The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1953-17

International Workshop on the Frontiers of Modern Plasma Physics

14 - 25 July 2008

Organised and self-organised magnetic confinement.

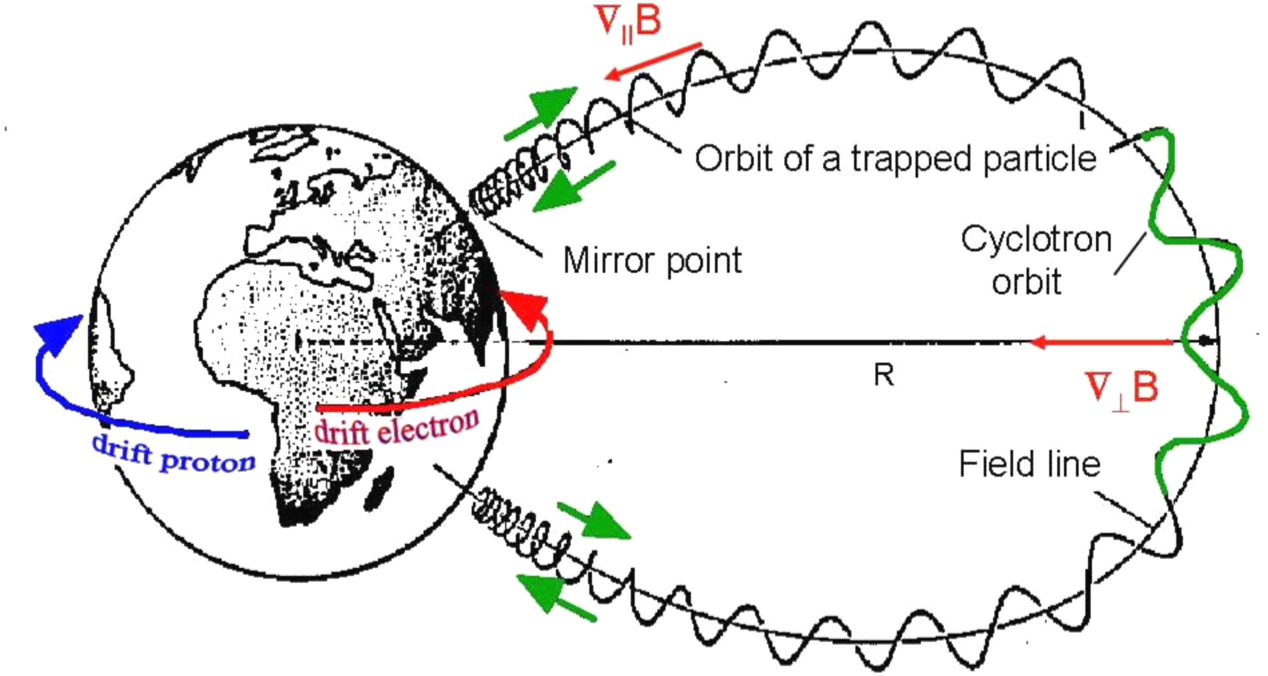
F. Wagner

Max Planck Institute for Plasma Physik
Greifswald
Germany

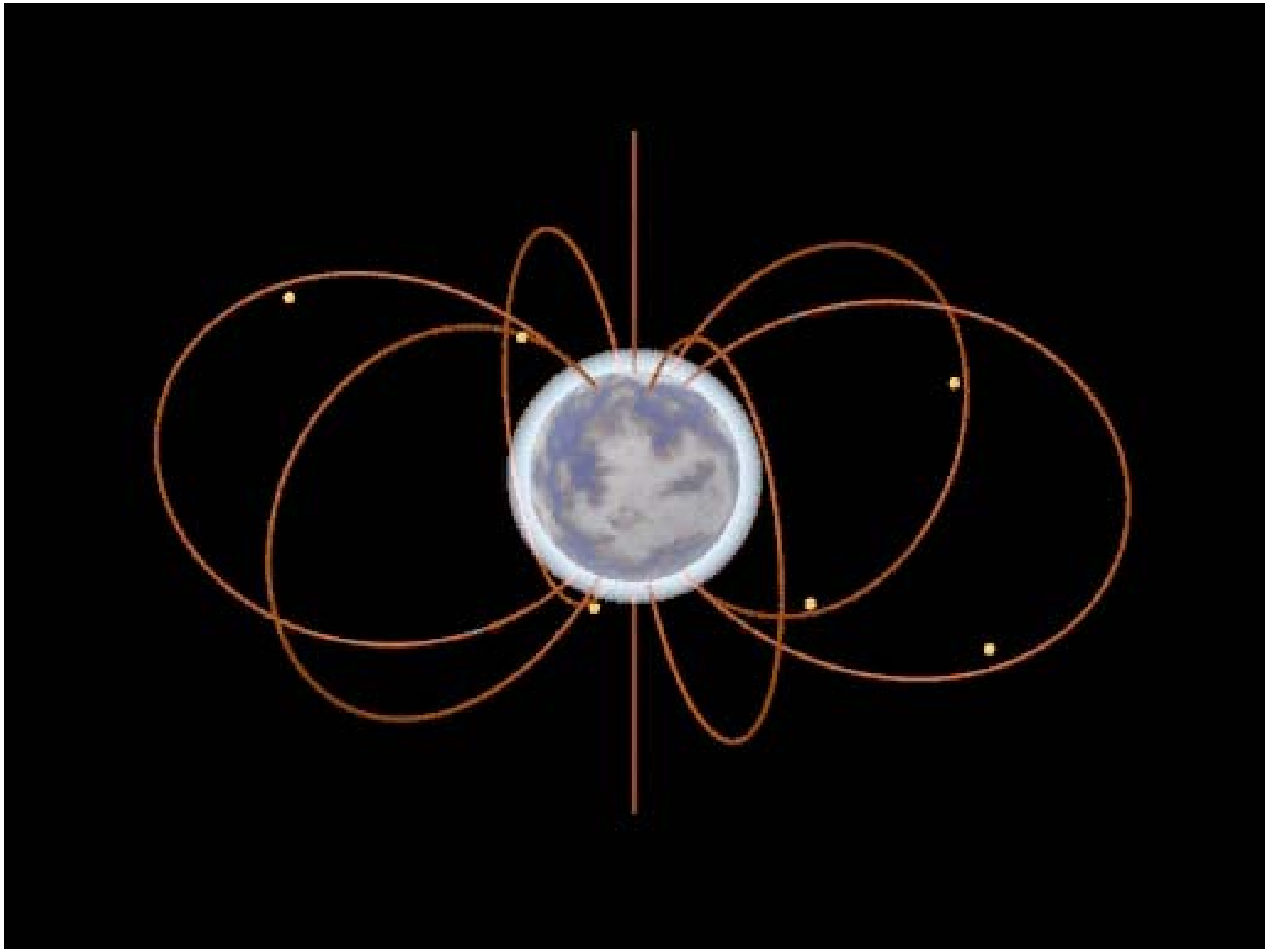
Organised and self-organised magnetic confinement

F. Wagner
Max-Planck Institut für Plasmaphysik, Greifswald, Germany
EURATOM Association

Particle orbits in inhomogeneous field



Particle orbits in inhomogeneous field

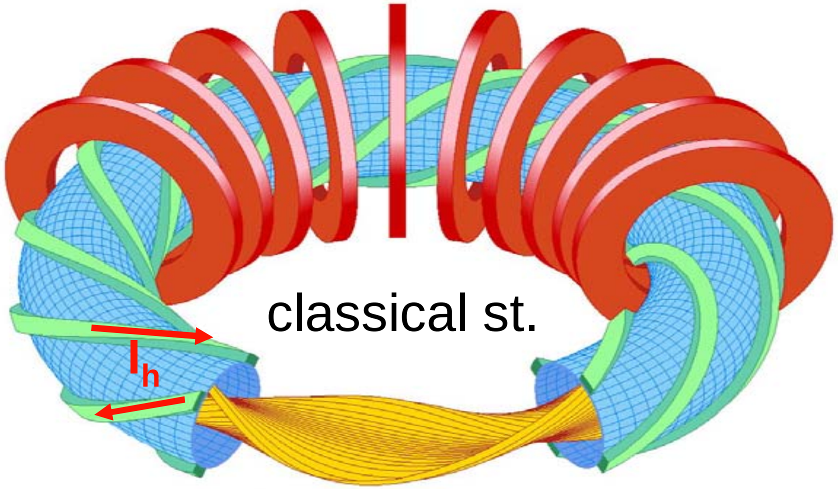


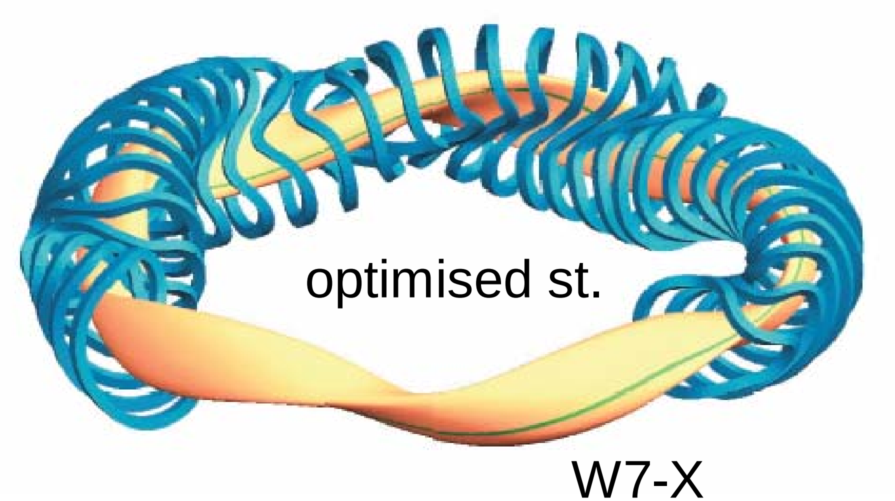
Two toroidal confinement systems

Issues of toroidal confinement:

- nested flux surfaces
- B_θ: rotational transform; confinement
- B_ϕ: stability
- geometry: no endlosses
- inhomogeneous field: B ~ 1/R

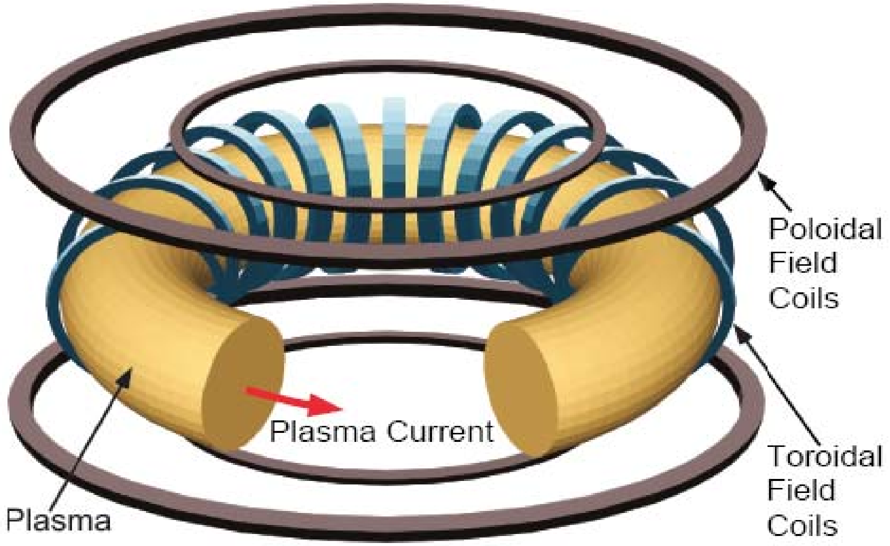
Stellarator





W7-X

Tokamak



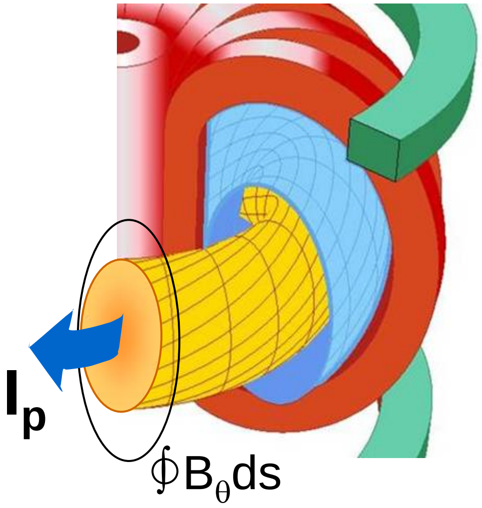
Why stellarators ?

Tokamak and stellarator are complementary

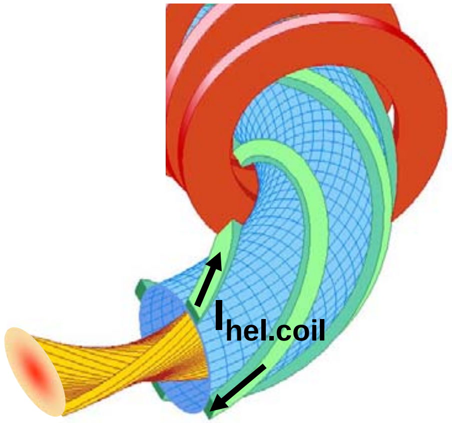
- in the tokamak, the current flows in the plasma
- in the stellarator, it flows in the coils
- the tokamak is pulsed
- the stellarator is for steady-state operation
- the tokamak can develop detrimental instabilities
- the stellarator is not 2-dimensional

The role of symmetry

Tokamak



Stellarator



Ampere´s law

Tokamak: **curl B = μ_0j**

Geometry: 2D: **B** = **B**(ψ,θ); $\partial/\partial\phi=0$

Stellarator: **curl B = 0**

3D: **B** = **B**(ψ,ϕ,θ)

no continuous symmetry;
Instead: toroidal periodicity: N

Noether's theorem

Emmy Noether

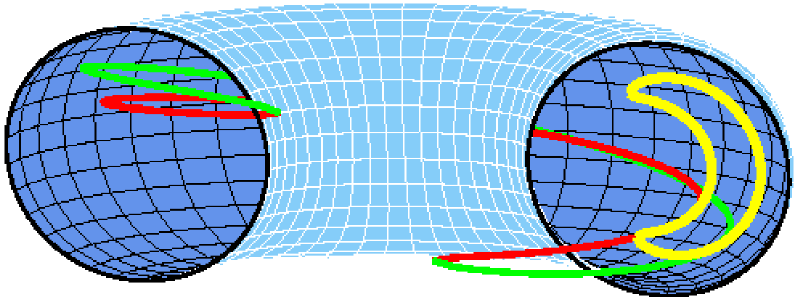
Theorem: in case of continuous symmetry an associated quantity is conserved

Here:
the canonical angular momentum p_ϕ

The consequence for 2D

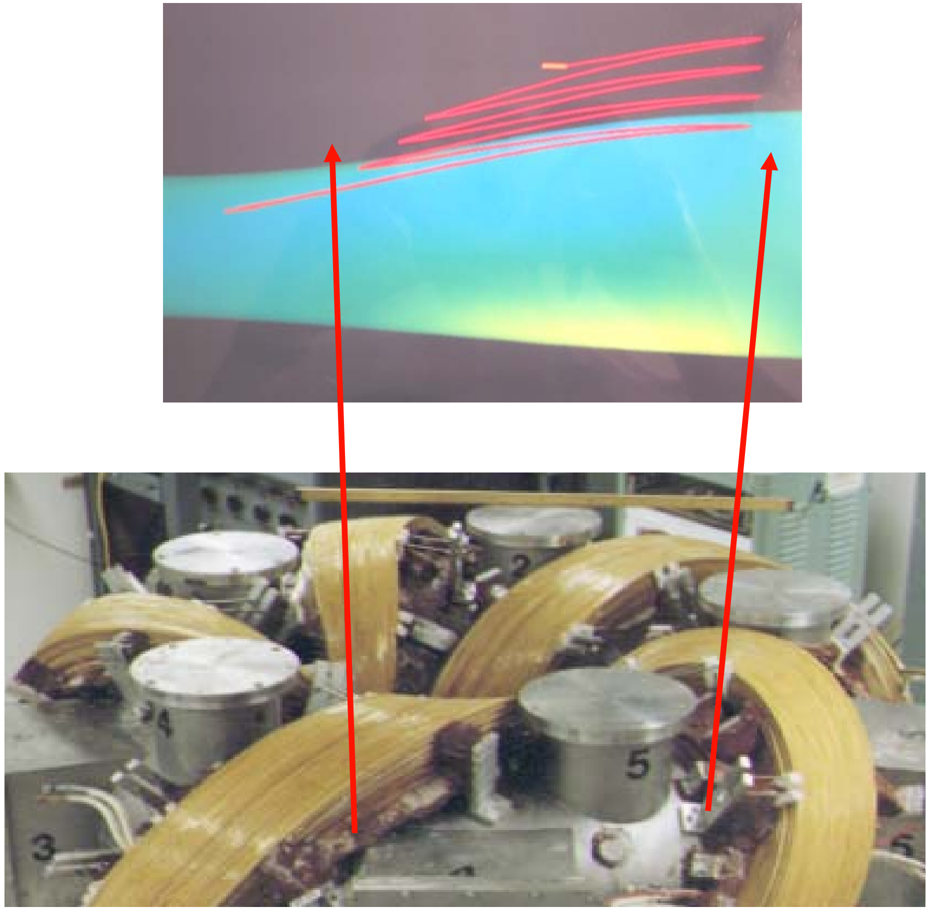
Orbits are periodic and particles are confined

