Experimental Progress on Zonal Flow Physics in Toroidal Plasmas

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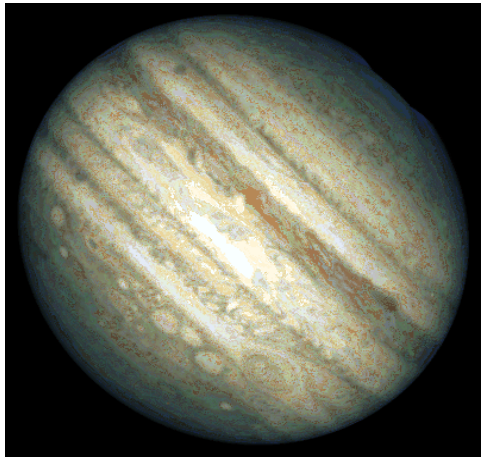
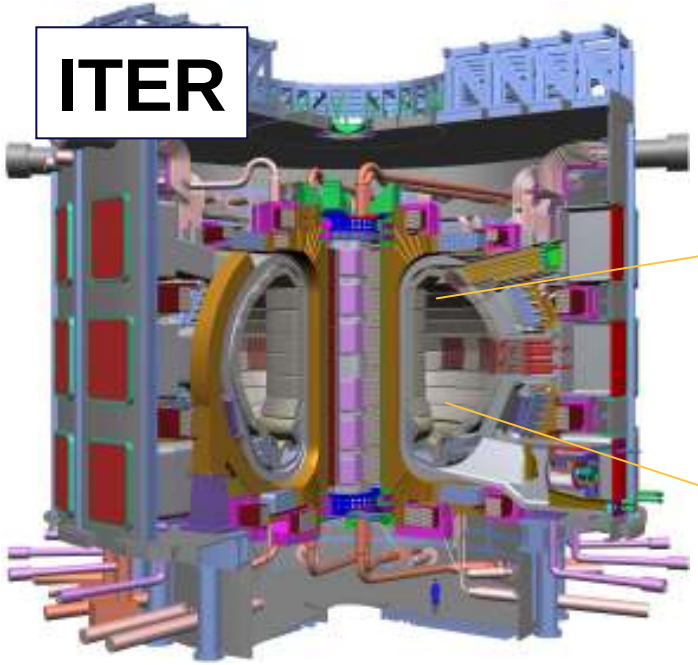
What is a ZONAL FLOW

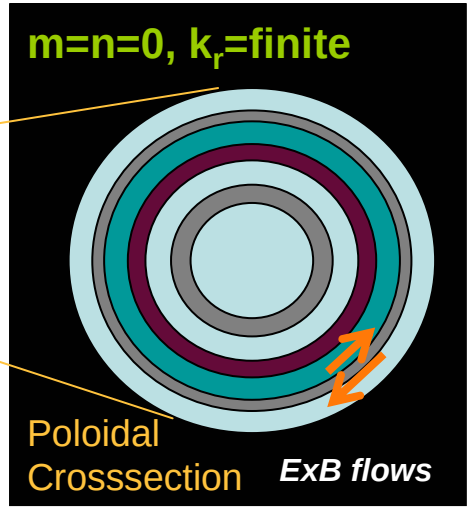
Is that really present in toroidal plasmas?

Zonal flows are ubiquitous.



Zonal flow in atmosphere in Jupiter





1. No linear instability

2. Turbulence driven

3. No radial transport

P. H. Diamond et al. PPCF 47 **R**35 (2005)

Two braches of ZFs in a toroidal plasma

i) stationary zonal flows (sZF)

