The basis of ITER confinement

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ITER is a "tokamak"

Poloidal field and rotational transform $\mathbf{t}$ from current $I_p$

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

Geometry: $R_0$, $a$, $a/R_0 = \varepsilon$

$b/a = \kappa$, $\delta =$ triangularly
The goals of ITER

The demonstration of the scientific and technological feasibility of fusion

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

Basis for $P_{\text{fus}}$ 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; $P_{\text{fus}} \sim n^2$;

$n$ is limited by Greenwald density limit $n_{GW}$

$\tau_E$: energy confinement time; determined by cross-field transport;

predicted ITER value taken from multi-machine scaling

$nT\tau_E > 6 \times 10^{21}$ m$^{-3}$ keV s
The pathfinders for ITER
The design parameters of ITER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>5.3 T</td>
</tr>
<tr>
<td>Plasma current</td>
<td>15 MA</td>
</tr>
<tr>
<td>Elongation $\kappa$</td>
<td>1.85</td>
</tr>
<tr>
<td>Triangularity $\delta$</td>
<td>0.49</td>
</tr>
<tr>
<td>Fusion power</td>
<td>400-500 MW</td>
</tr>
<tr>
<td>$Q$</td>
<td>$\sim$ 10</td>
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<tr>
<td>Burn duration</td>
<td>$\sim$ 400 s</td>
</tr>
</tbody>
</table>
The size of ITER

$\Delta \sim 2\ m; \ \delta \sim 1.3\ m$

Aspect ratio: $A = \frac{R_0}{a}$

$a$ determined by confinement to meet $nT\tau_E$ goal
Scaling of $\tau_E$ and projection to ITER

Prediction for ITER

$\tau_E = 3.7 \text{ s}$

$5.3 \text{ T}; 15 \text{ MA};$

$n = 1 \times 10^{20} \text{ m}^{-3} = 0.85 n_{GW}$

$P = 87 \text{ MW}$

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

Inverse aspect ratio

Elongation
The shape of the ITER plasma

Current is limited by safety factor $q$

$$q = 2.5 \ a^2 \ (B/R_{I_p}) \ ((1+k^2)/2) \geq 2 \ (q_{\text{ITER}} \sim 3)$$

Larger $\kappa \Rightarrow$ larger $I_p$

Degradation of confinement close to density limit and improvement with triangularity

$\tau_E/\tau_{E,\text{scaling}}$

$n_e/n_{e,\text{Greenwald}}$ (%%)
General requirements for ITER (1)

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

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

Ash removal from the system: divertor retention, recycling

Low \( Z_{\text{eff}} \): fluxes (ELMs, fast particle losses) materials (C, Be, W); erosion mechanisms \( D_l, v_{\text{l.in}}, \text{sawteeth} \)

Stable operation:
limits which terminate operation (via disruptions)
density limit (Greenwald): \( n_{\text{GW}} \sim 10^{20} \frac{I_p}{\pi a^2} \) (MA, m); \( n < 0.85 \ n_{\text{GW}} \)
beta-limit (Troyon): \( \beta \sim \frac{I_p}{aB} \)
current limit: \( q = 2.5 \ a^2 \ (B/R I_p) \ ((1+\kappa^2)/2) > 2 \ (q_{\text{ITER}} \sim 3) \)
elongation limit: \( \kappa < 2 \)
Avoidance of MHD leading to performance reduction

sawteeth in the core:
Relaxations of $T$; spreading of $\alpha$-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 $\sim 20$ MW/m$^2$

Alfven activities: fast particle spreading, losses
The basic operational regime for ITER: ELMy H-mode

\[ I_p \times 10 \text{ MA} \]
\[ P_{NBI} \text{ MW} \]

Magn. perturbation
\[ n=3, n=2, n=1 \]

\[ D_\alpha, \text{ upper divertor} \]

\[ \beta_N \]
\[ 4I_i \]

\[ q_{\text{min}} \]
\[ q(0) \]

\[ n_e \]
\[ Z_{\text{eff}} \]

DIII-D

\[ n_e = 0.4 \times 10^{20} \text{ m}^{-3} \]
\[ P_{NBI_{\text{abs}}} = 4.8 \text{ MW}. \]

