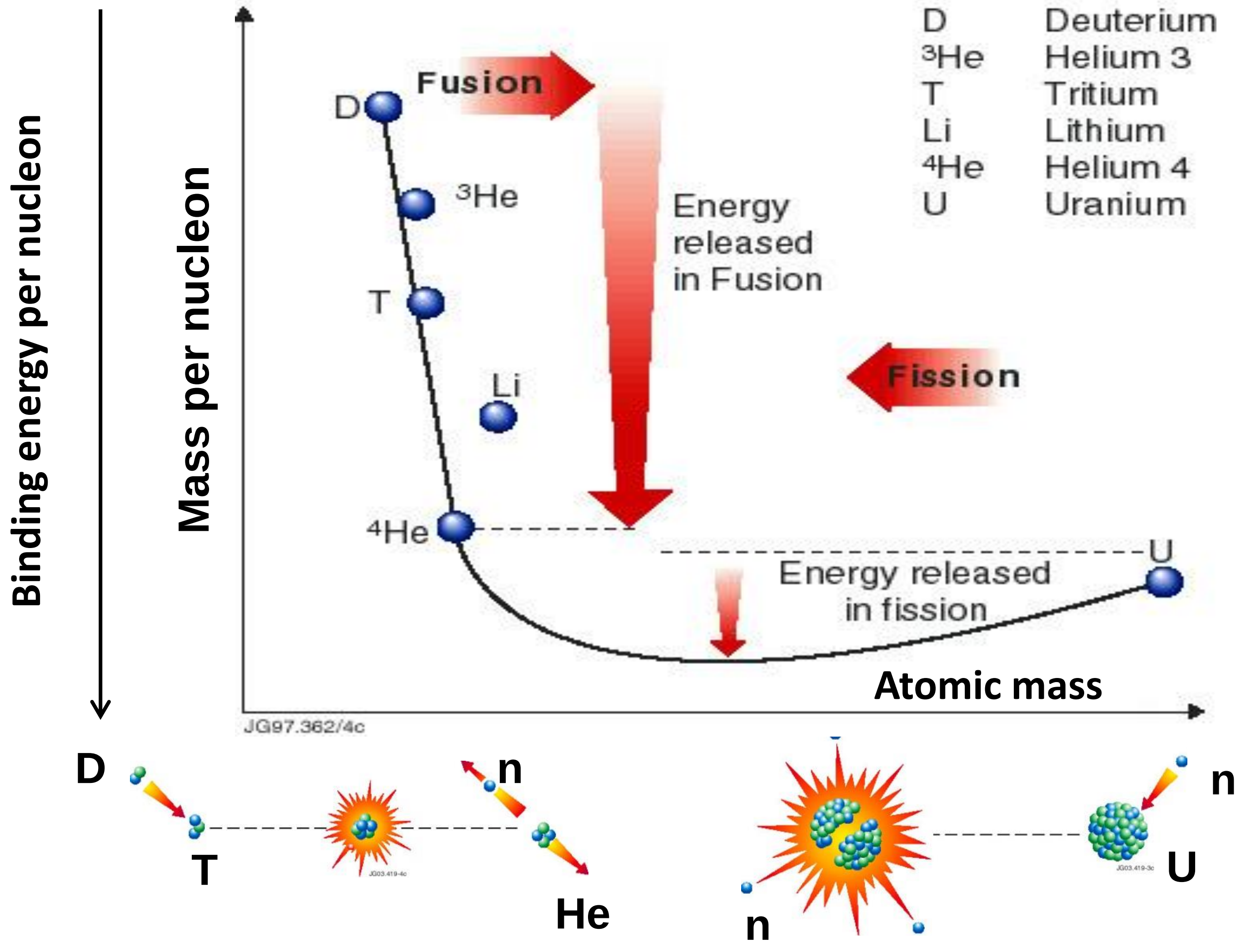
The physics of magnetised fusion plasmas

Xavier Garbet
IRFM
CEA Cadarache

Outline

- Introduction to fusion
- Physics of magnetised fusion plasmas – focus on:
  - instabilities
  - turbulent transport
  - control
- The ITER scientific programme.

Basic principle



Deuterium-tritium fusion reaction is the fastest path to a reactor

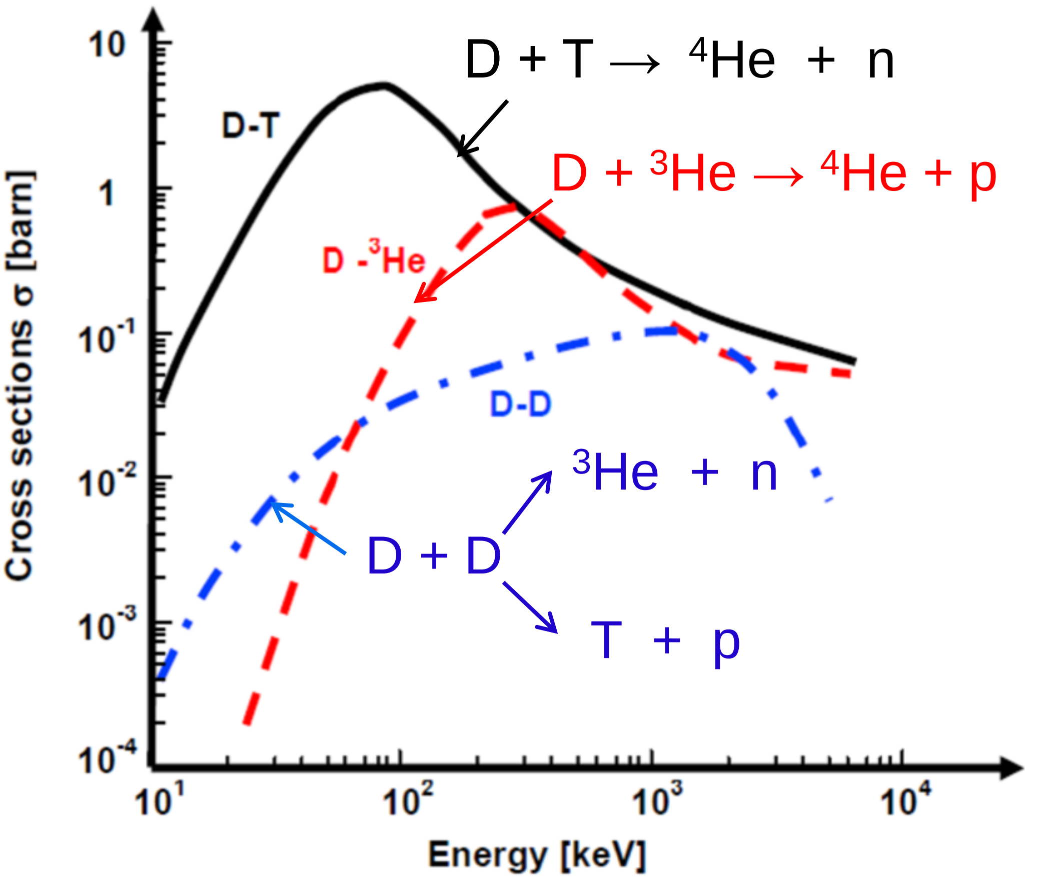
- Maximum DT cross-section E≈70keV.
- Beam-target fusion not efficient→ plasmas

