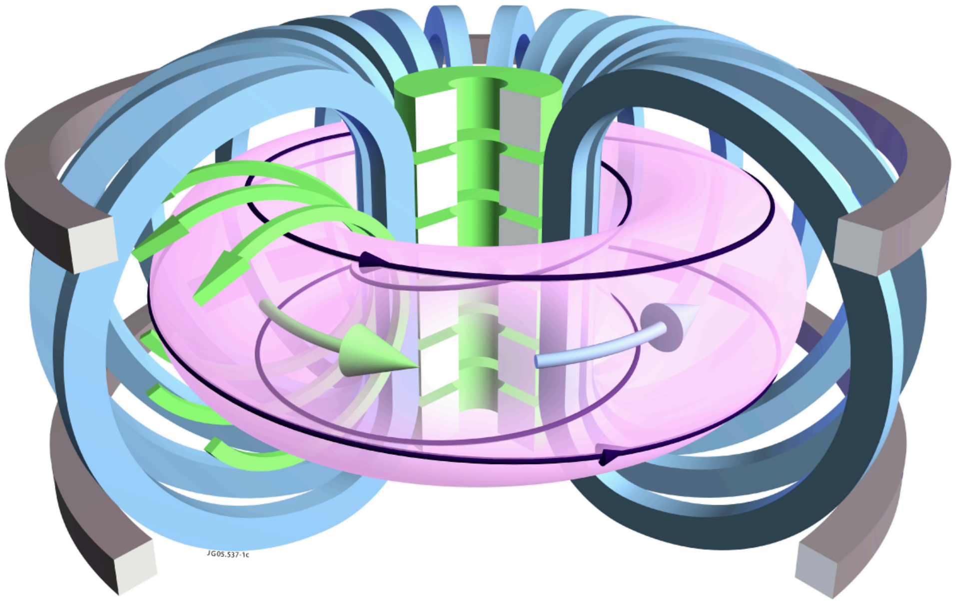

Self-Organization in Burning Plasmas

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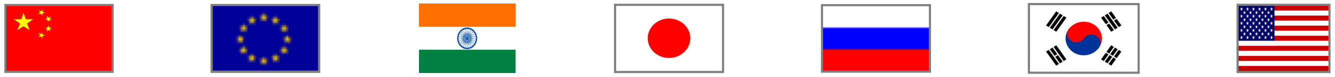
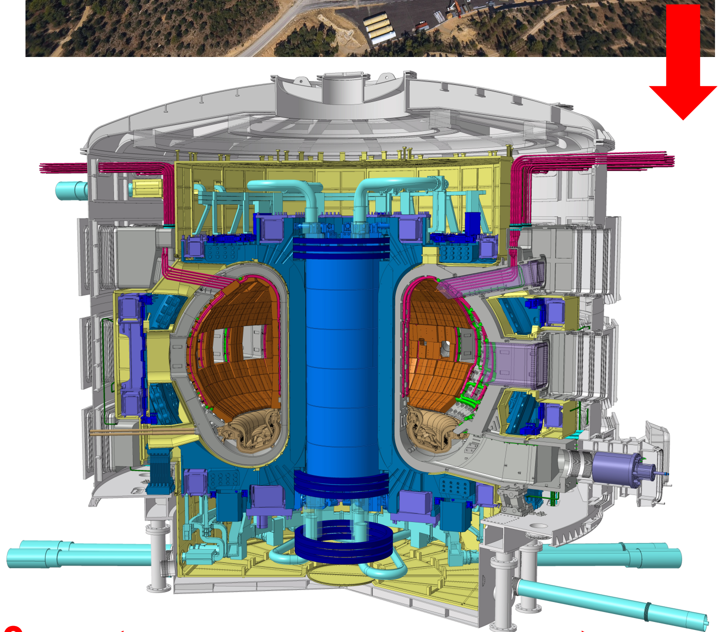
The ITER experiment, currently under construction, will allow us to study burning plasmas



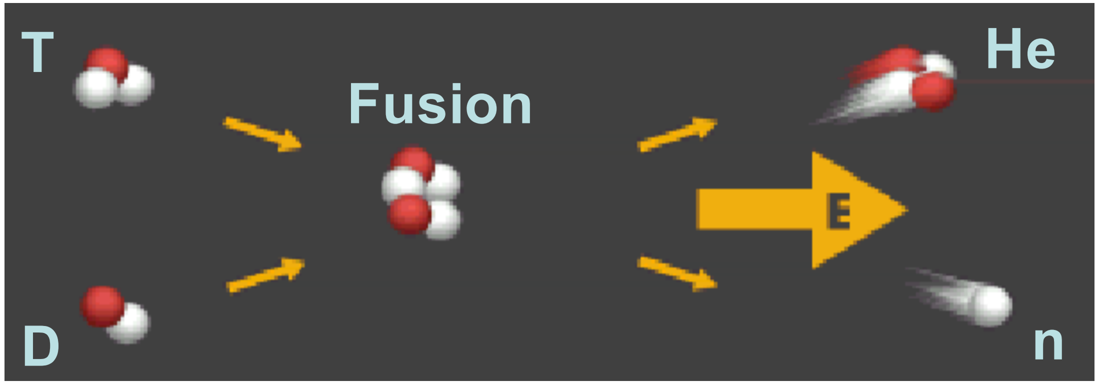
- **Overall programmatic objective:**
  - to demonstrate scientific and technological feasibility of fusion energy for peaceful purposes
- **Principal goal:**
  - to design, construct and operate a tokamak experiment at a scale which satisfies this objective
- **ITER is designed to confine a DT plasma in which α-particle heating dominates all other forms of plasma heating**