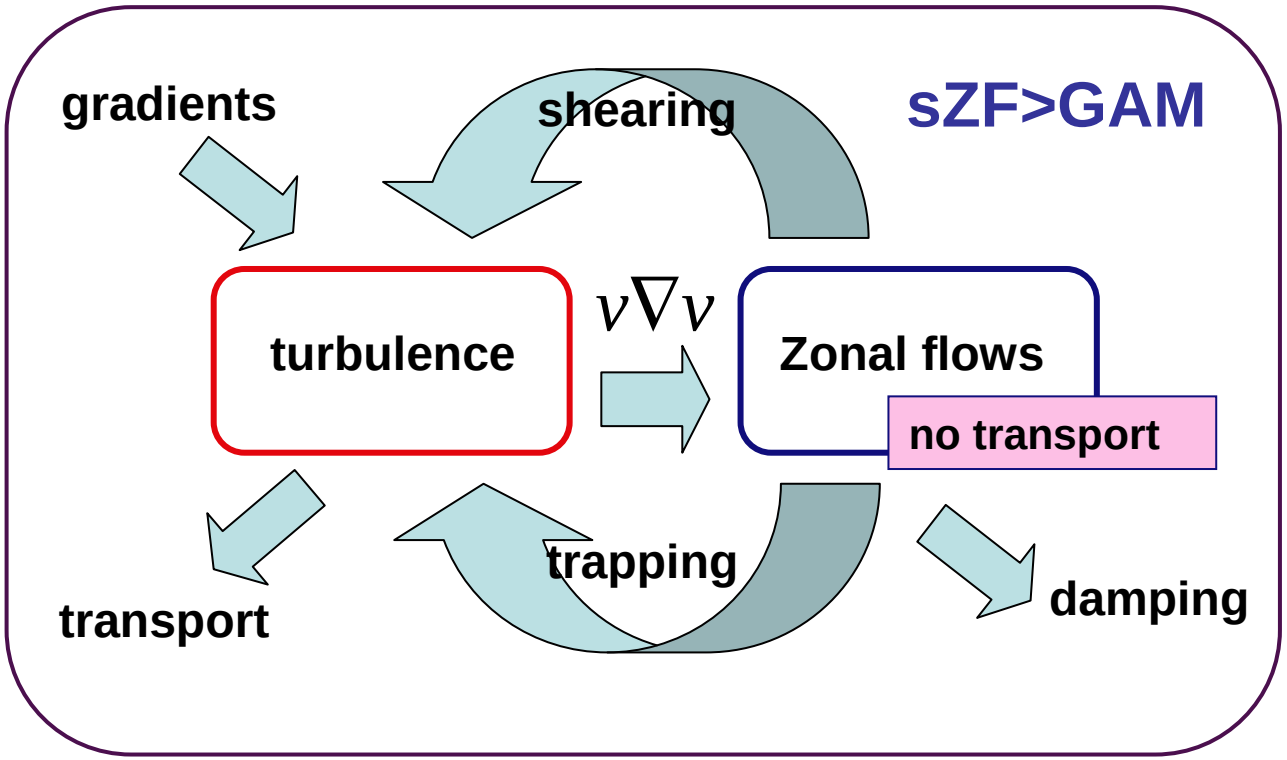
near-zero frequency ~0 kHz

ii) geodesic acoustic modes (GAMs)

an oscillatory branch ~ 10-50 kHz

Why are ZFs Important for Fusion?

Because the zonal flows are deeply associated with anomalous transport.



Plasma Transport

Drift waves

Drift waves + Zonal flows

the new paradigm

Nonlinear interaction between zonal flows and turbulence controls transport.

A question: the paradigm shift is experimentally supported?

Zonal Flow Experiments

A challenge to experimentalists

- electric field or flow measurements in high temporal and spatial resolution

Discoveries

i) zonal structure

symmetry (m=n=0)
a finite radial wavelength

ii) nonlinear coupling with turbulence

iii) effects on transport

Devices

ASDEX-U (reflectometry)

CASTOR (probes) **CHS(HIBP)**

CLD (probes) **CSDX (probes)**

DIIID (BES) **H1 (probes)**

HL-2A (probes) **HT-7 (probes)**

JIPPT-IIU (HIBP)

JFT-2M(HIBP&probes) **LMD (probes)**

T-10 (HIBP) **TEXT-U (HIBP)**

TJ-II(probes) **TJ-K(probes)**

More than a dozen papers have been published as a PPCF cluster (2006).

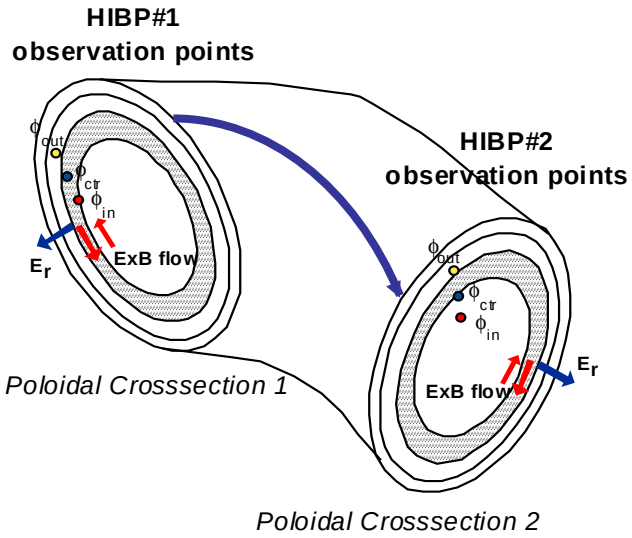
Existence of Stationary Zonal Flow

Proceeded by a pioneer work in HT-7, CHS has confirmed the existence of sZF

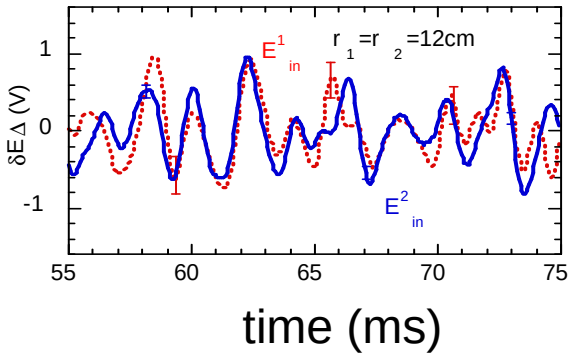
G. S. Xu et al., PRL **91** 125001 (2003).

