An experimentalist´s view of transport of plasma rotation in magnetically confined plasmas

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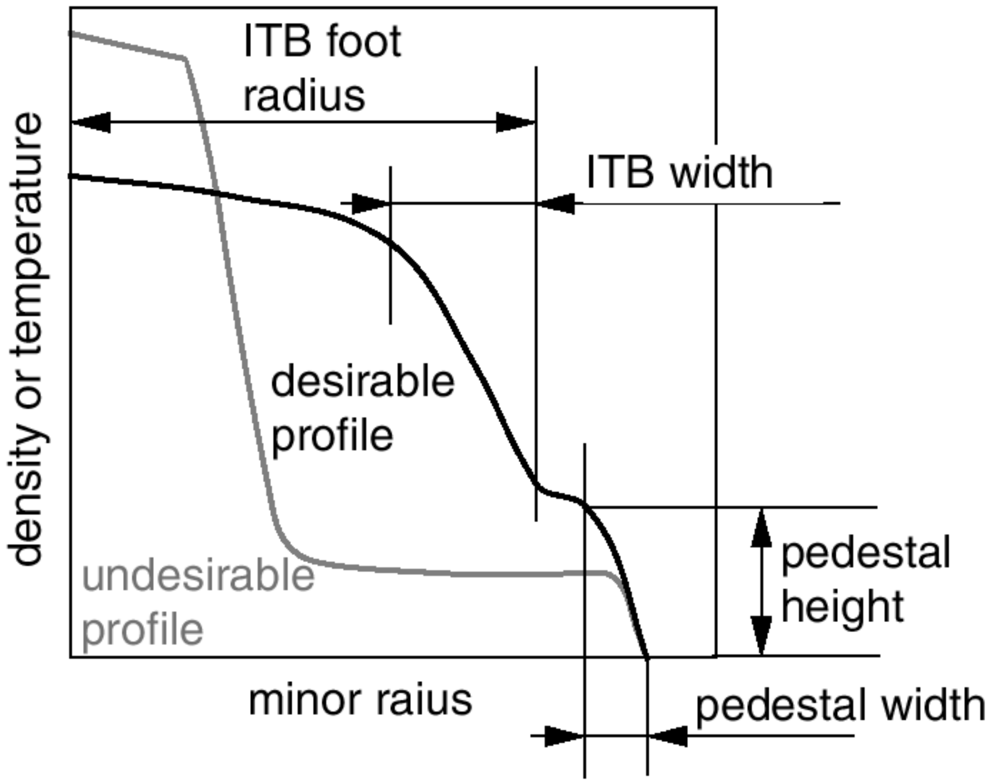
Internal and edge barriers



ITER relevant questions:

- **Spatial structure of ITB**: trigger, reactor relevant conditions ($T_e \approx T_i$).
- **Spatial structure of ETB**: trigger, scaling on pedestal height and width
- **Compatibility and linkage between ITB and ETB**: Softening or eliminating the ELM activities.

Transport barriers and momentum physics:

an important issue for ITER physics

Transport barriers and edge instabilities

JET

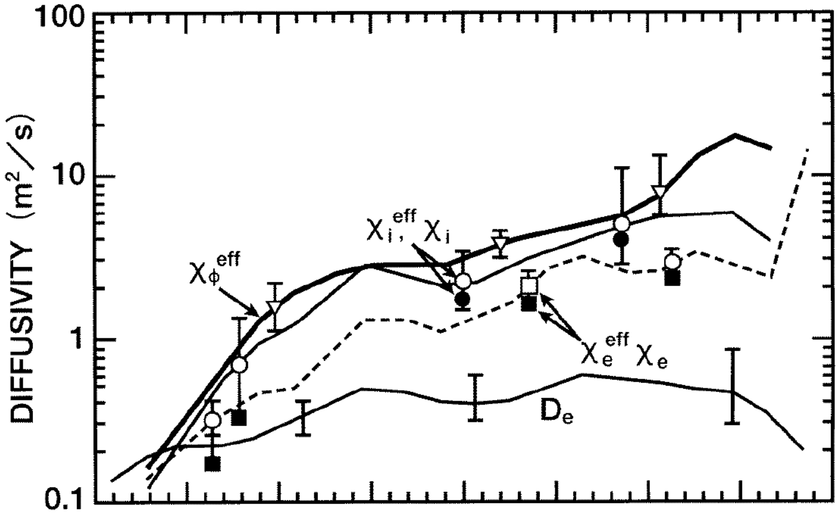
Recent fast camera studies has proven to provide useful information to study different fusion plasma relevant issues including plasma wall interaction, ELMs and disruption physics in JET.

Experimental findings show the expulsion of macroscopic particles from the wall after the occurrence of an ELM. Particles are observed to come out of an outer wall poloidal limiter and seem to be accelerated in the toroidal co-current direction.

These particles can be seen during 50 ms. ELMs are commonly seen in the images as a sudden increase of the light intensity.

A. Alonso et al., EPS-2007

Momentum transport vs energy transport



$$\chi_{\Phi}^{eff} \approx \chi_i^{eff} \approx 5\,D$$

Momentum confinement was reported to have a similar parameter dependence to that of the energy confinement time (S.D. Scott et al., PRL 1990).

Toroidal momentum transport: we should consider experimental modelling of momentum taking into account momentum pinch $[\chi_{\phi,eff} = \chi_{\phi} + L_u v_{pinch}]$

$$\chi_{\phi} / \chi_i \approx 1 \qquad v_{pinch} \approx 15\, m/s$$

(JET, Tala et al., EPS-2007)

Outline

- Key element of transport barriers
  - Role of ExB drifts and magnetic topology
- Development of plasma diagnostics: new physics
  - Electric field and Plasma rotation
- Mechanisms to drive rotation and Damping physics
  - Neoclassical and Anomalous
  - Experimental results
- Rotation and magnetic topology
  - SOL flows and L-H transition
  - Influence of magnetic ripple
- Rotation in ITER
- Conclusions

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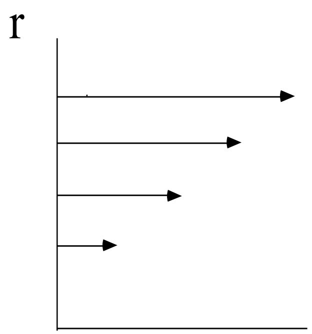
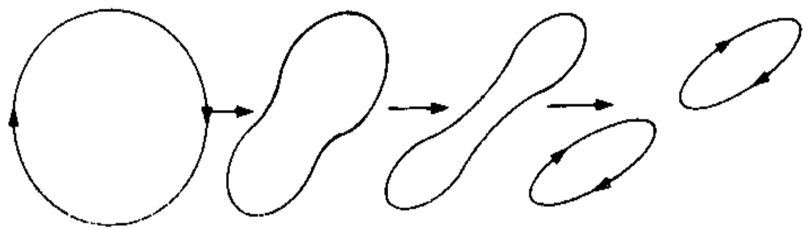
Sheared flows and turbulence

How to control transport and turbulence?

$$D \approx (L_r)^2 / \tau$$





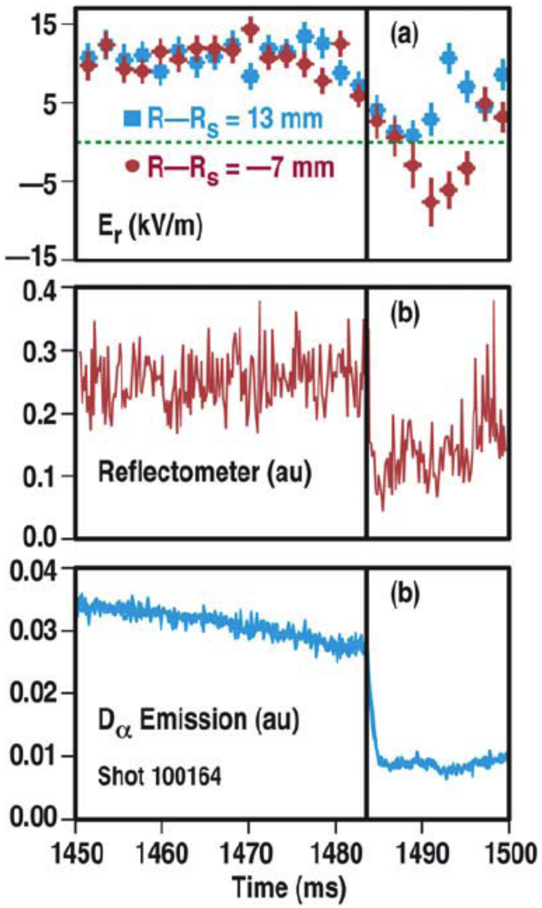
V = E / B

Decorrelation time due to sheared ExB flows < Decorrelation time of ambient turbulence

Radial force balance equation
(for any plasma species):

$$E_r = v_{\phi,i} B_\theta - v_{\theta,i} B_\phi + \frac{1}{Z_i e n_i} \nabla p_i$$

Transport barriers: electric fields and fluctuations

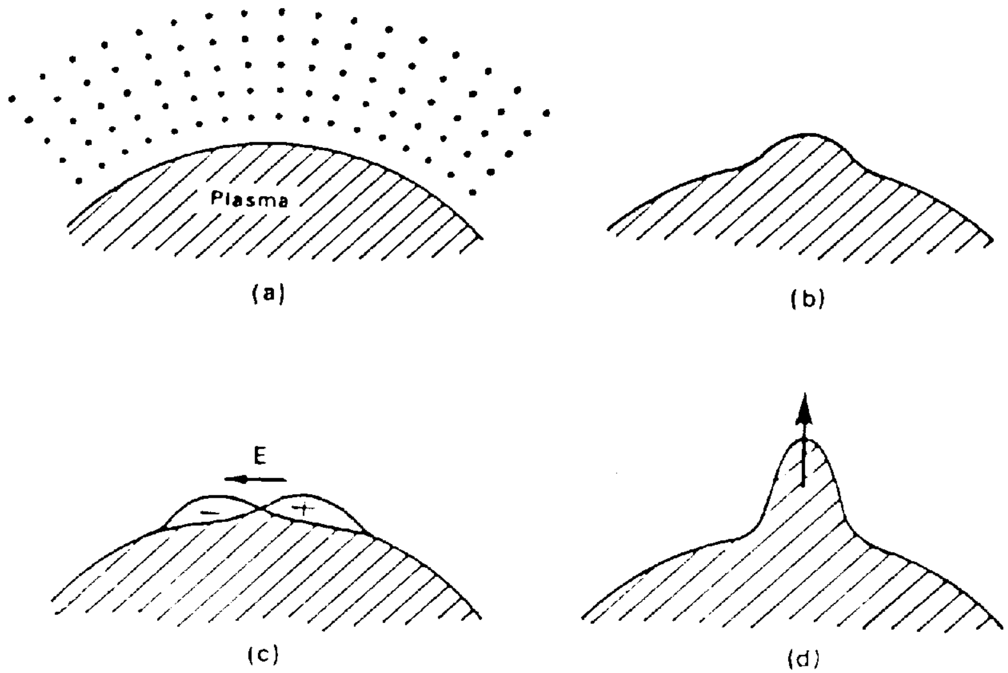


Temporal evolution of edge quantities during the development of ETB in D-III-D (Burrell et al.,)

Radial force balance equation (for any plasma species):

$$E_r = v_{\phi,i} B_\theta - v_{\theta,i} B_\phi + \frac{1}{Z_i e n_i} \nabla p_i$$

Non-uniform magnetic field, instabilities and flows



Plasma instability ("interchange instability") can develop in the plasma edge region in the presence of a magnetic field which comes out of the page and decreases with the distance to the plasma boundary (Fig.a).