$\Rightarrow$ a burning plasma experiment



d ~ 30 m

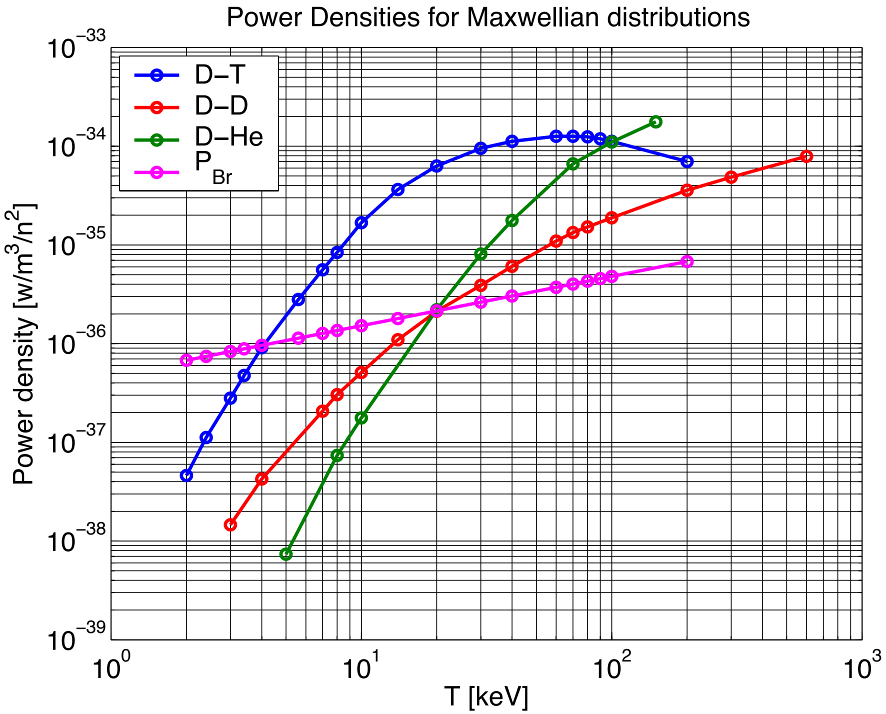
Fusion energy research focusses on the development of DT burning plasmas



+ 20% of Energy (3.5 MeV)

+ 80% of Energy (14.1 MeV)

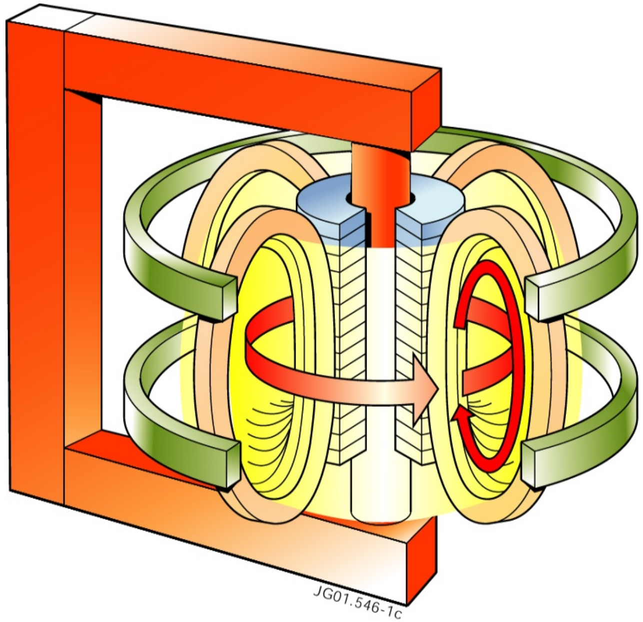
1 keV = 1.16 × 10^7 K



- **The D-T fusion reaction offers the simplest approach to significant power production under terrestrial conditions**

^{2}D + ^{3}T ⇒ ^{4}He (3.5 MeV) + ^{1}n (14.1 MeV)

The Tokamak is the most advanced toroidal magnetic confinement configuration



- **Inject gas into high vacuum chamber with a strong toroidal magnetic field (e.g. B_T ~ 5 T)**
- **Induce a toroidal electric field through transformer action, avalanche ionization produces plasma current creating poloidal magnetic field**