CHS

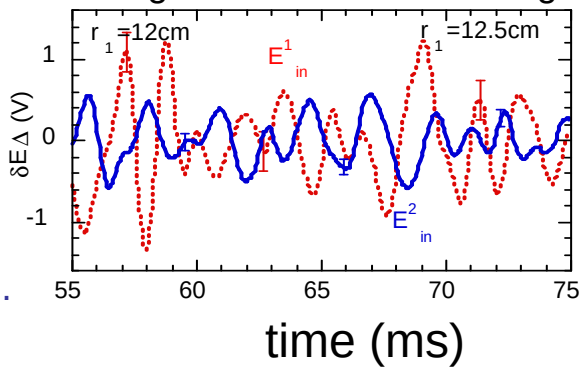
f~0.5 kHz



Showing Symmetry

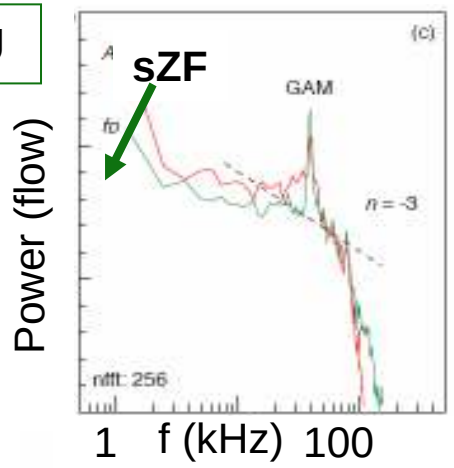


Showing a finite radial wavelength



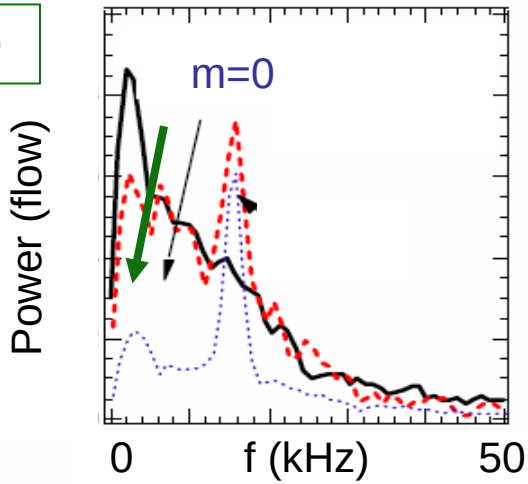
A. Fujisawa et al. PRL **93** 165002 (2004).

ASDEX-U



G. D. Conway, 31st EPS conf. London

DIII-D



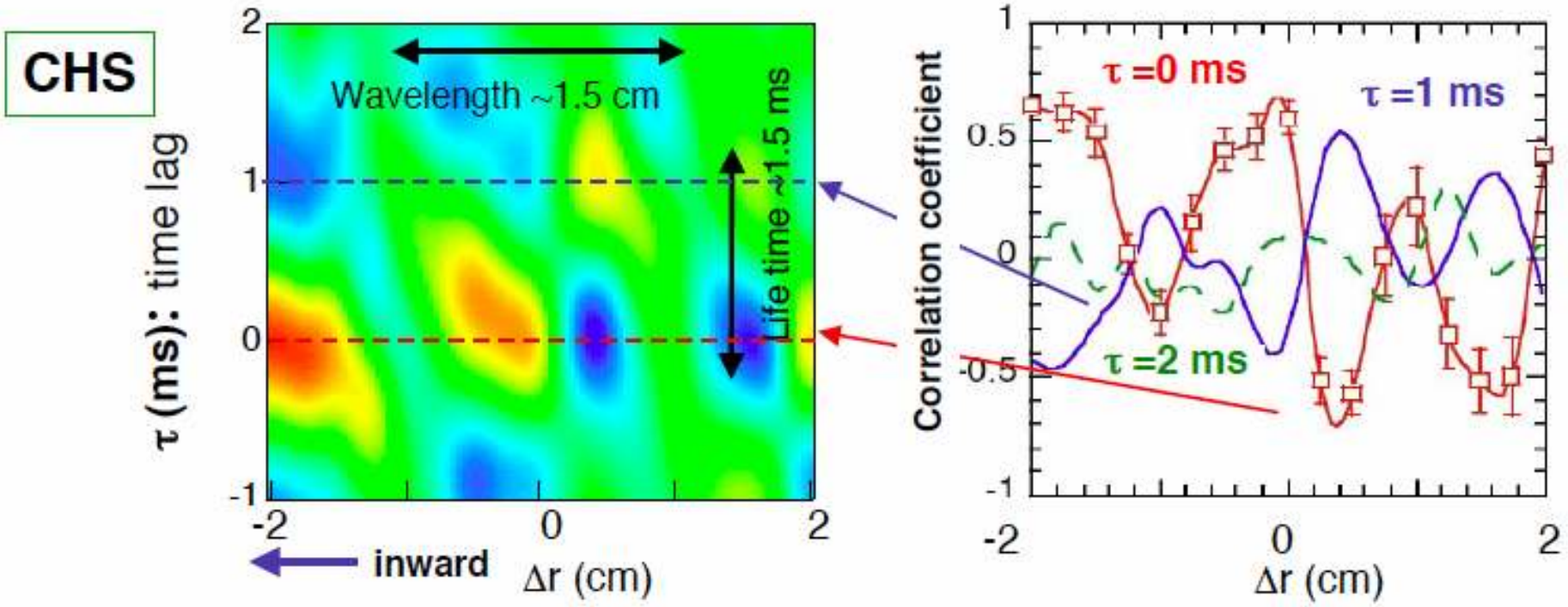
Zonal structure is found!

New techniques for ZF detection are developed in CATOR and CLD. **This IAEA EX2-3: G. Mckee et al.**

Pattern of Stationary Zonal Flow

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

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

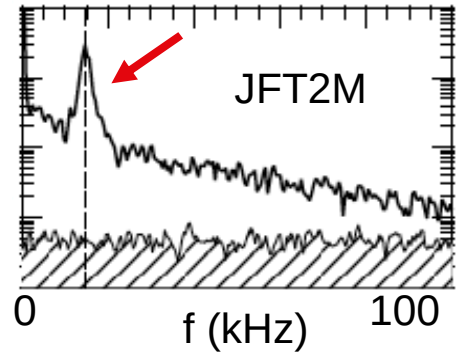


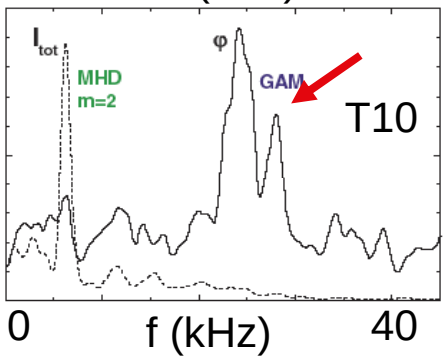
This is the discovery of stationary zonal flow.