$T \approx 20\text{keV}$

- Tritium generated with lithium:

$n + {}^6Li \rightarrow {}^4He + T$

+ neutron multiplier



Ignition is reached when the Lawson criterion is met

- Fusion in a plasma (ignition):

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

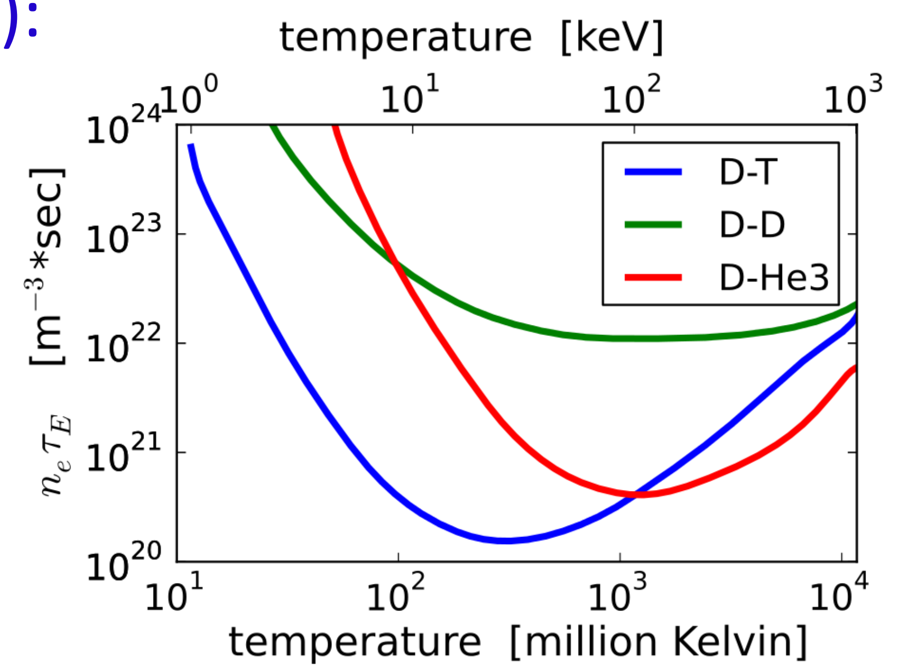
- Confinement time

$$\tau_E = \frac{energy\ content}{power\ losses}$$

- Magnetic confinement

  $T \approx 20\ keV \approx 200$ million K

  $n \approx 10^{20} m^{-3}$ $\tau_E \approx 5s$

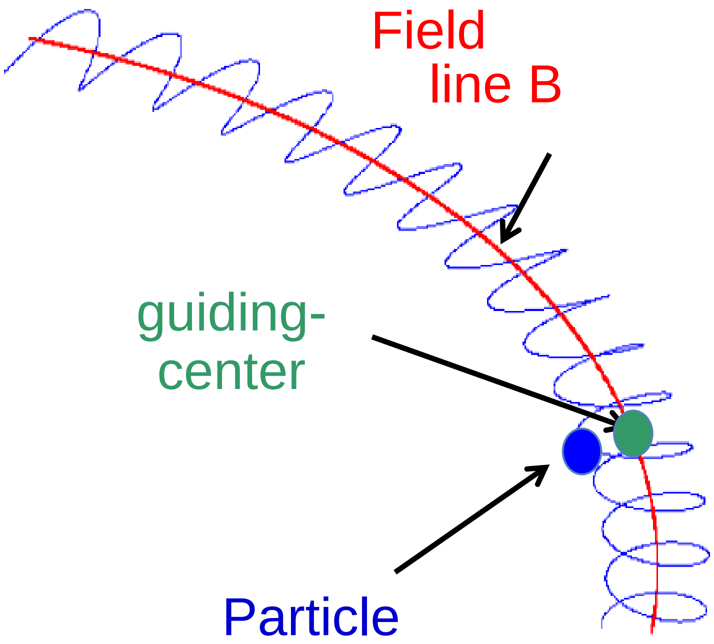


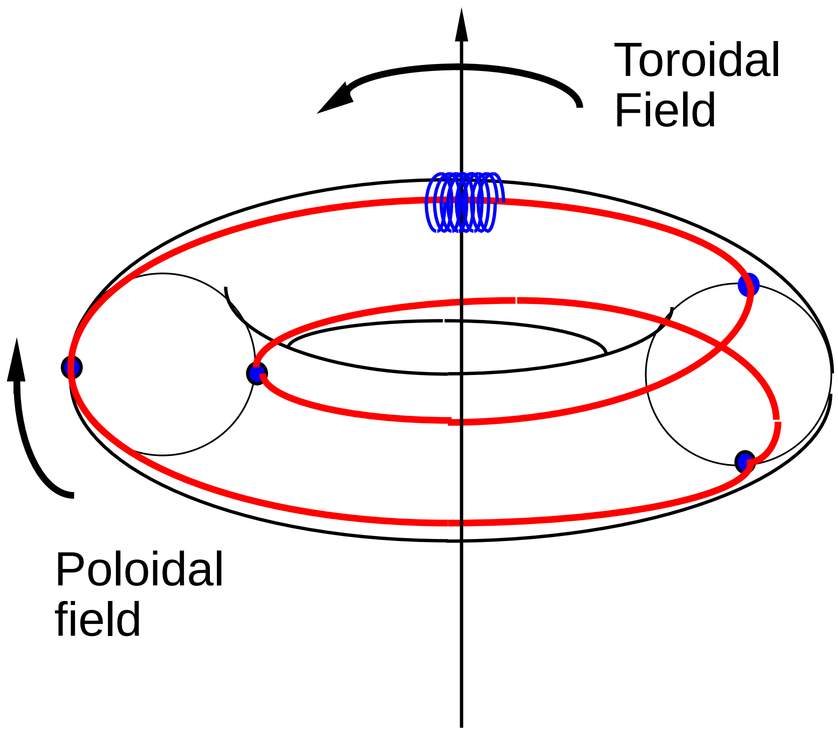
Minimum value of $n\tau_E$ vs T
https://en.wikipedia.org/wiki/Lawson_criterion