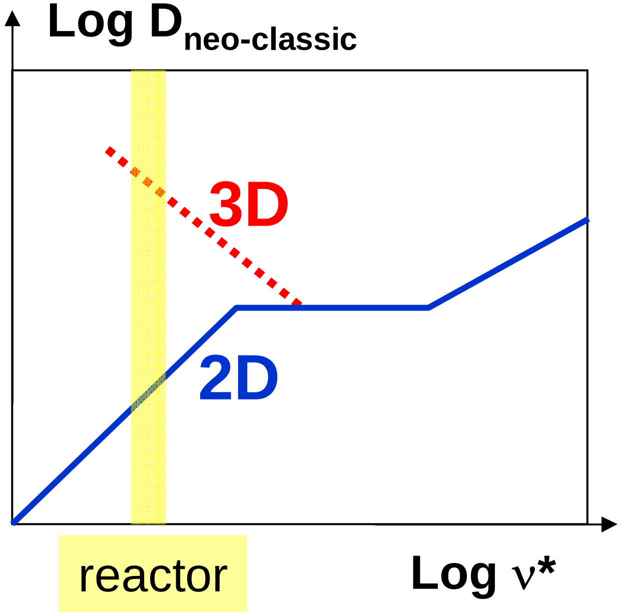
Banana particles



Consequence for 3D

helical ripple leads to collisionless
thermal and energetic particle losses





Neo-classical fluxes have
bad temperature scaling

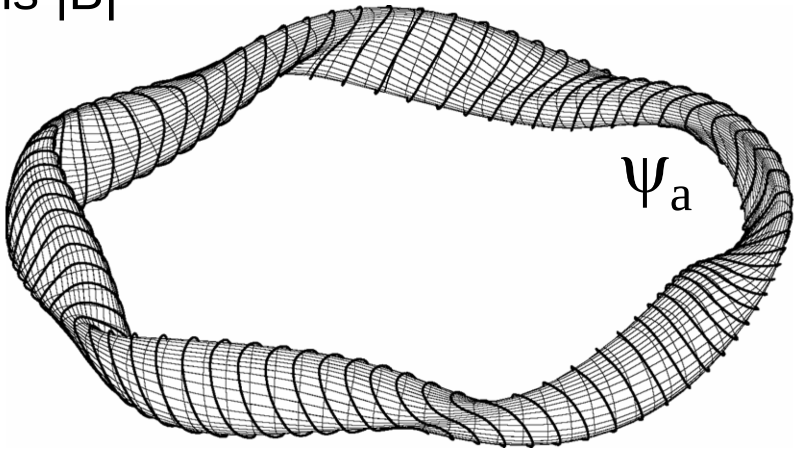
Stellarators
need optimisation

First topic: organised magn. confinement

Principle of stellarator optimisation

A. Boozer:

the relevant quantity for particle confinement is |B|
not **B** = (B_x, B_y, B_z)



J. Nührenberg:

|B| can be made 2D in (3D) helical systems
(expressed in magnetic coordinates)
⇨ quasi-symmetric systems

The plasma properties inside the volume ψ_a are determined by the geometry of ψ_a

Optimisation by variation of the shape of the flux surface geometry in a high-dimensional configuration space

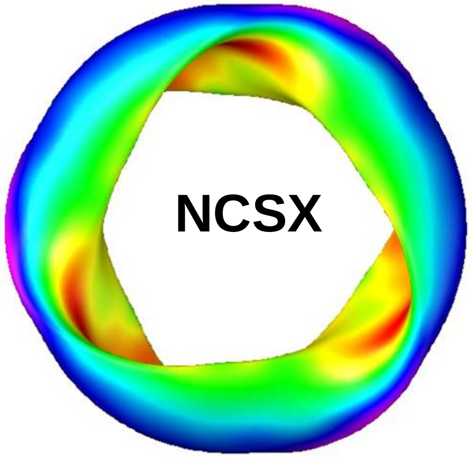
The optimisation procedure fixes geometrical parameters: A, κ, δ, N, iota, ..

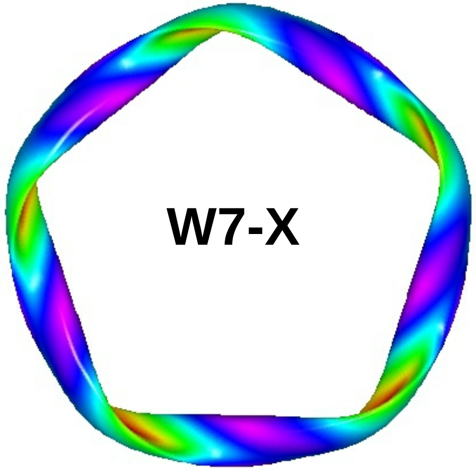
The family of quasi-symmetric systems

Quasi-helical

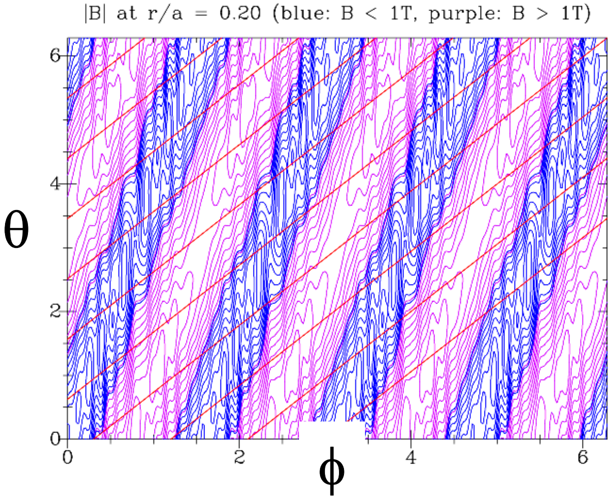
axial

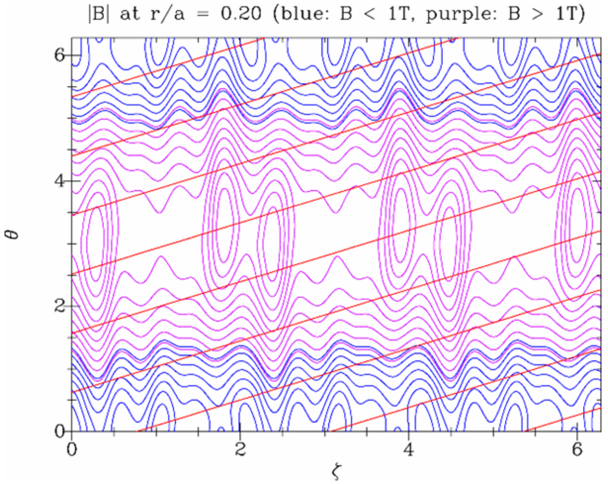
poloidal (isodynamic)

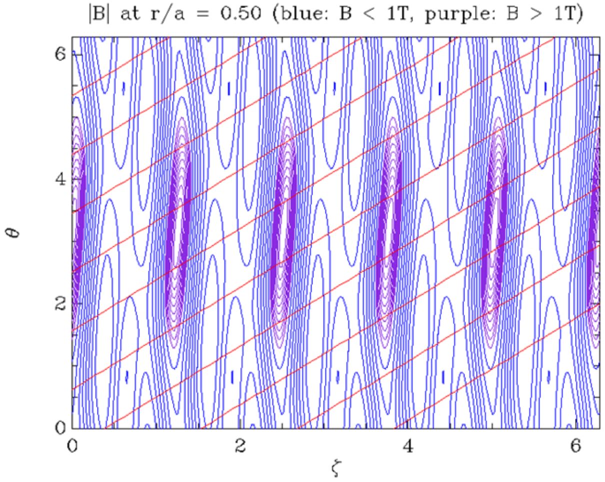




modB surfaces


|B| at r/a = 0.20 (blue: B < 1T, purple: B > 1T)


|B| at r/a = 0.20 (blue: B < 1T, purple: B > 1T)


|B| at r/a = 0.50 (blue: B < 1T, purple: B > 1T)

The physics behind optimisation

Principles of optimisation:

- reduction of trapped particle fraction => linked mirror concept

- reduction of radial particle drift
    => strong elongation => lower curvature
    => small variation of |B| along **B**

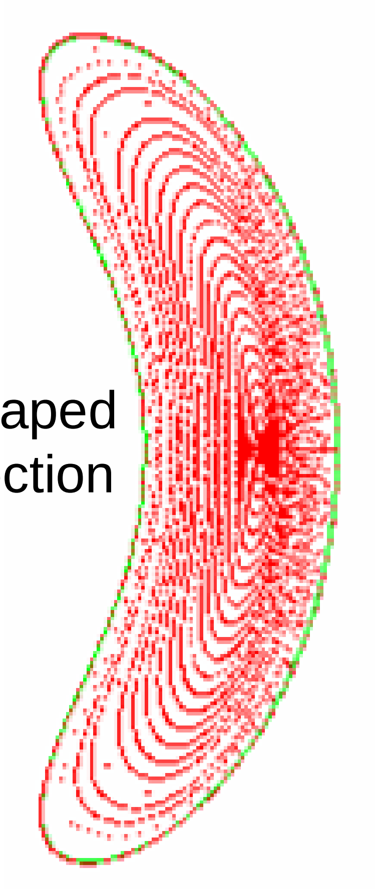
Small Pfirsch-Schlüter currents

Small Pfirsch-Schlüter diffusion

Small Shafranov shift

Improved stability limit against Mercier and resistive interchange modes

Side conditions: Magnetic well



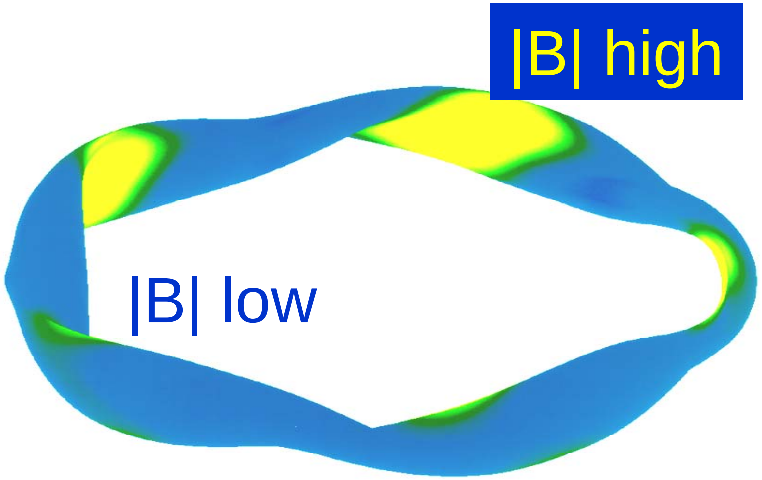
W7-X
Bean-shaped
cross-section

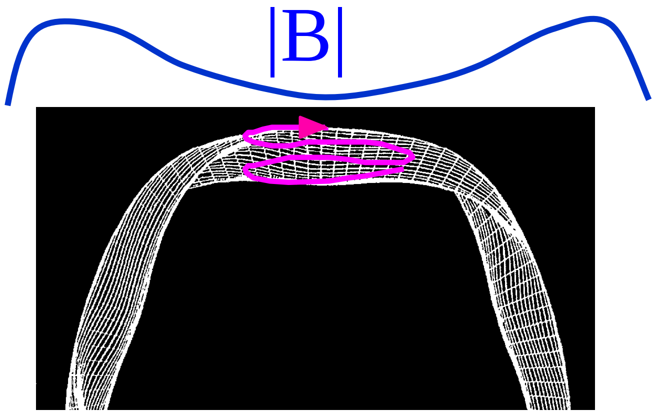
Ingredients for the optimisation (1)

Geometry is toroidally periodic (e.g. N=5) with straight sectors between corners

At the corners (high curvature, high drifts): |B| is increased => linked mirrors

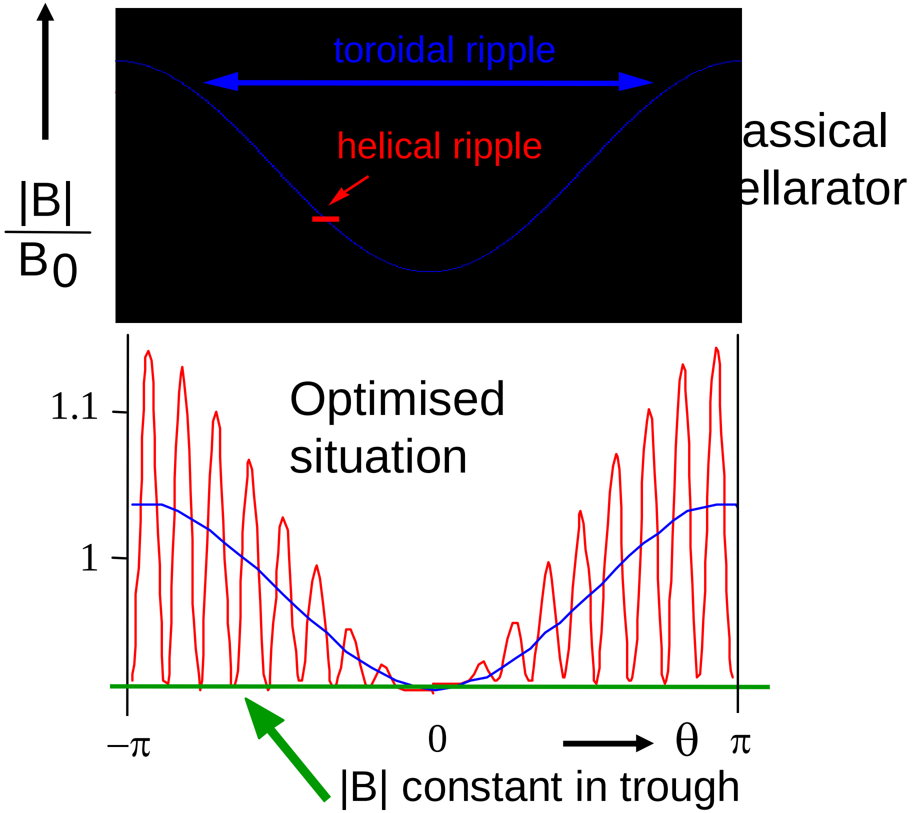
Consequence:
the trapped particles are removed from the zones of large vertical drifts.