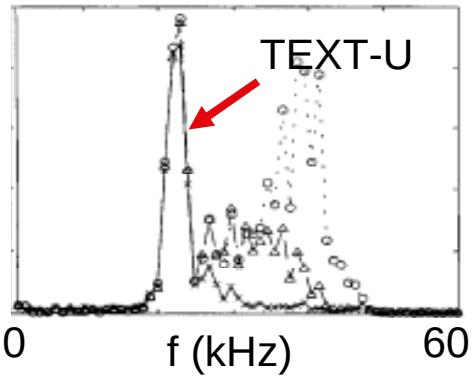
GAMs in Spectra

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

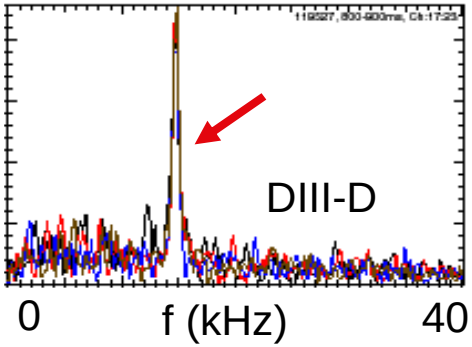
Potential (HIBP)



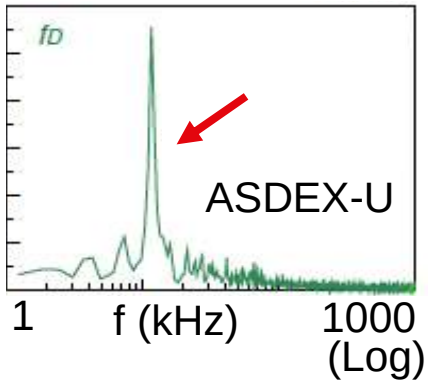




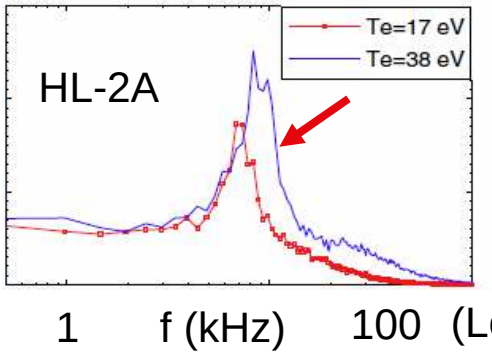
flow(BES)



flow(reflectometry)



potential (probe)

