# Transport in 'Fusion' Plasmas


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# Overview

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1. Preliminaries :
   - balance equations and fluxes
   - limitations of this lecture
   - basic assumptions
2. Neoclassical transport :
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   - trapped particles and banana orbits
   - different regimes
   - transport matrix
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# Overview

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5. Experimental methodology and conditions
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7. Experimental results - additionally heated plasmas
8. Conditions with improved confinement
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# 1. Preliminaries :
## *a. balance equations and fluxes*

Transport =
the flux of a plasma quantity from one place to another

Fluxes:
- make up difference between local sources and sinks
- can be driven by a gradient = diffusion
- can be carried by the fluid velocity = convection

Conservation laws:
Predict the time development of a plasma quantity

**Balance Equations**

For each species $j$:

- Particle Balance

$$\partial n_j/\partial t + \vec{\nabla} \cdot \vec{\Gamma_j} = \text{Sources - Sinks}$$

$$\vec{\Gamma_j} = -D\vec{\nabla} n_j + n_j \vec{V_c}$$

- Energy Balance

$$\partial(\frac{3}{2} n_j k T_j)/\partial t + \vec{\nabla} \cdot \vec{q_j} = \text{Sources - Sinks}$$

$$\vec{q_j} = -n_j \chi_j \vec{\nabla} T_j + \vec{\Gamma_j} \frac{5}{2} k T_j + \vec{q_{conv}}$$

- Momentum Balance

$$p \partial \vec{v}/\partial t + \vec{\nabla} \vec{\Pi} = \text{Sources - Sinks}$$

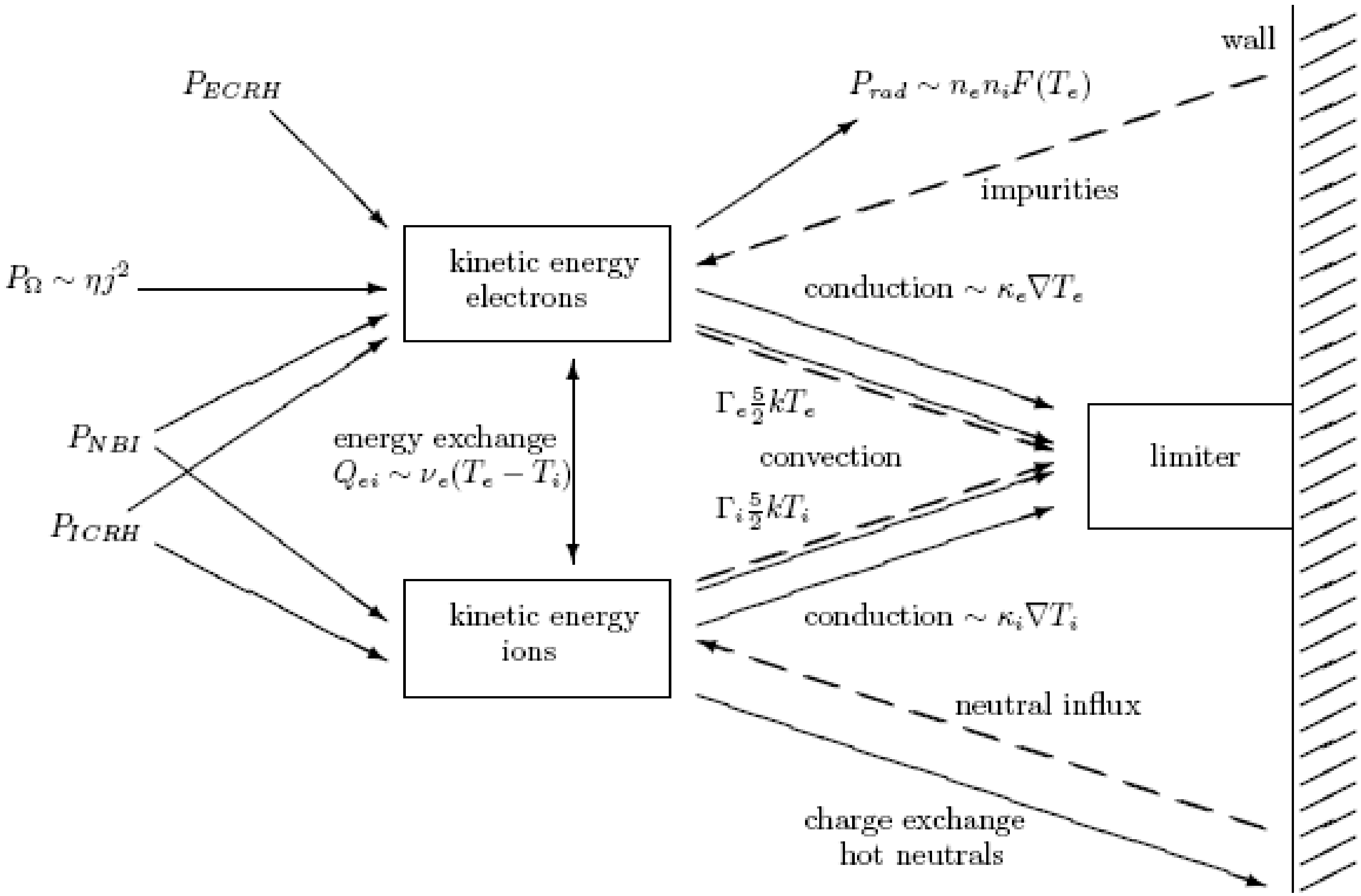
where $\vec{\Pi}$ is viscous tensor

- Difference electron - ion momentum $\Longrightarrow$ generalized Ohms law:

$$\vec{E} + \vec{v} \times \vec{B} = \eta \vec{j}$$

# Example: the energy balance

*Arrows: sources and sinks*
*Full/dashed lines: energy/particle fluxes*



# 1. Preliminaries :
## *b. Limitations of this lecture*

We limit ourselves to fusion-relevant plasmas
*(tokamak, stellarator, etc)*

a. Hot (typically 100 eV – 20 keV) → Fully ionized

*Consequence: no interaction with neutrals;*
*(Transport properties of partially ionized plasma completely different!)*

b. Strong magnetic field

*Consequence: large difference parallel / perpendicular transport*

c. Toroidal geometry → *curved field lines*

d. Additional poloidal field → *helical field lines*

# 1. Preliminaries :

## b. Limitations ctd: *Presence of strong magnetic field*

*(consider electrons (e); similar for ions)*

What distance can electrons travel ⁄⁄ and ⊥ field lines before colliding ?

Mean free path length along field line:

$$\lambda_{/\!/} = v_{th,e} * \tau_e$$

where $v_{th,e} = (2KT_e/m_e)^{1/2}$ is the thermal speed of the electrons

and $\tau_e \sim T_e^{3/2} / n_e$ is the electron collision time

Perpendicular to field line:

$$\lambda_{\perp} = \lambda_e \sim T_e^{1/2} / B \text{ } (\lambda_e = \text{electron Larmor radius})$$

*For typical tokamak plasma ($B = 3$ T; $T_e = 1$ keV; $n_e = 10^{20}$ $m^{-3}$):*

$$\lambda_{/\!/} \approx 100 \text{ m} ; \lambda_{\perp} \approx 1 \text{ mm}$$

*Consequence:*

*⁄⁄ diffusion / ⊥ diffusion ≈ $10^{10}$*

*$T_i$ , $T_e$, $n_e$ are constant along field lines*

# 1. Preliminaries :

## *b. Limitations ctd: Toroidal geometry & poloidal field*

Toroidal geometry →

- field lines are curved
- magnetic field strength not constant along field line

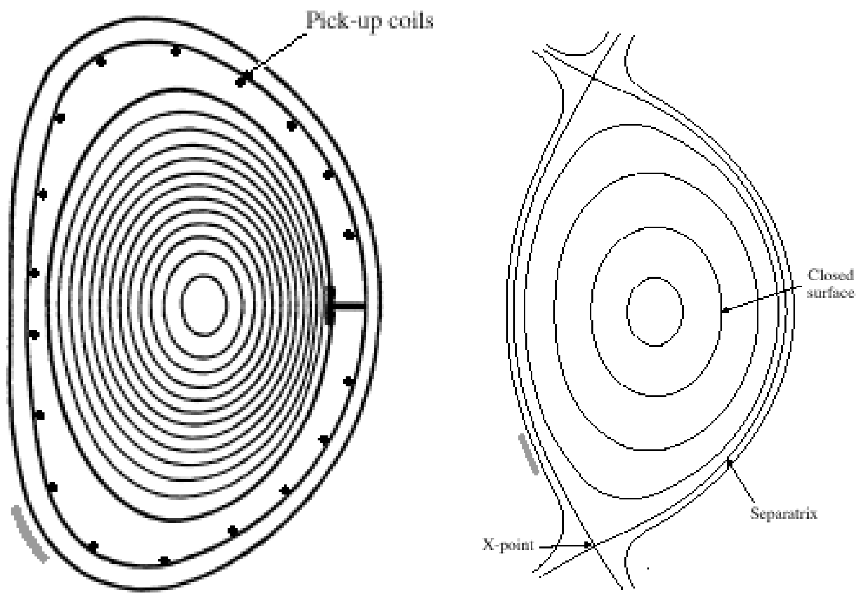
  → *particles can be 'trapped' on Low Field Side (magnetic mirror)*

Presence of poloidal field (generated by plasma current in tokamak) →

- helical field lines
- single field line fills surface;

  *$T_i$ , $T_e$, $n_e$ constant*

  *on these flux surfaces*



# 1. Preliminaries
## *c. basic assumptions*

1. **Geometry**: there exists a coordinate system
   - Which allows separation of variables
   - Which makes it possible to reduce the 3D-problem to 1.5D

     *'1.5D' refers to geometry more complicated than circular ('1D')*
2. **Decorrelation length** << plasma size
3. **Decorrelation time** << time scales of macroscopic evolution

***Consequences**: standard transport theory is not applicable when:*
*-the problem is genuine 3-D*
*-decorrelation length ≈ mesoscale length of self-organized structures*
*-decorrelation time ≈ time scale of variation of local quantities*

Therefore, e.g. percolating systems like boiling water and sandpile systems (transport by avalanches) hard to describe with standard transport theory

# 2. Neoclassical transport

## *a. introduction: Classical transport*

Fluid description (**j** = current density; $\eta$ = resistivity): combine

(1) simplified Ohm's law : $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta\, \mathbf{j}$

(2) pressure balance : $\mathbf{j} \times \mathbf{B} = \nabla p$

Take cross product of (1) with **B** :

$$\mathbf{E} \times \mathbf{B} + (\mathbf{v} \times \mathbf{B}) \times \mathbf{B} = \eta\, \mathbf{j} \times \mathbf{B} = \eta_\perp \nabla p$$

$$\mathbf{E} \times \mathbf{B} - v_\perp B^2 = \eta_\perp \nabla p$$

which gives $v_\perp = (\mathbf{E} \times \mathbf{B}) / B^2 - (\eta_\perp / B^2)\, \nabla p$

E x B drift — diffusion velocity in direction of $\nabla p$

Assume T constant ( $\nabla p = T \nabla n$), $\nabla p$ in radial direction, then diffusive flux:

$$\Gamma_\perp = n\, v_\perp = (\eta_\perp p / B^2)\, \nabla n$$

i.e. particle diffusion coefficient is

$D_\perp = \eta_\perp p / B^2$ *'classical transport' in straight geometry*

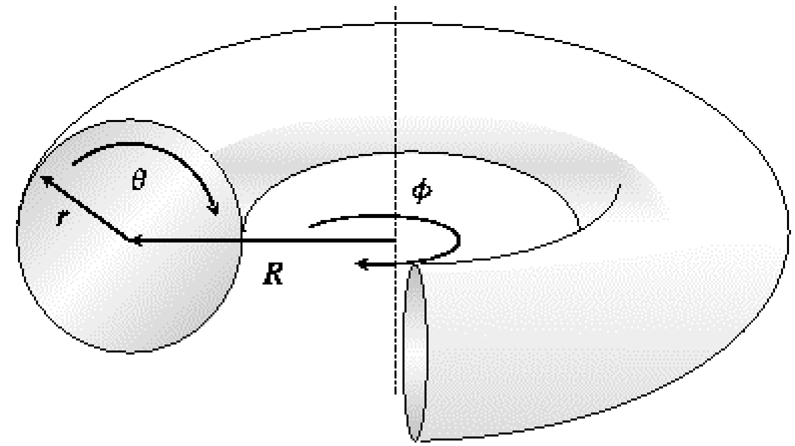
*As* $\eta_\perp \sim T^{-3/2}$, one has $D_\perp \sim n/(T^{1/2} B^2)$

*The same can be derived from random walk description with step length* $\lambda_e$ *and e-i collision time* $\tau_{ei} \sim T^{3/2} / n$ : $D_\perp \sim \lambda_e^2 / \tau_{ei} \sim n/(T^{1/2} B^2)$

*Similarly for thermal diffusion coefficients:* $\chi_e \sim \lambda_e^2 / \tau_{ee}$ and $\chi_i \sim \lambda_i^2 / \tau_{ii}$

# 2. Neoclassical transport

## *b. Trapped particles and Banana orbits*




Trapped particles due to magnetic mirror effect, note that B ~ 1/R !

