Turbulence suppression and ITER operation

Ben Dudson

Department of Physics, University of York, Heslington, York YO10 5DD, UK

7th March 2014

So far...

In this course we've looked at many topics in magnetic confinement fusion, including Classical and Neoclassical transport, currents and current drive, equilibrium and instabilities, turbulence and transport.

- There are many different areas of study in MCF which can (mainly) be studied independently of each other
- This can make an overview course like this seem incoherent; like a collection of small courses
- In the last two lectures I'll try to bring these different topics together
- Ultimate aim is to optimise the fusion performance within engineering limits, so will discuss ITER and DEMO operating scenarios

Ohmic performance

In tokamaks which are driven ohmically, the experimental energy confinement time scales like:

$$\tau_E^O = 0.07\overline{n_e} a R^2 q_{edge}$$

τ_E^O in seconds, $\overline{n_e}$ in $10^{20}\mathrm{m}^{-3}$, a and R in meters

Ohmic performance

In tokamaks which are driven ohmically, the experimental energy confinement time scales like:

$$\tau_E^O = 0.07\overline{n_e} a R^2 q_{edge}$$

τ_E^O in seconds, $\overline{n_e}$ in $10^{20}\mathrm{m}^{-3}$, a and R in meters

- Scales with the plasma volume
- Taking typical tokamak parameters $a/R \simeq 1/3$, $q_{edge} \simeq 5$ and $\overline{n_e} \simeq 1 \times 10^{20} m^{-3}$ then to get $\tau_E \simeq 3$ for ignition we'd need

$$R^O \sim 3m \qquad a^O \sim 1m$$

Ohmic performance

In tokamaks which are driven ohmically, the experimental energy confinement time scales like:

$$\tau_E^O = 0.07\overline{n_e} a R^2 q_{edge}$$

τ_E^O in seconds, $\overline{n_e}$ in $10^{20}\mathrm{m}^{-3}$, a and R in meters

- Scales with the plasma volume
- Taking typical tokamak parameters $a/R \simeq 1/3$, $q_{edge} \simeq 5$ and $\overline{n_e} \simeq 1 \times 10^{20} m^{-3}$ then to get $\tau_E \simeq 3$ for ignition we'd need

$$R^O \sim 3m \qquad a^O \sim 1m$$

- Classical transport $a^C \sim 10\mathrm{cm}$, Neoclassical $a^{NC} \sim 1\mathrm{m}$
- Experimental results give transport levels near neoclassical. This lead to the (some of) the initial optimism.

Limits to ohmic performance

In lecture 7 we found that ohmic heating has serious limits:

- It's inherantly pulsed: it depends on varying the current through a central solenoid which has current and heating limits
- Plasma resistivity falls with temperature, reducing heating power whilst plasma radiation loss increases with temperature. This limits the plasma temperature to around 3keV

Limits to ohmic performance

In lecture 7 we found that ohmic heating has serious limits:

- It's inherantly pulsed: it depends on varying the current through a central solenoid which has current and heating limits
- Plasma resistivity falls with temperature, reducing heating power whilst plasma radiation loss increases with temperature. This limits the plasma temperature to around 3keV

To increase plasma temperature to reactor relevant temperatures, additional ("auxilliary") heating is needed.

- In lectures 7 and 9 we looked at the main methods for doing this: NBI and RF heating
- Unfortunately, once this additional power was injected the confinement time fell (confinement degredation)

L-mode performance

Once auxilliary heating is used, the confinement degrades and is approximately given by the Goldston scaling law[1]:

$$\tau_E^G = 0.037 \frac{I R^{1.75} \kappa^{0.5}}{P^{0.5} a^{0.37}}$$

where I is the plasma current in MA, κ is the elongation, and P is the heating power in MW

[1] Goldston 1984, Yushmanov *et.al.* 1990

L-mode performance

Once auxilliary heating is used, the confinement degrades and is approximately given by the Goldston scaling law[1]:

$$\tau_E^G = 0.037 \frac{I R^{1.75} \kappa^{0.5}}{P^{0.5} a^{0.37}}$$

where I is the plasma current in MA, κ is the elongation, and P is the heating power in MW