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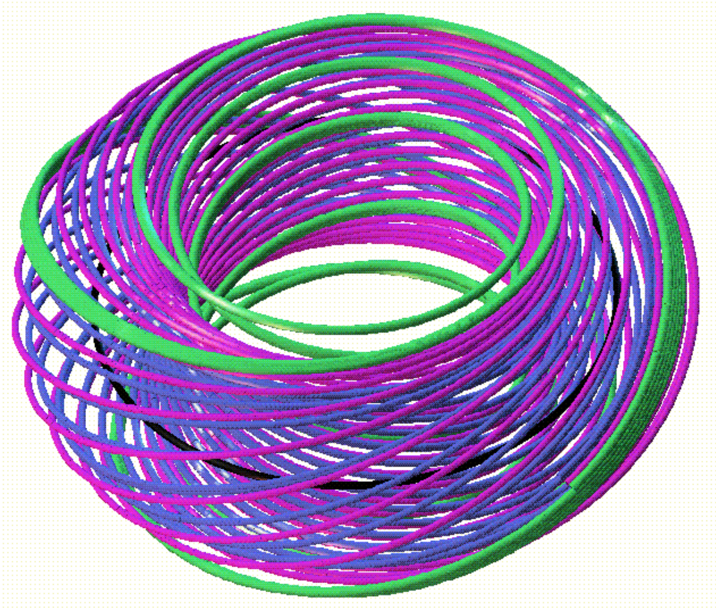
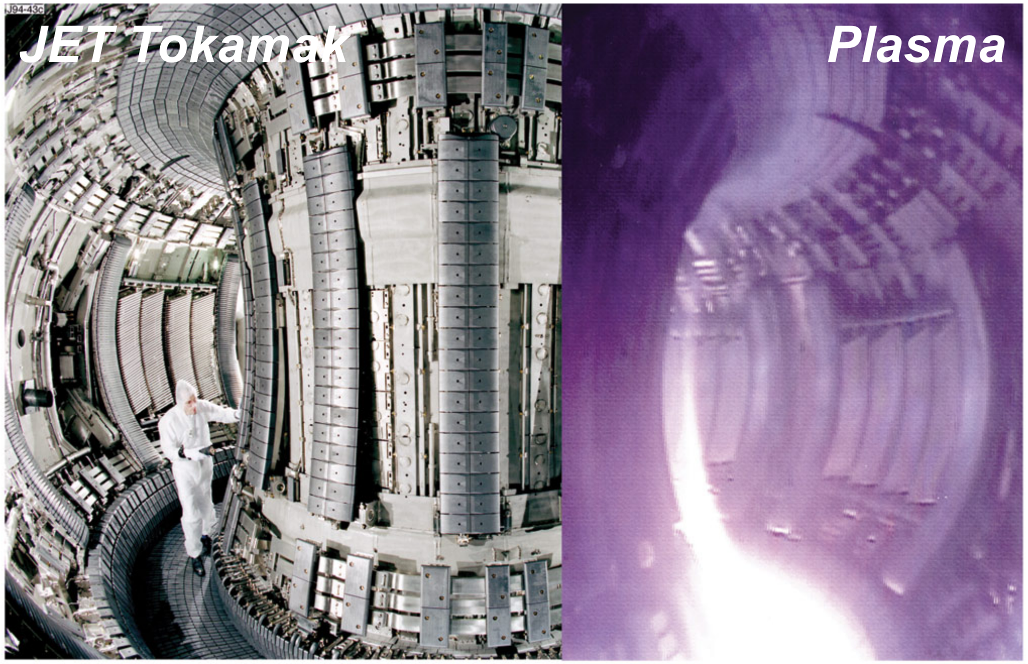


Combination of toroidal and poloidal fields produces helical field for plasma confinement:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

- **Inject gas into high vacuum chamber with a strong toroidal magnetic field (e.g. $B_T \sim 5$ T)**
- **Induce a toroidal electric field through transformer action, avalanche ionization produces plasma current creating poloidal magnetic field**



The conditions required for significant fusion power gain are well understood

Temperature - T_i: *$1\text{-}2 \times 10^8$ K (10-20 keV)*
(~10 × temperature of sun's core)

Density - n_i: *1×10^{20} m^{-3}*
(~10^{-6} of atmospheric particle density)

Energy confinement time - τ_E: *few seconds*
(plasma pulse duration ~1000s)

$$\tau_E = \frac{W_{th}}{P_{loss}} = 3\frac{\int nkT\, dV}{P_{loss}}$$

Fusion power amplification: $Q = \dfrac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$

