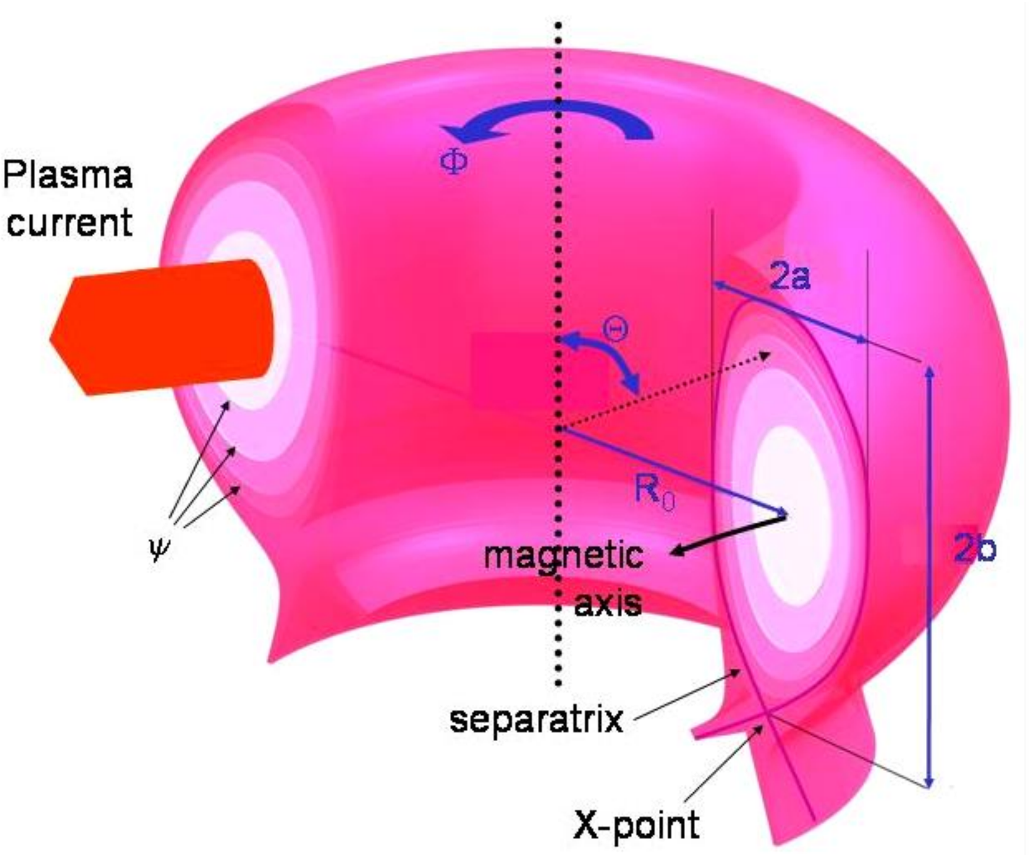
The basis of ITER confinement

F. Wagner

Max-Planck-Institut für Plasmaphysik, Greifswald, EURATOM Association



ITER is a „tokamak“

Poloidal field and rotational transform ι from current I_p

Separatrix, X- point, divertor for exhaust and power handling

Geometry: R_0, a, $a/R_0 = \varepsilon$
$b/a = \kappa$, δ = triangulariy

The goals of ITER

The demonstration of the scientific and technological feasibility of fusion

Fusion power P_{fus} ~ 400 - 500 MW (for 400 s); $Q = P_{fus}/P_{aux} \sim 10$

Basis for P_{fus} and Q: Lawson diagramme, triple-product $nT\tau_E \sim Q$

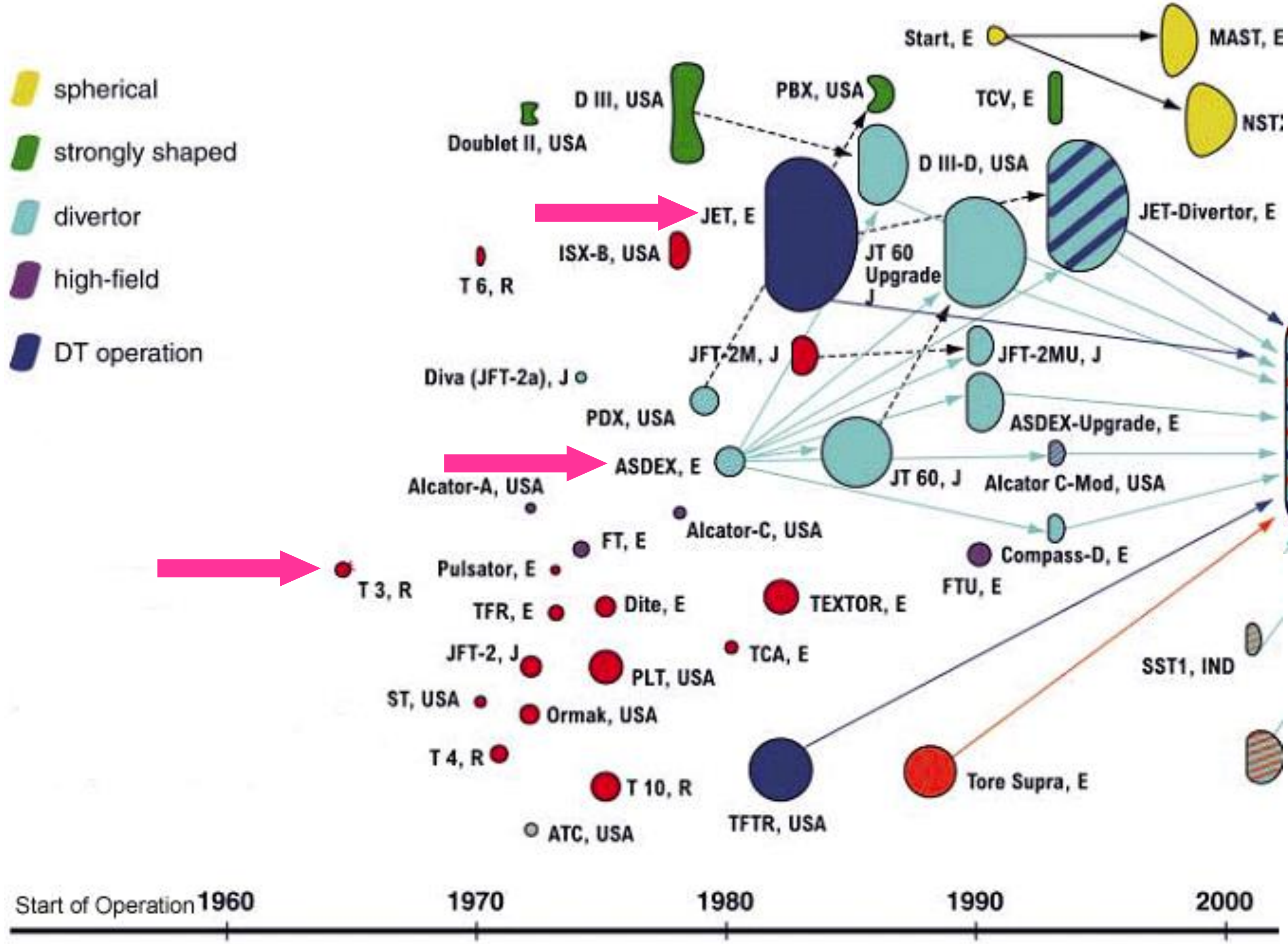
T: at maximum of fusion yield (15-20 keV)

n: is an operational parameter; $P_{fus} \sim n^2$;
n is limited by Greenwald density limit n_{GW}

τ_E = energy confinement time; determined by cross-field transport;
predicted ITER value taken from multi-machine scaling

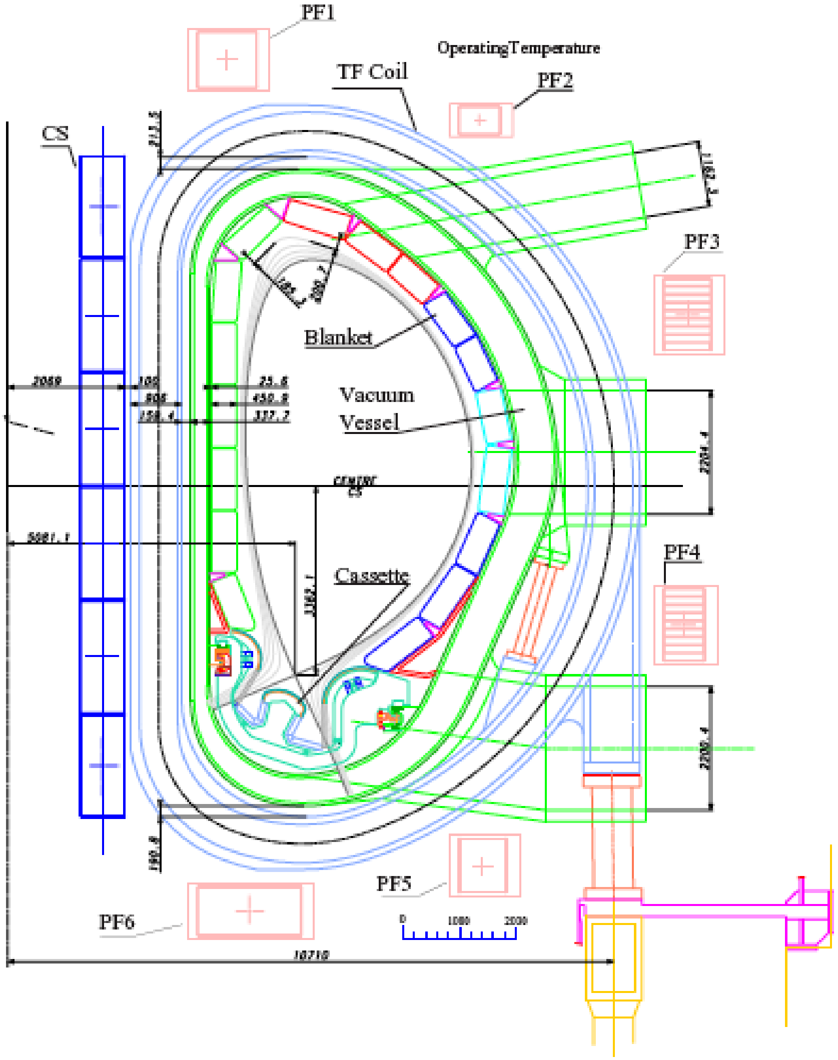
$nT\tau_E > 6\ 10^{21}\ m^{-3}$ keV s

The pathfinders for ITER



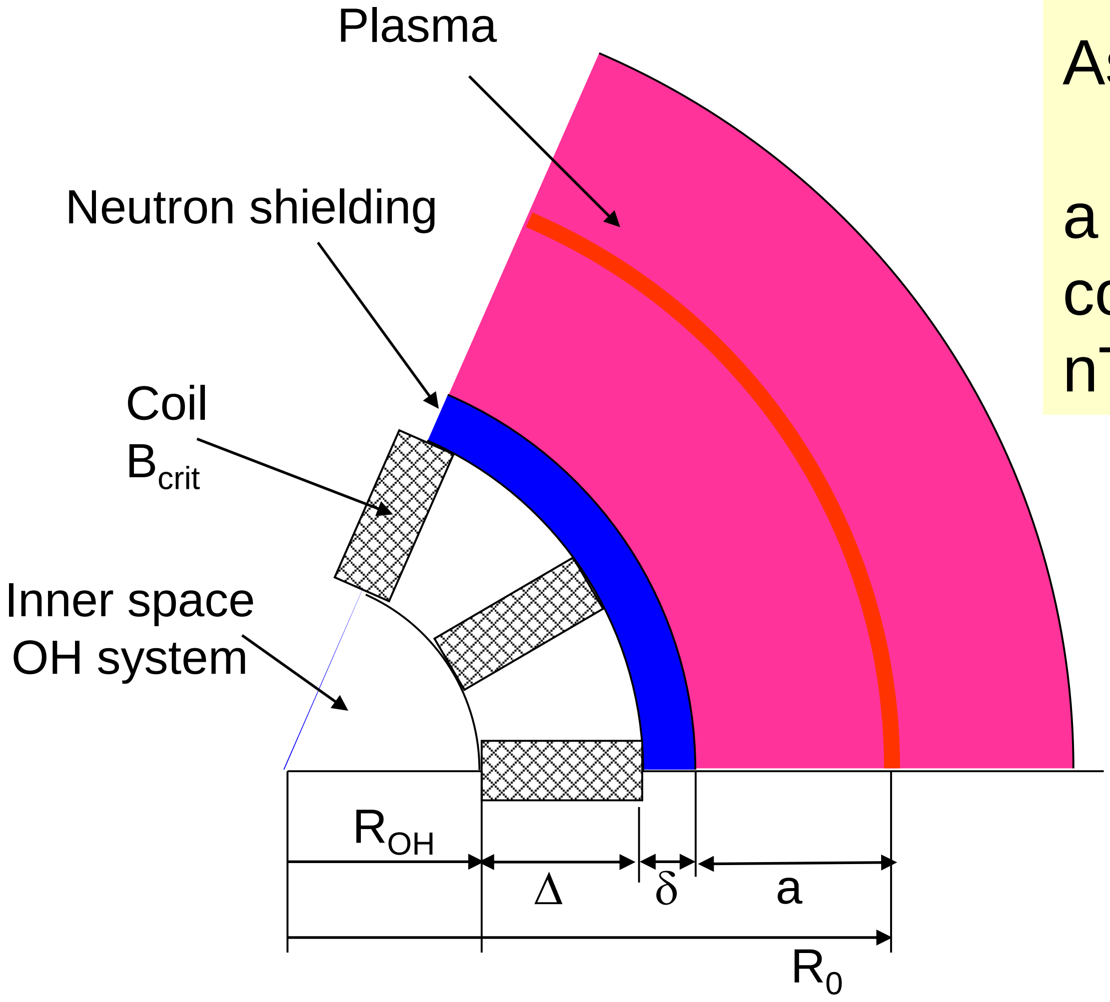
ITER

The design parameters of ITER



Major radius	6.2 m
Minor radius	2.0 m
Toroidal field	5.3 T
Plasma current	15 MA
Elongation κ	1.85
Triangularity δ	0.49
Fusion power	400-500 MW
Q	~10
Burn duration	~ 400 s

The size of ITER

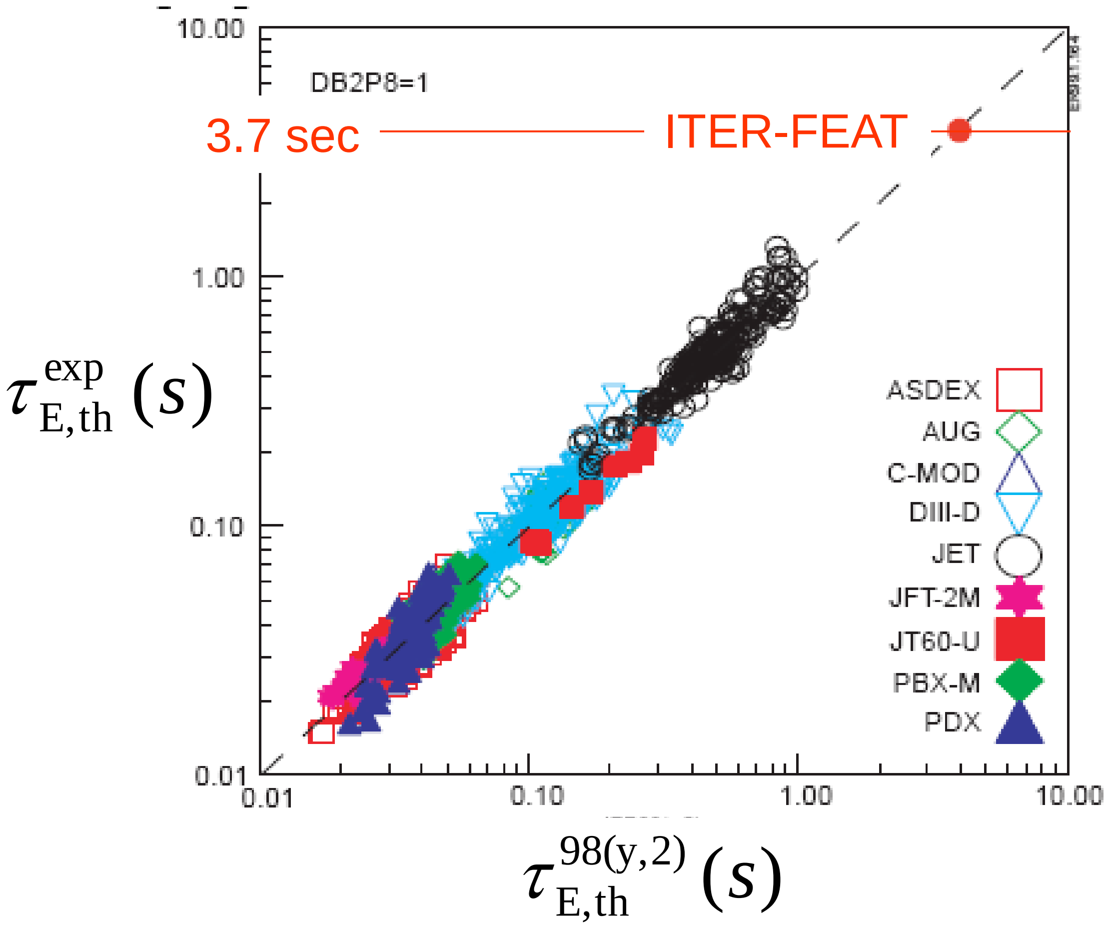


Δ ~ 2 m; δ ~ 1.3 m

Aspect ratio: $A = R_0/a$

a determined by confinement to meet $nT\tau_E$ goal

Scaling of τ_E and projection to ITER



Prediction for ITER

τ_E = 3.7 s

5.3 T; 15 MA;
n = 1 10^{20} m^{-3} = 0.85 n_{GW}
P = 87 MW

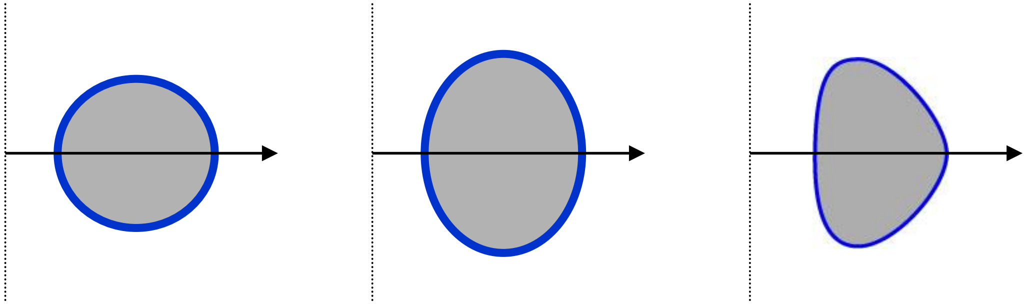
Plasma current

$$\tau_{\mathrm{E,th}}^{98(\mathrm{y},2)} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa^{0.78} \propto R^2 I_p P^{-2/3}$$

inverse aspect ratio

elongation

The shape of the ITER plasma

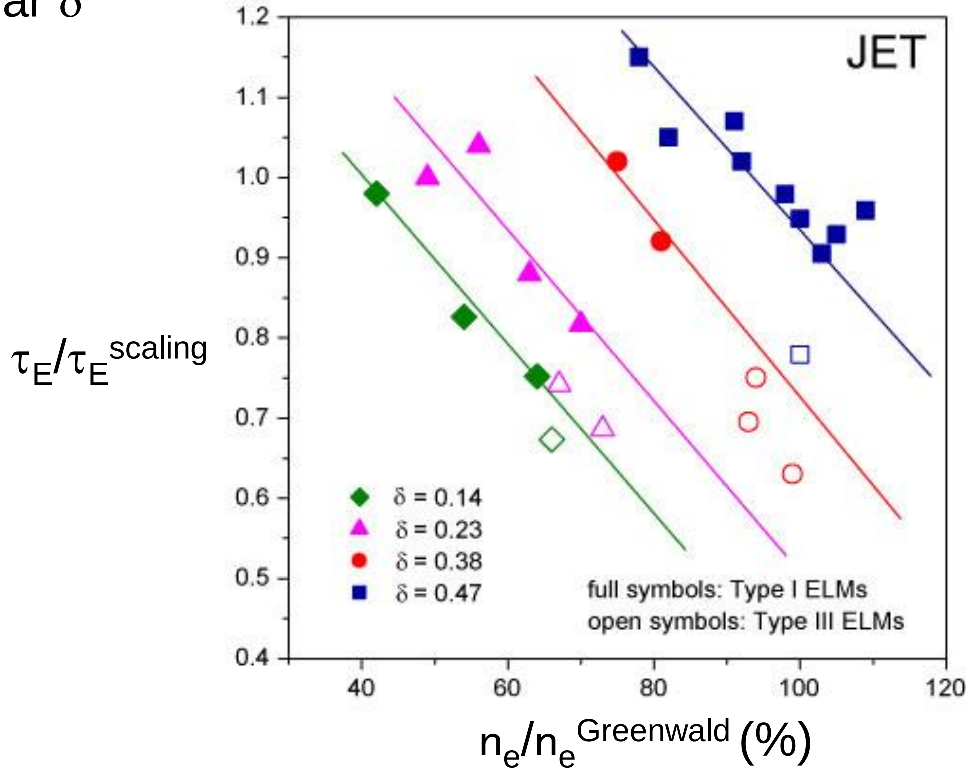


circular

elliptically elongated κ

triangular δ

Degradation of confinement
close to density limit
and
improvement with triangularity



Current is limited by safety factor q

$q = 2.5\, a^2\, (B/RI_p)\, ((1+\kappa^2)/2)$
$\geq 2\ \ (q_{ITER} \sim 3)$

Larger κ => larger I_p

General requirements for ITER (1)

Achieve projected fusion yield: heating (internal, external) and confinement

Ash removal in the core: Transport (D, v_{in}); $\tau_{He}^{*}/\tau_{E} \sim 5$

Ash removal from the system: divertor retention, recycling

Low Z_{eff}: fluxes (ELMs, fast particle losses)
materials (C, Be, W); erosion mechanisms
D_I, $v_{I.in}$, sawteeth

Stable operation:

- limits which terminate operation (via disruptions)
  - density limit (Greenwald): $n_{GW} \sim 10^{20}\ I_p/\pi a^2$ (MA, m) ; $n < 0.85\ n_{GW}$
  - beta-limit (Troyon): $\beta \sim I_p/aB$
  - current limit: $q = 2.5\ a^2\ (B/RI_p)\ ((1+\kappa^2)/2) > 2$ ($q_{ITER} \sim 3$)
  - elongation limit: $\kappa < 2$

General requirements for ITER (2)

Avoidance of MHD leading to performance reduction

sawteeth in the core:
Relaxations of T; spreading of α-particles, triggering of NTMs

neo-classical tearing modes (NTM):
limit in energy content W ($\beta_N = \frac{\beta(\%)}{I_p(MA)/aB}$) $\beta_n < 2$ (2.8)

Edge localised modes (ELMs): divertor power fluxes ~ 20 MW/m^2

Alfven activities: fast particle spreading, losses

The basic operational regime for ITER: ELMy H-mode

I_p (x10) MA
P_{NBI} MW

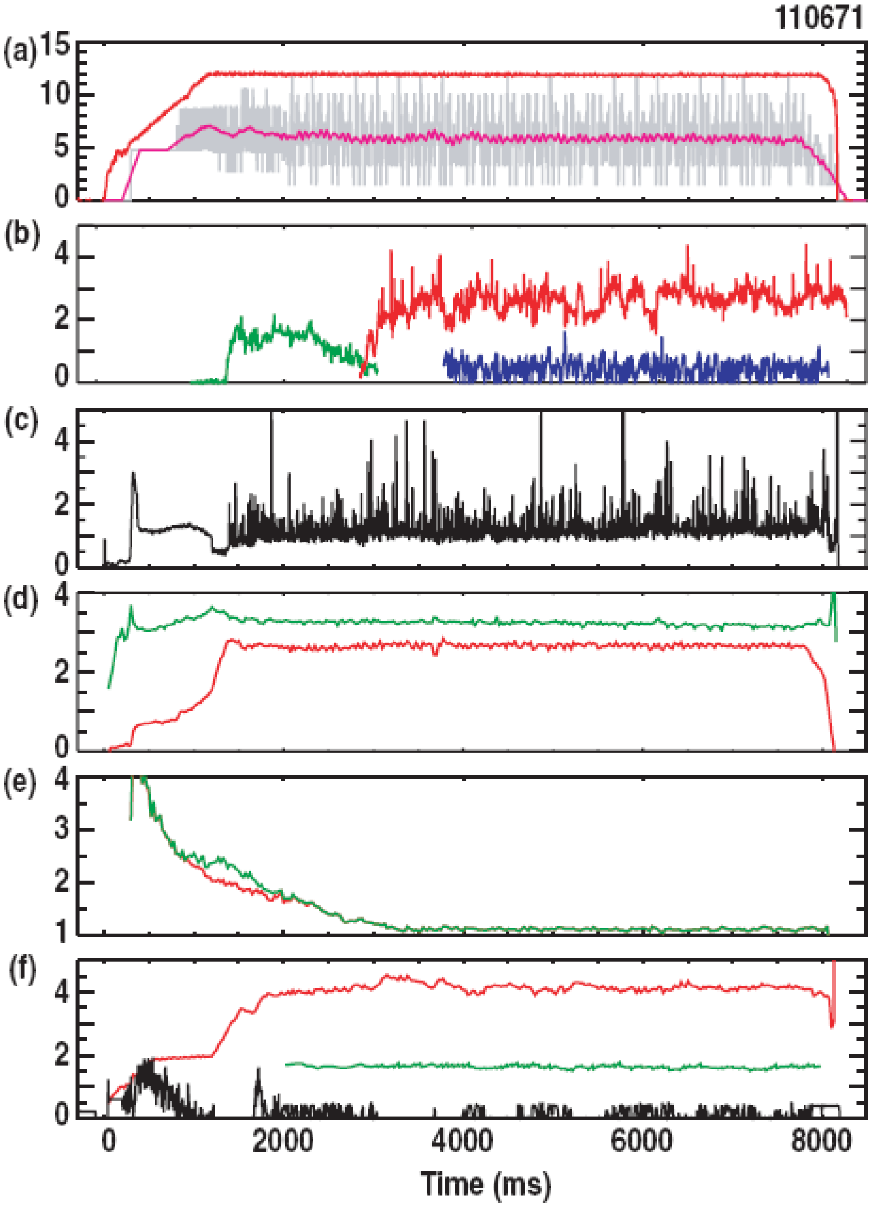
Magn. perturbation
n=3, n=2, n=1

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.

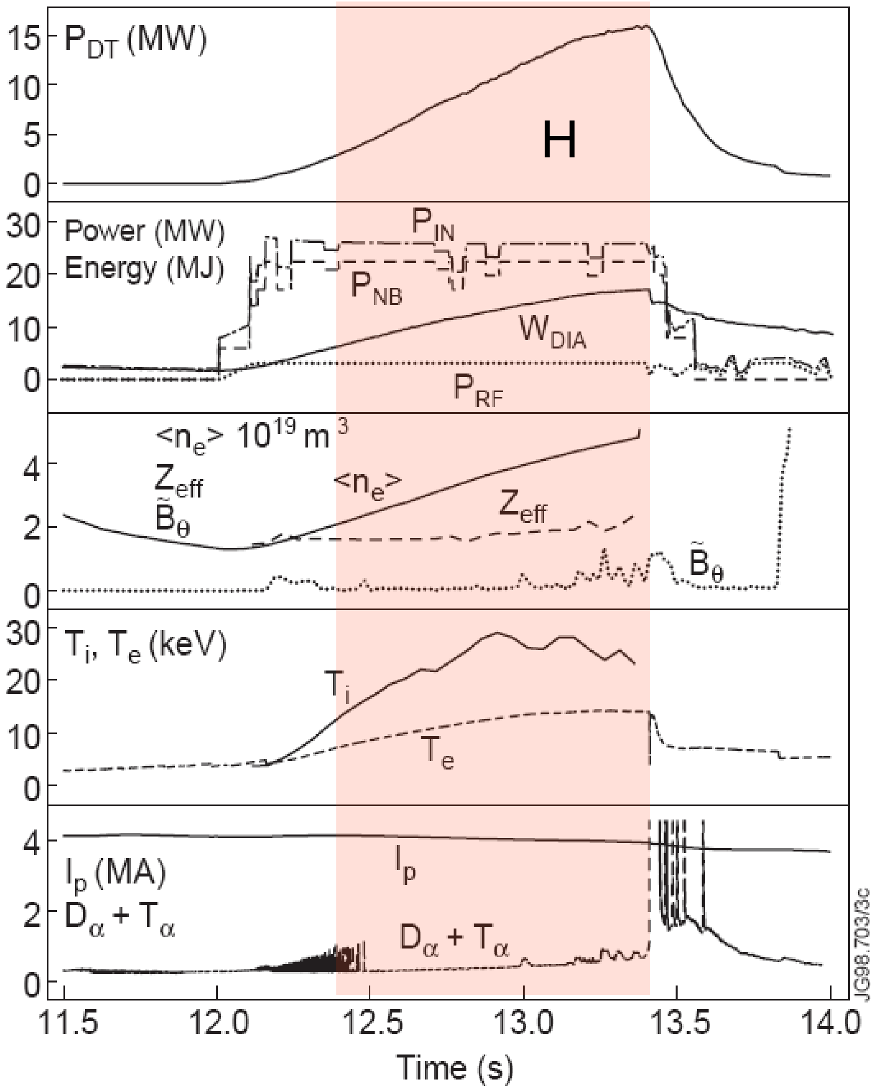
$\beta \sim 3\%$
$\beta_N = 2.7$
$H_{89} = 2.6$
$(H_{89} = \tau^H{}_E/\tau^L{}_E)$
$n_e/n_{eGW} = 0.4$

Mapped to
ITER
Q=10

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

Qualification of the H-mode

The 16.1 MW DT discharge of JET



Characteristics of the H-mode

Confinement improved to the L-mode by factor 2 (H_{89} =2)

Edge pedestal

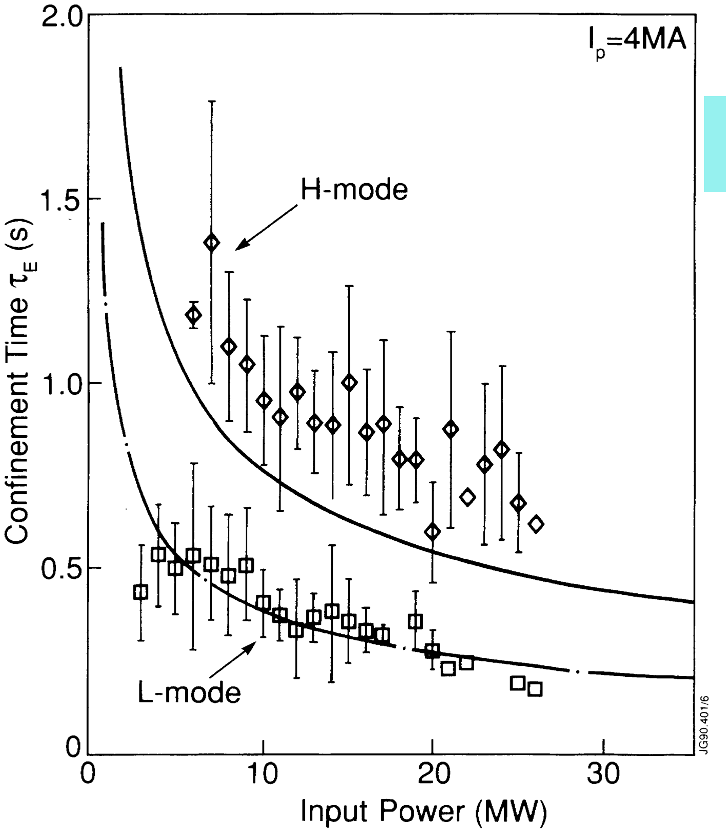
ELMs

Power threshold:
H-mode: P > P_{LH}

$$P_{LH} = 2.84 M^{-1} B^{0.82} \bar{n}_{20}^{0.58} R a^{0.81} \text{ (MW)}$$

Note the isotopic dependence

In Deuterium, P_{LH}^{ITER} ~ 50 MW

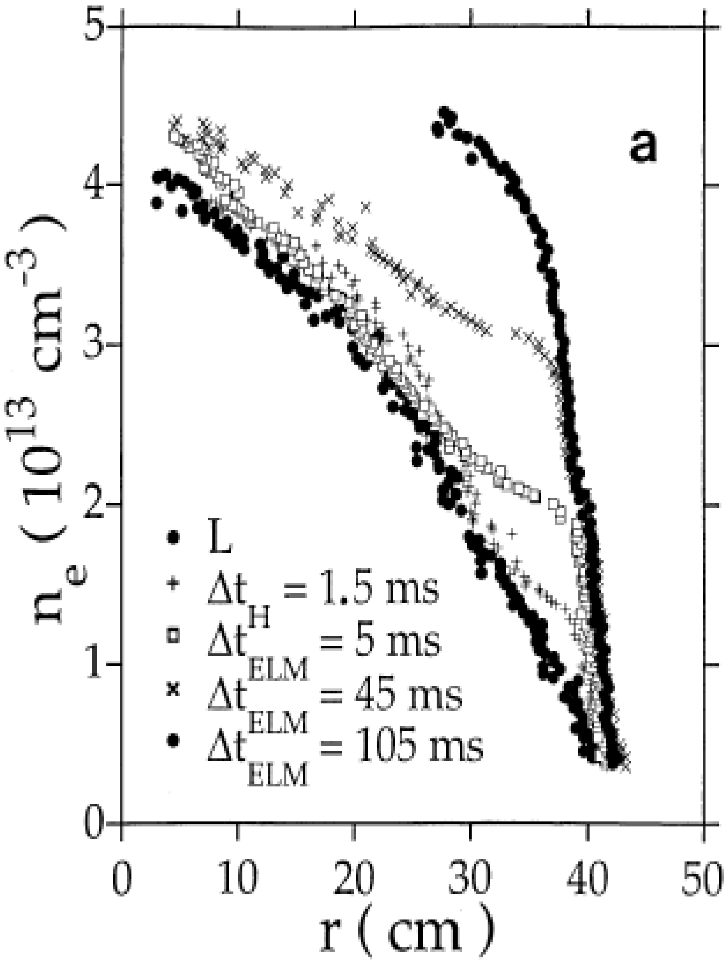


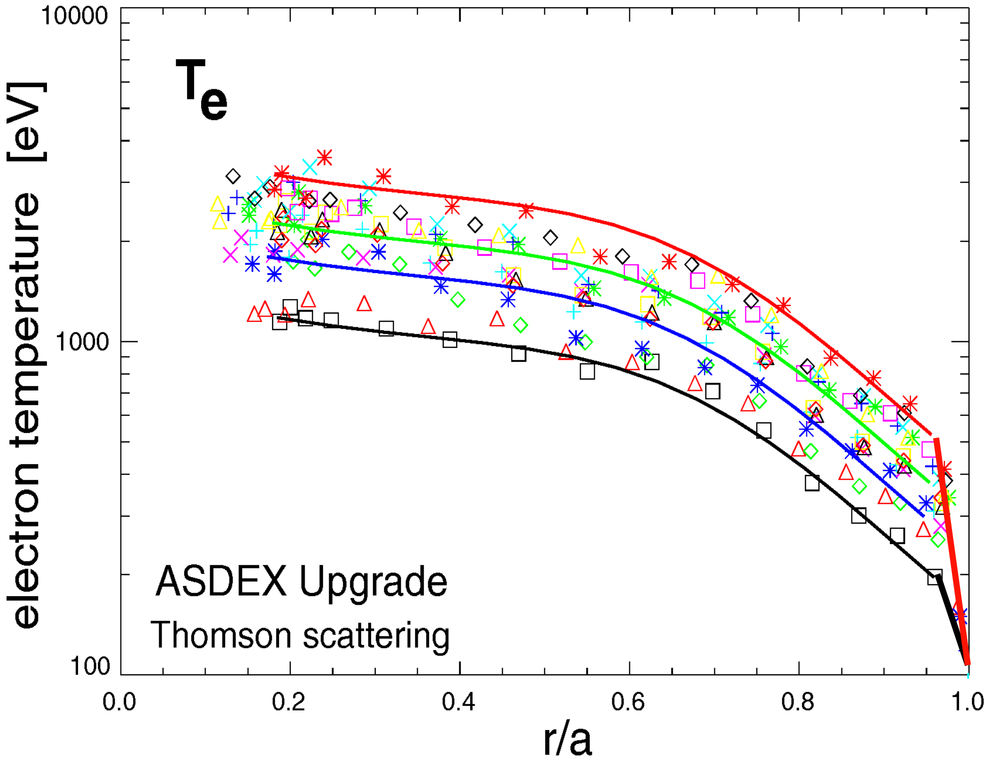
JET

Profile characteristics of the H-mode

Development of a pedestal

Edge transport barrier





Note the similarity of the T_e profiles
“profile stiffness”

What one would like to know beforehand

Which Q and P_{fus} will be achieved?

How do Q and P_{fus} depend on external parameters e.g. B.

Is the H-mode accessible: P_{LH} (special question: $P_{LH} = f(A_i)$)?

What is the pedestal height, specifically T-pedestal ?

What is the density profile shape ?

Will the ITER plasma rotate?

Will ITER operate in advanced confinement modes?

At what n/n_{GW} does the confinement degradation set in?

Will there be sawteeth in the core: amplitude and period ?

The inner relations of a fusion plasma

The T pedestal height has strong impact on T(0), on P_{fus} and Q

The density profile shape – peaked or flat?

peaked at large v_{in}/D

medium n_e - gradients : turbulent fluxes lower

strong n_e - gradients: turbulent fluxes higher because of TEMs

strong peaking: neo-classical impurity accumulation?

higher n_e-gradients => smaller T-gradients => lower fusion yield

In case of toroidal flow: does it reduce turbulence and even cause ITBs

(depends on torque and χ_ϕ)

The stiffness of the T-profiles:

very stiff: weak increase of T with power; Q goes down with P_{aux}

Abbreviations: TEM = trapped electron mode

ITB = internal transport barrier

Predictions by dimensionless scaling

0-dimensional scaling allows the prediction of τ_E e.g. via the $\tau_{E,th}^{98(y,2)}$

Profile knowledge needs theory-based transport models for
energy, particles and impurities; not available in necessary detail

One step before: similarity approach = scaling along dimensionless parameters

Relevant dimensionless parameters (Kadomtsev):

$\beta \propto nT/B^2$	measure for the energy content, the driving mechanisms
$\nu^* \propto Rq/\lambda_{mfp} \propto Rqn/T^2$	measure for dissipation
$\rho^* = \rho_{Li}/a \propto \sqrt{T}/aB$	measure of the orbit effects

The 98(y,2) τ_E scaling in dimensionless parameters: $\tau_E B \sim \rho^{*\,-2.7}\, \beta^{-0.9}\, \nu^{*-0.01}$

problem

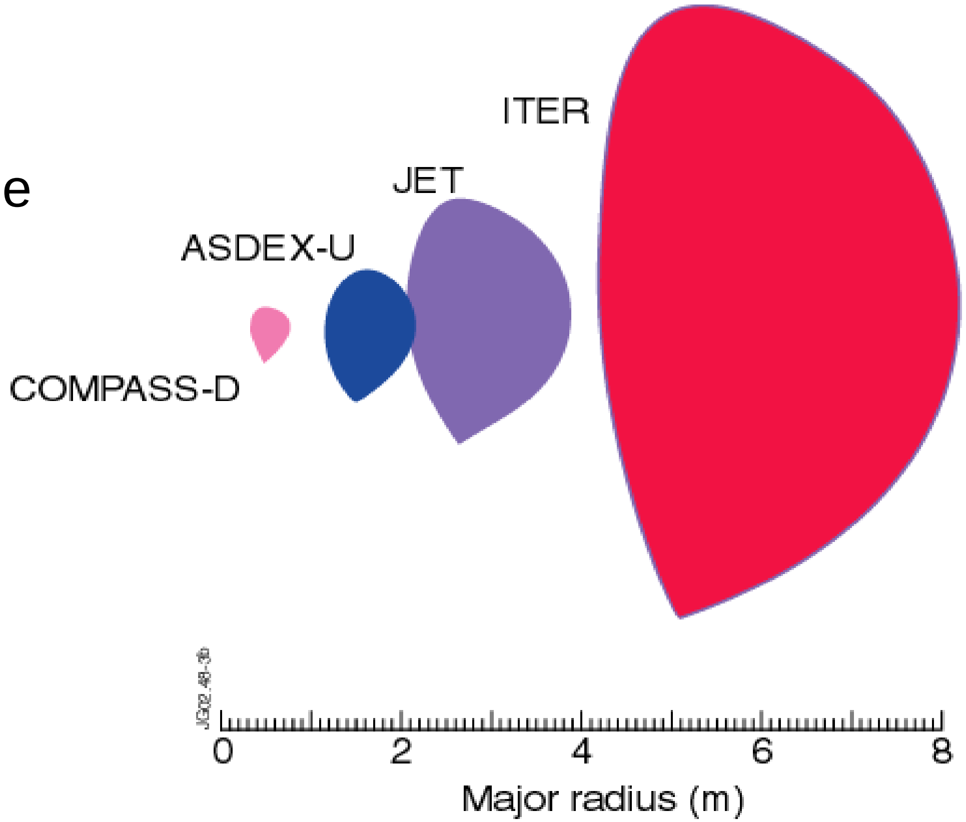
A geometrically similar family

Compare plasma states with identical parameters

(ρ*, β , ν* , q , geometry (A, κ, δ), profile shapes..)