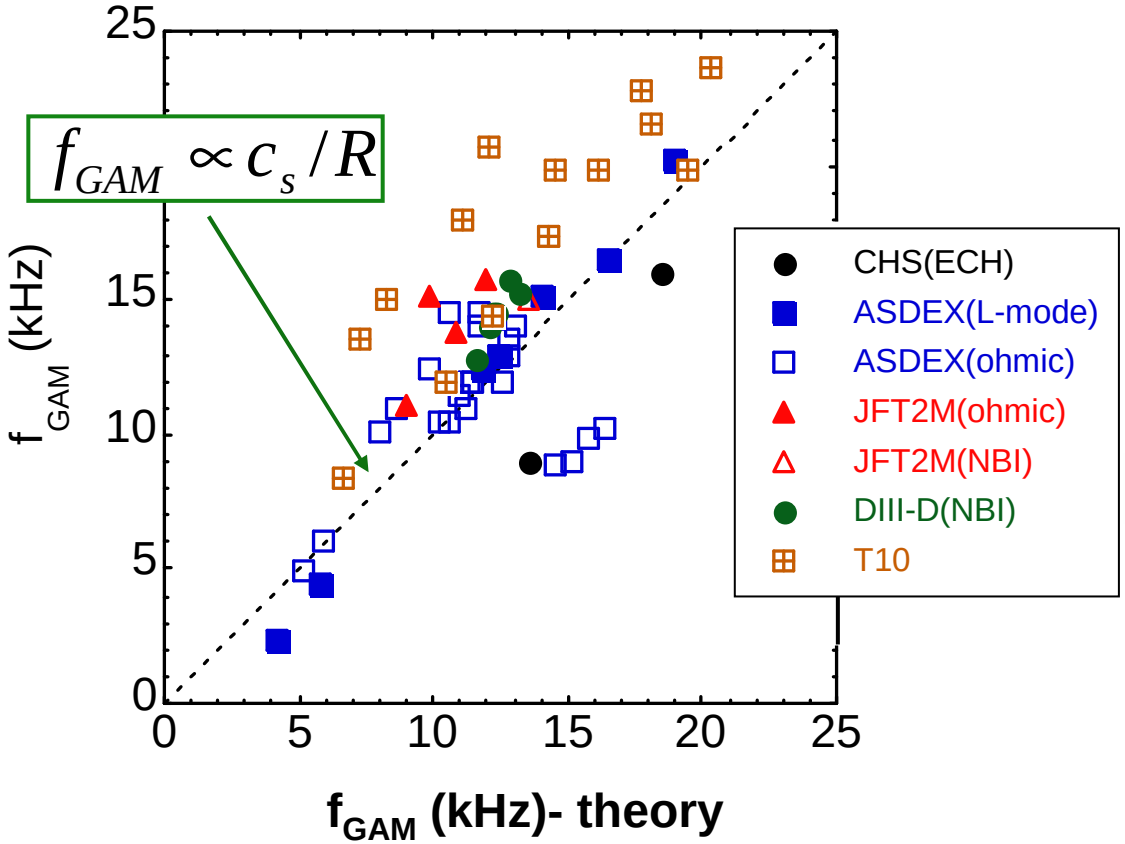


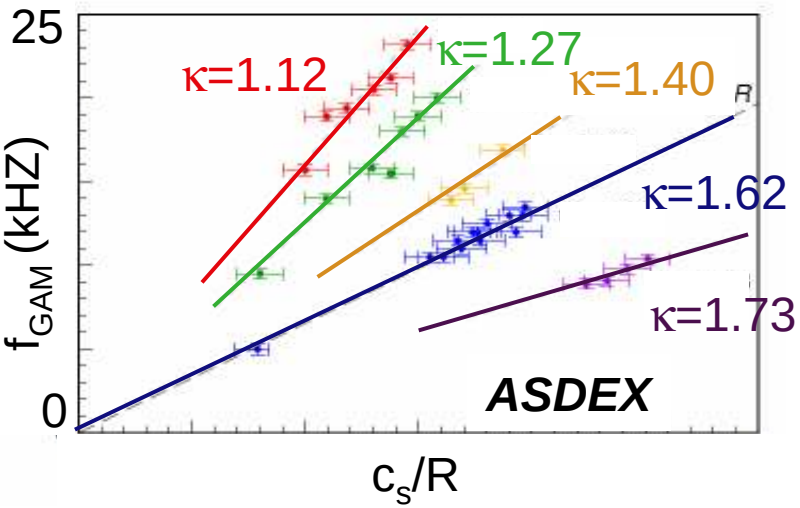
Coherent modes have been detected in many toroidal devices

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

This IAEA EX/P4-35 L.W. Yan et al.

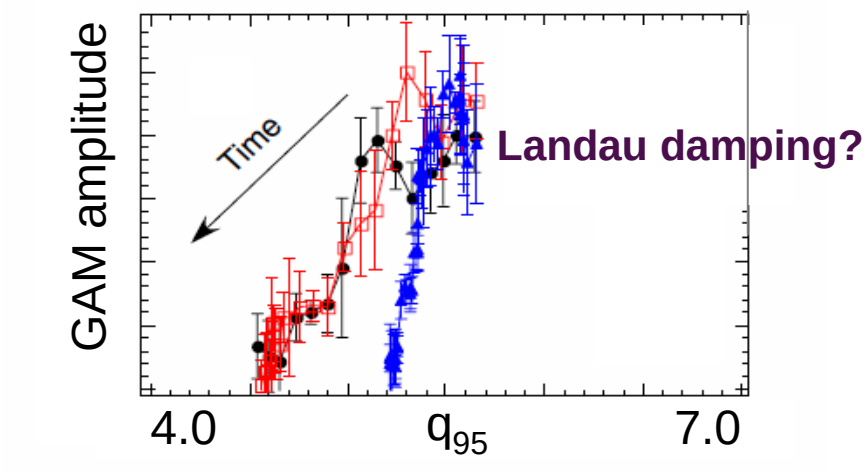
GAM Frequency Dependence





This IAEA EX2-1 G. Conway et al.

The frequency of the coherent modes satisfies the expected dependence.



Landau damping?

The studies of GAM have an impact on understanding of plasma turbulence

G. R. McKee et al., PPCF **48** S123 (2006).

How to Prove Nonlinear Couplings

Bicoherence analysis can quantify the strength of three wave coupling.

$f_1+f_2= f_3$ $(k_1+k_2= k_3)$

(bicoherence=0, if $f_1+f_2\neq 0$)

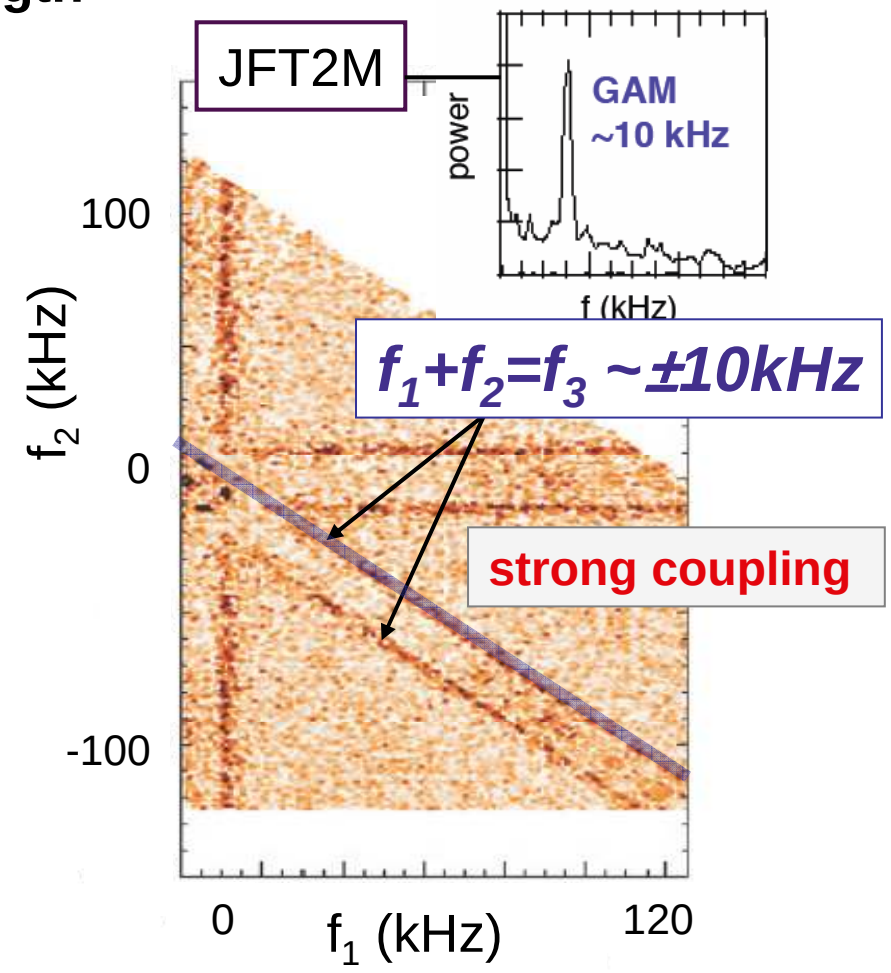
Other techniques (energy transfer, autocorrelation, etc.) are developed M. Shats et al., PPCF **48** S17 (2006).

