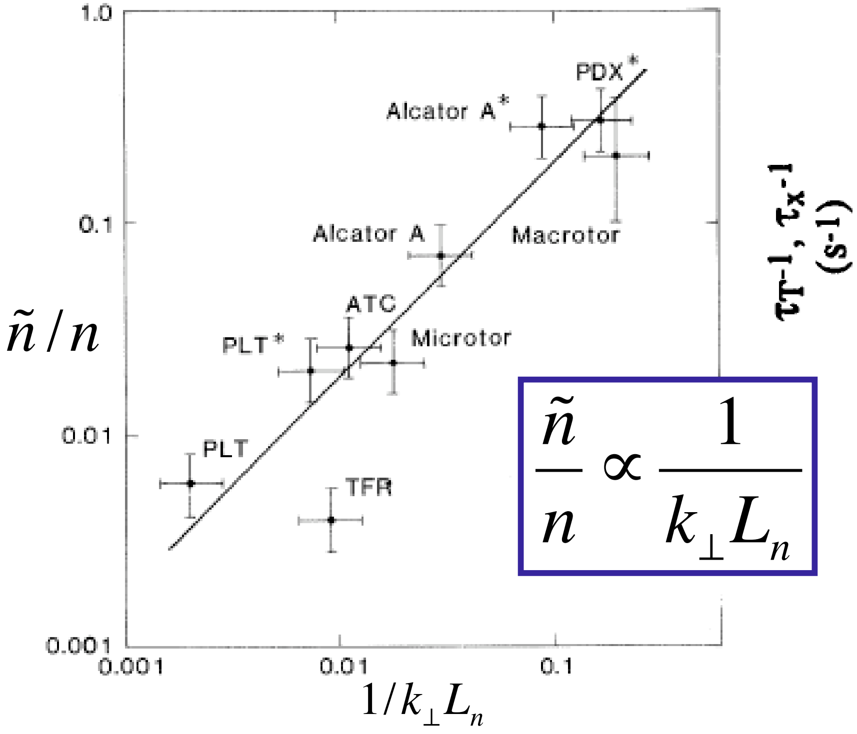
Turbulence & Transport (1970-1980’s)

ATC

Wave-scattering played an important role in the turbulence studies in early days

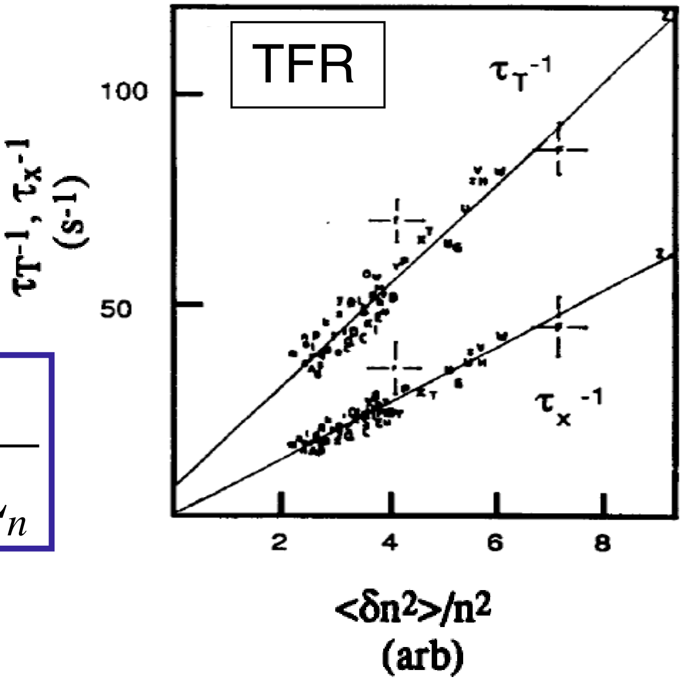


E. Mazzucato, PRL **36** 792 (1976)



$$\frac{\tilde{n}}{n} \propto \frac{1}{k_\perp L_n}$$

C. Surko, R. Slusher, Science **221** 817 (1983)



TFR group, Nucl. Fusion **26** 1303 (1986)

EXISTENCE OF DRIFT WAVE TURBULENCE and TURBULENT TRANSPORT has been proven.

A Sketch of Turbulence Research

local & linear & deterministic view

- Drift wave turbulence (micro-scale fluctuations)

1976 turbulence spectra (waves-cattering)

mixing length estimate

- Discoveries of improved confinement modes

1982 H-mode in ASDEX

Bifurcation physics

Sheared flow (macroscopic flows)

- Discovery of zonal flow concept

2004 Identification of zonal flows

A paradigm shift (zonal flows & drift waves)

meso-scale structure $\propto \sqrt{a\rho}$

non-local & nonlinear & probablistic view

Diagnostics Developments

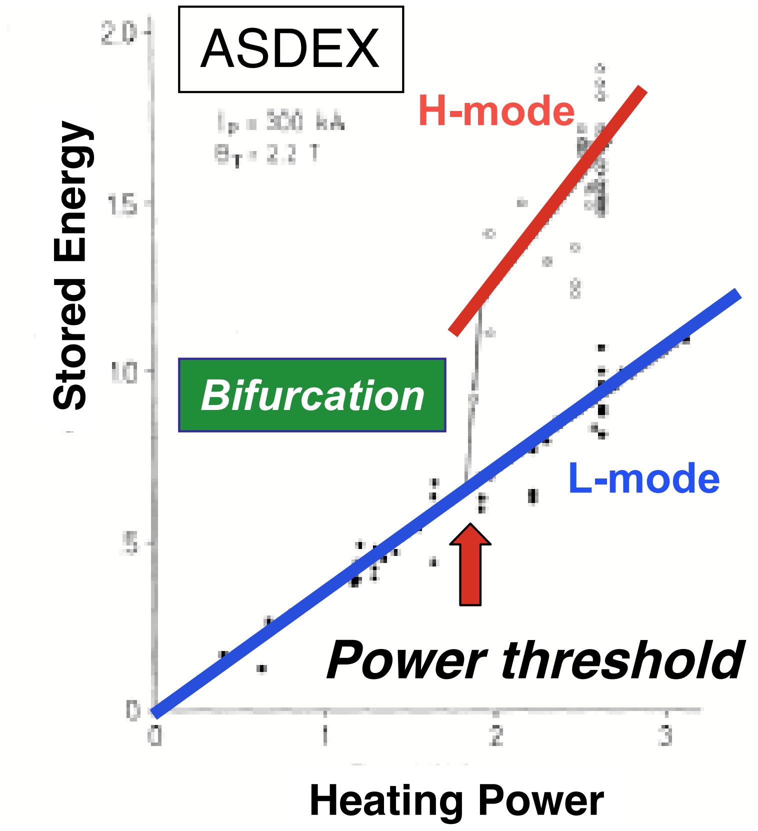
A point measurement

1D or profile measurements

Wider (2D-3D) multipoint measurements

Improved Confinement Mode I

- Discrete change in energy
- Existence of multiple states



F. Wagner et al., PRL 49 1408 (1982)

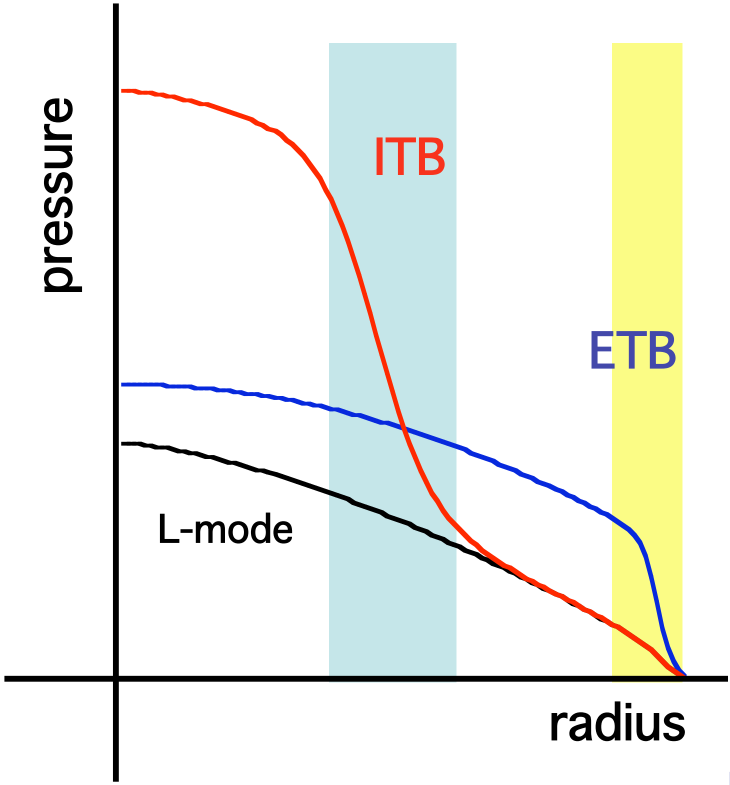
A list of Improved Confinement modes

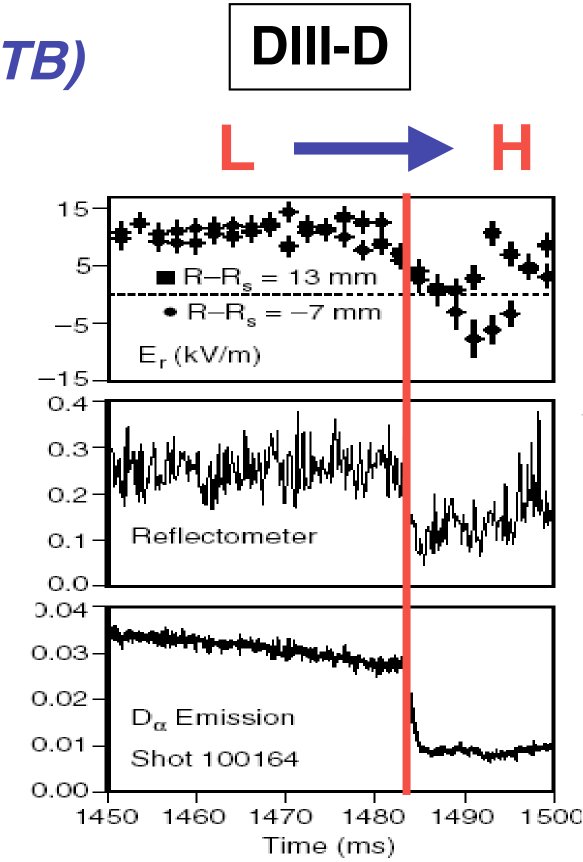
H-mode	ASDEX	1982
Supershot	TFTR	1987
PEP-mode(ITB)	JET	1992
H-mode (ETB)	W7-AS&CHS	1993
High-β_p (ITB)	JT-60	1994
ERS (ITB)	TFTR	1995
NCS (ITB)	DIII-D	1995
RI-mode	TEXTOR	1995
N-ITB(ITB)	CHS	1999
HDH (ETB)	W7-AS	2002
SDC (ITB)	LHD	2006

The findings have made it begin to dig the confinement law out of the phenomena.