Scale transport coefficients along dimensionless parameters; map profiles

Devices with comparable geometry (A, κ, δ)



Dimensionless scaling of engineering parameters (K. Lackner)

q, β and ν^* are kept fixed under the following scaling:

$I_p \propto B\ a$

$n \propto B^{4/3}\ a^{-1/3}$

$T \propto B^{2/3}\ a^{1/3}$

Under these circumstances, the energy content W scales: $W \propto B^2\ a^2$

From these relations, the scaling of the external parameters B (or I_p), P_{heat} and n (Φ_{gas}) can be obtained along dimensionally correct paths when scaled as B*, P* and n*:

$$B^* = Ba^{5/4} \propto \beta^{1/4}\, \nu*^{\ -1/4}\ \rho*^{\ -3/2}$$

With the assumption of gyro-Bohm scaling the following scaling for the heating power P is obtained:

$$P^* = P_{heat}a^{3/4} \propto \beta^{7/4}\, \nu*^{\ -3/4}\ \rho*^{\ -3/2}$$

The density can be scaled in 3 different ways; the physically most reasonable one is the one which varies closest to the (dimensional) Greenwald limit:

$$n^* = n\ B^{-1}\ a^{3/4} \propto \beta^{3/4}\, \nu*^{\ 1/4}\ \rho*^{\ -1/2}$$

Dimensionless scaling of engineering parameters

Under the condition that n* is kept constant, the operational range of present devices and that of ITER can be plotted in a diagram of dimensionally correct parameters:

For present devices:

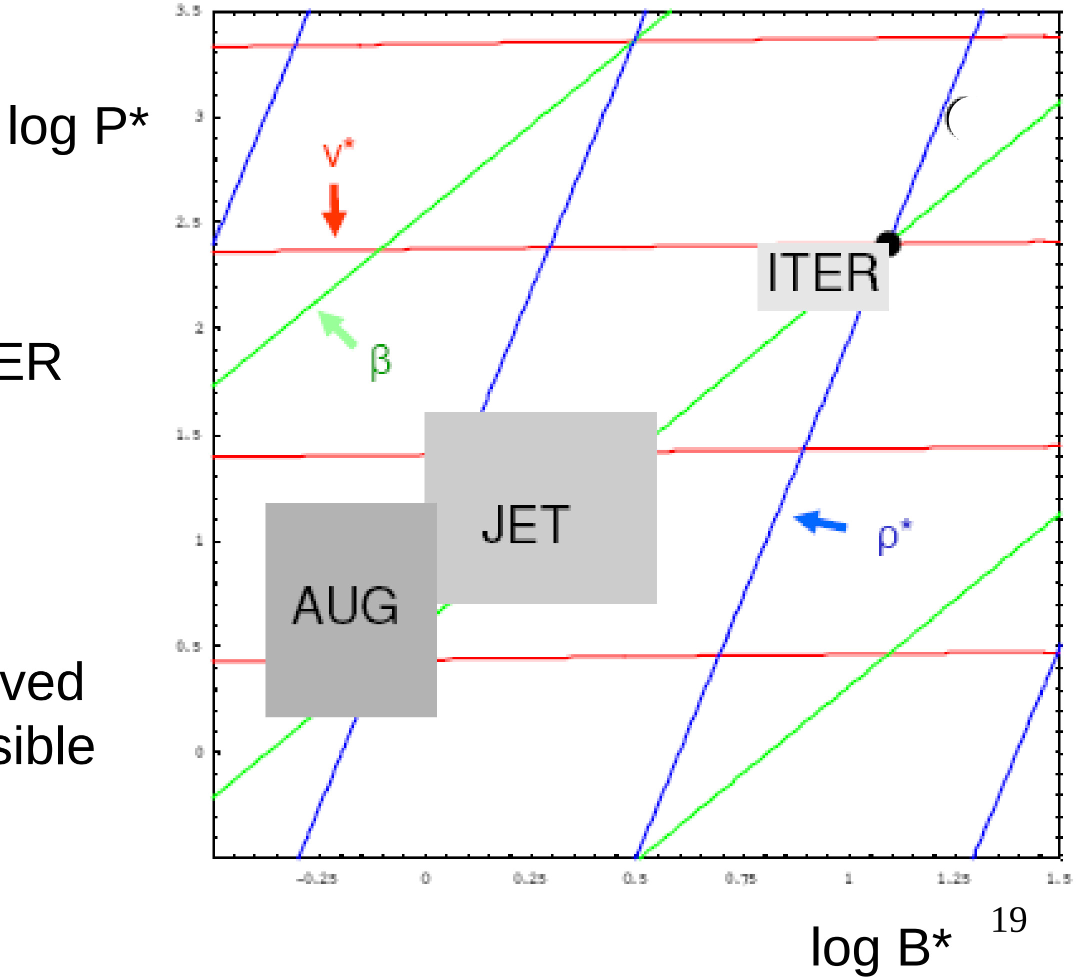
Possible:

operation at the β of ITER

Not possible:

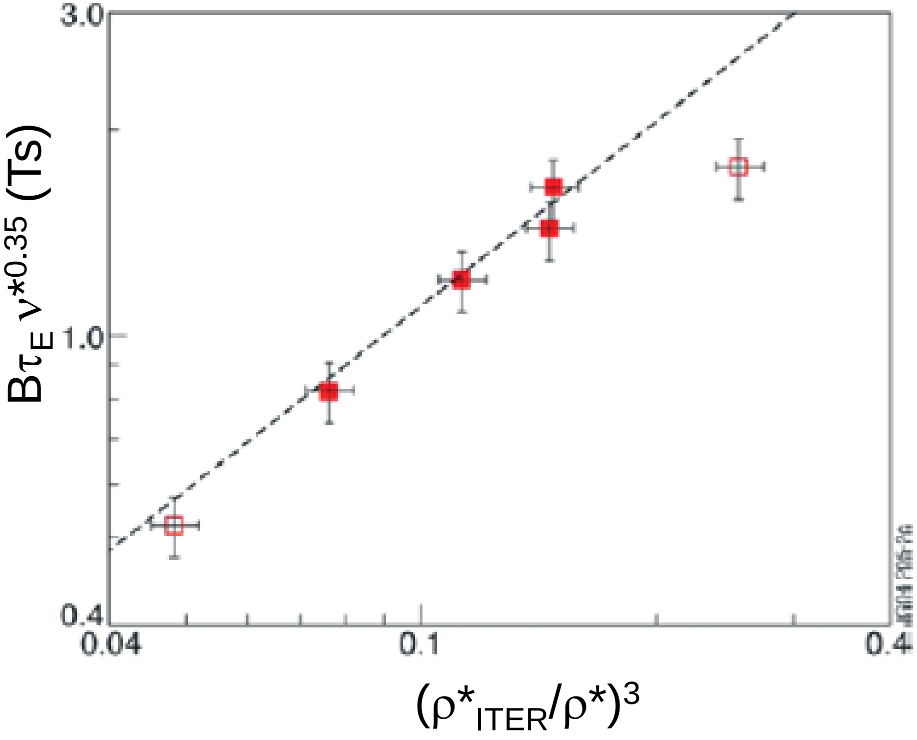
operation at ρ* or ν*

If the density constraint is removed operation at the ITER ν* is possible



The scaling with $\rho^* = \rho_{Li}/a$

This scaling goes to the basics of confinement: Bohm- or gyro-Bohm scaling



Bohm – scaling:
Turbulence correlation length ~ $\sqrt{a\rho_L}$

$\tau_{EB} \sim \rho_L^2$

gyro-Bohm scaling:
Turbulence correlation lenght ~ ρ_L

$\tau_{Eg\text{-}B} \sim \rho_L^3$

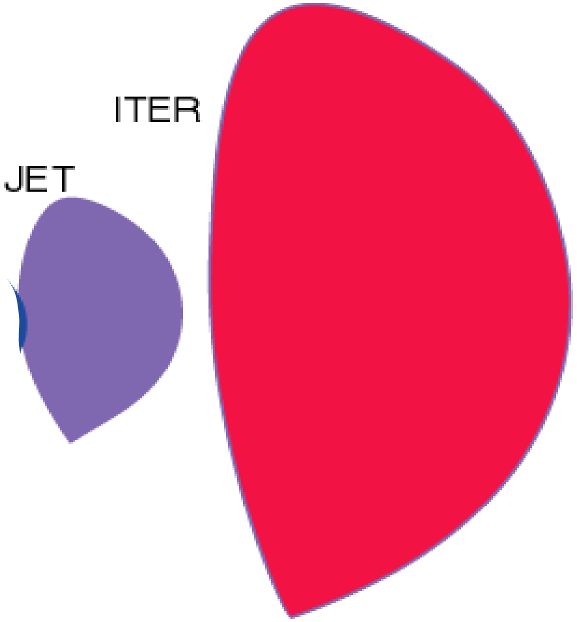
Global scaling: $\tau_E B \sim \rho^{*-(2.78-3.15)}$

X. Garbet, Data from JET and DIII-D

The scaling with ρ* from JET to ITER

Dimesionless scaling from JET to ITER at ν^* = const. and β = const.

$I_p \propto B\, a$
$n \propto B^{4/3}\, a^{-1/3}$
$T \propto B^{2/3}\, a^{1/3}$
$\rho^* \propto B^{-2/3}\, a^{-5/6}$

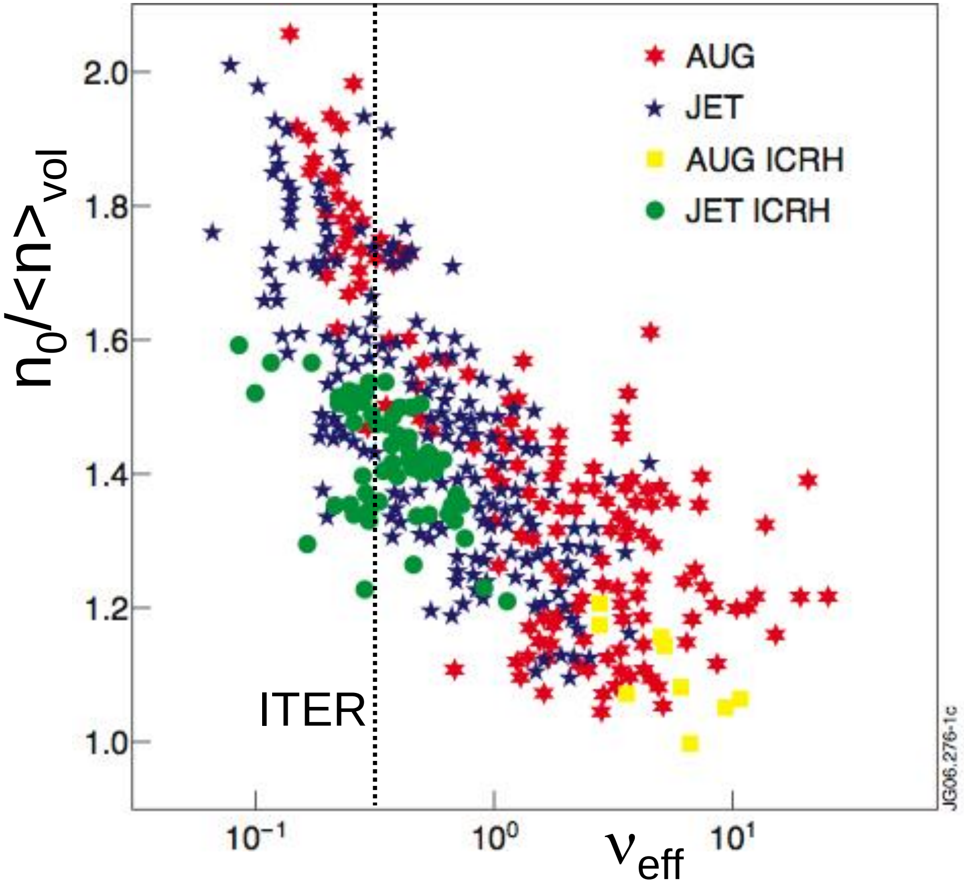


Outcome of JET ITER-like discharge
"ITER" / JET

B = 5.6 / 3.46 T
a = 2.0 / 0.96 m
τ_E = (3.74 – 5.6) / 0.51 sec
Pfus = 275 MW
Q = (6.2 – 12.3)

The scaling with ν*

The scaling of particle transport
with collisionality



Global scaling: $\tau_E B \sim \nu^{*-(0.01-0.35)}$

This subtlety not obtained from global scaling.

Peaking factor >1.35 expected for ITER.

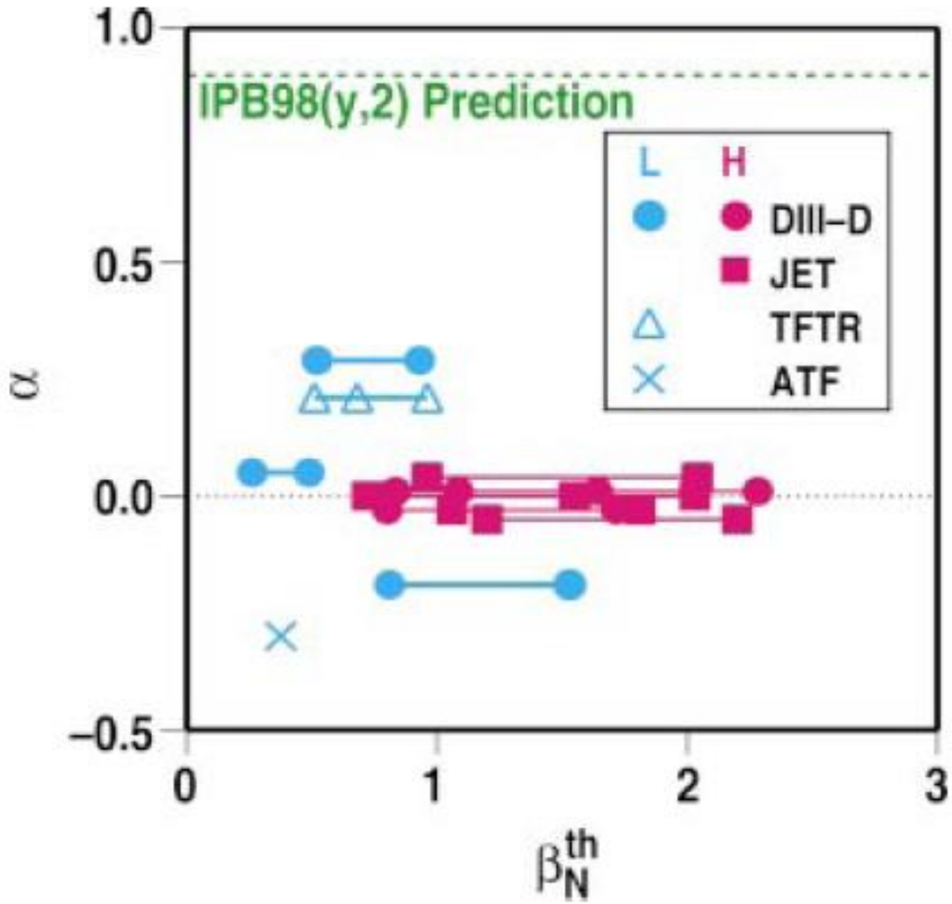
Possible chain:
$v_{in} \Rightarrow n_0/\langle n\rangle_{vol} \Rightarrow c_{He} \Rightarrow Q$

[359] Angioni C. *et al* 2003 *Phys. Rev. Lett.* **90** 205003
[360] Angioni C. *et al* 2003 *Phys. Plasmas* **10** 3225

The scaling with beta

Global scaling: $\tau_E B \sim \beta^{-\alpha}$ with α = -0.9

The devoted scans show α ~ 0: big conflict !



(beta expressed as $\beta_N = \beta / I_p/aB$)

Petty, DIIID

The impact of the β-scaling

POP-CON diagrammes

Volume average
n, n/n_{GW} versus T

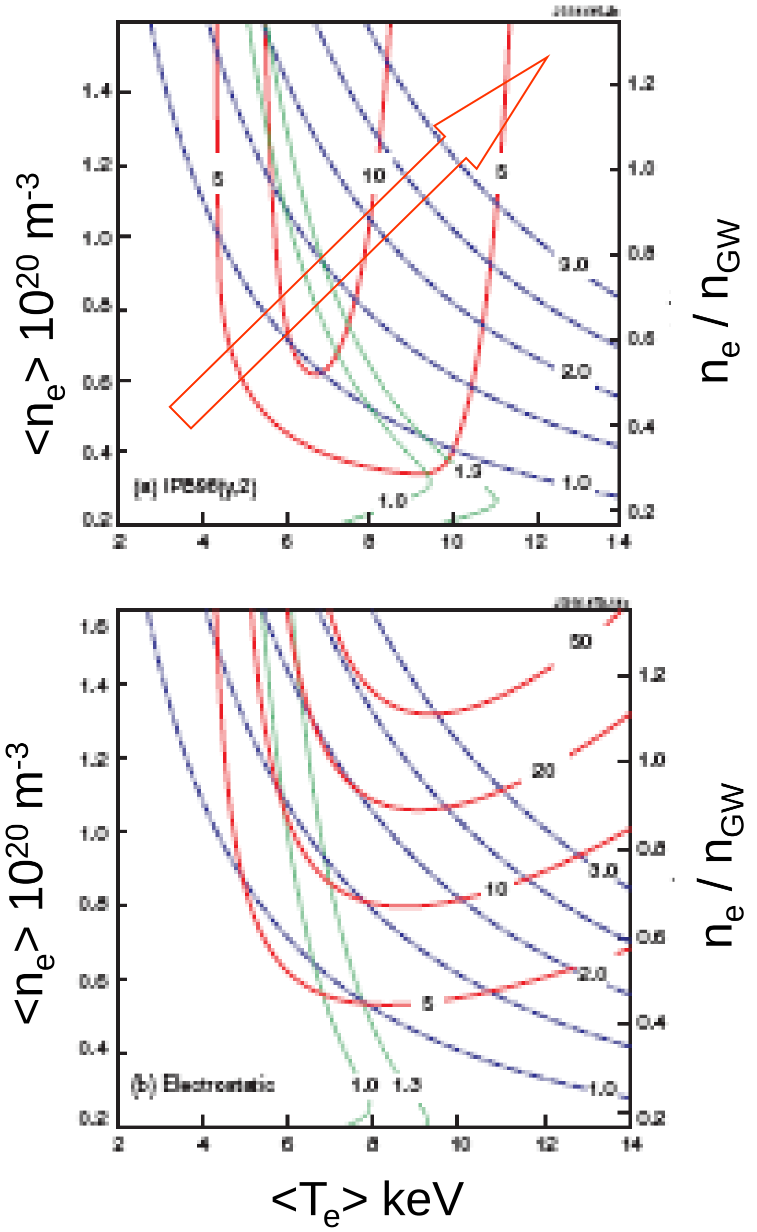
For different Q (red)

with

different β_N (blue)

and

different P/P_{LH} (green)



Basis is the 98(y,2) scaling

$\tau_E B \sim \beta^{-0.9}$

Basis is a pure el. static model

$\tau_E B \sim \beta^0$

Petty, DIIID

In summary

Confinement predictions for ITER

Dimensional scaling: 3.6 sec

Dimensionless scaling: 3.3 sec

Understanding transport and modelling scenarios

What are the robust confinement characteristics

which evolve from a complex chain of interactions and causalities

and which ultimately need theoretical understanding

and predictive modelling ?

Collisional transport: neo-classical transport

Transport based on Coulomb collisions in toroidal geometry

Heat diffusivities:

$\chi_i \sim \chi_{i,neo}$ at low heating power, at peaked n_e profiles or inside ITBs
χ_e always turbulent

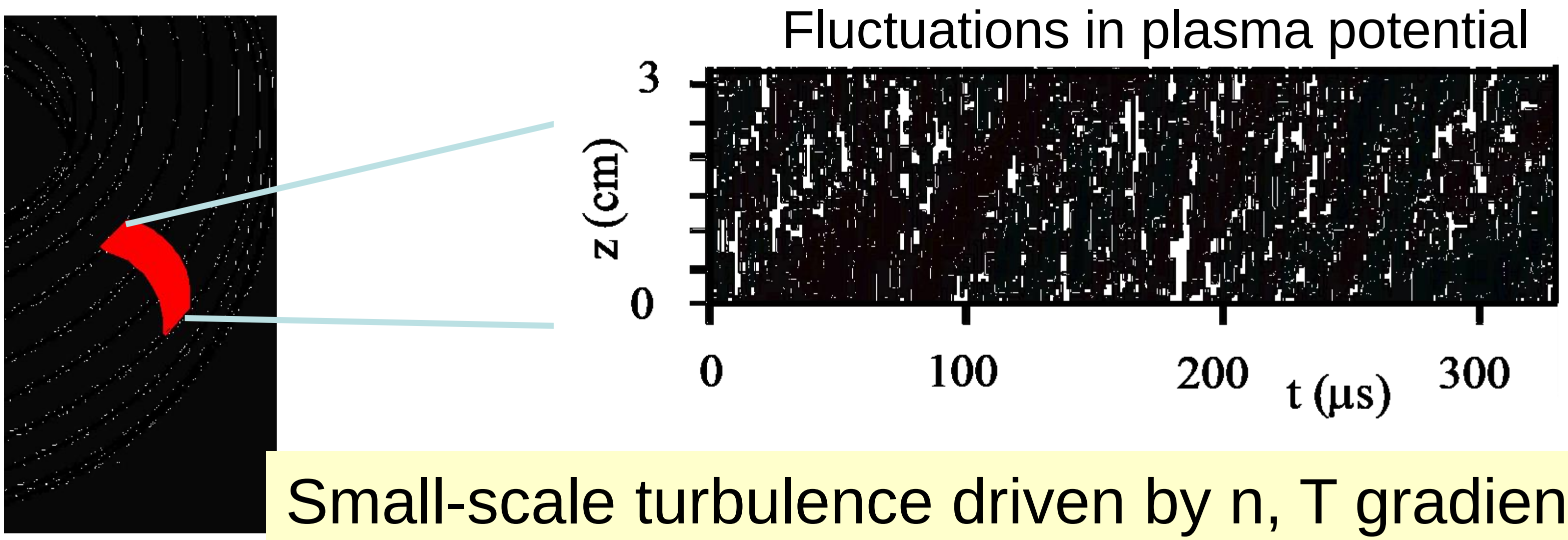
D and D_I normally turbulent;
$v_{in} \sim v_{in,neo} = v_{warepinch}$ at high collisionality
$v_{I,in}$ normally neo-classical: impurity accumulation with peaked proton profiles

Momentum transport mostly turbulent

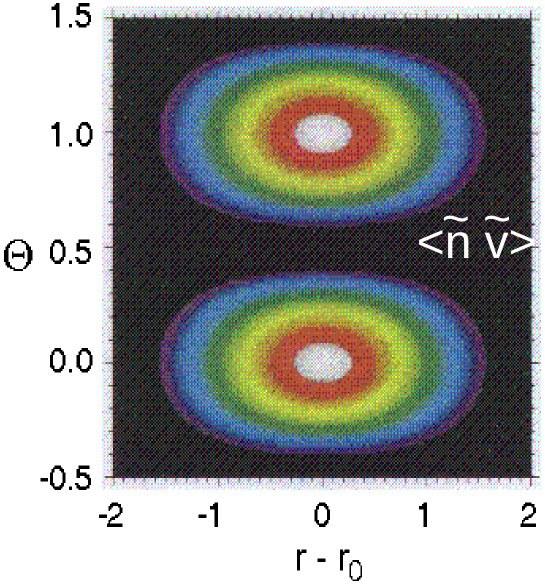
Effects of paralled dynamics often neo-classical
- bootstrap current
- neo-classical correction to resistivity
- fast particle slowing down
- flow damping

Ambi-polar electric field mostly neo-classical.