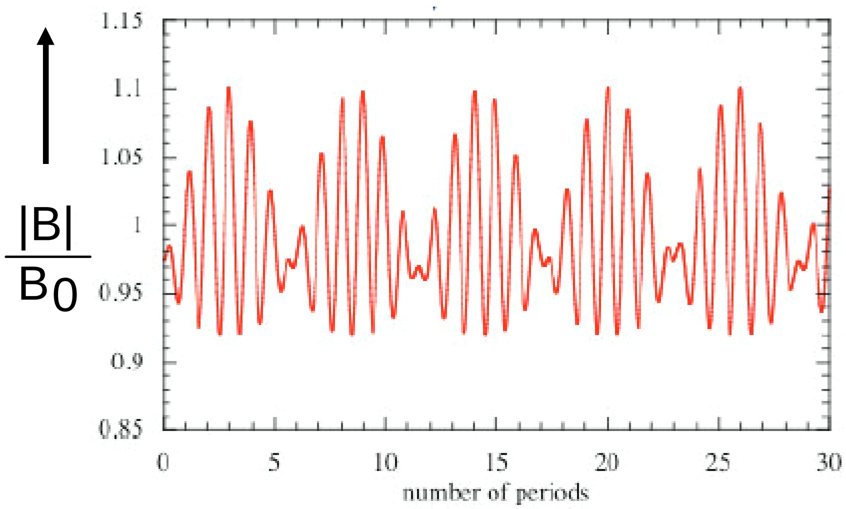


Ingredients for the optimisation (2)

Sigma optimisation



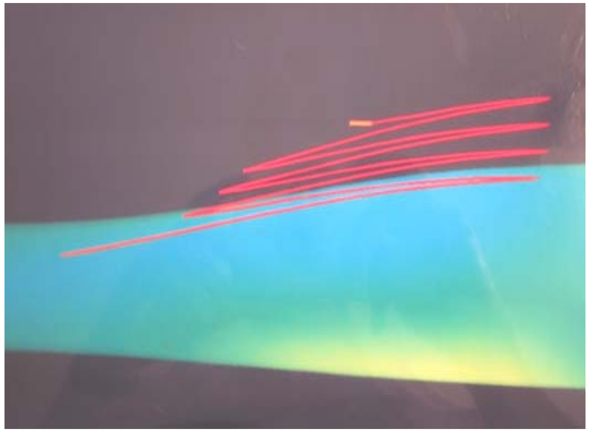
W7-X



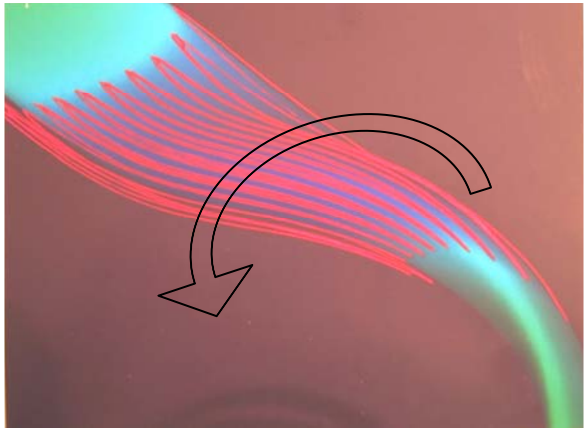
Achievements by optimisation

Drift of helically trapped particle

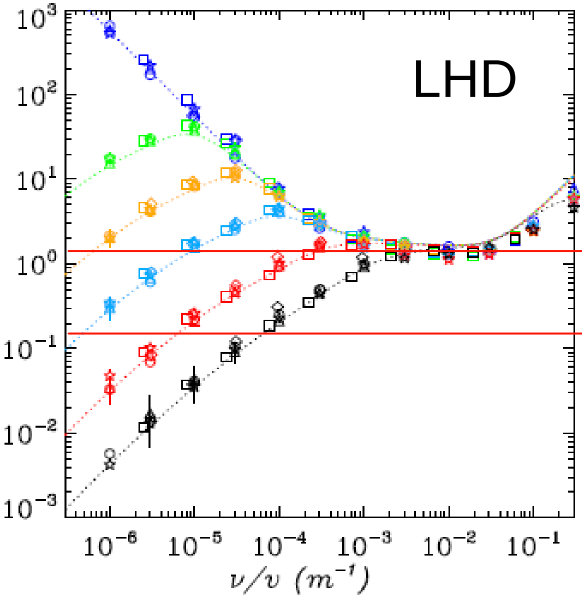
W7-AS (predecessor of W7-X)

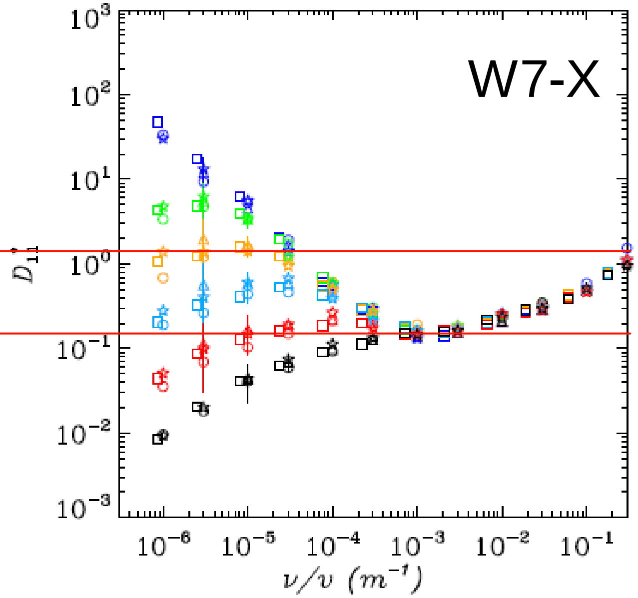


W7-X



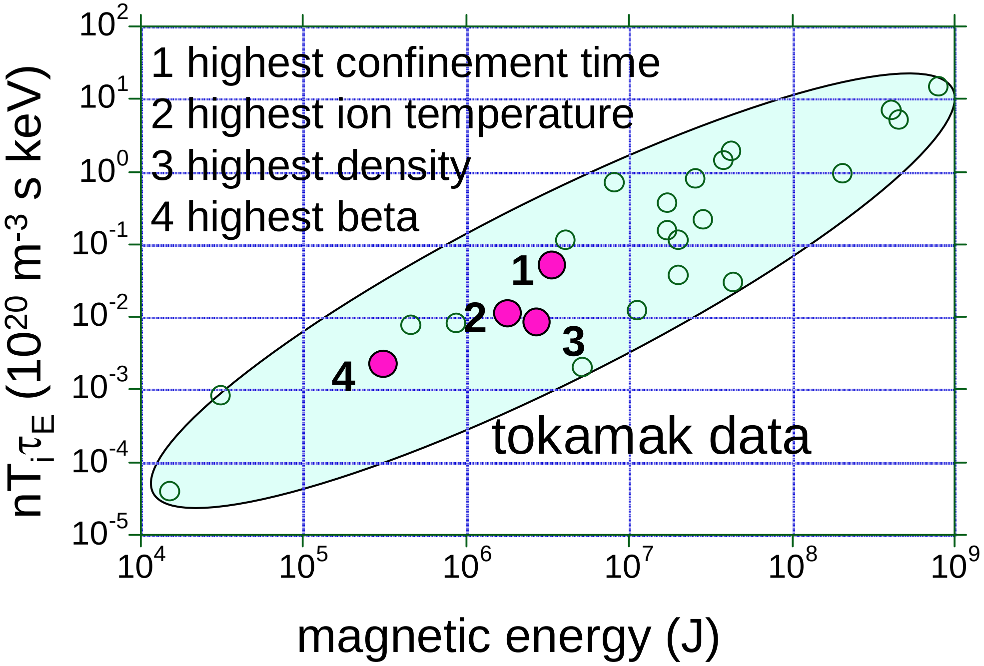
D^*_{11}





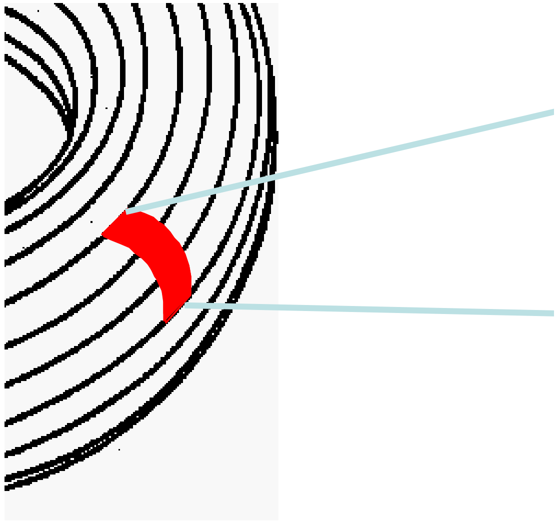
Neo-classical diffusion

Comparision of tokamak and stellarator triple product

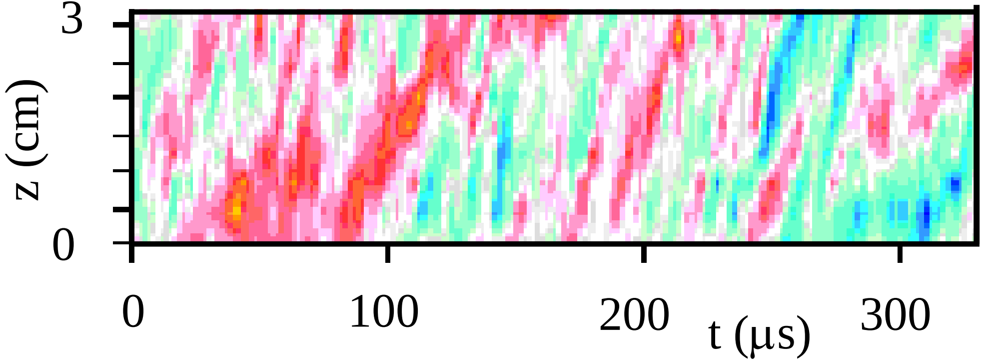


2nd topic: self-organised magnetic confinement

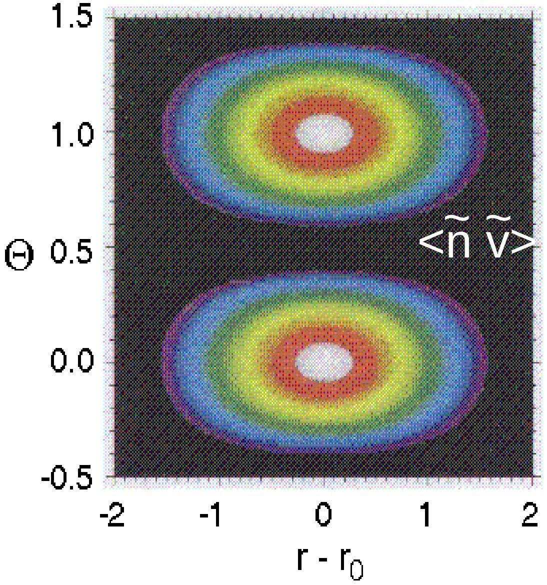
Turbulent transport



Fluctuations in plasma potential



Space scales:

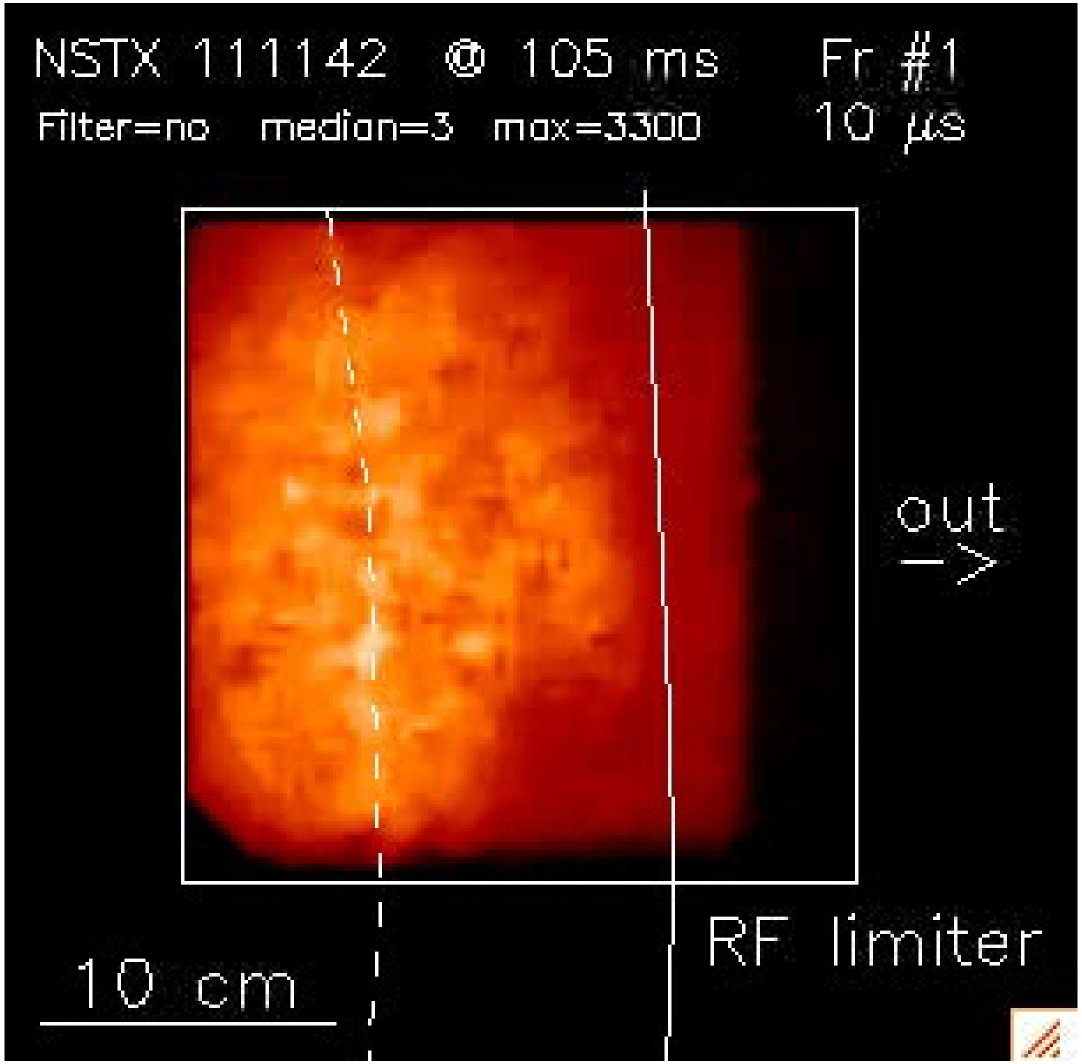


Gradient length L_p: 1m,
perp. correlation length: $k_\perp \sim 1$ cm
parallel correlation length: $k_{||} << k_\perp$