Consider electron following field line on flux surface with radius r

Magnetic moment $\mu = m v_\perp^2 / (2B)$ constant in time (De Blank pg.25)
Denote with subscript '0' velocity at LFS, where $B=B_{min}$, then :

$$(1)\ v_\perp^2 / B = v_{\perp,0}^2 / B_{min}$$

At bounce point $v_{/\!/} = 0$, so conservation of energy:

$$(2)\ v_{\perp b}^2 = v_{\perp 0}^2 + v_{/\!/ 0}^2$$

Combining (1) and (2):

$$(3)\ B_b/B_{min} = 1 + (v_{/\!/ 0}^2 / v_{\perp 0}^2)$$

# 2. Neoclassical transport

## *b. Trapped particles and Banana orbits (ctd)*

Last eq.:

$$(3)\ B_b/B_{min} = 1 + (v_{/\!/0}^{\,2} / v_{\perp 0}^{\,2})$$

Since B ~ 1/R,

$$(4)\ B_{max} / B_{min} = (R_0+r) / (R_0-r) \sim 1 + 2r / R_0$$

Thus, requirement for trapping (combine 3 and 4):

$$v_{/\!/0} / v_{\perp 0} < (2\varepsilon)^{1/2}$$

where $\varepsilon = r / R_0$ is the so-called inverse aspect ratio

Notes:

- In centre of torus: r → 0, so fraction of trapped particles $f_{trap} \sim \varepsilon^{1/2} \rightarrow 0$
- This is ideal description, assuming no collisions …

# 2. Neoclassical transport

## *b. Trapped particles and Banana orbits (ctd)*

Let's now consider the orbits of passing and trapped particles

Remember that inhomogeneous & curved B both give rise to drifts, the $\nabla$B drift and curvature drift:

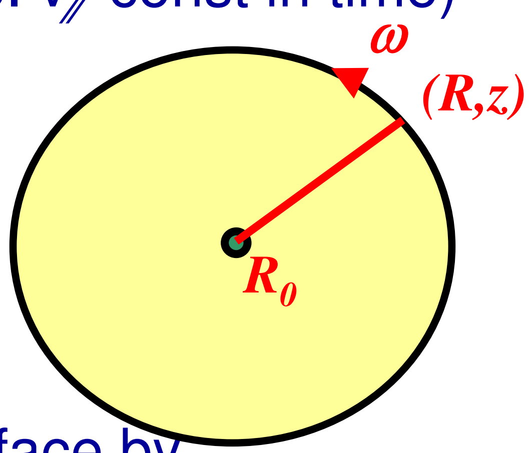
$$v_d = m_e\,(v_{/\!/}^2 + 1/2\, v_\perp^2\,)\,/\,(eRB)$$

First strongly passing particle (strongly: $v_{/\!/} >> v_\perp$, i.e. $v_{/\!/}$ const in time)

Project orbit on poloidal plane: rotation frequency

$$\omega = (B_\theta/B)\, v_{/\!/}\,/\,r$$

$$dR/dt = \omega z \quad ; \quad dz/dt = -\omega\,(\,R\text{-}R_c\,) + v_d$$




Then, using $v_{/\!/}$ constant :

$$(\,R - R_c - v_d/\omega\,)^2 + z^2 = constant$$

This is circular surface displaced from magnetic surface by

$$d = -\,v_d\,/\,\omega \approx \varepsilon\, v_{/\!/}\,/\,\omega_{c\theta}$$

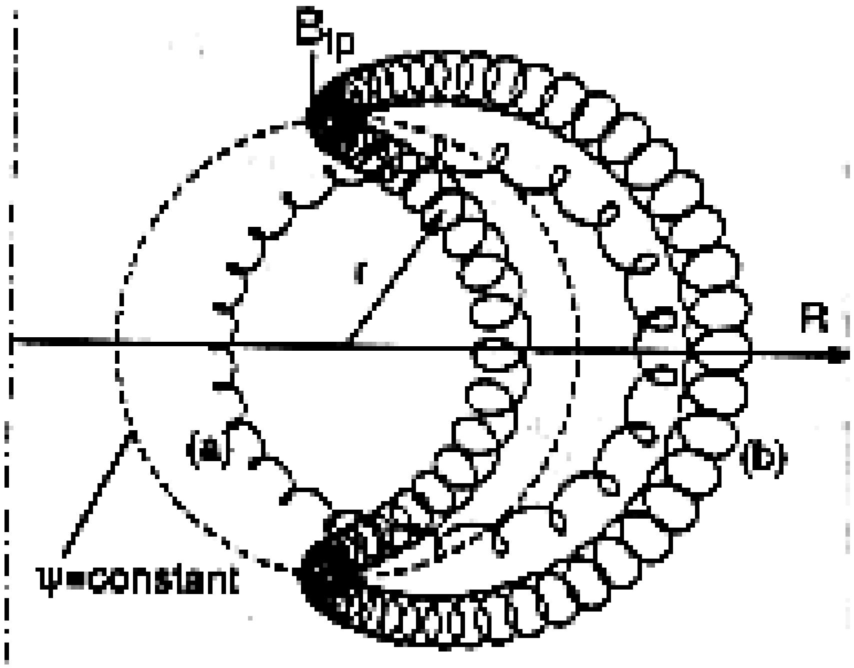
with $w_{c\theta}$ the cyclotron frequency due to $B_\theta$

# 2. Neoclassical transport

## *b. Trapped particles and Banana orbits (ctd)*

Similarly the orbit of trapped particles can be calculated (not done here)
Result : poloidal cross-section is banana shaped, with half width

$$\Delta_b = v_{/\!/0} / \omega_{c\theta}$$




*Poloidal cross-section of tokamak; Particle orbits projected onto this surface: 'passing' and 'trapped particles' depending on ratio $v_{/\!/} / v_{\perp}$*

# 2. Neoclassical transport

## *c. Different regimes: banana regime*

Important parameter dimensionless collisionality:

$$\nu_e^* = \tau_{banana} / \tau_e = R_0\, q / (\tau_e v_{th,e}\, \varepsilon^{3/2})$$

Previous formulas only make sense if electrons can complete their banana orbits before colliding, i.e. if $\nu_e^* < 1$
This is called the banana regime

Heuristic: random walk for trapped particles
for trapped particles the step size is the banana-orbit width $\Delta_b$
So, because only the trapped particles contribute:

$$D_{banana} \sim f_{trap}\, \Delta_b^2 / \tau_e \sim \varepsilon^{-3/2} q^2 \lambda_e^2 / \tau_e \sim \varepsilon^{-3/2} q^2 D_{class}$$

Similar expressions for electron and ion thermal diffusion coefficient $\chi_{e,i}$

# 2. Neoclassical transport

## c. Different regimes: Pfirsch-Schlueter regime

Collisional or Pfirsch-Schlueter regime :

$$\nu_e^* > \varepsilon^{-3/2}$$

I.e. mean free path length < connection length along field line between HFS and LFS of torus

PS transport arises from ExB term in equation for $v_\perp$ on page 10.

Result (not derived here) is:

$$D_{PS} = D_{class}\,(1 + \alpha\, q^2\,)$$

with again similar expressions for electron and ion thermal diffusion coefficient $\chi_{e,PS}$ and $\chi_{i,PS}$
where $\alpha$ is a numerical factor or order 1 (different for $D_{PS}$ , $\chi_{e,PS}$ , $\chi_{i,PS}$ )

# 2. Neoclassical transport

## *c. Different regimes: plateau regime*

Plateau regime : intermediate between banana and PS:

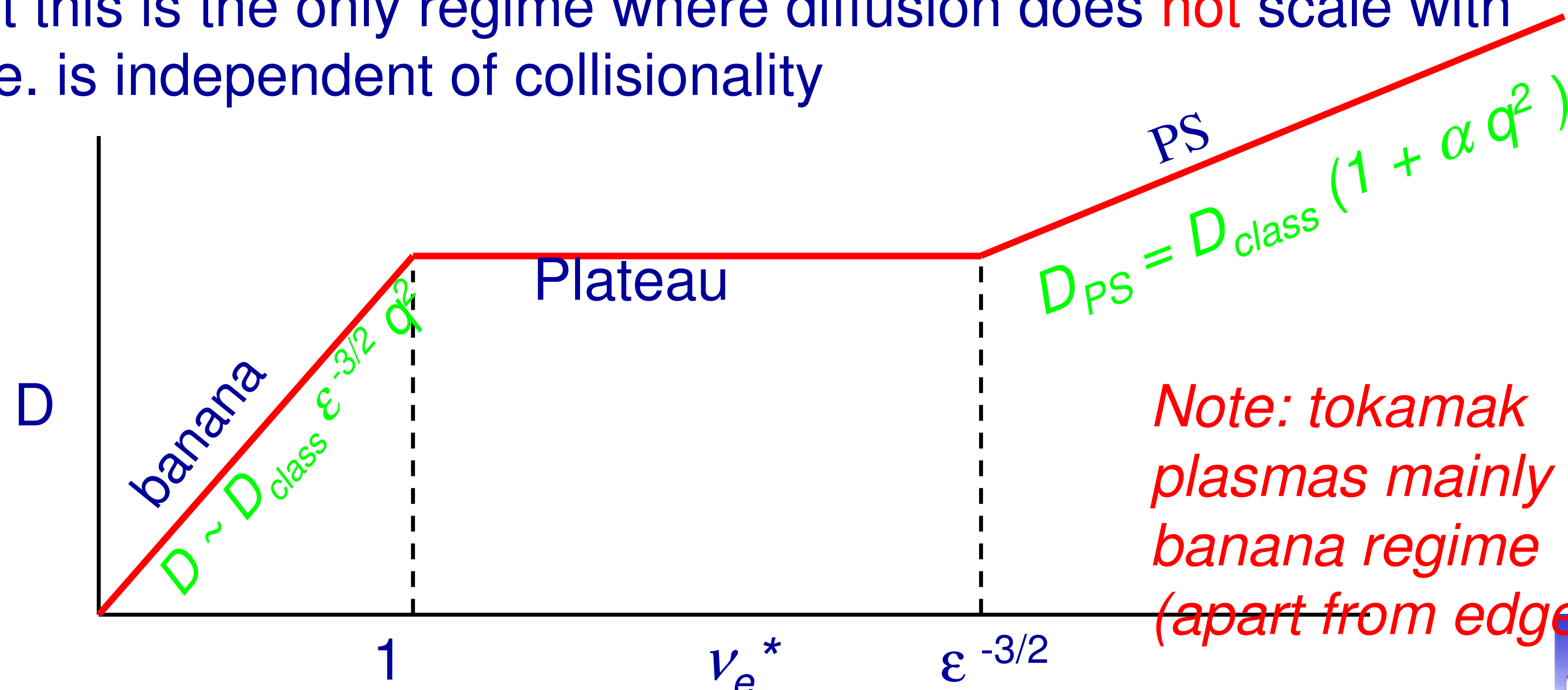
$1 < \nu_e^* < \varepsilon^{-3/2}$

In this regime transport coefficients scale (not derived here) like:

$D_{Plat} \sim q\, T_e\, \lambda_e$

with again similar expressions for $\chi_{e,Plat}$ and $\chi_{i,Plat}$

Note that this is the only regime where diffusion does not scale with $D_{class}$ , i.e. is independent of collisionality




*Note: tokamak plasmas mainly in banana regime (apart from edge)*

# 2. Neoclassical transport

## *d. Transport Matrix*

Back to basics:

Transport = the flux of plasma quantity from one place to another

Fluxes: make up difference between local sources and sinks
can be driven by a gradient = diffusion

| Flux | | driving gradient | diffusion coefficient |
|---|---|---|---|
| particle flux | $\Gamma$ | $\nabla n$ | D |
| electron heat flux | $q_e$ | $\nabla T_e$ | $\chi_e$ |
| Ion heat flux | $q_i$ | $\nabla T_i$ | $\chi_i$ |
| current density | j | $E_{/\!/}$ | $\sigma$ |

Rigid derivations (not done here) would show that in the 3 regimes there is not only a particle flux driven by $\nabla n$ *(diff.coeff. D)*, but that there is also a $\Gamma$ driven by $\nabla T_e$ , $\nabla T_i$ *and* $E_{/\!/}$

Same holds for the electron and ion heat fluxes and for current density

# 2. Neoclassical transport
## *d. Transport Matrix*

So in fact neo-classical transport is described by a 4x4 transport matrix:

$$\begin{pmatrix} \Gamma \\ q_e \\ q_i \\ j \end{pmatrix}_\Psi = -\begin{pmatrix} D & M_{12} & M_{13} & w \\ M_{21} & n\chi_e & M_{23} & M_{24} \\ M_{31} & M_{32} & n\chi_i & M_{34} \\ b_n & b_{Te} & b_{Ti} & \sigma \end{pmatrix} \begin{pmatrix} \nabla n \\ \nabla T_e \\ \nabla T_i \\ E_{//} \end{pmatrix}_\Psi$$

Ware pinch: consider toroidal equation of motion:

$$d/dt(m_e v_\phi) = -e\,(\,E_\phi + (v \times B)_\phi\,)$$

Take time average over one banana orbit of trapped particle: LHS = 0 →

$$<(v \times B)_\phi> = -\,E_\phi$$

Since $(v \times B)_\phi> = v_\perp B_\theta$, we have

$$<v_\perp> = -\,E_\phi / B_\theta$$

yielding particle flux

$$\Gamma \sim \varepsilon^{1/2}\, n\, E_\phi / B_\theta$$

So term in transport matrix: $w \sim \varepsilon^{1/2}\, n / B_\theta$

# 2. Neoclassical transport

## *d. Transport Matrix*

Ware pinch is important in tokamak physics: it creates peaked density profiles also in the absence of central particle sources
*(note however: real inward particle pinch usually much larger than Ware pinch, due to other effects)*

Similar to inward particle flux due to $E_\phi$ there exists current driven by density (and temperature) gradients: the bootstrap current
*(terms b in transport matrix)*

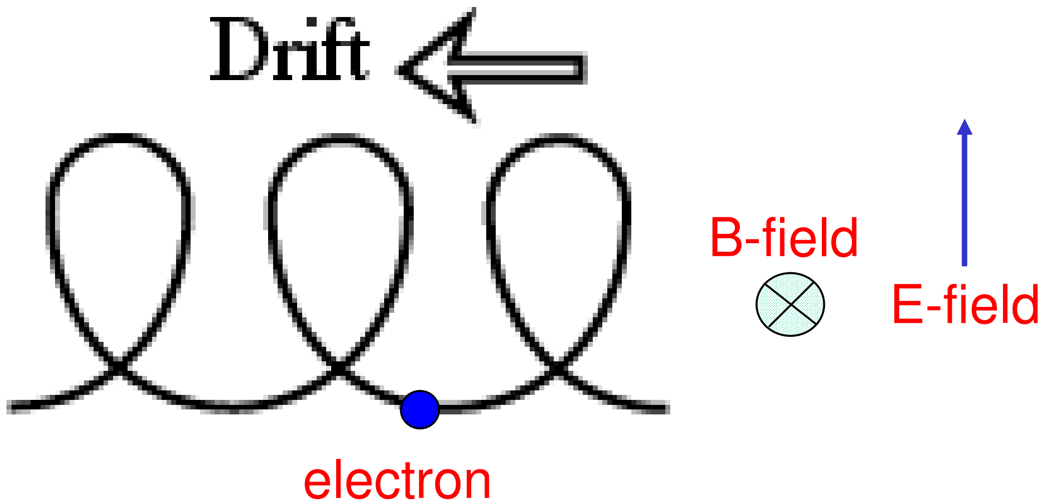
Very important in tokamak physics:
Inductive current drive is by nature limited in time, so any non-inductive current drive is very welcome
*(Baron von Muenchhausen …)*