Reynolds stress to drive mean flow

-Direct evaluation of perpendicular term $\langle \tilde{v}_\perp \tilde{v}_r \rangle$ has been widely performed (CSDX, HT-6M, LMD, TJ-K, etc.) G. R. Tynan et al.PPCF **48** S51 (2006).

- Direct measurement of energy transfer term from turbulence to flow is performed in TJ-II, showing importance of parallel component $\langle \tilde{v}_\parallel \tilde{v}_r \rangle$.

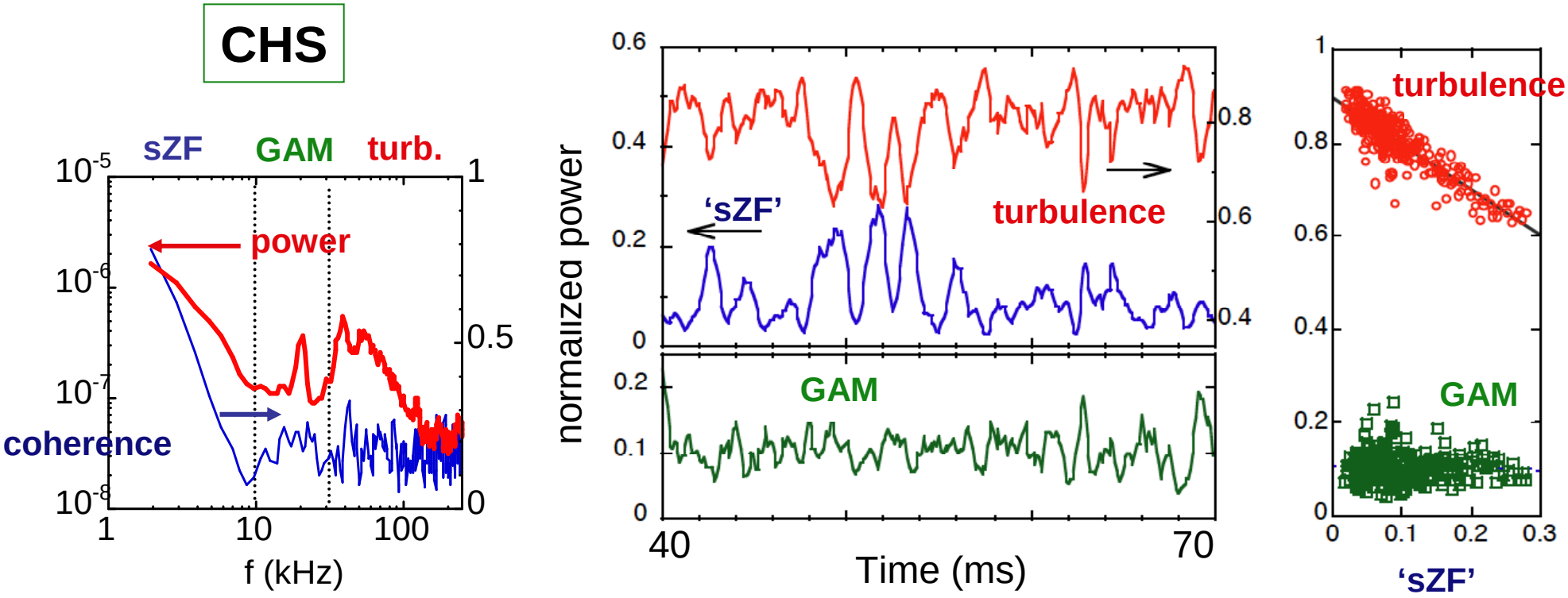
This IAEA EX/P7-2 C. Hidalgo et al.



This IAEA EX2-2 K. Hoshino et al.

Energy Transfer between ZF and Turbulence

Turbulence power changes intermittently with ‘zonal flow’