Time scales:
Drift frequency: $c_s/L_p = 10^6\ s^{-1}$

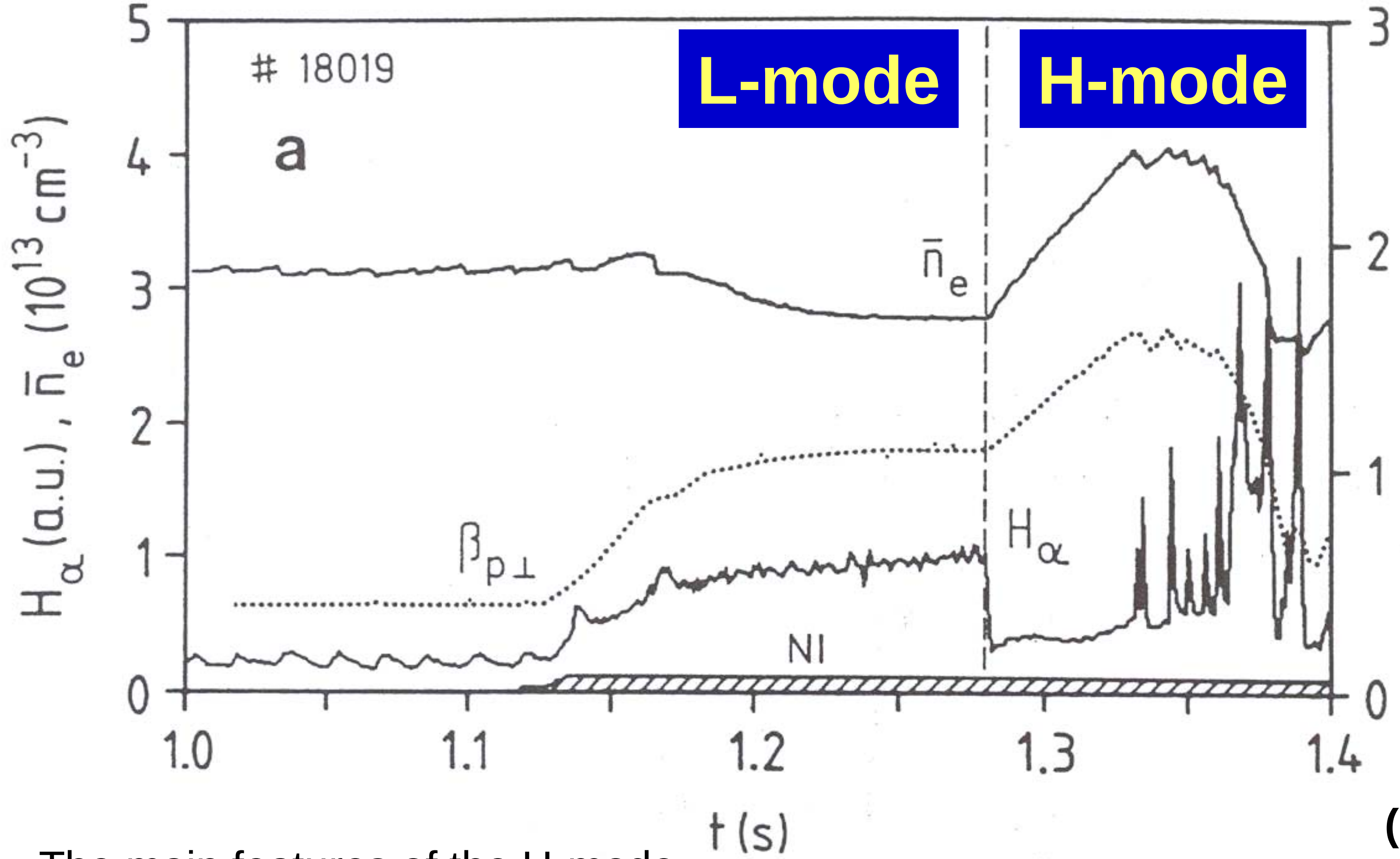
$$D_{turb} \approx \frac{\gamma}{k_\perp^2} \sim 1 m^2/s \quad \Rightarrow \tau_E \sim 1 s$$

Movie of edge turbulence



S.J. Zweben *et al.*,
Phys. Plasmas **9** (2002) 1981

Self-organisation of toroidal fusion plasmas



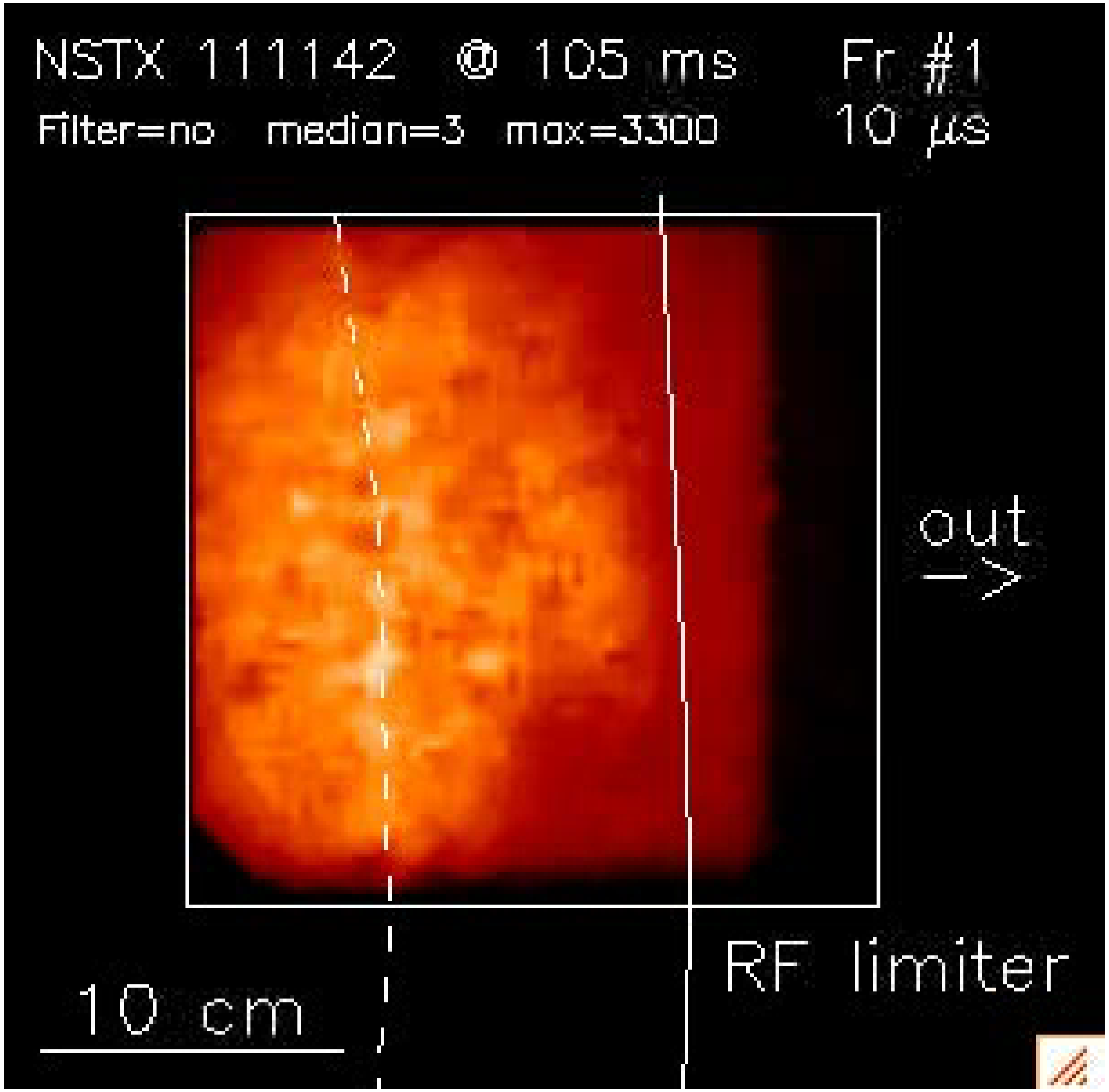
β_{pol}
$\sim \langle p \rangle / B^2$

(ASDEX,1982)

The main features of the H-mode

- a spontaneous and distinct transition during the heating phase
- both energy- and particle confinement time increase
- the tracer for the transition is the Hα-radiation
- new instabilities appear in the H-phase: ELMs, edge-localised modes

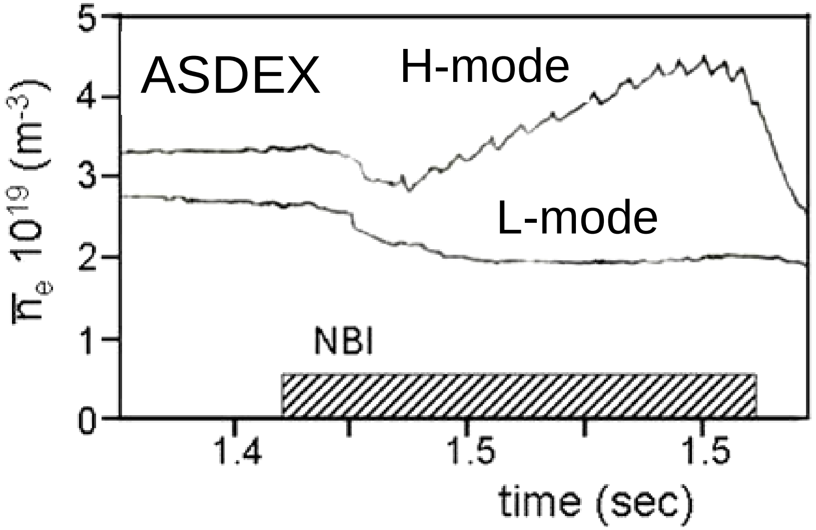
Macroscopically visible H-mode transition

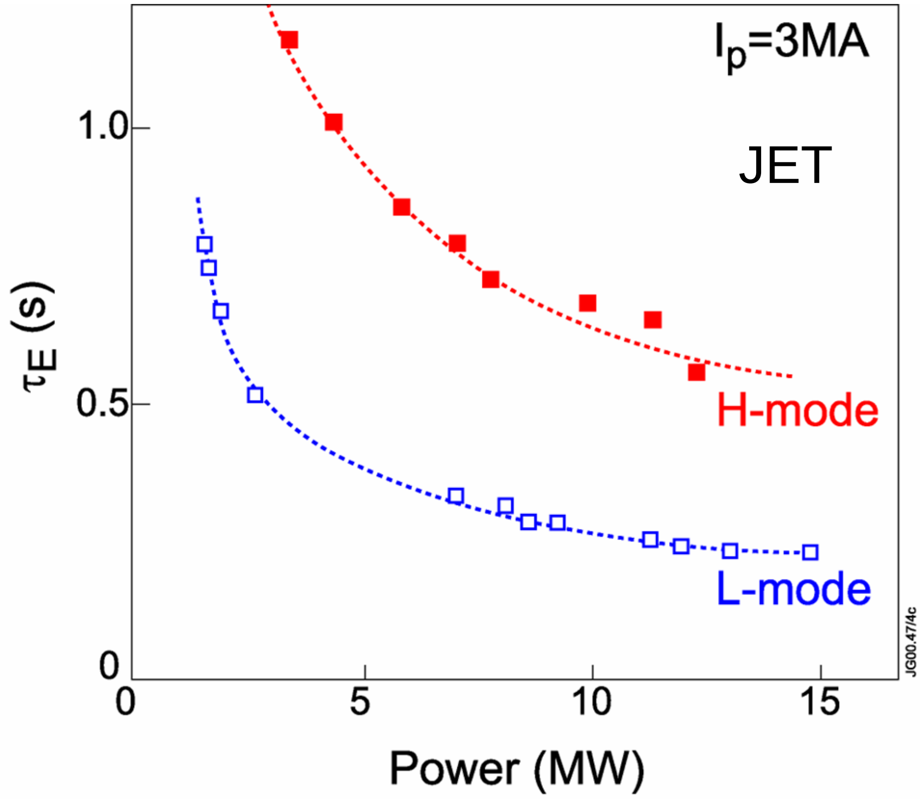


L- and H-mode branches

Particle confinement

Energy confinement





Two well separated branches
Space inbetween not accessible
(at given plasma setting)

Def. $H = \tau_E^H/\tau_E^L$

Benefit of improved confinement

The importance of improved confinement:

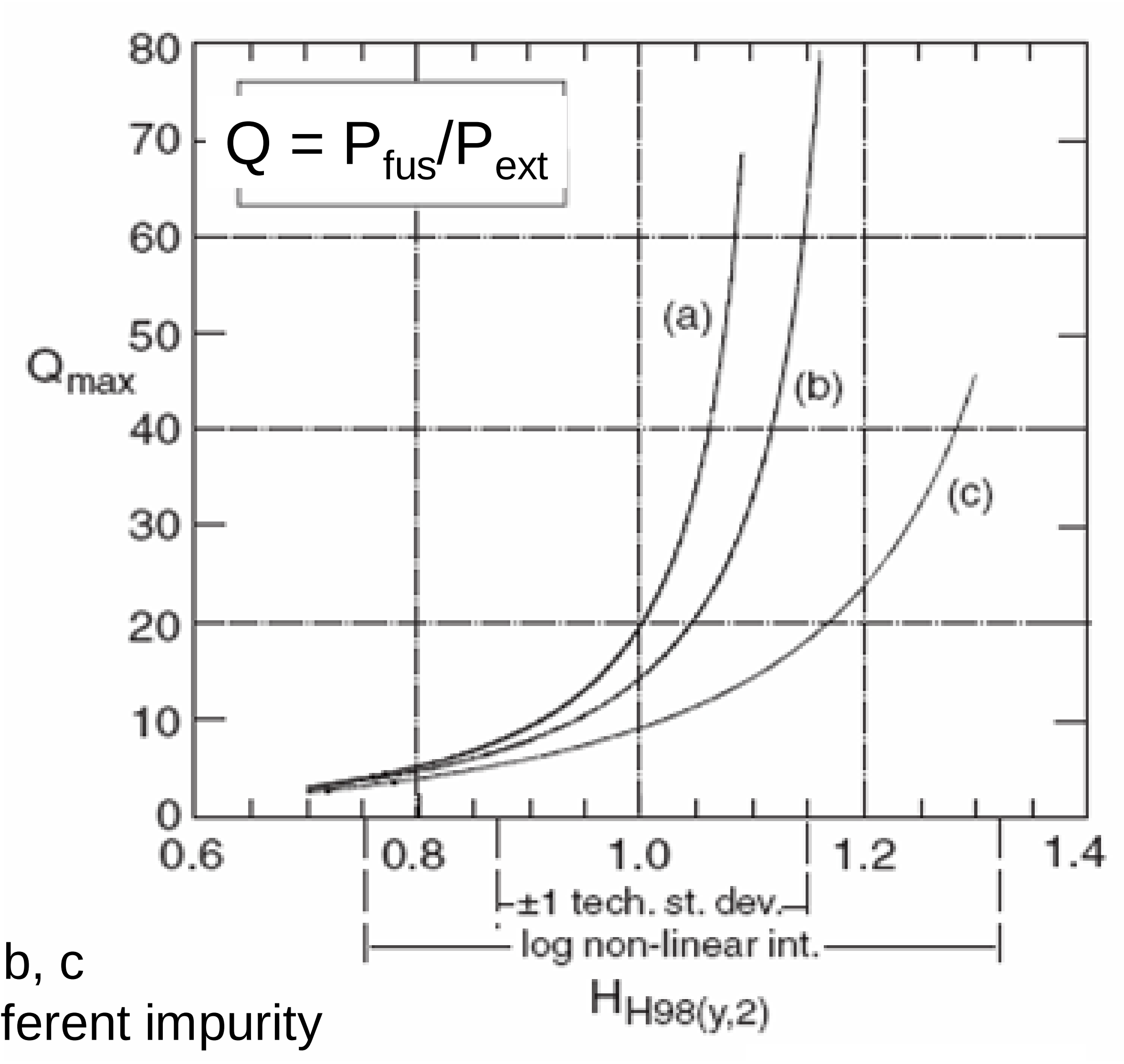
Improvement factor: $\tau_E \Rightarrow H\tau_E$