Charged particles stay close to field lines

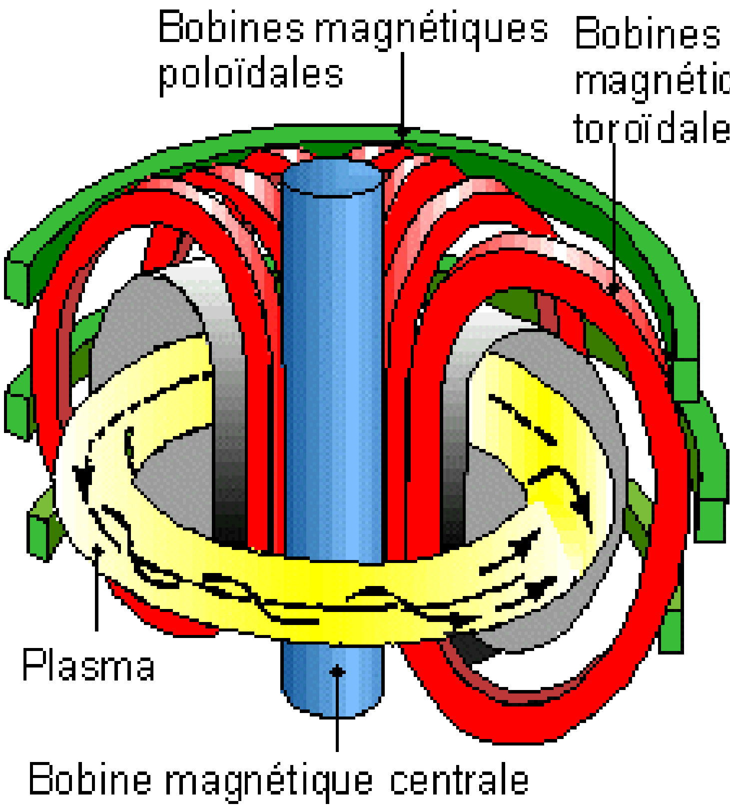
Regular magnetic field + bounded trajectories $\rightarrow$

field lines are winded on tori called magnetic surfaces

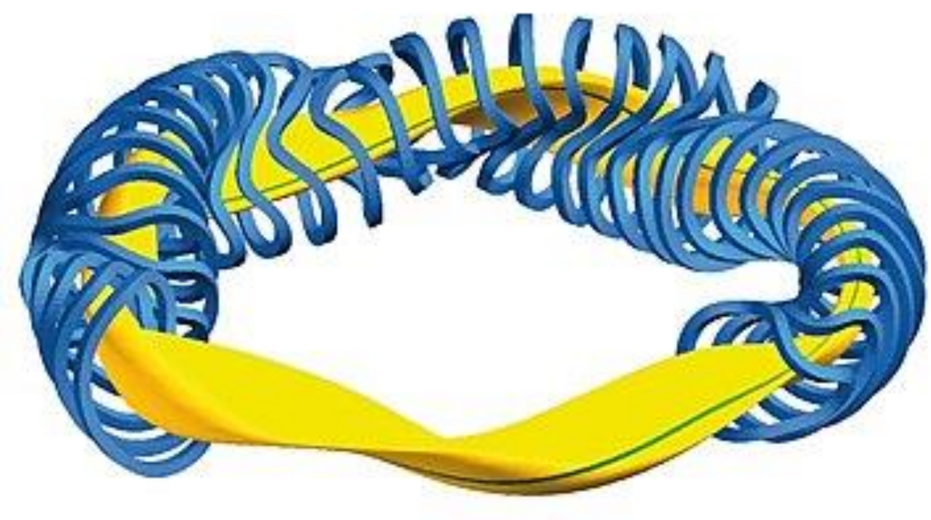




Helical fields can be produced in several ways



Tokamak

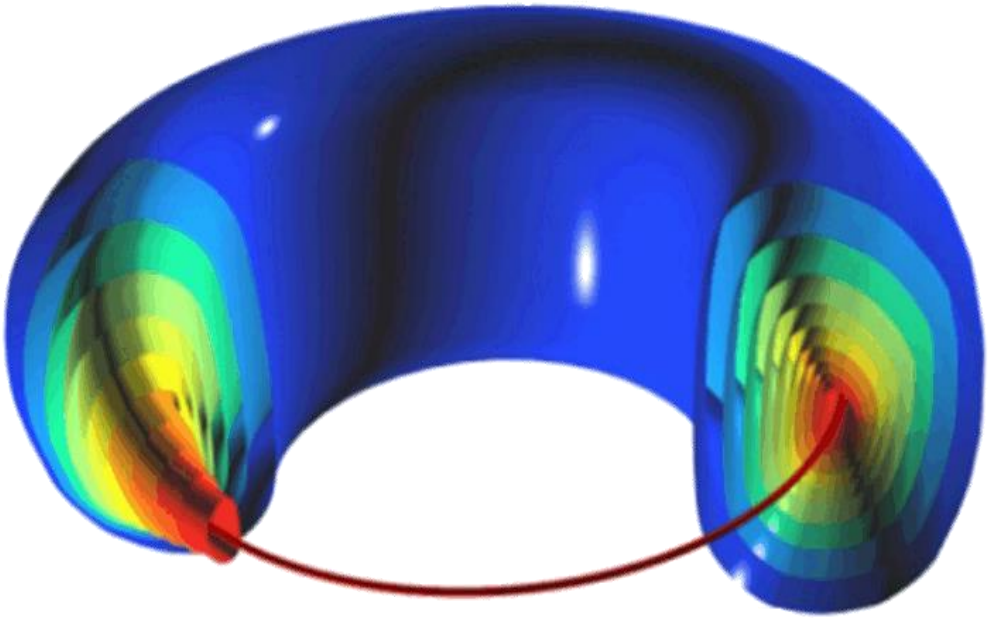


Stellarator W7X

Magnetic pressure balances kinetic pressure

- Magnetic surfaces are isobar, isothermal.