# 3. Models of turbulence

## a. Electrostatic Turbulence:

Background: E x B drift

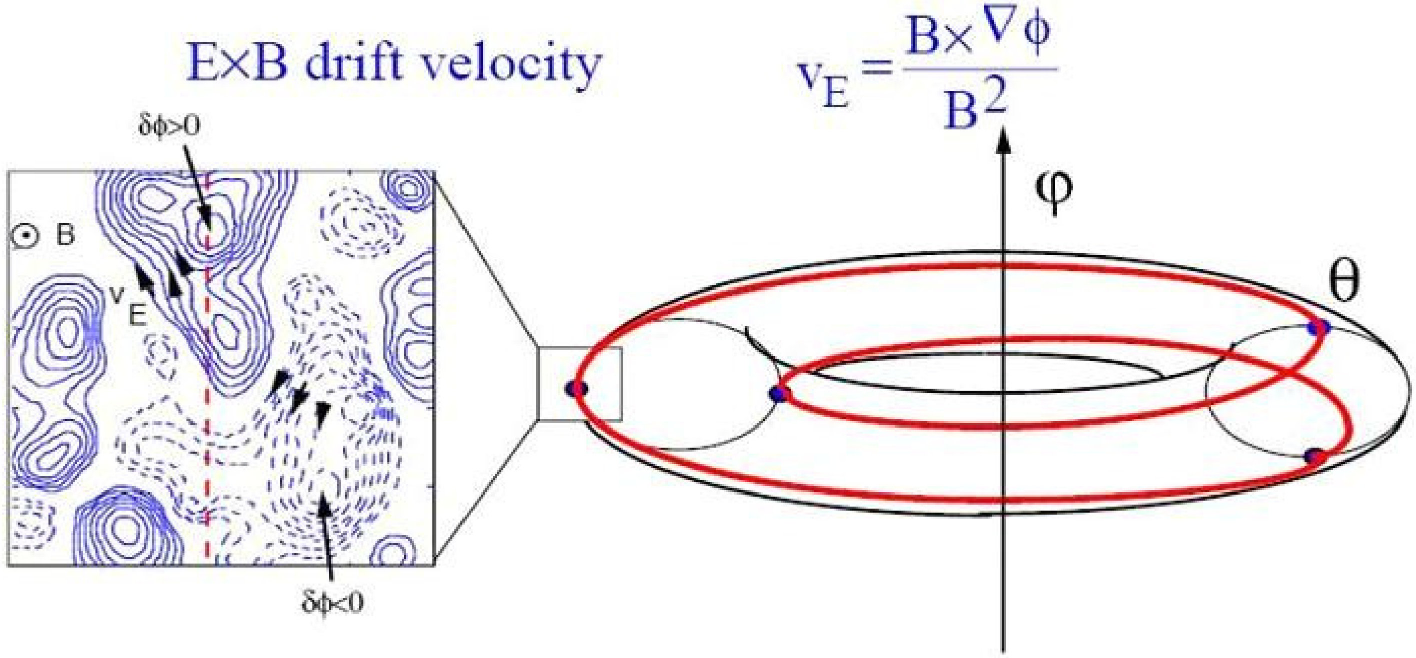
$$v_E = \frac{\vec{E} \times \vec{B}}{B^2}$$



# 3. Models of turbulence

## a. Electrostatic Turbulence (ctd):

Assume now that there are fluctuations in E:




Diffusive transport estimated from random walk process: $D_{turb} \sim \chi_{turb} \sim \left|v_{E^{\sim}}\right|^2 \tau_c$

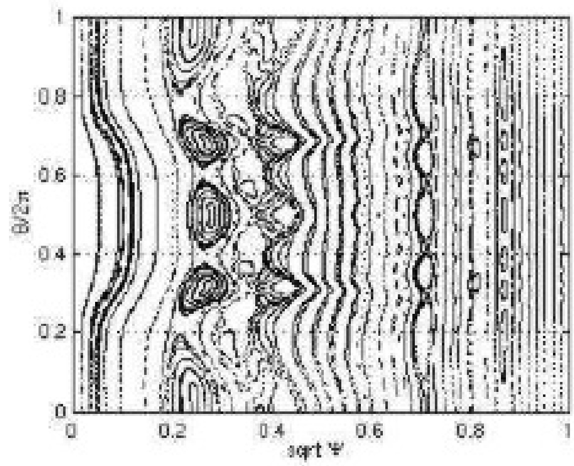
with $E^{\sim}$ the fluctuating electric field, and $\tau_c$ a correlation time;

One can show that $1/\tau_c$ ~ max linear growth rate $\gamma_{max}$

# 3. Models of turbulence

## b. Magnetic Turbulence:

Basics: Magnetic Turbulence →
broken flux surfaces →
stochastic meandering of field lines




Famous Rechester-Rosenbluth formula:

$$\chi_e(\perp) = (\tilde{B}/B)^2 \, \chi_e^{classical}(//)$$

This formula only holds for a fully stochastic field.

In real life, magnetic fluctuations are normally too small for full stochasticity;
Instead, one sees alternative layers of intact and broken flux surfaces (islands);
Then above formula needs some correction factor.

*In both types of turbulence mesoscale self-organized structures may arise, violating basic assumptions on geometry and decorrelation length & time*

# 4. Neoclassical predictions and experimental values

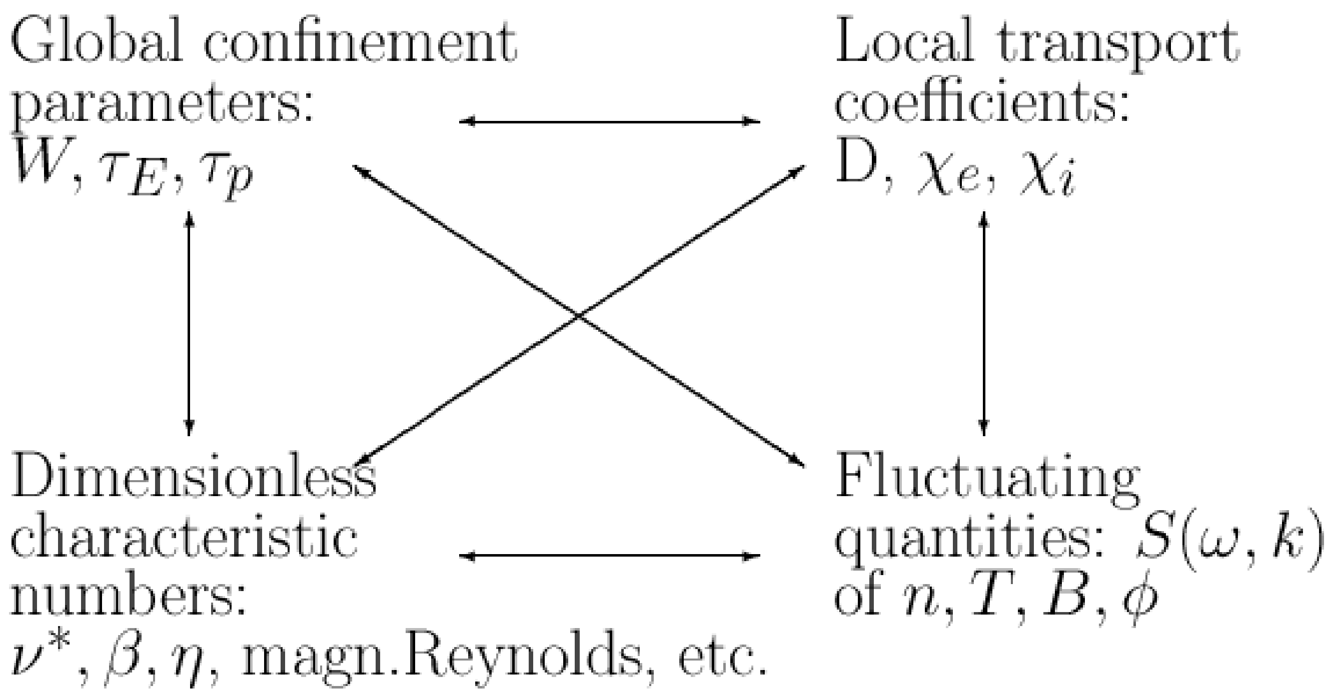
## Neoclassical formulas:

- D from $D_{ban} \approx \nu_e \rho_{e\theta}^2 (r/R)^{0.5}$ to $D_{PS} \approx \nu_e \rho_{i\phi}^{\ 2} ( 1 + 2q^2 )$
- $\chi_e \approx D$; $\chi_i = (m_i/m_e)^{0.5} \chi_e$
- $v_{inw} = - E_\phi / B_\phi (r/R)^{0.5}$
- trapped particle correction on resistivity: $\{ 1\text{-}1.95(r/R)^{0.5} \}^{-1}$
- bootstrap current $j_{bs} = -(r/R)^{0.5} (T/B_\theta) \nabla n_e$
- viscosity: large/small for poloidal / toroidal flows

# 4. Neoclassical predictions and experimental values *(ctd)*

| **Numerical predicted values:** | ***Experimental values:*** |
| --- | --- |
| $\chi_e \approx 10^{-2} – 10^{-1}$ m²/s | *1-10 $m^2/s$: 2 orders !* |
| $\chi_i \approx 10^{-1} – 1$ m²/s | *1-10 $m^2/s$: 1 order* |
| $v_{inw} \approx 10^{-2} – 0.5$ m/s | *0.1-5 m/s: 1 order* |
| $j_{bs} \approx 10^4 – 5.10^5$ A/m² | *As predicted* |
| $v_{pol} \approx 10^3$ m/s | *As predicted* |
| $v_{tor} \approx 10^4 – 10^6$ m/s | *As predicted* |

# 5. Experimental methodology and conditions




- Can be done in quasi steady-state: $A^{-1}\partial A/\partial t \ll \tau^{-1}$
- Better: dynamically, to better unravel individual terms of equations, but
    - modulation must be small
    - $f_{mod} \ll f_{fluctuations}$

***In the following we briefly consider each of these four categories***

# 5a. Global Confinement Quantities

Based on total particle and energy content (N,W)

**Balance equations**:

$$\partial N/\partial t + N/\tau_p = \text{wall desorption} + \sum\Phi_{ext}$$

$$\partial W/\partial t + W/\tau_E = \sum P_{ext}$$

where $\sum\Phi_{ext}$ and $\sum P_{ext}$ denote the external particle & heat sources

wall desorption = R $N/\tau_p$ , R 'recycling coefficient'

**Particle** and **energy confinement time**:

$$\tau_p^* = \tau_p / (1-R) = N/(\sum\Phi_{ext} - \partial N/\partial t)$$

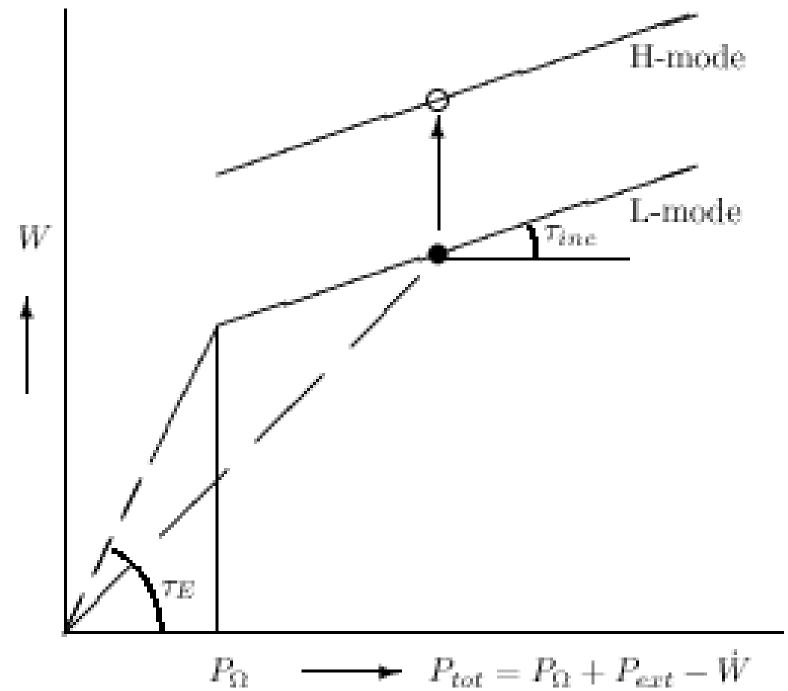
$$\tau_E = W/(\sum P_{ext} - \partial W/\partial t)$$

Often W nonlinear function of $\sum P_{ext}$

Therefore one defines

**incremental energy confinement time**:

$$\tau_{inc} = \partial W/ \partial(\sum P_{ext} - \partial W/\partial t)$$



# 5b. Local Transport Coefficients

Calculate **fluxes** crossing $\Psi$ and relate them to local gradients at $\Psi$
Every flux driven by more than one gradient → transport matrix
For simplicity we consider here only 2 fluxes $\Gamma$ and $q_e$

One needs to know **deposition profile** of particle and heat sources, and take into account **sinks** and **changes in time**:

$$\begin{pmatrix} \Gamma \\ q \end{pmatrix}_\Psi = \frac{1}{\text{Area}} \begin{pmatrix} \Sigma\Phi_{\text{ext}}(\Psi) \\ \Sigma P_{\text{ext}}(\Psi) \end{pmatrix} - (\text{Sinks}) - \begin{pmatrix} \dot{N}(\Psi) \\ \dot{W}(\Psi) \end{pmatrix}$$

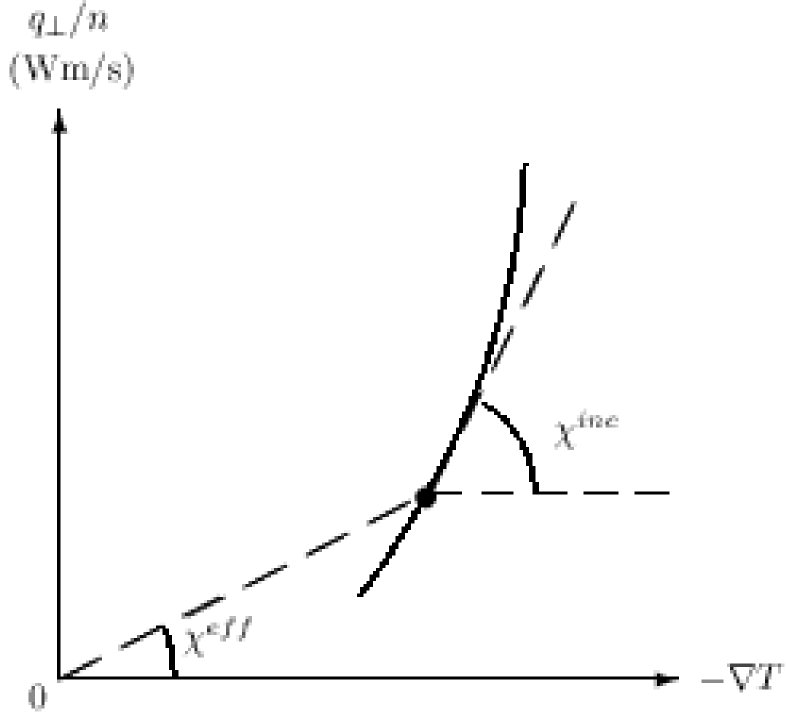
*Implicit assumption :*

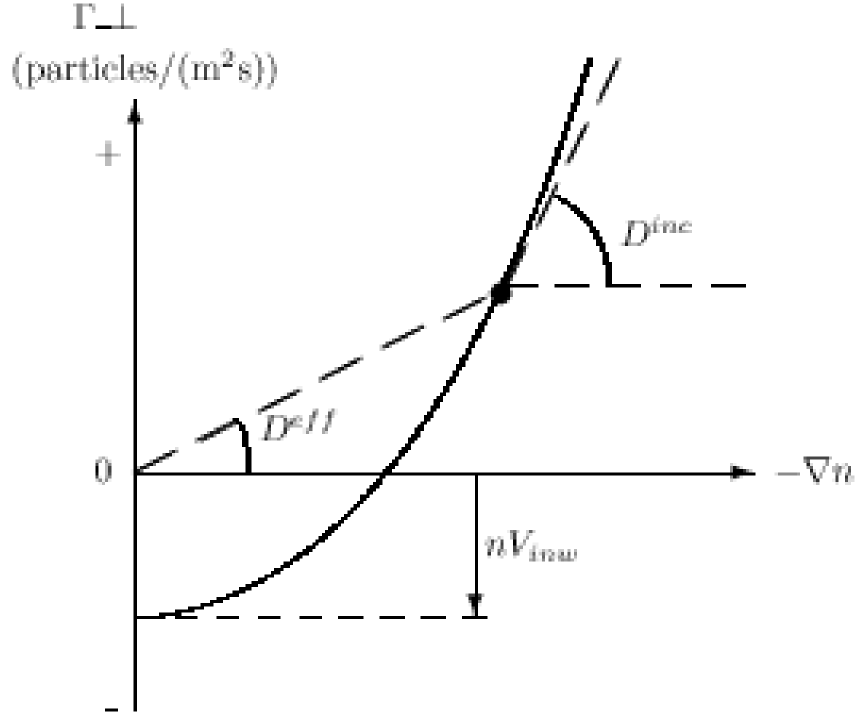
*- plasma parameters dependent on $\Psi$ only (turbulence maybe of ballooning nature, i.e. different in/outboard)*