- To estimate I, use $2\pi a B_\theta \simeq \mu_0 I$ and so $I \sim 5 a B_\theta$, I in MA.
- Taking $B_\theta \sim 1$T, and the ITER values $P = 50$MW, $\kappa = 1.8$ and $a/R \simeq 1/3$

$$\tau_E \sim 0.02 R^{2.38} \quad \Rightarrow R^G \sim 9m \quad a \sim 3m$$

- This is significantly worse than the Ohmic scaling, and so is known as Low confinement mode or L-mode

[1] Goldston 1984, Yushmanov *et.al.* 1990

Turbulence in MCF

In the last two lectures we saw that small-scale instabilities exist in magnetic confinement devices:

- Electron drift wave, destabilised by dissipation which slows electrons and introduces a phase shift between $E \times B$ advection and density variation
- ITG mode, destabilised by ion temperature gradients and ∇B or curvature drifts
- ETG mode on scales smaller than ρ_i, destabilised by electron temperature gradients and ∇B or curvature drifts
- TEM driven by pressure gradients and trapped particles sampling only part of the torus.

Any of these can lead to turbulence, and enhanced transport of particles and energy out of the plasma.
Injecting additional heating provides additional instability drive.

Zonal flows

In fluid / plasma turbulence there is a coupling between small fluctuations and mean "zonal" flows[2]: **Reynolds stress**.

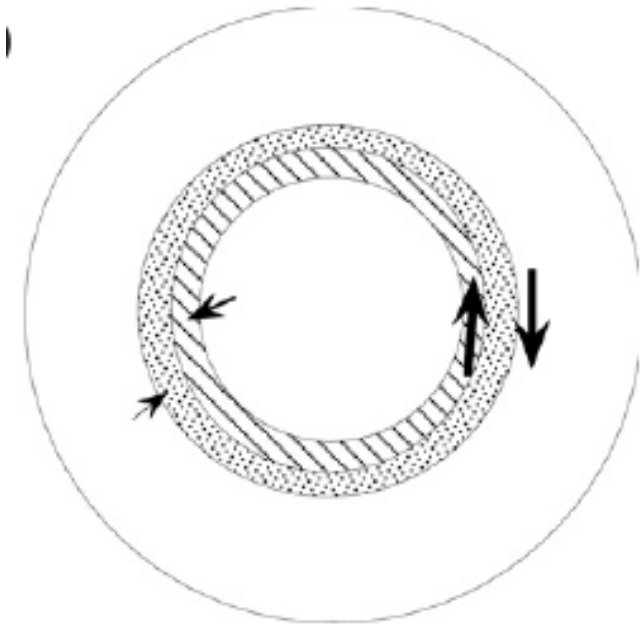

Figure : P.Diamond *et.al.*, PPCF 2005. Figure 4a

- Plasma turbulence generates sheared "zonal" flows
- Sheared flows stretch and break up turbulent eddies, reducing the turbulence
- If the shearing rate is faster than the growth rate then instabilities can be stabilised

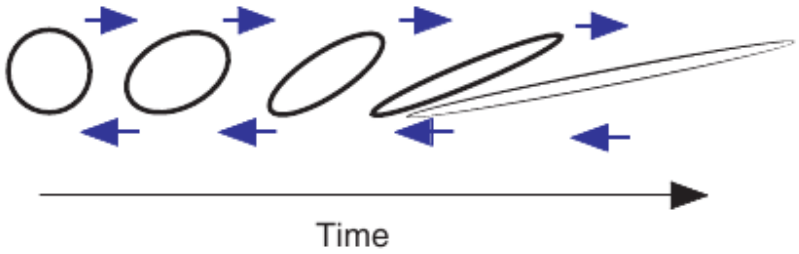

Figure : P.Diamond *et.al.*, PPCF

H-mode

In 1982 on ASDEX an unexpected discovery was made[3]