- Pressure gradient → plasma expands → balanced by Lorentz force



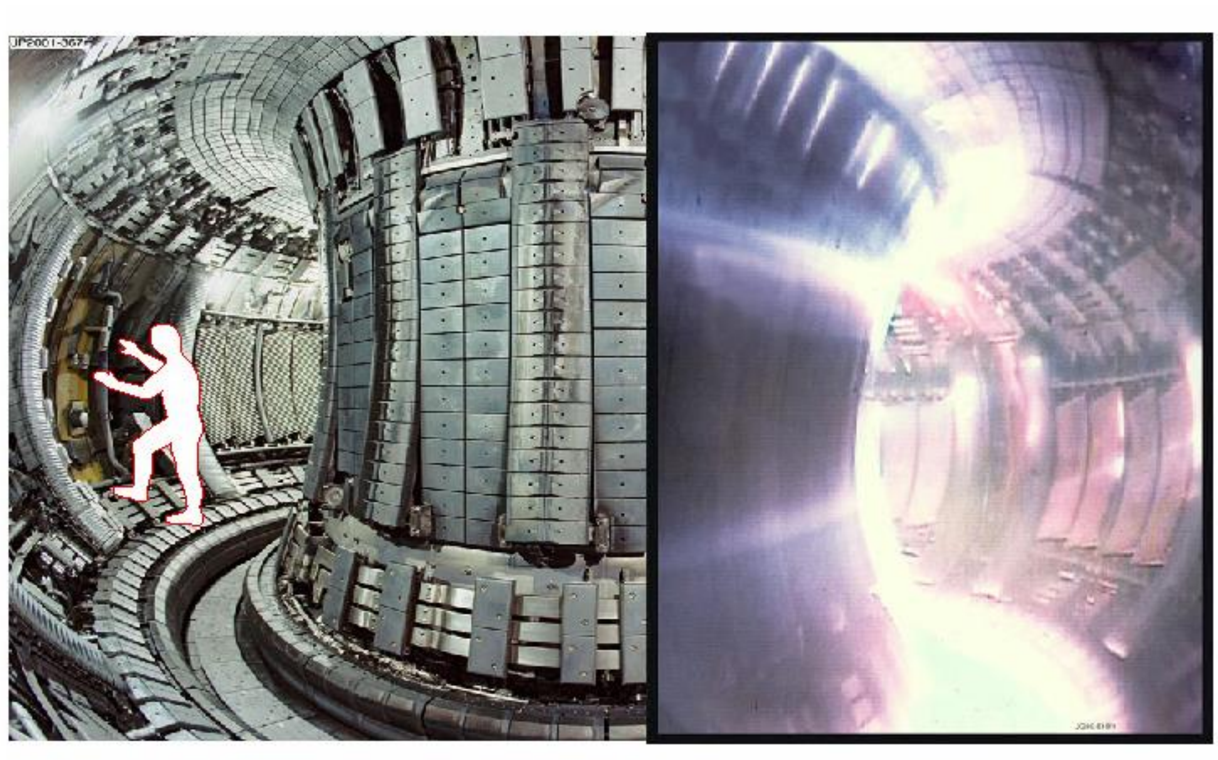
Nested magnetic surfaces

Key ingredients of the physics of magnetised fusion plasmas

The four pillars of fusion plasma physics

- Stability ☑.
- Confinement ☑.
- Heating and fuelling ☒.
- Plasma-wall interaction ☒.

JET



The operational domain is set by large scale instabilities

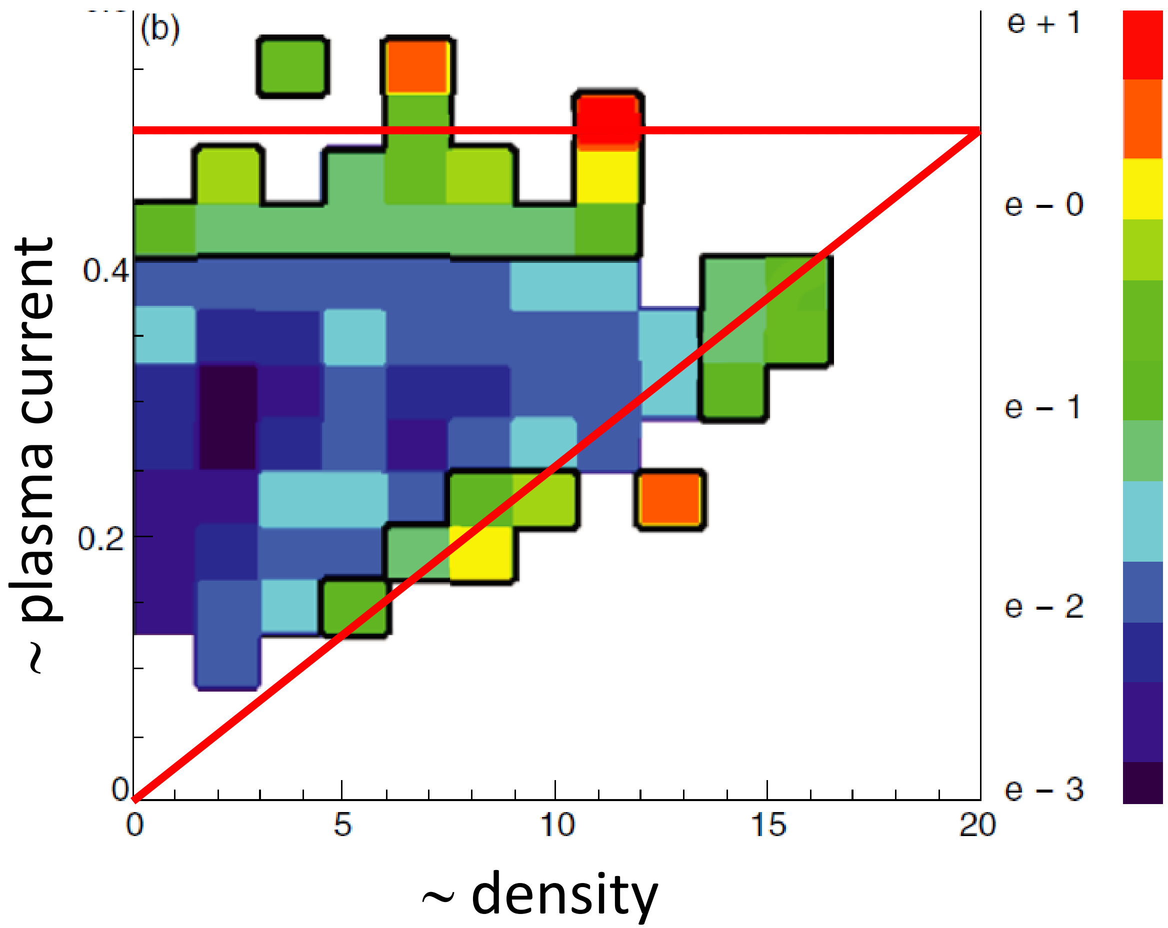
MHD instabilities:

- pressure
- current
- radiative losses

Fate of an instability:

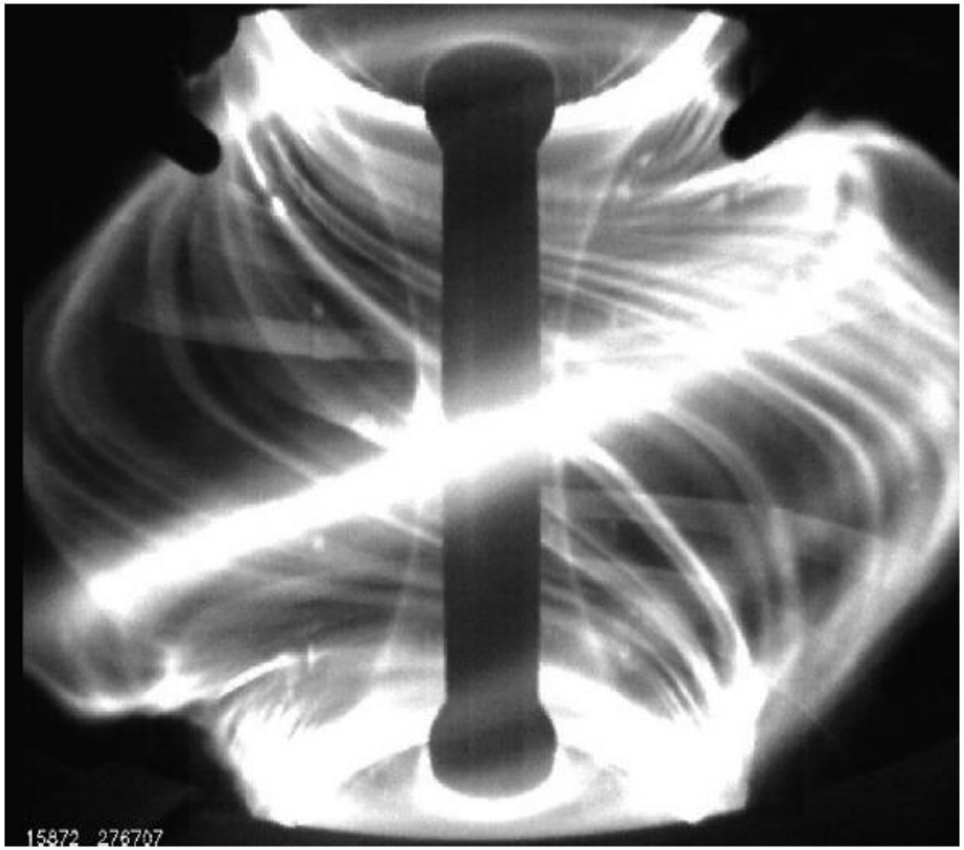
- disruption
- oscillations
- steady-state

De Vries 09 - disruptivity JET



Relaxation oscillations are controlled thanks to helical magnetic fields

- Pressure or current exceeds instability threshold → fast relaxation → recovery.
- Bursts of particle and heat fluxes.