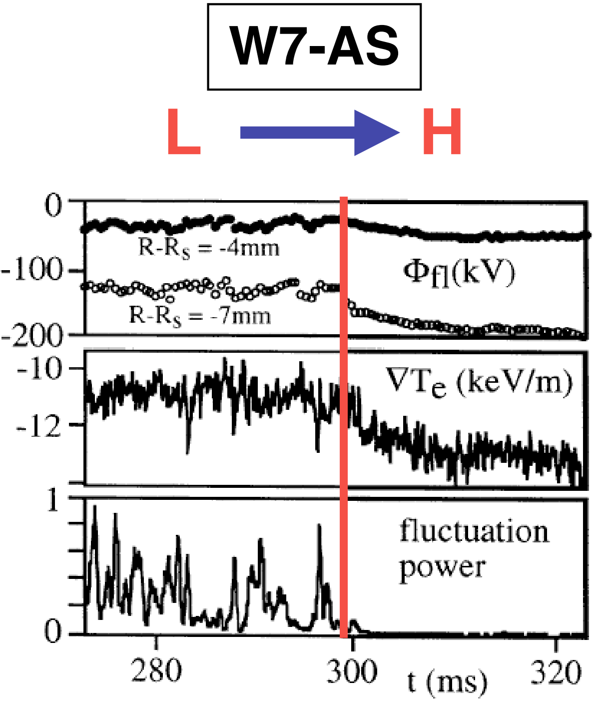
Improved Confinement Mode II

Transport barriers (ETB & ITB)





K. H. Burrell, Rev. Sci. Instrum. 72 906 (2001)



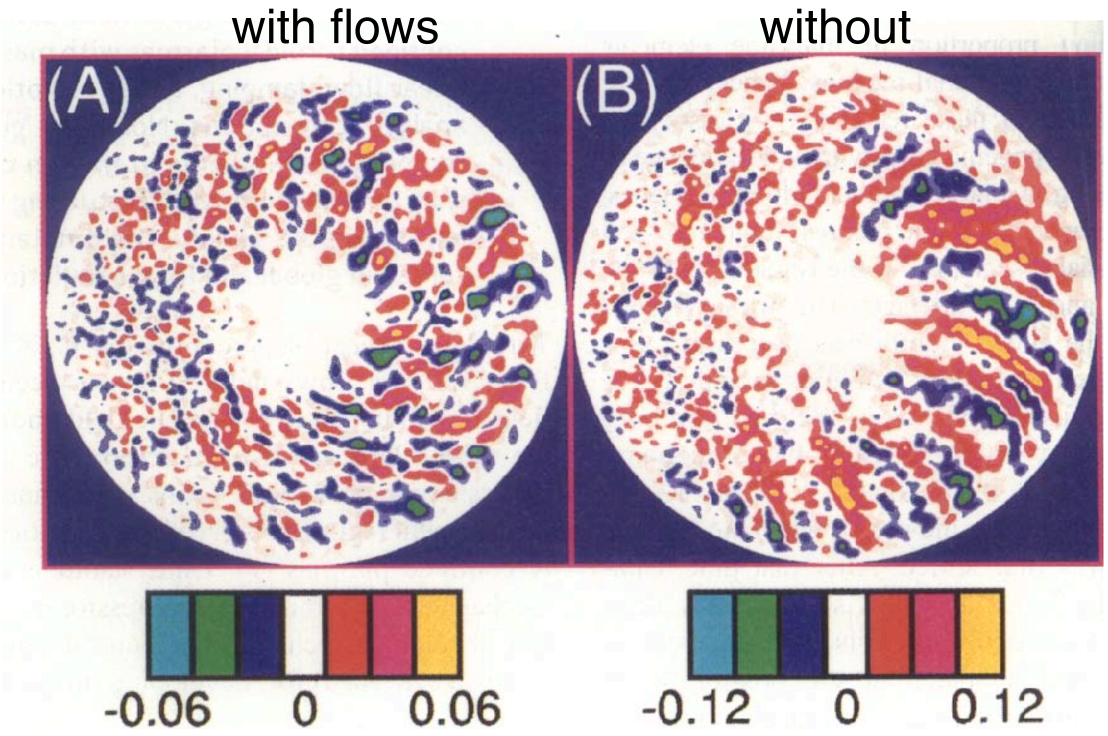
F. Wagner et al. PPCF 39 A23 (1997)

Turbulence suppression is observed at the barriers

Bifurcation property is demonstrated in transport barrier formations

Shear Flow Stabilization I - Simulation

Sheared mean flows tear the turbulence eddies apart



Z. Lin et al., Science **281** 1835 (1998)

H. Bigrali et al., Phys. Fluids B **2** 1(1990)

Theoretical Expressions

Empirical form

$$\boxed{\gamma < \omega_{E\times B}(\sim dv_{E\times B}/dr)}$$

T. S. Hahm et al., Phys. Plasmas **2** 1648 (1995)

General form

$$\boxed{\chi = \frac{\chi_L}{1+\beta(E_r')^{\alpha}}}$$

K. C. Shaing et al., 12th IAEA **Vol. 2** p13 (1988)

K. Itoh et al., PPCF **36** 123 (1994)

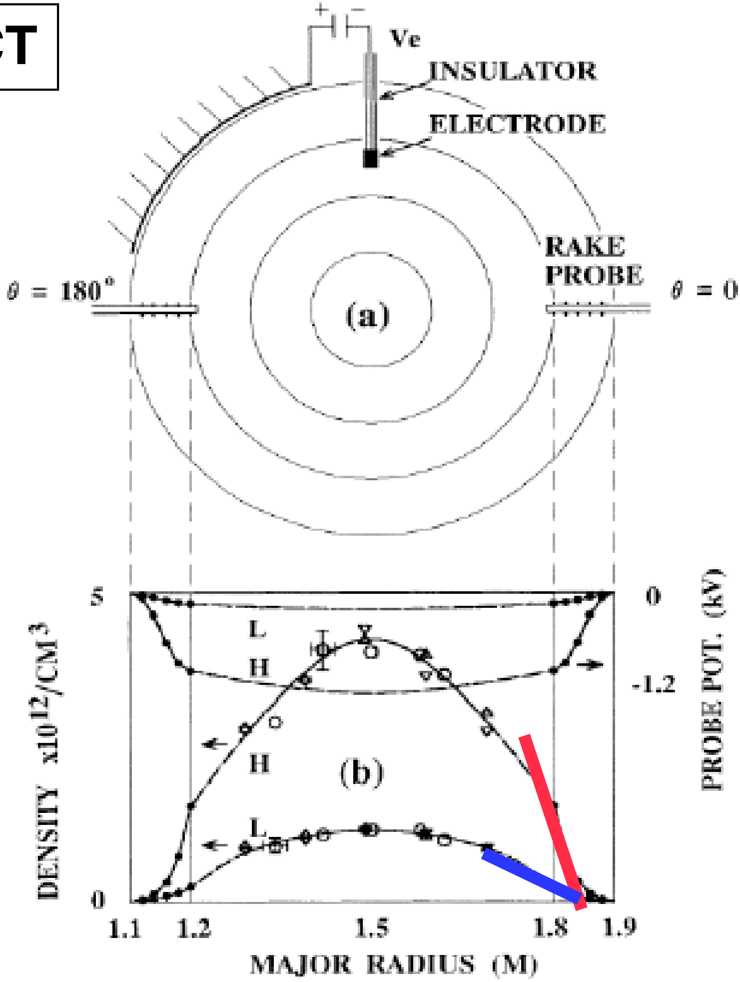
Theories and simulations have demonstrated that the turbulence should be suppressed by **sheared poloidal flows**.

The world-wide experimental efforts have begun to confirm the hypothesis.

Shear Flow Stabilization II

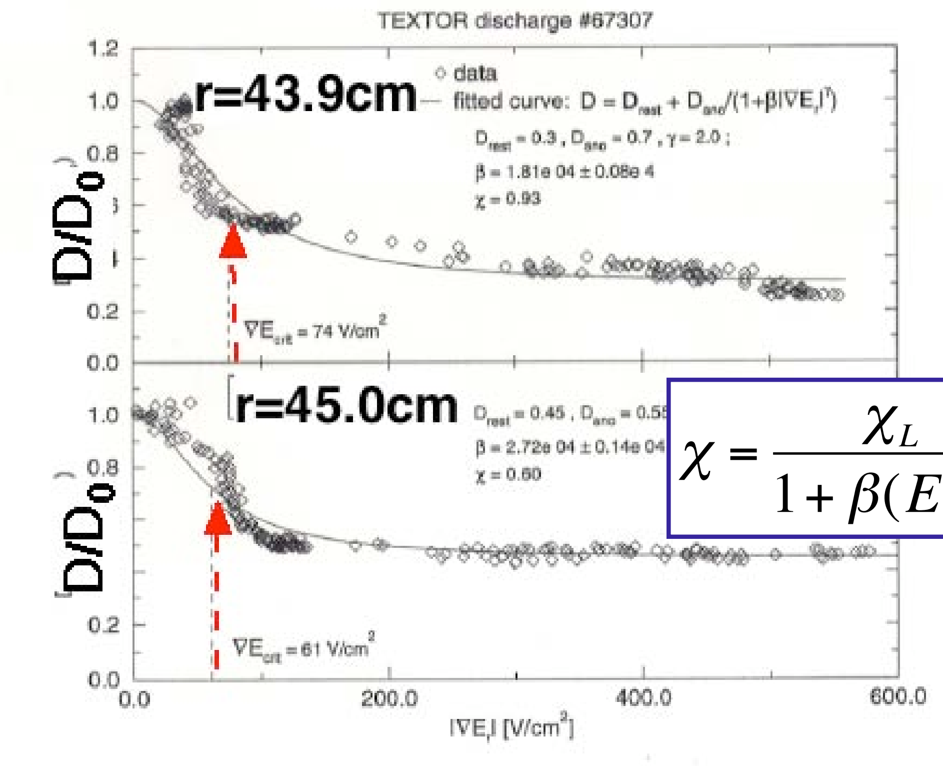
Bias Experiments & Observation

CCT



R. J. Taylor et al. PRL **64** 2365 (1989)

TEXTOR



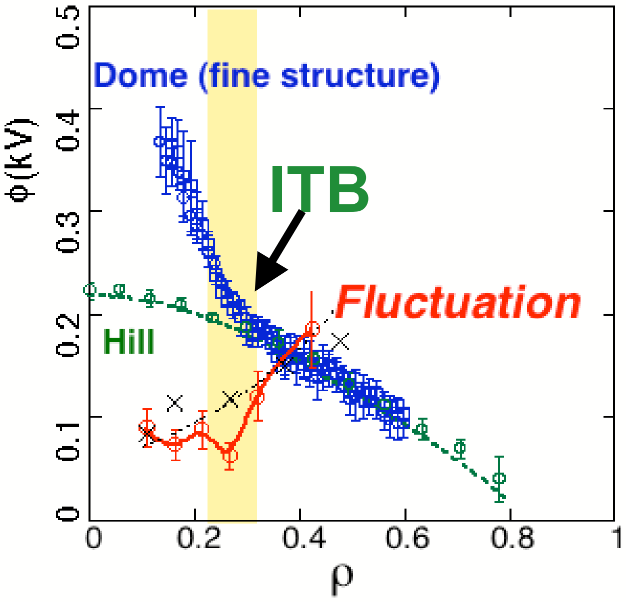
$$\chi = \frac{\chi_L}{1 + \beta (E_r^{'})^{\alpha}}$$

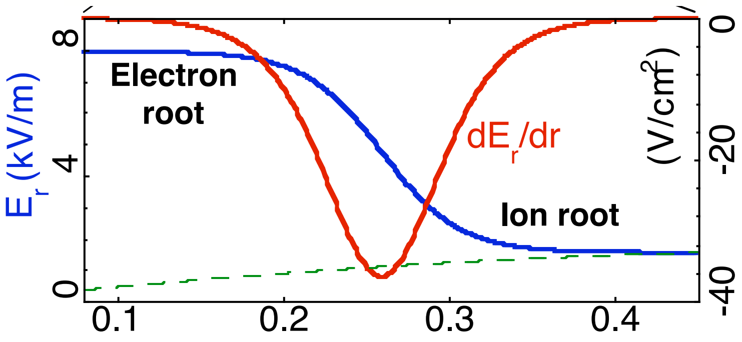
R. Weynants et al. PPCF **40** 635 (1998)

External driven sheared flows reduce fluctuations to form transport barrier.