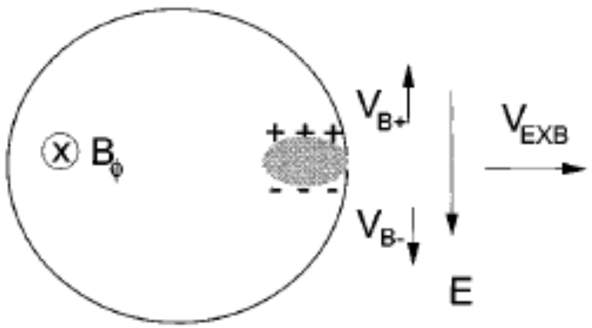
In Fig. b, the plasma has developed a sight hump; the ions and electrons drift in opposite directions under the influence of the inhomogeneous magnetic field resulting in an electric field (Fig. c). Under the combined influence of this electric field and the magnetic field the small bump will tend to grow creating an unstable situation in the plasma region in which the magnetic field intensity decreases as one moves radially out of the plasma boundary region.

As a consequence of this mechanism, strong poloidal asymmetries are expected in the amplitude of fluctuations and turbulent transport, the maximum corresponding to those regions where the magnetic field intensity decreases as one moves away from the plasma.

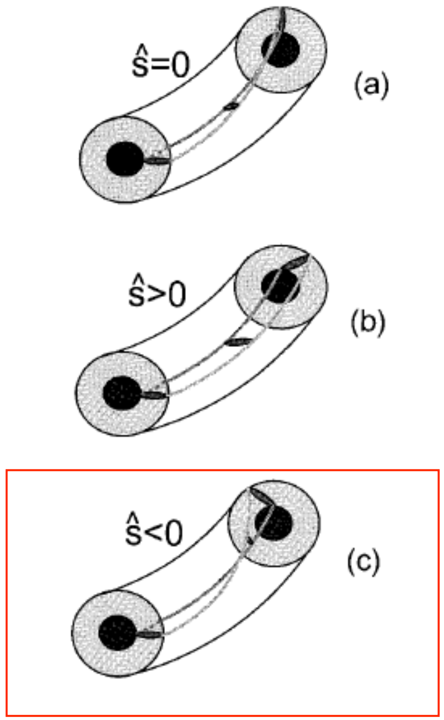
Poloidal asymmetries in turbulent transport can drive flows in the plasma boundary region.

Magnetic topology, transport and rotation

1) Magnetic shear



T. M. Antonsen et al., Phys. Plasmas 3 (1996) 2221



$\hat{s} = q' r / q$

2) Rational surfaces (rotation, transport barriers, instabilities,…)

3) Magnetic ripple (rotation, confinement, ELMs,….)

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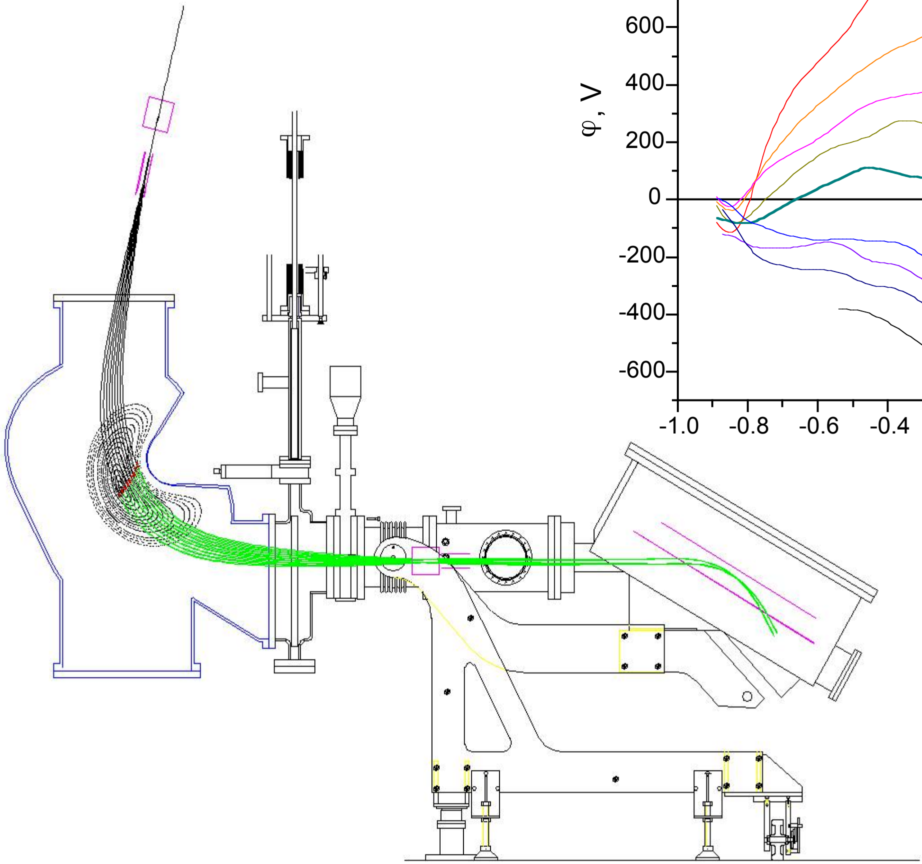
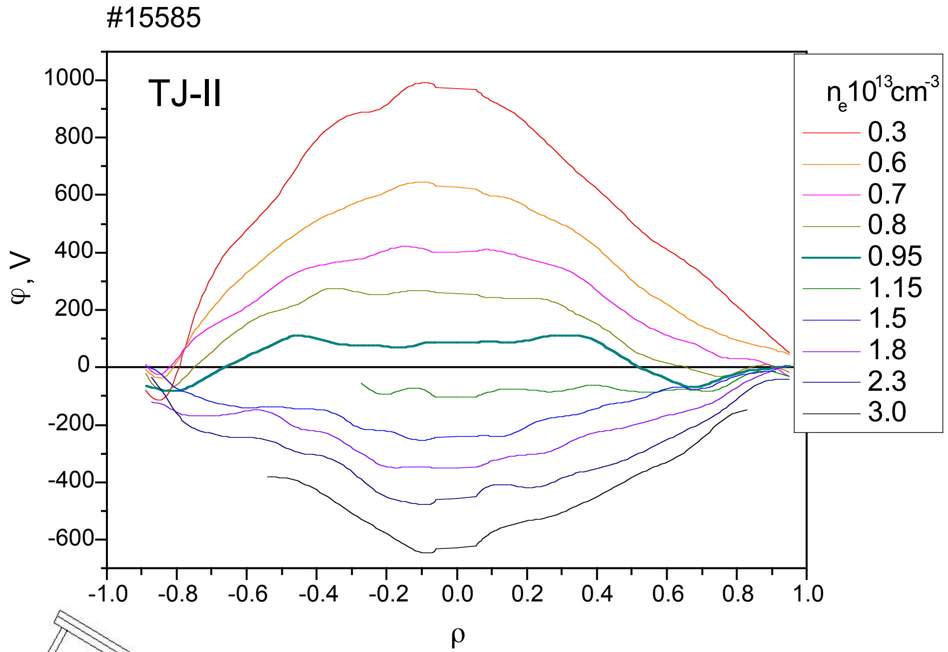
Measurement of electric fields: HIBP

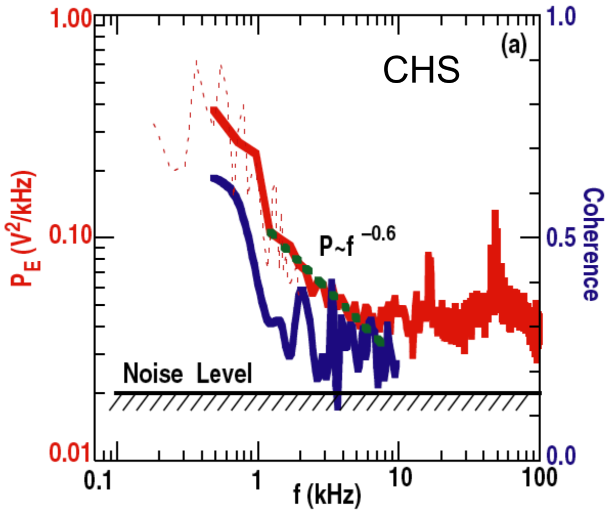




$$Cs^{1+} + e \rightarrow Cs^{2+}$$

$$\Delta E = e\Phi$$

Improving diagnostics: trigger of new physics



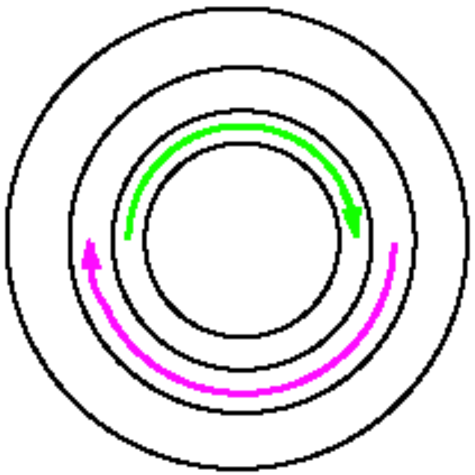
Fujisawa et al., Phys. Rev. Lett 93 (2004) 165002)

Using a unique experimental set-up (two HIBP systems separated toroidally 90 degrees in the CHS stellarator, it has been shown that:

1) The electric field fluctuation f < 10 kHz shows long-range crrelation and reflects the activity of low frequency oscillations.