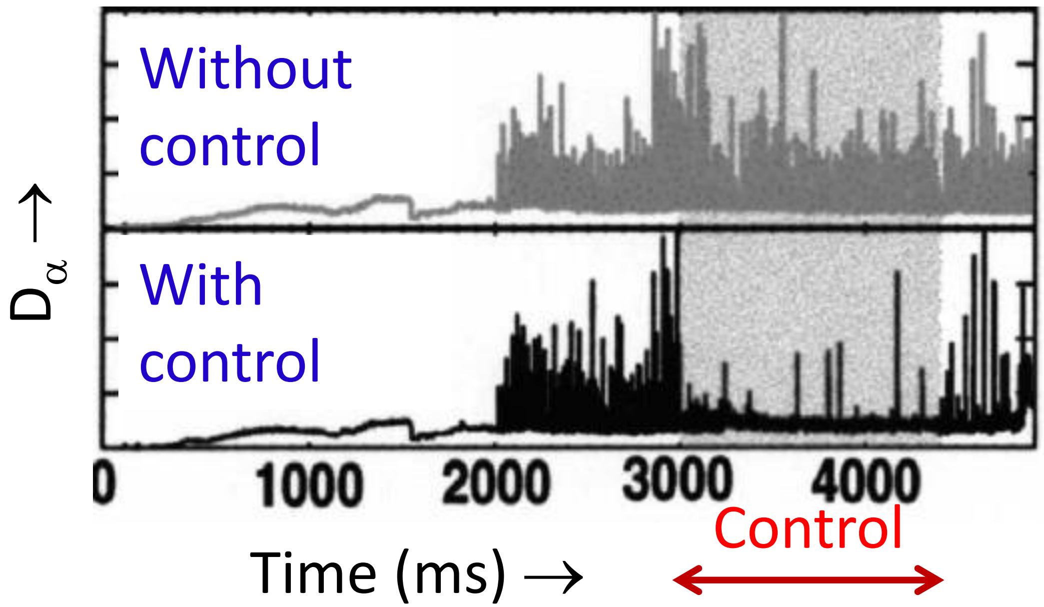


A. Kirk, MAST, CCFE

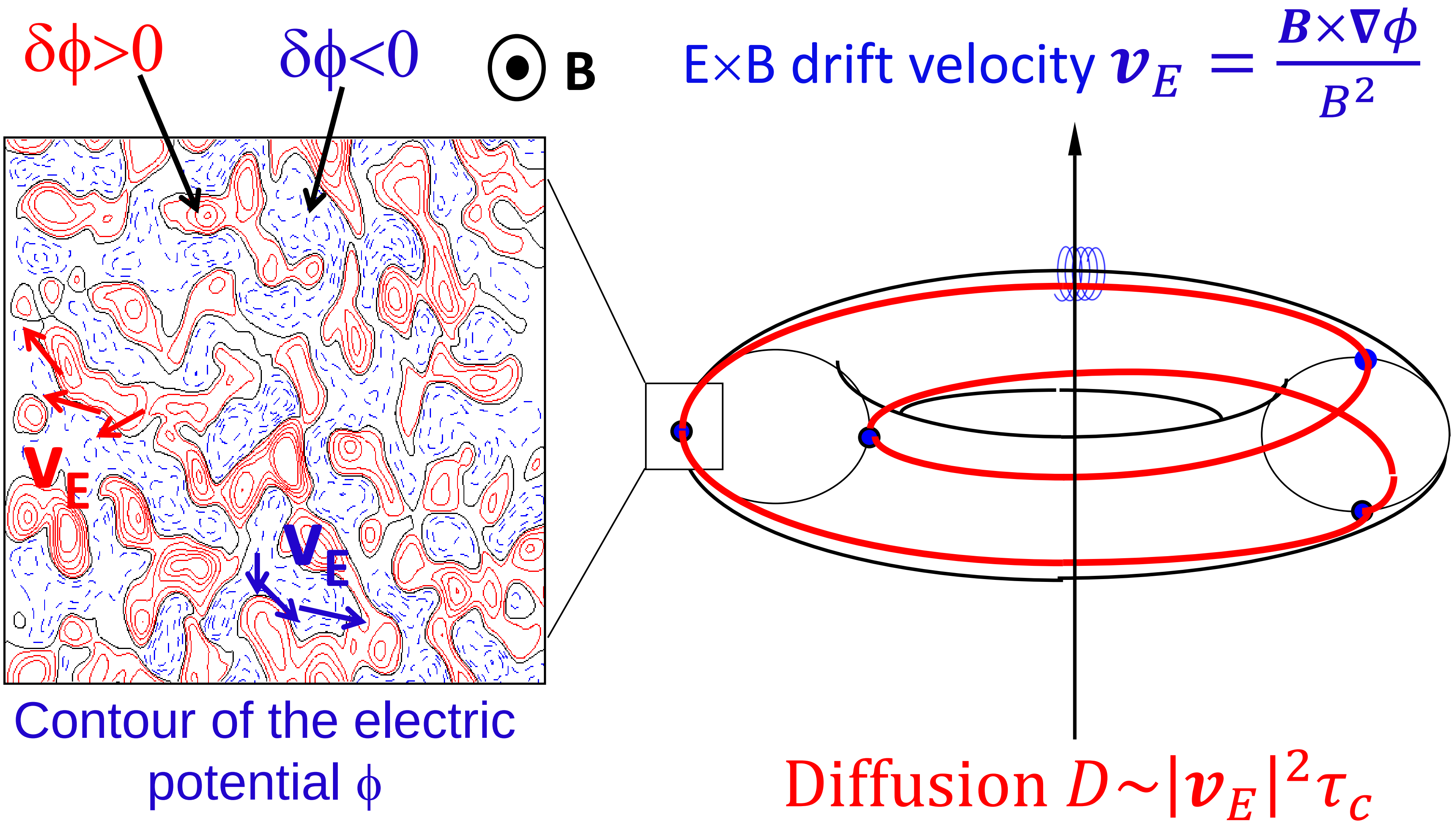
Relaxation oscillations are controlled thanks to helical magnetic fields

- Pressure or current exceeds instability threshold → fast relaxation → recovery.
- Bursts of particle and heat fluxes.