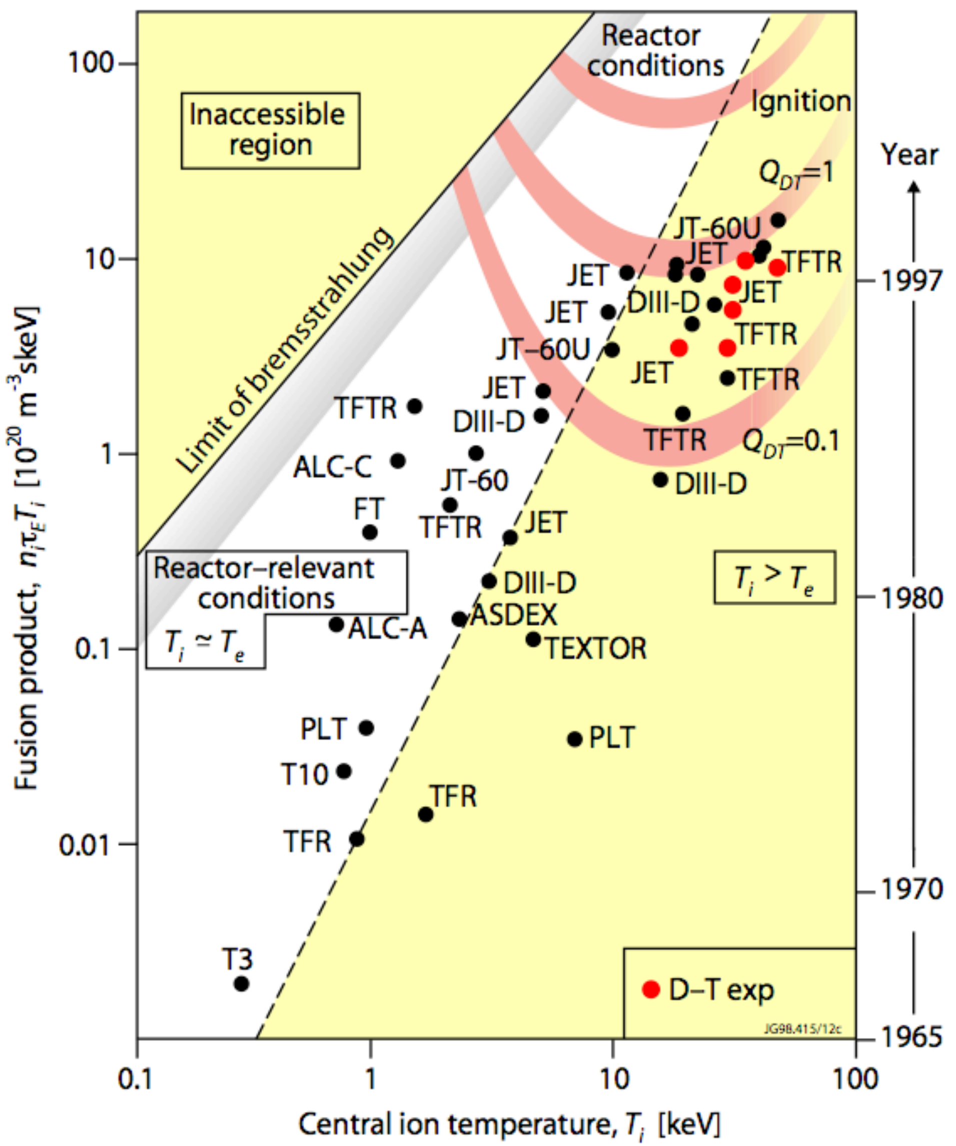
*⇒ **Present devices: Q ≤ 1***

*⇒ **ITER: Q ≥ 10***

*⇒ **'Controlled ignition': Q ≥ 30***

DT experiments on existing major facilities have laid the basis for studies of burning plasmas

- Existing experiments have achieved $nT\tau$ values ~ 1×10^{21} $m^{-3}skeV$ ~ Q_{DT} = 1
- JET and TFTR produced DT fusion powers of >10 MW for ~1 s
- ITER is designed to a scale which should yield Q_{DT} > 10 at a fusion power of ~ 500 MW for ~ 400s, allowing exploration of the burning plasma regime under stationary conditions



Heat and particle transport in fusion plasmas is generally dominated by turbulence

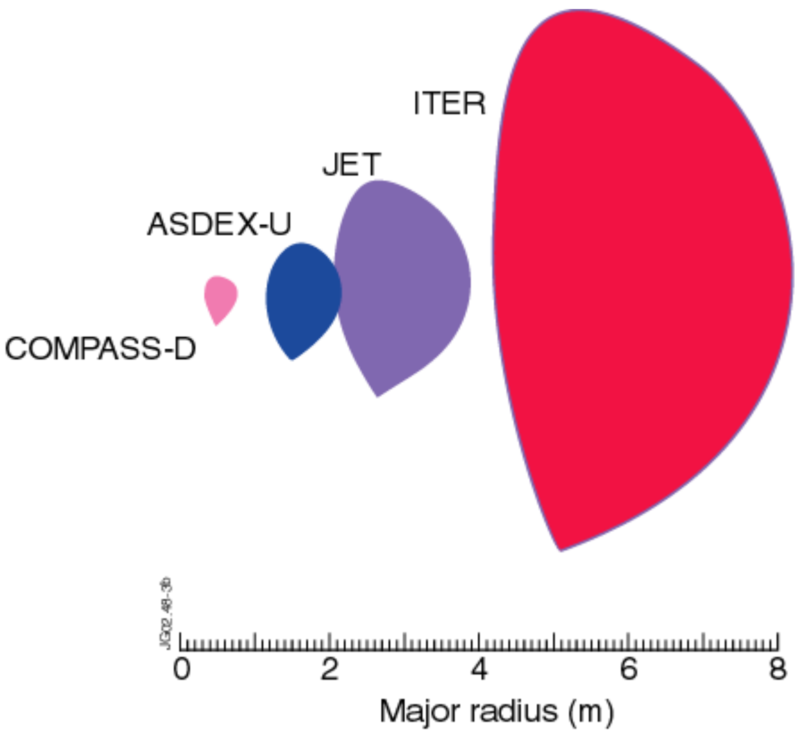
