Experimental Confinement Studies Beyond ITER

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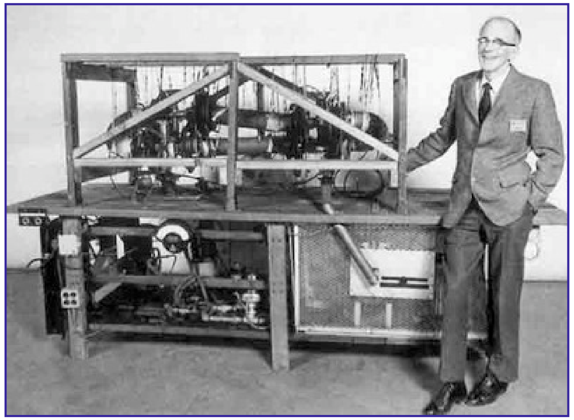
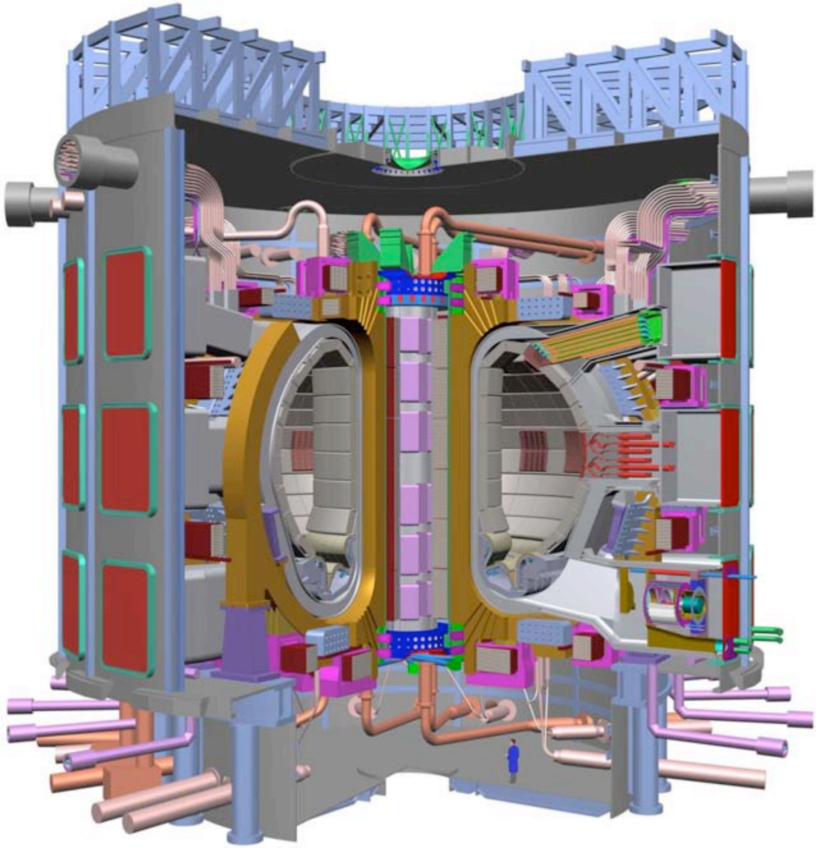


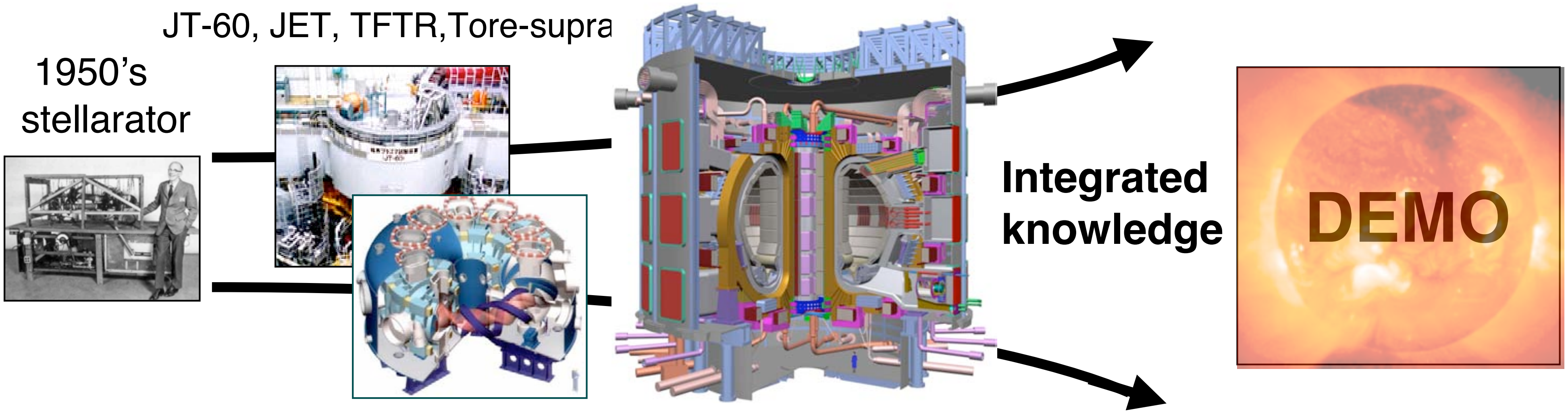


\- *A brief review based on comparison between stellarators and tokamaks in ITC18*

Introduction

Many kinds of devices have been tested for more than 50 years.

Tokamaks, stellarators, RFP, Mirrors and so on



JT-60, JET, TFTR,Tore-supra

1950's
stellarator

Integrated knowledge

LHD, CHS, H-J, TJ-II, H1, W7-AS HSX,TU-heliac….

The understanding from the first principle should be mandatory to realize an economic and high-performance devices in future.