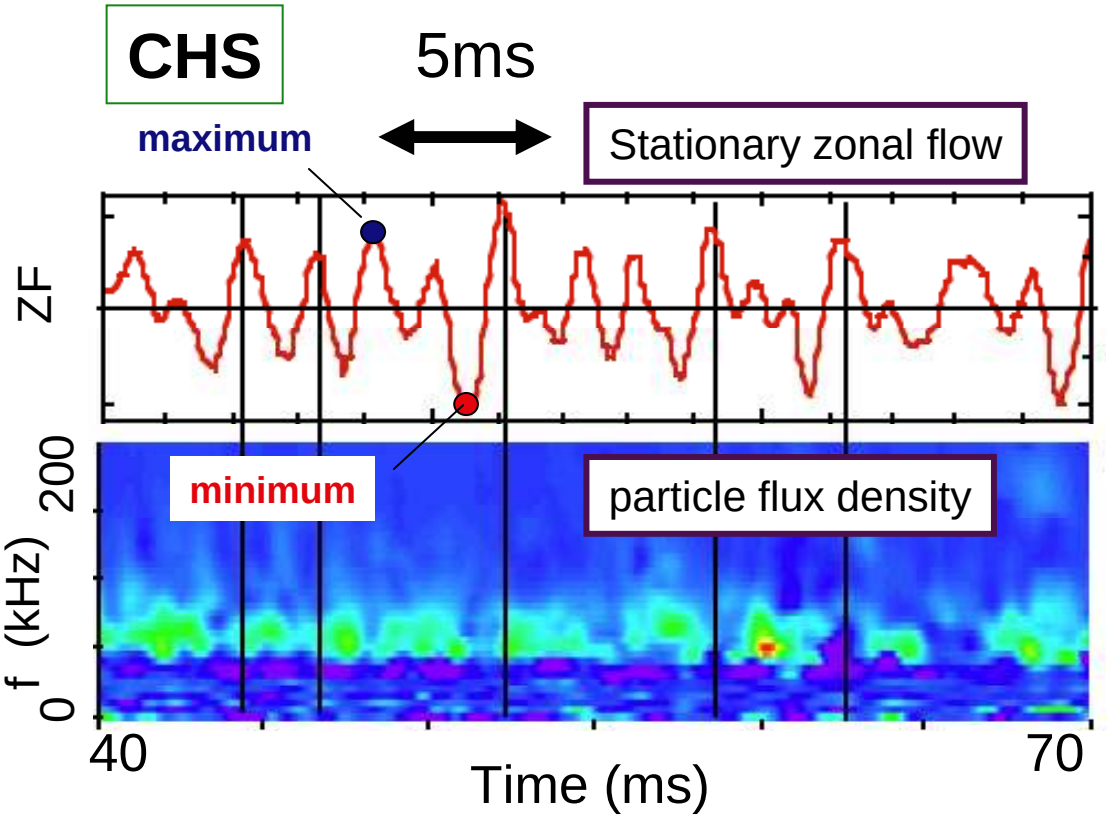
Anti-phase behavior suggests direct energy transfer between ‘zonal flow’ and turbulence

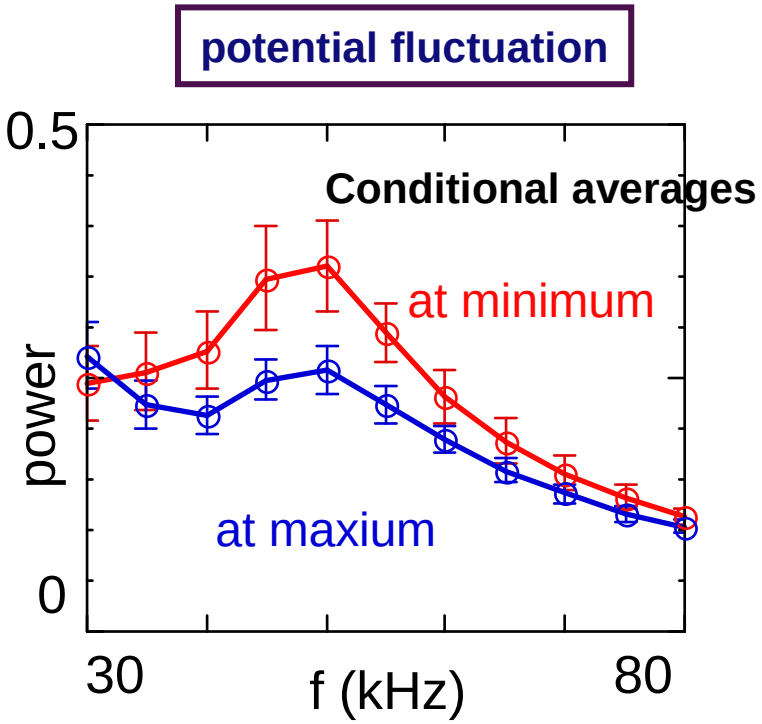
A. Fujisawa et al. PPCF **48** A365 (2006).

Effects on Transports

ZF Effects on Transport

HIBP has an advantage in simultaneous measurements of ZF and particle flux





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

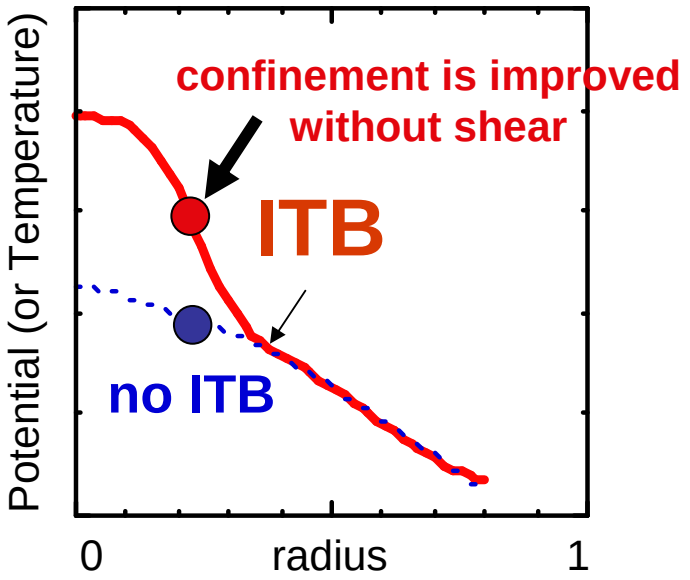
Particle flux is really modulated with stationary zonal flow.

Similar result is obtained for GAMs in JFT-2M.