2) Low frequency fluctuations has a phase shift close to zero.

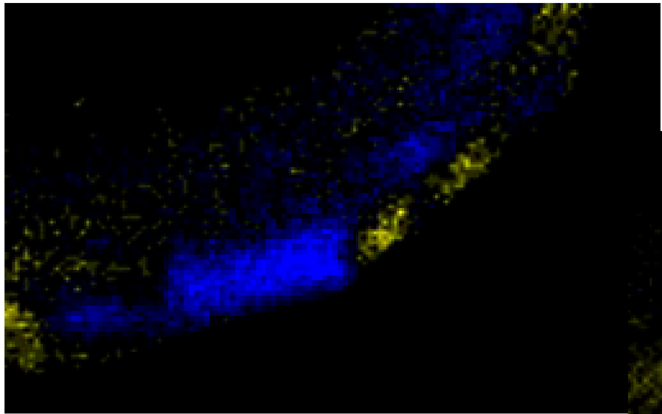
These results are consistent with zonal flows with n=0 and m = 0, providing the most clear evidence of zonal flows in fusion plasmas.



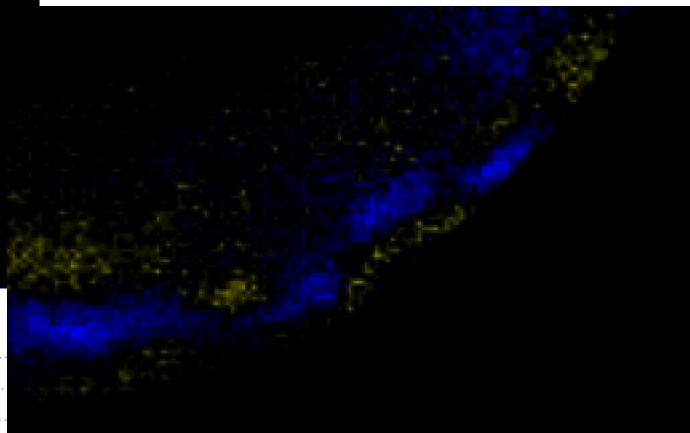
Zonal flows (stable modes driven by turbulence that regulate turbulent transport by shearing apart the turbulent eddies) is an important ingredient of transport in fusuion plasmas.

Flows can be 2-D visualized with fast cameras: they are developed in a time scale of tens of μs

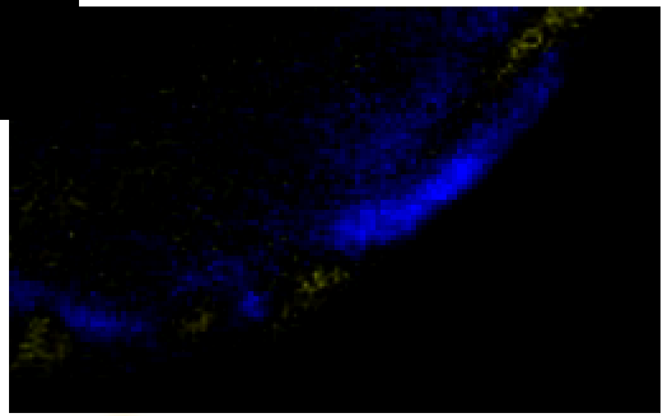
$n < n_{th}$



$n \approx n_{th}$

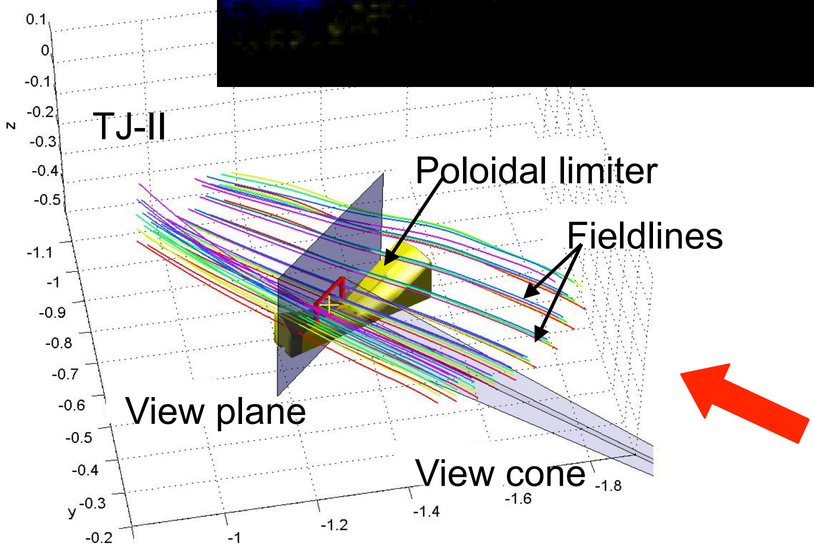


$n > n_{th}$



Alonso et al.,

PPCF-2006



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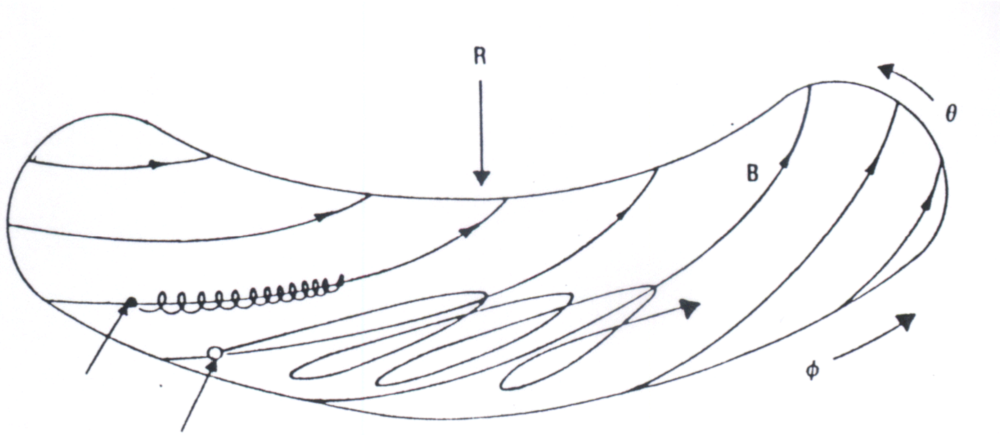
Particle orbits, collisionality and rotation

$\mu =$ *magnetic moment of a gyrating particle*

$IA: \quad I = q\omega_c / 2\pi, \quad A = \pi r_L^2 = \pi v_\perp^2 / \omega_c^2$