- **A well developed 'neoclassical' theory of transport in toroidal plasmas has been derived from analysis of collisional processes:**
  - unfortunately, it doesn't do a good job of describing heat and particle transport across the magnetic field
    $\Rightarrow$ turbulence normally dominates

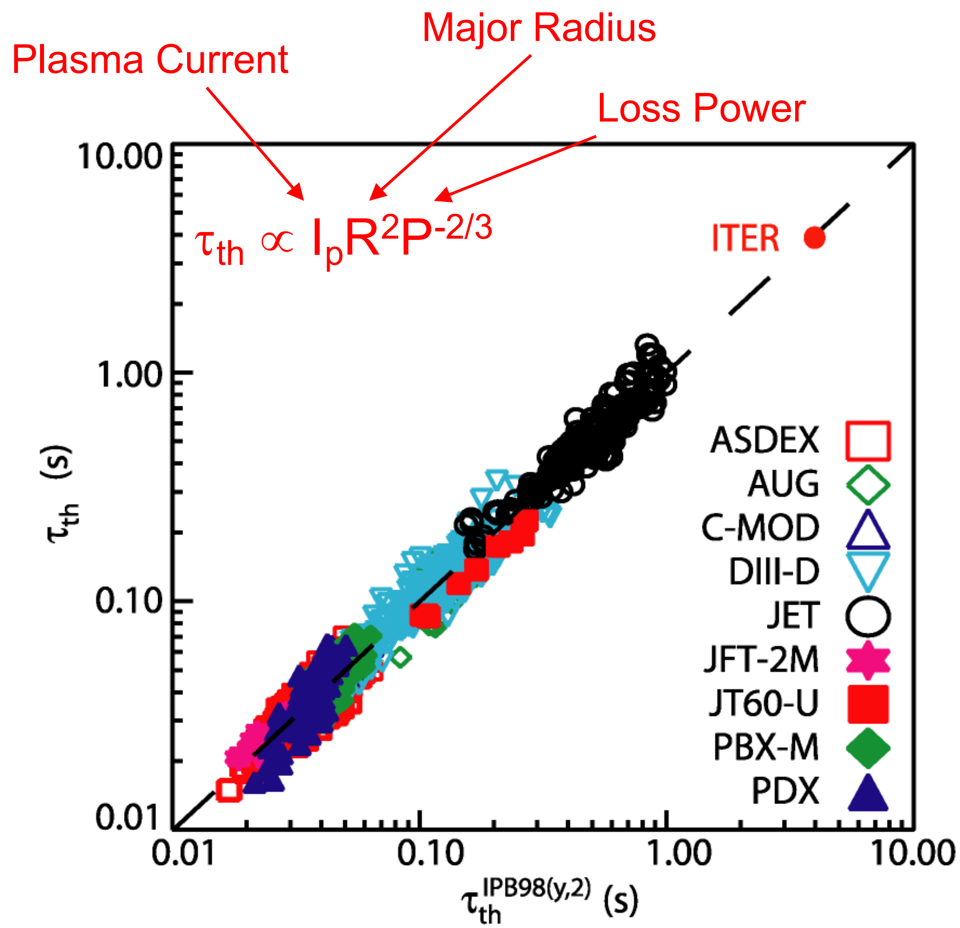
- **Free energy available within the plasma can generate turbulence and magnetohydrodynamic instabilities (mhd) which reduce plasma confinement quality**
  - small scale turbulence dominates collisional transport processes
  - physics-based quantitative predictions of transport processes (and global confinement) not yet possible