Ignition:

$$\frac{\langle p \rangle \, \tau_E}{a^2 B_t^2} \sim H^2$$

Triple product:

$$nT\tau_E \propto H^2$$



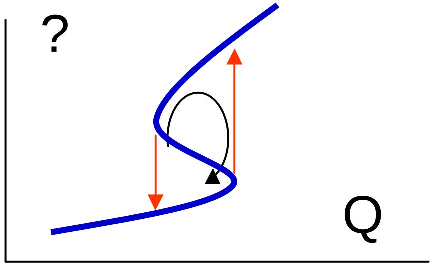
$Q = P_{fus}/P_{ext}$

a, b, c
different impurity
confinement

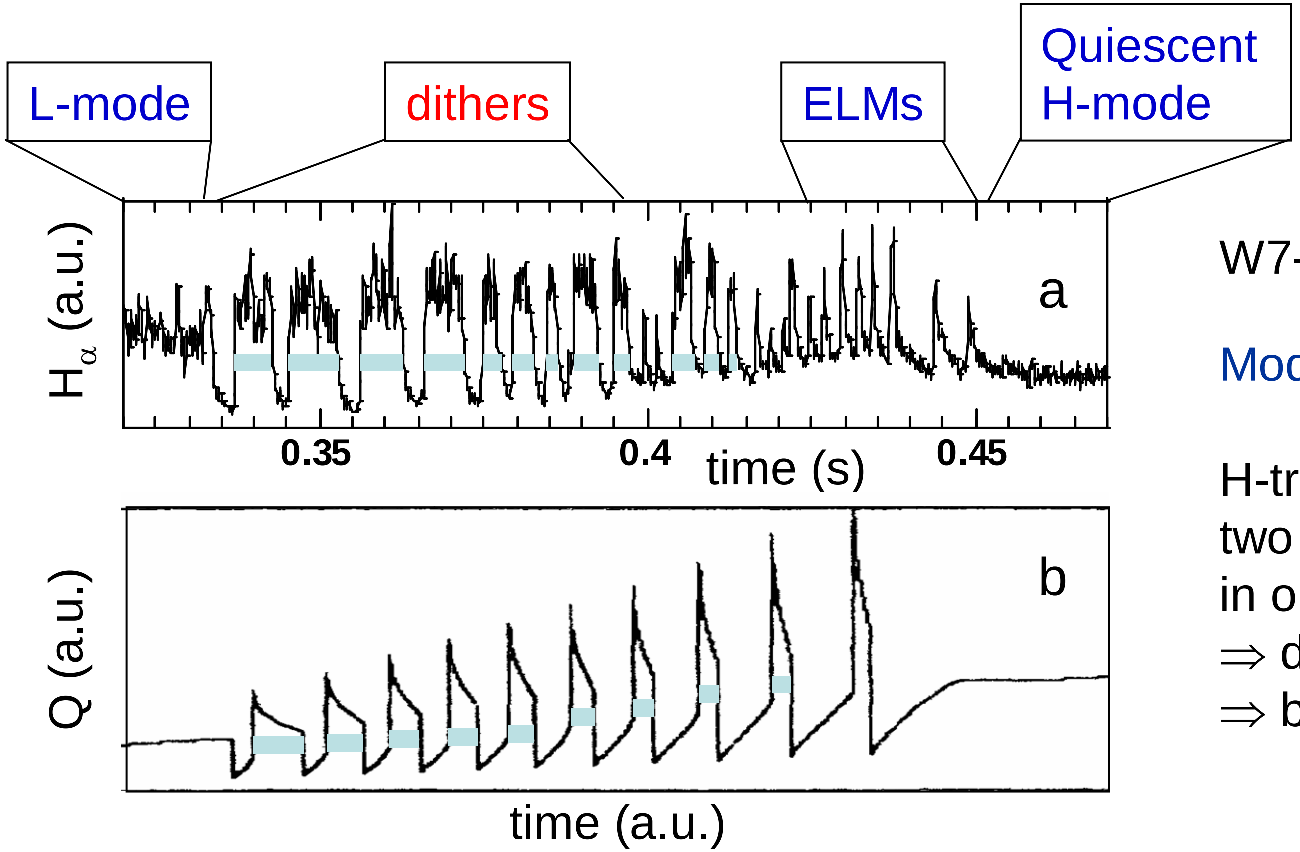
V. Mukhovatov

The H-mode as bifurcation phenomenon

Theory: Development of bifurcation models



A feature of bifurcations: Limit-cycle oscillations (dithers)



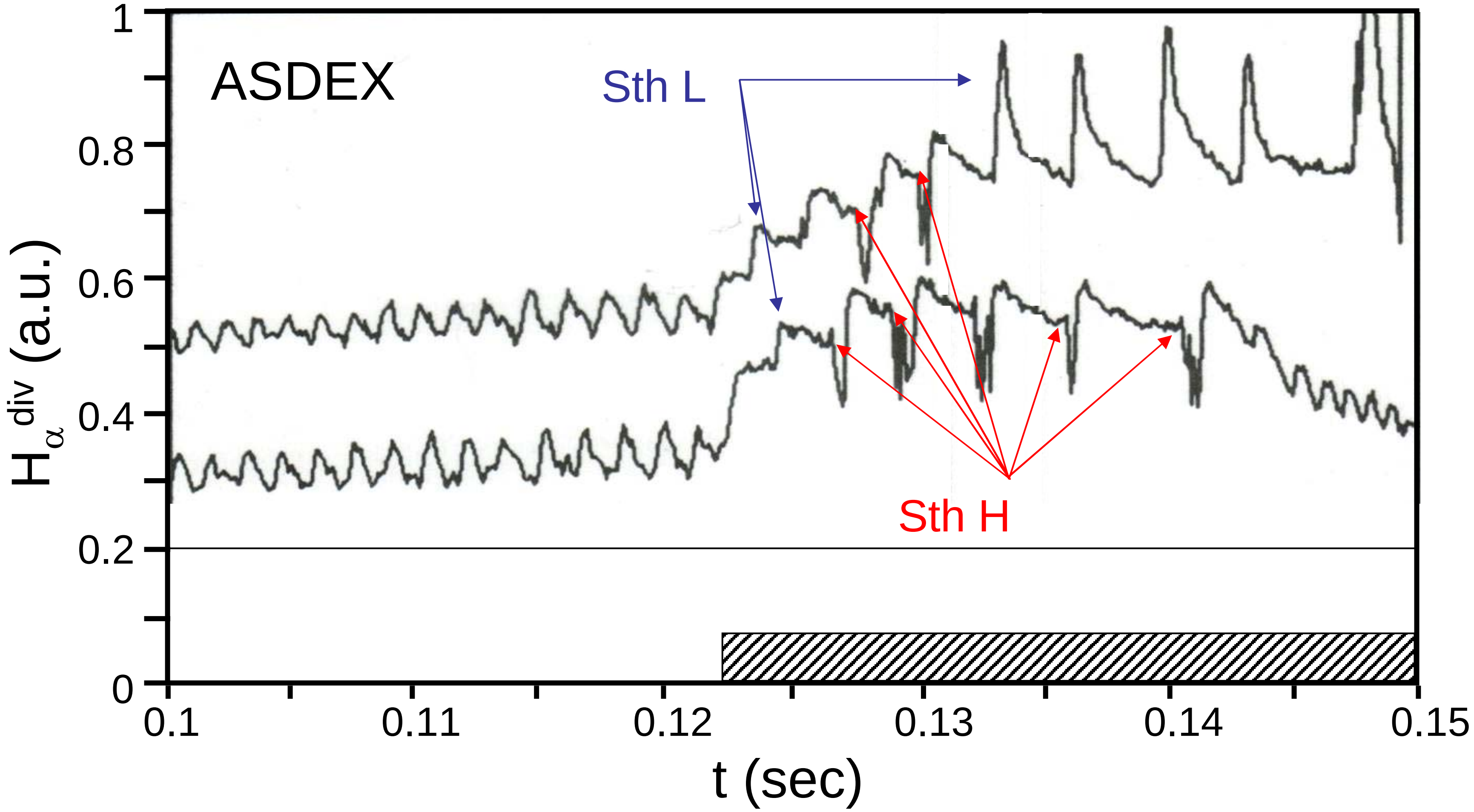
W7-AS

Model by H. Zohm:

H-transition initiates two processes going in opposite direction
⇒ deeper into H
⇒ back to L

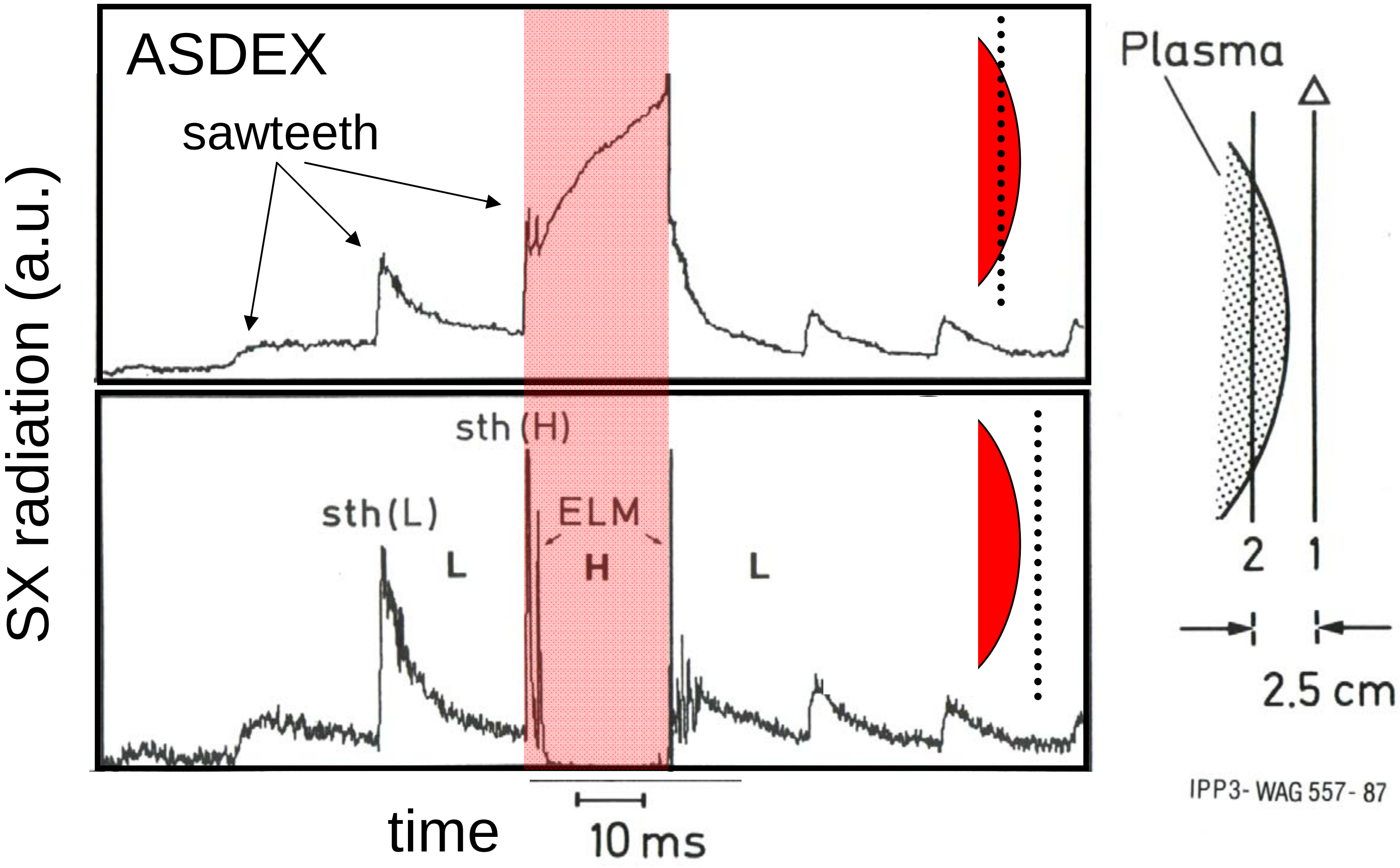
Observations leading to understanding

Sawteeth trigger short H-phases



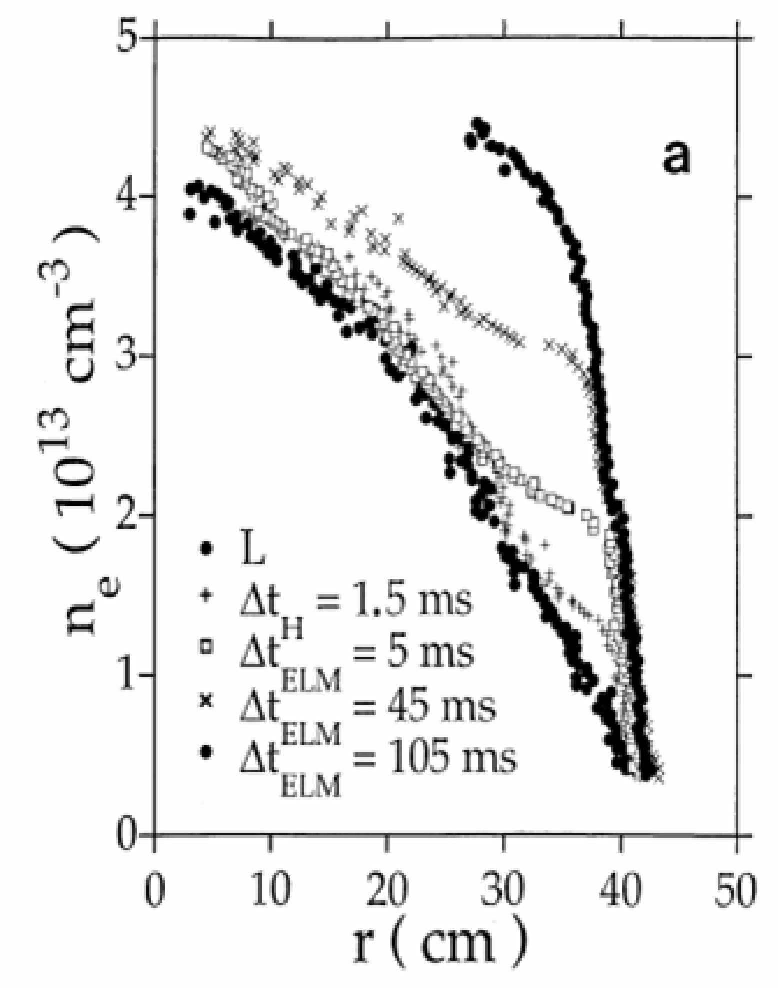
Development of an edge transport barrier

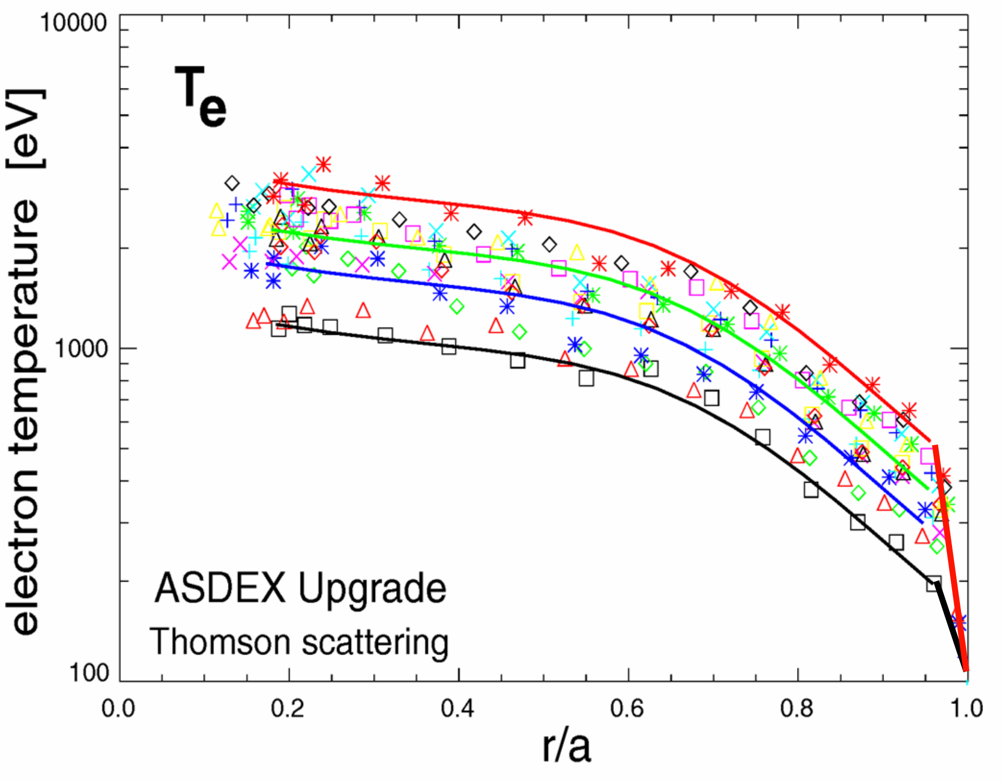
Edge and SOL probed with sawteeth after NBI switch-on