$\text{Then} \quad \mu = \frac{m v_\perp^2}{2B} = \frac{W_\perp}{B}$

$$d\mu / dt = 0$$

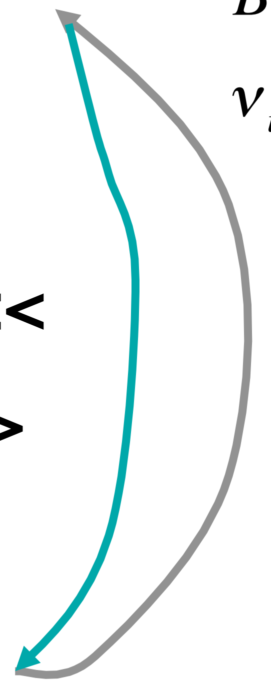


Banana orbit

$\nu_{ii} \propto T_i^{-3/2}$

$\nu_{ii} <<$

$T_i >>$

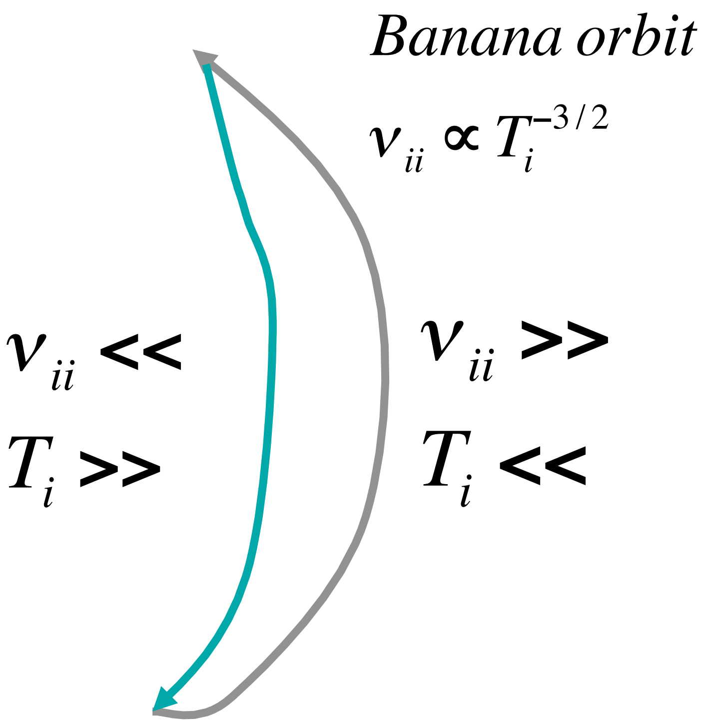


$\nu_{ii} >>$

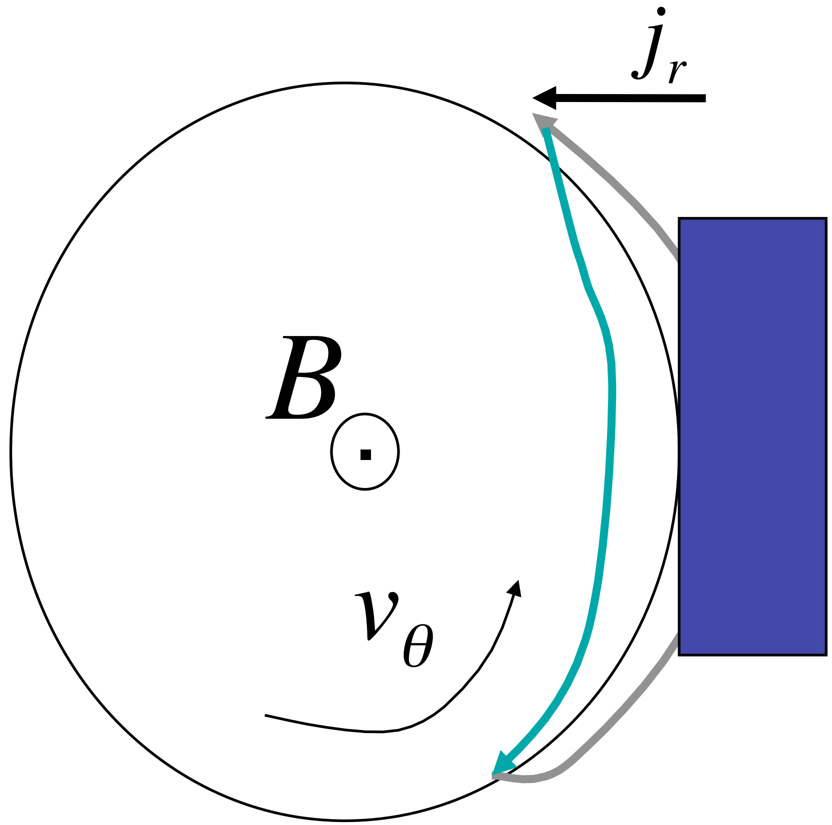
$T_i <<$

$$v_\theta \propto \frac{d T_i}{d r}$$

Particle orbits, collisionality and rotation



$$v_\theta \propto \frac{dT_i}{dr}$$



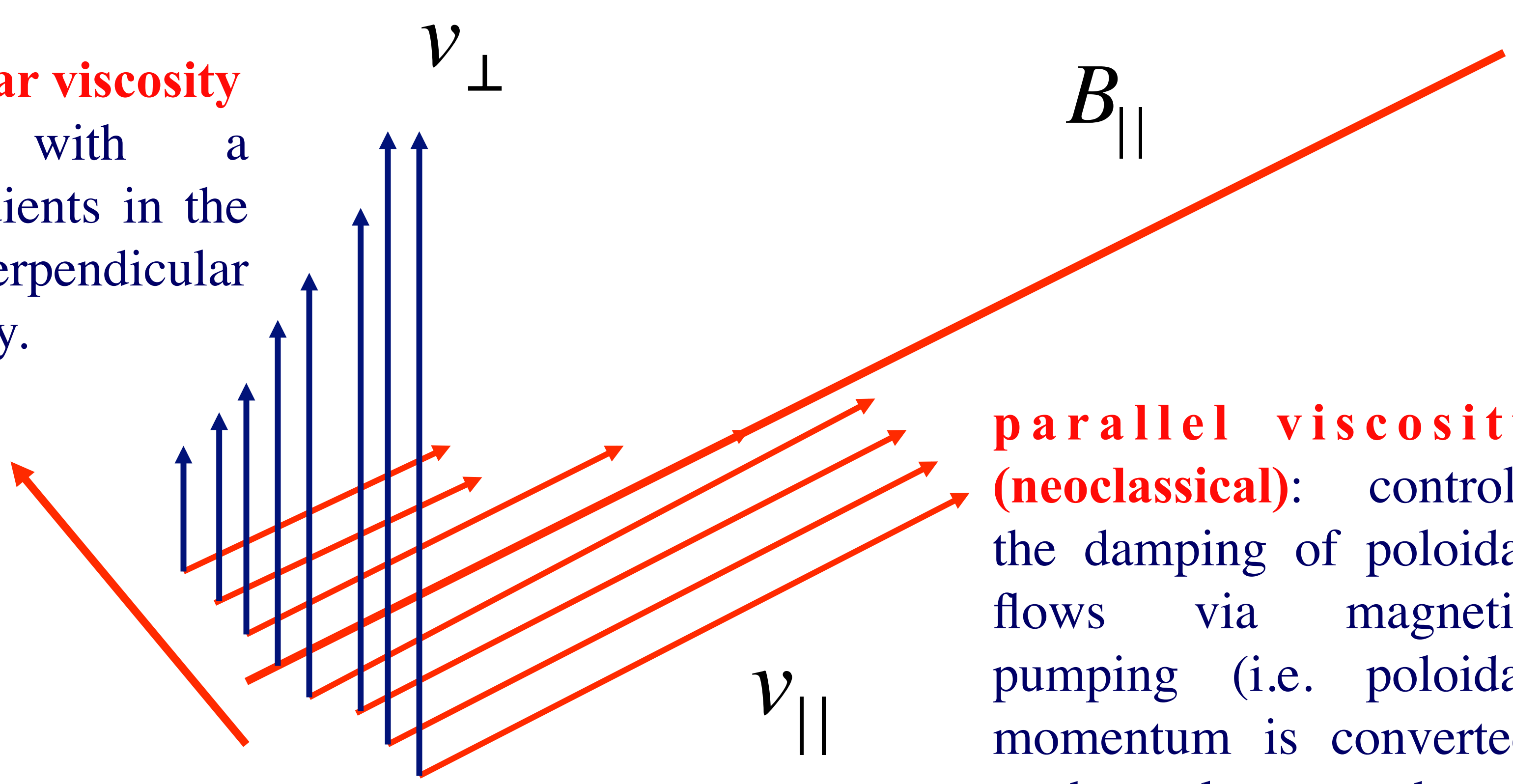
Poloidal rotation due to the losses of ions interacting with thelimiter

Steady state

Drive = damping

Viscosity and magnetic traps

Perpendicular viscosity associated with a velocity gradients in the direction perpendicular to the velocity.



parallel viscosity (neoclassical): controls the damping of poloidal flows via magnetic pumping (i.e. poloidal momentum is converted to thermal energy due to the change in the magnetic field strength).

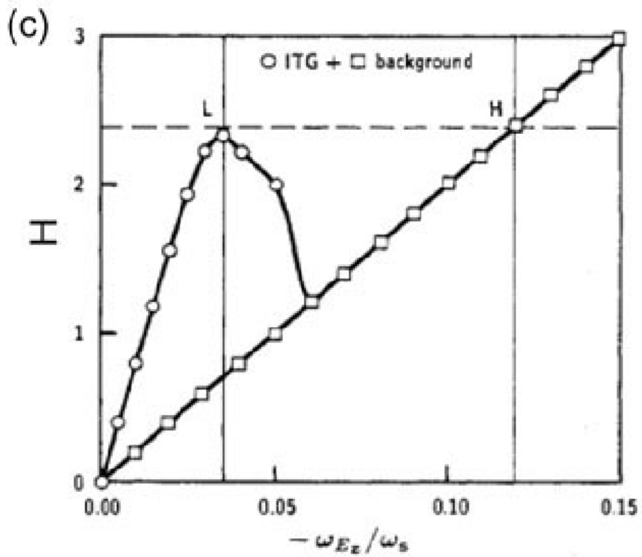
Read paper:

Physics of magnetic pumping

Hassam et al., Phys Fluids 12 (1978) 21

Role of viscosity on L-H transition

F. Wagner et al., Phys of Plasmas 12 (2005) 072509



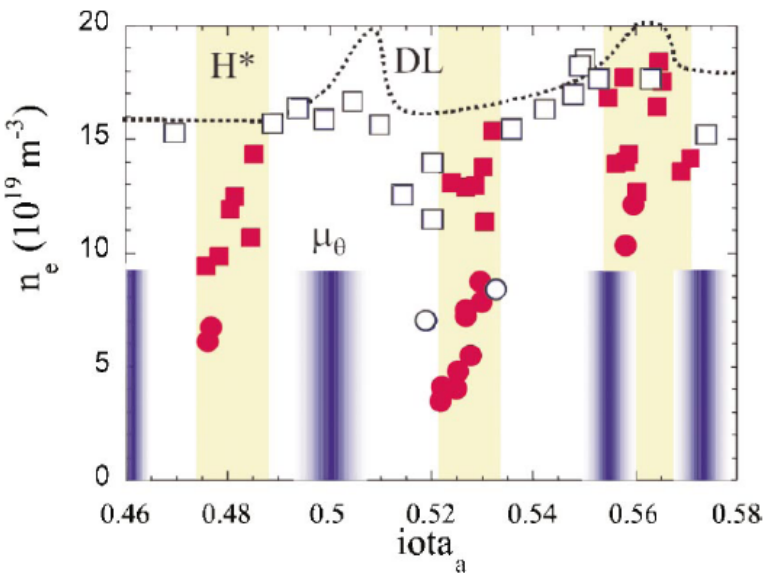


FIG. 24. (Color). $n_e - \iota(a)$ operational H-mode range. The symbols discriminate between L- (open) and H-mode (closed) plasmas. The dashed curve shows the expected density limit for 0.4 MW NBI (the variation with ι originates from the variation of a_{eff}, causing the power density, which is a scaling parameter, to vary). The zones of large poloidal flow damping are also indicated (bars, denoted by μ_Θ).

The existence of a maximum in the turbulent viscosity of ITG modes can play a role in the bifurcation theory of the H-mode.

Staebler et al., NF 1993

Does the relaxation time of flows depend on magnetic configuration ?

An approach to measure viscosity

Evolution of radial electric and plasma flows in plasmas subject to fast transients

What is the characteristic time to reach steady-state?