Shear Flow Stabilization III

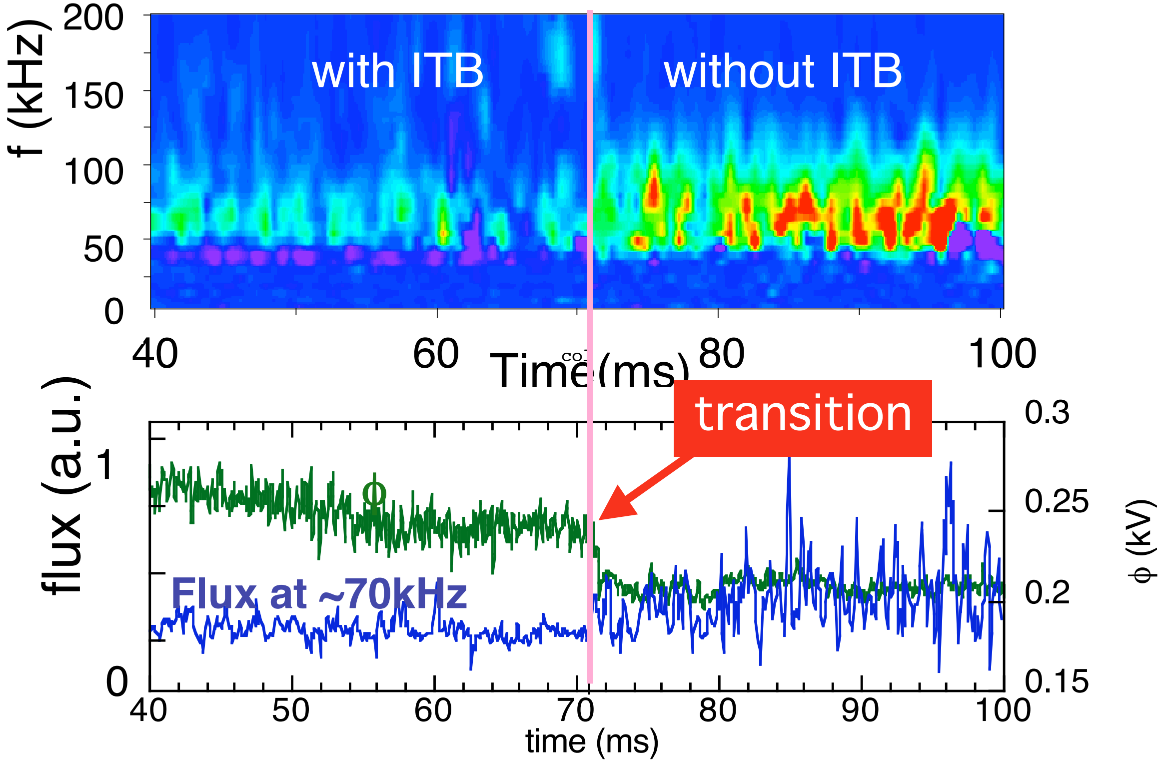
In ITB, spatio-temporal properties of shear-stabilization are observed





CHS

Turbulence is really suppressed at the E_r-shear layer



A. Fujisawa et al., PPCF **48** S205 (2006).

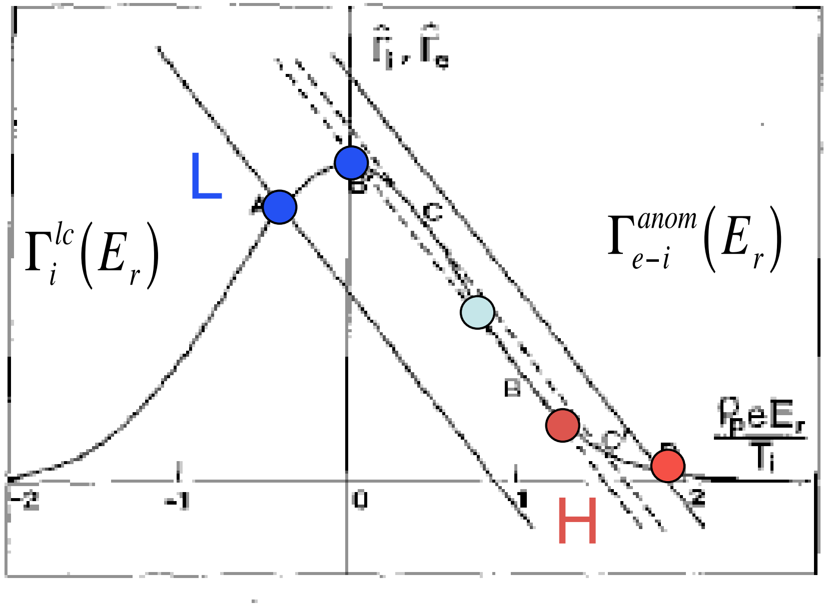
A number of experiments have confirmed sheared flow mechanisms

Physics of Bifurcation I

Bifurcation nature could be associated with properties of plasma flows

$$\varepsilon_0 \varepsilon_p \frac{\partial E_r}{\partial t} = \Gamma_{e-i}^{anom}\left(E_r\right) - \Gamma_i^{lc} - \Gamma_i^{bv} - \Gamma_i^{v\nabla v} - \Gamma_i^{Neo} + \Gamma_e^{Neo} - \Gamma_i^{CX} + \cdots$$

Some terms on the right-hand-side show strong nonlinearity.
This causes the bifurcation of plasma flows.



Itoh & Itoh model

$$\Gamma_{e-i}^{anom}\left(E_r\right) + \Gamma_i^{lc}\left(E_r\right) = 0$$

S-I. Itoh, K. Itoh, PRL **60** 2276 (1988)

Shaing model

$$\Gamma_i^{bv}\left(E_r\right) + \Gamma_i^{lc}\left(E_r\right) = 0$$

K. C. Shaing E.C. Crume Jr., PRL **63** 2369 (1989)

Transition should happen much faster that confinement time scale

High temporal resolution is necessary for experimental confirmation

It is complicated in H-mode where a number of radial currents components are expected

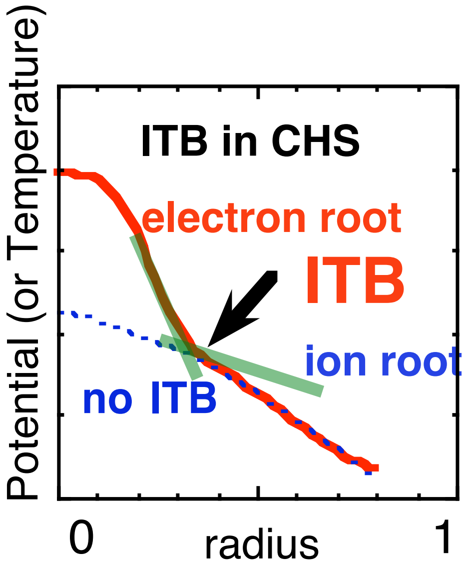
Physics of Bifurcation II

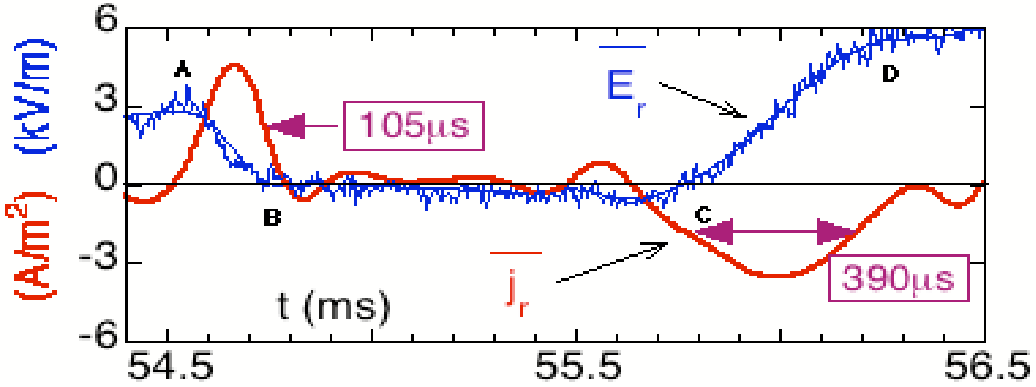
A simple case: ITBs in stellarators

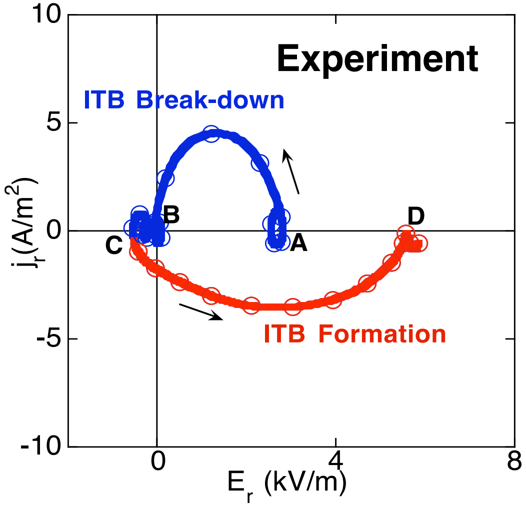
neoclassical term is dominant

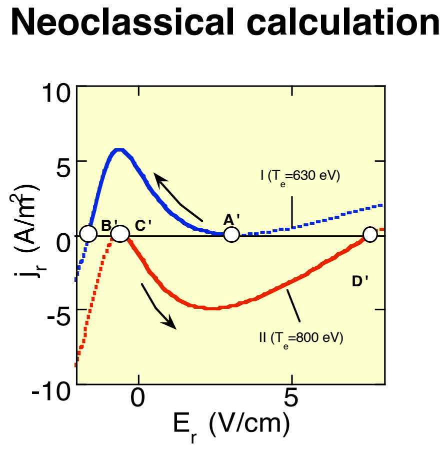
$$\varepsilon_0\varepsilon_p \frac{\partial E_r}{\partial t} = -\Gamma_i^{Neo}(E_r)+\Gamma_e^{Neo}(E_r)+\cdots$$

CHS









Electric field transition happens
in much faster time scale (~100us)
than confinement timescale (~ a few ms).

The electric field bifurcation is a key mechanism for transport bifurcation

A. Fujisawa et al. PRL **79** 1054 (1997)

Physics of Bifurcation III

Turbulent Reynolds stress term $\Gamma_i^{v\nabla v} \propto \partial_r \langle \tilde{v}_\vartheta \tilde{v}_r \rangle$

$$\varepsilon_0 \varepsilon_p \frac{\partial E_r}{\partial t} = \Gamma_{e-i}^{anom} - \Gamma_i^{lc} - \Gamma_i^{bv} - \Gamma_i^{v\nabla v} - \Gamma_i^{Neo} + \Gamma_e^{Neo} - \Gamma_i^{CX} + \cdots$$

Turbulence can drive the flows!

The generated flows should have shearing on turbulence

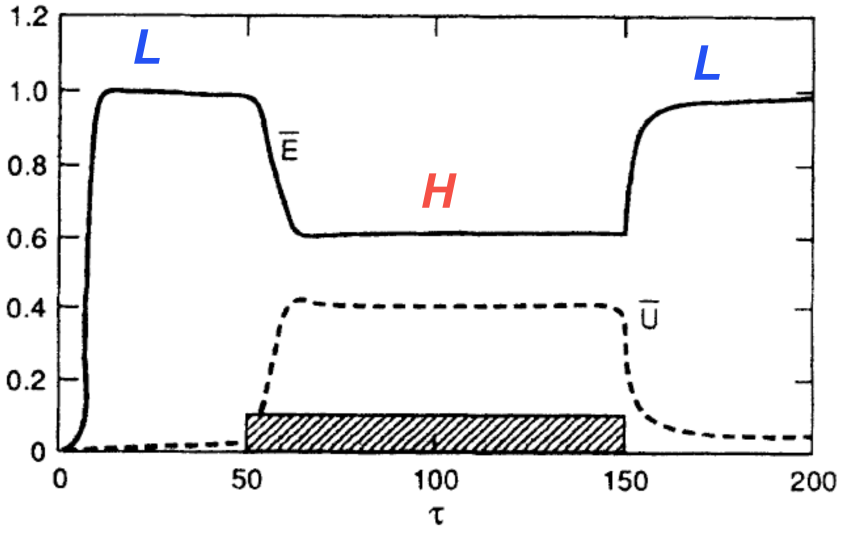
$$\frac{1}{2}\frac{dE}{dt} = \gamma_0 E - \alpha_1 E^2 - \alpha_2 UE$$

E: fluctuation

$$\frac{1}{2}\frac{dU}{dt} = -\mu U + \alpha_3 UE$$

U: flow

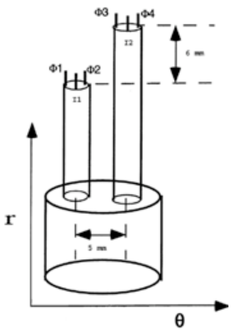
Steady state condition gives two stable solutions corresponding to L and H-mode!!