- **Parallel transport (along magnetic field lines) equilibrates heat and particle fluctuations rapidly, but measured values of perpendicular heat transport typically exceed 'neoclassical' predictions by:**
  - about an order of magnitude for the ion channel
  - at least two orders of magnitude for the electron channel

Empirical predictions of τ_E are derived from 'scaling' analysis

- **Since turbulent transport is difficult to predict quantitatively:**
  - we use scaling experiments to predict the level of energy confinement in future experiments such as ITER

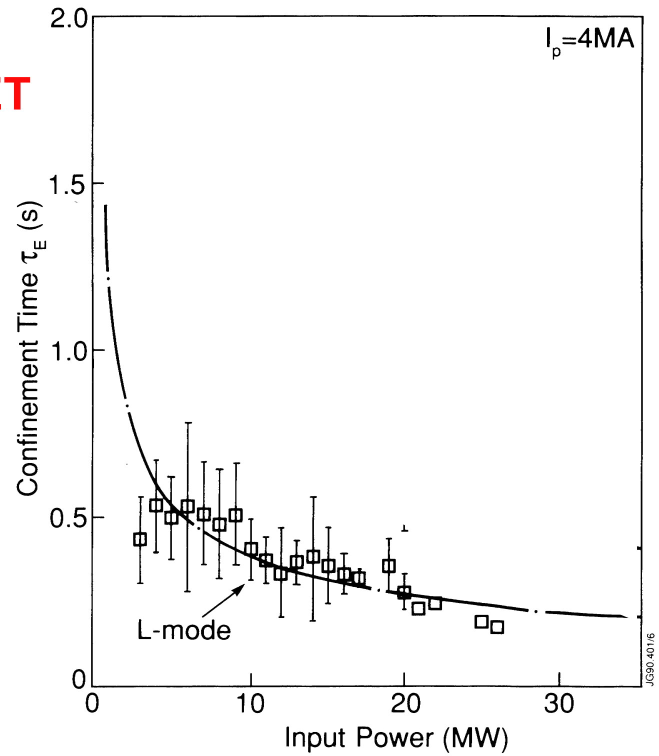


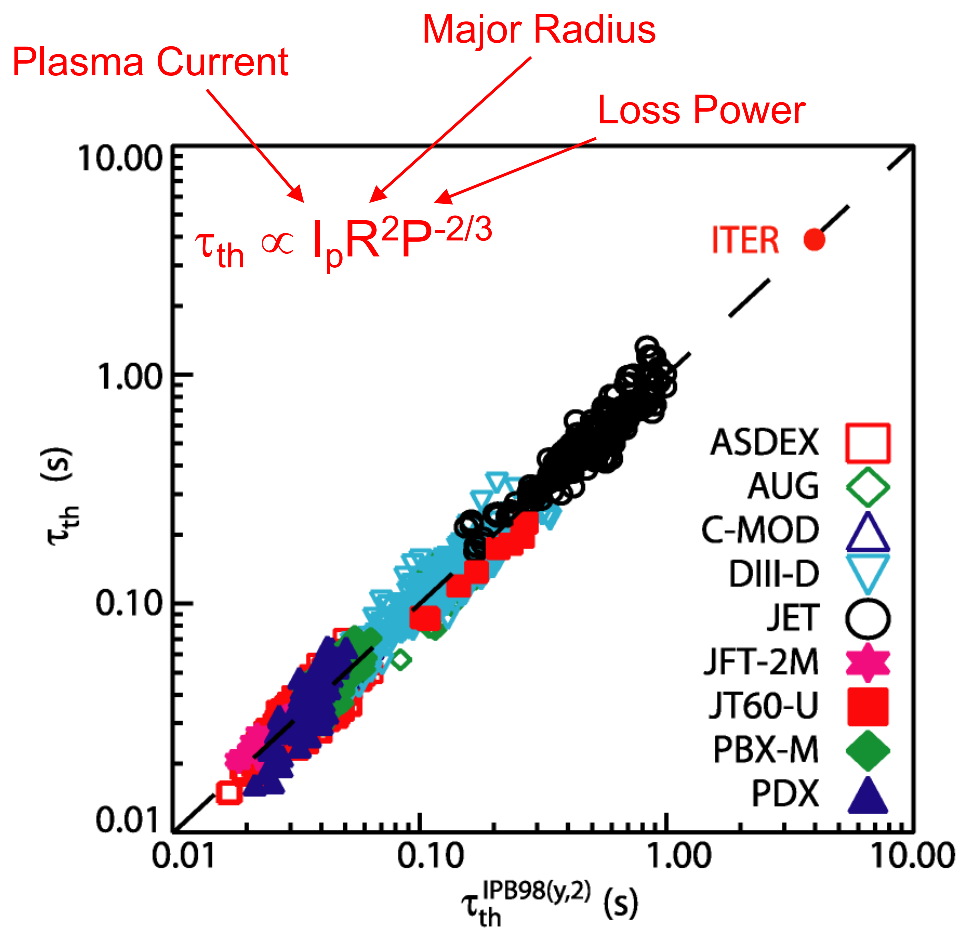


A bifurcation in the behavior of τ_E is observed under certain conditions

- **It is found that the plasma confinement state (τ_E) can bifurcate:**
  - two distinct plasma regimes, a low confinement (L-mode) and a high confinement (H-mode), result

JET

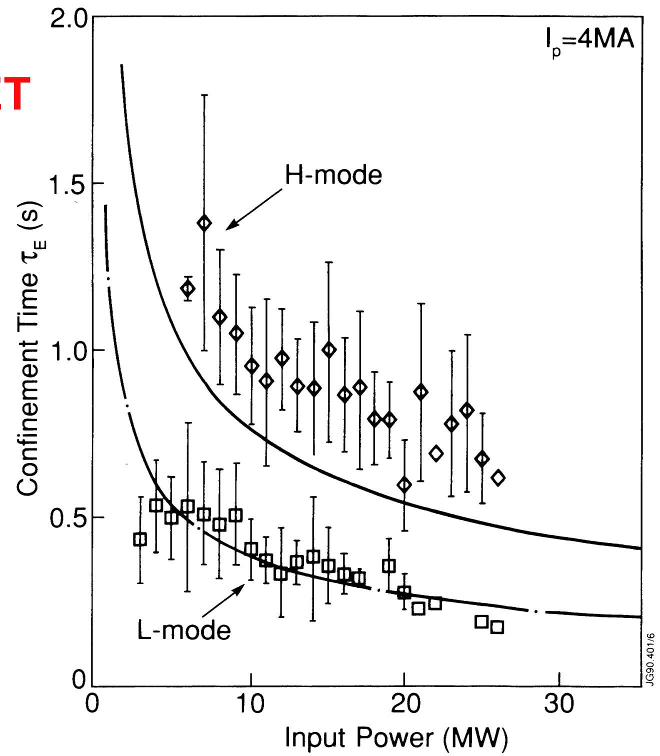


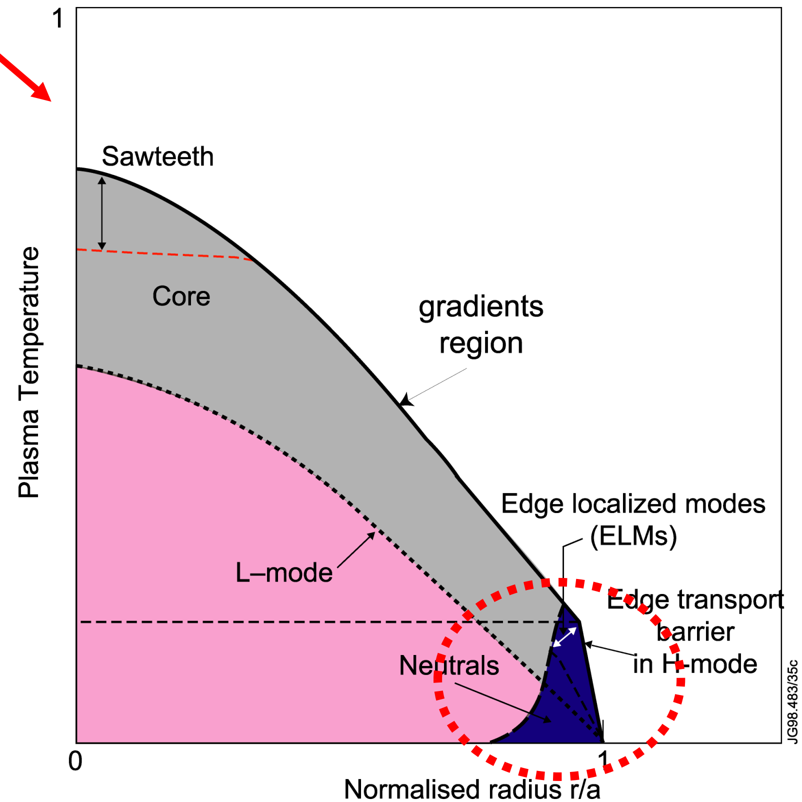


A bifurcation in the behavior of τ_E is observed under certain conditions

- **It is found that the plasma confinement state (τ_E) can bifurcate:**
  - two distinct plasma regimes, a low confinement (L-mode) and a high confinement (H-mode), result
  - this phenomenon has been shown to arise from changes in the plasma flow in a narrow edge region, or pedestal, just a few centimetres wide