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

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

![Graph showing various plasma parameters over time including DT power, energy, electron density, effective charge, temperature, current, and impurity concentration.](image)
Characteristics of the H-mode

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

Edge pedestal

ELMs

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

$$P_{LH} = 2.84 M^{-1} B^{0.82} n_{20}^{0.58} Ra^{0.81} \text{ (MW)}$$

Note the isotopic dependence

In Deuterium, $P_{LH}^{\text{ITER}} \sim 50 \text{ MW}$
Profile characteristics of the H-mode

Development of a pedestal

Edge transport barrier

ASDEX Upgrade
Thomson scattering

Note the similarity of the $T_e$ profiles
"profile stiffness"
What one would like to know beforehand

Which $Q$ and $P_{\text{fus}}$ will be achieved?

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

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

What is the pedestal height, specifically $T_{\text{pedestal}}$?

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 $P_{\text{fus}}$ and $Q$

The density profile shape – peaked or flat?
- peaked at large $v_{\text{in}}/D$
  - 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 $\chi_{\phi}$)

The stiffness of the T-profiles:
- very stiff: weak increase of T with power; Q goes down with $P_{\text{aux}}$

Abbreviations: TEM = trapped electron mode
ITB = internal transport barrier
Predictions by dimensionless scaling

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

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):

$$\beta \propto n T / B^2$$

measure for the energy content, the driving mechanisms

$$\nu^* \propto Rq/\lambda_{\text{mfp}} \propto Rqn/T^2$$

measure for dissipation

$$\rho^* = \rho_{\text{Li}} / a \propto \sqrt{T / aB}$$

measure of the orbit effects

The 98(y,2) $\tau_E$ 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
\((\rho^*, \beta, \nu^*, q, \text{geometry } (A, \kappa, \delta), \text{profile shapes}..)\)

Scale transport coefficients along dimensionless parameters; map profiles

Devices with comparable geometry \((A, \kappa, \delta)\)
Dimensionless scaling of engineering parameters (K. Lackner)

q, \( \beta \) and \( \nu^* \) are kept fixed under the following scaling:

\[
\begin{align*}
I_p & \propto B \ a \\
n & \propto B^{4/3} \ a^{-1/3} \\
T & \propto B^{2/3} \ a^{1/3}
\end{align*}
\]

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 \( I_p \)), \( P_{\text{heat}} \) and \( n \) (\( \Phi_{\text{gas}} \)) can be obtained along dimensionally correct paths when scaled as \( B^*, P^* \) and \( n^* \):

\[
B^* = B a^{5/4} \propto \beta^{1/4} \ \nu^*^{-1/4} \ \rho^*^{-3/2}
\]

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

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

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:

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

Not possible: operation at $\rho^*$ or $\nu^*$

If the density constraint is removed operation at the ITER $\nu^*$ 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 $\sim \sqrt{a\rho_L}$ 
$\tau_{EB} \sim \rho_L^2$

gyro-Bohm scaling: 
Turbulence correlation length $\sim \rho_L$ 
$\tau_{Eg-B} \sim \rho_L^3$

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

X. Garbet, Data from JET and DIII-D
The scaling with $\rho^*$ from JET to ITER

Dimensionless scaling from JET to ITER at $\nu^* = \text{const.}$ and $\beta = \text{const.}$

\[
\begin{align*}
I_p & \propto B a \\
n & \propto B^{4/3} a^{-1/3} \\
T & \propto B^{2/3} a^{1/3} \\
\rho^* & \propto B^{-2/3} a^{-5/6}
\end{align*}
\]

Outcome of JET ITER-like discharge

"ITER" / JET

\[
\begin{align*}
B &= 5.6 / 3.46 \ \text{T} \\
a &= 2.0 / 0.96 \ \text{m} \\
\tau_E &= (3.74 - 5.6) / 0.51 \ \text{sec} \\
P_{\text{fus}} &= 275 \ \text{MW} \\
Q &= (6.2 - 12.3)
\end{align*}
\]
The scaling of particle transport with collisionality

Global scaling: \( \tau_{EB} \sim \nu^{-(0.01-0.35)} \)

This subtlety not obtained from global scaling.

Peaking factor \( >1.35 \) expected for ITER.