P. H. Diamond et al., PRL **72** 2565 (1994)

Physics of Bifurcation IV

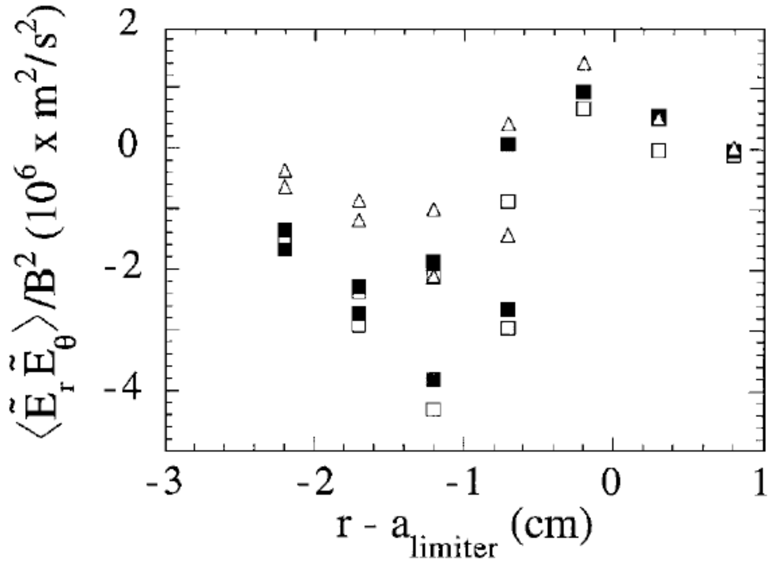
Does turbulent Reynolds stress really generate plasma flows ?



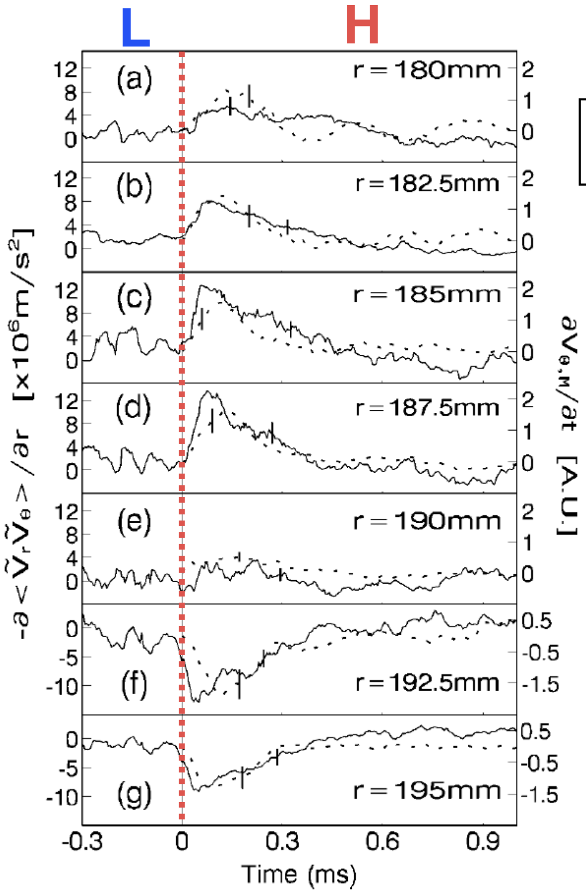
ISTTOK

Multi-point measurements for evaluating Reynolds stress

Showing a significant contribution of turbulent Reynolds stress.



C. Hidalgo et al., PRL **83** 2203 (1999)



HT-6M

Y. H. Xu et al. PRL **84** 3867 (2000)

Turbulent Reynolds stress plays a role in H-mode transition

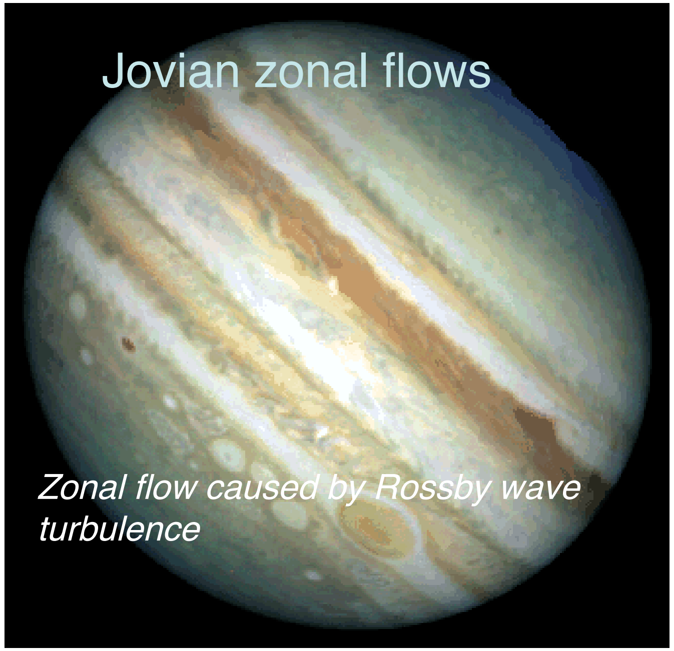
Many simulations have shown an important role of TRS even in L-mode transport

Concept of Zonal Flows

The concept of zonal flows is not so new

Hasegawa-Mima equation (1977)

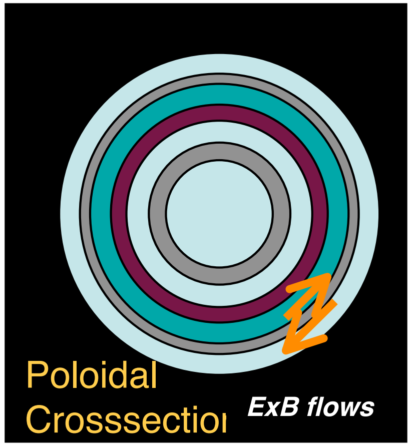
$$\frac{\partial}{\partial t}(\nabla^2\varphi - \varphi) - [(\nabla\varphi \times \hat{z}) \cdot \nabla]\left(\nabla^2\varphi + \ln\frac{\omega_c}{n_0}\right) = 0$$



Jovian zonal flows

Zonal flow caused by Rossby wave turbulence

Zonal flows are ubiquitous



A number of simulations show the importance of zonal flows on transport.
Experimental identification was an urgent issue.

Zonal flows in toroidal plasma

- stationary zonal flows
- geodesic acoustic modes

Features & Tasks

i) zonal structure

symmetry (m=n=0)

a finite radial wavelength

no transport

ii) nonlinear coupling with turbulence

iii) effects on transport

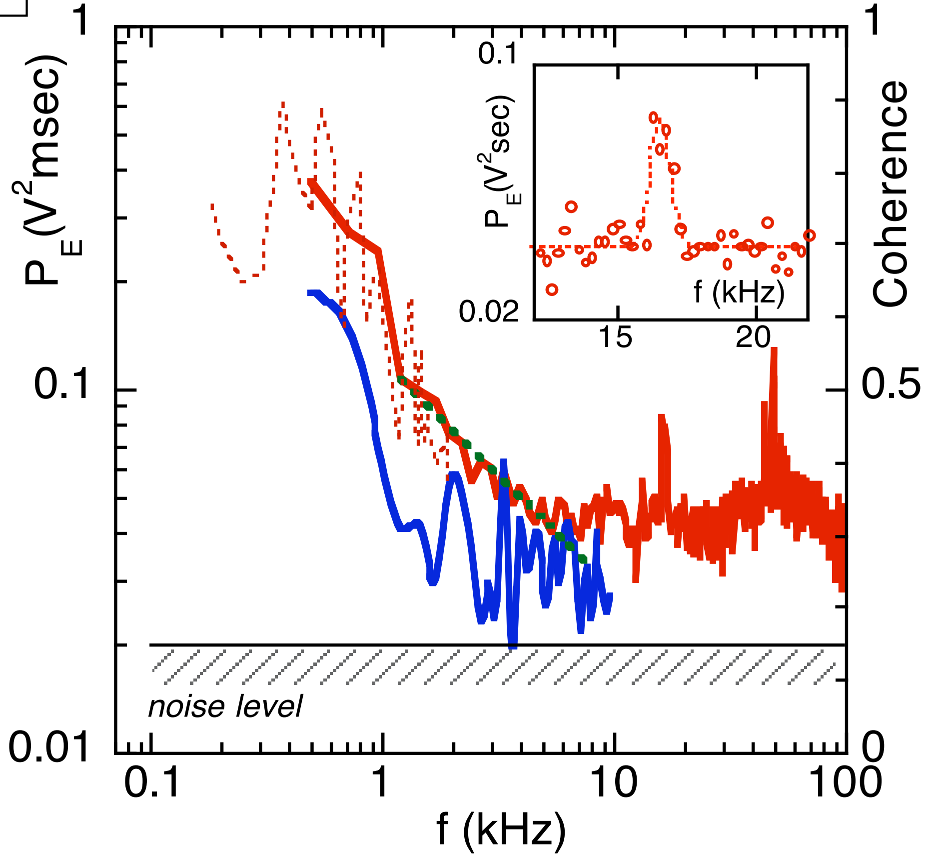
P. H. Diamond et al. PPCF **47** R35 (2005)

Identification of Zonal Flows I

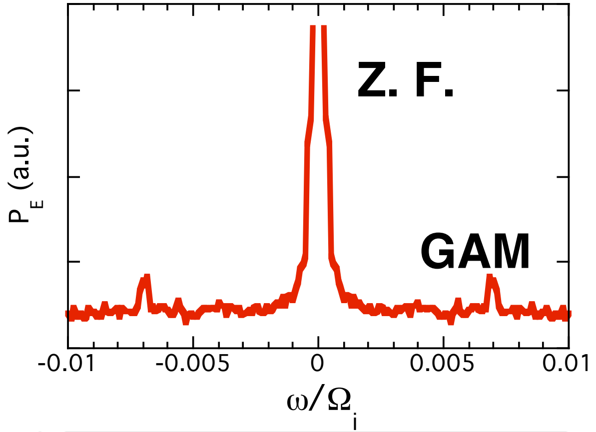
Do zonal flows really exist in toroidal plasmas?