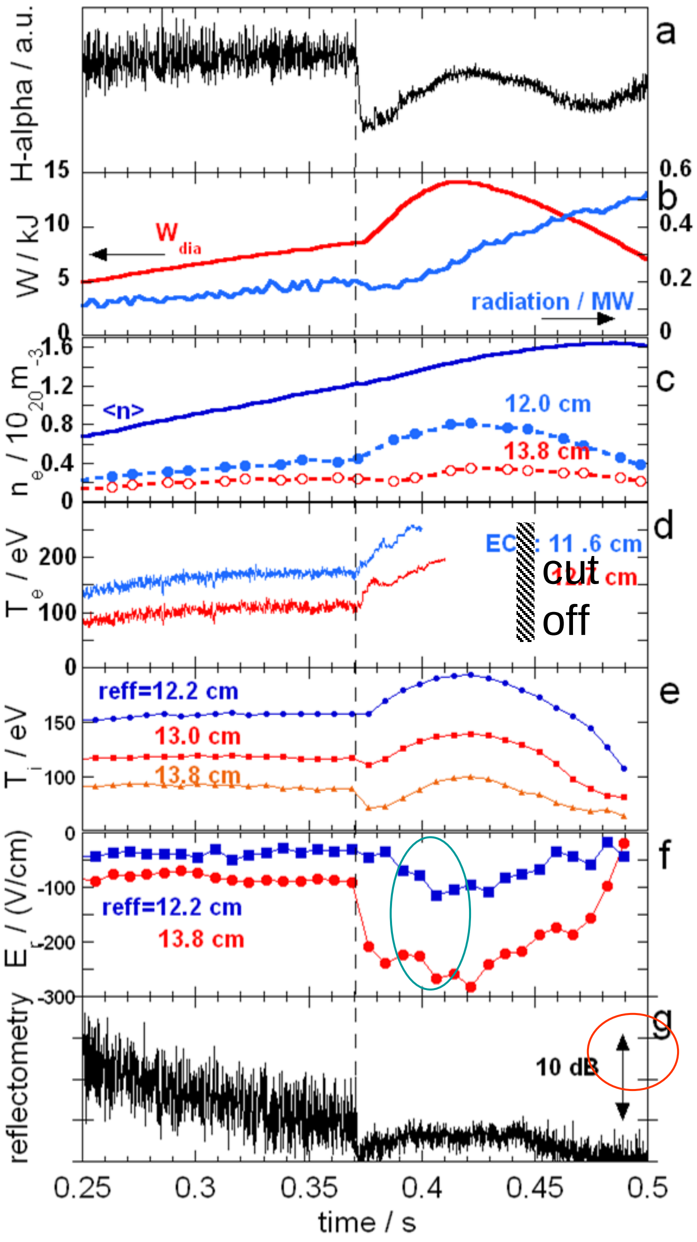
Edge Transport Barrier in density and temperature

Edge transport barrier





Summary of H-mode observation



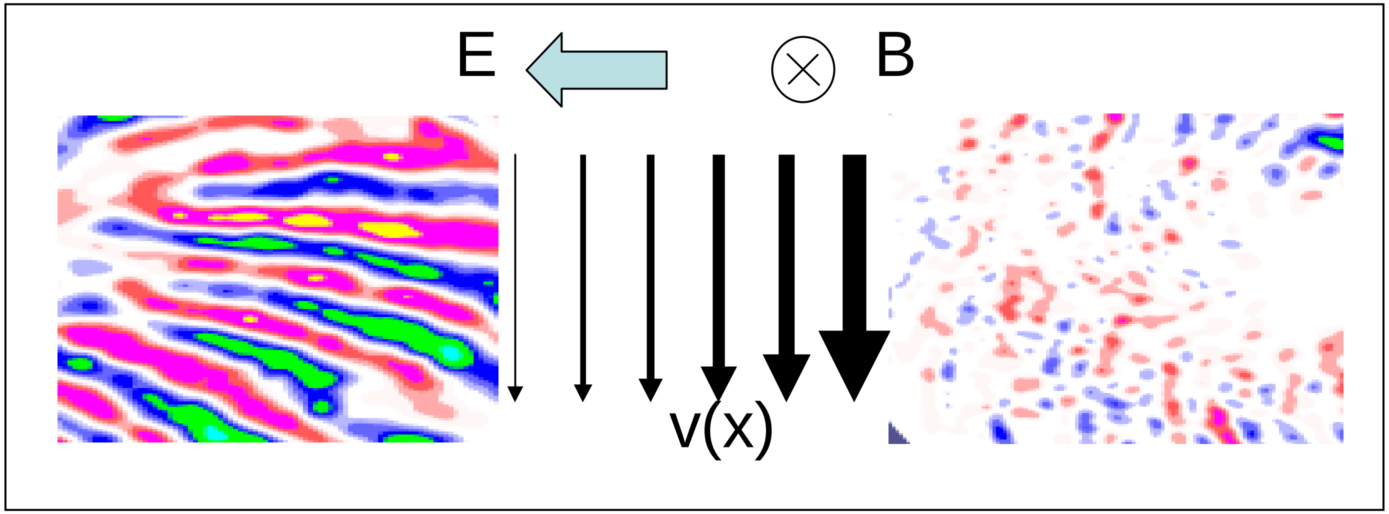
Results from W7-AS stellarator:

Implication:

H-mode is a ubiquitous operational regime in toroidal confinement

The plasma self-organizes its turbulence level

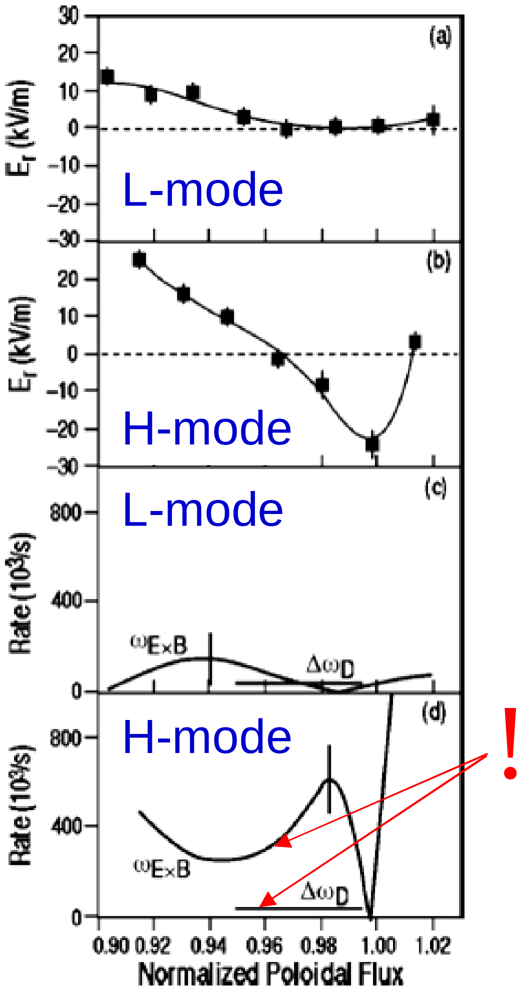
1. Step: sheared flow decorrelates turbulence
   Biglary, Diamond, Terry
   Bo Lehnert (1966)



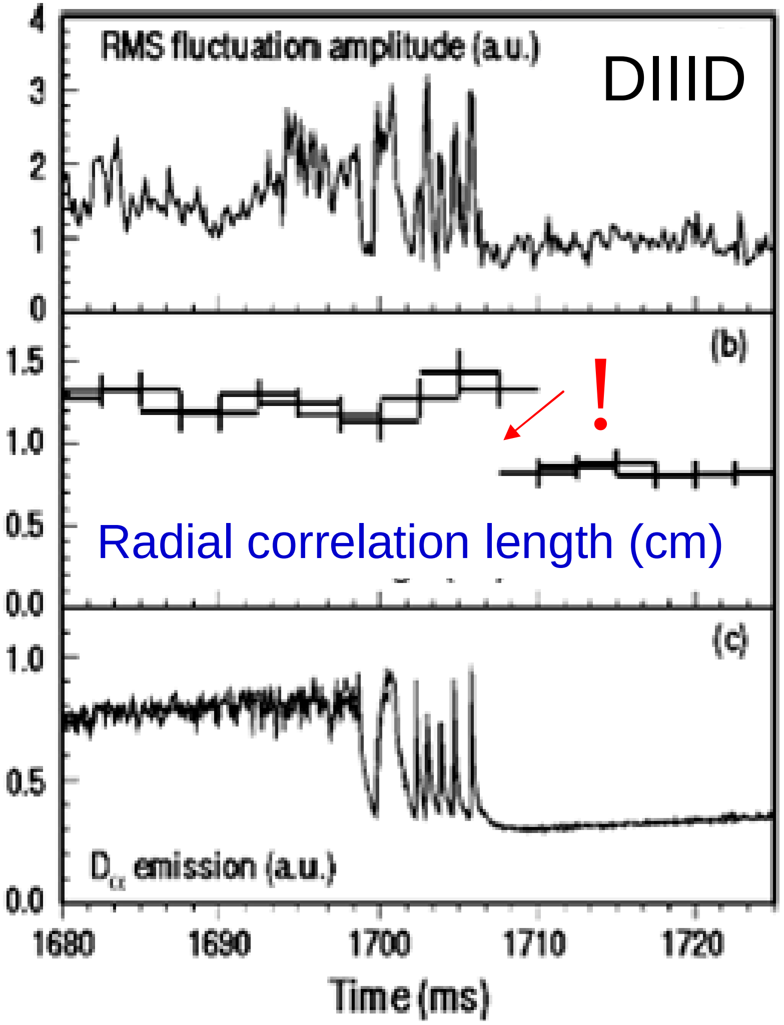
Shear flow decorrelation of turbulence

Conditions for flow-decorrelation

$\omega_{E\times B} > \gamma_{lin} \, (\Delta\omega_D)$



Reduction of radial correlation length



Condition:
sheared flow; ∇E_r

Probe (Textor):

$\nabla|E_{r,crit}|$ = 50-80 V/cm^2

DIII-D:

$\nabla|E_{r,crit}|$ = 50-100 V/cm^2

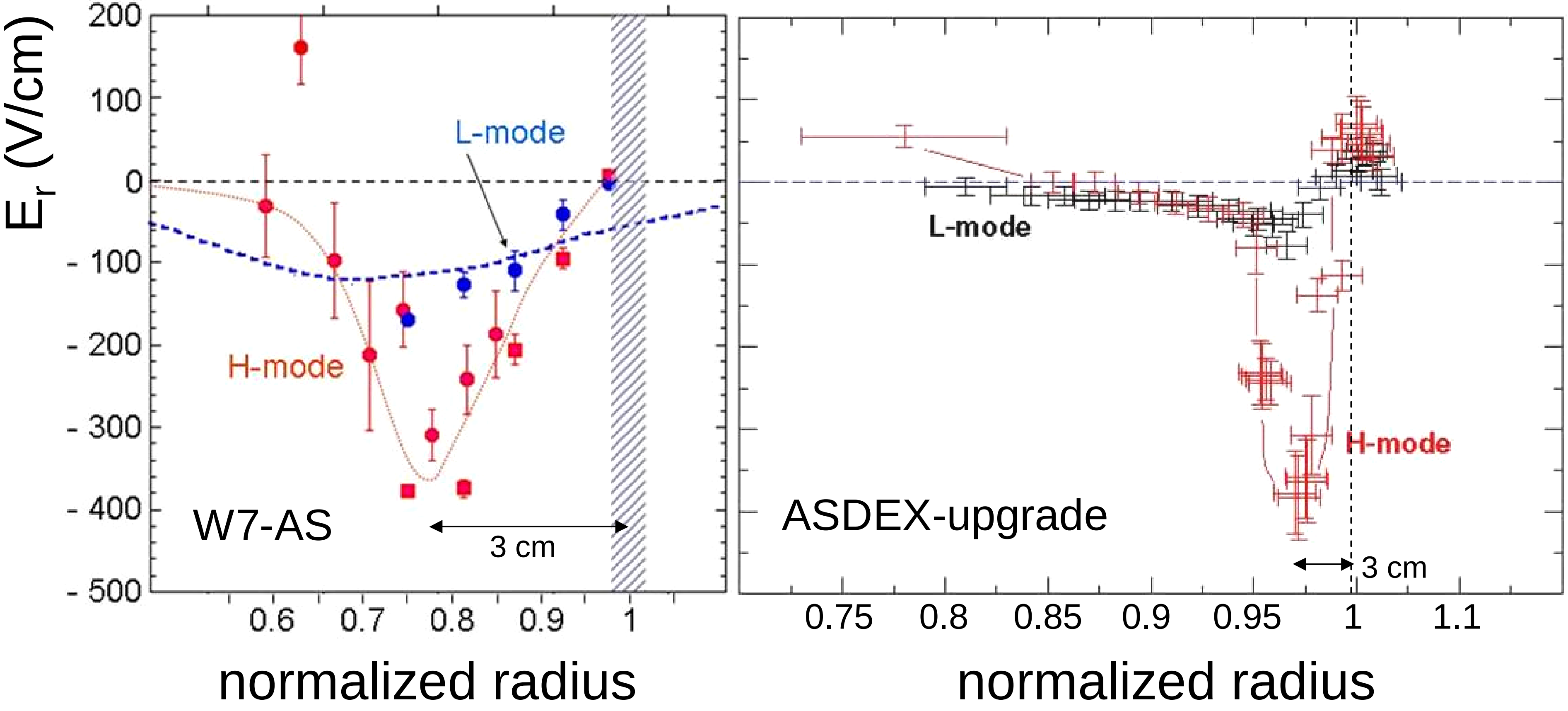
W7-AS:

$\nabla|E_{r,crit}|$ ~ 90 V/cm^2

K.H. Burrell, Phys.Plasmas

Origin of the sheared flow: $E_r(r)$

Role of the edge radial electric field



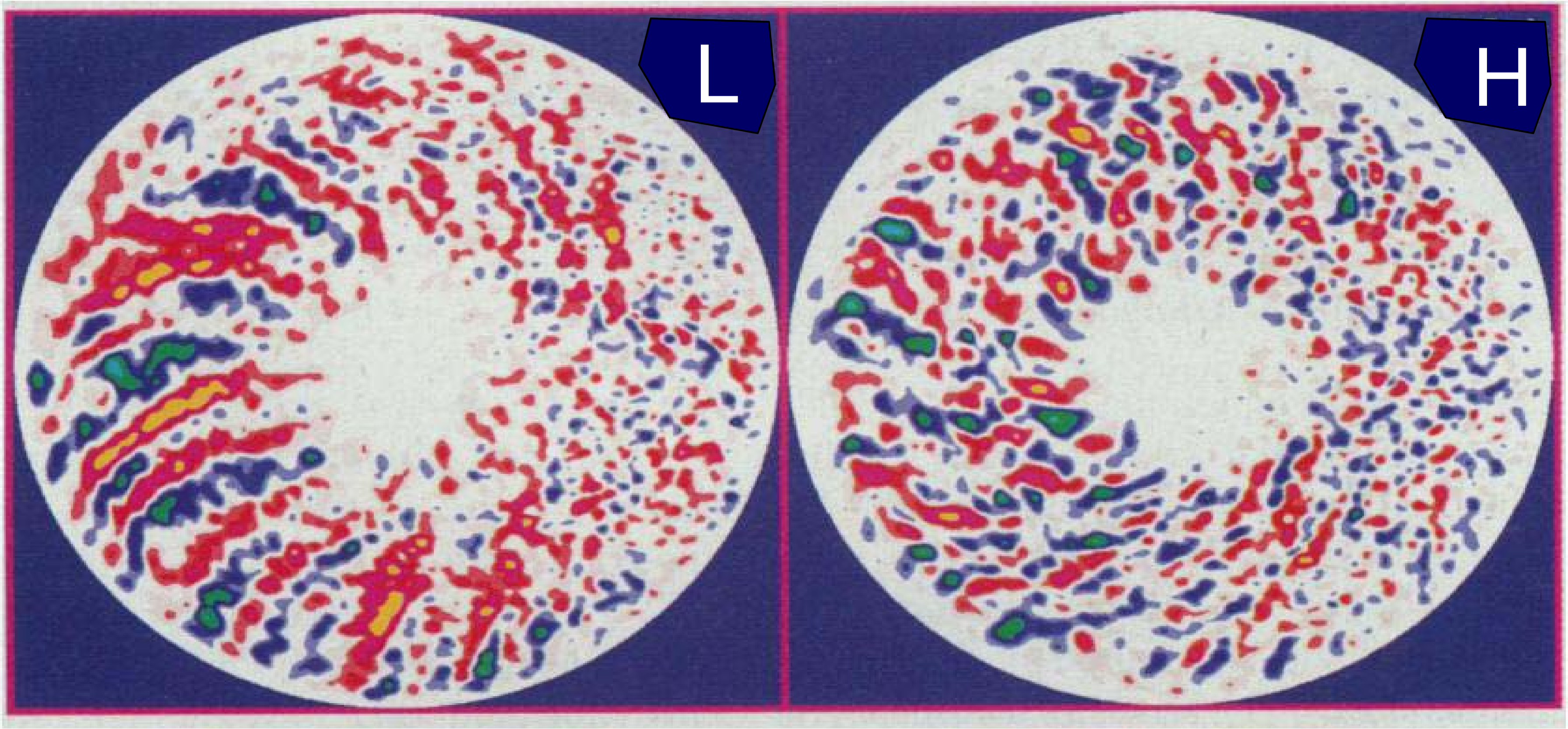
Generic feature of the H-mode: development of an E_r-well inside separatrix