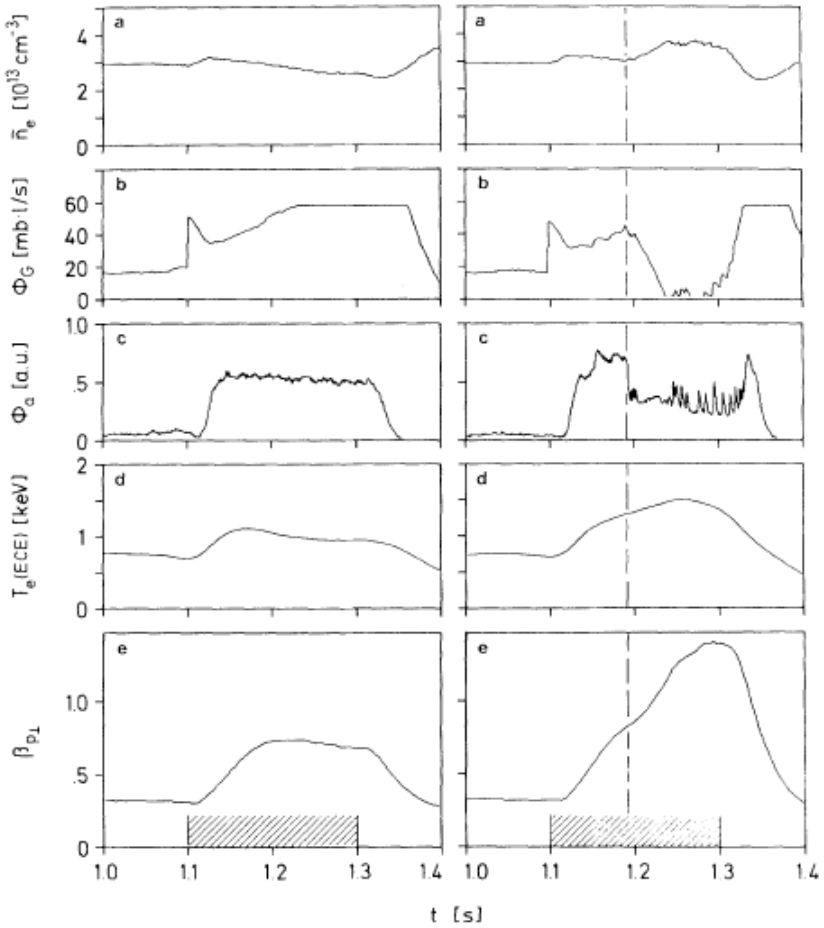

Figure : F.Wagner *et.al.* 1982, Fig 1

- Graphs show line averaged density $\overline{n_e}$, External gas flux Φ_G, exhaust atom flux Φ_a, central T_e, and poloidal Beta.
- Left: L-mode discharge with 1.6MW of NBI heating
- Right: H-mode discharge with 1.9MW (18% increase)
- Sudden increase in particle and energy confinement time to values similar to Ohmic discharges