Turbulent transport


Fluctuations in plasma potential

Small-scale turbulence driven by n, T gradients



Space scales:

perp. correlation length: $k_\perp \sim \rho_i$ (ρ_e)

parallel correlation length: $k_{||} << k_\perp$

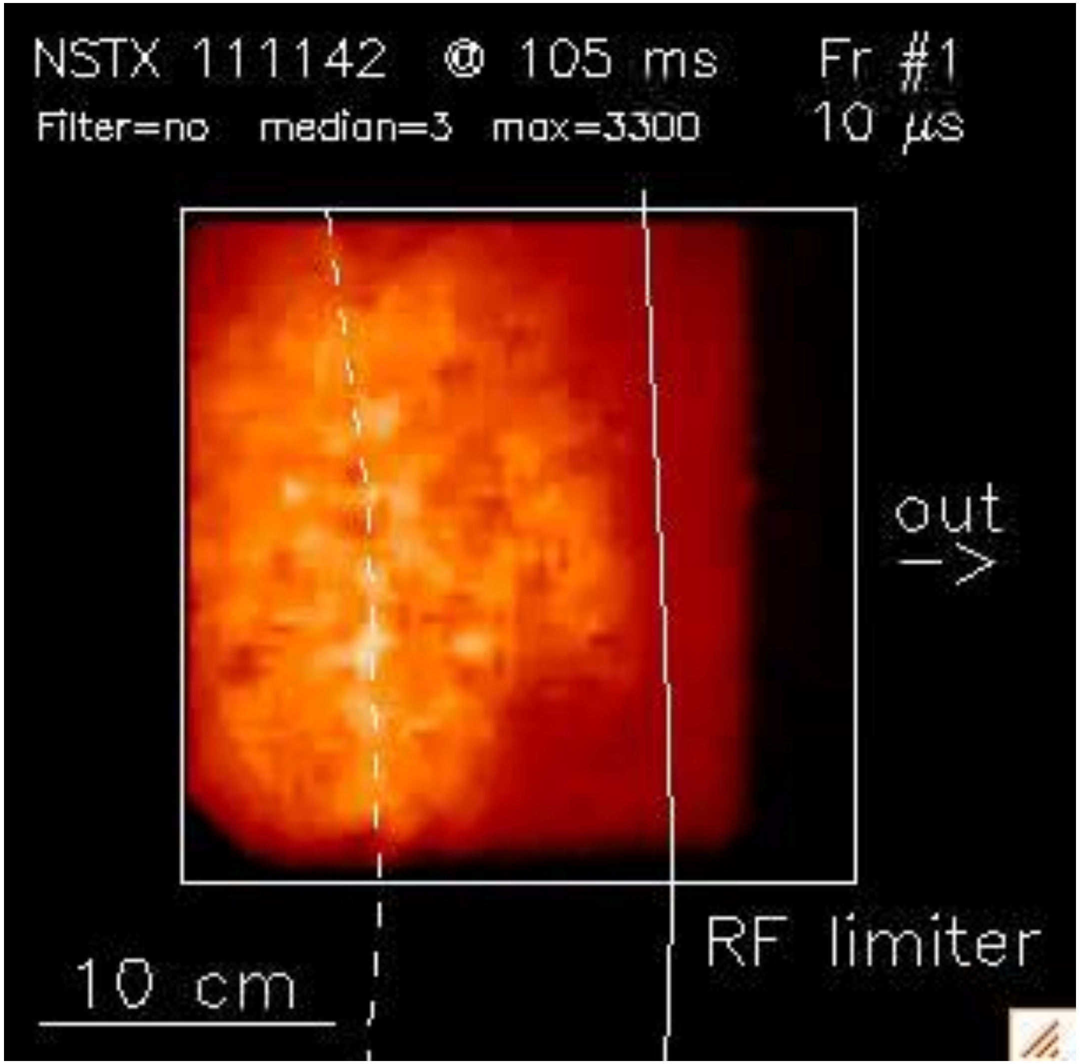
Gradient length $L_p >> k\perp^{-1}$

Time scales:

Drift frequency: $\omega \sim c_s/L_p$; v_{The}/L_n

$$D_{turb} \approx \frac{\gamma}{k_\perp^2} \quad \sim 1 m^2/s \quad => \tau_E \sim O(1s)$$

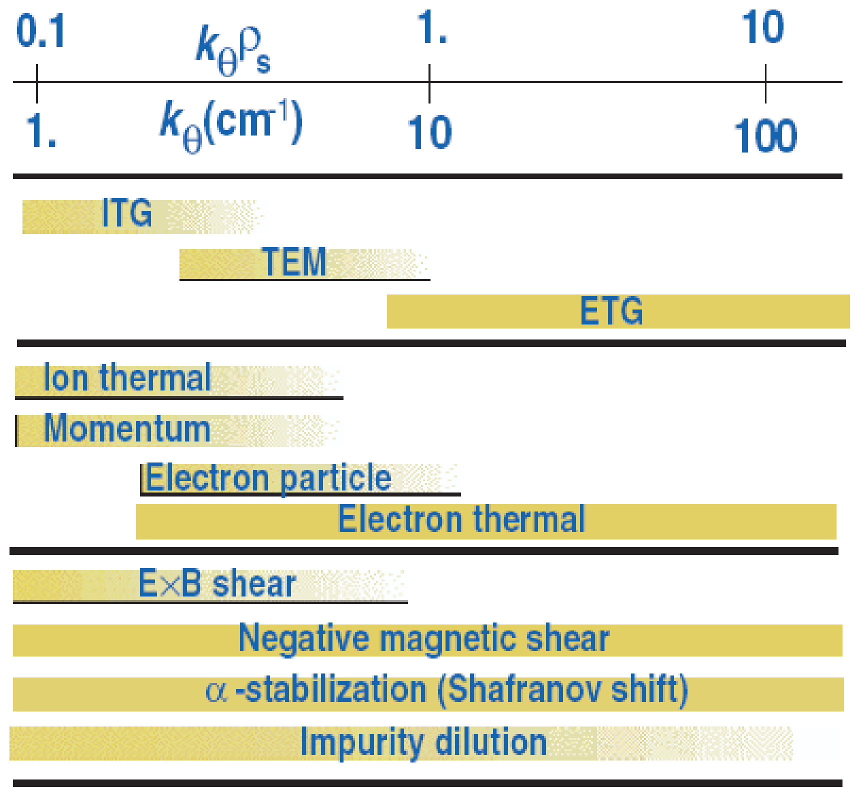
Movie of edge turbulence



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

Classification of instabilities

TRANSPORT IS DRIVEN BY SEVERAL TURBULENCE MODES WITH A RANGE OF SPATIAL SCALES



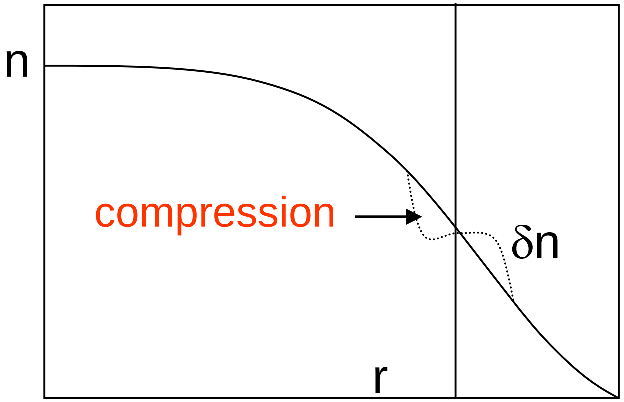
DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

[22] Doyle E.J. *et al* 2000 *Fusion Energy 2000: Proc. 18th Int. Conf. (Sorrento, 2000)* (Vienna: IAEA) CD-ROM file EX6/2 and http://www.iaea.org/programmes/ripc/physics/fec2000/html/fec2000.htm

Basic elements of turbulence dynamics

A density perturbation leads to flows
of the ions in perpendicular direction (polarisation drift)
of the electrons in parallel direction
charge separation => ExB flows convect plasma

collisionality and trapped particles can affect the electron flow

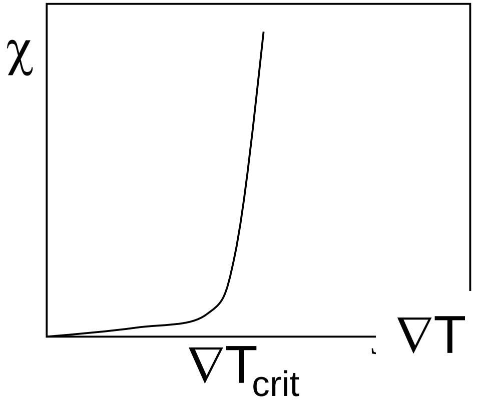


The density perturbation gives rise to compression and expansion

The same picture for temperature gradient driven instabilities

Thresholds and growth rates depend on
the ratio of relative T to relative n variations
e.g. steep density gradients can suppress ITG modes

$$\eta = d \ln T / d \ln n = L_n/L_{T;} \quad d \ln T = dT/T = - L_T^{-1}$$



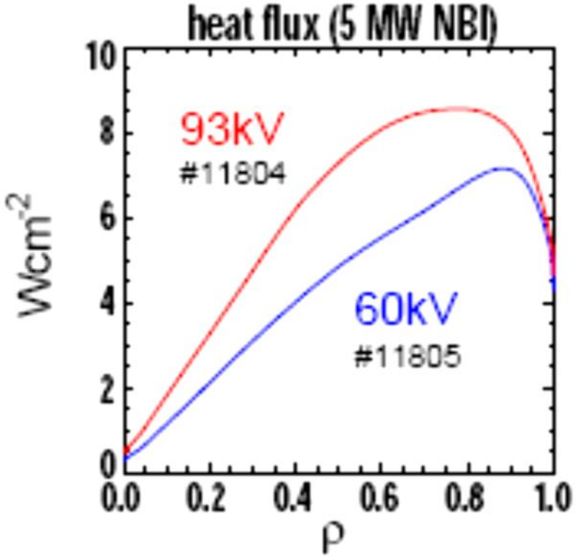
Critical gradients exist with strongly rising χ when surpassed:

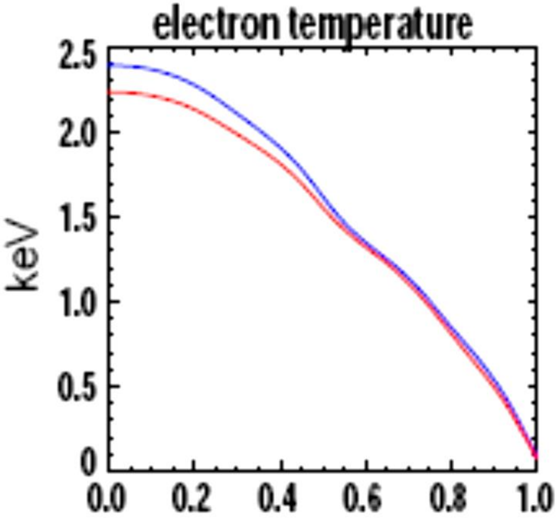
For toroidal modes, the instability threshold depends on R/L_T

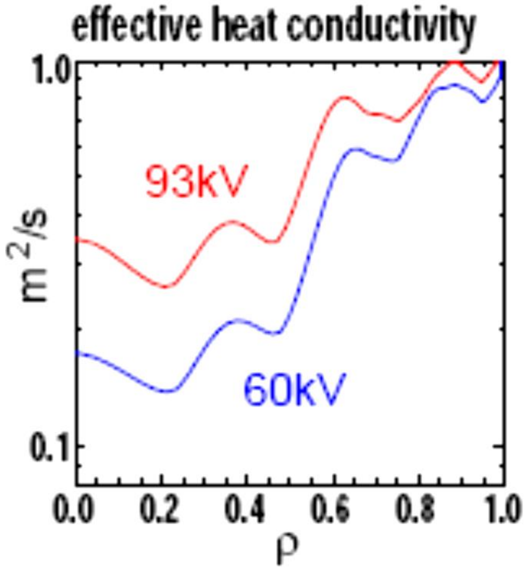
Experimental evidence of critical gradients

Profile resilience in tokamaks

ASDEX-upgrade







„Stiff" T_e profiles

$T/\nabla T$ ~ const.

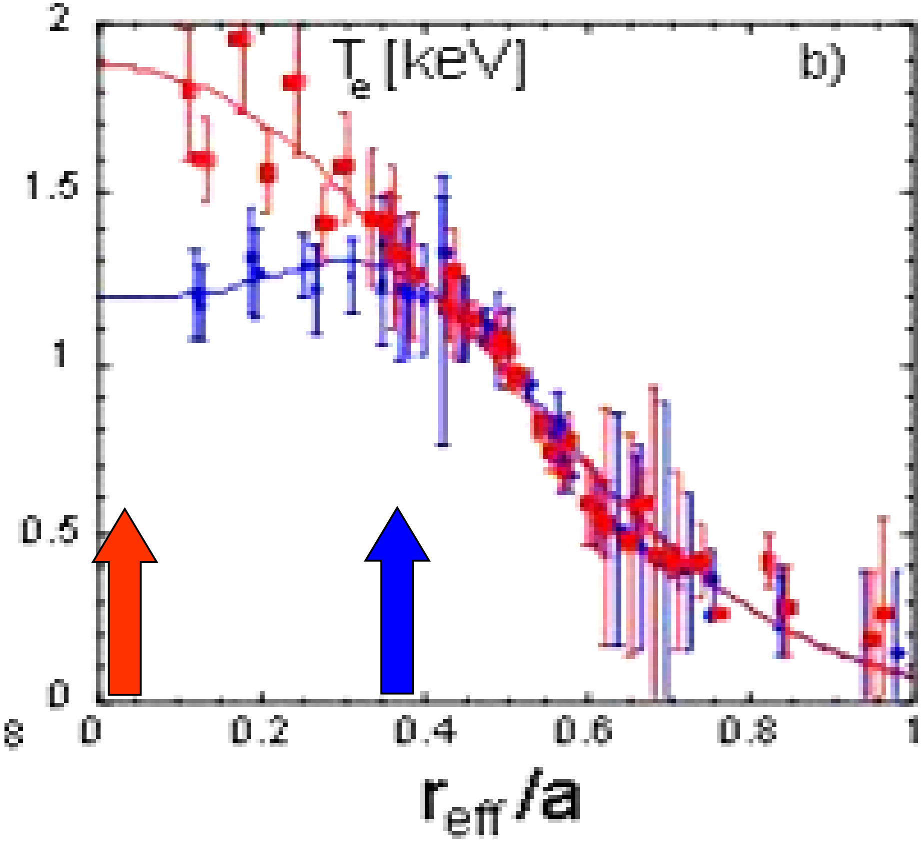
Also: stiff T_i profiles

Further experimental evidence from heat-wave studies.

Heat conduction determined by heat flux and boundary condition but not by local parameters

“Orthodox” profile shapes in stellarators

W7-AS



Variation of T_e profile

with variation of location

of power deposition

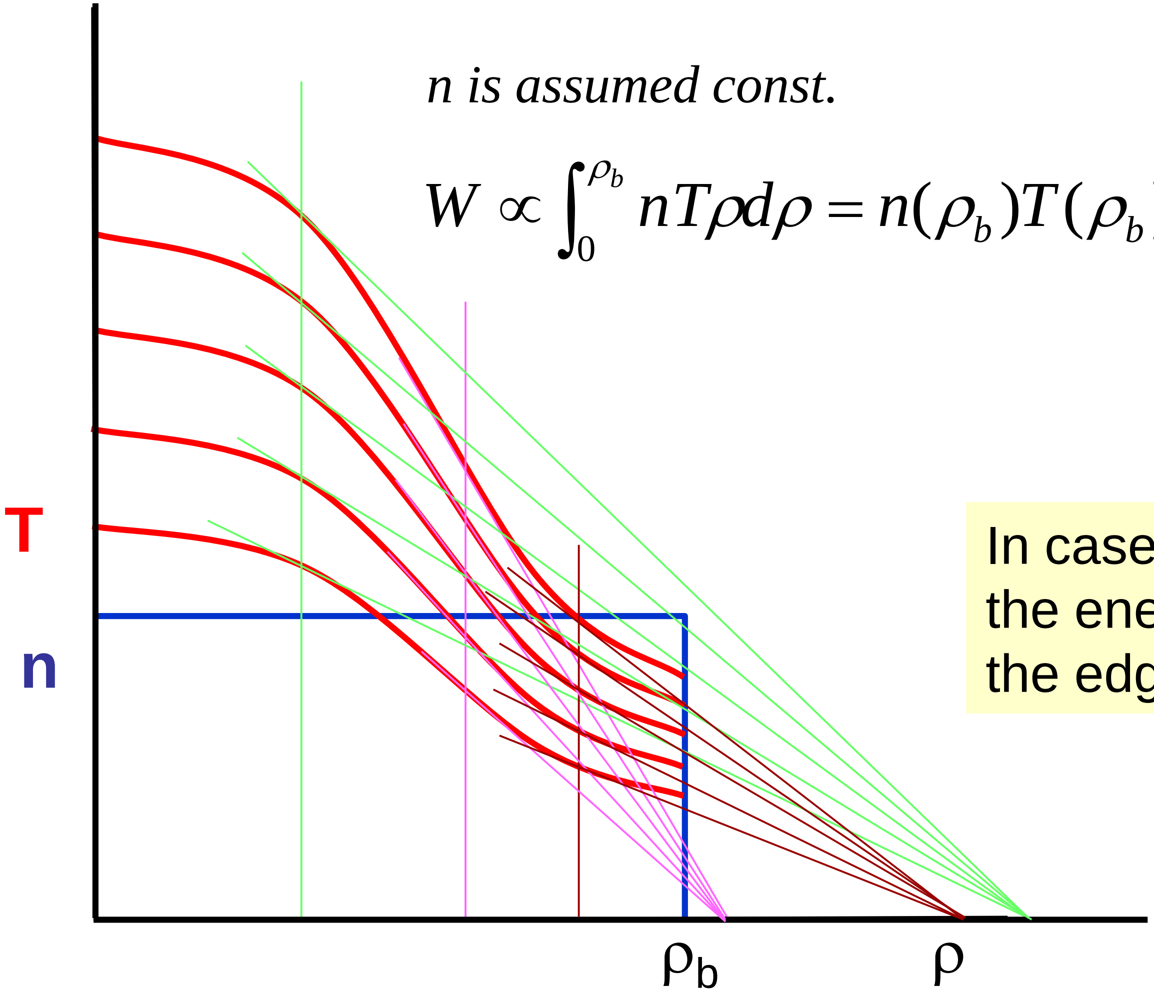
The corollary of profile resilience

$d\ lnT = dT/T = -\ L_T^{-1}$

Critical condition: $R/L_T > (R/L_T)_{crit}$*: transport sharply increases*

n is assumed const.

$$W \propto \int_0^{\rho_b} nT\rho d\rho = n(\rho_b)T(\rho_b)\int_0^{\rho_b} e^{a/R\int_{\rho_b}^{\rho} R/L_T d\rho'} \rho d\rho \propto p(\rho_b)$$

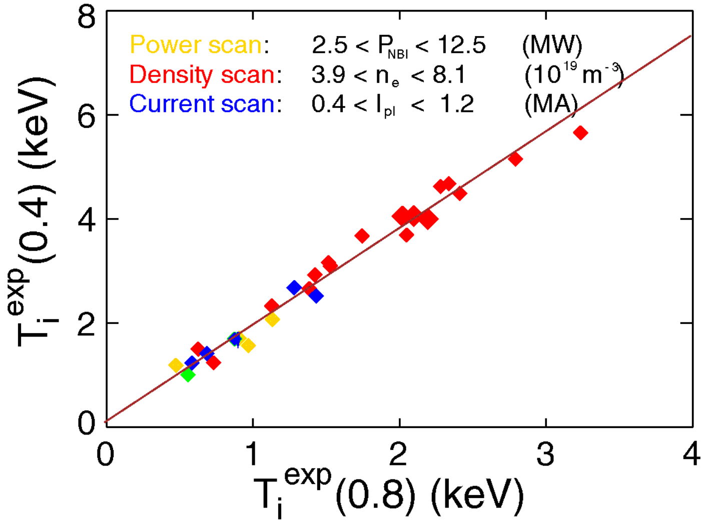


In case of profile resilience the energy content W depends on the edge pedestal pressure

“ The tail wags the dog ”

ASDEX-upgrade

The ion temperature at half radius is proportional to the temperature at the edge

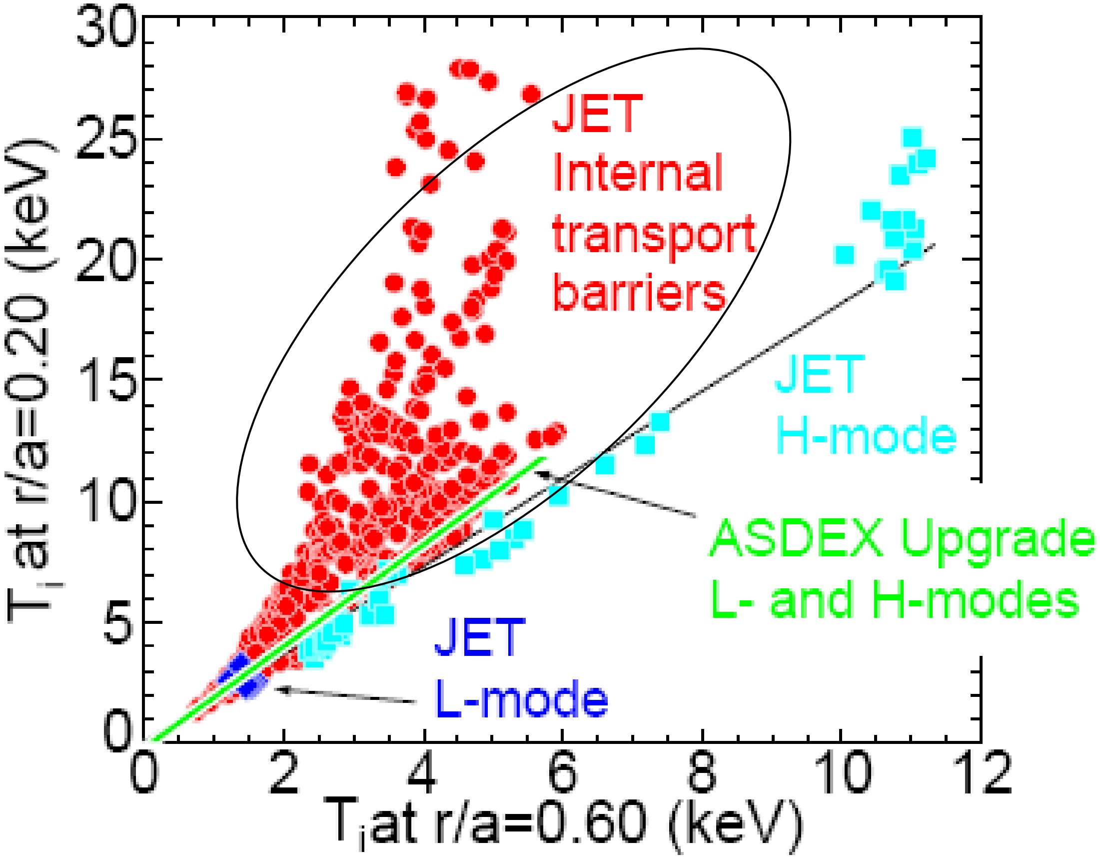


This linear relation is roughly independent of
- plasma current
- heating power
- density
- ion mass

See discussion later on H-mode pedestal

A.G. Peeters et al., Nuclear fusion **42** 1376 (2002)