# 5b. Local Transport Coefficients *(ctd)*

**Special approaches:**

- neglect off-diagonal terms ($M_{ij}$=0 for i≠j) → $D^{eff}$, $\chi^{eff}$
- limit to quasi-stationary situations (∂n/∂t=0, etc)
- actively modulate N or W to get dynamic values of D, from propagation velocity of particle/heat waves → $D^{dpp}$, $\chi^{hpp}$
- if nonlinear relation flux-gradient: look at incremental values ∂(flux)/∂ (gradient); usually $D^{inc} = D^{dpp}$ and $\chi^{inc} = \chi^{hpp}$



# 5c. Dimensionless Parameters

-Each transport model depends on different set of characteristic **dimensionless numbers**

-E.g.**neoclassical** transport depends critically on so-called **collisionality**, i.e. (banana orbit length) / (collisionfree mean path length)

-In general easy to calculate these numbers from experimental data

-However, due to interrelation between these numbers via T, n, j, etc, difficult to vary only one whilst keeping constant the others

# 5c. Dimensionless Parameters

Most important numbers:

| | |
|---|---|
| $\rho^*$ | ratio between Larmor radius and plasma radius |
| $\beta$ | ratio between plasma kinetic pressure and magnetic pressure |
| $\nu^*$ | collisionality as explained above |
| $\lambda_n/\lambda_T$ | ratio between gradient scale lengths of density and temperature profile |
| **s** | magnetic shear = q/r / (dq/dr) |
| $\mathbf{q_a}$ | variation of poloidal angle with toroidal angle following field lines at plasma edge |
| $\varepsilon, \kappa, \delta$ | geometrical parameters: aspect ratio, elongation, triangularity of the plasma |

*There are many more numbers which may be even more important but those can be rewritten as combinations of the ones above*

# 5d. Fluctuations

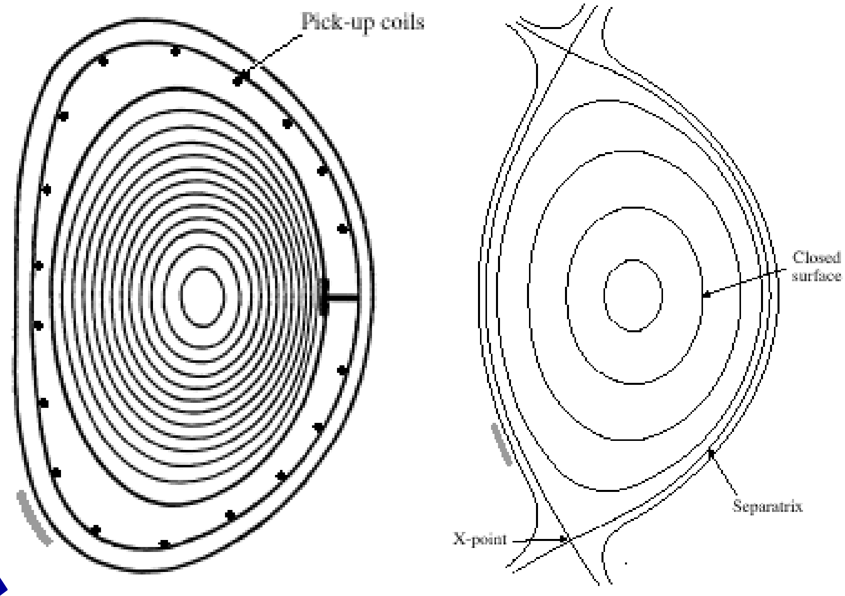
From basic quantities (n, T, B, electrostatic potential $\Phi$) one wants to know:

- **fluctuation levels**
- **wavelength**
- **growth rate**
- **phase correlation between them**

Only density fluctuations reasonably well accessible.
Others either very complicated or still under development

*Question: relation between measured fluctuations and heat/particle transport*
*Note: information only on fluctuation **level** not sufficient; also phase information needed*

# 5e. Experimental Plasma Conditions

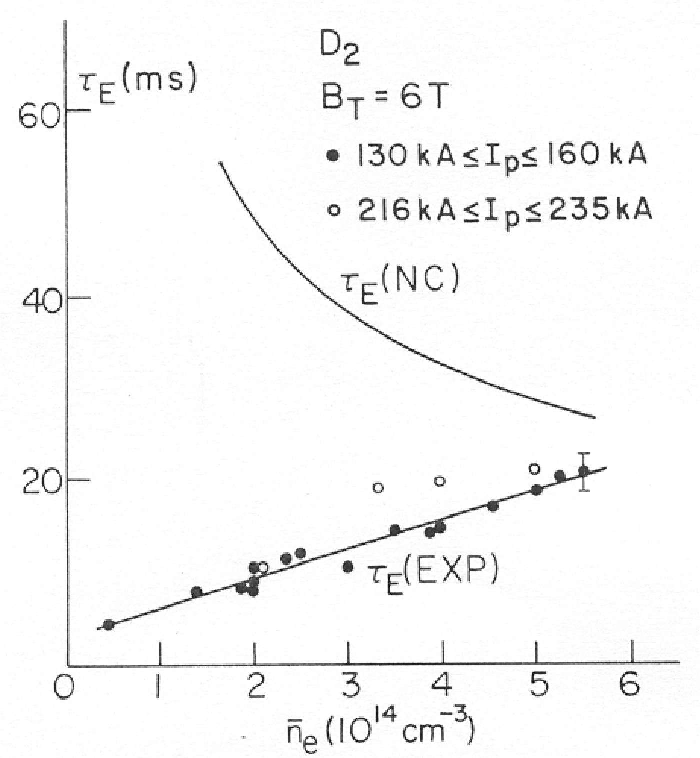



- Geometry: *circular ←→ elongated*
- Configuration : *limiter ←→ divertor*
- Heating : *ohmic ←→ additional*
    - *ion (tail) heating (NBI, ICRH) ←→ electron heating (ohmic, ECRH, LH)*
    - *global (ohmic, NBI) ←→ localized (ECRH, ICRH, LH)*
- Current drive : *LHCD, ECCD, NBCD ←→ not*
- Fuelling : *edge (gas puff) ←→ core (NBI, pellets)*
- Toroidal momentum input : *NBI, edge biasing ←→ not*

# 6. Exp.results a: ohmic plasmas

## *Small devices*

***Alcator-A (1978):***




Similar results obtained at other small tokamaks:

confinement ~ density

Is called

LOC = Linear Ohmic Confinement

Neo-Alcator Scaling:

$\tau_E \sim \langle n \rangle \, a \, R^2 \, q_a^{0.5}$

However, saturation where

$\chi_{effective} \rightarrow \chi_{ion\_neoclassical}$

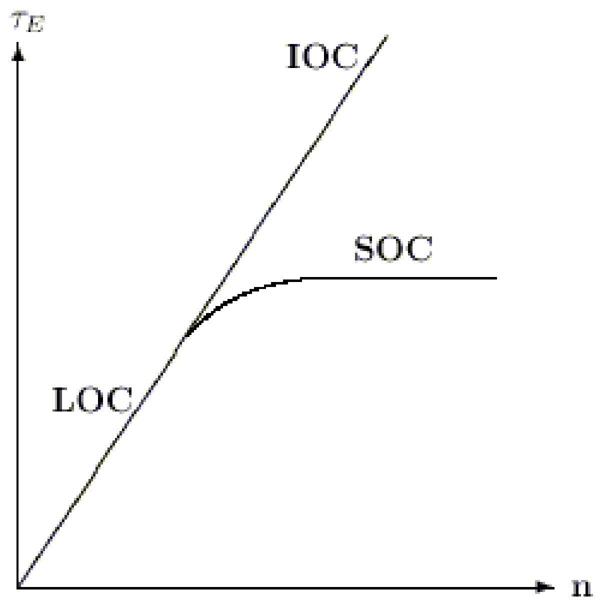
Is called

SOC = Saturated Ohmic Confinement

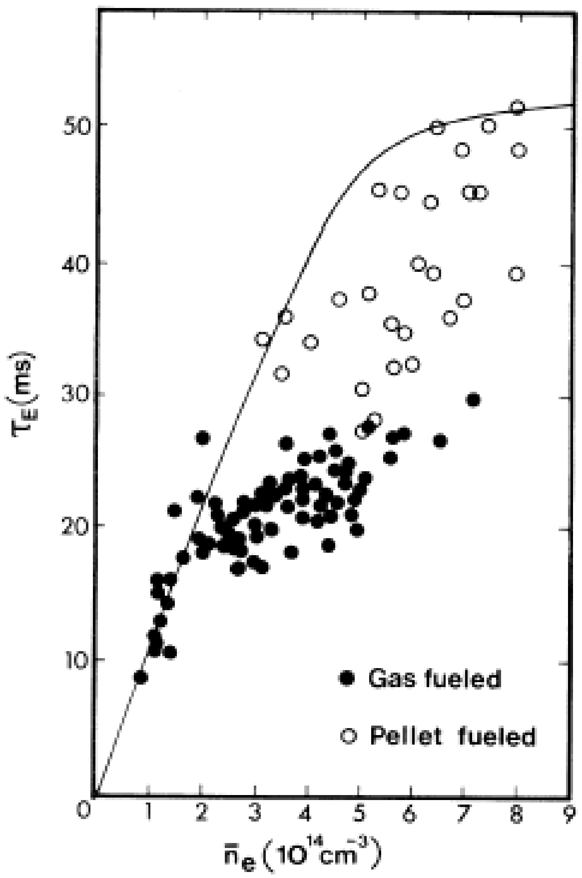
From Gondhalekar et al, IAEA-conf. 1978

# Ohmic plasmas - *Small devices (ctd)*

However:
LOC can be restored at SOC-densities when peaked n profile can be created (e.g. with central pellet fuelling):
IOC = Improved Ohmic Confinement




***Alcator-C (1984):***




*From Greenwald et al, PRL 53 (1984)*

# Ohmically heated plasmas: *Large devices*

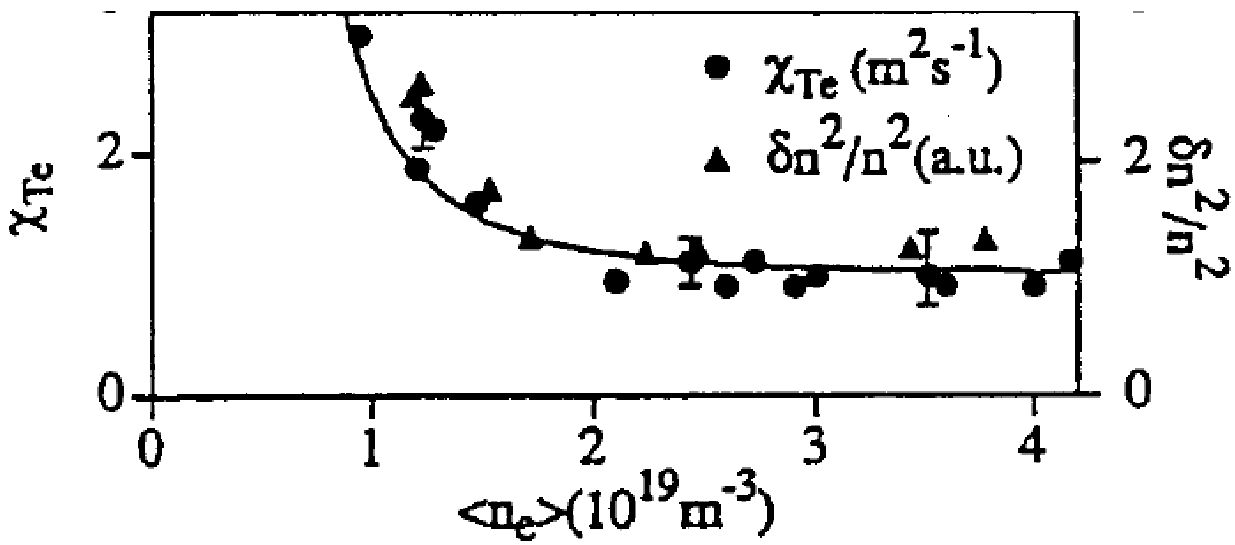
All large tokamaks find the same:

- Neo-Alcator Scaling does not fit well
- Only small density range with LOC
- At most densities one has SOC, with
  - $\chi_{electron} \approx \chi_{ion}$
  - $\chi_{ion} = (3\text{-}10)\ \chi_{ion\text{-}neoclassical}$

# Ohmically heated plasmas: *interpretation*

Interpretation: at least 2 anomalous transport mechanisms at work:
- one is damped linearly with density acting on electrons only and responsible for LOC behaviour;
- another one is only slightly influenced by density and acting on both ions and electrons alike.