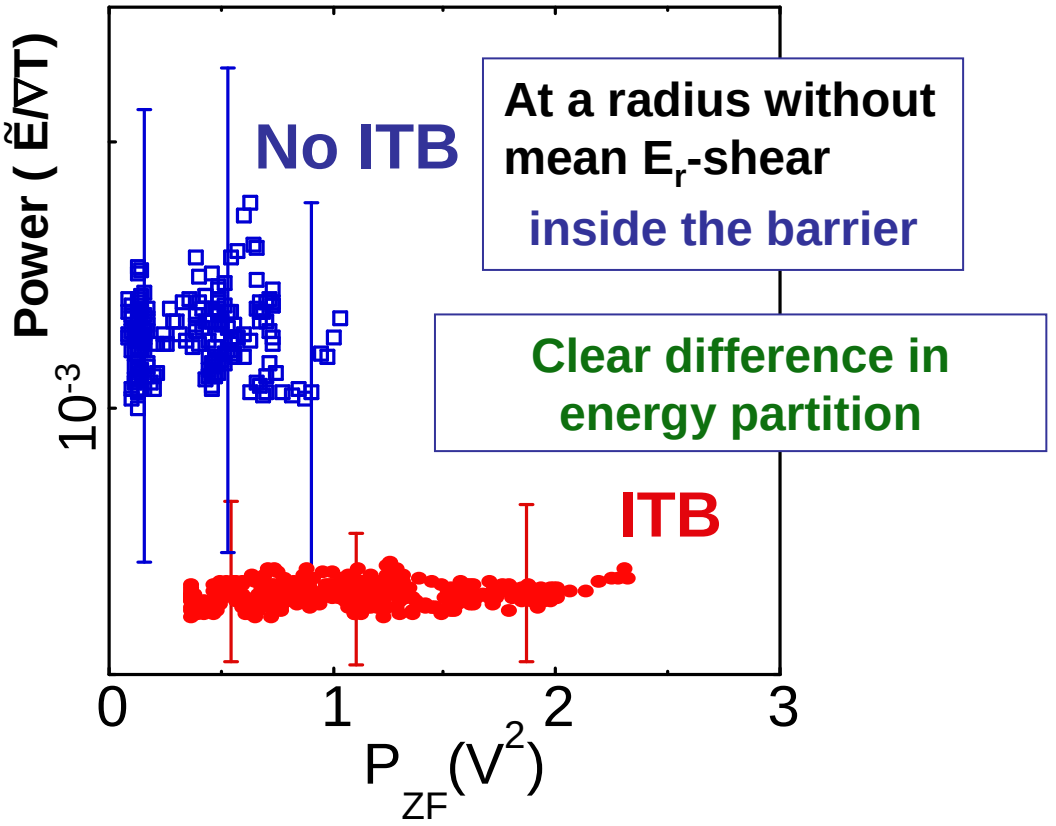
T. Ido et al., PPCF **48 S**41 (2006)

Better Confinement in Enhanced ZF

CHS Why is the confinement improved in shearless regime inside the barrier?



Common ITB in helical plasmas



At a radius without mean E_r-shear inside the barrier

Clear difference in energy partition

A larger fraction of zonal flows contributes to confinement improvement inside the barrier! **Importance of zonal flows on confinement is demonstrated.**

What Experiments Achieved

	structure	nonlinear coupling	effects on transport
S-ZF	n=0 confirmed m=0 confirmed k_r=finite confirmed	confirmed (temporal correlation)	Importance of flow energy partition is demonstrated Turbulence modulation is observed.
GAM	m=0 confirmed n=m=0 in a case k_r=finite proven $f_{GAM} \sim c_s/R$ Eigenmode property	confirmed (bicoherence)	Turbulence modulation is observed

The experiments on zonal flows have made a large progress.

The obtained knowledge are still fragmental, but **support the fundamental expectations of the theories.**

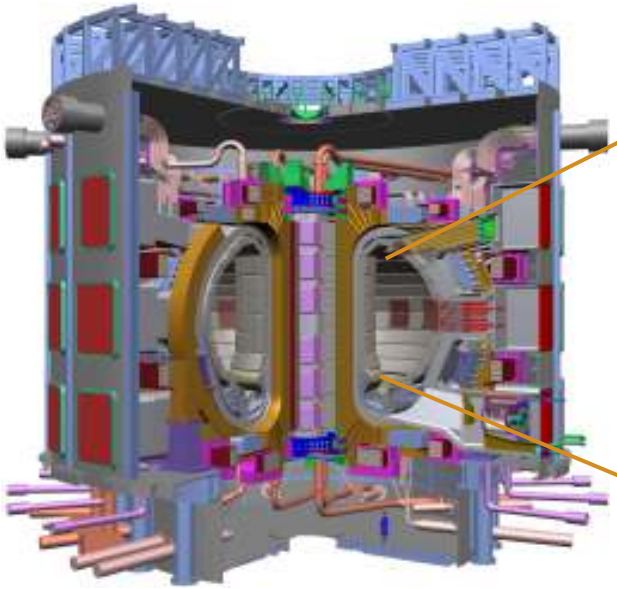
Summary

The world-wide experiments on zonal flows show,

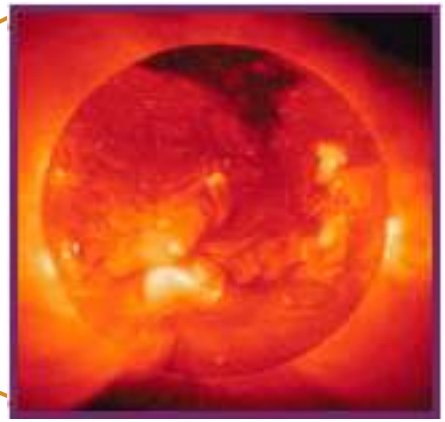
ASDEX-U, CASTOR, CHS, CLD, CSDX , DIII-D, H1, HL-2A, HT-6M, HT-7, JFT-2M, JIPPT-IIU,LMD, T-10, TEXT-U, TJ-II, TJ-K and so on

- Zonal flows really do exist in toroidal plasmas.

- The experiments support the paradigm shift!



Common physics



Drift waves

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Drift waves + Zonal flows

- The prospect of ITER is enhanced.

ITER will be more analogous to the Sun than the Jupiter.