Universality, scalability of critical gradients



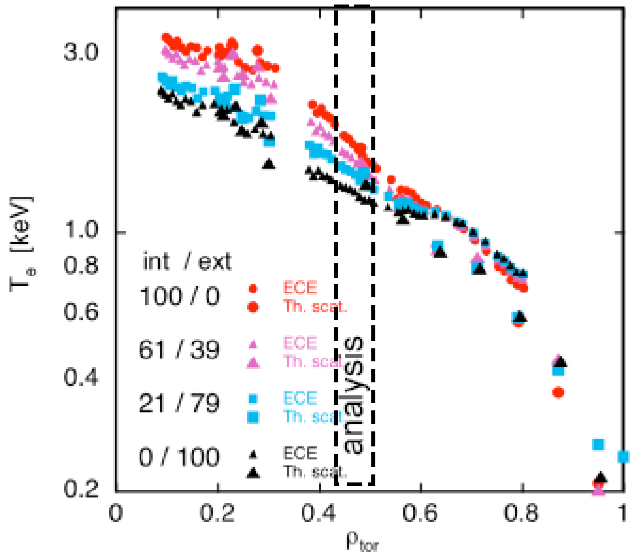
JET and ASDEX-upgrade show similar profile relations: $T_i(\rho_a) \propto T_i(\rho_b)$ in L- and H-modes

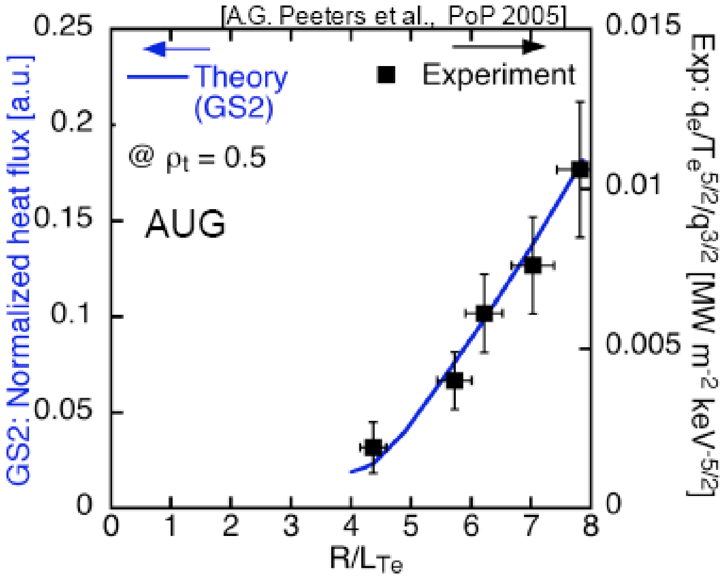
Electron temperature profile stiffness and TEM

ASDEX-upgrade; F. Ryter

Comparison of experimental results with gyro-kinetic calculations

On-axis and off-axis





R/L_{Te} varies continuously

$R/L_{Te} \approx 4$ with off-axis

TEM dominant modes

Threshold in R/L_{Te} agrees

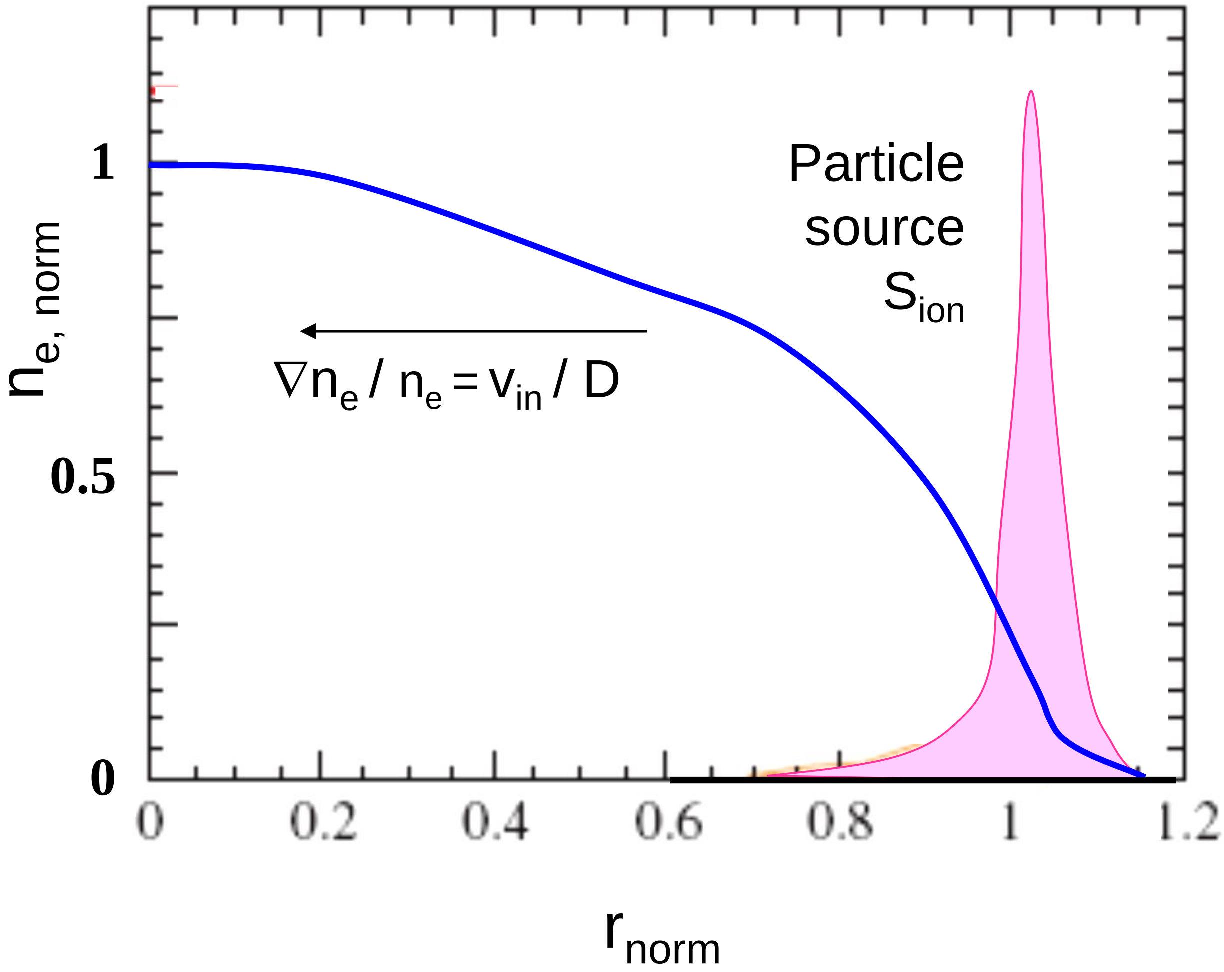
Slope $q_e = f(R/L_{Te})$ agrees

Similar results from T_i profile analysis and γ and R/L_{Ti} for ITGs

Particle transport

Observation: gradient in n in radial zones with $S_{ion} = 0$.

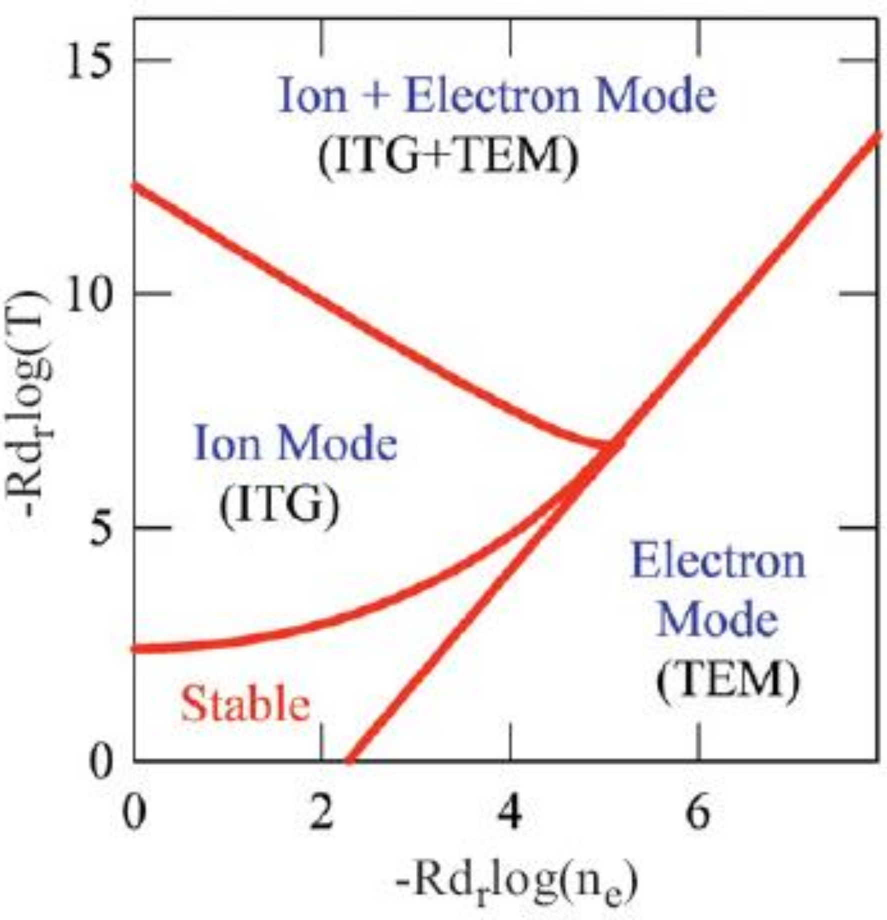
$\Gamma = -D \nabla n_e + v_{in} n_e$



Consequence of peaked n_e profiles

Stability diagramme for ITG and TEM modes

X. Garbet, PPCF, 2004



Expectation: effected is either electron or ion transport or both (e.g. when temperatures are largely different)

How to improve the confinement ?

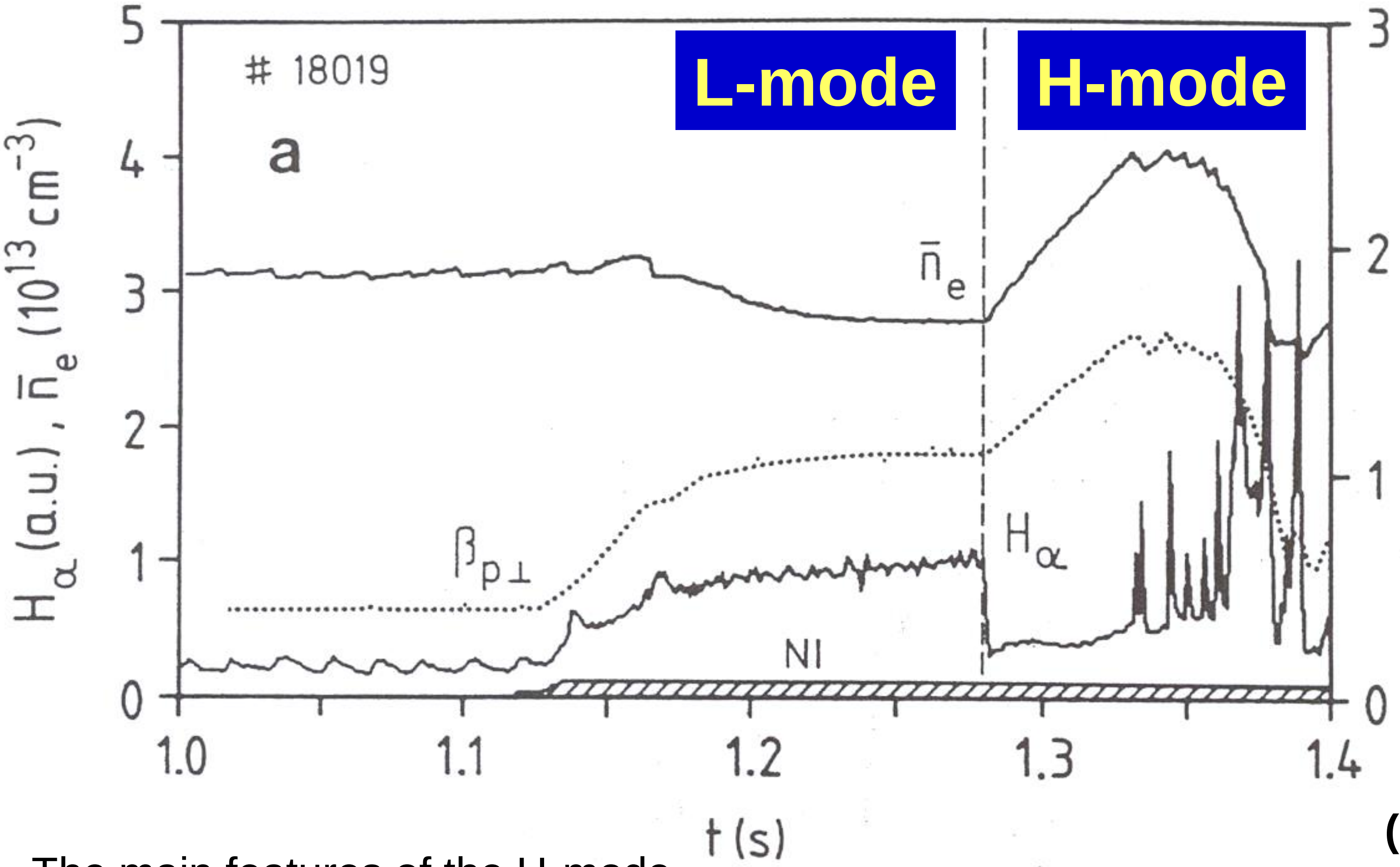
Basic problem now:

Plasma heating does not much increase the energy content

but increases only the turbulence level

beneficial would be the increase of the edge pressure pedestal
but: MHD limits

H-mode and edge transport barrier



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

(ASDEX,1982)

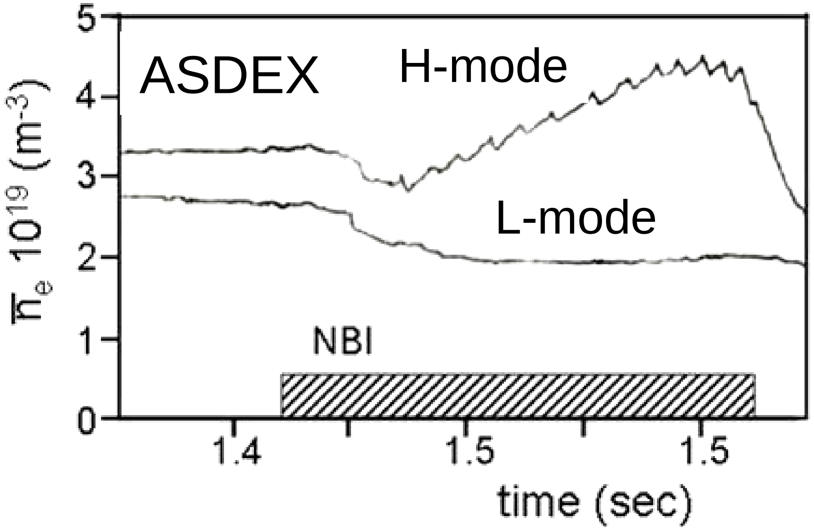
The main features of the H-mode

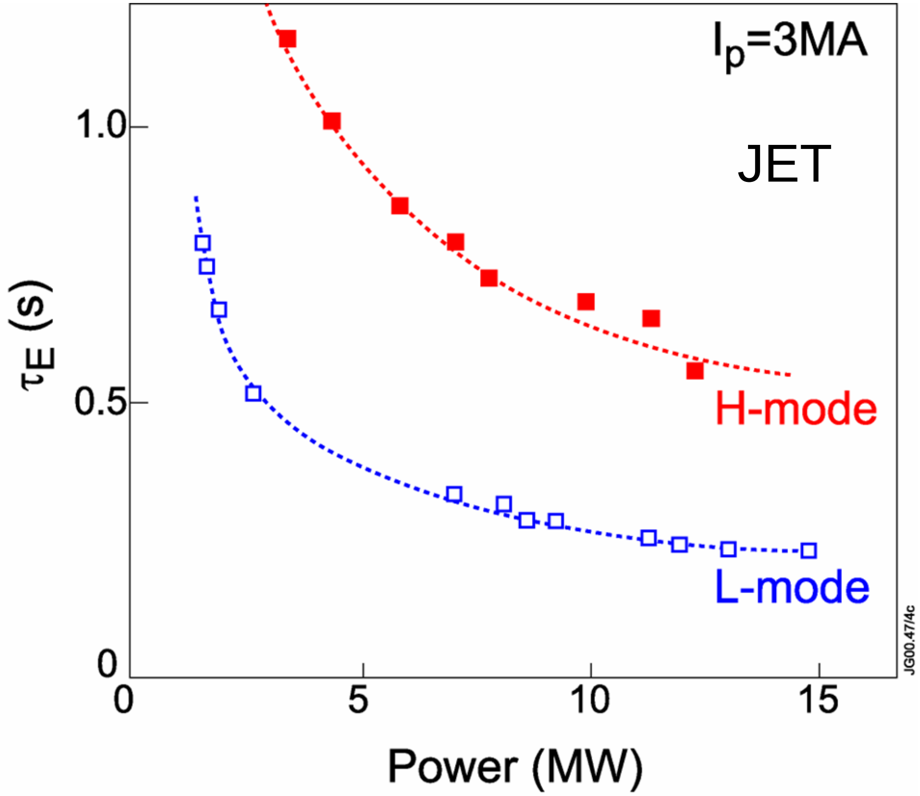
a spontaneous and distinct transition during the heating phase
both energy- and particle confinement time increase
the tracer for the transition is the $H\alpha$-radiation
new instabilities appear in the H-phase: ELMs, edge-localised modes

L- and H-mode branches

Particle confinement

Energy confinement





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

Def. $H_{89} = \tau_E^H / \tau_E^L$

Benefit of improved confinement

The importance of improved confinement:

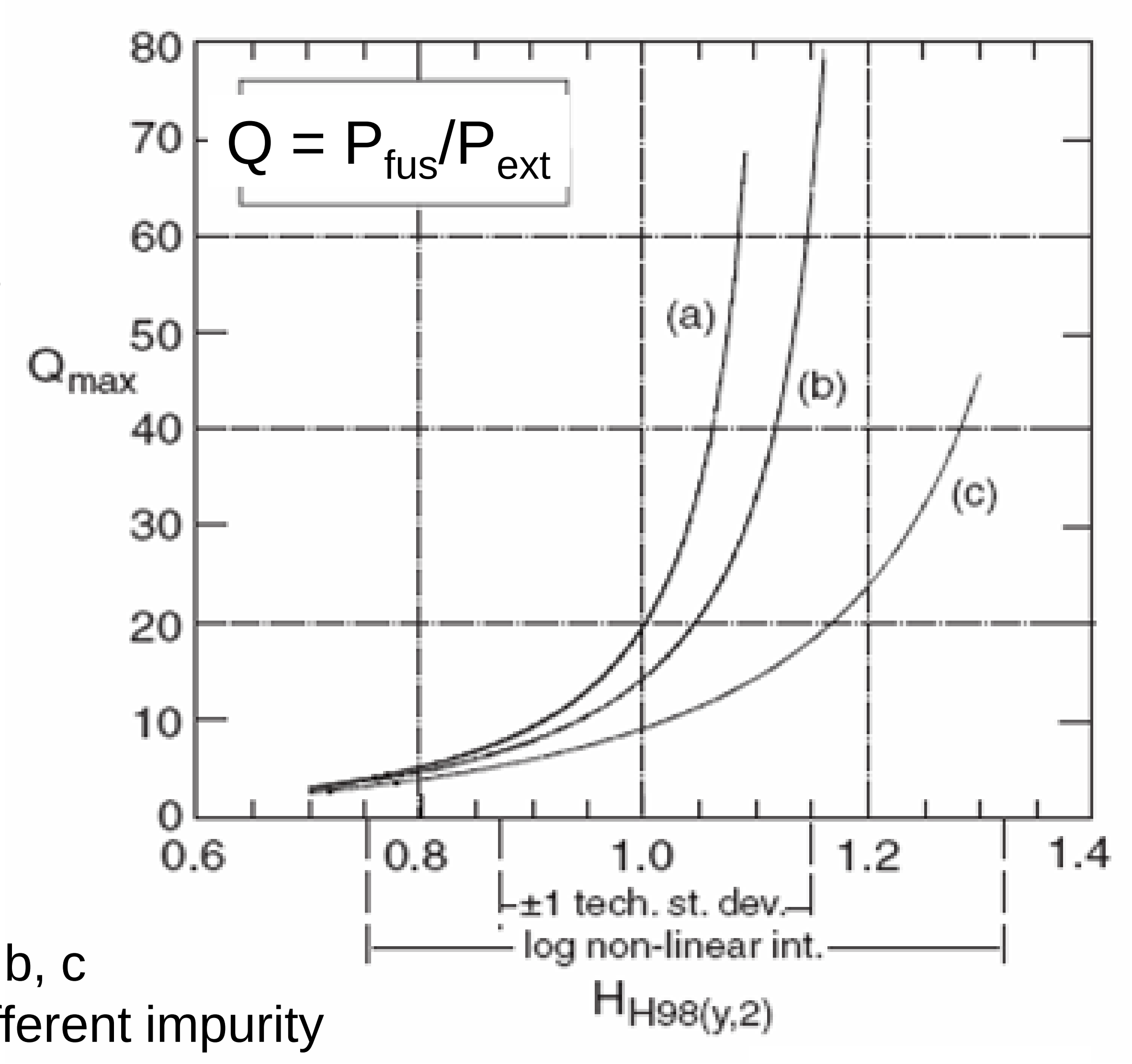
Improvement factor: $\tau_E \Rightarrow H\tau_E$

Ignition:

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

Triple product:

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

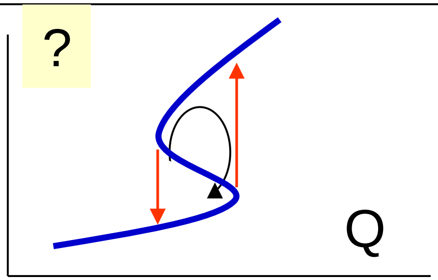


a, b, c
different impurity
confinement

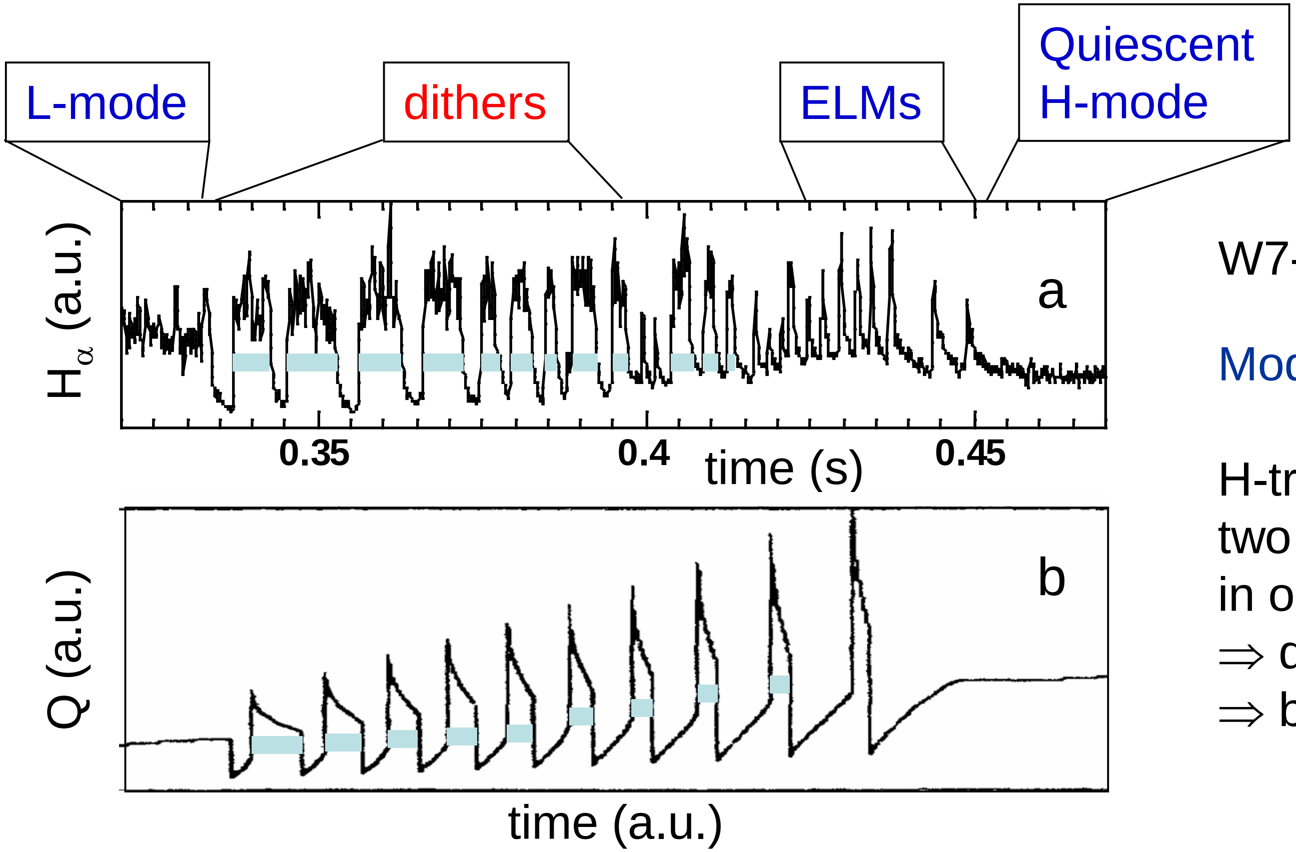
V. Mukhovatov

The H-mode as bifurcation phenomenon

Theory: Development of bifurcation models



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



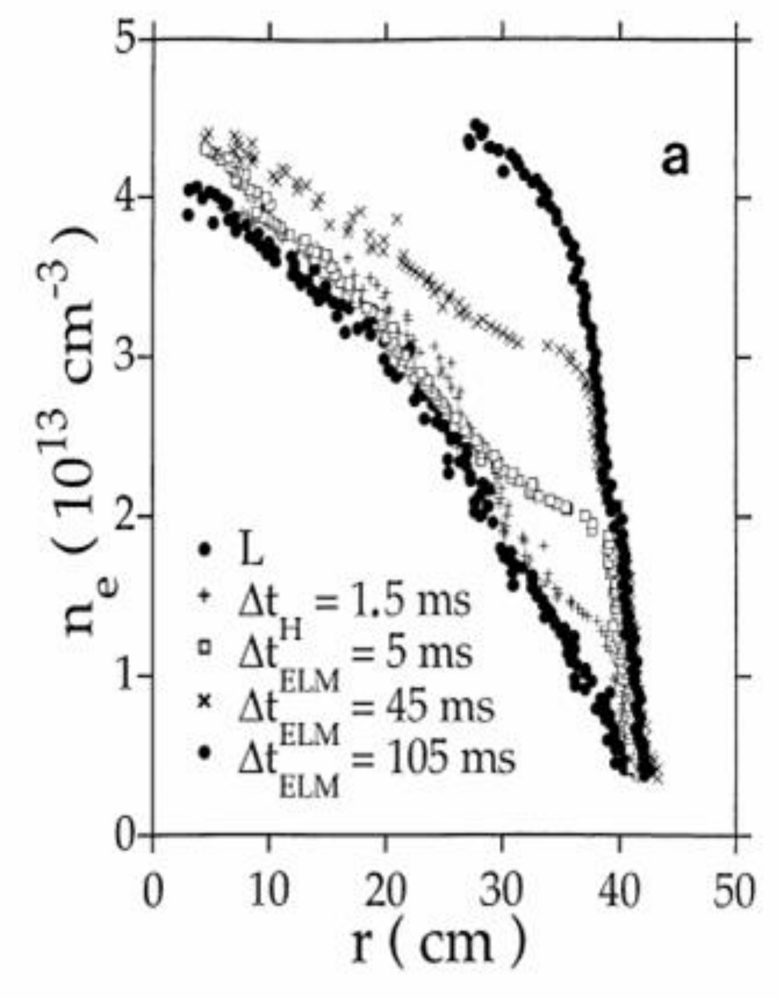
W7-AS (Stellarator !)

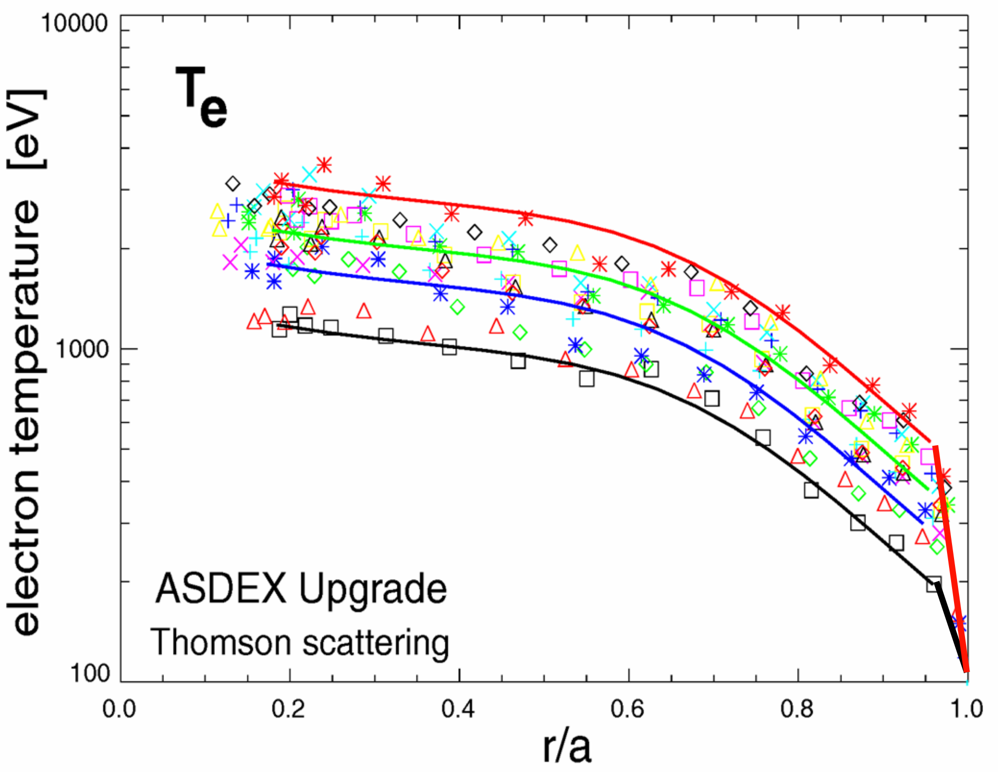
Model by H. Zohm:

H-transition initiates two processes going in opposite direction
$\Rightarrow$ deeper into H
$\Rightarrow$ back to L

Edge Transport Barrier in density and temperature

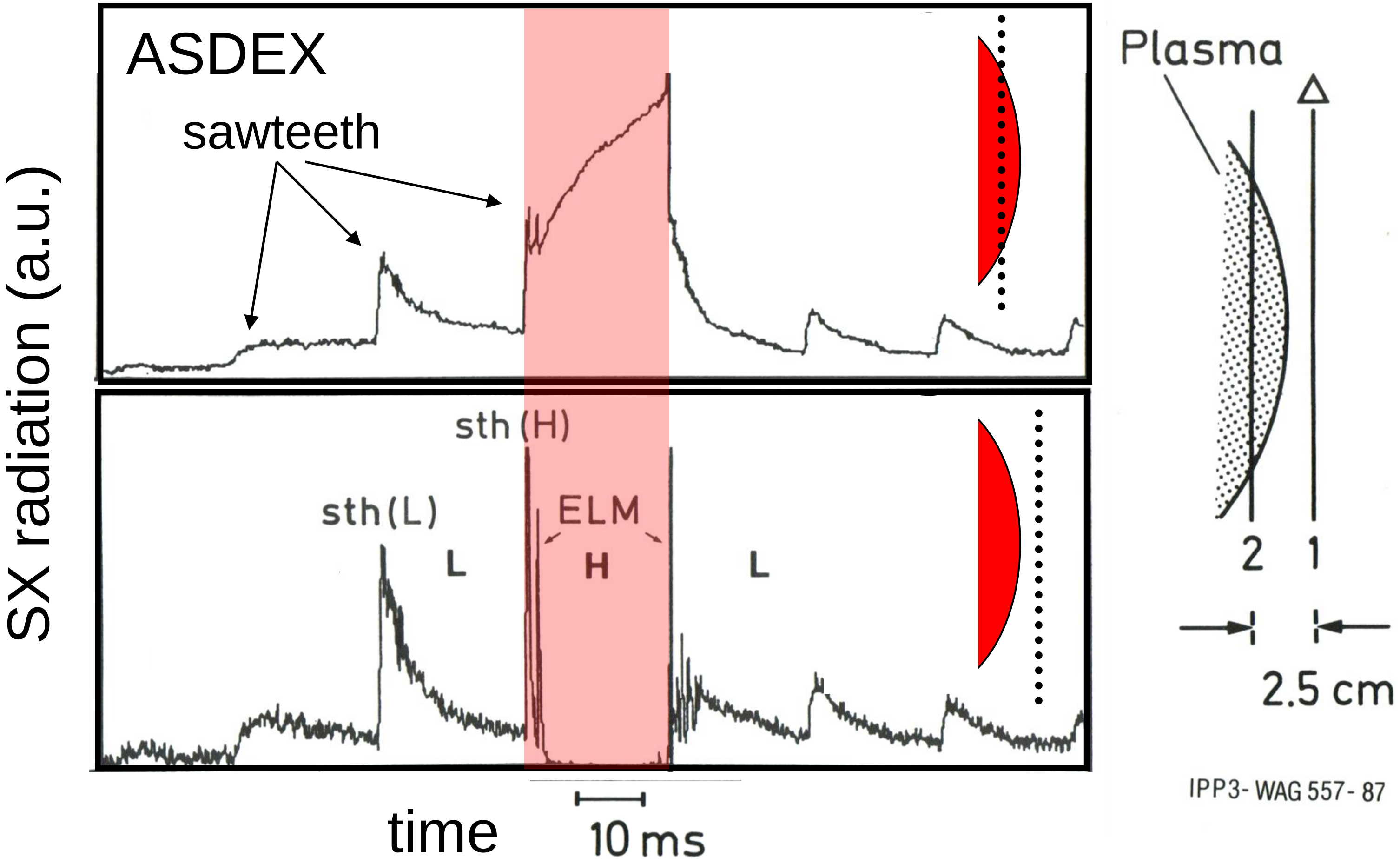
Edge transport barrier





Development of an edge transport barrier

Edge and SOL probed with sawteeth after NBI switch-on



The plasma self-organizes its turbulence level

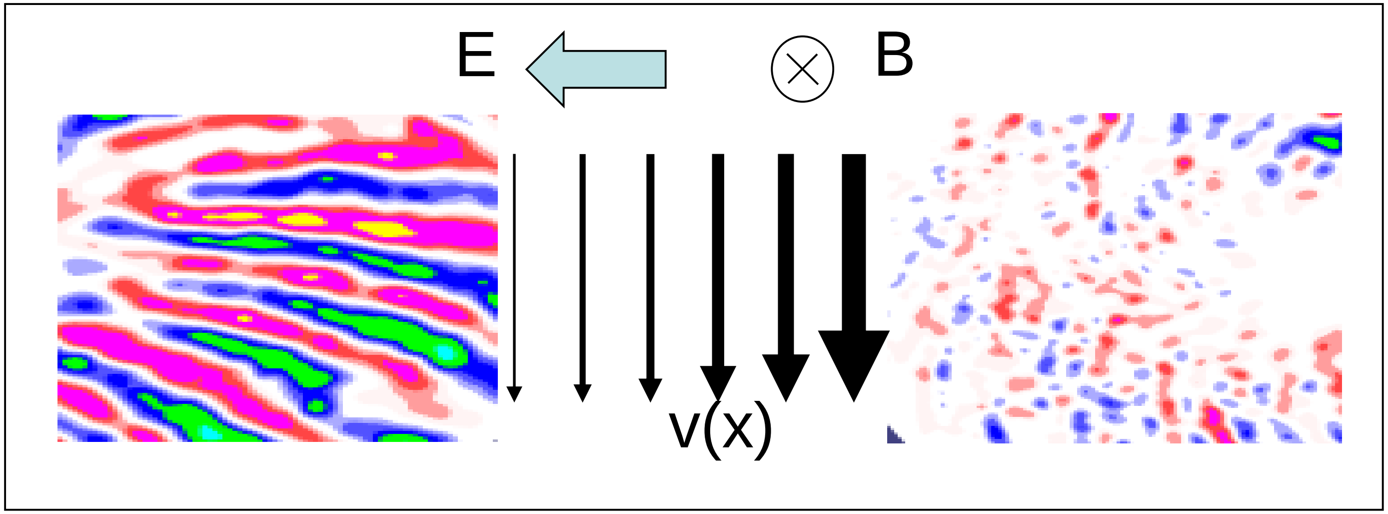
1. Step: sheared flow decorrelates turbulence

History:

S-I and K Itoh: bifurcation model on basis of E_r

Biglary, Diamond, Terry: shear decorrelation concept

Bo Lehnert (1966): 1st prophecies



Shear flow decorrelation of turbulence

Conditions for flow-decorrelation

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

$$\omega_{ExB} = \frac{r}{q}\frac{\partial}{\partial r}\left[qV_{E\theta}/r\right]$$

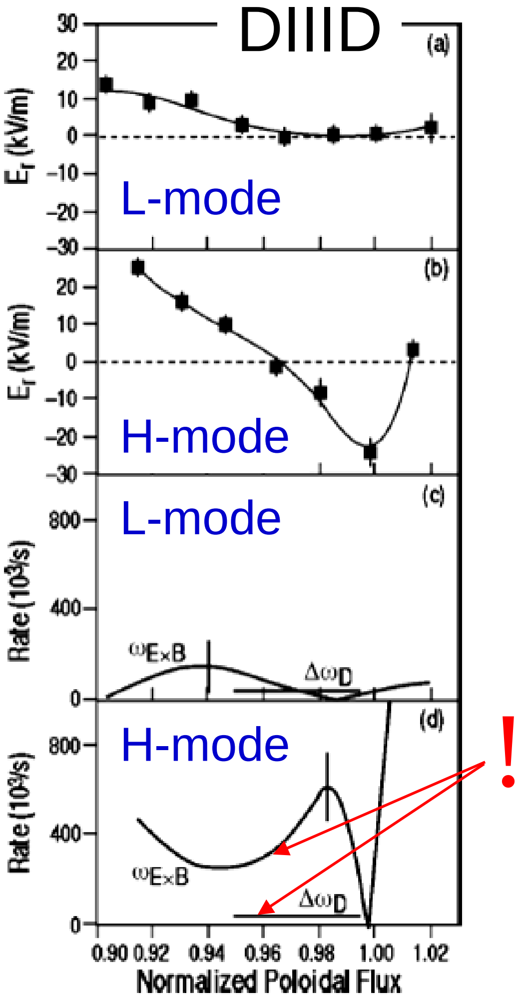
$\nabla|E_{r,crit}|$ = [V/cm^2]

DIII-D: 50 -100

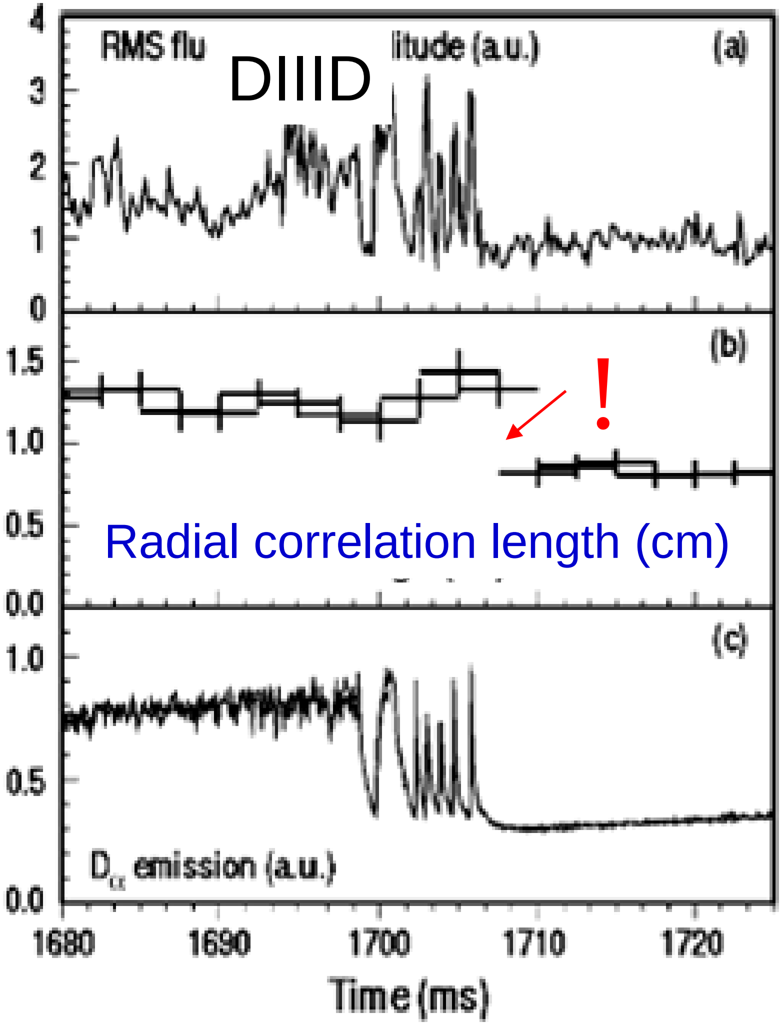
W7-AS: ~ 90

TEXTOR

(Probes): 50 - 80

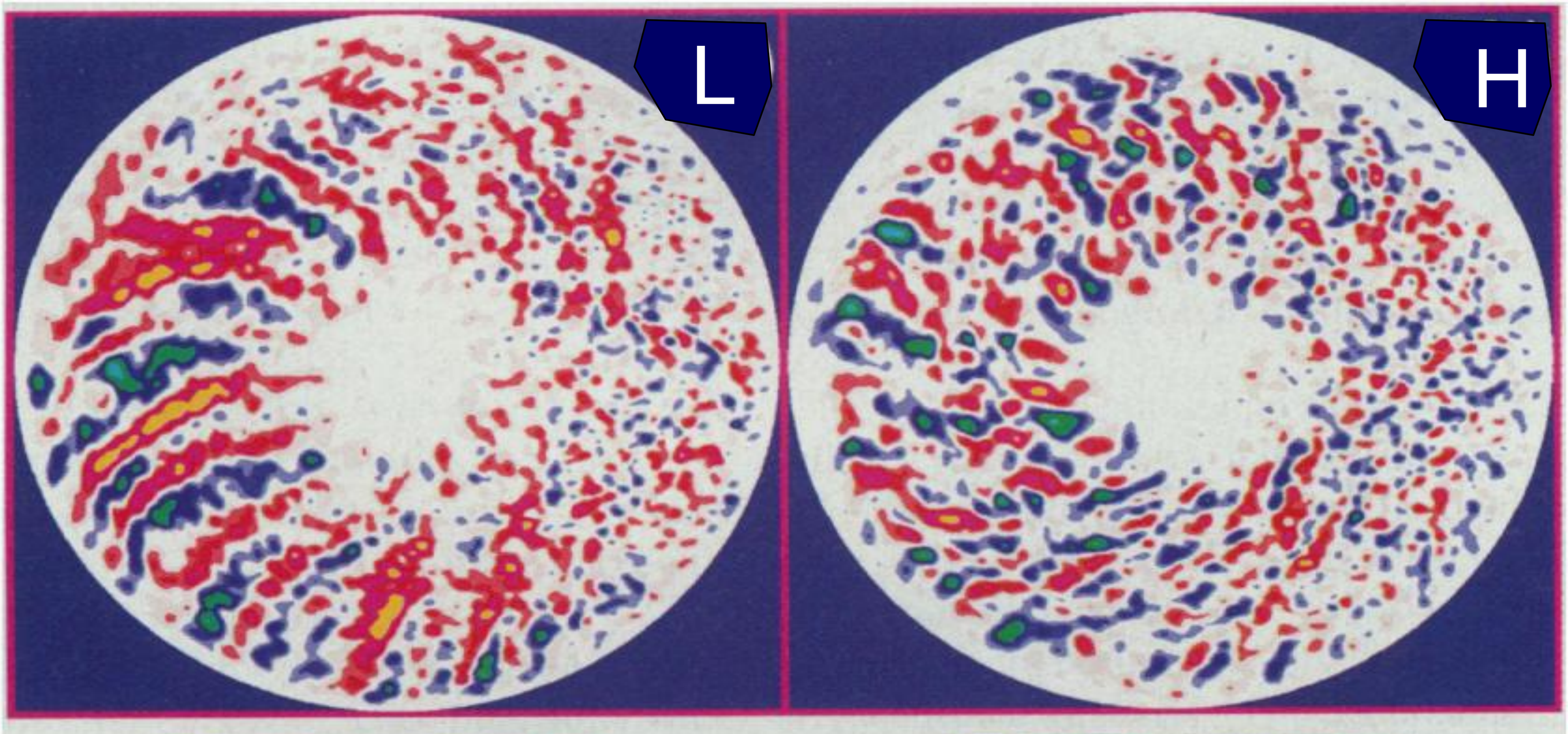


Reduction of radial correlation length



Modelling of shear-flow decorrelation

Gyrokinetic particle simulation of plasma microturbulence



$\longrightarrow \nabla B$

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

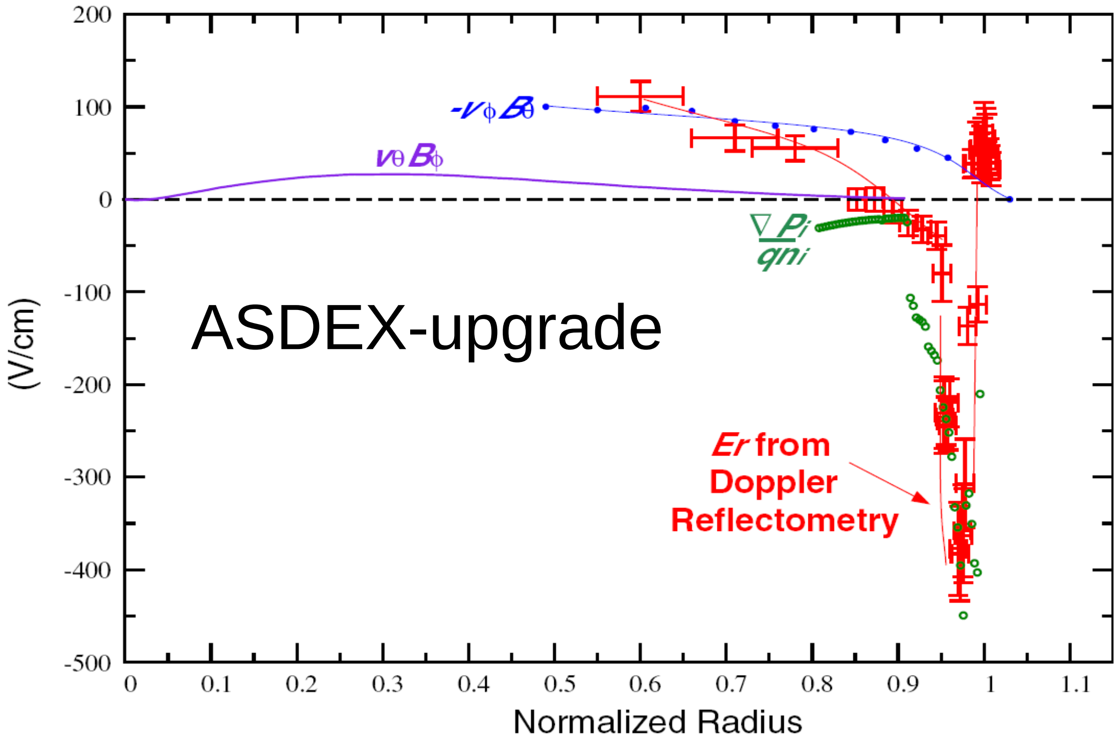
$$\Gamma = -D_1\boxed{(E_r)}n\left\{\frac{1}{n}\frac{\partial n}{\partial r} - q\boxed{\frac{E_r}{T}} + \frac{D_{12}}{D_{11}}\frac{1}{T}\frac{\partial T}{\partial r}\right\}$$