*Confirmed by n˜ measurements:*
- *dropped dramatically with density in LOC*
- *levels off to low, but still significant constant value of a few % in SOC*

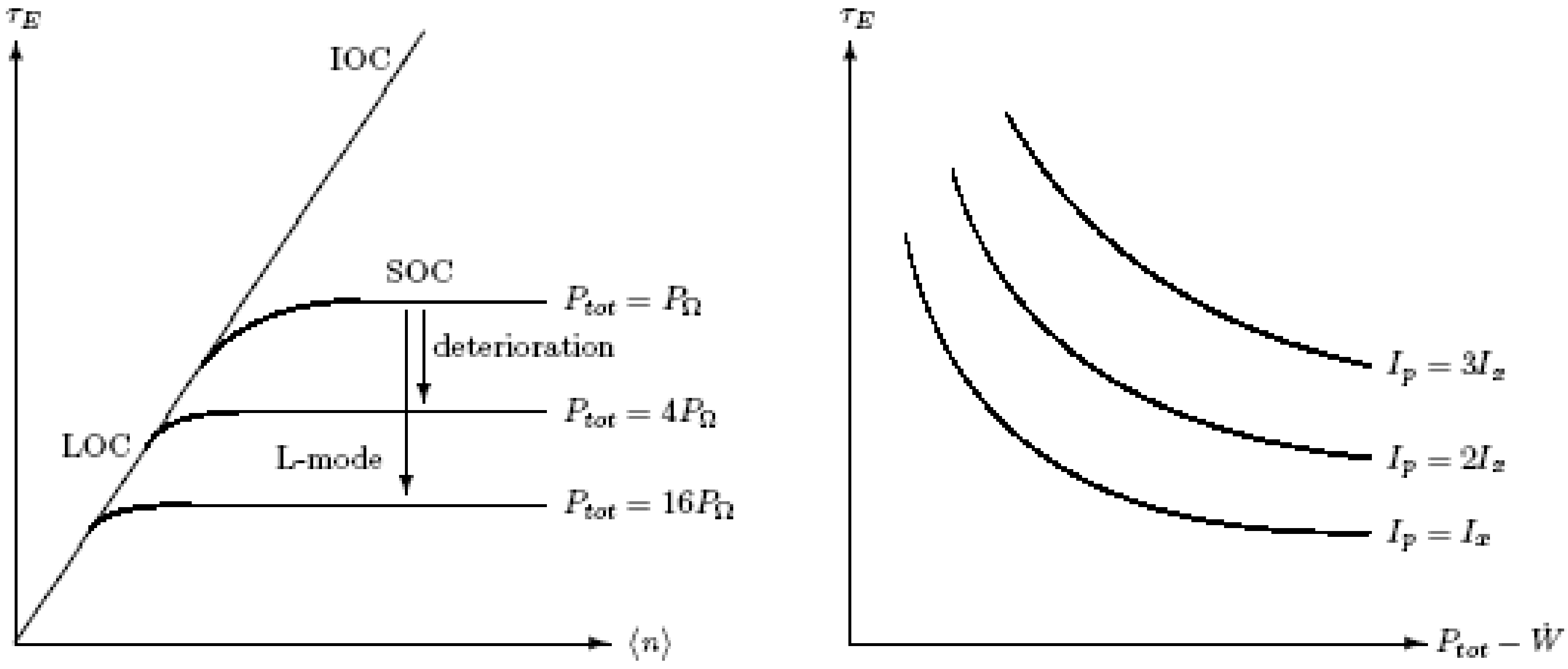



(Result from Tore SUPRA)

# 7. Experimental results b: additionally heated plasmas

Disappointing results at first: even worse than SOC: **L-mode**:

- W ~ $P_{tot}^{0.5}$ only → $\tau_E$ ~ $P_{tot}^{-0.5}$
- W nearly independent of n (like SOC)
- $\tau_E$ increases with $I_p$

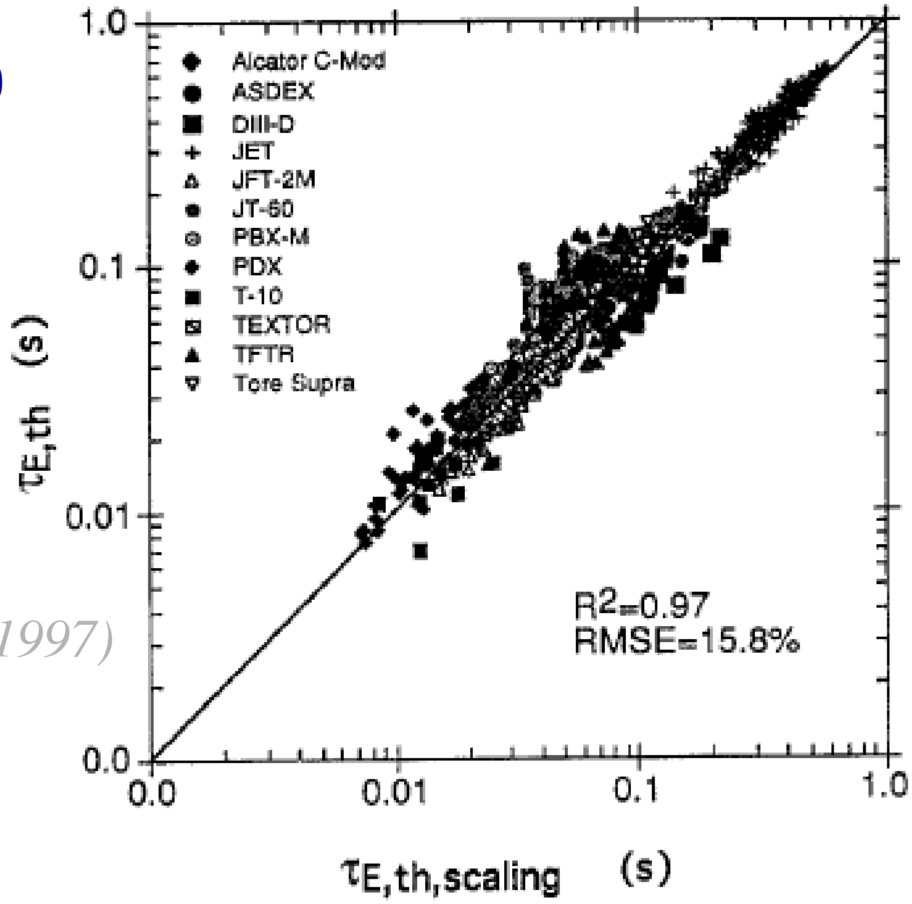


# additionally heated plasmas *(ctd)*
# *scaling laws*

L-mode Scaling Law, based on ~1800 discharges covering wide range of parameters :

$$\tau_E = 0.037\ I_p^{0.74}\ B^{0.2}\ \kappa^{0.67}\ R^{1.38}\ a^{0.31}\ n^{0.24}\ M^{0.26}\ P^{-0.57}$$

*From Kaye et al, NF 37 (1997)*




*Drawback:*
*based on experimental knob settings*
*in stead of characteristic dimensionless parameters*
*(which would give insight into physics mechanisms)*

# additionally heated plasmas *(ctd)*
# *local transport*

**Some notes** (not exhaustive):

a. L-mode deterioration of confinement reflected in the local heat diffusivities

b. In general $\chi_e^{eff} \sim \chi_i^{eff} \sim D_{momentum}$

c. At high power $\chi_i^{eff}$ may be ~ 10 * neoclassical prediction

d. Perturbative experiments (heat- and particle pulse propagation) → off-diagonal elements in the transport matrix are important
E.g. the particle flux is strongly influenced by temperature gradients

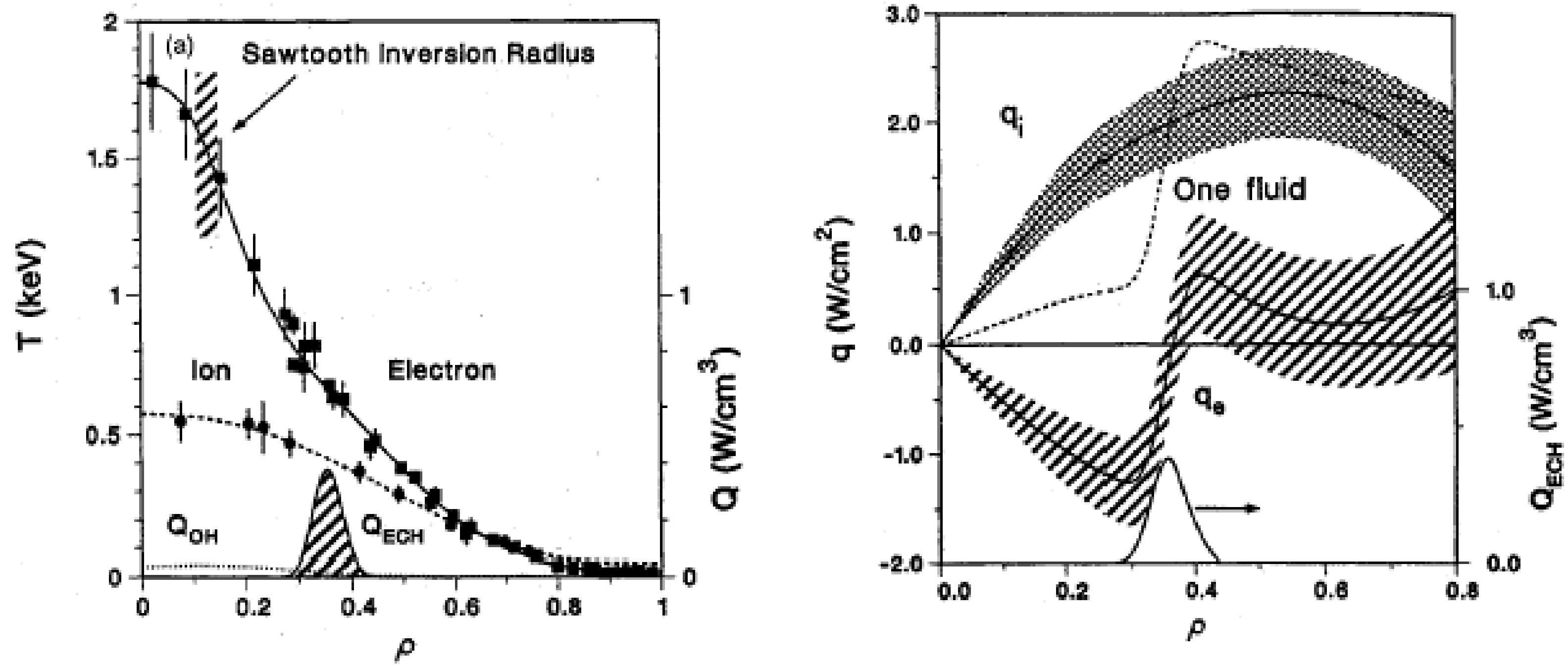
# additionally heated plasmas *(ctd)*
# *local transport*

**Some notes** (ctd):

e) Off-axis ECRH in DIII-D →

→ electron "heat-pinch", i.e. net inward electron heat flux, not present in the total heat flux

→ role of off-axis terms in transport matrix important



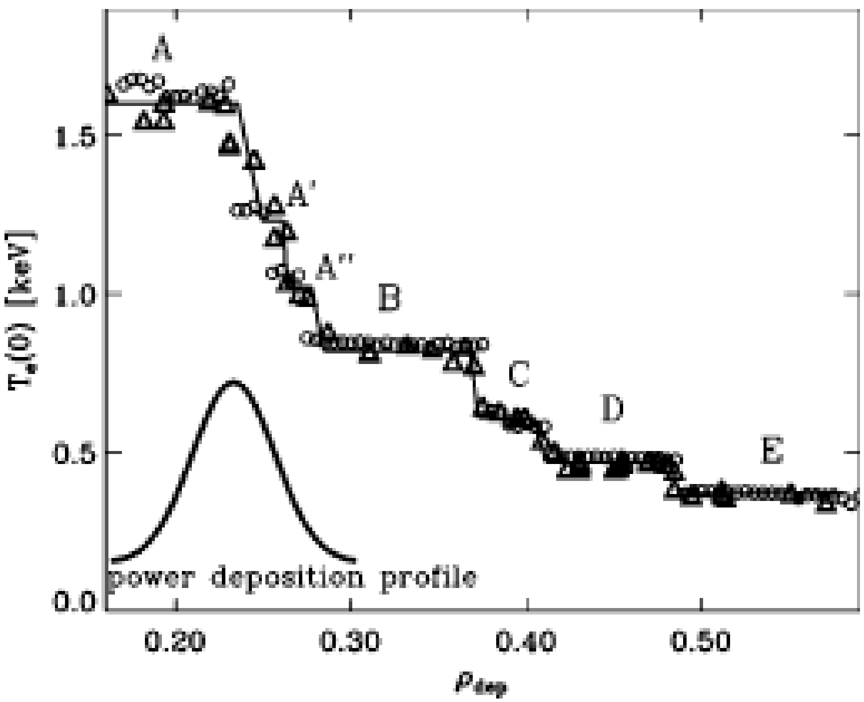

*From Petty et al, NF 34 (1994)*

# additionally heated plasmas *(ctd)*
# *local transport*

**Some notes** (ctd):

f) Inhomogeneous diffusion:
Thomson scattering at Dutch RTP with spatial resolution of 1% of a
→ strong electron thermal barriers near radii with q(r) ≈ (half-)integer
→ Suggests L-mode confinement is in reality a global description of a very inhomogeneous and discontinuous plasma state

*From de Baar et al, PP 6 (1999)*



# 8. Improved confinement
## *a. Theory (very globally)*

**Turbulence suppression**:

a. Direct reduction/quench of growth rate

*e.g.* $\gamma_{ITG}$ *decreased by density peaking*

b. Tear apart turbulent eddies by ExB shear

condition: $\gamma_{ExB} > \gamma_{lin}$

Note that $E_r$ has 3 components, determined by $v_\phi$, $v_\theta$ and $\nabla p$

So shear in one of those may locally suppress turbulence

**Role of magnetic field**:

a. Magnetic shear s may influence growth rate

b. Density of rational surfaces (gap near zero shear surface; gap near low rational q values); gap prevents mode coupling

# 8. improved confinement

## *b. Experimental results*

**Improved confinement conditions in chronological order:**

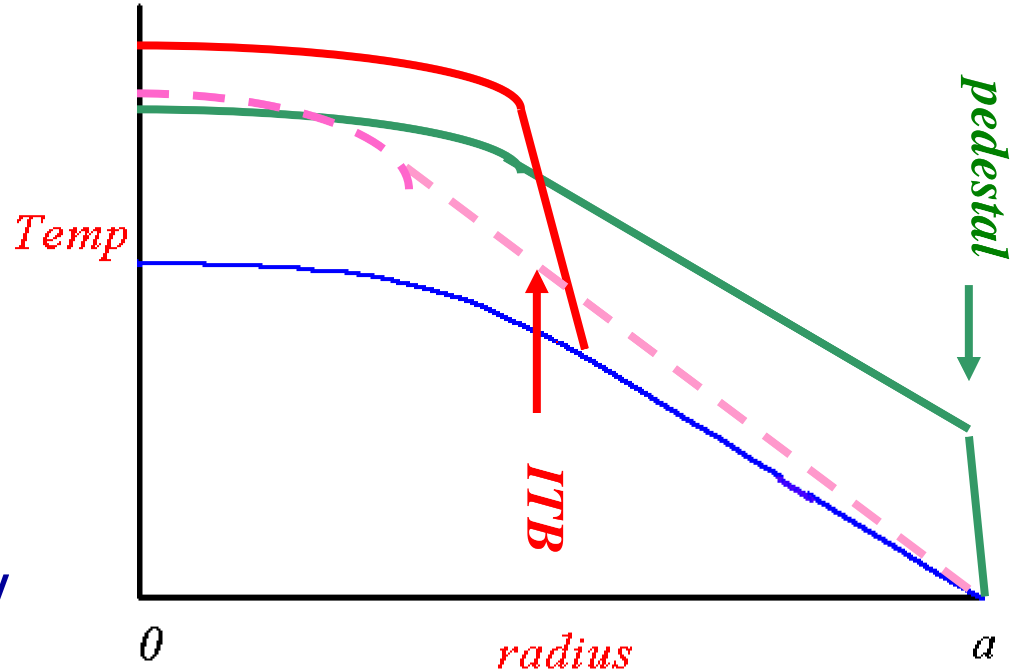
a. **H-mode = High Confinement mode**
b. **Peaked density (Supershots, PEP-modes)**
c. **Inverted shear by hollow j-proflles (NCS; PEP-modes)**
d. **RI-modes (Radiative Improved modes)**

# Improved confinement classification

Improved confinement may be due to:

- edge transport barrier (ETB or 'pedestal')
- internal transport barrier (ITB)
- general steepening of profiles