Outlines of Talk

1. Advantage of Stellarators

Density limit & attractive confinement regime

2. Transport and New Paradigm

For realizing a better magnetic field configuration in turbulent transport

3. Beyond Simple Comparison

Roles of low temperature devices

4. Summary

High Density Operation

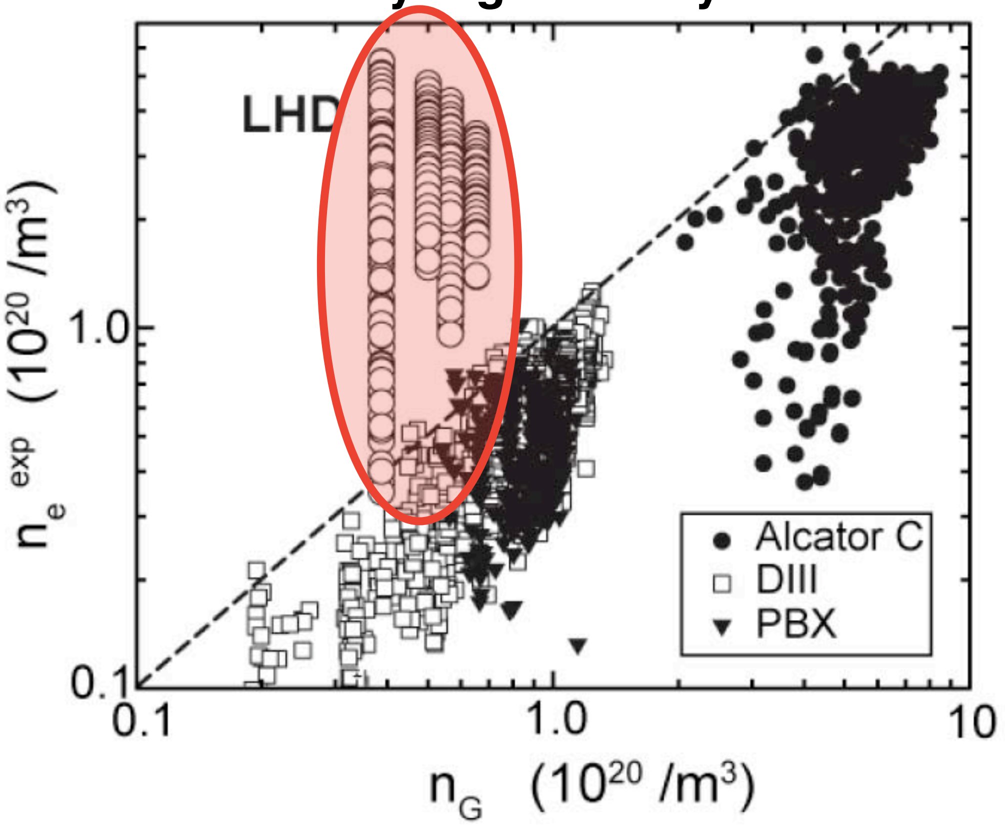
Records in tokamaks

Ion Temp.	40 keV (JT-60U)
Conf. Time	1.2 s (JET)
beta	40 %(START)
Electron Temp.	20 keV (ASDEX-U)
Stored Energy	17 MJ (JET)
Fusion Product	1.5x10^{20} m^{-3}skeV (JT-60U)

From K. Yamazaki & M. Kikuchi ITC12

Greenwald limit $n_{\mathrm{limit}} \propto \frac{I_p}{\pi a^2}$

Extremely High Density Limit



Courtesy of Prof. H. Yamada

Stellarators can easily exceed the Greenwald density.