[3] F.Wagner *et.al.* Phys. Rev. Lett. 49, 1408-1412 (1982), 852 citations

H-mode

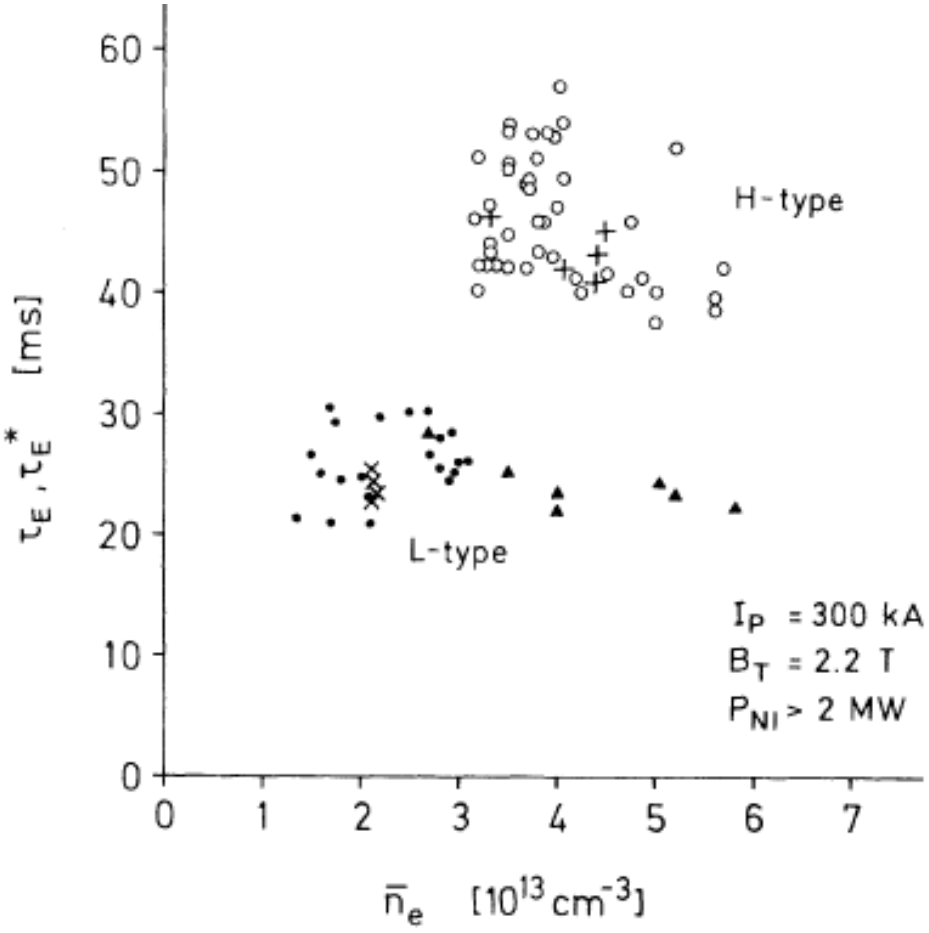

Figure : F.Wagner *et.al.* 1982, Fig 2

- Approximate doubling of confinement time
- Solid triangles: Limiter plasmas
- Closed circles and 'x': L-mode
- Open circles and '+': H-mode

H-mode

Experiments show a power threshold, and very fast transition $\sim 100\mu$s during which turbulence levels at the edge drop dramatically.