- Experiments supporting the role of magnetic viscosity (magnetic ripple)

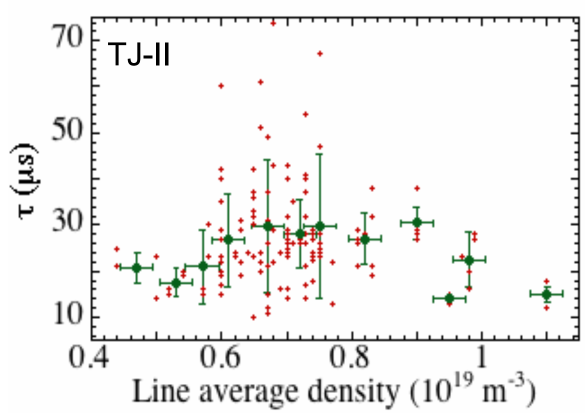
$\tau \quad \approx \mu_{MP}{}^{-1}$

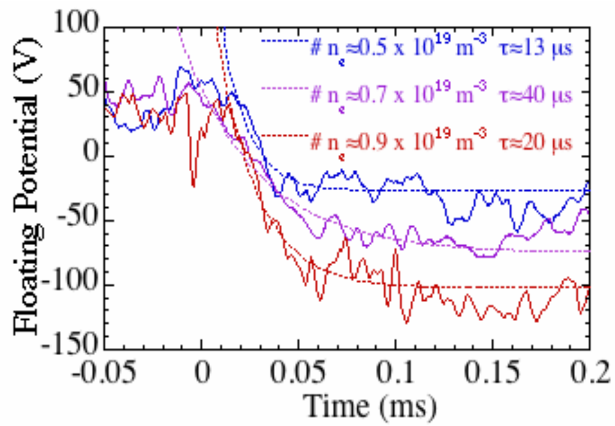
- Experiments supporting the role of turbulence

$\tau \approx \tau_{\text{correlation}}$

- Experiments supporting the role of CX (neutrals)

$\tau \approx <\sigma_{\chi\xi}\, \varpi_{\iota}> \nu_{\nu}>^{-1}$





M.A. Pedrosa et al., EPS-2007

Comparisons of time scales decay

Experimental findings show strong similarity in the decay time of plasma potential and radial electric fields in the plasma boundary of stellarator and tokamak plasmas (M.A. Pedrosa et al., EPS-2007).

DEVICE	TJ-II Stellarator	CASTOR Tokamak	HSX[1] Stellarator
Major radius (m)	**1.5**	**0.4**	**1.2**
Magnetic field (T)	**1**	**1**	**0.5**
Line Average Density (m^{-3})	**(0.4 - 1) x 10^{19}**	**1 x 10^{18}**	**0.5 x 10^{18}**
Relaxation time (µs)	**10 - 50**	**10 - 30**	**15 - 50**

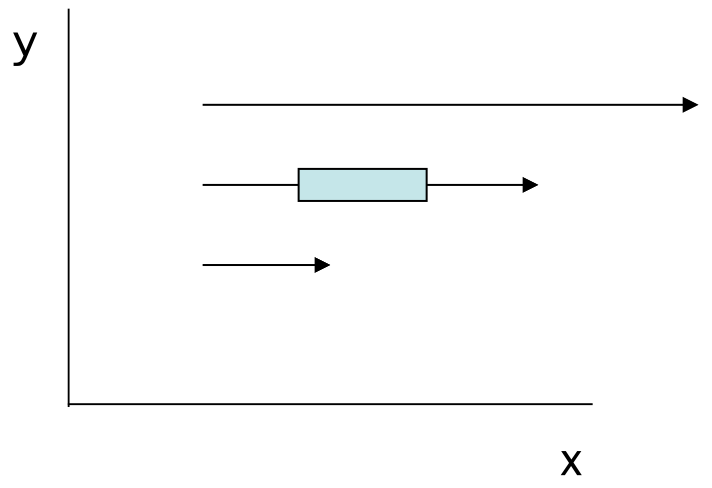
This result can help to quantify the importance of anomalous versus neoclassical mechanisms on the damping physics of radial electric fields and flows in fusion plasmas.

(1) S.P. Gerhardt, J.N. Talmadge, et al., Phys. Rev. Lett. 94 (2005) 015002

Positive viscosity

The resistance of fluids to shearing motion is a well known observation. The tendency of sheared motion to be reduced with the passage of time, if no other forces are at work to maintain it, leads to the concept of (positive) coefficient of viscosity

$$\tau = \mu \frac{\partial u}{\partial y}$$



The momentum flux is directed from regions of larger values of mean flow toward regions of smaller values.

Negative viscosity

The eddy momentum flux is directed from regions of smaller values of mean flow toward regions of larger values.

This effect has a direct impact in the development of differential rotation

The subject of negative eddy viscosity has its origins from the calculation of Reynolds stresses from observed data mainly concerning earth's atmosphere.

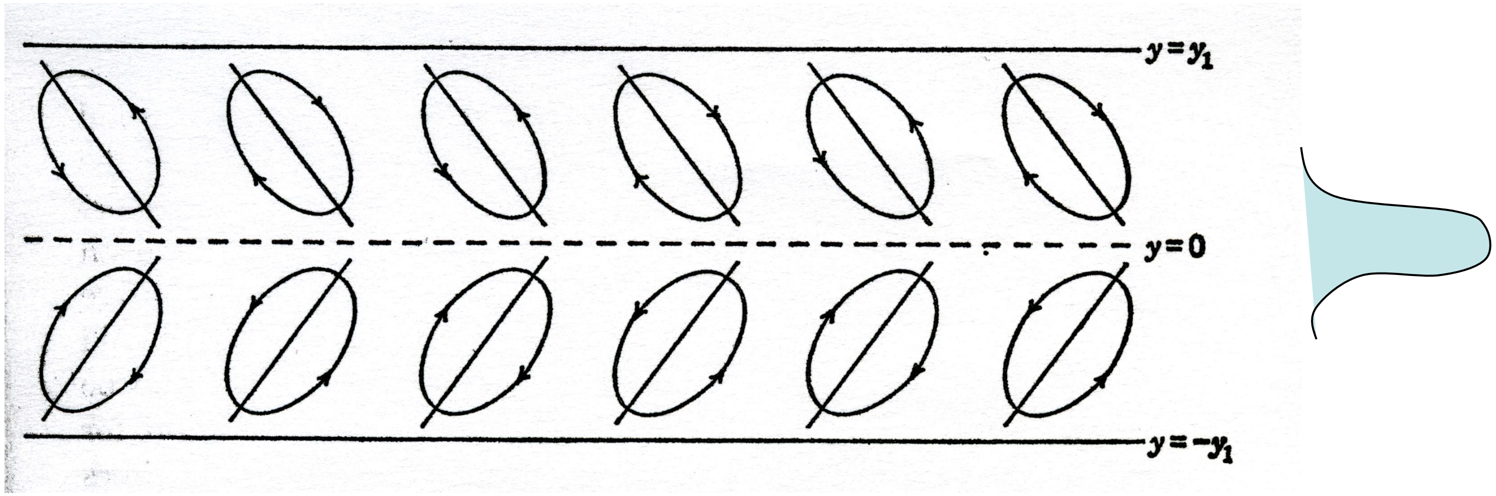
Physics of negative viscosity phenomena

(with applications to earth and solar atmospheres, spiral galaxies, oceanic circulations)

V. P. Starr , Earth and planetary science series, McGraw-Hill (1968).

Negative viscosity: geometrical interpretation

Flow having a momentum transport into the central portion of the channel.



The essential features are the elliptical circulations and the systematic tilts of their major axes.

Negative viscosity physics

Key ingredients:

•The eddies which transport momentum contrary to the gradient of mean flow must have a supply of eddy kinetic energy.

•Eddy tilting (symmetry breaking)

•Turbulent "irregulaties"

•The mean flow must be subject to some form of braking action so as not to increase without limit (e.g. positive viscosity). But, also this braking should be low enough to allow flow development.

Sustained negative viscosity effects are to be found in systems with great complexity (especially where eddy forcing takes place from the outside):

atmosphere, galaxies, starts,……fusion plasmas

Physics of negative viscosity

Poloidal

Turbulent anisotropy (Eddy tilting)

$$\boxed{\frac{\partial \left\langle \tilde{v}_r \, \tilde{v}_\theta \right\rangle}{\partial r} = \mu V_\theta}$$

DC rotation

Positive viscosity
(e.g. Neoclasical,…)

Turbulent irregularities

Parallel

$$\boxed{\frac{\partial < \tilde{v}_r \, \tilde{M}_{||} >}{\partial r} \approx \mu \, \Delta M_{||}}$$

See. Diamond, Itoh, Hahm, PPCF 2005

Quantifying the link between global flows and turbulence: **energy transfer**

DC flows ⟷ **Energy Transfer** ⟷ **turbulence**

Equations for the mean flow (E) and turbulence (k) kinetic energy evolution

$$\left.\begin{aligned} \frac{dE}{dt} + \nabla \bar{T} &= -P - \bar{\varepsilon} \\ \frac{dk}{dt} + \nabla T' &= P - \varepsilon \end{aligned}\right\}$$

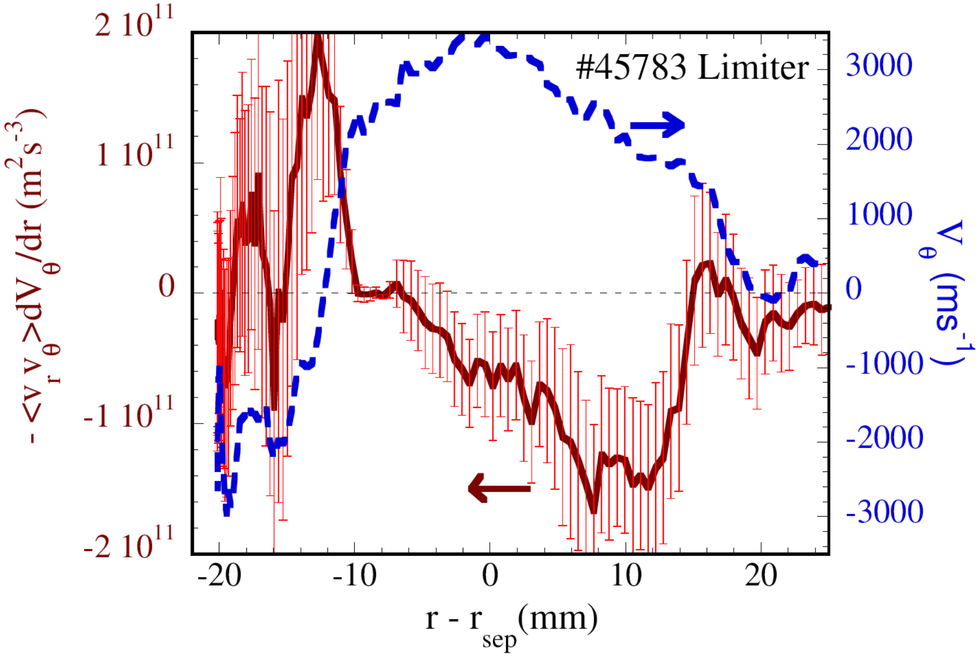
McComb

The Physics of Fluid Turbulence(Oxford University Press 1990)

$$P \equiv -\langle v_i v_j \rangle \frac{\partial \langle V_i \rangle}{\partial x_j}$$