Behavior around Density Limit

Several scenarios around density limit are known, e.g., **Breathing**

No any violent instabilities have been reported ⟷ **Disruption**

ECRH power ~100 kW

A transition to another state

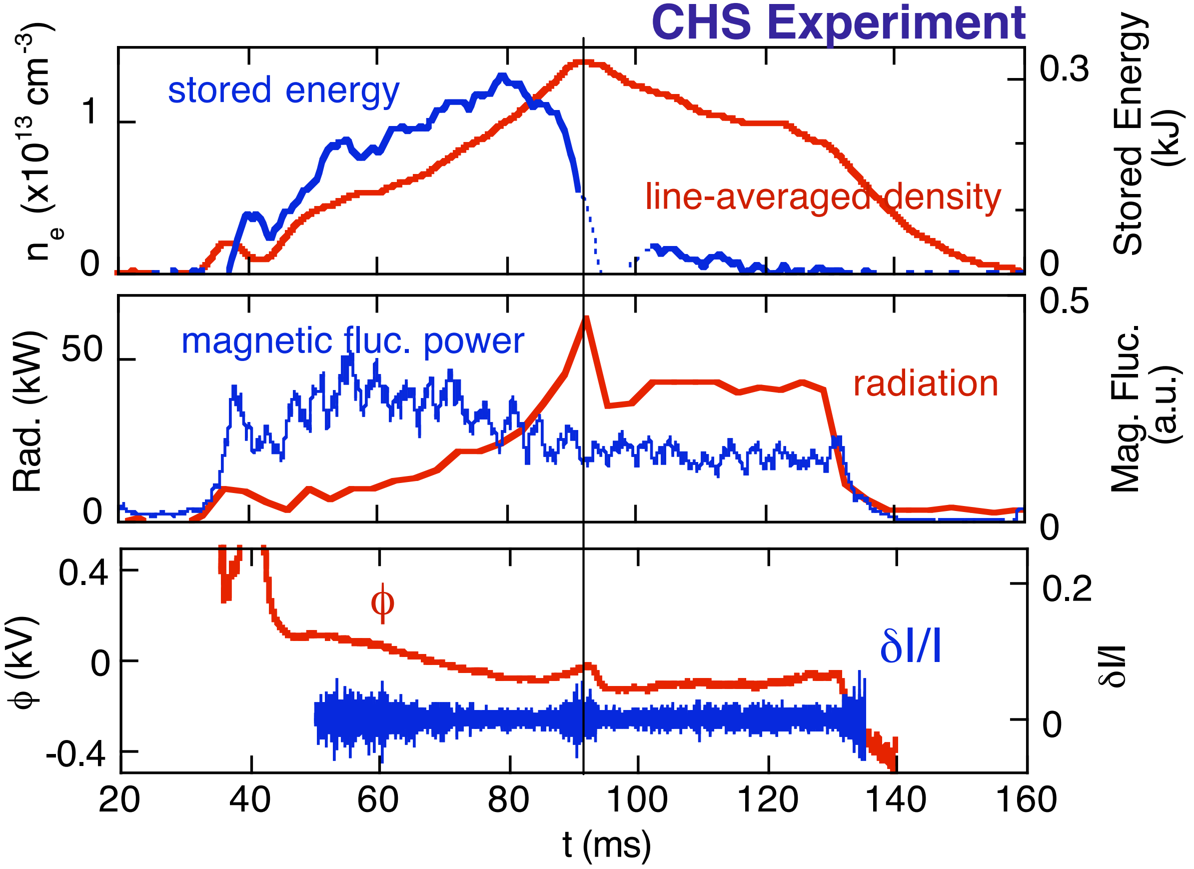
High T ⟶ **Low T**

An increase in transport is suggested before the transition

Sudo Scaling

$$n_{\mathrm{limit}} \propto \sqrt{PB}$$

CHS Experiment

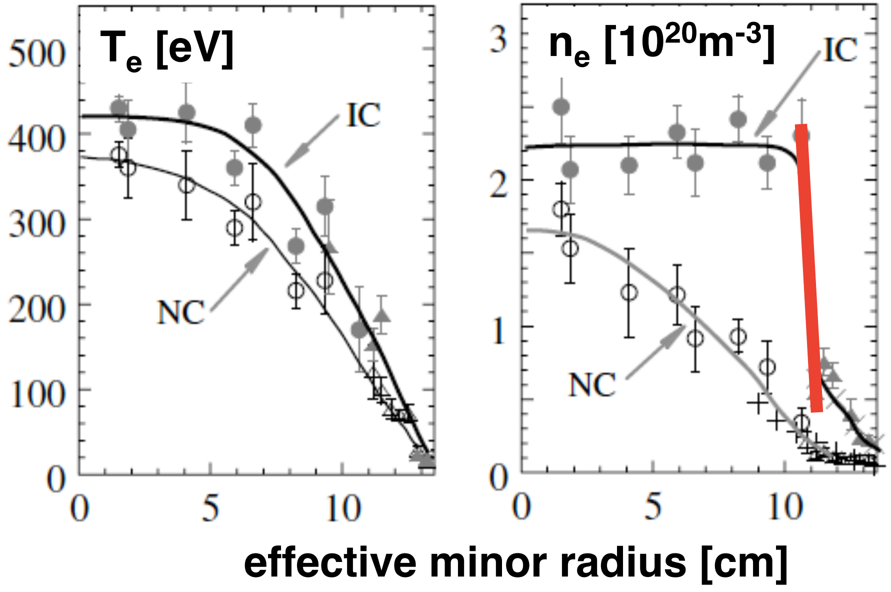


Transport around density limit can be investigated without any current driven instabilities in stellarators

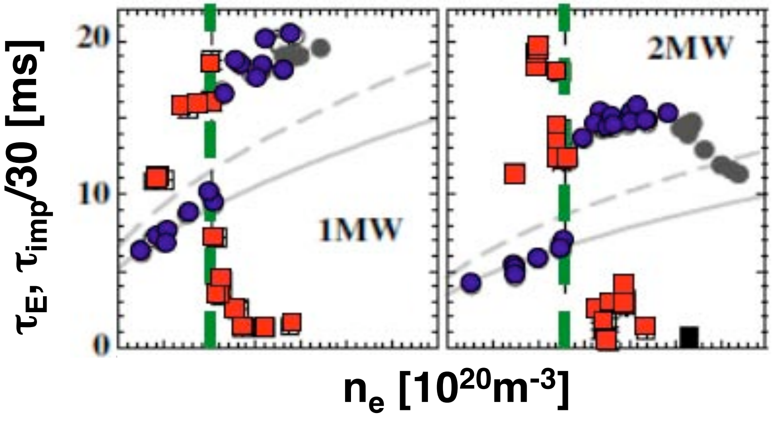
Impurity Purging

Improved confinement with high density (SDC & HDH)

HDH-mode (W7-AS)



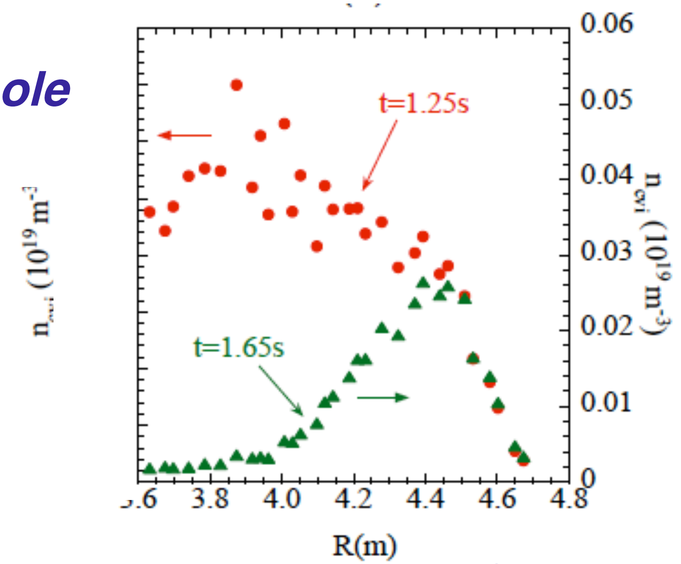
K. McCormick et al., Phys. Rev. Lett. **89** 015001 (2002)



Attractive improved confinement regimes have been found in stellarators

Spontaneous ash removal may be expected
The mechanisms should be clarified

Impurity hole (LHD)



M. Yoshinuma this conference

Transport & New Paradigm

- Configuration Optimization

Collisional Transport & Barrier Formation

TRANSPORT = COLLISIONAL+TURBULENCE

$$D \propto \Delta^2 \nu$$

Random walk

Banana particles (tokamak)

Helically trapped particles (stellarators)