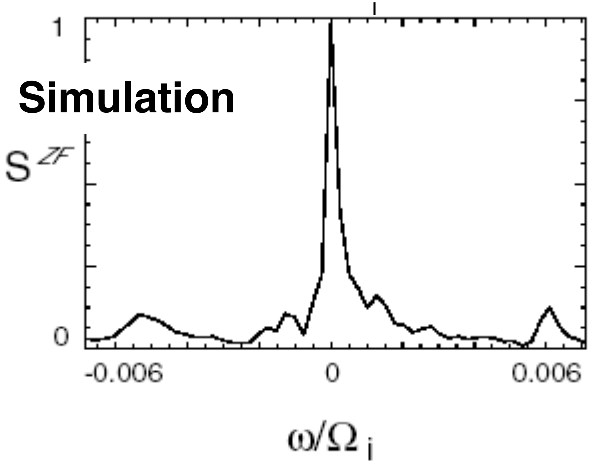
CHS

Electric Field Spectrum (measured with HIBP)



A. Fujisawa et al., PRL **93** (2004) 165002

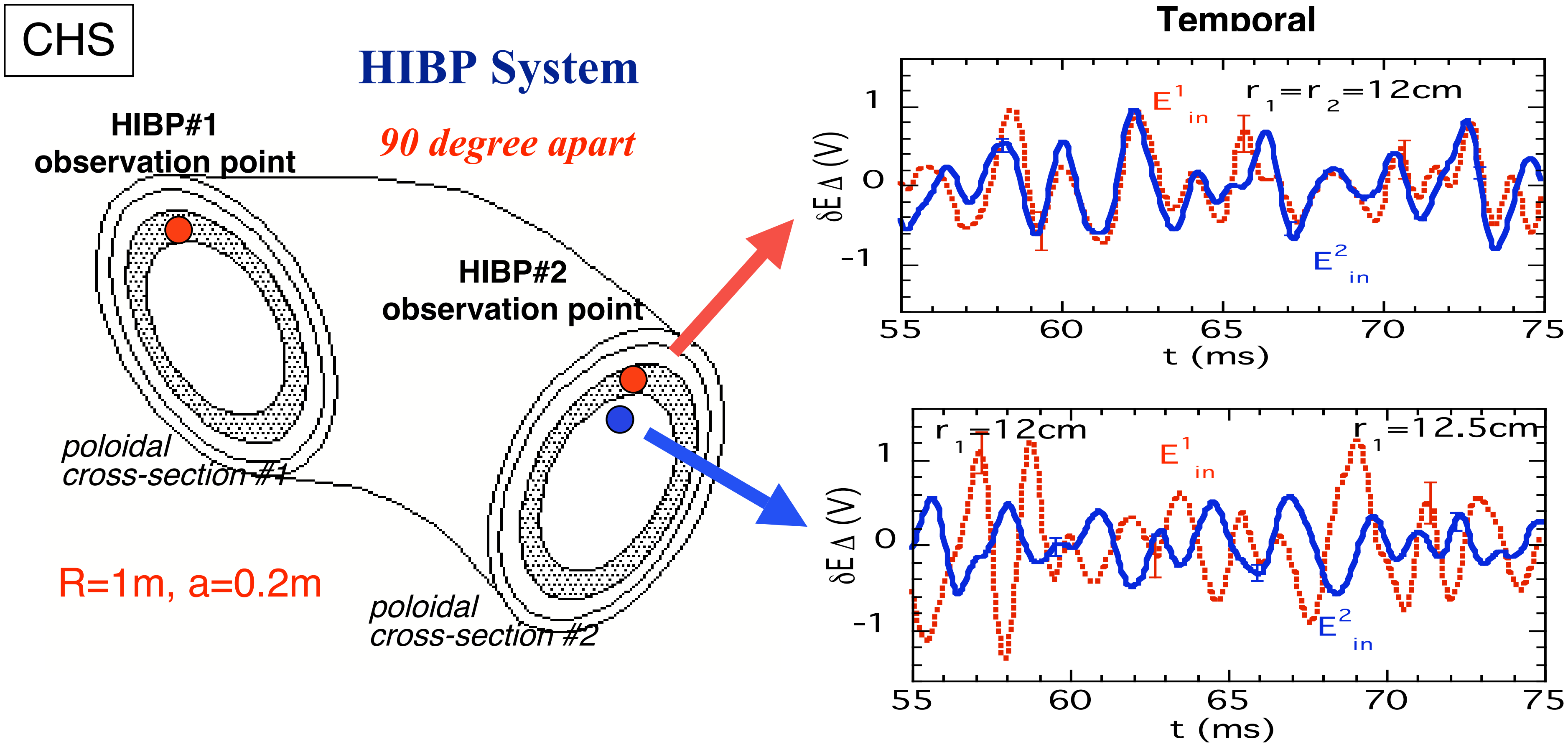




T.S. Hahm et al. PPCF **42** A205 (2000)

Zonal flows have been identified in the measurements using twin HIBPs

Identification of Zonal Flows II



Symmetric around the axis, with a finite radial wavelength.

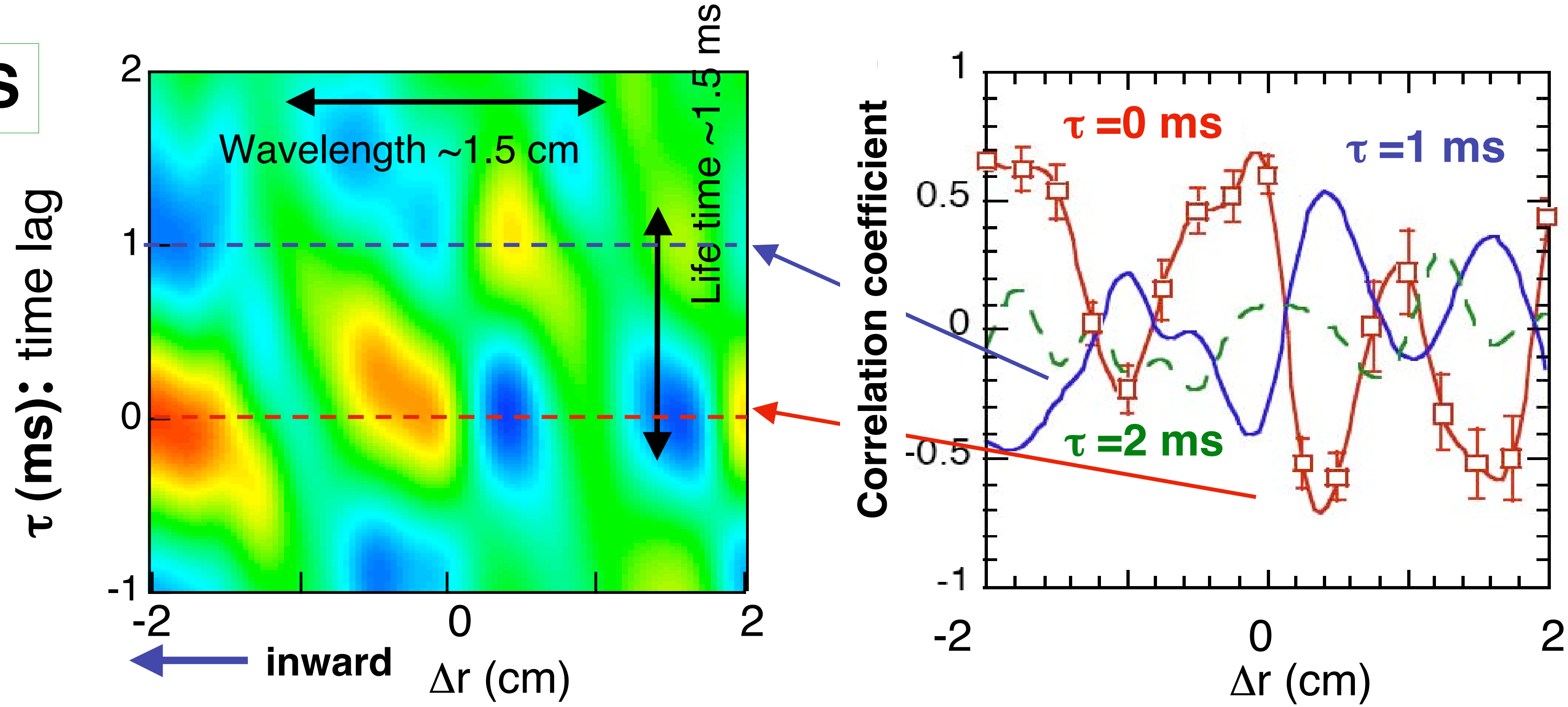
The phase difference is robust, and dependent on radial distance.

Identification of Zonal Flows III

Using the cross-correlation functions between two electric fields at different radii,

$$C_{crs}(r_1,r_2,\tau) = \left\langle E_1(r_1,t)E_2(r_2,t+\tau)\right\rangle / \sqrt{\left\langle E_1^2(r_1,t)\right\rangle \left\langle E_2^2(r_2,t+\tau)\right\rangle}$$

CHS

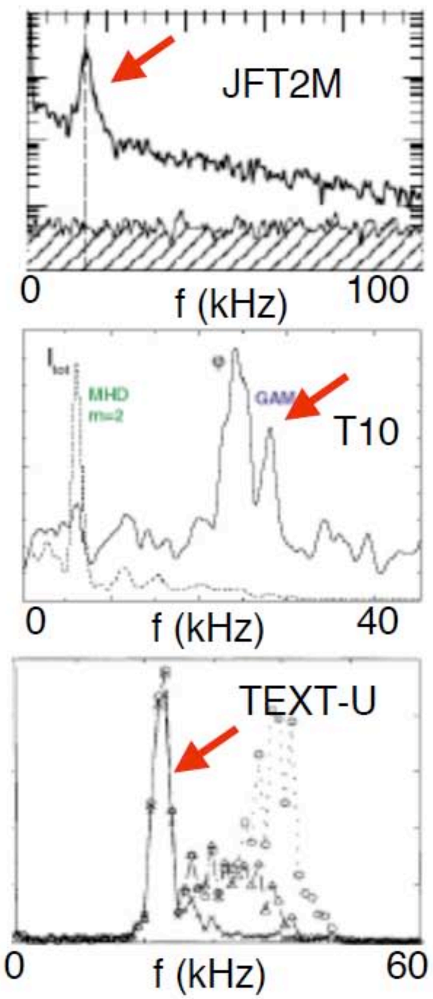


The observation confirms the zonal structure of the fluctuations of the low frequency.

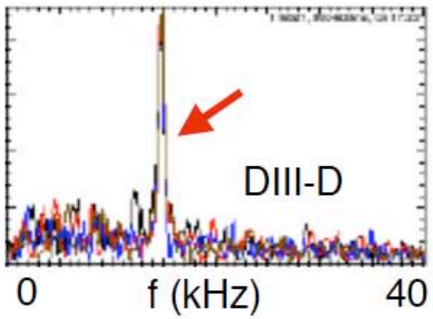
Identification of Zonal Flows IV

After H1-heliac reported the existence of GAM, M. G. Shats et al., PRL **88** 45001 (2002)

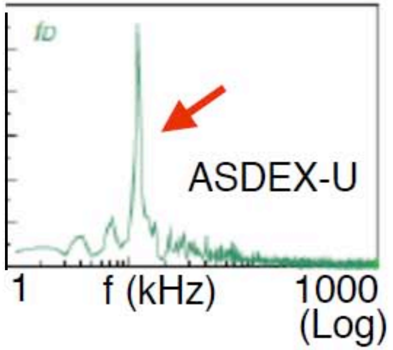
Potential (HIBP)



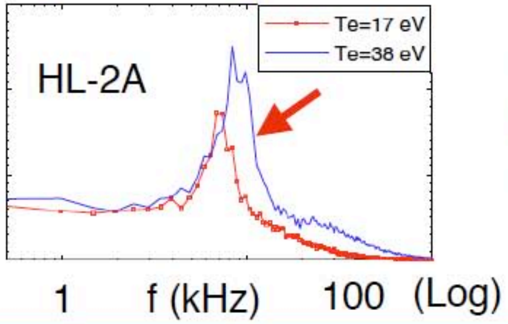
flow(BES)



flow(reflectometry)



potential (probe)



Coherent modes have been detected in many toroidal devices

The HL-2A tokamak confirms the complete symmetry (n=m=0) of GAM

The study of GAM is the most flourishing part in zonal flow experiments

How do we prove nonlinear interaction?

A number of techniques have been developed to clarify nonlinear coupling between turbulent elements.