Evans DIII-D 2004



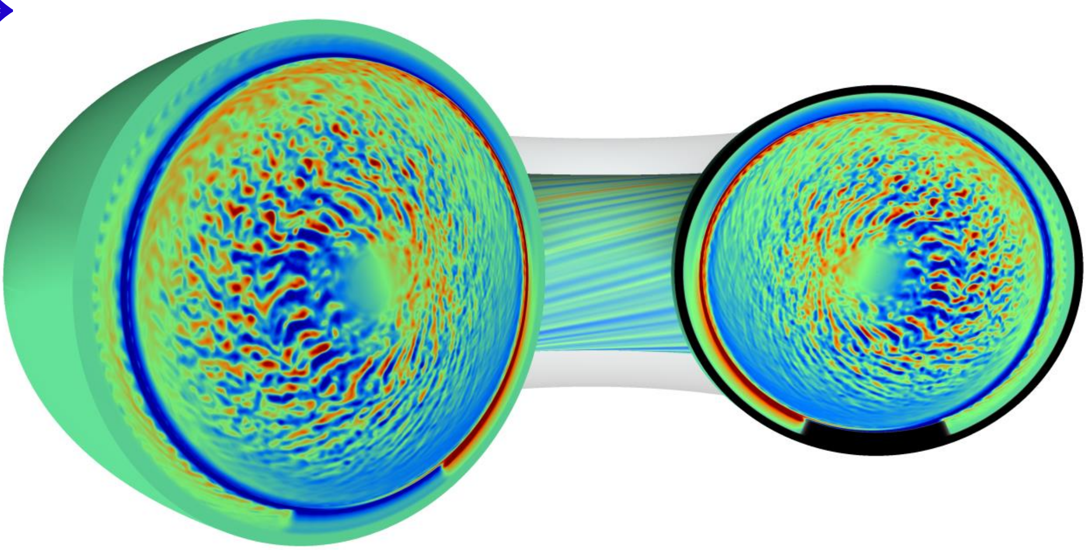
Fluctuations of the electric field drive turbulent transport



Turbulent transport rules the confinement time

- Micro-instabilities → fluctuations.
- Convective cells → turbulent diffusion.
- Confinement time ~

$$\tau_E \sim \frac{a^2}{D} \sim \frac{size^2}{diffusion}$$



Grandgirard & Sarazin code GYSELA

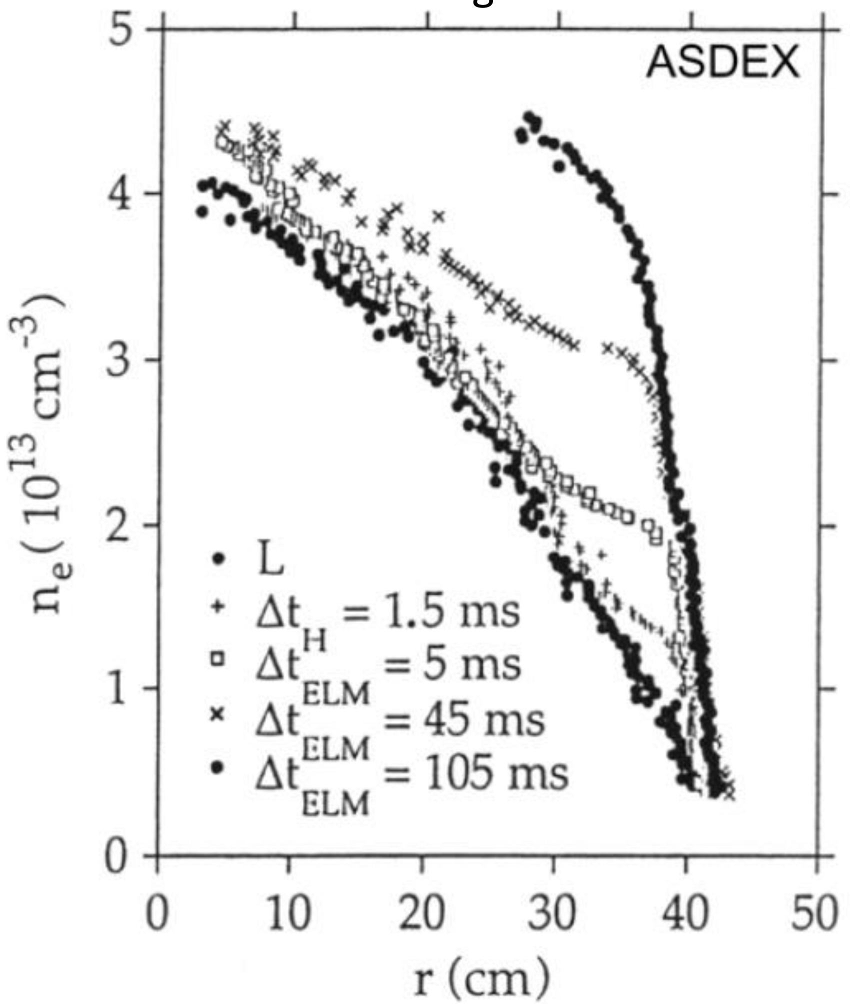
Confinement is improved above a power threshold: LH transition

- Discovered on the Asdex tokamak (1982).
- Confinement time improves by a factor ~ 2.
- Gradients increase in a layer. Fick's law