JET

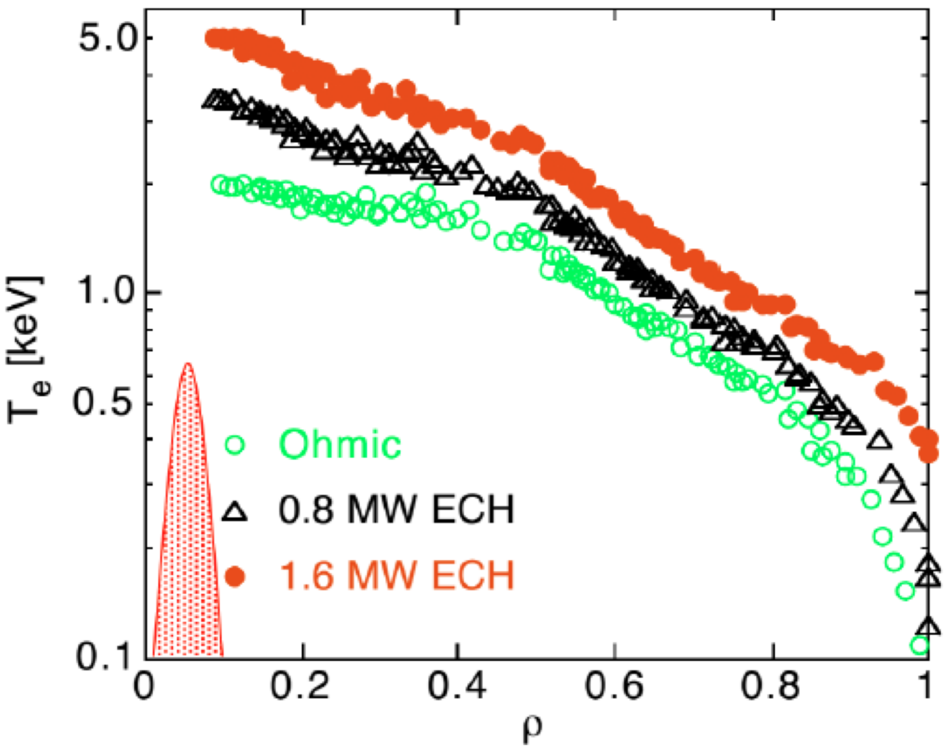




Evidence for self-organization in observed in ‘profile stiffness’

- Experimental evidence over several decades suggested that plasma profiles in tokamaks increased in ‘self-similar’ fashion, e.g. electron temperature
- ‘Profile stiffness’ indicates that there is little change in temperature gradient in response to large changes in heat flux

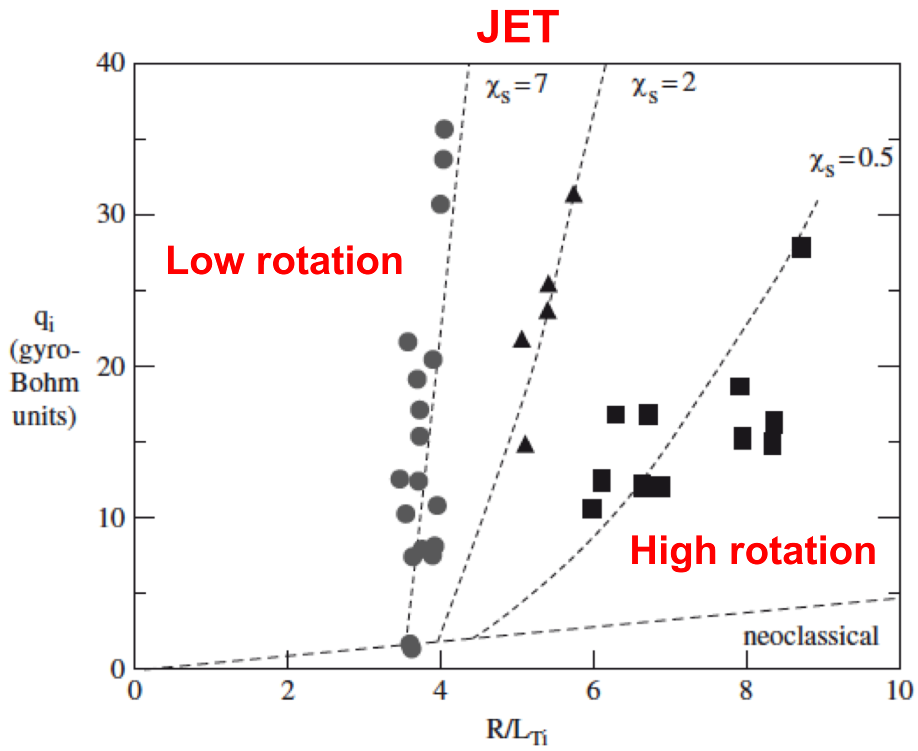
ASDEX Upgrade



F Ryter et al,
Plasma Phys Control Fusion **43** A323 (2001)

‘Profile stiffness’ reflects threshold behaviour expected for certain turbulent instabilities

- Studies show that experimental heat flux, q_i, rises sharply above a threshold value, or ‘critical gradient’, $R.\nabla T_i/T_i = R/L_{Ti}$
- This behaviour corresponds to that predicted for certain classes of turbulent instabilities
- Degree of ‘stiffness’ found to depend on plasma rotation - implying influence of rotation on instability amplitude