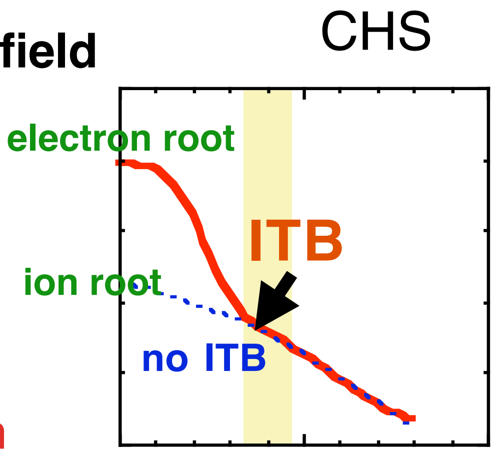
Bipolar diffusion in stellarators

Bifurcation of radial electric field

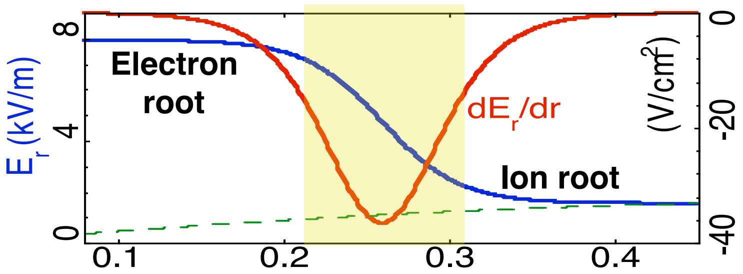
electron & ion roots

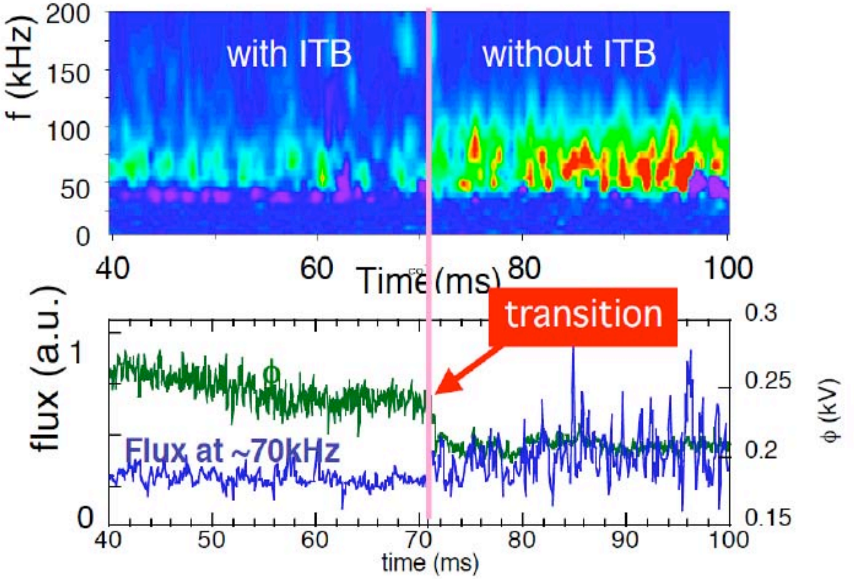
Transport Barrier

The bifurcation mechanism is exceptionally clear



ITB Layer





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

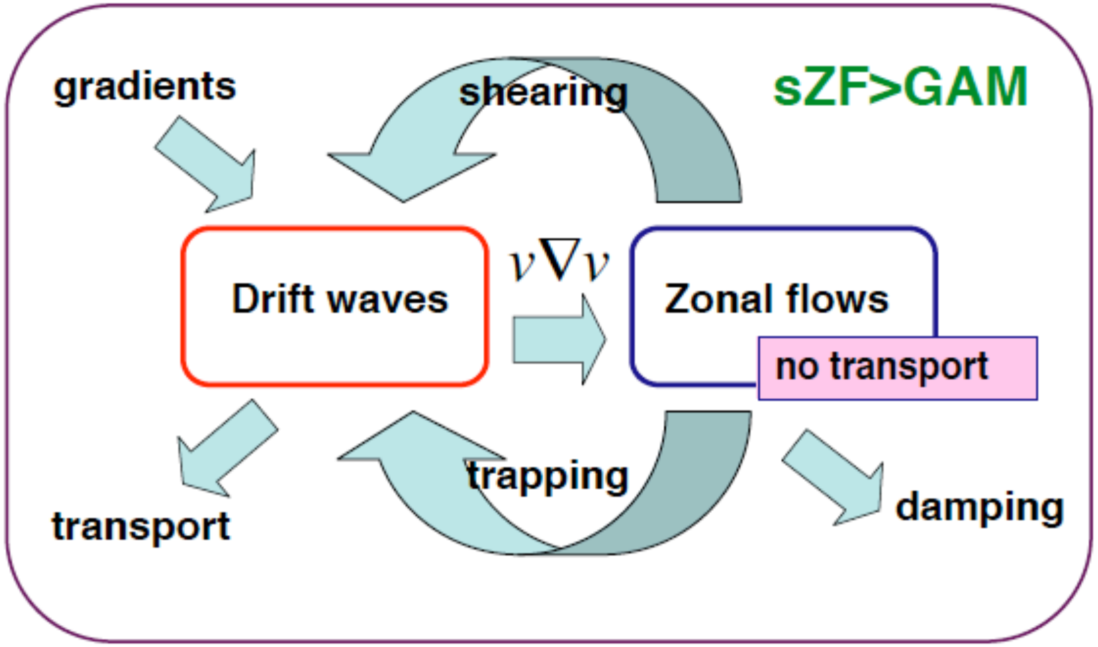
Non-axisymmetric nature (or helical ripple structure) can be the cause for barrier formation