Amplitude Correlation Technique

F. J. Crossley et al., PPCF **34** 235 (1992)

H. Xia, M. G. Shats, Phys. Plasmas **11** 561 (2004); probe in H1-heliac

Power Transfer Function (PTF) Analysis

C. P. Ritz et al., Phys. Fluids B **1** 153 (1989); probe in TEXT

J. S. Kim et al., Phys.Plasmas **3** 3998 (1996); BES in TFTR

H. Xia, M. G. Shats,PRL **91** 155001 (2003); probe in H1-Heliac

P. Manz et al., PPCF **50** 035008 (2008); probe in TJ-K

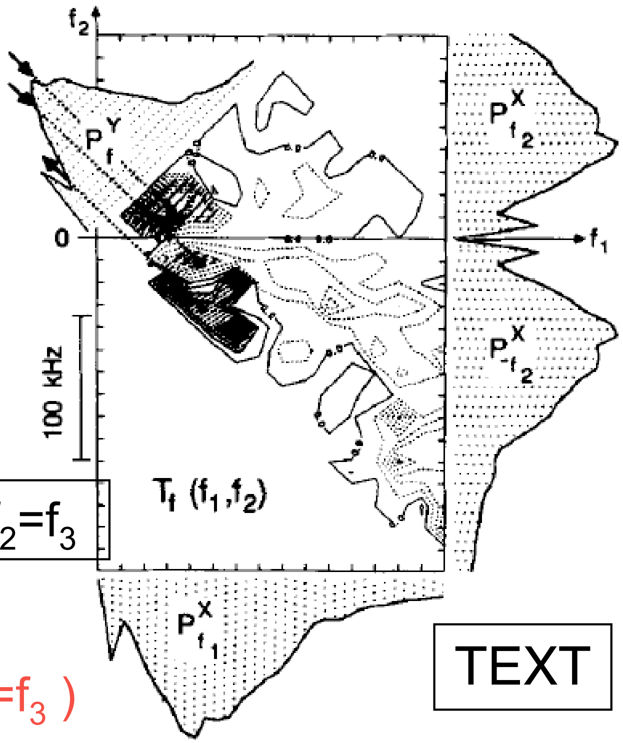
Bicoherence Analysis

For evaluation of strength of three wave couplings ($f_1+f_2=f_3$)

Y. C. Kim, E. J. Powers, Trans. Plasma Sci **PS-7** 120 (1979)

C. Hidalgo et al., PRL **71** 3127 (1993); probe in ATF

PTF analysis

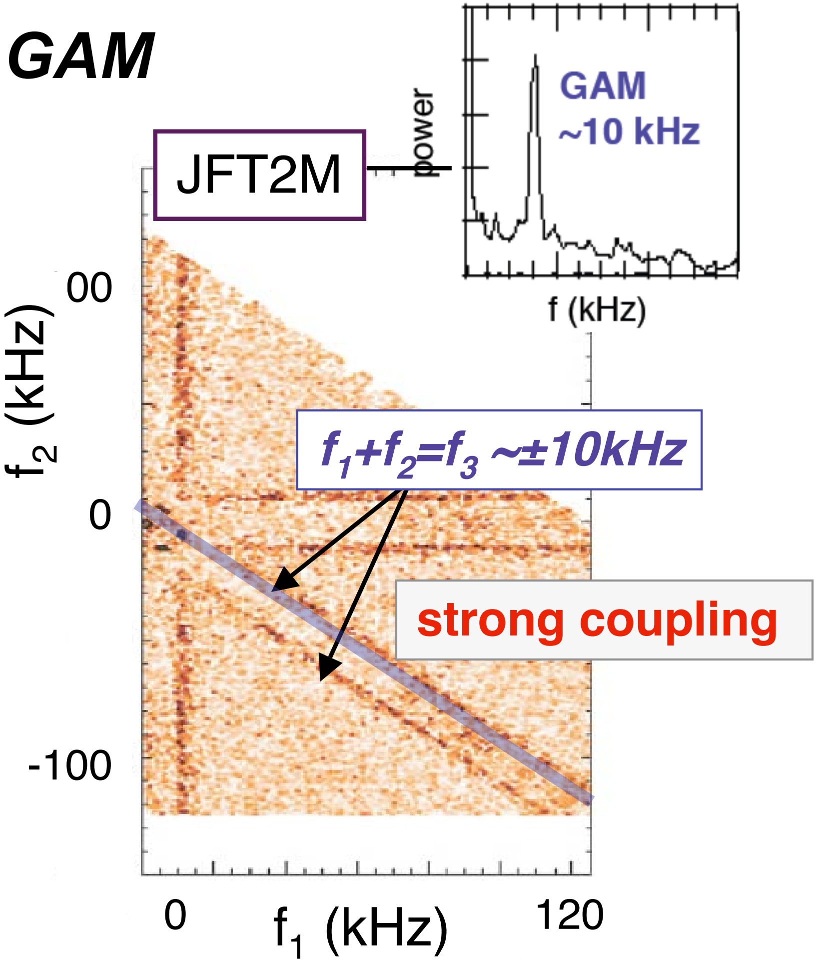


$f_1+f_2=f_3$

TEXT

How do we prove nonlinear interaction?

GAM

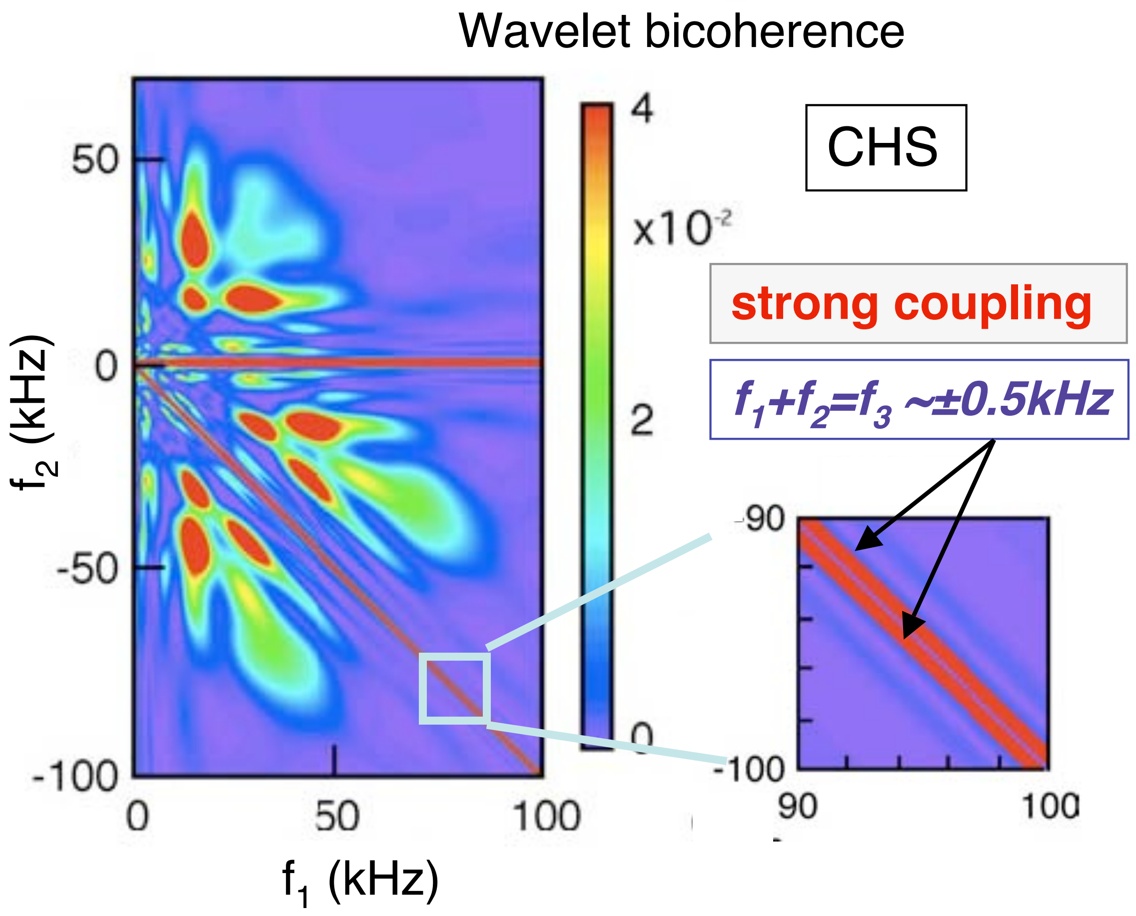


$f_1+f_2=f_3$ ~±10kHz

strong coupling

Y. Nagashima et al. PRL **95** 095002 (2005)

SZF



strong coupling

$f_1+f_2=f_3$ ~±0.5kHz

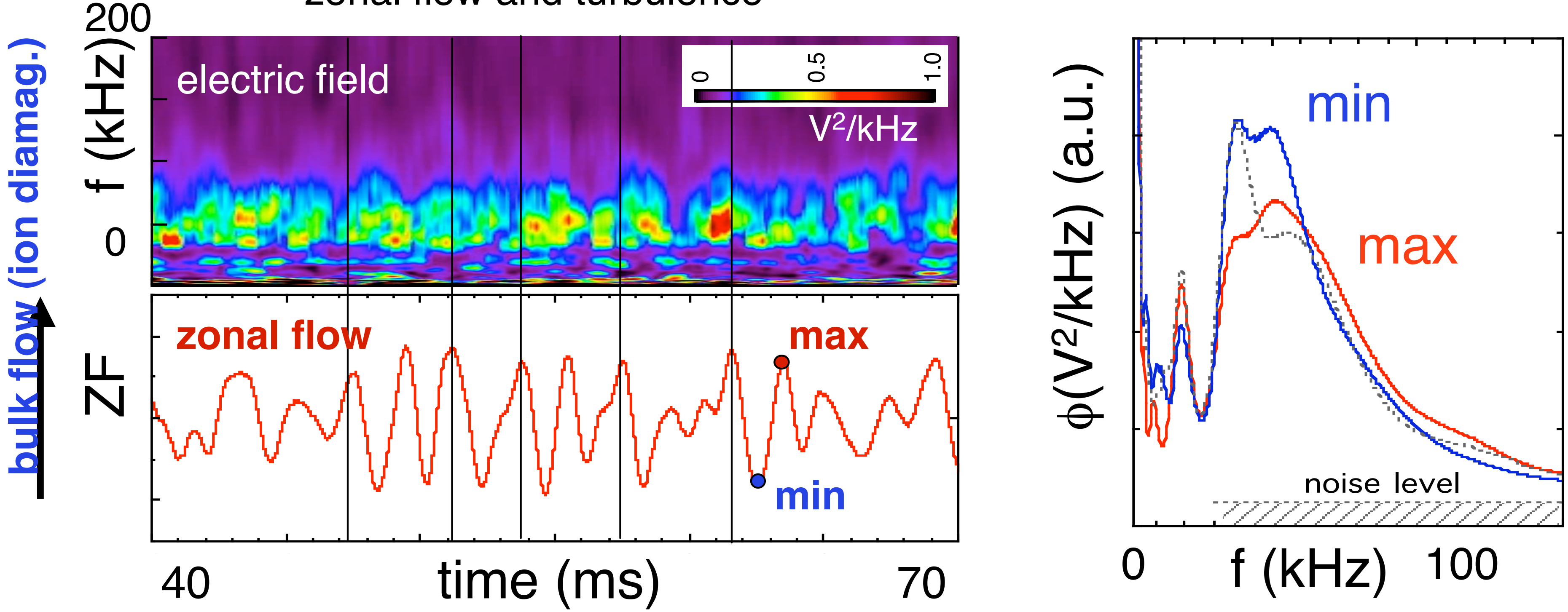
A. Fujisawa et al., PPCF **49** 211 (2007)

Coupling between zonal flows and background turbulence is confirmed using **bicoherence analysis**

How do we prove nonlinear interaction?