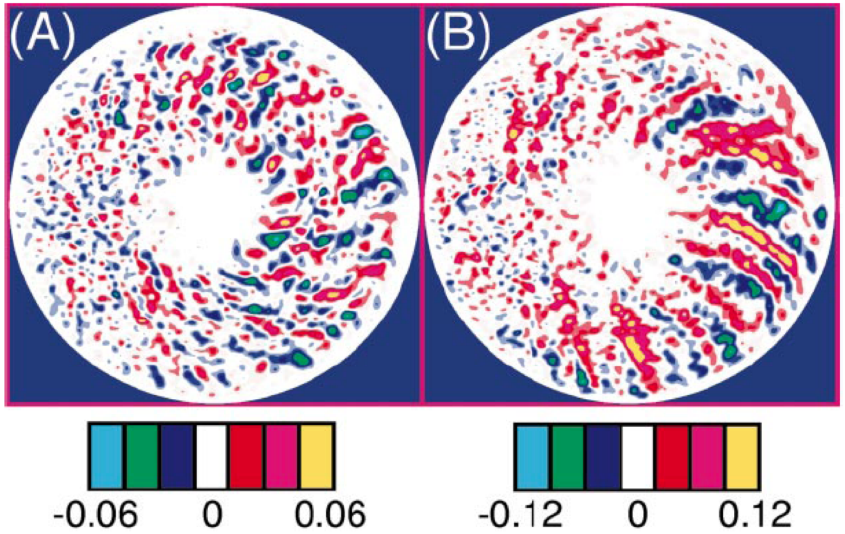


P Mantica et al,
Phys Rev Lett **102** 175002 (2009)

Turbulence saturation mechanism also shows evidence for 'self-organization'

- Massive computational simulations of microturbulence have confirmed predictions of analytic theory:
  - Fluctuating E × B driven 'zonal flows' develop non-linearly within the turbulence and produce 'shearing' of the turbulent eddies, reducing plasma transport
  - Zonal flows act as saturation/ self-regulation mechanism of the turbulence via 'shearing' of turbulent eddies
- Existence of zonal flows confirmed in experimental measurements

Z Lin et al, Science **281** 1835 (1998)



Simulations of poloidal distribution of fluctuation potential, $e\Phi/T_i$:

(A) E × B flows included

(B) E × B flows suppressed

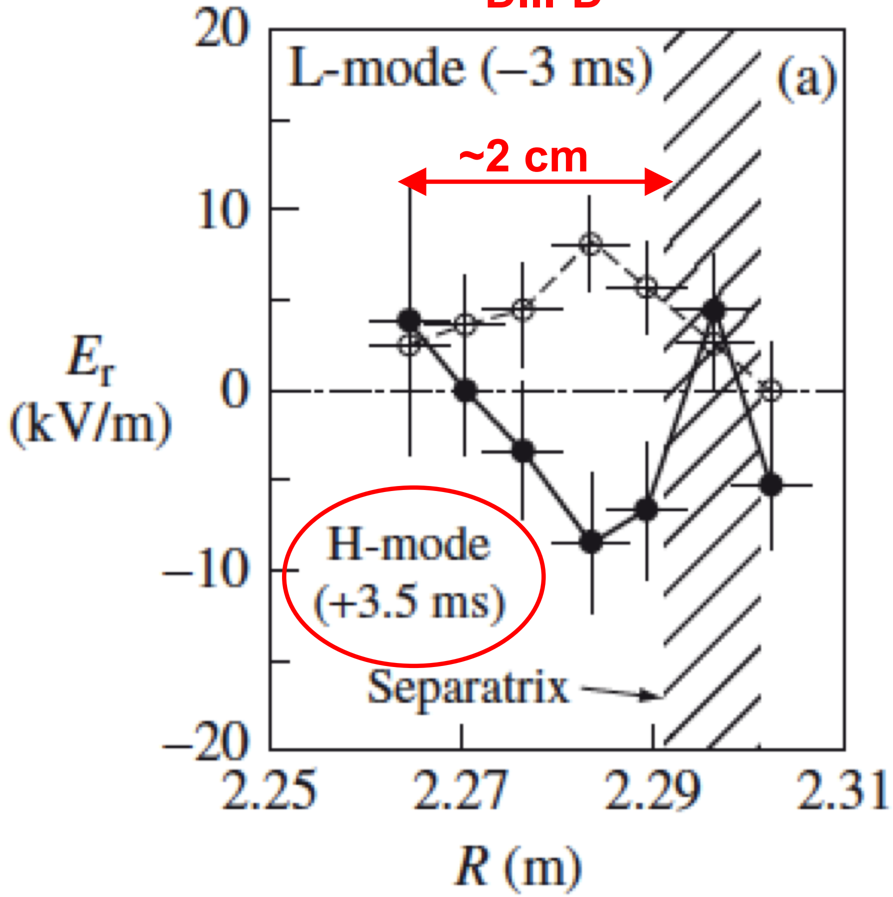
The H-mode bifurcation is understood in terms of E × B turbulence suppression

- The H-mode is correlated with a change in rotational shear at the plasma edge associated with the development of a radial electric field:
  - turbulence is stabilized when the shearing rate for the modes is of order of the mode growth rate:

    $$\omega_{E\times B} \sim \gamma_{max}$$

- However, debate is ongoing as to whether the shearing process is dominated by zonal flows (resulting from 'Reynolds stress') or velocity shear driven by 'neoclassical' E-field generation (ion orbit loss or pressure gradient)

DIII-D



KH Burrell et al,
Phys Plasmas **1** 1536 (1994)

Summary

- **Extensive physics studies of magnetically confined toroidal plasmas have laid the basis for the production and study of burning plasmas in ITER**
- **Experimental, theoretical and computational analysis of heat and particle transport are unravelling the complexities of turbulence driven transport:**
  - self-organization phenomena are critical to an understanding of the non-linear behaviour of turbulence and its influence on plasma confinement quality
- **Self-organization processes are likely to assume even greater importance in the burning plasma regime:**
  - internal heating by α-particles and the interaction with α-driven mhd modes may introduce additional non-linear aspects of plasma behaviour
  - possible modes of plasma operation allowing true steady-state operation of tokamak plasmas may also give rise to self-organization phenomena