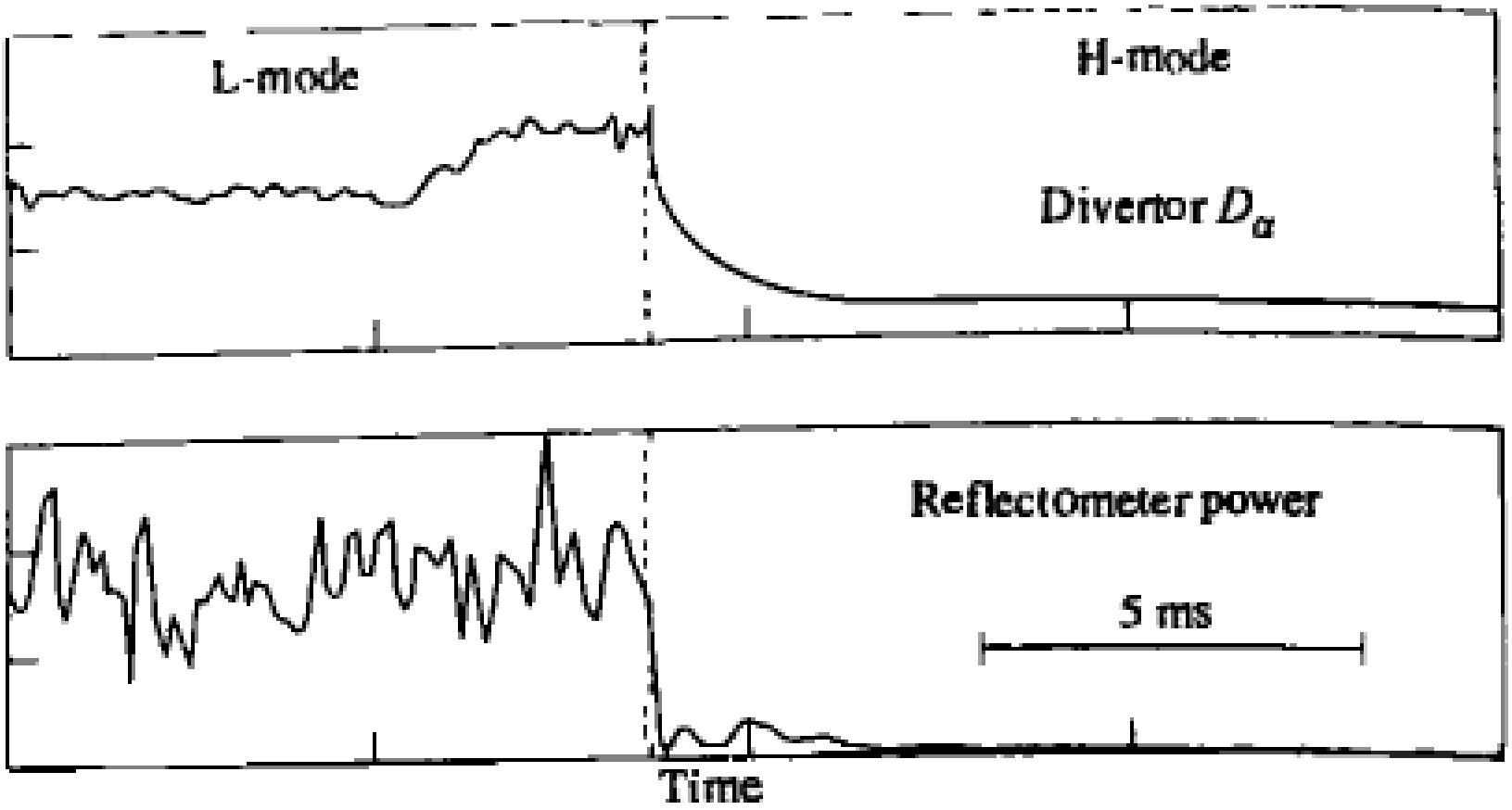

Figure : L-H transition on DIII-D tokamak. Wesson fig 4.17.3

Radial electric field

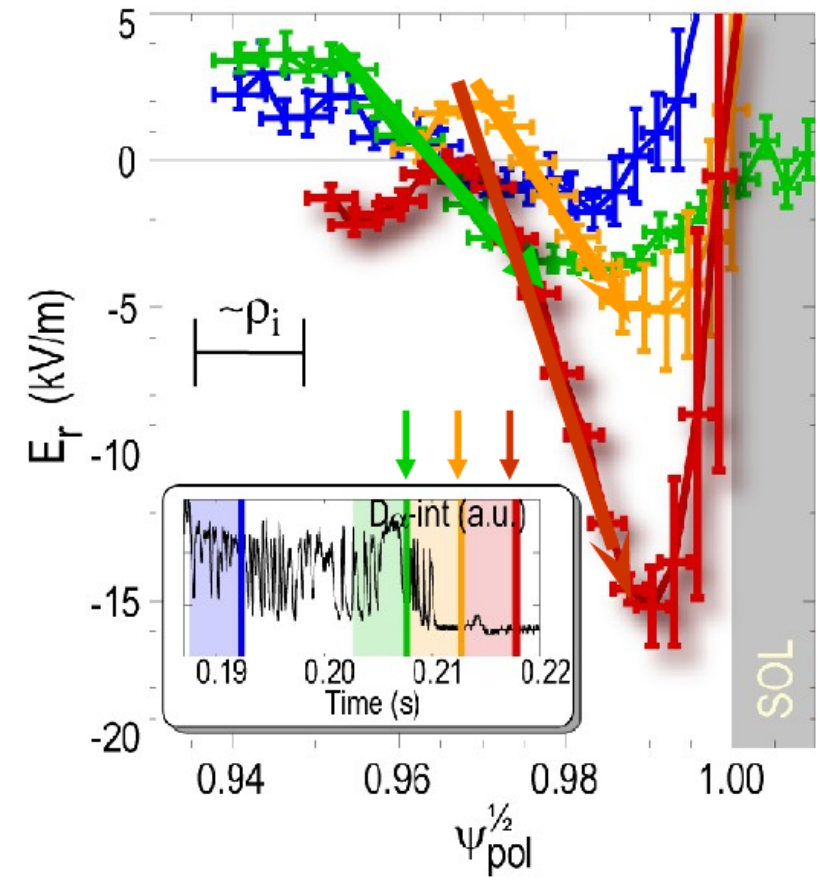

Figure : L-H transition on MAST. H.Meyer IAEA FEC 2008

- In H-mode a steep gradient in radial electric field is seen
- **NB** This is measured using rotation velocity of Helium ions so there is uncertainty in the ion velocity
- This E_r corresponds to a poloidal $E \times B$ zonal flow which forms rapidly.
- Current research studying formation of n_e, T_e pedestals and E_r well

Radial force balance

The radial electric field E_r is given by the radial force balance from

$$n_s m_s \frac{d\underline{v}}{dt} = n_s q_s \left(\underline{E} + \underline{v} \times \underline{B}\right) - \nabla p_s$$

$$\Rightarrow E_r = \frac{1}{q_s n_s} \frac{dp_s}{dt} + v_{\phi,s} B_\theta - v_{\theta,s} B_\phi$$

- Measured experimentally using CXRS on impurity species
- In H-mode ions are electrostatically confined, but electrons are magnetically confined
- Subject to several feedback mechanisms. E_r depends on transport of heat, particles and momentum, but alters these through shearing of turbulence flows
- Nonlinear feedback leads to possibility of transitions / bifurcations

Getting into H-mode

There are many factors which seem to influence the transition into H-mode, and the reasons why are not really understood. Some of the key ones seem to be:

- Cleanliness: high-Z impurities raise the power threshold or prevent L-H transition
  - H-mode not seen in limiter plasmas
  - Remove impurities from walls using Glow Discharge (GDC)
  - Coating the walls in a layer of Beryllium
- Direction of ∇B drift: L/H power threshold is $\sim 2\times$ higher when the ion ∇B drift is away from the X-point compared to case with drift in opposite direction. "Universal" result, seen on all tokamaks
- Neutral gas fuelling: location of the fuelling (inboard / outboard)

Theories of H-mode

There are several theories proposed to explain aspects of H-mode, but the process is not really understood

- Negative radial electric field may be driven by outward flux of ions: Ion orbit loss[4].
- Flows in the scrape off layer are thought to change E_r at the plasma boundary and so affect the L-H transition.
  See papers by LaBombard and Greenwald.
- A possibility is that H-mode is an electron effect, and that the ions play a passive role.
  - Ion temperatures are hard to measure, but thought to vary more slowly than electron temperature
  - See papers by Kagan and Catto

[4] K.C.Shaing and E.C.Crume,Jr Phys. Rev. Lett **63** 2369 (1989)

H-mode performance

- Performance of H-mode plasmas is usually given in terms of the "H factor". Relative to a fit to H-mode performance (e.g H98), or to L-mode scaling H_L.
- Estimate of scaling of the fusion performance $Q = P_{fusion}/P_{heating}$ is shown below:

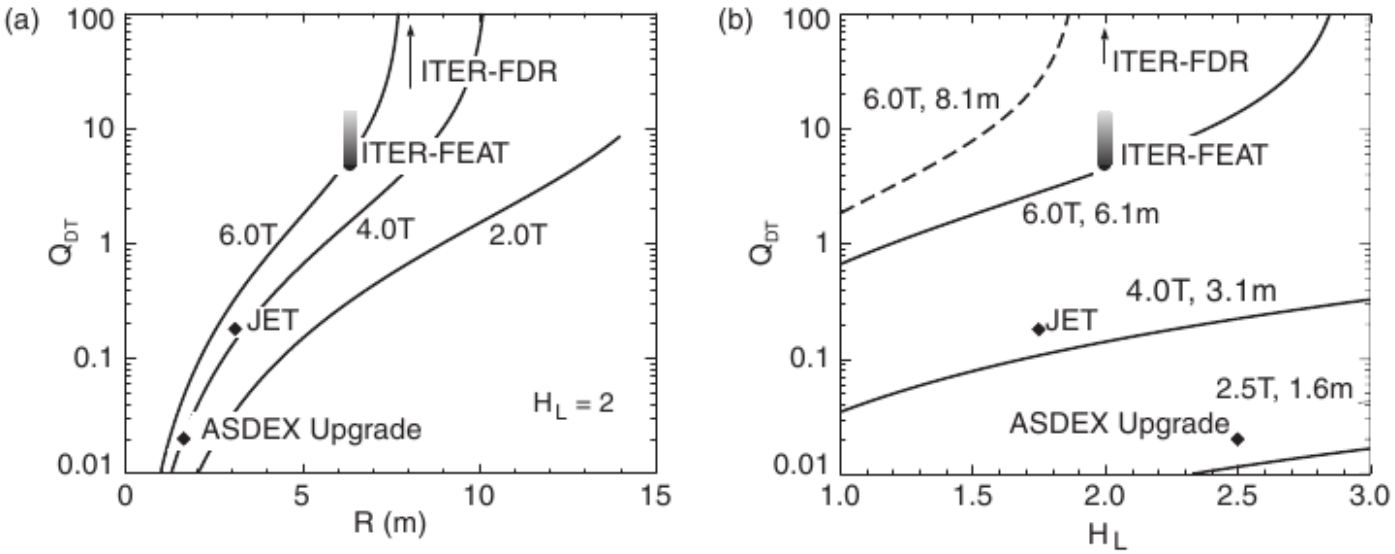

Figure : Fusion performance against R and H-mode enhancement. R.C.Wolf Plas. Phys. Cont. Fus. **45** (2003) R1-R91

- H-mode takes Q of ITER from ~ 1 to $\sim 8 - 10$

Internal Transport Barriers

In addition to the H-mode Edge Transport Barrier (ETB), steep gradient regions have also been found to form inside the plasma called Internal Transport Barrier (ITBs)[5]

- ITBs are if anything even less well understood than ETBs
- Also affected by power deposited inside their location
- Creation of radial electric fields and shear flow[6]
- Often form at rational q surfaces, or where magnetic shear goes to zero

[5] Y.Koide *et.al* Phys. Rev. Lett. **72** 3662 (1994)
R.C.Wolf Plasma Phys. Cont. Fus. **45** (2003) R1-R91

[6] J.W.Connor *et.al.* Nucl. Fusion **44** (2004) R1-R49

Internal Transport Barriers

In addition to the H-mode Edge Transport Barrier (ETB), steep gradient regions have also been found to form inside the plasma called Internal Transport Barrier (ITBs)[5]

- ITBs are if anything even less well understood than ETBs
- Also affected by power deposited inside their location
- Creation of radial electric fields and shear flow[6]
- Often form at rational q surfaces, or where magnetic shear goes to zero

ITBs offer the possibility of further improving performance:

- Reduce transport and increase pressure gradients, allowing a more compact reactor
- Drives additional bootstrap current, maximising non-inductive current fraction

[5] Y.Koide *et.al* Phys. Rev. Lett. **72** 3662 (1994)
R.C.Wolf Plasma Phys. Cont. Fus. **45** (2003) R1-R91
[6] J.W.Connor *et.al.* Nucl. Fusion **44** (2004) R1-R49

Summary

- Auxilliary heating of plasmas leads to confinement degradation as turbulence increases.
- Scaling of confinement time $\tau_E \sim IR^2/\sqrt{P}$ is lower than for Ohmic plasmas, so called **L-mode**
- Above a power threshold a transport barrier can form at the plasma edge, associated with a radial electric field and sheared $E \times B$ flows
- On fast ($< 100\mu$s) timescales turbulence is suppressed and a pressure **pedestal** forms
- This **H-mode** operation is the standard "baseline" operating scenario for ITER, and essential if it is to achieve $Q = 10$
- Transport barriers have also been found to form inside the core: **Internal Transport Barriers** which are the basis of some advanced tokamak scenarios