There are four terms in the k equation: the mean flow convection (dk/dt), the turbulent transport, the dissipation (ε) and the production (P). The production term (P) appears with different sign both in the mean-kinetic-energy equation and turbulent-kinetic-energy equation

Energy transfer in tokamaks (JET)



$$P \approx -\langle v_\perp v_r \rangle \frac{\partial V_\perp}{\partial r}$$

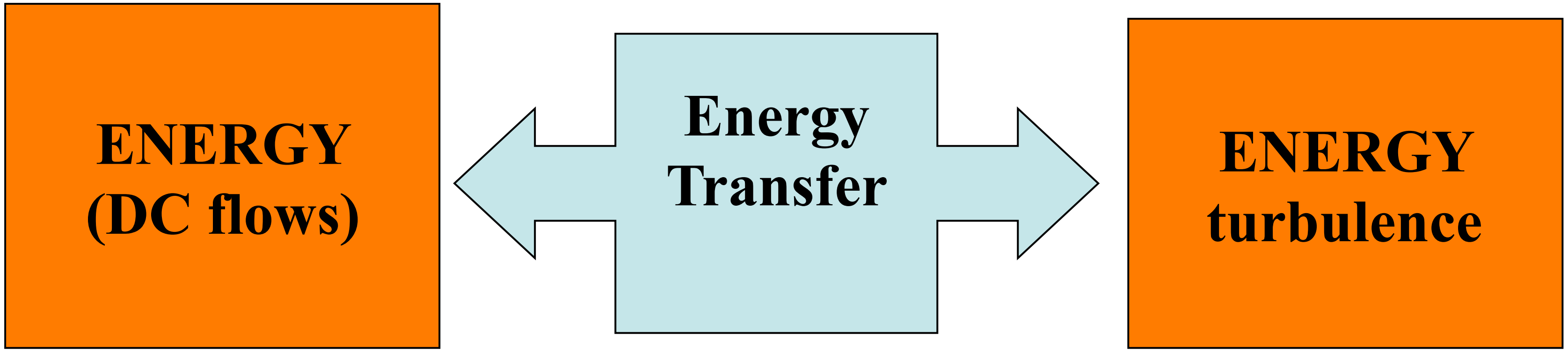
It has been found that the energy transfer from DC flows to turbulence can be both positive and negative in the proximity of sheared flows.

Furthermore, the energy transfer rate is comparable with the mean flow kinetic energy normalized to the correlation time of turbulence, implying that this energy transfer is significant.

These results show that turbulence can act as an energy sink and energy source for the mean flow near the shear layer, emphasizing the important role of turbulence to understand perpendicular dynamics.

E. Sánchez et al., J. of Nuclear Materials 337 (2005) 296.

2-D or 3-D physics ?

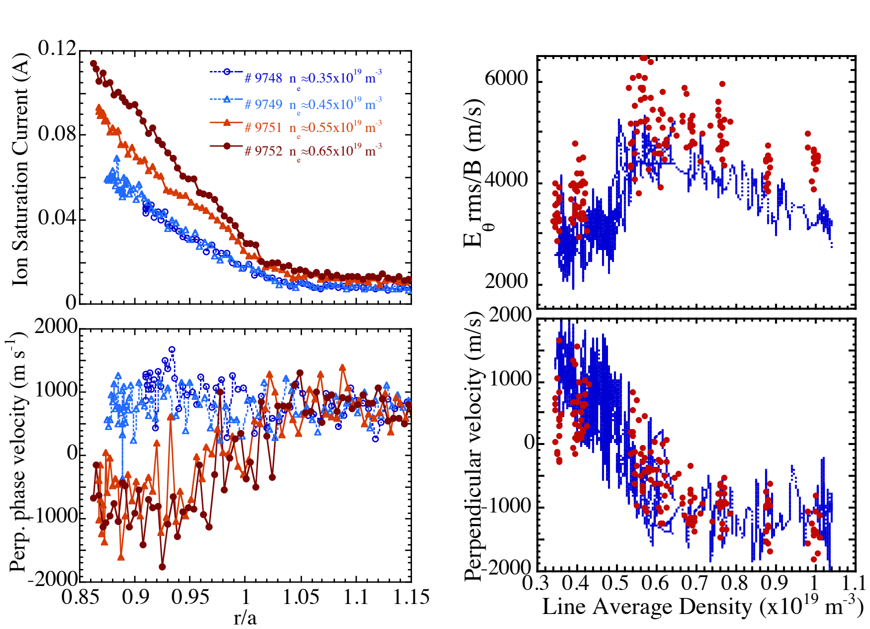


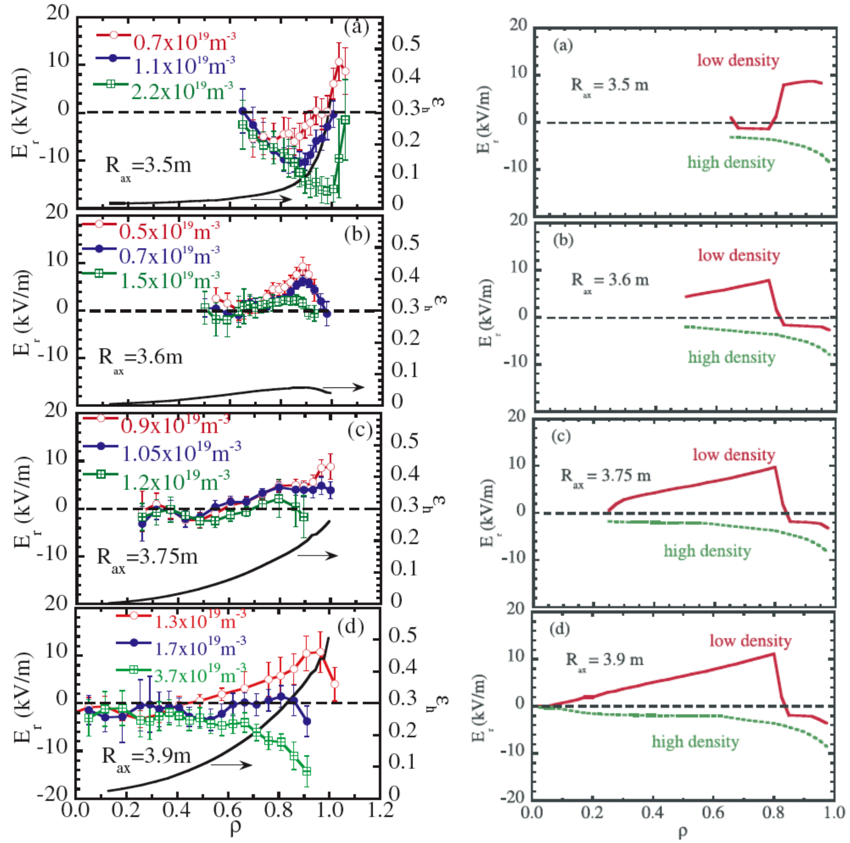
2-D $$P \approx -< v_{\perp} v_r > \frac{\partial V_{\perp}}{\partial r}$$

3-D $$P \approx -< v_{\parallel} v_r > \frac{\partial V_{\parallel}}{\partial r} -< v_{\perp} v_r > \frac{\partial V_{\perp}}{\partial r}$$

B. Gonçalves, et al., Phys. Rev. Lett. 96 (2006) 145001

Why sheared flow development:
neoclassical and turbulent mechanisms ?





•There is a coupling between the onset of sheared flow development and the level of turbulence. Sheared flows and fluctuations in TJ-II appear to be organized near marginal stability. The universality of this property is easily understood assuming that edge sheared flows are controlled by turbulence.

C. Hidalgo et al., Phys Rev. E / M.A. Pedrosa et al., PPCF 2005

•TJ-II results are consistent with a second order phase transition model (negative viscosity)

B.A. Carreras et al., Phys. of Plasmas (2006)

In LHD the radial electric field can be controlled by the magnetic configuration (ripple). Results are consistent with NC calculations

K. Ida et al., Nuclear Fusion 2005

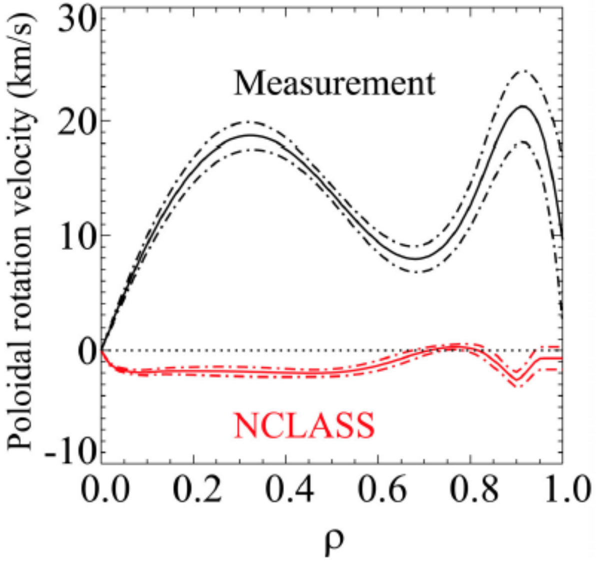
ANOMALOUS POLOIDAL PLASMA ROTATION IN DIII-D

V.M. Solomon et al PoP- June 2006

Neoclassical prediction from NCLASS is much smaller than observed experimentally

- Measured plasma profiles input into NCLASS
  - electron temperature, electron density, ion temperature, carbon impurity density, and (corrected) toroidal velocity for the discharge
- Again the profile is obtained by averaging the analysis over *t* =[3000-4000] ms.
- NCLASS prediction for C VI poloidal velocity smaller than measurement by an **order of magnitude**.
- Even disagreement in the direction of the rotation!
  - Interestingly, the neoclassical prediction for the deuterium poloidal velocity shows curious agreement with the carbon measurement, both in direction and magnitude.