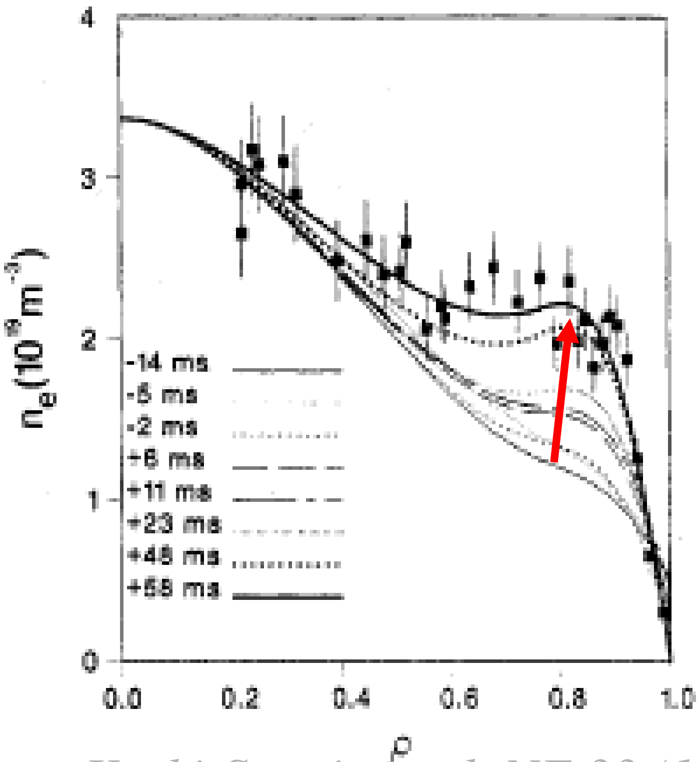
In first 2 cases transport locally maybe down to neo-classical



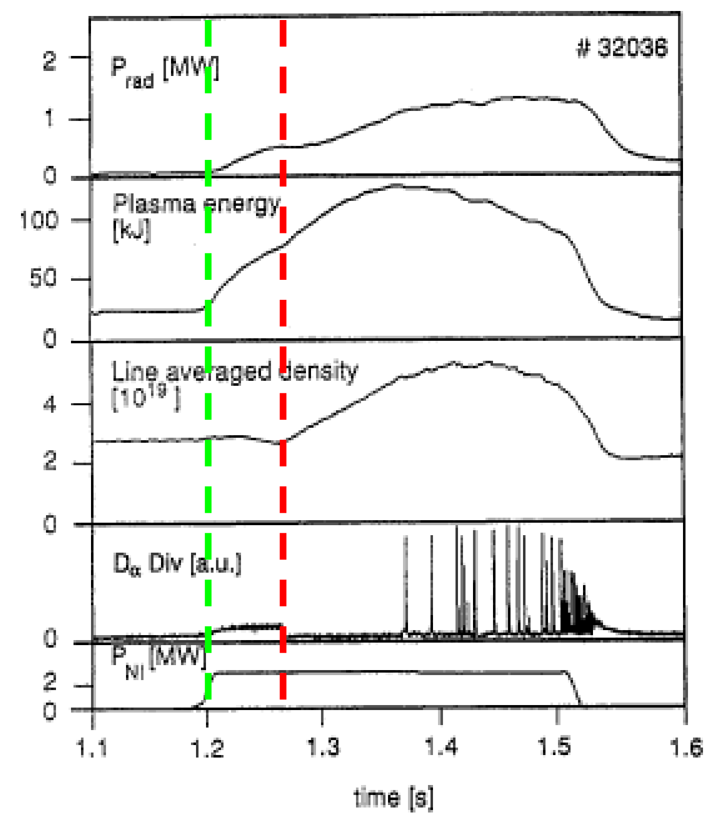
# a. H-mode = High Confinement mode

**L→ H transition:**
- first on ASDEX (mid 80ies), then on all large tokamaks
- sudden development of edge barrier ('pedestal') on all channels

*Density profile evolution (DIII-D)*




*Transition on ASDEX*



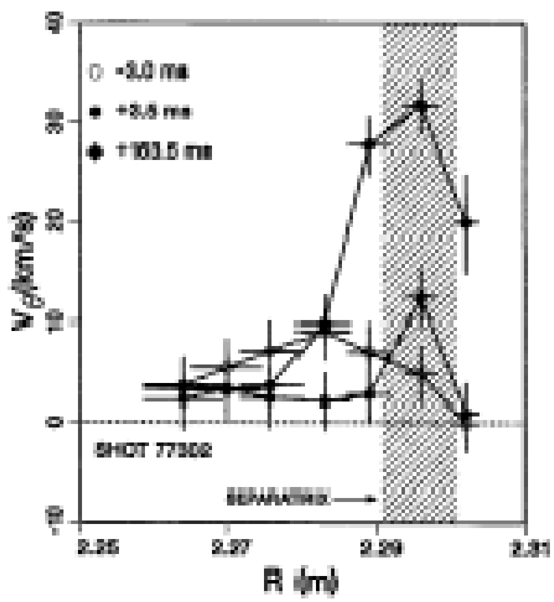

*From Kurki-Suonio et al, NF 33 (1993)*

# a. H-mode = High Confinement mode *(ctd)*

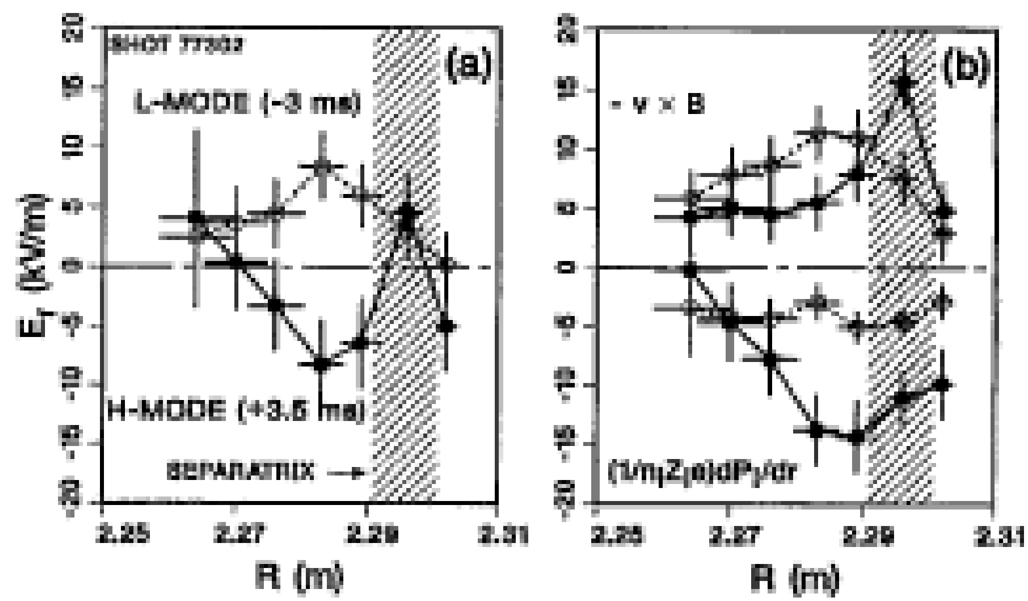
**L→ H transition:**

- only above critical level of heat flux
- sudden change in poloidal edge rotation and in $E_r$
  (supports ExB-shear hypothesis)

*Poloidal rotation (DIII-D)*




*$E_r$ evolution (DIII-D)*

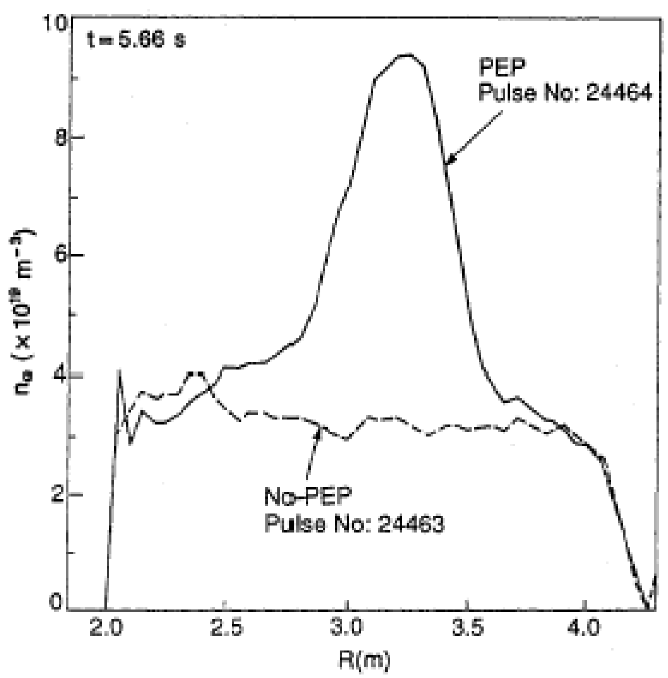


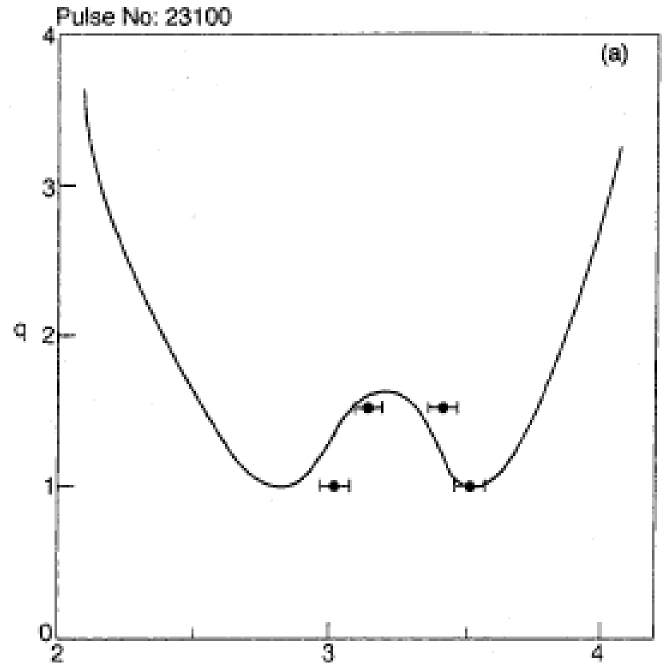

*From Burrell et al, PP 1 (1994)*

# b. Peaked density (PEP-mode, Supershots)

**PEP (=Pellet Enhanced Performance) Mode in JET:**

- create very peaked density profile with deep pellet fuelling
- strong bootstrap current due to large ∇n → reversed shear
- reduced transport



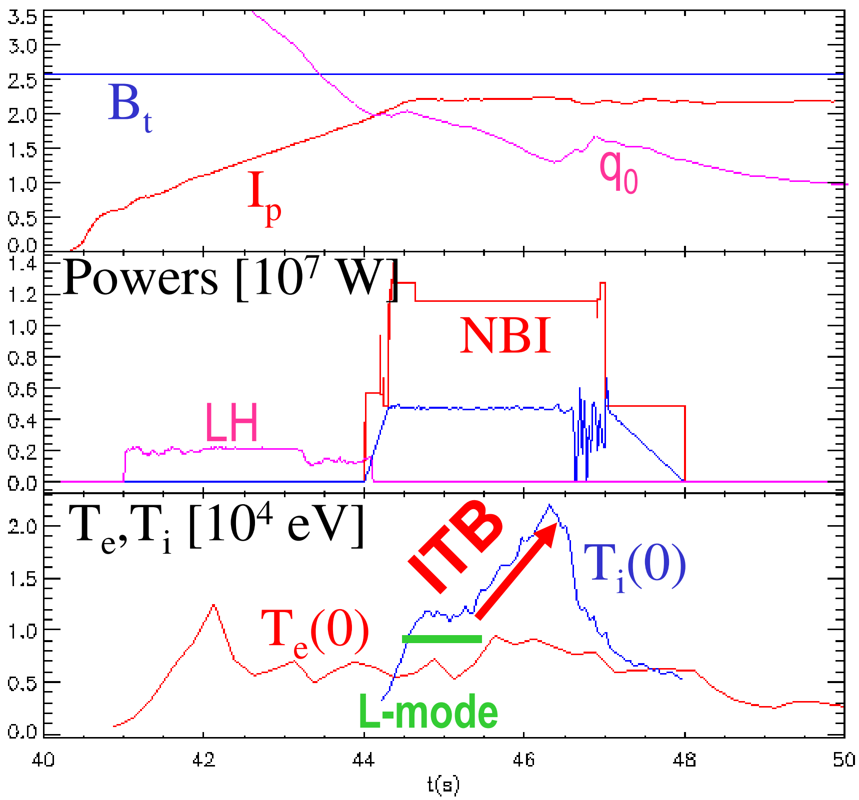




*From Smeulders et al, NF 35 (1995)*

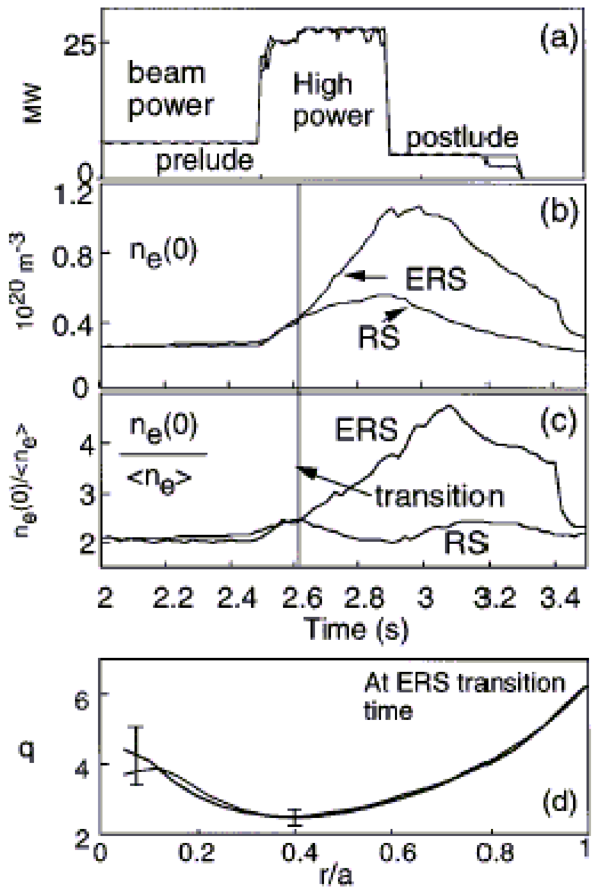
# c. Inverted/low shear (hollow/flat j-profile)

Terminology:
NCS (Negative Central Shear) = RS (Reversed Shear)
OS = Optimized Shear (used for regime with flat but not reversed shear)