New Paradigm for Turbulent Transport

Magnetic well & shear: associated with linear stabilization of instabilities

New Paradigm: associated with the saturation of instabilities

PLASMA TURBULENCE



gradients

shearing

sZF>GAM

Drift waves

$v\nabla v$

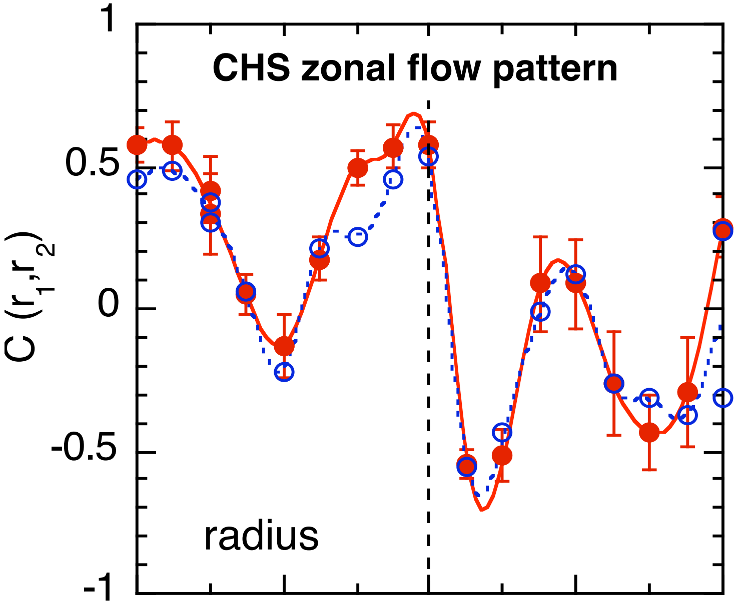
Zonal flows

no transport

transport

trapping

damping



A. Fujisawa et al., Phys. Rev. Lett. **93** 165002 (2004)

The new paradigm is confirmed experimentally.

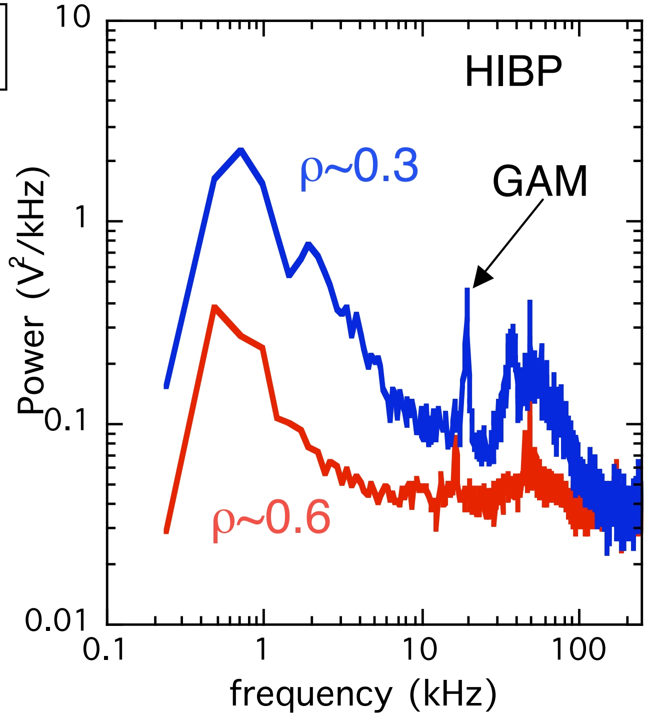
Flow damping rate is really a key for turbulent transport.