Possible chain:
\( \nu_{in} \Rightarrow n_0/\langle n \rangle_{vol} \Rightarrow c_{He} \Rightarrow Q \)
The scaling with beta

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

The devoted scans show $\alpha \sim 0$: big conflict!

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

Petty, DIIID
The impact of the $\beta$-scaling

POP-CON diagrammes

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

For different $Q$ (red)
with different $\beta_N$ (blue)
and different $P/P_{LH}$ (green)

Basis is the 98(y,2) scaling
$\tau_{EB} \sim \beta^{-0.9}$

Basis is a pure el. static model
$\tau_{EB} \sim \beta^0$

Petty, DIII-D
In summary

Confinement predictions for ITER

Dimensional scaling: 3.6 sec
Dimensionless scaling: 3.3 sec
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:
\( \chi_i \sim \chi_{i,\text{neo}} \) at low heating power, at peaked \( n_e \) profiles or inside ITBs
\( \chi_e \) always turbulent

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

Momentum transport mostly turbulent

Effects of parallel 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: \( k_\perp \sim \rho_i (\rho_e) \)
parallel correlation length: \( k_\parallel \ll k_\perp \)
Gradient length \( L_p \gg k_\perp^{-1} \)

Time scales:
Drift frequency: \( \omega \sim c_s/L_p; v_{\text{The}}/L_n \)

\[
D_{\text{turb}} \approx \frac{\gamma}{k_{\perp}^2} \sim 1\text{ m}^2/\text{s} \Rightarrow \tau_E \sim O(1\text{s})
\]
Movie of edge turbulence

S.J. Zweben et al.,
**Classification of instabilities**

**Transport is driven by several turbulence modes with a range of spatial scales**

<table>
<thead>
<tr>
<th>Indicative turbulence scales</th>
<th>( k_{θs} ) (cm(^{-1}))</th>
<th>0.1</th>
<th>1.</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_{θ} ) (cm(^{-1}))</td>
<td>1.</td>
<td>10</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

**Turbulence mechanisms**

- ITG
- TEM
- ETG

**Affected transport channels**

- Ion thermal
- Momentum
- Electron particle
- Electron thermal
- \( E \times B \) shear

**Stabilization mechanisms**

- Negative magnetic shear
- \( α \)-stabilization (Shafranov shift)
- Impurity dilution

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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

\[ \eta = \frac{d \ln T}{d \ln n} = \frac{L_n}{L_T}; \quad d \ln T = \frac{dT}{T} = - L_T^{-1} \]

Critical gradients exist with strongly rising \( \chi \) when surpassed:

For toroidal modes, the instability threshold depends on \( R/L_T \)
Profile resilience in tokamaks

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

„Stiff“ $T_e$ profiles

$T/\nabla T \sim \text{const.}$

Also: stiff $T_i$ profiles

Further experimental evidence from heat-wave studies.
“Orthodox” profile shapes in stellarators

W7-AS

Variation of $T_e$ profile with variation of location of power deposition
The corollary of profile resilience

\[ d \ln T = \frac{dT}{T} = - L_T^{-1} \]

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

\[ n \text{ is assumed const.} \]

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

In case of profile resilience the energy content \( W \) depends on the edge pedestal pressure
The 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

Similar results from $T_i$ profile analysis and $\gamma$ and $R/L_{Ti}$ for ITGs
Particle transport

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

\[ \Gamma = -D \nabla n_e + v_{\text{in}} n_e \]

\[ \nabla n_e / n_e = v_{\text{in}} / D \]
Consequence of peaked $n_e$ profiles

Stability diagramme for ITG and TEM modes

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

X. Garbet, PPCF, 2004
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
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.

\[ \beta_{\text{pol}} \sim \frac{\langle p \rangle}{B^2} \]  

(ASDEX, 1982)
L- and H-mode branches

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

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

Particle confinement

Energy confinement

ASDEX

JET

$I_p=3$MA

H-mode

L-mode
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:

\[
nT \tau_E \propto H^2
\]

\[Q = \frac{P_{\text{fus}}}{P_{\text{ext}}}
\]

\( a, b, c \) 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 (Stellarator !)