Radial extent of well independent of machine size

In stellarators: E_r-well in the L-phase already quite deep => $P_{th}^{STELL} < P_{th}^{TOK}$

Modelling of shear-flow decorrelation

Gyrokinetic particle simulation of plasma microturbulence



→ ∇B

Z. Lin at al., Science

The Origin of E_r at the edge

2D:

Fluxes, transport coefficients are intrinsically ambi-polar and do not explicitely depend on E_r

$\langle j_r \rangle = 0$, independed of E_r

3D:

$\langle j_r \rangle = 0$, ensured by $\Gamma_e = \Gamma_i$: enforced ambi-polarity

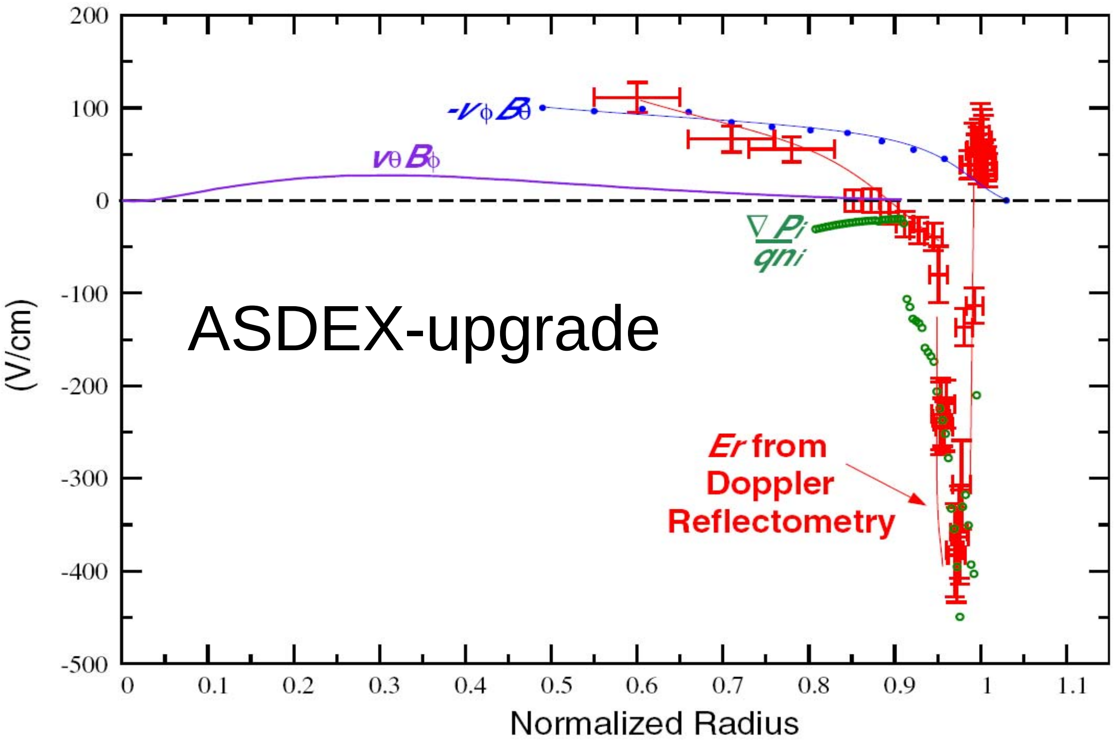
$$\Gamma = -D_1\boxed{(E_r)}\,n\left\{\frac{1}{n}\frac{\partial n}{\partial r} - q\boxed{\frac{E_r}{T}} + \frac{D_{12}}{D_{11}}\frac{1}{T}\frac{\partial T}{\partial r}\right\}$$

$E_r = \nabla p_i / en + (D_{12}/D_{11} - 1)\,\nabla T_i$

The composition of E_r

Radial force balance: $E_r = \nabla p_i / e n_e - v_\theta B_\phi + v_\phi B_\theta$

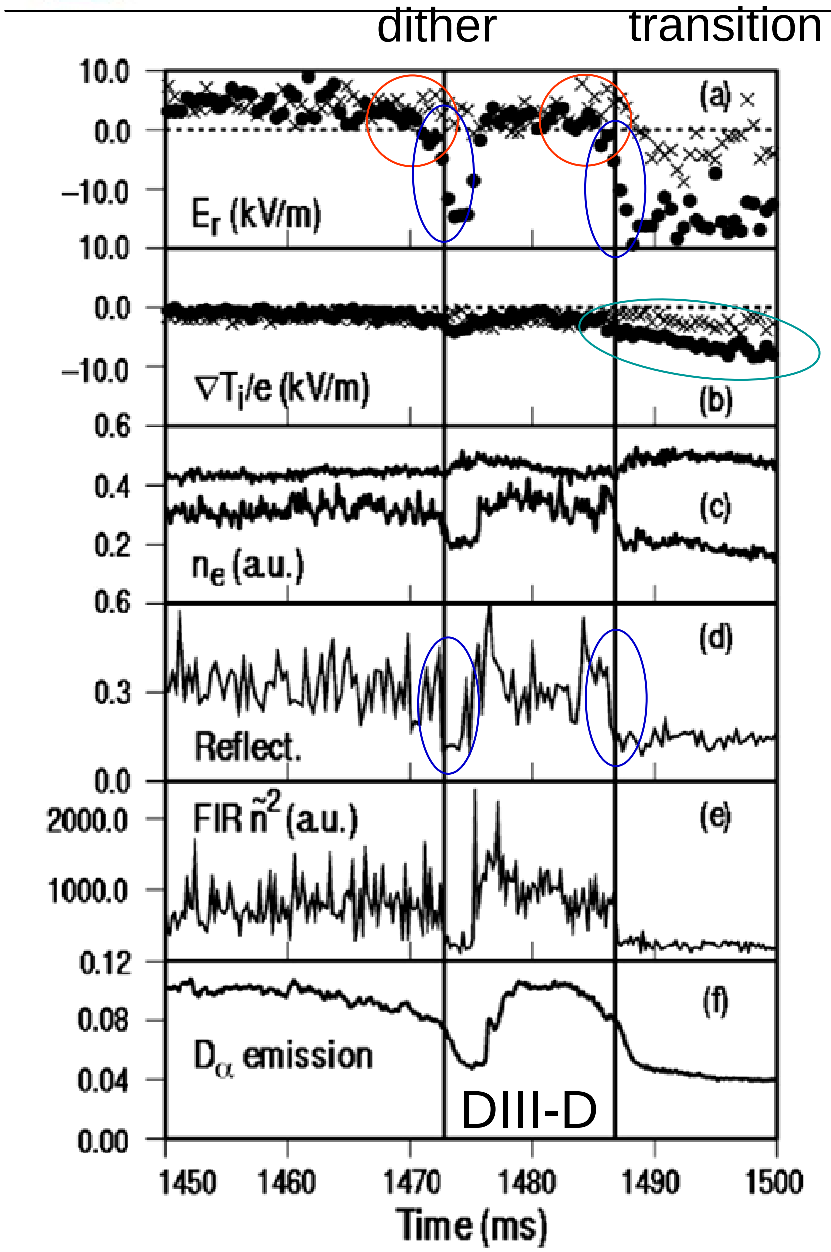
Tokamak: 2D



Turbulence ⇩ => pressure gradient ⇧ => flow increases ⇧ => turbulence ⇩

∇p_i plays an important role In a fully developed H-mode: it stabilises the mode

Temporal characteristics of L $\Rightarrow$ H



There is a pre-phase

Jump of E_r at the L=>H transition

($\tau << \tau_E$)

W7-X, JFT-2M: t ~ 12 μs

T_i changes slowly

∇p_i cannot be the transition trigger

Short timescale indicates:
Transition trigger related to $v_\theta B_\phi$

Turbulence level drops joinly with E_r

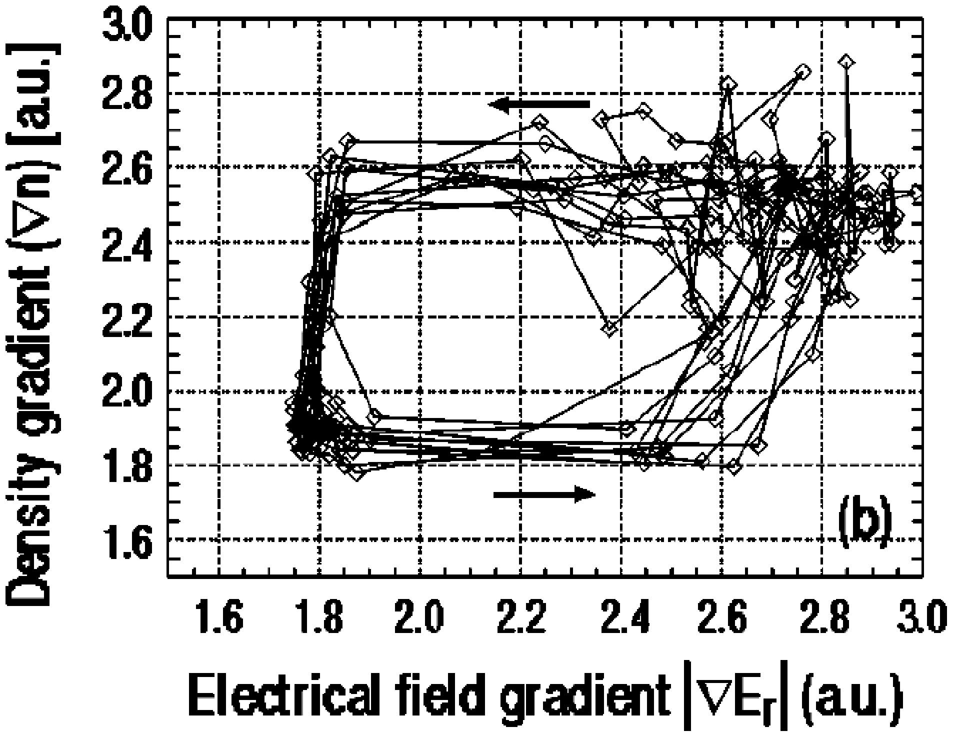
R.A. Moyer et al., Phys.Plasmas, 2, 2397, 1995

Causality between E_r and ∇p_i

TEXTOR: H-mode induced by polarisation probe

E_r is oscillating

n_e ($\text{grad}p_i$) also oscillates



Analysis done by K.H. Burrell, Phys. Plasmas

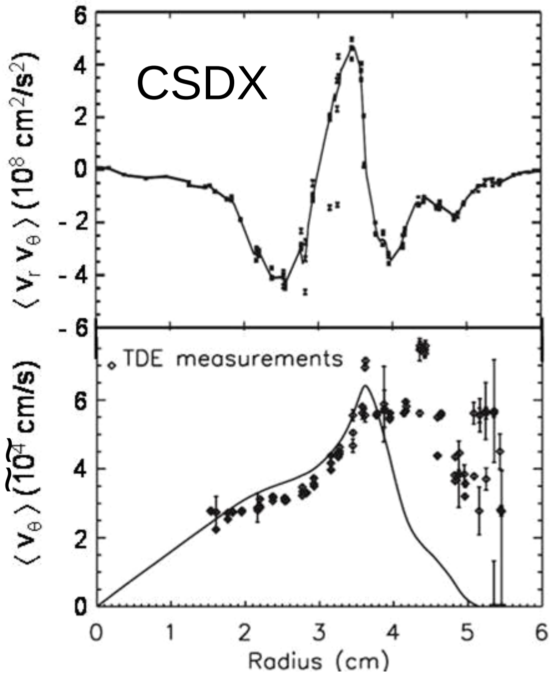
Causality: ∇E_r leads n_e by about 5 ms

2^{nd} step: Turbulence produces flow

Turbulence => Reynoldsstress $(<\tilde{v}_r\tilde{v}_\theta>)$ => flow => decorrelation of turbulence

Poloidal force balance: $0 = j_r B/n_i - m_i \mu_\theta v_{\theta i} + m_i \vartheta/\vartheta r\, (<\tilde{v}_{ri}\tilde{v}_{\theta i}>)$

Reynolds stress
leads to steady-state flow



linear device!

Understanding parts of the H-mode

Self-induced flows from the turbulence field regulates the turbulence level.

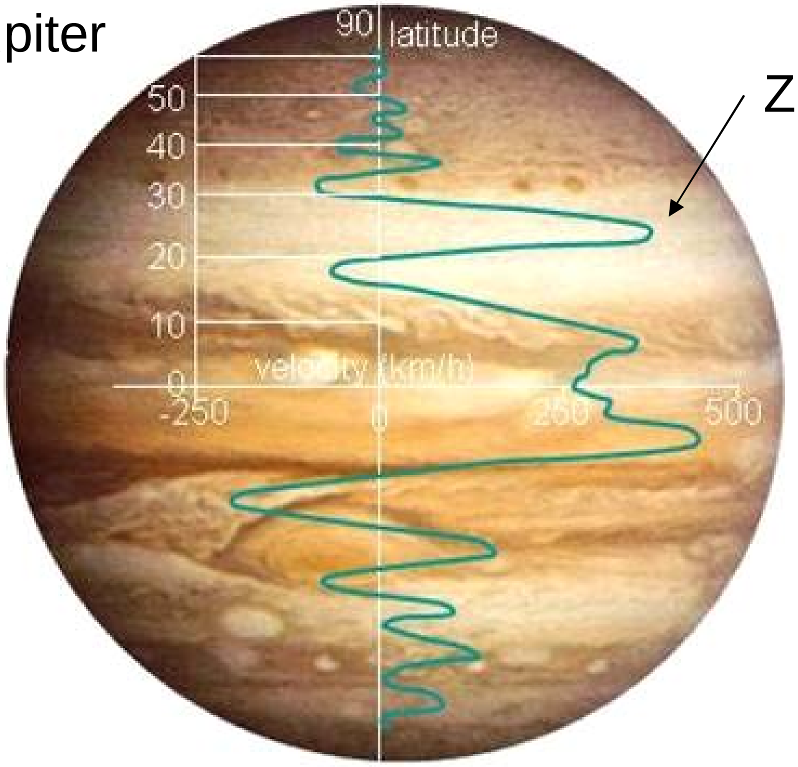
Mechanisms:
- Reynolds stress
- spectral transport from small to large scales
- flows, zonal flows, GAMS

sheared flow reduces turbulence

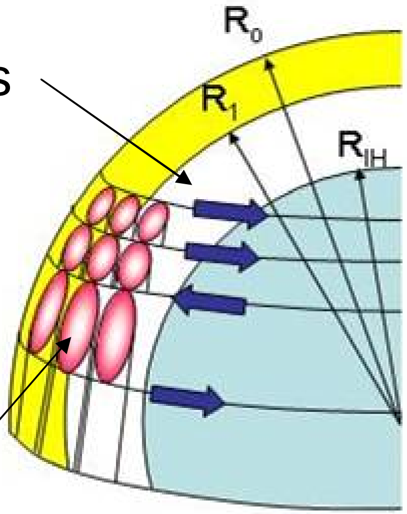
∇p_i rises, deepens E_r well; stabilises H-mode