Comparison in Spectra

Common features in fluctuation spectra of stellarator and tokamak

I) stationary zonal flows, ii) GAMs, iii) drift waves

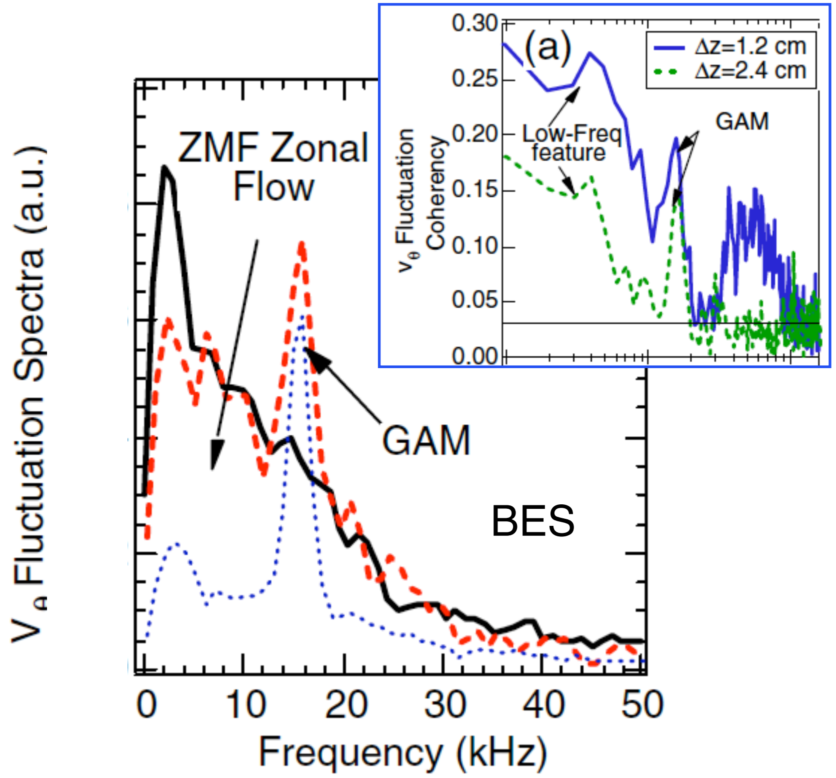
CHS



GAM in JIPPT-IIU is ~100 V

Y. Hamada et al., NF 45 81 (2005)

DIII-D



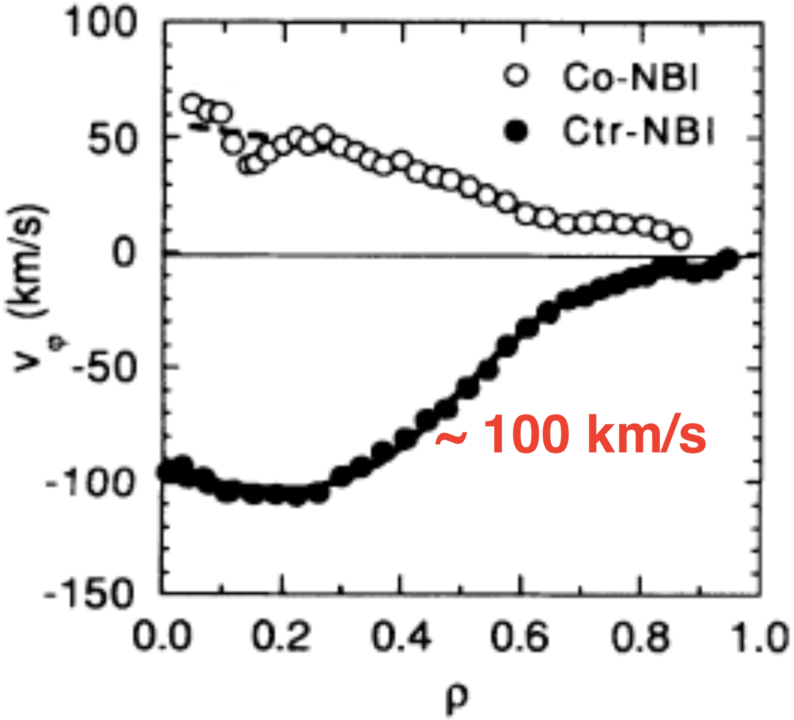
D. K. Gupta et al., PRL **97** 125002 (2006)

Zonal flow fraction appears to be large in tokamaks

Comparison in Flow Damping Rate

Comparison between Flow Damping Rate in Tokamak and Stellarators

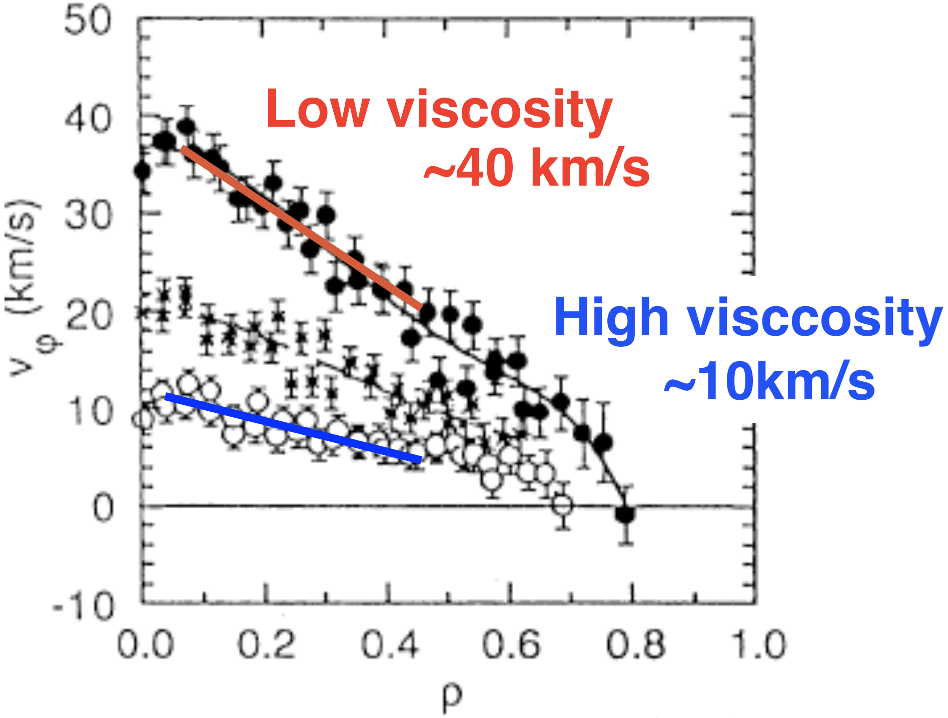
JFT-2M (tokamak)



~ 100 km/s

K. Ida et al., Phys. Rev. Lett. **68** 182 (1992)

CHS (heliotron)



Low viscosity
~40 km/s

High visccosity
~10km/s

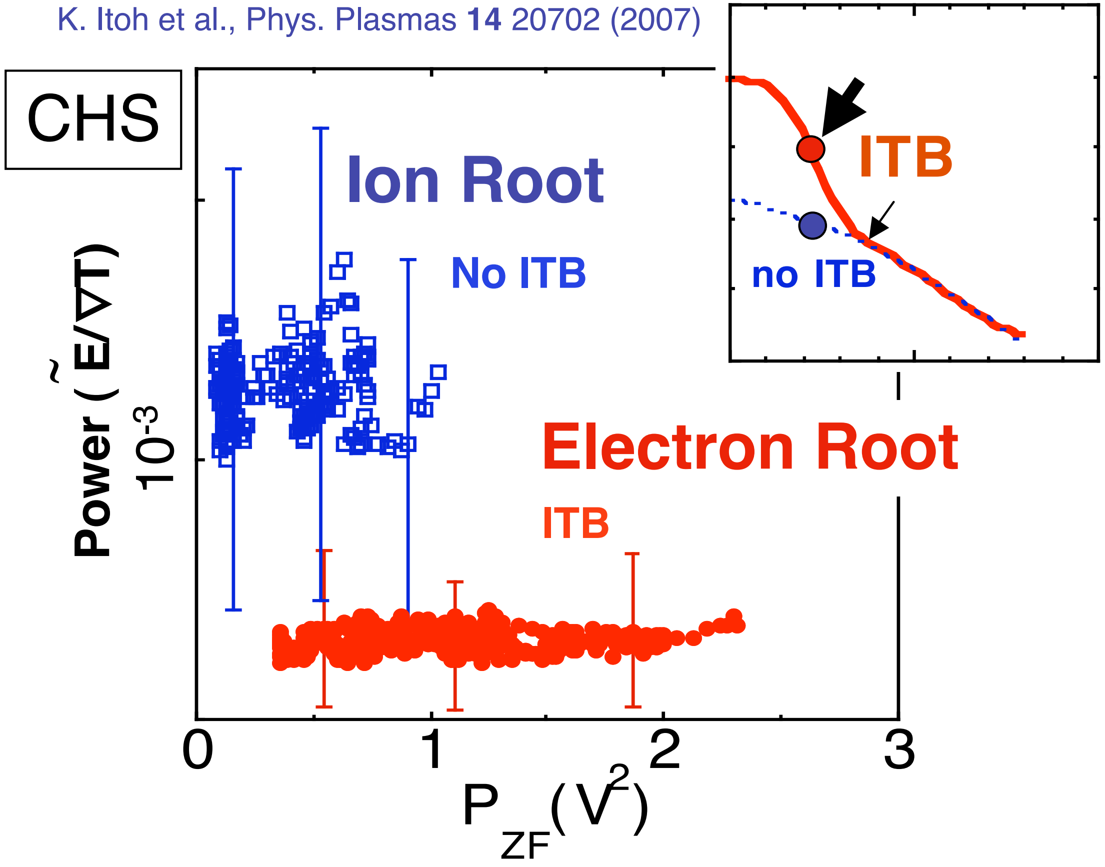
K. Ida et al., Phys. Rev. Lett. **67** 58(1991)

Inhomogeneity of configuration (or parallel viscosity) damps the plasma flow.