*JET OS example:*




*TFTR NCS example:*



# c. Inverted/low shear *(ctd)*

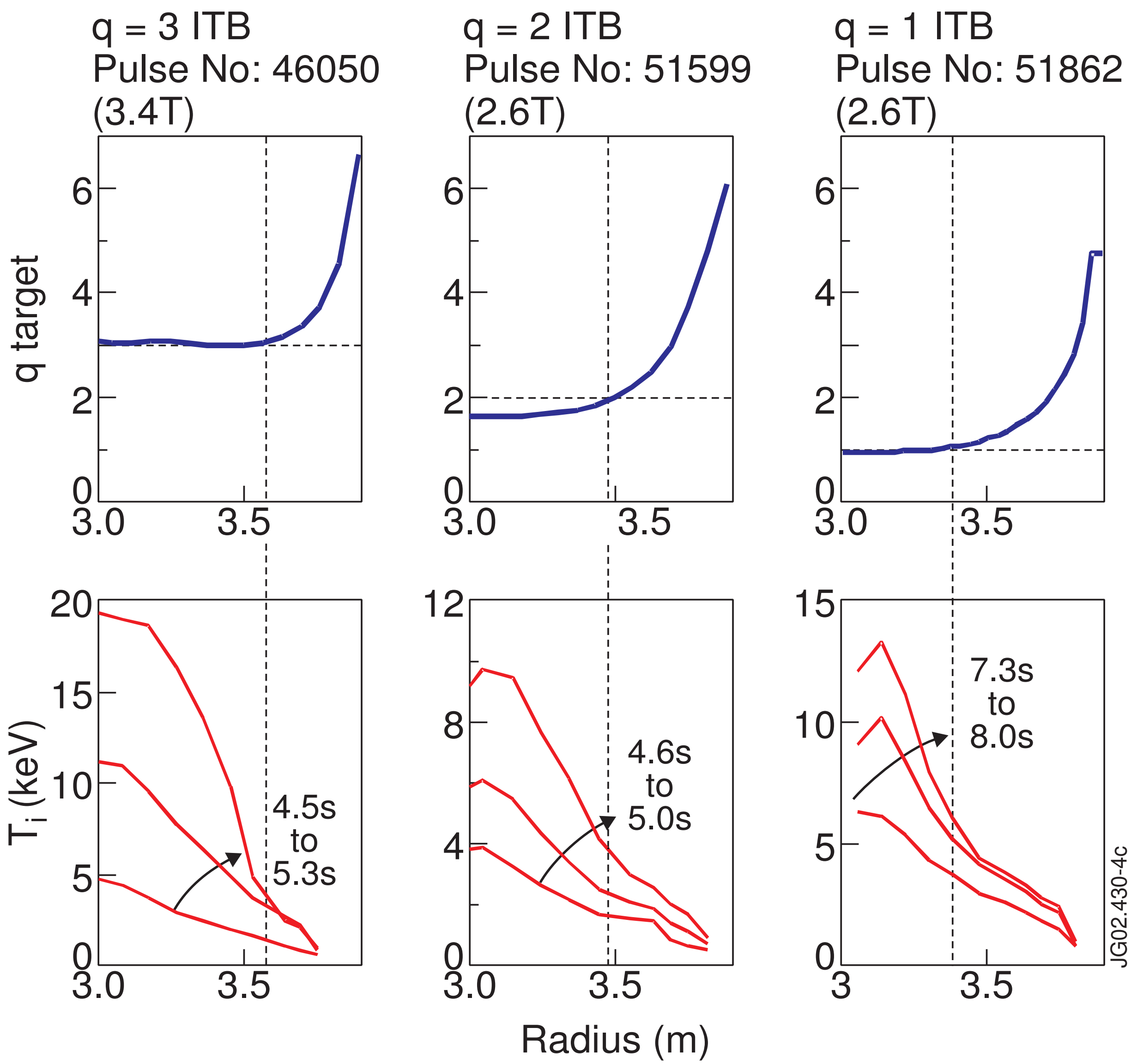
As $E_r$ has three terms, with $v_{tor}$, $v_{pol}$, and $\nabla p$, respectively, increasing input power and/or torque would help to meet criterium $\gamma_{ExB} > \gamma_{lin}$

Indeed, in JET OS and TFTR NCS discharges a threshold power has to be exceeded to trigger an ITB

*However …..*

- *this is not so in JET Reversed Shear*
- *timing of input power important -> points towards role of q*

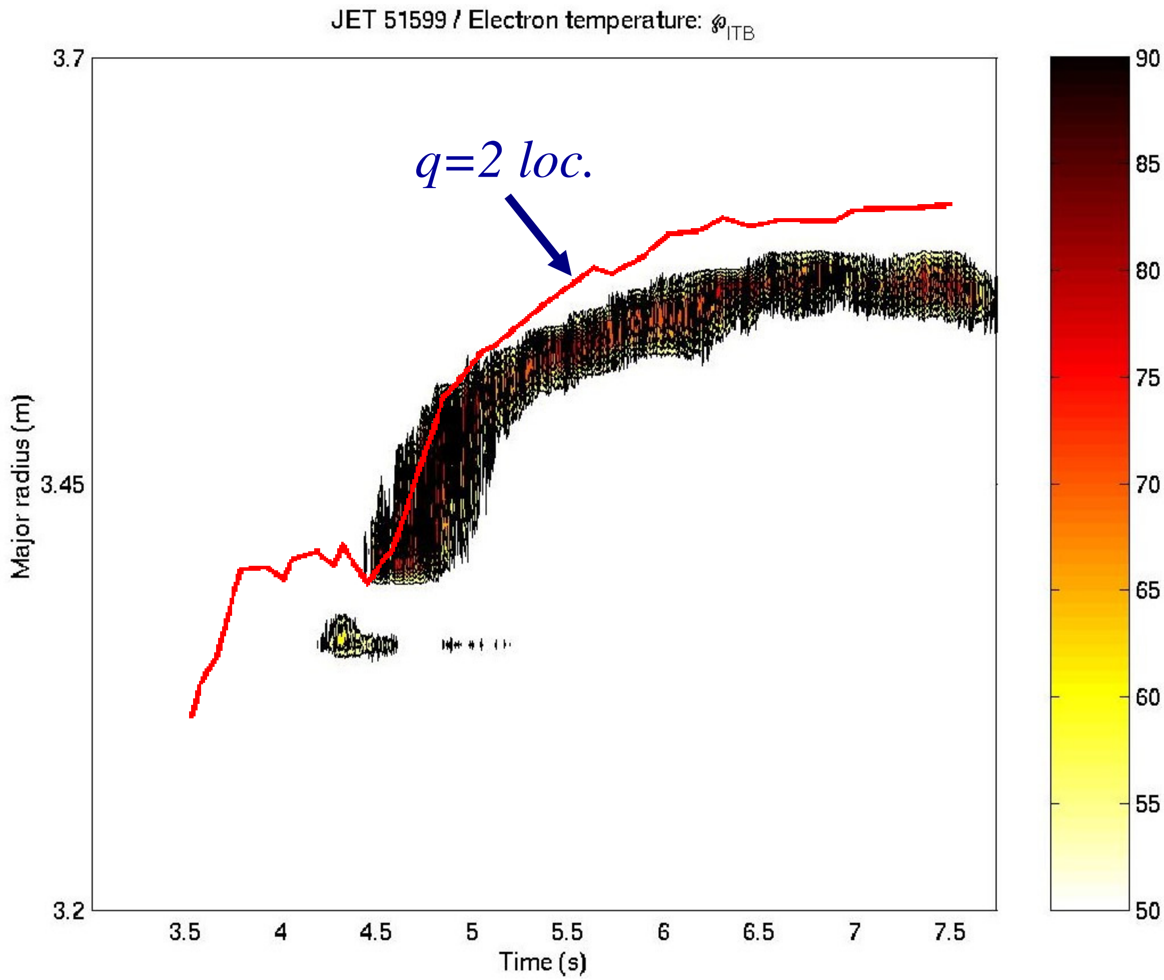
# RS/OS (ctd)




*OS in JET:*
*ITB formed when*
*$q_{min}$ crosses 3, 2, 1*

*From Joffrin et al, NF 42 (2002)*

# RS/OS (ctd):
## *evolution of ITB in Optimized Shear plasmas*



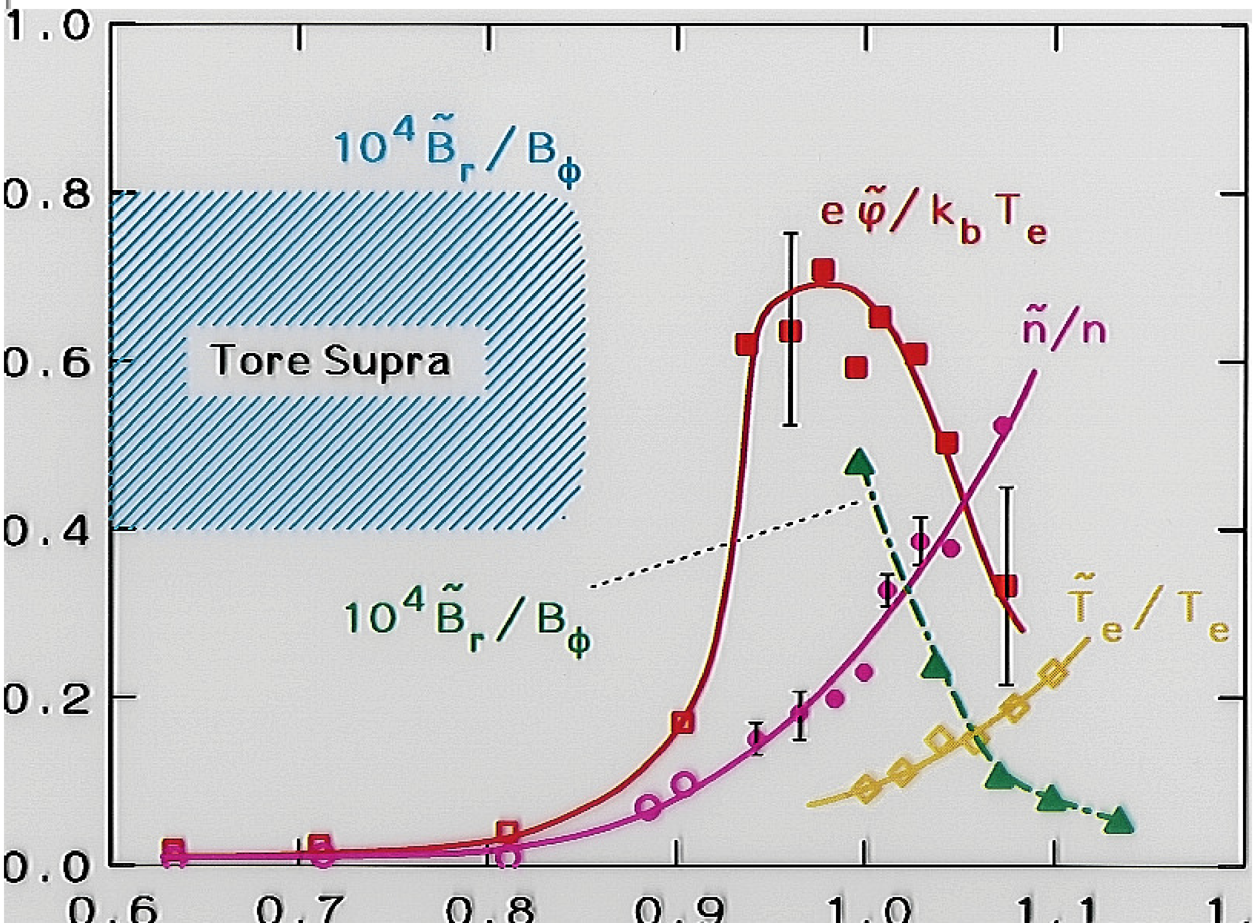

Once triggered, the ITB amplifies itself due to evolution of plasma parameters – does q profile play role in ITB evolution ?

*First an example of ITB evolution in an OS discharge :*

*Yes, ITB follows q=2*

# 9. Fluctuations

*Summary of measurements (TEXT, Tore Supra):*




*r/a*

Turbulence summarized
Edge:
broad band ($\Phi^{\sim}$,$n^{\sim}$),
probably electrostatic,
up to 10s %

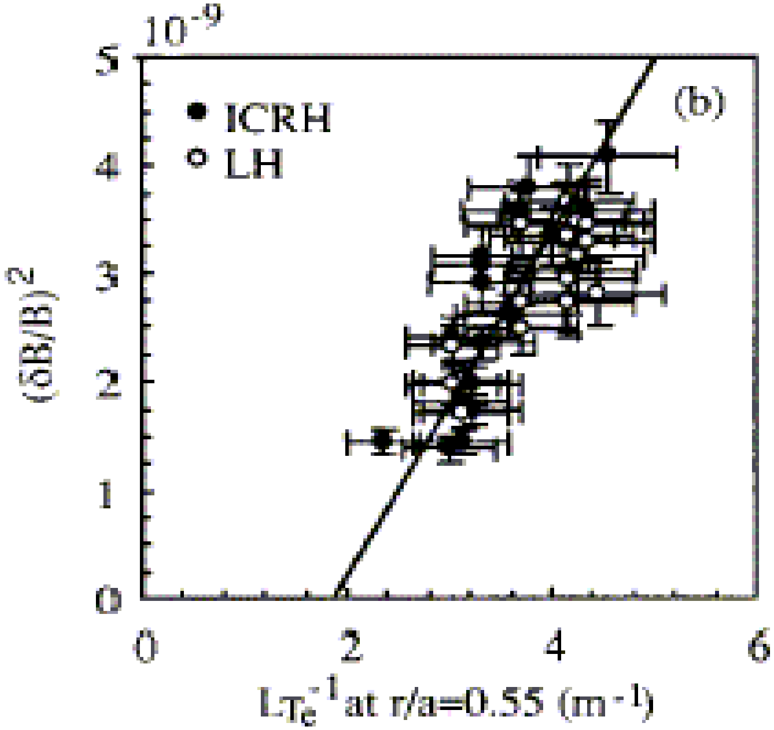
Core:
other broad band
($n^{\sim}$,$B^{\sim}$),
likely magnetic,
few % ($n^{\sim}$),
few 0.1% ($B^{\sim}$)

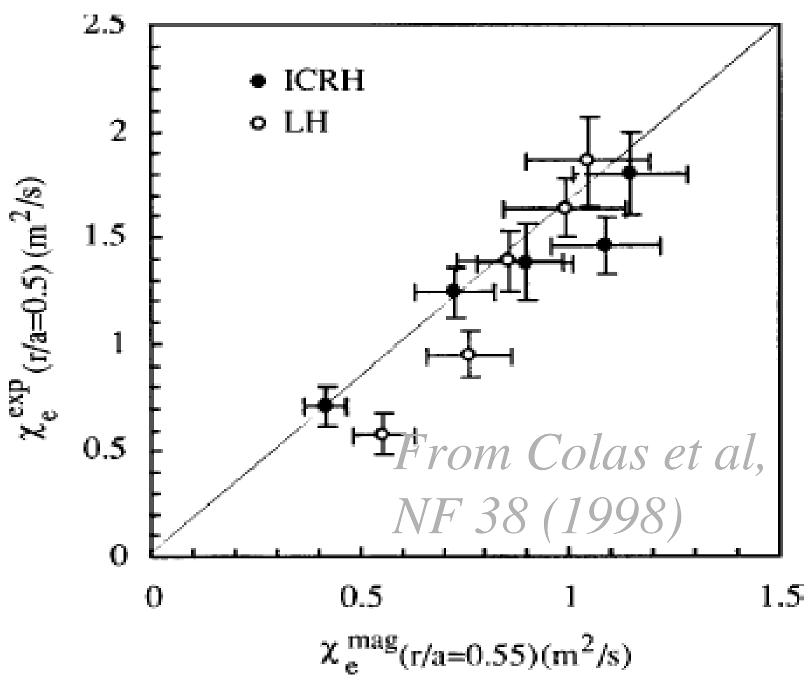
# Fluctuations: link with transport *quantitatively*