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

The composition of E_r

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

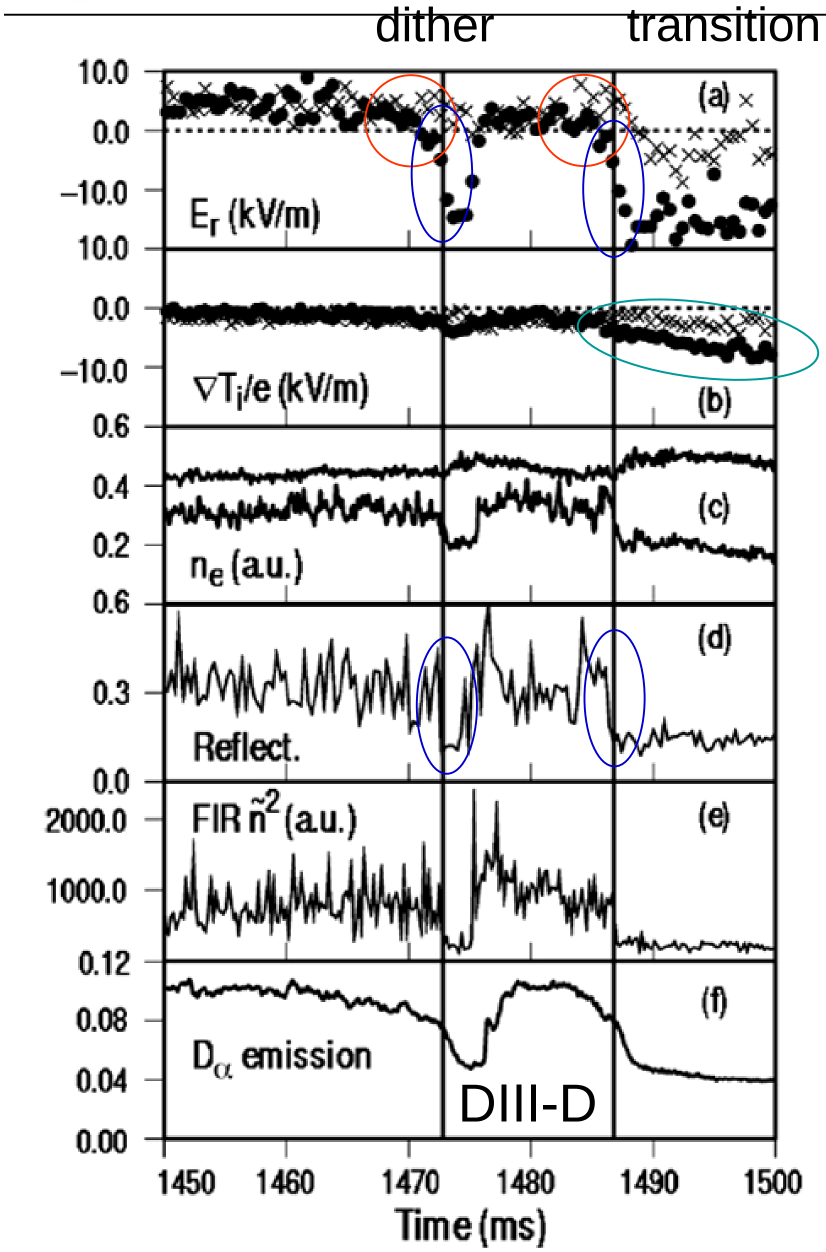
Tokamak: 2D



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

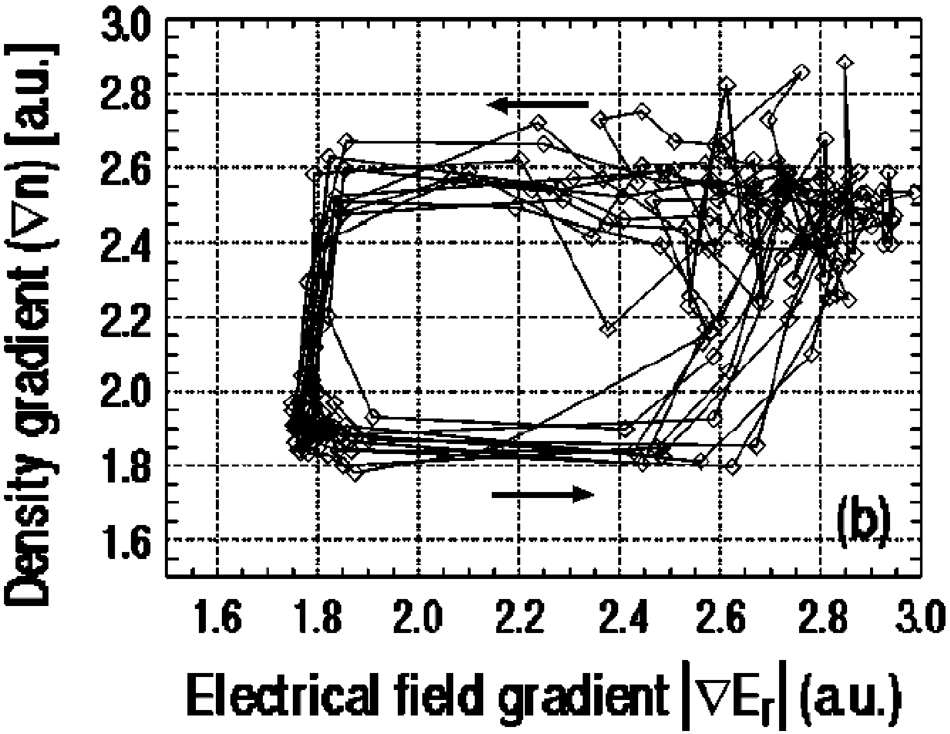
R.A. Moyer et al., Phys.Plasmas, 2, 2397, 1995

Causality between E_r and ∇p_i

TEXTOR: H-mode induced by polarisation probe

E_r is oscillating

n_e (gradp$_i$) also oscillates



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

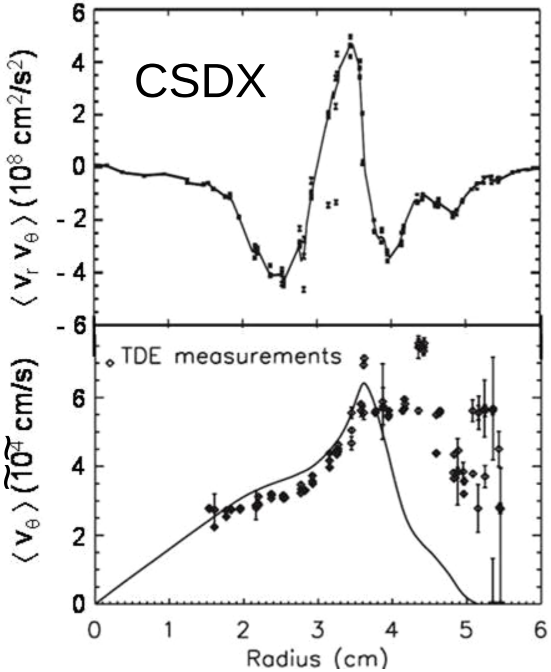
Causality: ∇E_r leads n_e by about 5 ms

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

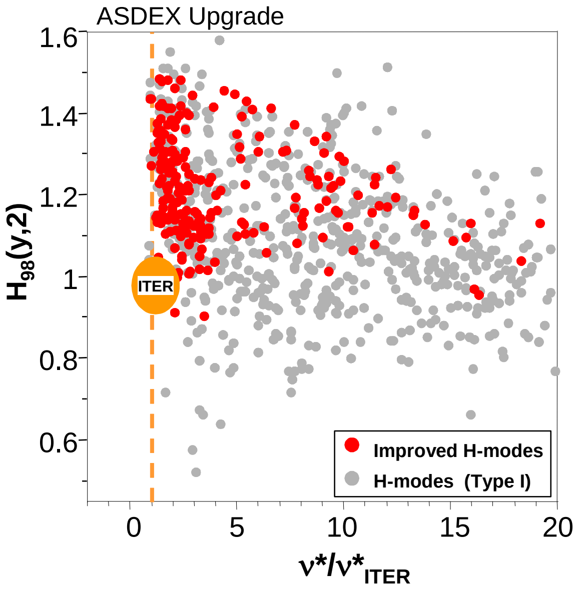
Self-induced flows from the turbulence field regulates the turbulence level.

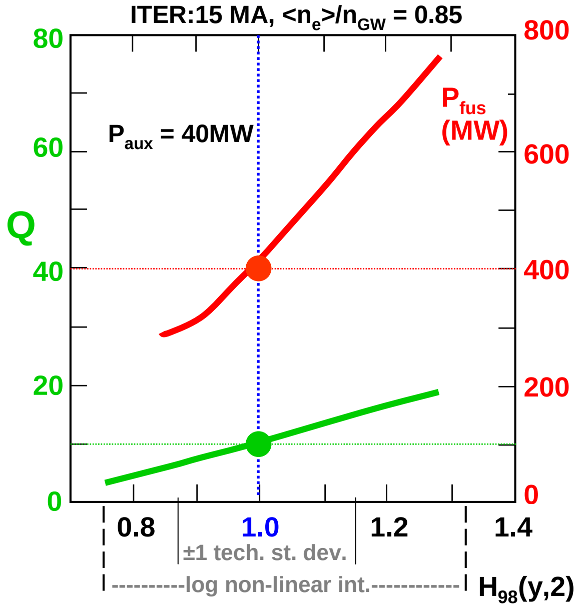
Mechanisms:
- Reynolds stress
- spectral transport from small to large scales
- equilibrium flows, zonal flows, GAMS

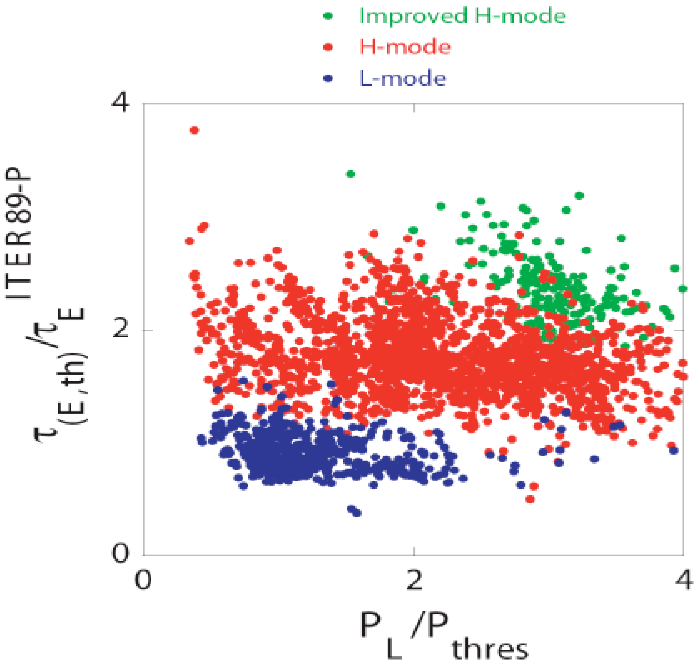
sheared flow reduces turbulence

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

Improved H-mode





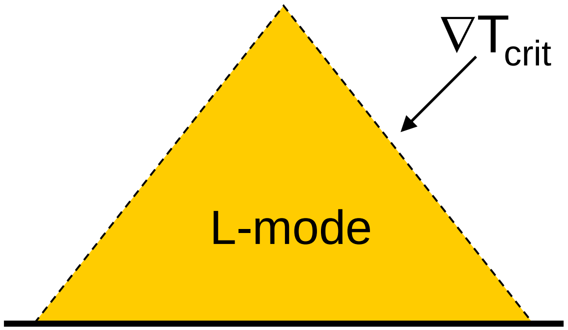


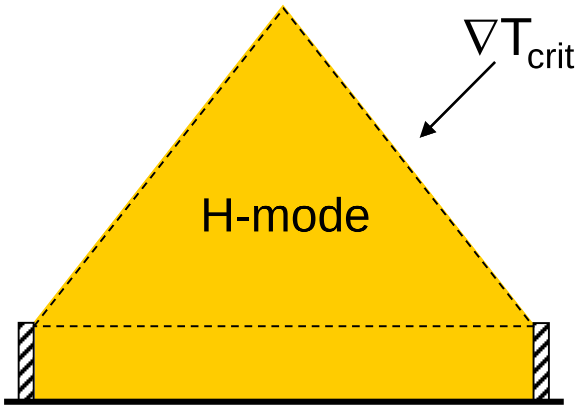
G. Sips, ASDEX-upgrade

Instead of 70 MW
ITER would need
140 – 280 MW

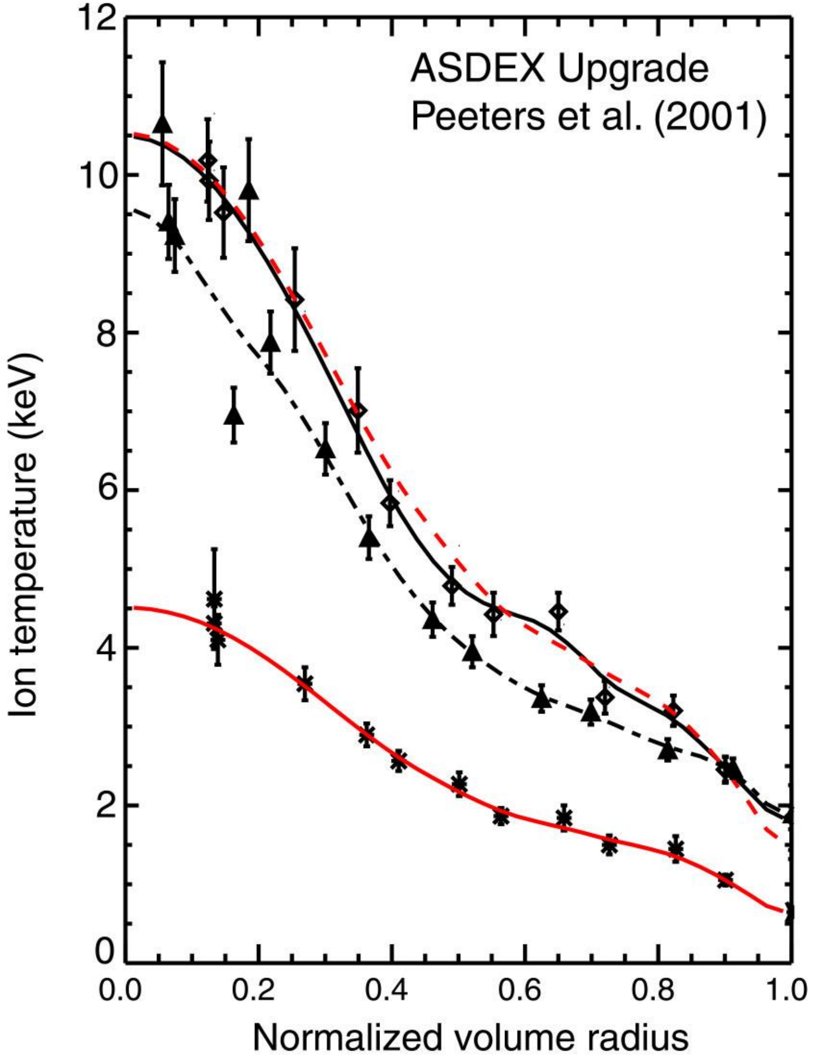
L.Gionnone et al PPCF 46 (2004) 835

Internal transport barriers

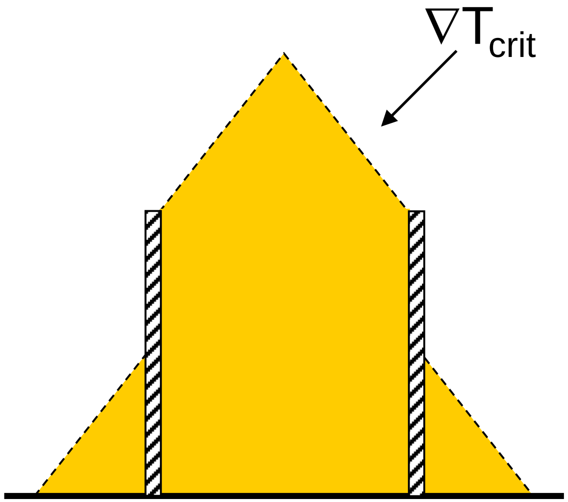




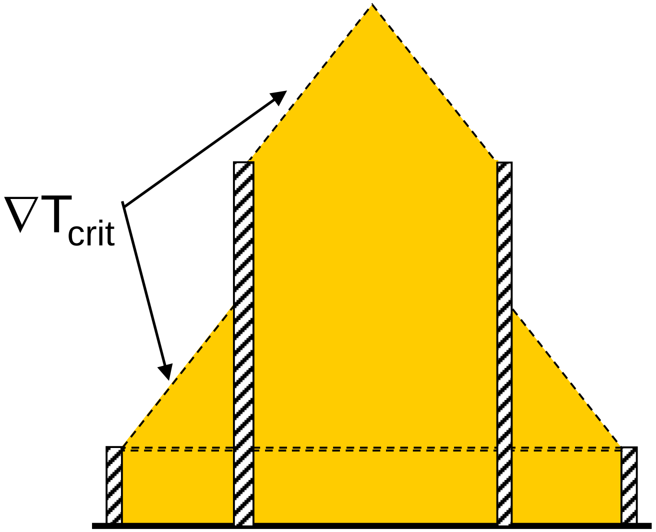
ITB



New options

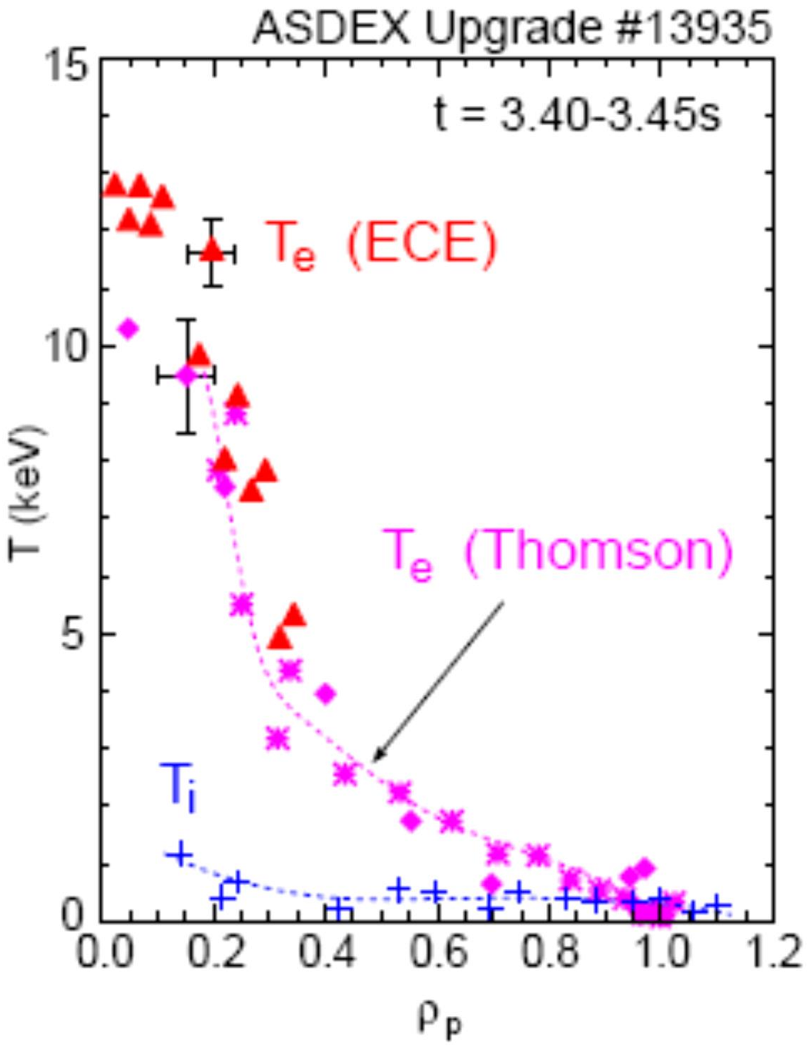


Internal transport barrier (ITB)