CHS

zonal flow and turbulence

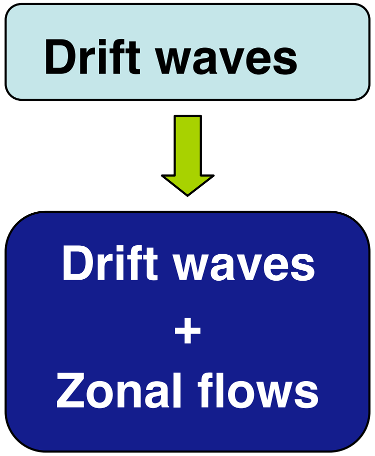


A. Fujisawa et al., JPSJ **76** 033501 (2007).

Turbulence power is modulated with zonal flow phase

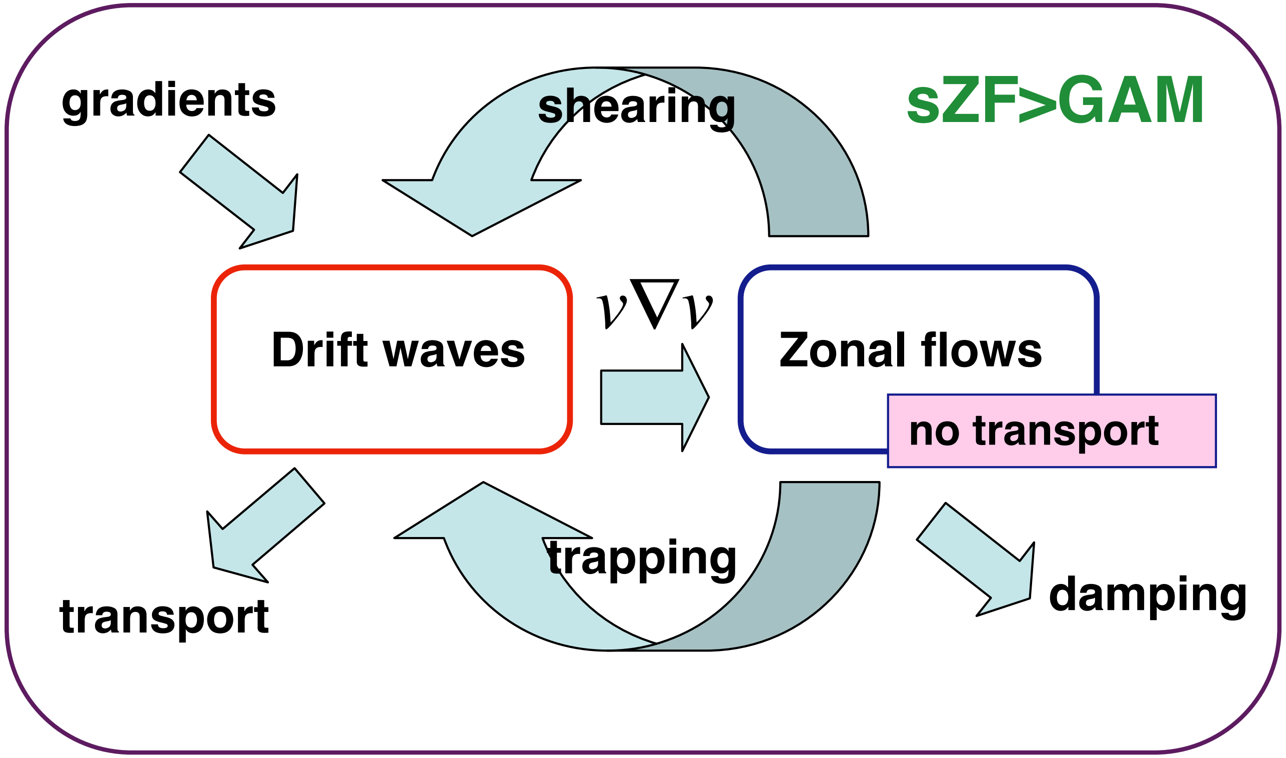
New Paradigm for Plasma Transport I

1970-1980s



the paradigm shift

PLASMA TURBULENCE



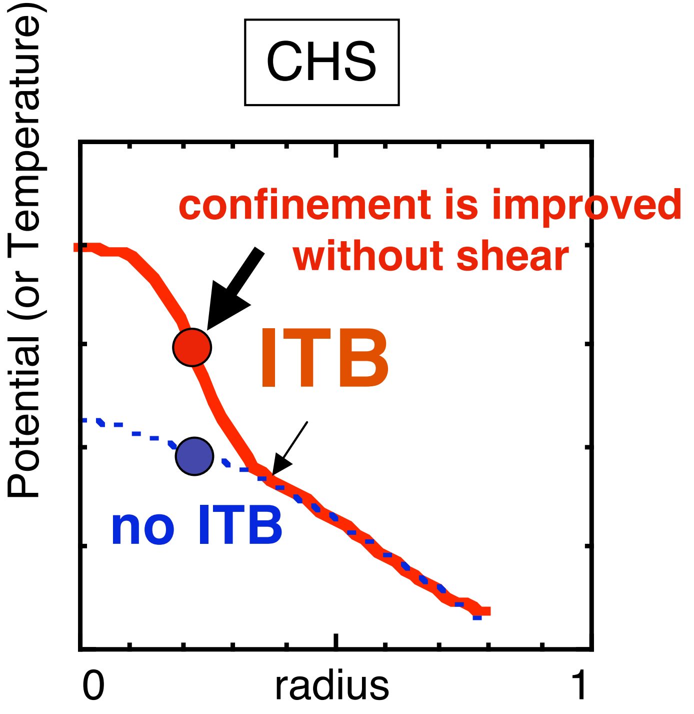
The plasma turbulence is regarded as a system of zonal flows and drift-waves

Nonlinear interaction between zonal flows and turbulence controls transport.

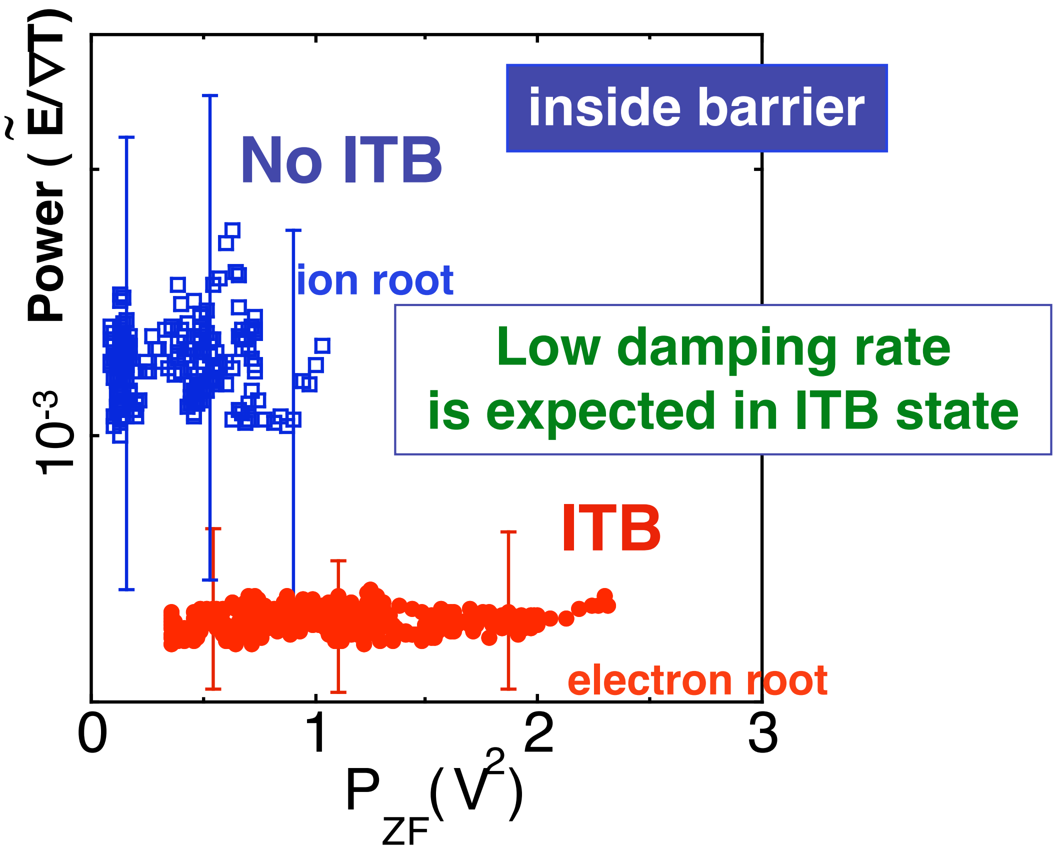
Energy partition between zonal flows and turbulence should be a key

New Paradigm for Plasma Transport II

A mystery: **why is the confinement improved inside the barrier?**



confinement is improved without shear



Low damping rate is expected in ITB state

K. Itoh et al., Phys. Plasmas **14** 20702 (2007)

A larger fraction of zonal flows contributes to improving the confinement inside.

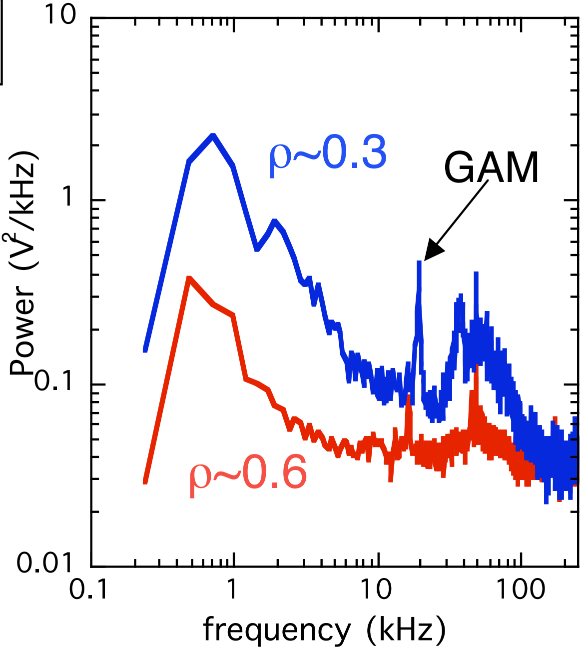
Energy partition between zonal flows and drift waves is really the key for confinement

New Paradigm for Plasma Transport III

The flow spectra consists of ZF, turbulence & GAM

CHS

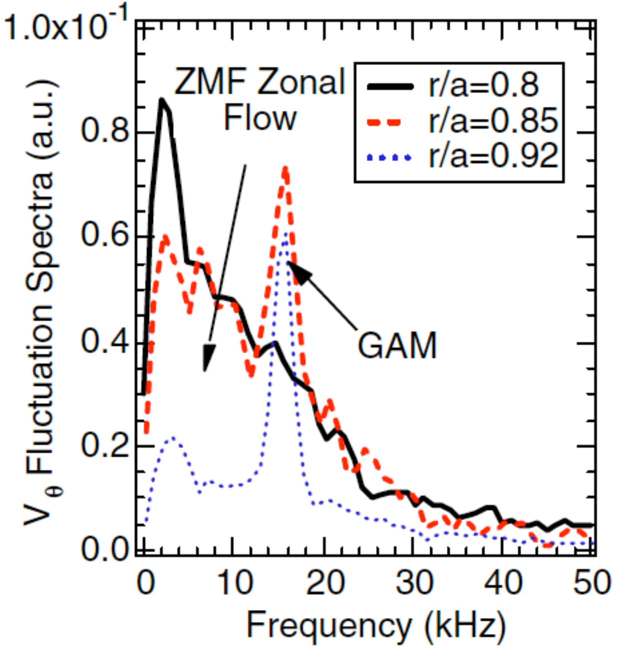
HIBP



DIII-D

BES

D. K. Gupta et al., PRL **97** 125002 (2006)



Dependence of spectra on dimensionless parameters should be investigated

$$\tau_{\mathrm{E}}^{\mathrm{L}} \propto \tau_{\mathrm{B}} \rho_*^{0.15} \beta^{-1.41} \nu_*^{0.19} M^{0.67} q^{-3.74} \varepsilon^{-0.09} \kappa^{3.22}$$

Scaling in dimensionless form

B. B. Kadomtsev Sov. J. Plasma Phys. **1** 295 (1975)

Such studies give fundamental understanding of plasma transport based on the new paradigm