Model by H. Zohm:

H-transition initiates two processes going in opposite direction
⇒ deeper into H
⇒ back to L
Edge Transport Barrier in density and temperature

Edge transport barrier

- \( n_e \) (10^{13} \text{ cm}^{-3} )
- \( r \) (cm)
- \( T_e \) [eV]
- \( r/a \)

ASDEX Upgrade
Thomson scattering

\( \Delta t_{ELM} = 45 \text{ ms} \)
\( \Delta t_{ELM} = 105 \text{ ms} \)
\( \Delta t_H = 5 \text{ ms} \)
\( \Delta t_H = 1.5 \text{ ms} \)
Development of an edge transport barrier

Edge and SOL probed with sawteeth after NBI switch-on

ASDEX

sawteeth

SX radiation (a.u.)

Plasma

2 1

2.5 cm

IPP3- WAG 557- 87

46
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

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

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

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

DIII-D: 50 - 100
W7-AS: ~ 90
TEXTOR (Probes): 50 - 80

Reduction of radial correlation length

DIII-D

L-mode

H-mode

Radial correlation length (cm)
Modelling of shear-flow decorrelation

Gyrokinetic particle simulation of plasma microturbulence

Z. Lin at al., Science
The Origin of $E_r$ at the edge

2D:
Fluxes, transport coefficients are intrinsically ambi-polar and do not explicitly depend on $E_r$

$<j_r> = 0$, independent of $E_r$

3D:
$<j_r> = 0$, ensured by $\Gamma_e = \Gamma_i$: enforced ambi-polarity

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

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

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

Turbulence $\downarrow$ => pressure gradient $\uparrow$ => flow increases $\uparrow$ => turbulence $\downarrow$

$\nabla p_i$ 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: $t \sim 12$ $\mu$s

$T_i$ changes slowly

$\nabla p_i$ cannot be the transition trigger

Short timescale indicates:

Transition trigger related to $v_\theta B_\phi$

Turbulence level drops jointly with $E_r$

---

Causality between $E_r$ and $\nabla p_i$

TEXTOR: H-mode induced by polarisation probe

$E_r$ is oscillating

$n_e (\nabla p_i)$ also oscillates

Causality: $\nabla E_r$ leads $n_e$ by about 5 ms

Analysis done by K.H. Burrell, Phys. Plasmas
2\textsuperscript{nd} step: Turbulence produces flow

Turbulence $\Rightarrow$ Reynolds stress ($\langle \tilde{v}_r \tilde{v}_\theta \rangle$) $\Rightarrow$ flow $\Rightarrow$ decorrelation of turbulence

Poloidal force balance: $0 = j_r B/n_i - m_i \mu_\theta v_{\theta i} + m_i \partial / \partial r (\langle \tilde{v}_r \tilde{v}_\theta \rangle)$

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

$\nabla p_i$ 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

\[ \nabla T_{\text{crit}} \]

L-mode

H-mode

ITB

\[ \mathrm{ASDEX Upgrade} \]
\[ \text{Peeters et al. (2001)} \]
New options

Internal transport barrier (ITB)

External and internal transport barriers

$\nabla T_{\text{crit}}$
Electron transport barrier with electron resonance heating in special mode: counter – ECCD which shapes the q-profile.
ITBs simultaneously in $T_i$ and $T_e$
Most probable: shear-flow effect for i-ITB (1)

- ITB layer with steep temperature gradient

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

ASDEX Upgrade

Steep transport barrier at \( r/a \approx 0.5 \) with toroidal flow

strongly sheared plasma rotation

\( \Rightarrow \) \( \frac{dE_r}{dr} \)

measured \( E_r \sim v_{\text{tor}} \cdot B_{\text{pol}} \) fullfills

condition for turbulence suppression
Another aspect: ITB location and that of $q_{\text{min}}$

q-profile and transport barrier positions are directly coupled

From Fujita et al., 1998
This dependence is of specific importance because it implies that discharges with a large ratio of $j_{\text{bootstrap}}/j_{\text{plasma}}$ can develop ITBs.
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\times 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 ≤ Q ≤ 10
- 5.6 keV => Q ≥ 10

Discrepancy: due to different “stiffness” in the models

\( P_{\text{fus}} \) depends sensitively on density profile in case of an inward convective term: on He recycling.

\( P_{\text{fus}} \) has a sensitive dependence on B: \( P_{\text{fus}} \sim B^{3.5} \)
The hope for ITER

Internal Transport 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