Ideal: **quantitative agreement**

measured fluctuation level ←→ observed heat/particle transport

<u>Example</u>: measurement of magnetic turbulence in Tore Supra: fluctuation level ~ 5 $10^{-5}$, inducing right level of electron heat transport




*From Colas et al, NF 38 (1998)*

*Strong argument in favour of magnetic turbulence as driving force of anomalous electron heat transport!*

# Fluctuations: link with transport *qualitatively*

**Qualitative agreement** is another way to prove the role of fluctuations.

- Either in time,

  i.e. sudden drop of turbulence level at transition to an enhanced confinement regime

- Or in radial position,

  i.e. radial dependence of the turbulence level reflects radial dependence of transport level

Either of this is a strong indicator that indeed the fluctuations were driving the anomalous transport

Many **observations of this**, e.g:

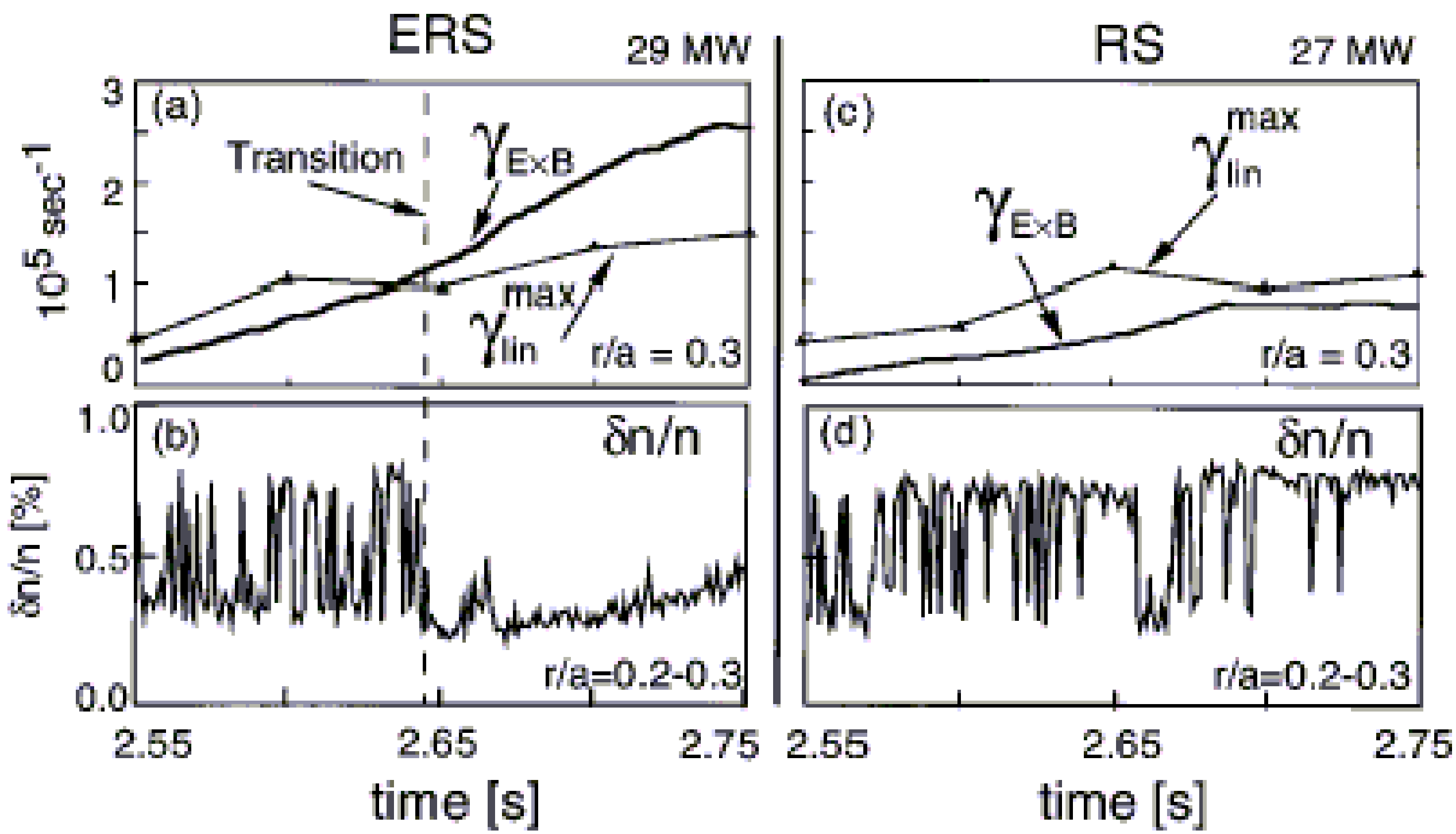
1. Transition RS → ERS in TFTR (E stands for Enhanced),
2. Electron ITB in electron heated JET discharges:

   fluctuation level sharply increases outside the ITB

3. Transition L → RI in TEXTOR: edge fluctuations sharply drop

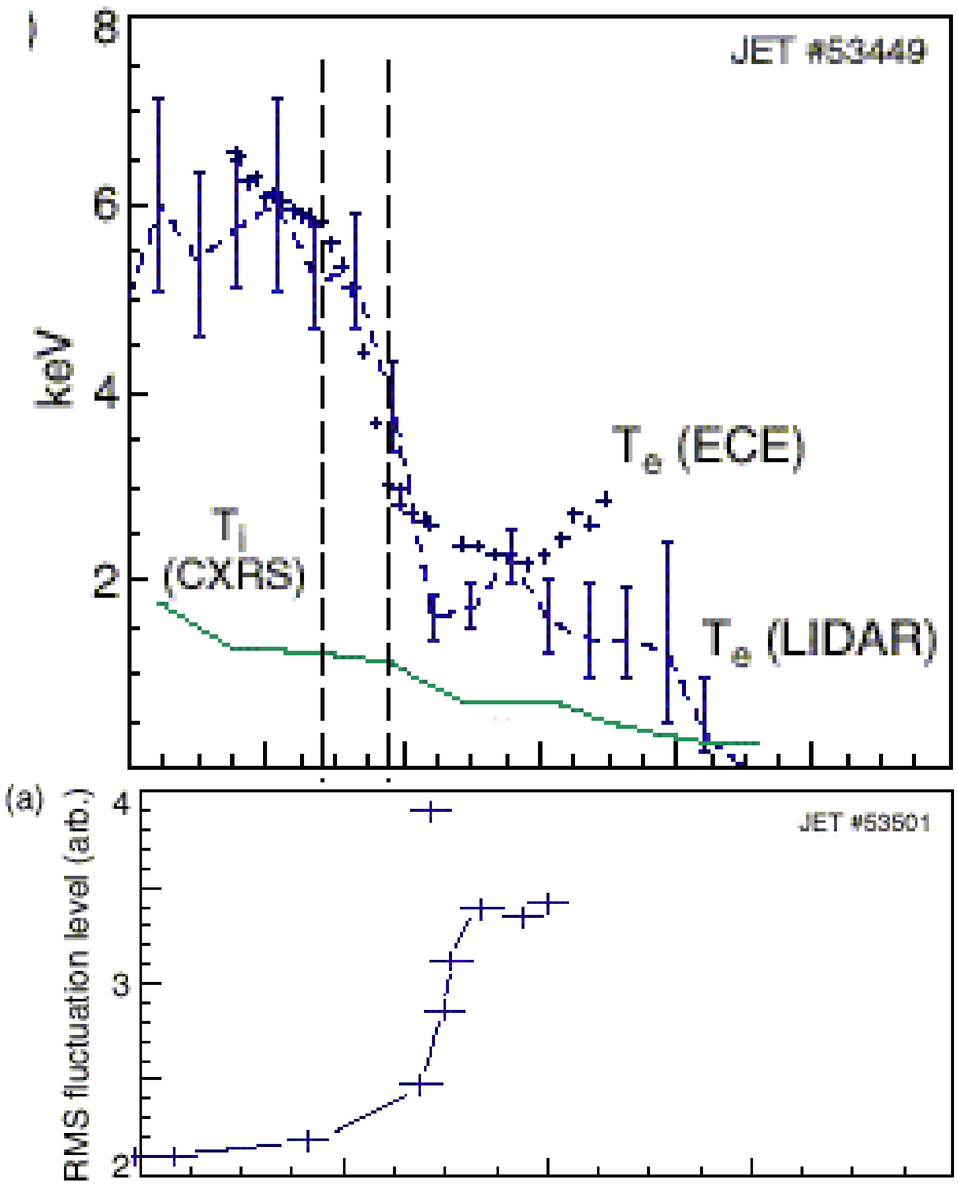
# Link with transport *qualitatively (ctd)*

Example 1 : Transition RS → ERS in TFTR (change in **time)**




*From Synakowski et al, PP 4 (1997)*

# Link with transport *qualitatively (ctd)*

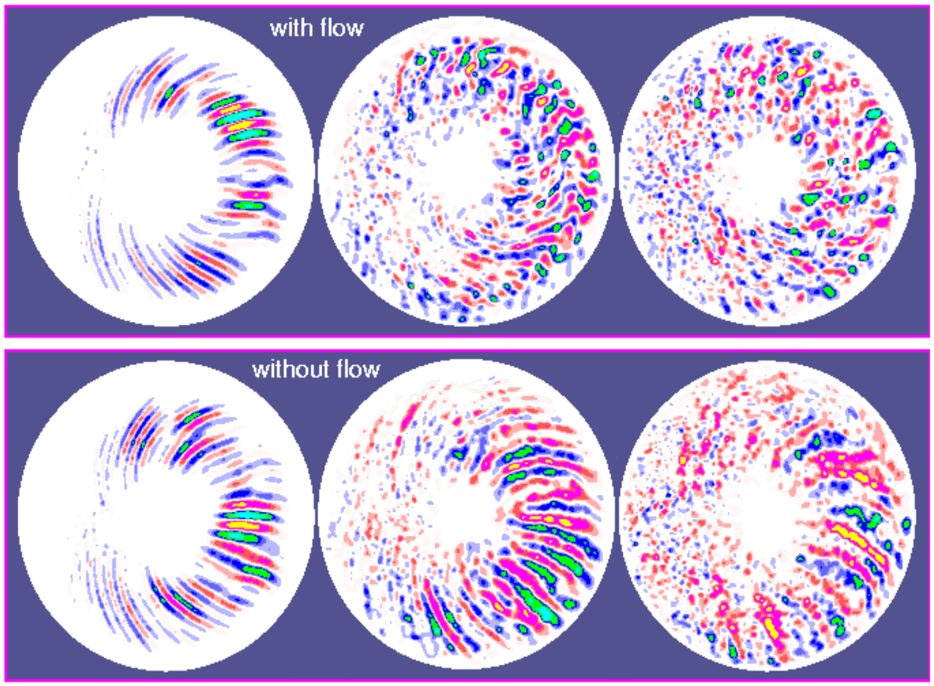



Example 2 : Electron ITB
In electron heated JET discharges (change in **place**)

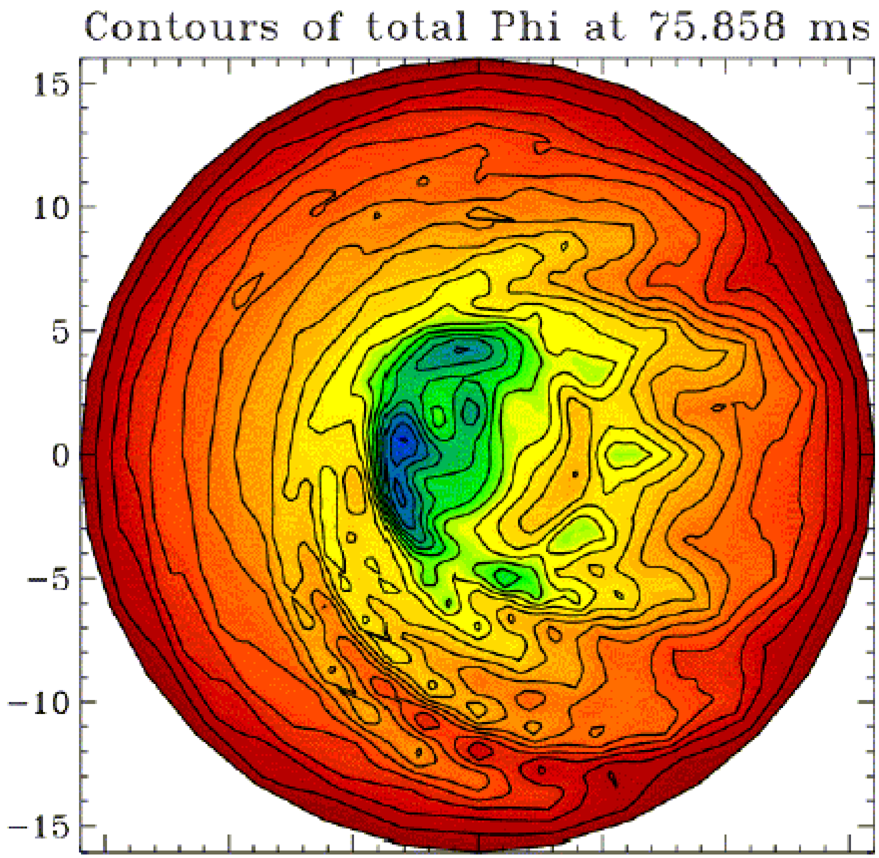
*From Conway et al, PPCF 44 (2002), p.1167*

# Fluctuations *(final remark)*

**Important note**: simulations show that turbulence is truly 3D, so 1D-measurements don't tell us the (full) truth ….




Z. Lin, Science 281 (1998) 1835




A.Thyagaraja, RTP-simulation

# 10. Discussion & Conclusions

## *position of theory*

- Collisional (neo-classical) transport theory:

  well understood

  + : correct for some transport channels (j, heat transport // B)

  - : way off for cross-field thermal transport

-Drift wave theory (electrostatic turbulence)

  Most eleborated anomalous transport model

  Many 'branches (ITG, TEM, ….)

  + : Magnitude of (ion) transport coeff. reasonably correct

  + : Density fluctuation level as predicted

  - : Radial dependence of coefficients deviates

  - : Does not explain many exp. observations, impying that other mechanisms are (also) active

# 10. Discussion & Conclusions

## *final remarks*

- Transport in tokamaks is of turbulent nature
- Probably 2 or 3 turbulence mechanisms acting at the same time
- Turbulence causes the particle, momentum and heat transport to vary simultaneously in a similar way
- There are strong non-diagonal elements in the transport matrix
- Turbulence level can be reduced by
    - steepening of the density profile (IOC, supershot, RI-mode)
    - change of the shear in $E_r$ (H-mode)
    - inversion of the magnetic shear (NCS, PEP-mode)
    - maybe increase in magnetic shear (current ramp)

Final remark: Probably incorrect to consider electrostatic turbulence neglecting magnetic turbulence;
Unified theory needed, with broken magnetic field topology,
in the presence of potential fluctuations such that
field and potential fluctuations mutually reinforce each other