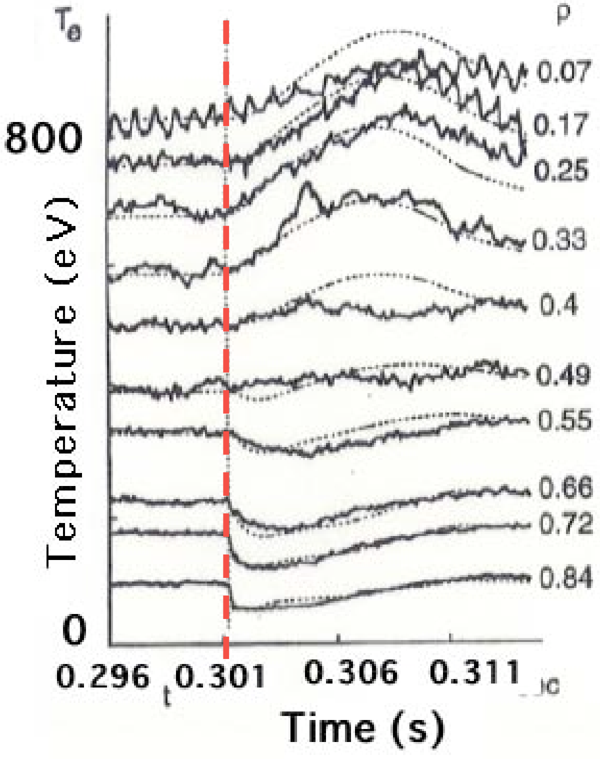
Future Directions

A Mystery in Plasma Transport

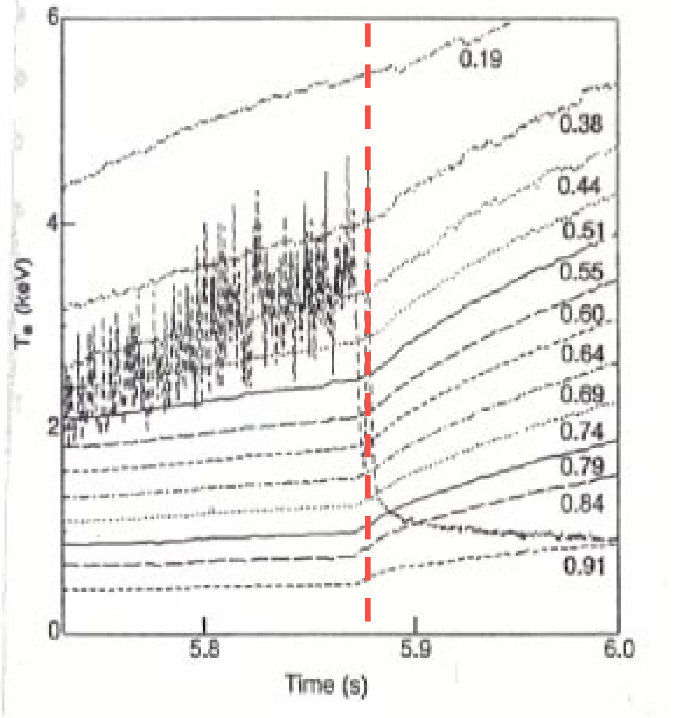
Non-local Transport

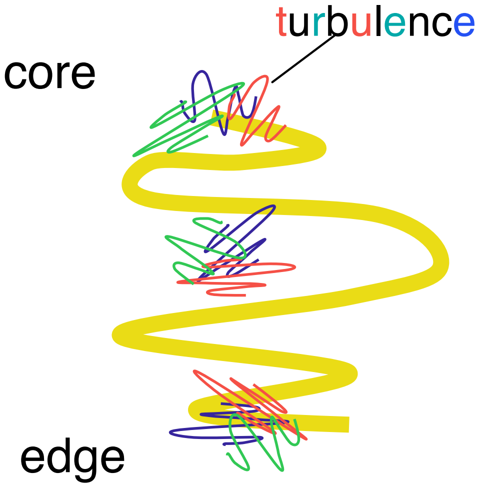
- How does the core plasma know the change happening at the edge

TEXT



JET





Edge turbulence may link core turbulence through the interaction with long wavelength fluctuations

K. Gentle et al., PRL **74** 3620 (1995).

J. G. Cordey et al., Nucl. Fusion **35** 505 (1995).

Disparate scale interaction could be a key to solve the mystery.

For Future Research I

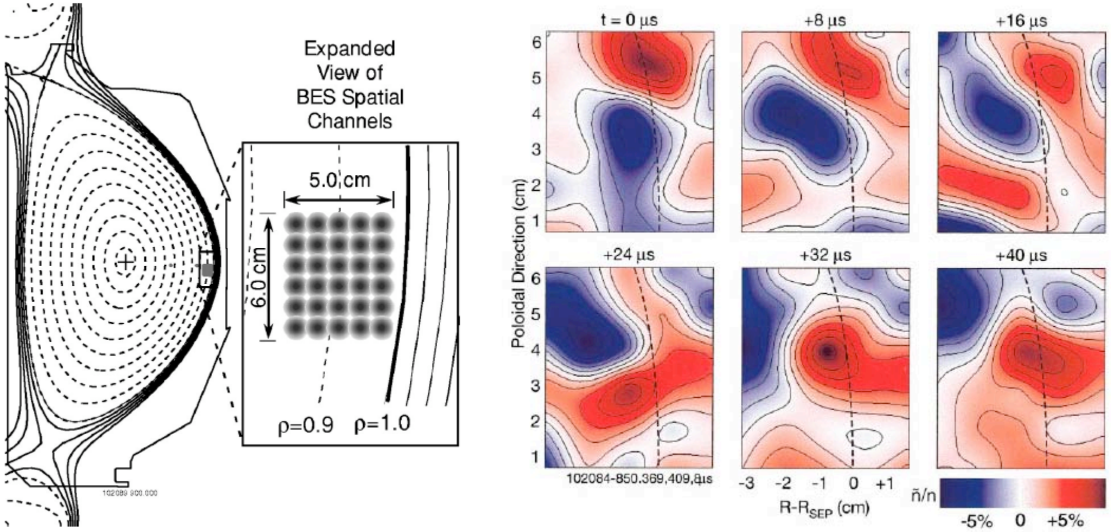
Disparate scale interaction should be investigated to clarify not only the non-local transport, but also **plasma turbulence and confinement**

Simultaneous measurements of

1. **Micro-scale turbulence**
2. **Macroscopic structures**
3. **Mesoscopic fluctuations**

furthermore, in many physical quantities (electric field, density, temperature, magnetic field and so on)

DIII-D/BES

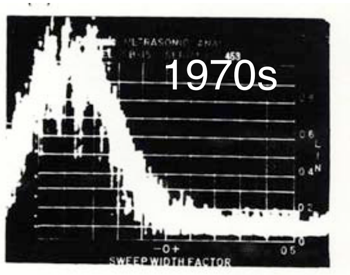


G. McKee et al., RSI **74** 2014 (2003)

At least wider range observation (2D-3D) with fine scale measurements

Computers become cheaper and faster, and can manage massive experimental data.

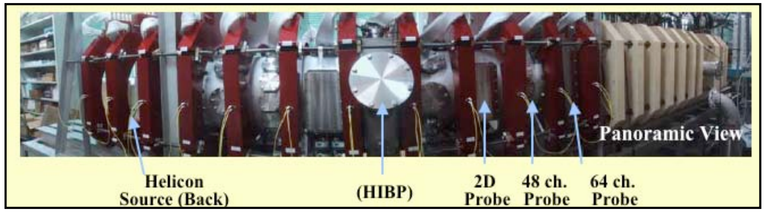
Now it is the time for us to really do turbulence studies!



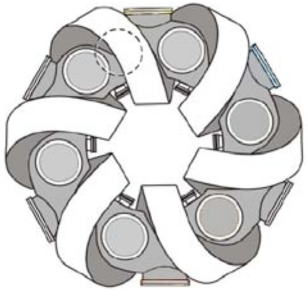
For Future Research II

High accessibility and flexibility for physical experiments can be realized in low temperature plasmas - ***Roles of such devices are strengthen.***

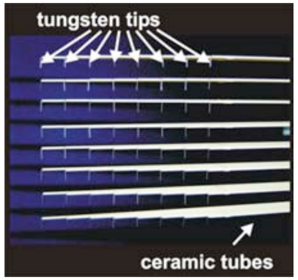
LMD-U

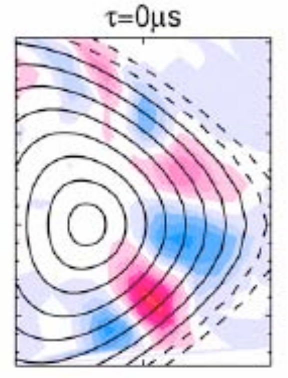


TJ-K



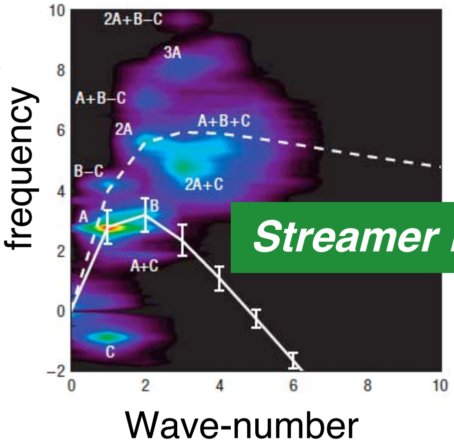
2D probe array





U. Stroth et al., Phys. Plasmas **11** 2558 (2004)

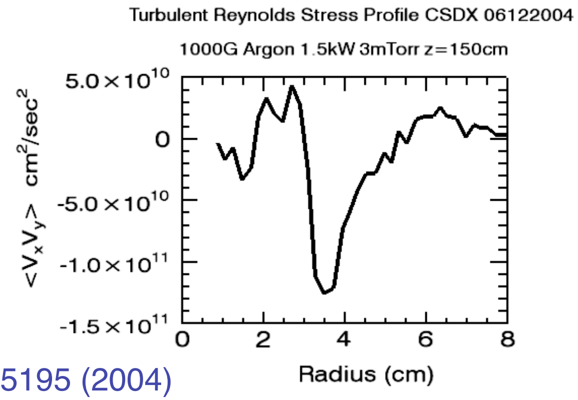
Multi-channel probe



Streamer identified

T. Yamada et al., Nature Phys. In press

CSDX



G. Tynan et al., Phys. Plasmas **11** 5195 (2004)

The ultimate physical laws should be expressed in dimensionless form

$$\tau_E^L \propto \tau_B \rho_*^{0.15} \beta^{-1.41} \nu_*^{0.19} M^{0.67} q^{-3.74} \varepsilon^{-0.09} \kappa^{3.22}$$

Summary

The world-wide efforts have found a number of improved confinement modes

Bifurcation property of plasma flows can be a cause of barrier formation

Interplay between flows and turbulence forms transport barriers

Now a new paradigm of plasma transport is coming up

Turbulence is regarded as a system of zonal flows and drift waves.

It should be the time to solve the remaining mysteries in plasma transport

Disparate scale interaction should be the key.

It should be the role for young plasma physicists to elevate the obtained knowledge to the laws of plasma confinement

Now we have good tools for observing the plasma turbulence

***cf.* The studies of heat engine deduced the second law of thermodynamics**

The studies of fusion should provide something universal for science

Review Papers

Reviews of transport barriers

F. Wagner, Plasma Phys. Control. Fusion **49** B1 (2007)

F. Wagner, Plasma Phys. Control. Fusion **48** A217 (2006)

A. Fujisawa, Plasma Phys. Control. Fusion **45** R1 (2003)

K. Itoh, S. -I Itoh, Plasma Phys. Control. Fusion **48** 1 (1998)

Reviews of turbulence & zonal flows

P. H. Diamond, K. Itoh, S-I. Itoh, T. S. Hahm, Plasma Phys. Control. Fusion **47** R35 (2005)

A. Fujisawa et al., Nucl. Fusion **47** S718 (2007)

Reviews of turbulence experiments

P. C. Liewer, Nucl. Fusion **25** 543 (1985)

A. Wootton et al., Phys. Fluids B **2** 2879 (1990).

Reviews of tokamak and stellarator comparison

U. Stroth, Plasma phys. Control. Fusion **40** 9 (1998)