Confinement & Flow Damping Rate

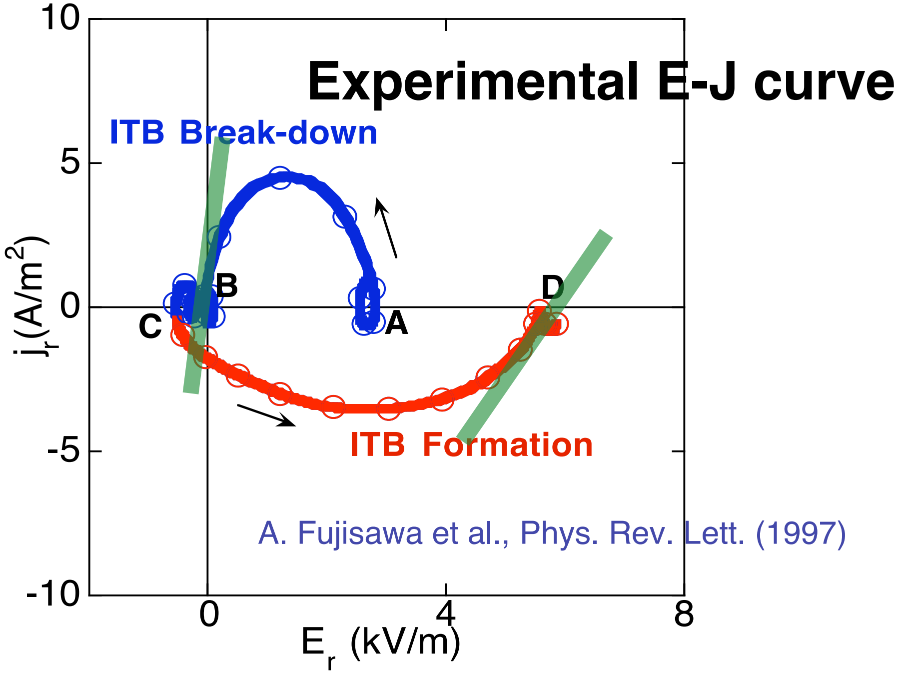
The low damping rate enhances the zonal flow fraction & confinement.

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



effective viscosity

$$\delta\tilde{j}_{turb} + \left(\frac{\partial j}{\partial E_r}\right)\delta\tilde{E}_r = 0$$



A. Fujisawa et al., Phys. Rev. Lett. (1997)

Parallel viscosity + magnetic well & shear

New concept to optimize configuration in turbulent transport

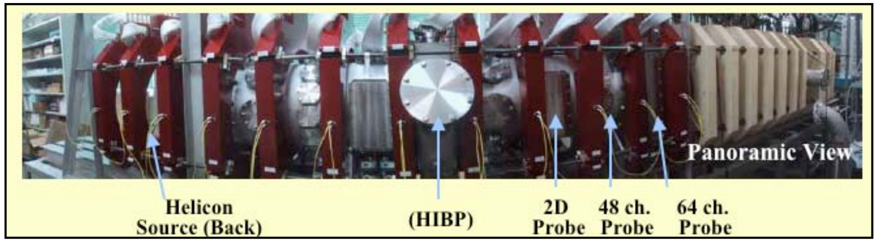
Beyond Simple Comparison

- *Roles of Low Temperature Devices*

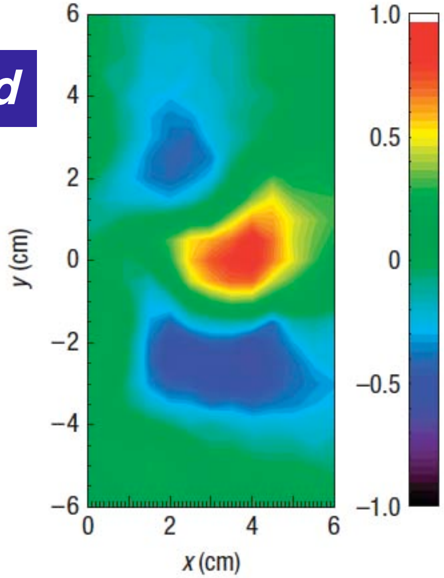
Experiments for Fundamental Processes

High accessibility and flexibility for physical experiments can be realized in low temperature plasmas