External and internal transport barriers

Electron ITB



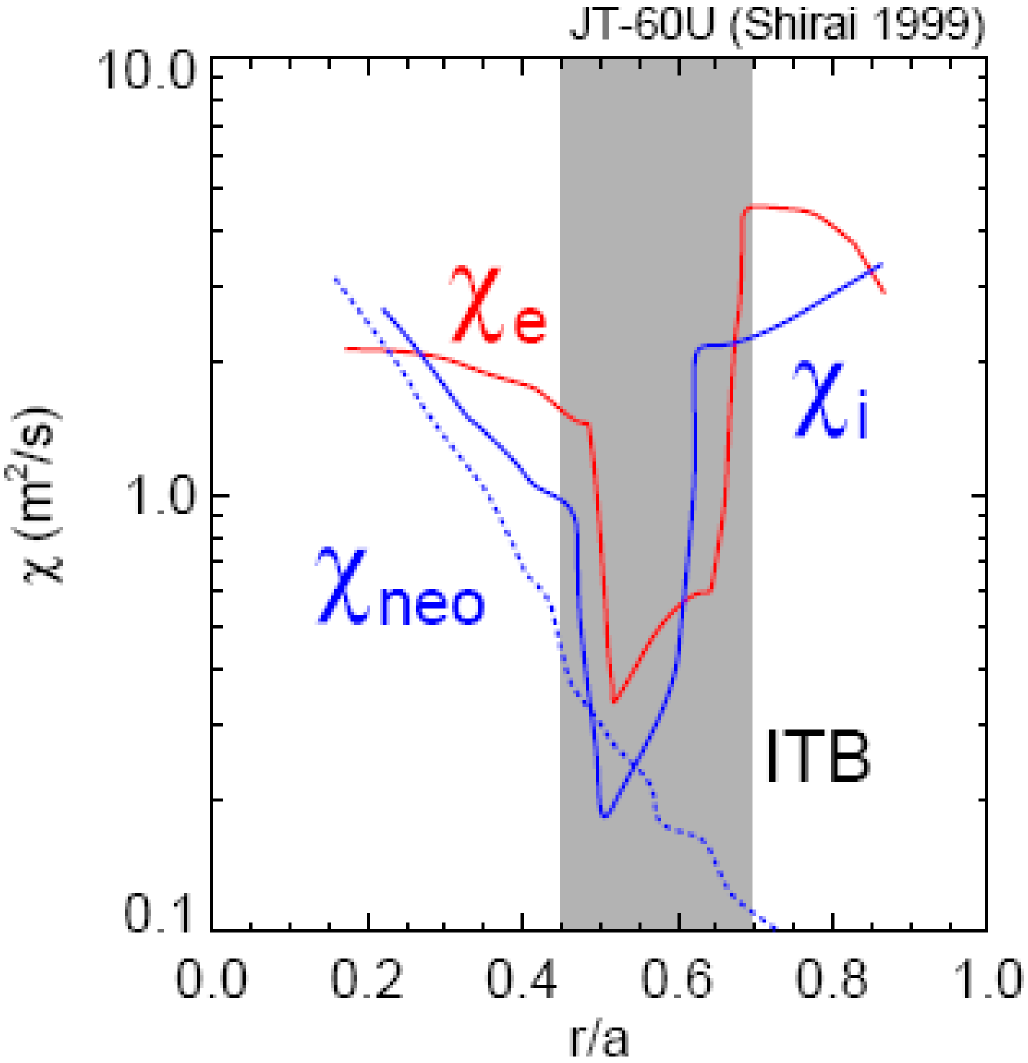
Electron transport barrier
with electron resonance heating

in special mode:

counter – ECCD

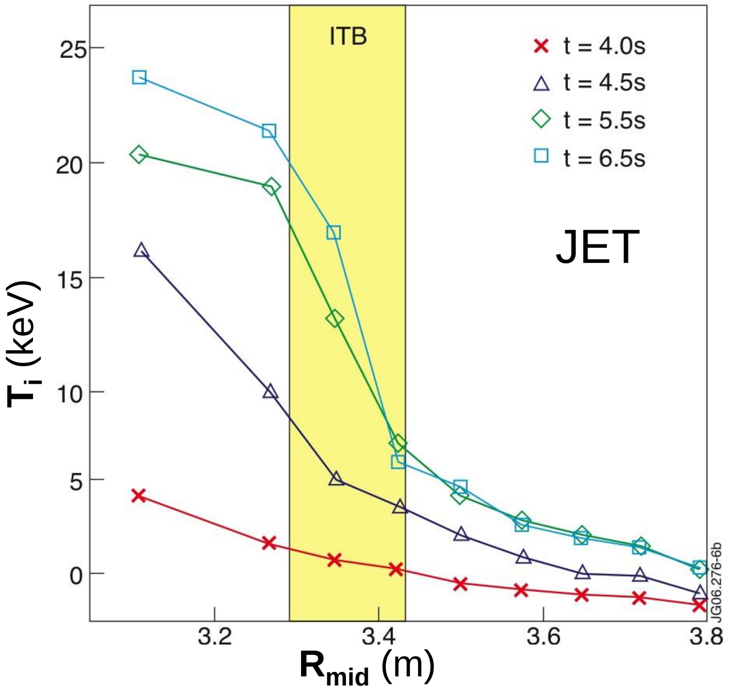
which shapes the q-profile

ITBs simulaneously in T_i and T_e



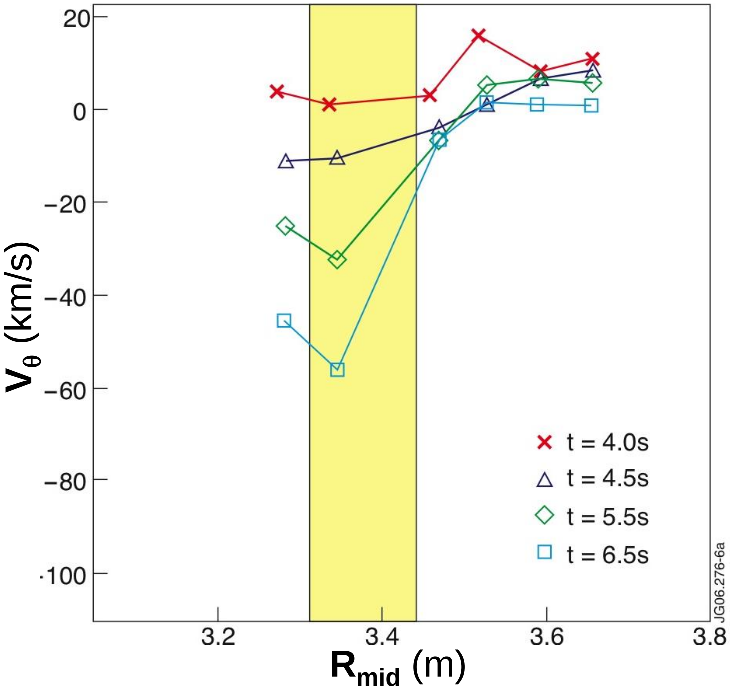
Most probable: shear-flow effect for i-ITB (1)

Ion temperature profiles during ITB formation



- ITB layer with steep temperature gradient

Poloidal velocity from charge exchange, during ITB formation

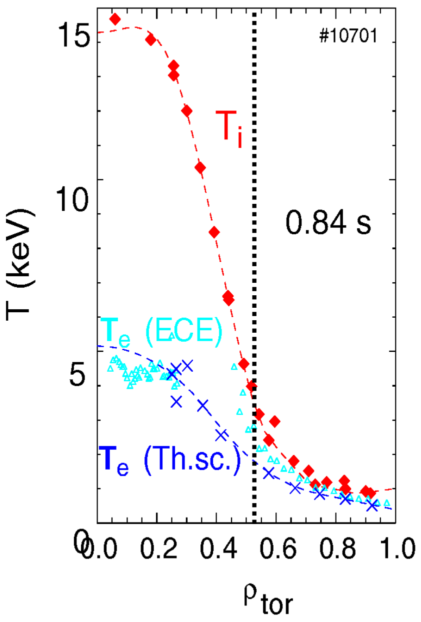


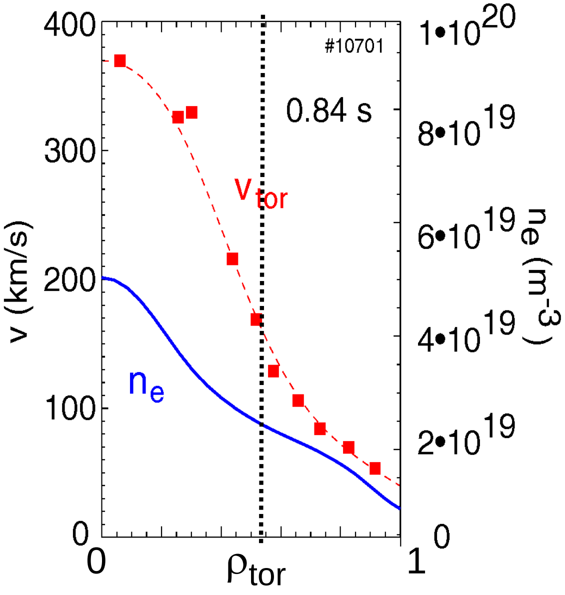
- Measured poloidal velocity in ITB layer (60km/s) highly anomalous, far higher than neoclassical (~5-10km/s)

K. Crombie PRL (2006)
M. Watkins

Most probable: shear-flow effect for i-ITB (2)

ASDEX Upgrade





Steep transport barrier
at r/a ≈ 0.5 with toroidal flow

strongly sheared plasma rotation

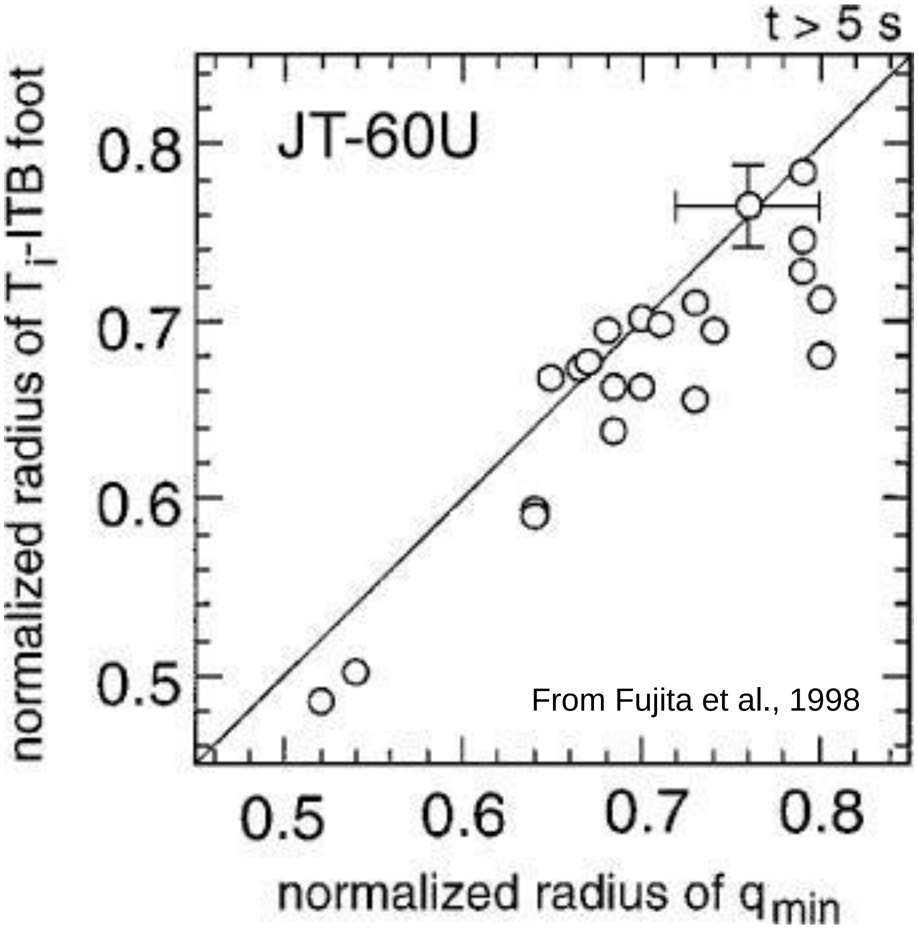
=> dE_r/dr

measured $E_r \sim v_{tor} \cdot B_{pol}$ fullfills

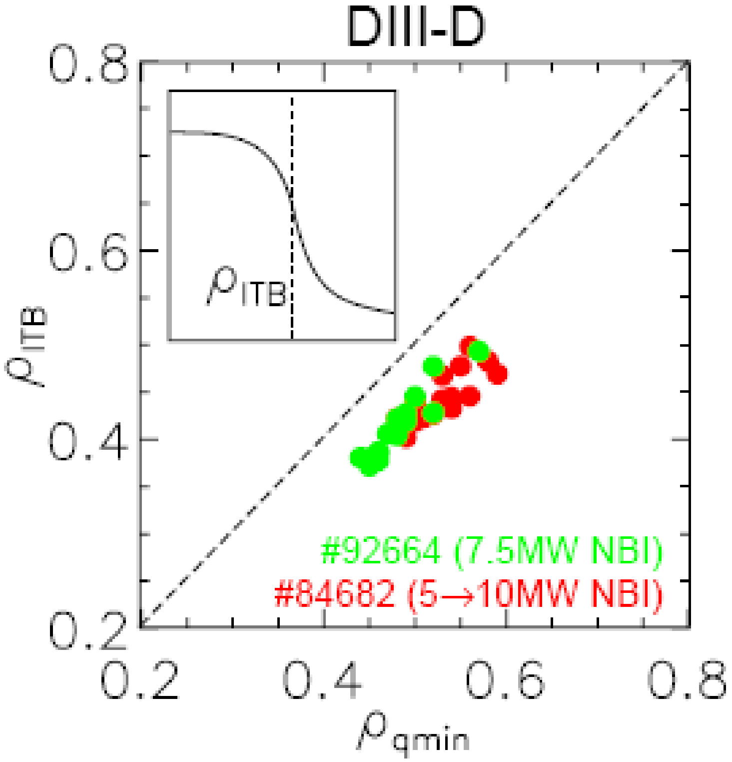
condition for turbulence suppression

Another aspect: ITB location and that of q_{min}

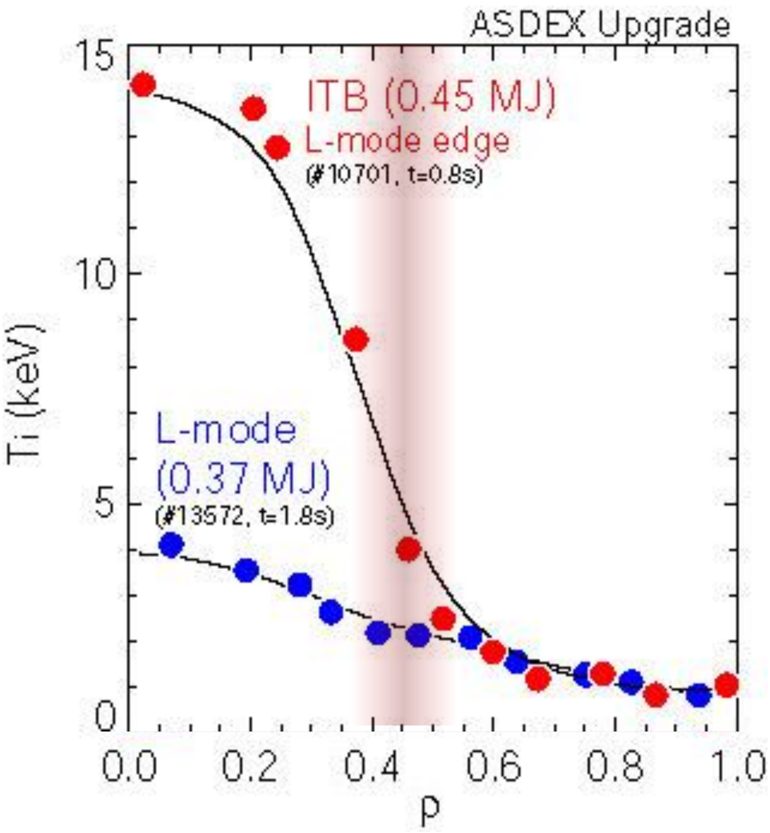
q-profile and transport barrier positions are directly coupled

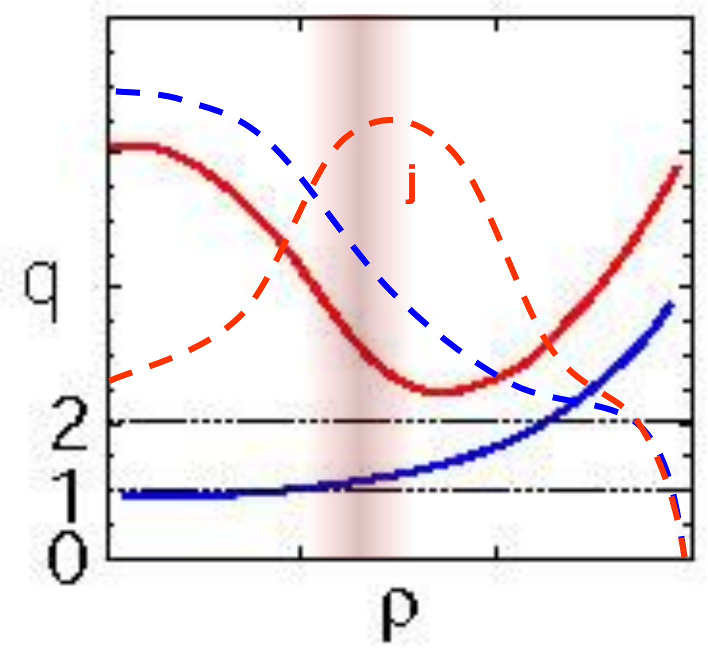


From Fujita et al., 1998



q- profiles (shear) with ITBs





This dependence is of specific importance because it implies that discharges with a large ratio of $j_{bootstrap}/j_{plasma}$ can develop ITBs.

Conditions for ITB development

Three key parameters influence turbulent transport

Safety factor

Low density of rational surfaces

Magnetic shear

Low or negative magnetic shear reduces or suppresses turbulence

Prevents resonance between trapped particle precession and turbulence drift

Sustained by external current drive and bootstrap current

E×B flows

Shear flow decorrelation

In summary

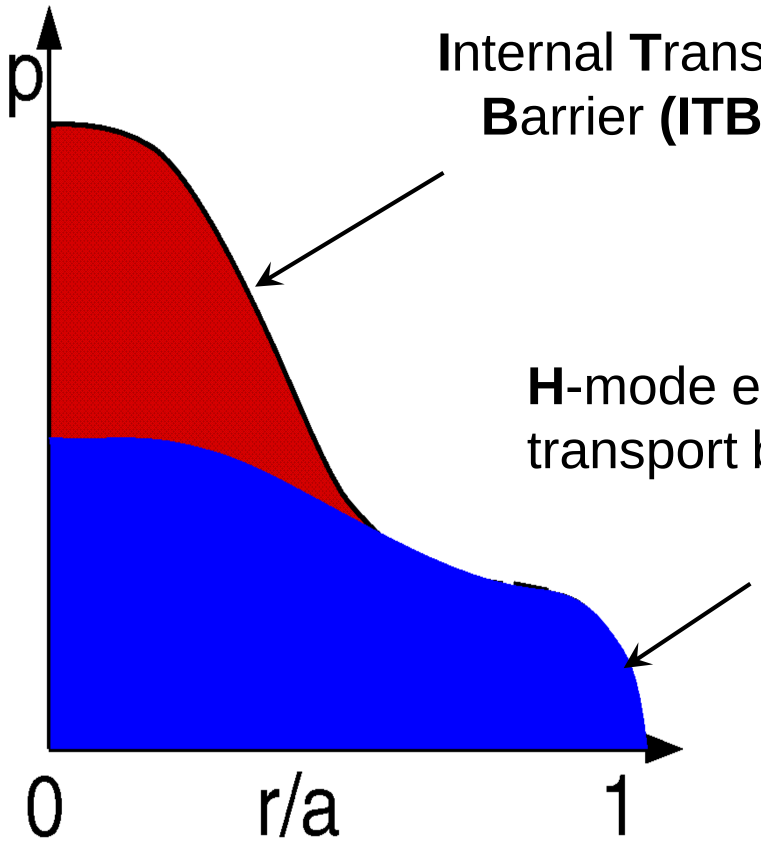
Q ~ 10 is in agreement with the overall confinement scaling and is reasonably backed by
- dimensionless scaling and
- theory-based transport modelling

Predictions for pedestal temperature (for Q =10, T = 3 - 4 keV necessary):
- 2.7 keV => $4 \leq Q \leq 10$
- 5.6 keV => $Q \geq 10$
  - Discrepancy: due to different “stiffness” in the models

P_{fus} depends sensitively
- on density profile
- in case of an inward convective term: on He recycling

P_{fus} has a sensitive dependence on B: $P_{fus} \sim B^{3.5}$

The hope for ITER



Internal **T**ransport
Barrier **(ITB)**

H-mode edge
transport barrier

Acknowledgement

Material used and papers consulted from

Chapter 2: Plasma confinement and transport; E.J. Doyle et al. NF 47 (2007)

R. Budny
D. Campbell
X. Garbet
O. Gruber
K. Lackner
V. Mukhovatov
A. G. Peters
F. Ryter
R. Stambaugh

others