DIII-D QH-mode



But agreement in some cases (TCABR)

Severo et al., Nuclear Fusion 43, 1047 (2003)

Anomalous toroidal momentum transport

Alcator C-mod [Lee et al., Phys. Rev. Lett. (2003) / J. Rice et al., Nuclear Fusion 44 (2004) 379

- **In Alcator C-mod, following the H-mode transition toroidal momentum (anomalous) is observed to propagate in from the plasma edge, although there is no external source**

  [Lee et al., Phys. Rev. Lett. 91 (2003) 205003].

- **This redistribution is clearly linked with an edge physics phenomenon**

  [J. Rice et al., Nuclear Fusion 44 (2004) 379]

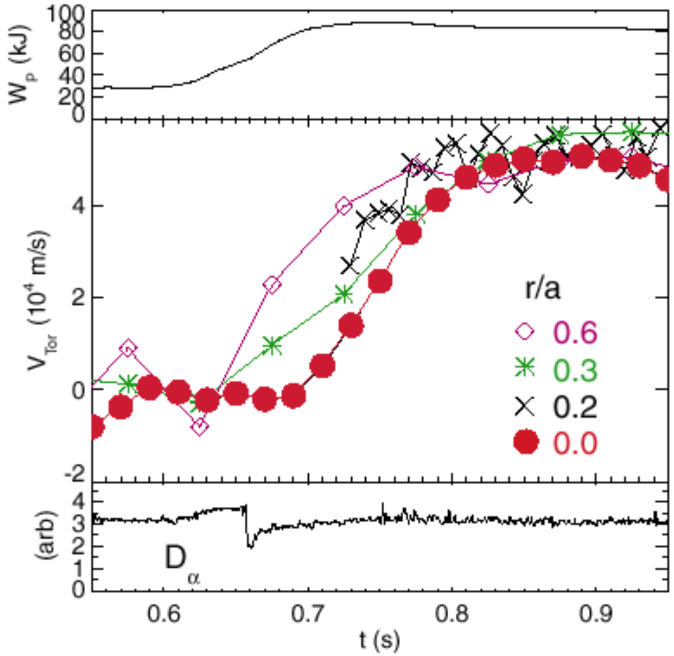


FIG. 1 (color). The plasma stored energy, impurity toroidal rotation velocity at three radii (red dots, green asterisks, and purple diamonds for $r/a = 0.0$, 0.3, and 0.6, respectively), magnetic perturbation rotation (×) at the sawtooth inversion radius ($r/a \sim 0.2$), and the edge D_α brightness for an ICRF heated EDA H-mode discharge.

Why edge momentum source?

Why anomalous toroidal rotation?

Fast particle effects and electric fields

- Spontaneos plasma rotation of near perpendicular NBI and Lower Hybrid current drive plasma in JT-60U [Koide et al., IAEA(1992)]
- The flow reversla in the CHS stellarator can be explained by the flow driven by large radial electric fields [K. Ida et al., PRL (2002)]
- Toroidal rotation, with symmetric ICRF spectra with no or very little momentum input, has been observed on many tokamaks, but its origin is not yet fully understood [L. Eriksson et al., (2003)]

Neoclassical effects

[Rogister et al., Nuclear Fusion 42 (2002) 1144]

However, experiments in Alcator C-mod show momentum diffusivities which are large compared with neo-classical diffisitivites [J. Rice et al., NF (2004)]

Turbulence driven mechanisms

[B. Coppi NF (2002), X. Garbet et al., Phys. Plasmas (2002), O. Gürcan et al., PoP-2007]

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- Conclusions

L-H power threshold values shows a parametric dependence with plasma density and magnetic field (tokamaks)

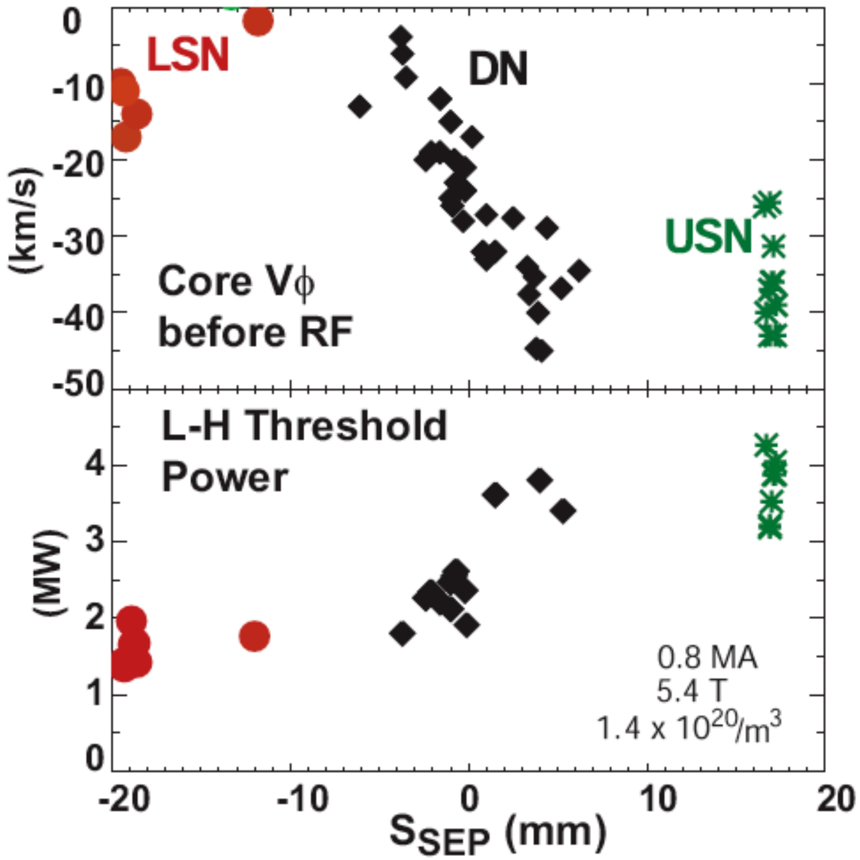
$$P_{th} \propto n^{\alpha} B^{\beta} \quad (\alpha \approx \beta \approx 1)$$

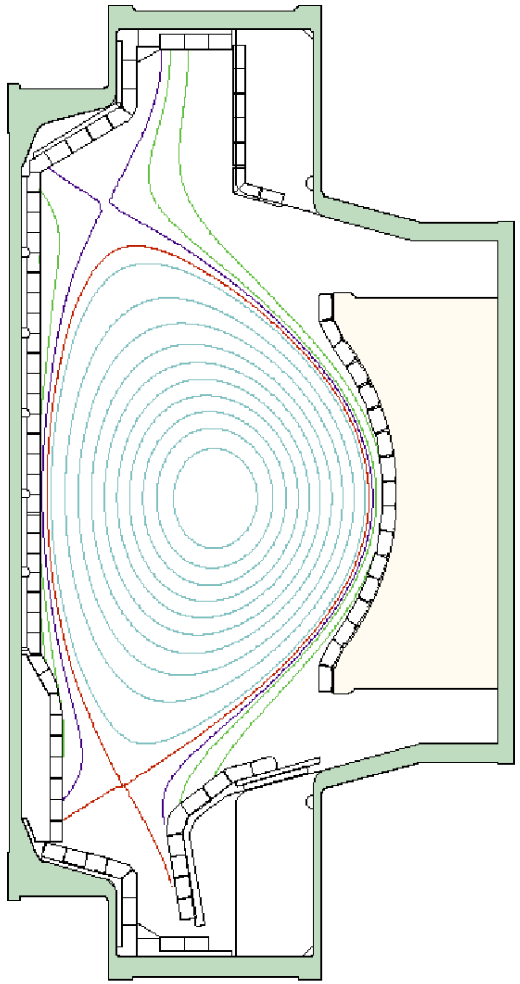
F. Ryter et al., Nuclear Fusion 36 (1996) 1217