LMD-U



Streamer identified

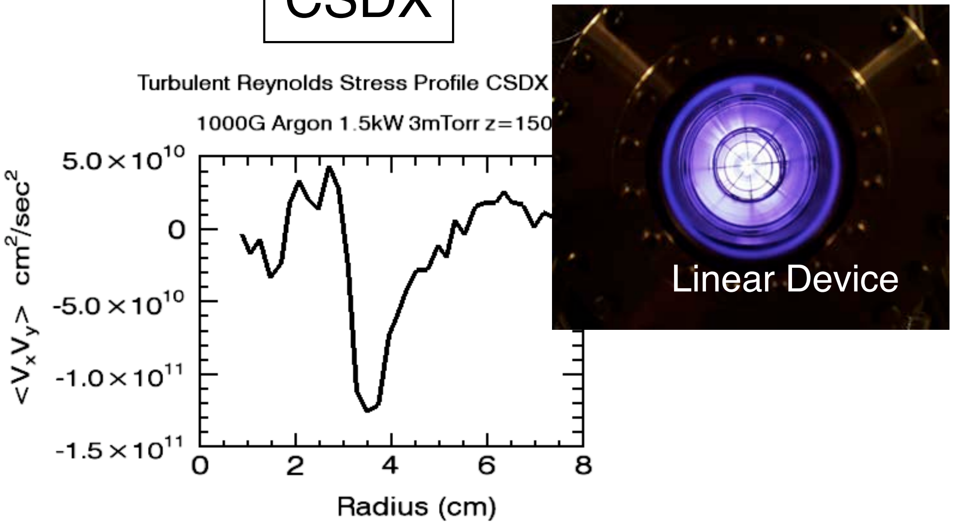


T. Yamada et al., Nature Phys. In press

Toroidal Plasmas

H1-Heliac, TJ-K, TU-Heliac, etc

CSDX



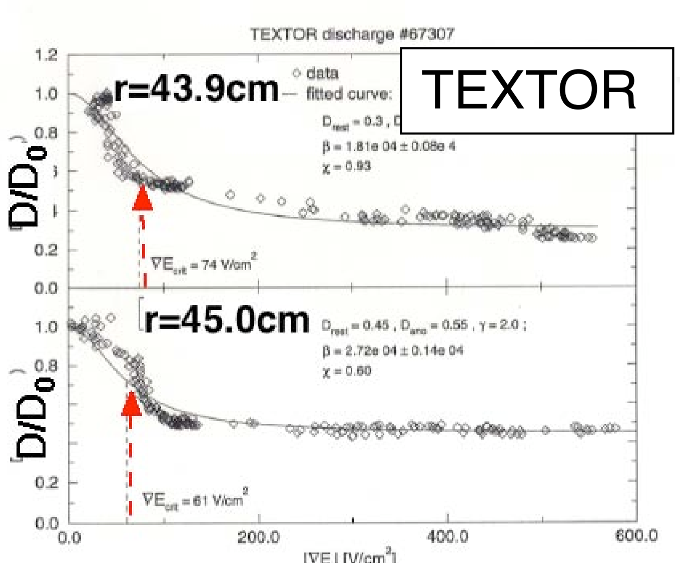
TRS for ZF Drive Confirmed

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

Roles of such devices are strengthen even in the era of burning.

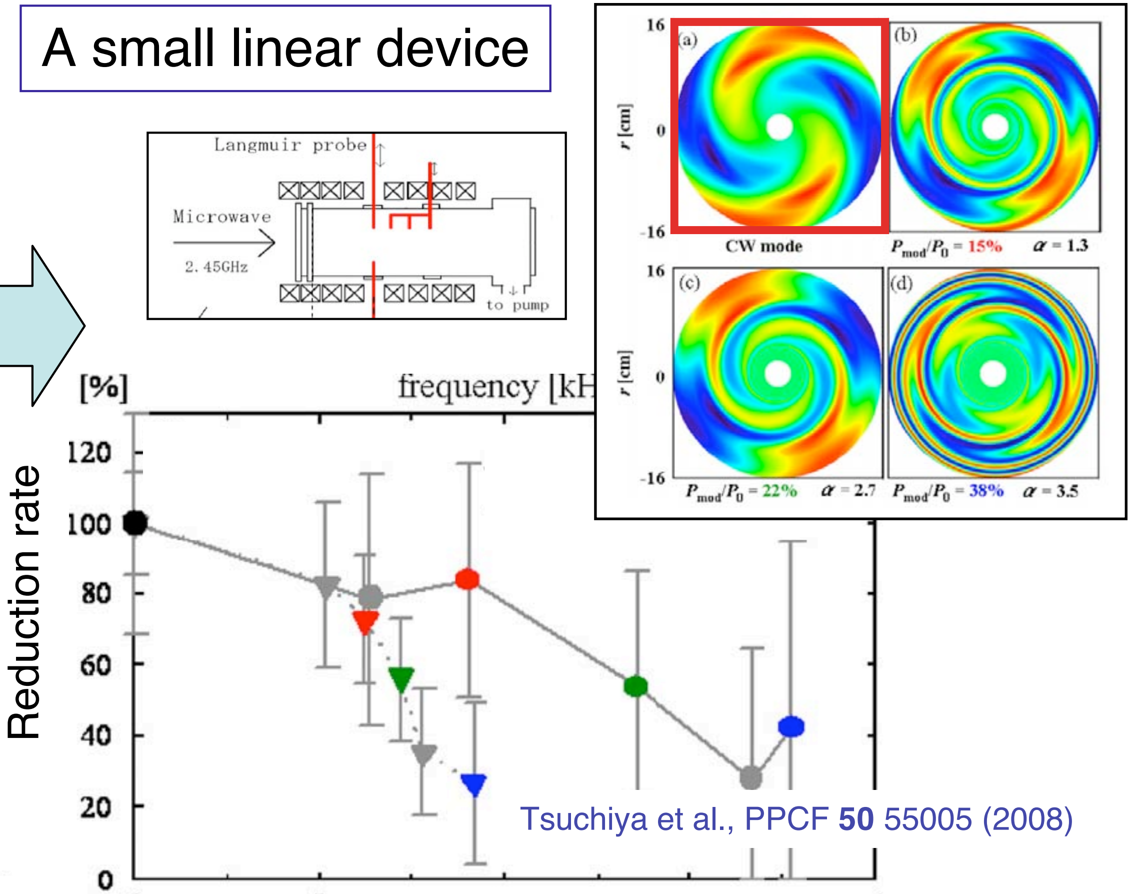
Controlled Shear Flow Experiments

A small university machine gives a deep insight into the turbulence shearing



Shear strength

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



Tsuchiya et al., PPCF **50** 55005 (2008)

Shear strength

Expression of turbulence shearing

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

Cheap, but these experiments give physical confidence

Summary

1. Stellarators are advantageous in steady state operation and high density limit.

2. Neoclassical transport of stellarators could be larger, however, it is the cause to create the transport barrier simultaneously.

3. Turbulence transport should be affected by the flow damping rate. Parallel viscosity or magnetic field inhomogeneity gives a new concept to optimize the magnetic field configuration in terms of turbulent transport.

4. The understanding from the first principle is essentially necessary. The roles of low temperature devices are emphasized for the confinement studies of toroidal plasmas.