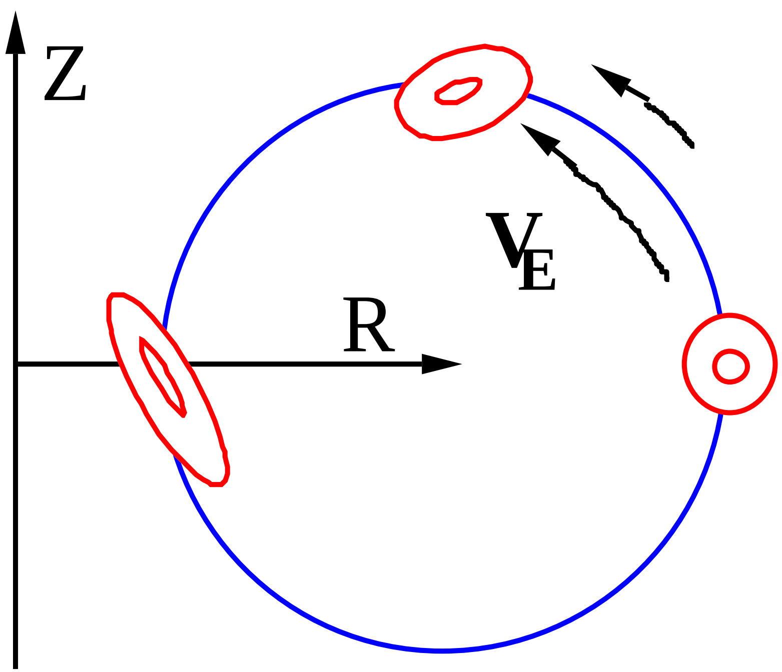
$$\Gamma = -D\nabla n = cte$$

→ transport barrier

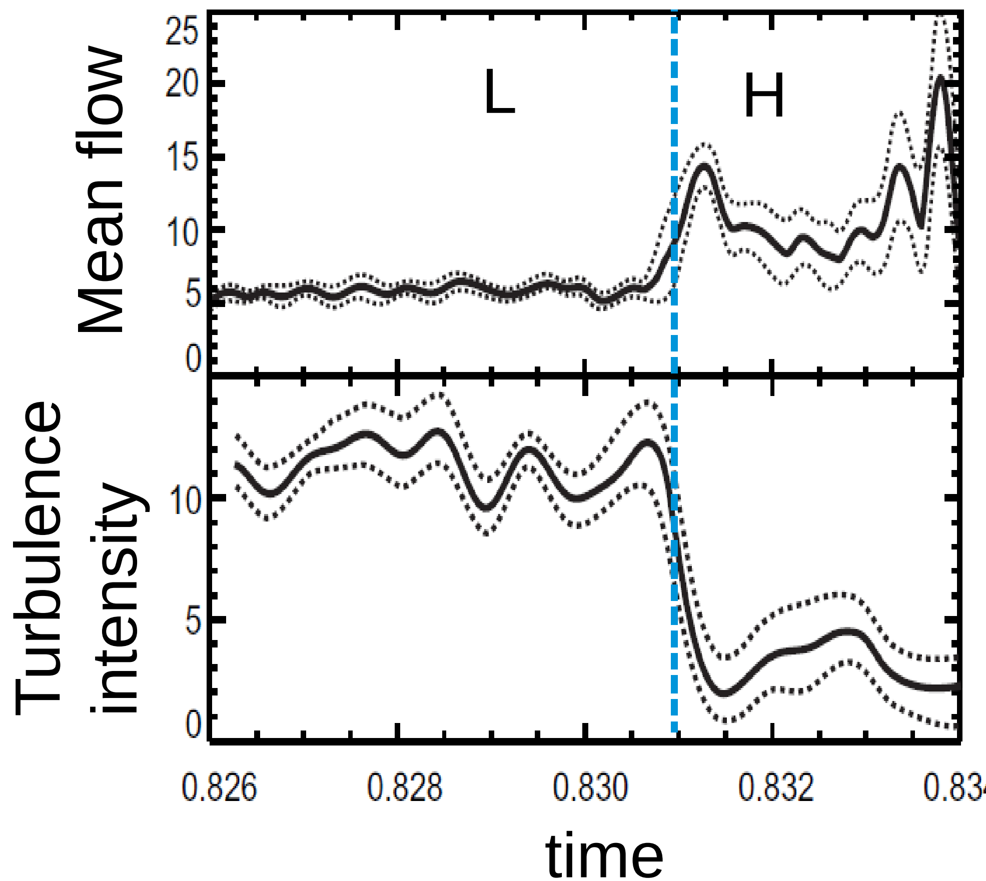
F. Wagner ASDEX 1991



LH transition is due to vortex shearing



Cziegler C-Mod 2014



The ITER scientific programme

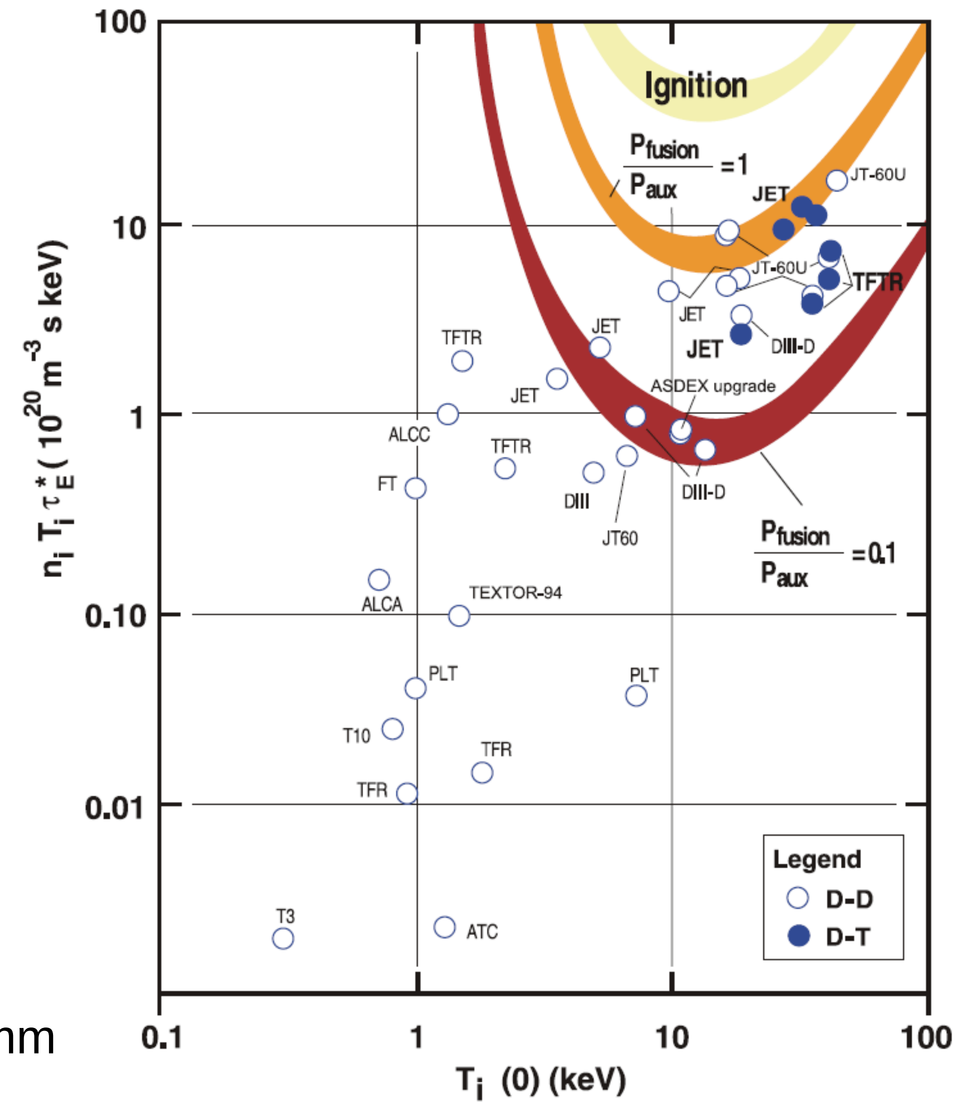
Break even has been reached transiently on JET and JT-60SU