Short detour to the planets

Jupiter



Zonal flows



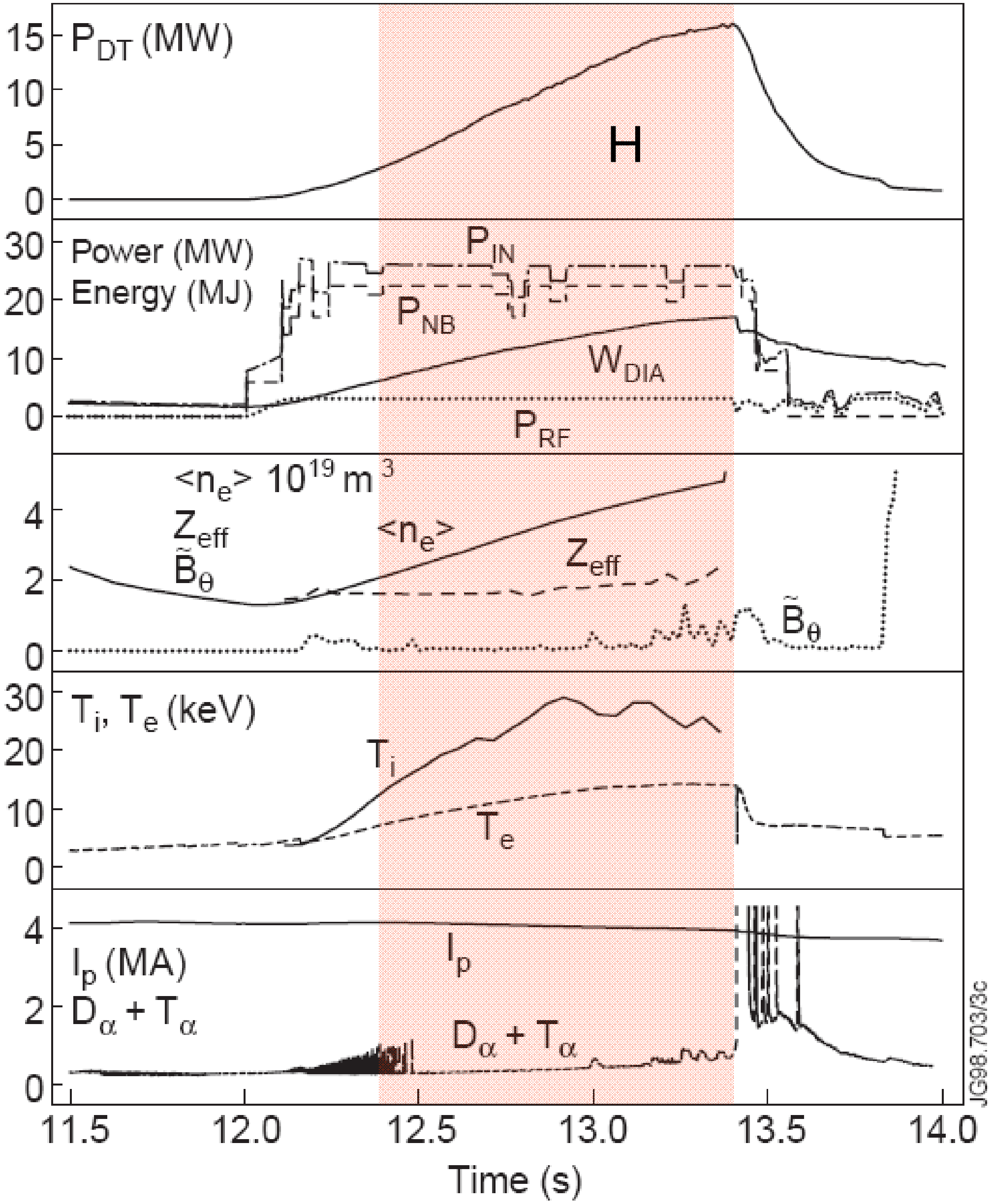
convective cells drive ZFs
via Reynolds stress

Formation of large-scale flows from turbulence via RS
in laboratory experiments,
the sonic wind in gases,
meandering flows in oceans, Jet stream, in the ionosphere
e.g. Rossby waves (Coriolis force instead of Lorentz force)
in the sun

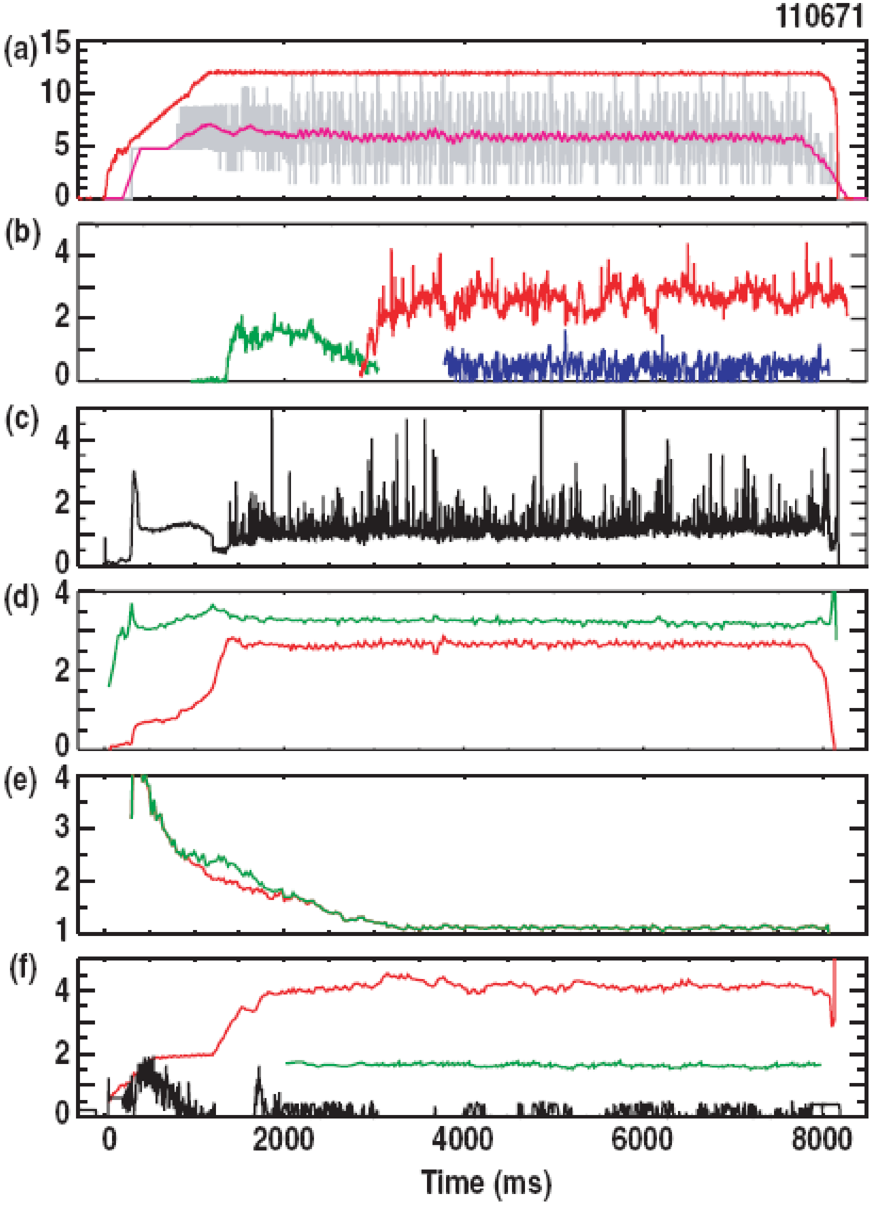
Achievements in the H-mode

The 16.1 MW DT

discharge of JET



High-performance discharges: Tokamak



Ip (x10) MA
P_{NBI} MW

Magn. perturbation
n=3, n=2, n=1

D_α, upper divertor

β_N
$4l_i$

q_{min}
q(0)

n_e
Z_{eff}

DIII-D

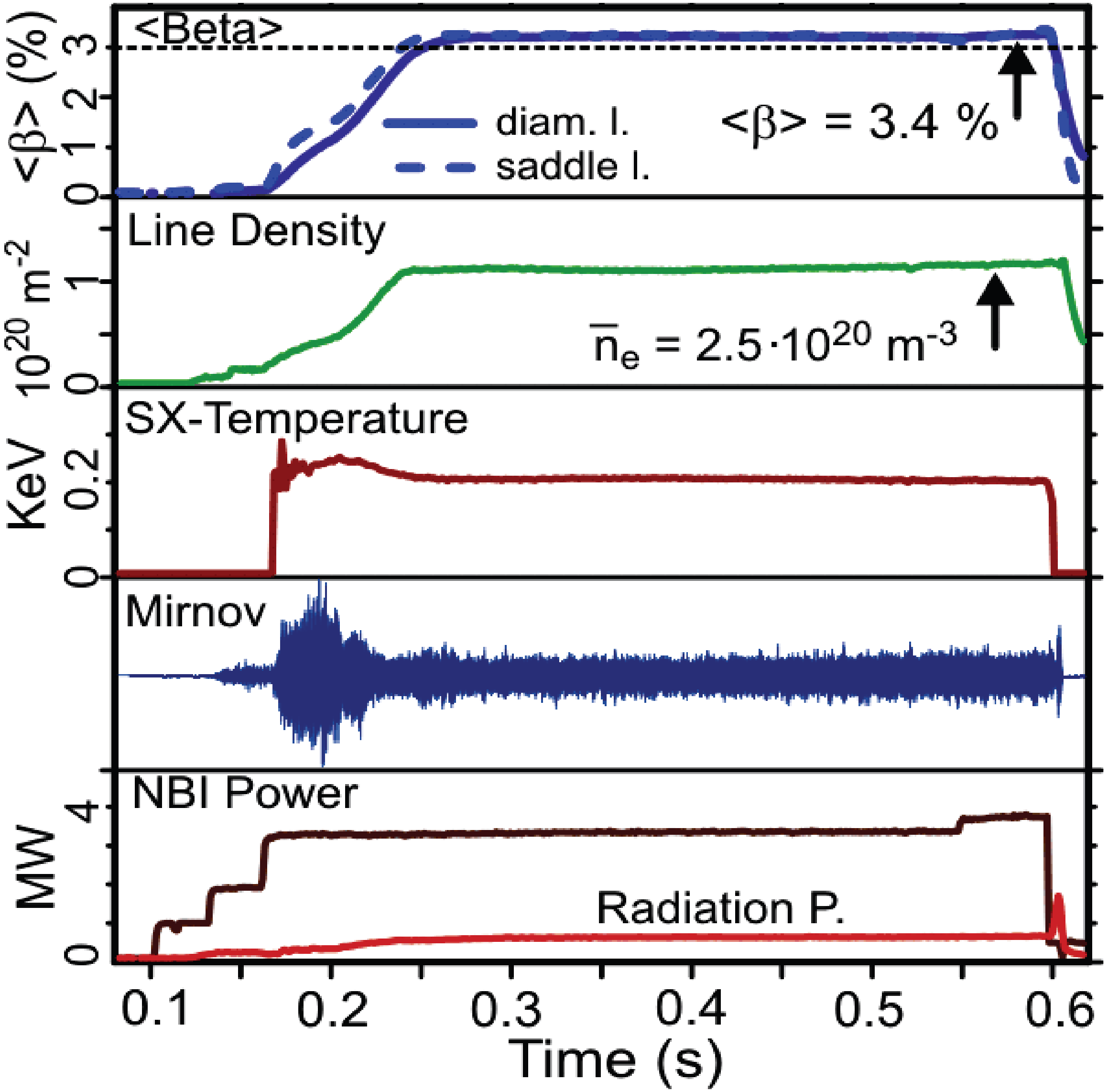
$n_e = 0.4\ 10^{20}\ m^{-3}$
$P_{NBIabs} = 4.8$ MW.

$\beta \sim 3\%$
$\beta_N = 2.7$
$H_{89} = 2.6$
$n_e/n_{eGW} = 0.4$

Mapped to
ITER
Q=10

Steady-state
$\Delta t \sim 36\ \tau_E$

Long-pulse HDH discharge of W7-AS



HDH regime

$B = 0.9$ T
$n_e = 2.5\ 10^{20}$ m^{-3}
$P_{NBIabs} = 2.5$ MW

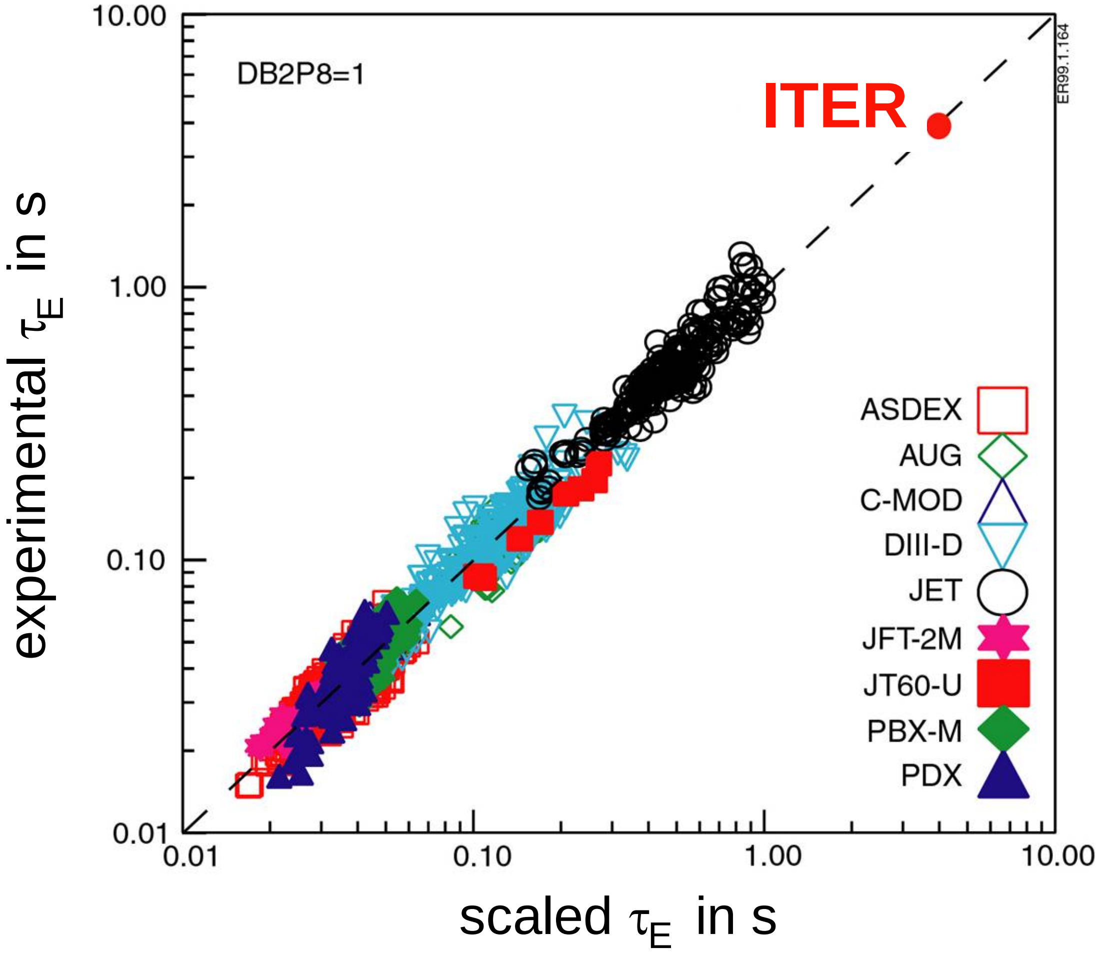
$\beta = 3.4\%$
$\beta_N \sim 9.3$
$H_{ISS95} = 1.4$
$n_e/n_{eGW} = 2.5$
$\tau_I/\tau_E \sim 2$
$\Delta t \sim 36\ \tau_E$

Prediction from regression analysis

Multi-experiment data base: Scaled $\tau_E = C\, a^{x1}R^{x2}B^{x3}I^{x4}n^{x5}P^{x6}A_i^{x7}\kappa^{x8}\ldots$

$x^1, x^2, x^4 > 0$

$x^6 < 0$ power degradation



Summary

1. The role of geometry: it allows to organise good confinement (properties)

    axi-symmetric shaping: elongation, triangularity improve turbulent tokamak transport;

    non-axi-symmetric shaping:
        improves stellarator equilibrium, stability and non-turbulent (neo-classical) transport (what about turbulent transport?).

2. The plasma self-organises in the H-mode such that the turbulence is lower at larger driving forces and that the ignition conditions are approached.

The situation is involved however:
The understanding involves the
- power balance
- the toroidal momentum balance
- the poloidal momentum balance
- the SOL flow and viscous momentum transfer