E. Righi et al., Nuclear Fusion 39 (1999) 309

Power Threshold and magnetic configuration

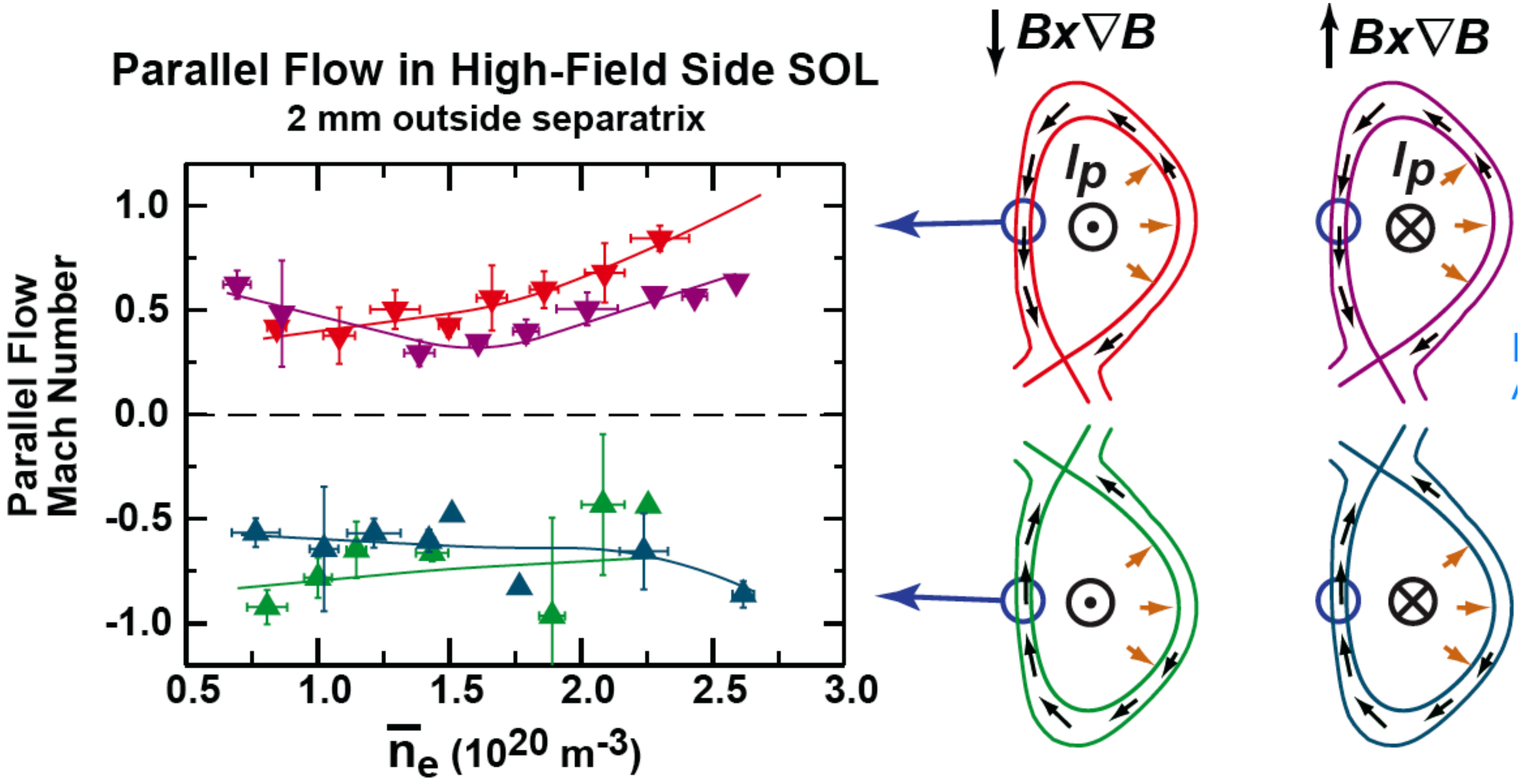
LaBombard et al., PoP 2005





Results appear to consistent with SOL flows causing the differences in the $P_{threshold}$ with configuration (not with the transition)

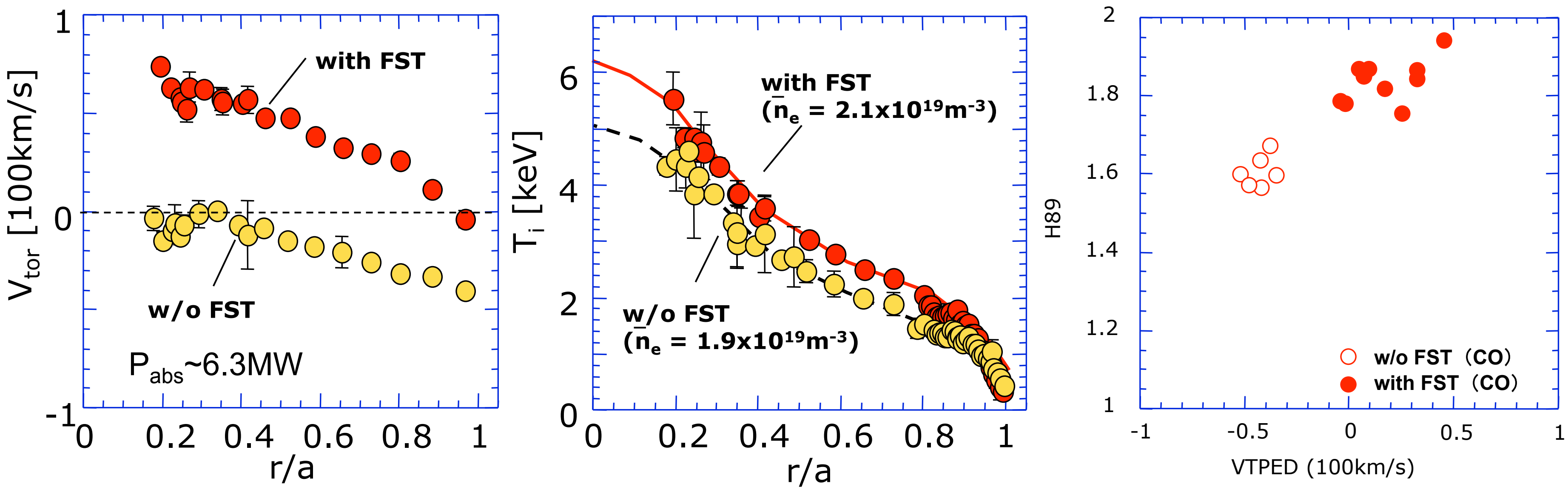
A. Hubbard et al., TTF-2007



SOL flow direction depends only on X-point location. Results consistent with transport-driven flux. Hubbard (TTF-2007)

Experiments in Tore-Supra are also consistent with this interpretation (J. Gunn, IAEA-2006)

Effect of Toroidal Field Ripples on Plasma Rotation and Confinement (JT-60U, JET)



After reduction of toroidal field ripple with ferritic inserts (FST) in JT-60U

- Higher pedestal pressure ~20% is obtained.
- At the same *n*eped, higher *T*iped was obtained with wider pedestal width and steeper gradient.
- Larger co-rotation (or smaller ctr-*V*t).
- Better confinement by ~20%.

Ripple amplitude in one of hidden variables in rotation scalings

S. Ide et al., 2006

- Key element of transport barriers
  - Role of ExB drifts and magnetic topology
- Development of plasma diagnostics: new physics
  - Electric field and Plasma rotation
- Mechanisms to drive rotation and Damping physics
  - Neoclassical and Anomalous
  - Experimental results
- Rotation and magnetic topology
  - SOL flows and L-H transition
  - Influence of magnetic ripple
- Rotation in ITER
- Conclusions

Plasma rotation and ITER

Role of external momemtum input:

e.g. collisional torque due to slowing down of fast beam ions (NBI). But NBI driven rotation will be limited in ITER.

Role of internal momentum sources:

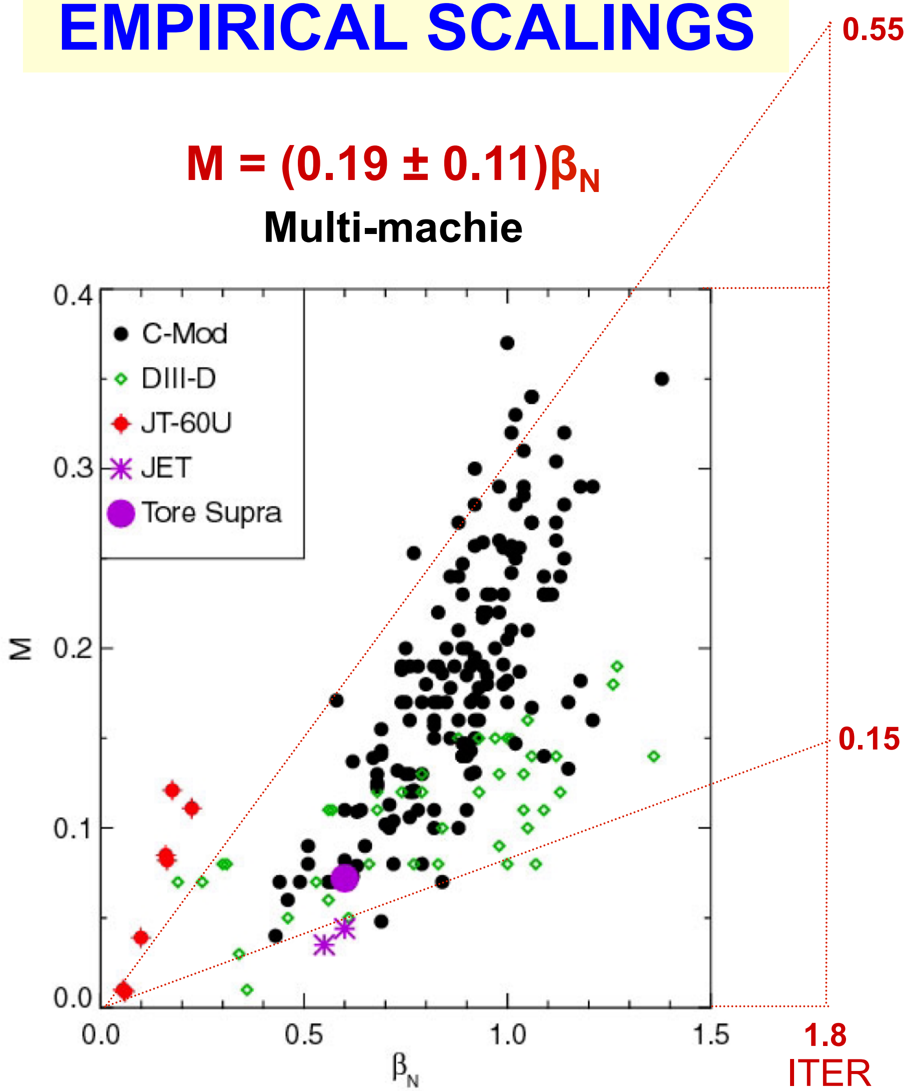
e.g. spontaneous rotation

Spontaneous Toroidal Rotation

EMPIRICAL SCALINGS

$M = (0.19 \pm 0.11)\beta_N$

Multi-machie



J.E. Rice et al 21st Fusion Energy Conference, Chengdu, 2006

Spontaneous Toroidal Rotation in ITER

Let us assume that ITER Inductive Q=10 regime with β_N=1.8 is obtained with RF and α-heating only.

Then, applying $M = (0.19 \pm 0.11)\beta_N$ scaling we get

$$V_{tor} = (350 \pm 200)\ \mathrm{km/s}.$$

These values are (2 - 8 times) higher than estimations for NBI driven rotation.

V. Mukhovatov, 10th ITPA-2006

Conclusions

Momentum transport physics is an important issue in magnetically confined plasmas (ITER relevant).

Projections of ITER plasma performance require better understanding of plasma rotation including

- Rotation at combined NBI + RF + alpha-particle heating
- Spontaneous toroidal rotation
- Anomalous poloidal rotation
- Effect of magnetic topology

Momentum transport is an active area of research in magnetic fusion devices (tokamaks, stellarators, RFPs) and basic plasma experiments