- JET (EU) , JT-60SU (Japan) have achieved transiently

$P_{fusion} \approx P_{aux}$

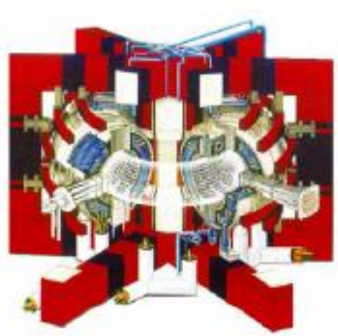
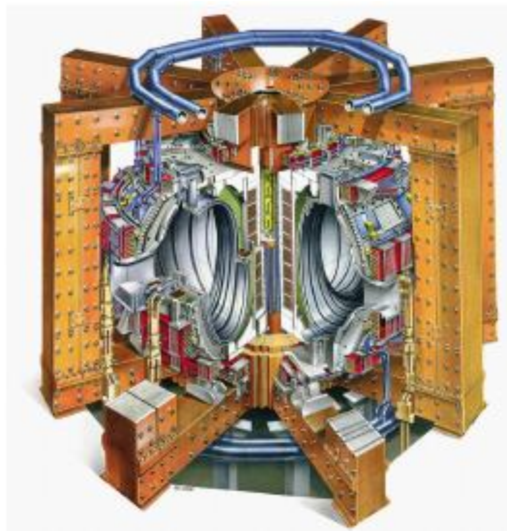
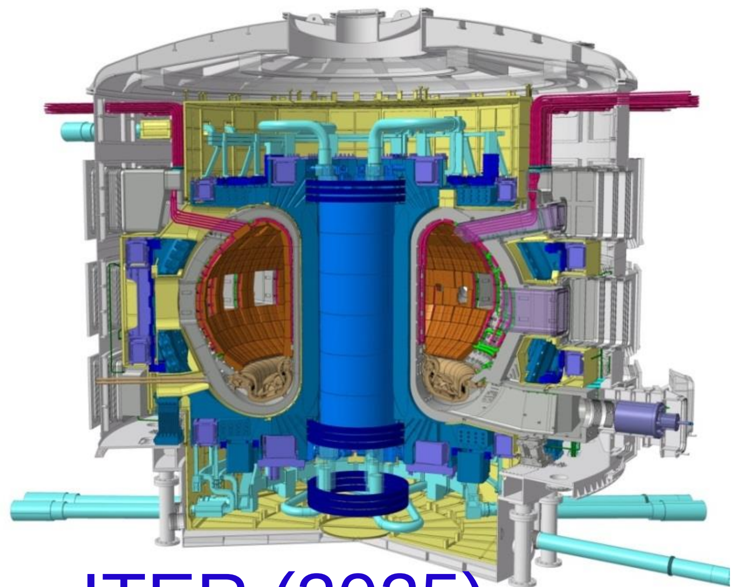
$$\rightarrow Q = \frac{P_{fusion}}{P_{aux}} \simeq 1$$

- WEST (France) ≈ 6mn long discharge , EAST(China) ≈ 2mn



Unterberg & Samm

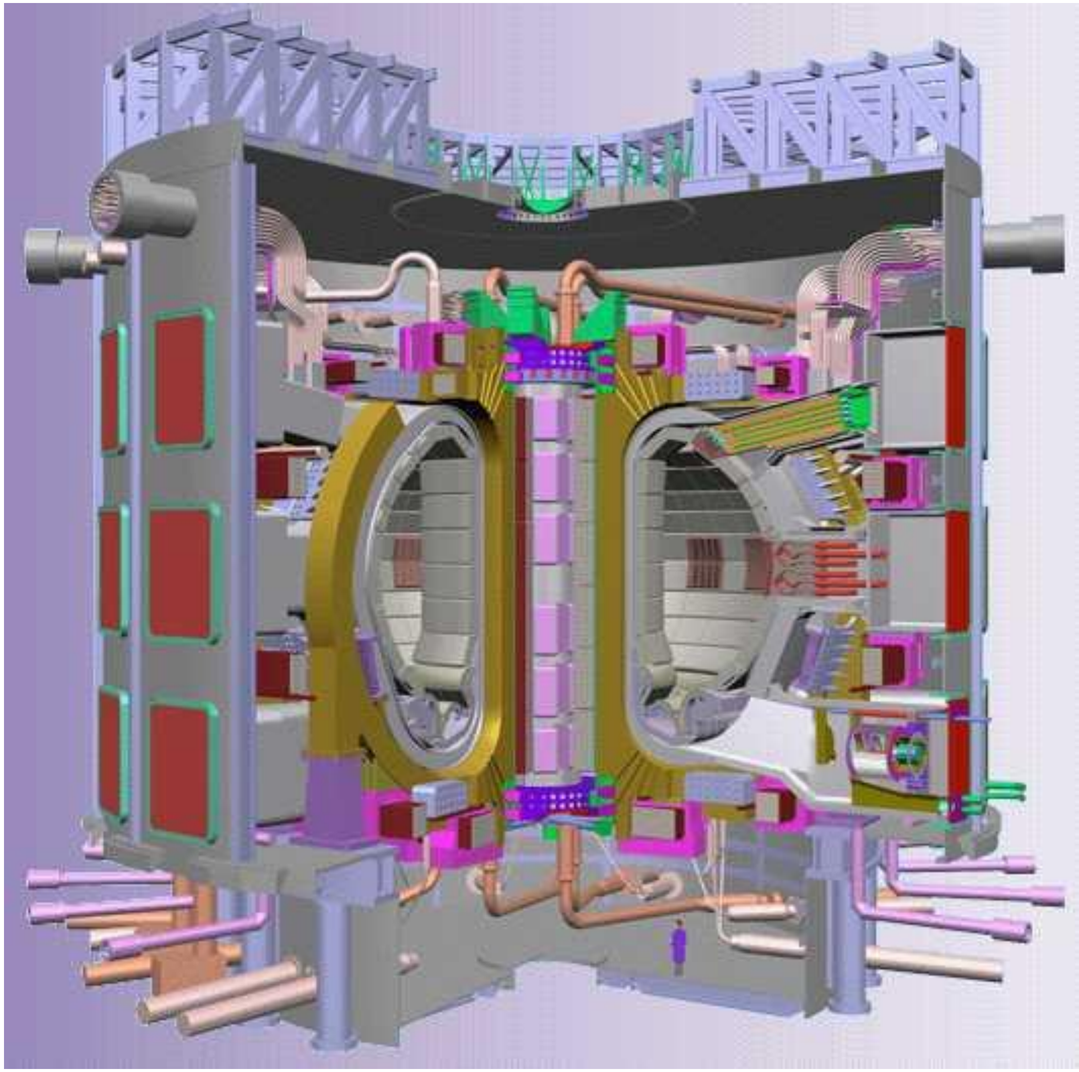
Bigger for a higher yield …

WEST	JET	ITER (2025)
25 m^3	80 m^3	830 m^3
	~ 16 MW	~ 500 MW
Q<1	Q ~ 1	Q ~ 10

ITER will be the largest tokamak ever built

R (m)	6.2
a (m)	2
V_P (m^3)	830
I_P (MA)	15 (17)
B_t (T)	5.3
δ,κ	0.5, 1.85
P_{aux} (MW)	75-110
P_{fus} (MW)	500
Q (P_{fus}/P_{in})	10
β_T, β_P	2.5%, 0.7



The scientific programme of ITER: highlights

- Significant α heating: plasma self-organisation.
- MHD: active control of instabilities – effect of α particles.
- Confinement : control of turbulent transport-improved confinement.
- Particle and heat exhaust in steady burning plasmas.
- Prototype of tritigen blankets.

Work site – top view

June

2019

Conclusion and perspectives

- Interest in fusion: fuel, safety and waste handling.
- On short term: preparation of the ITER scientific programme – modelling and experiments on available tokamaks.
- Longer term: exploitation of ITER, structure materials under high neutron fluence, plasma facing components, high field superconductors.