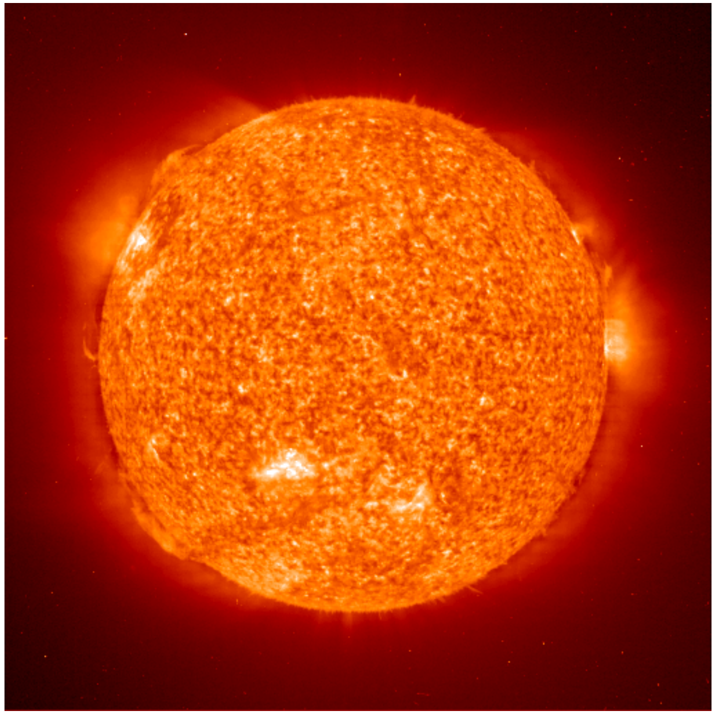
Introduction to Fusion Physics



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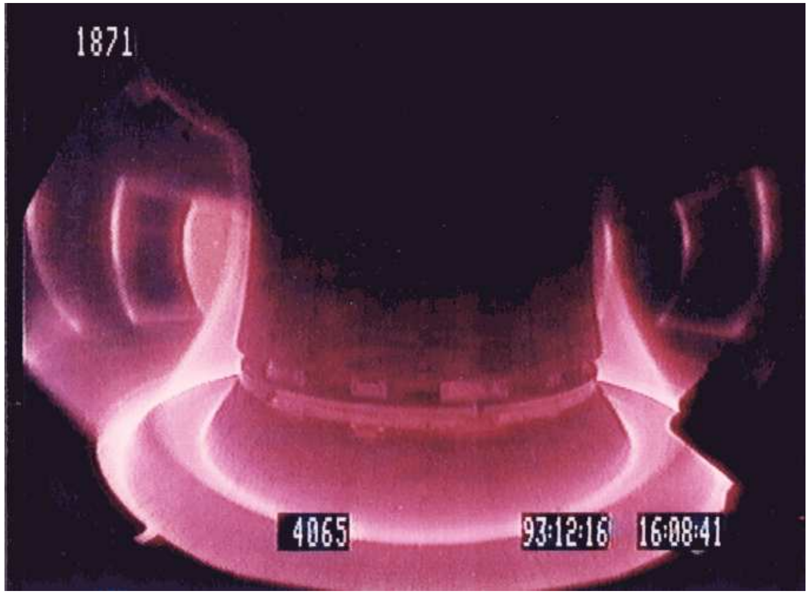
85748 Garching

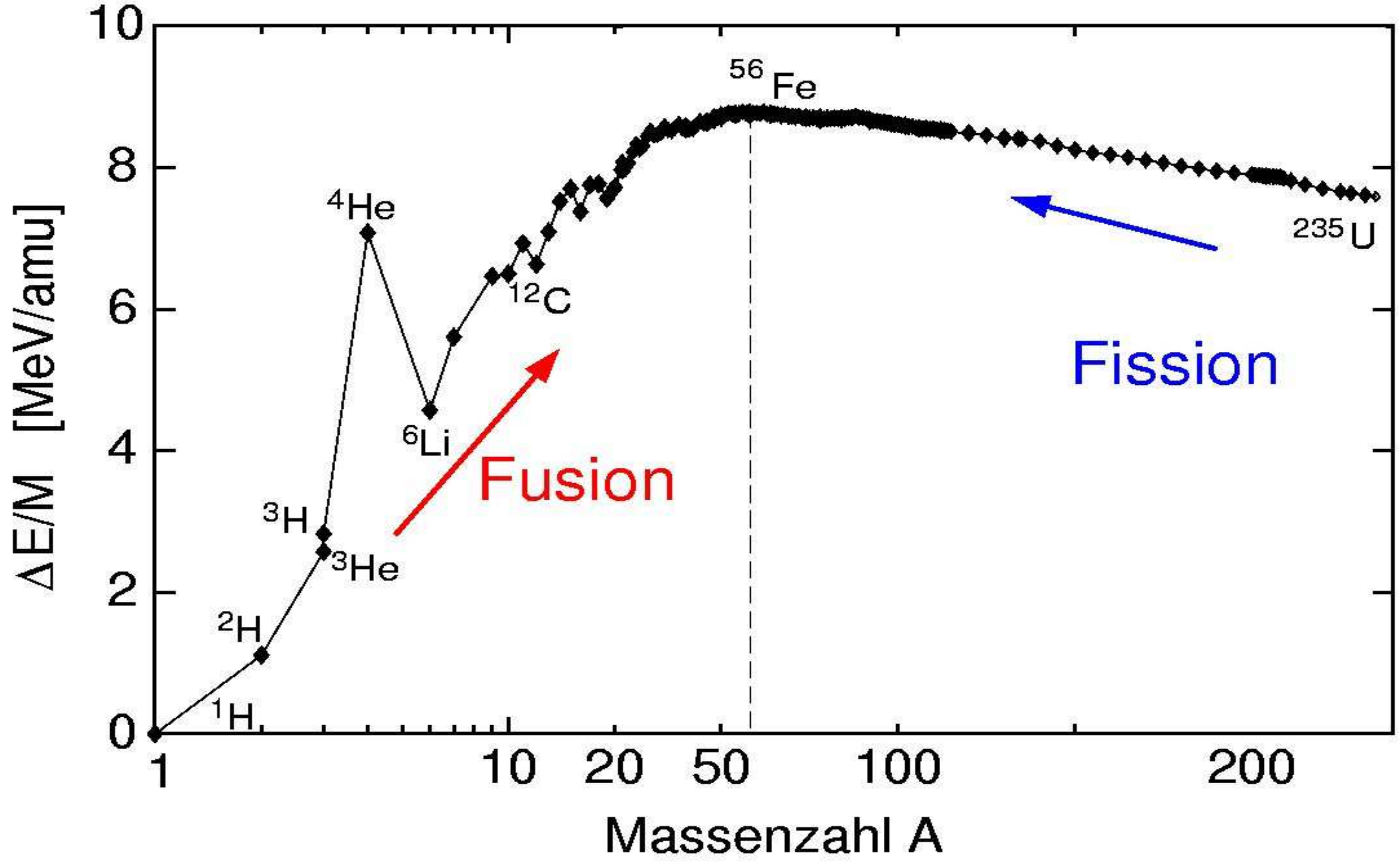


DPG Advanced Physics School
‚The Physics of ITER'
Bad Honnef, 22.09.2014

Energy from nuclear fusion

Reduction of surface tension – energy gain

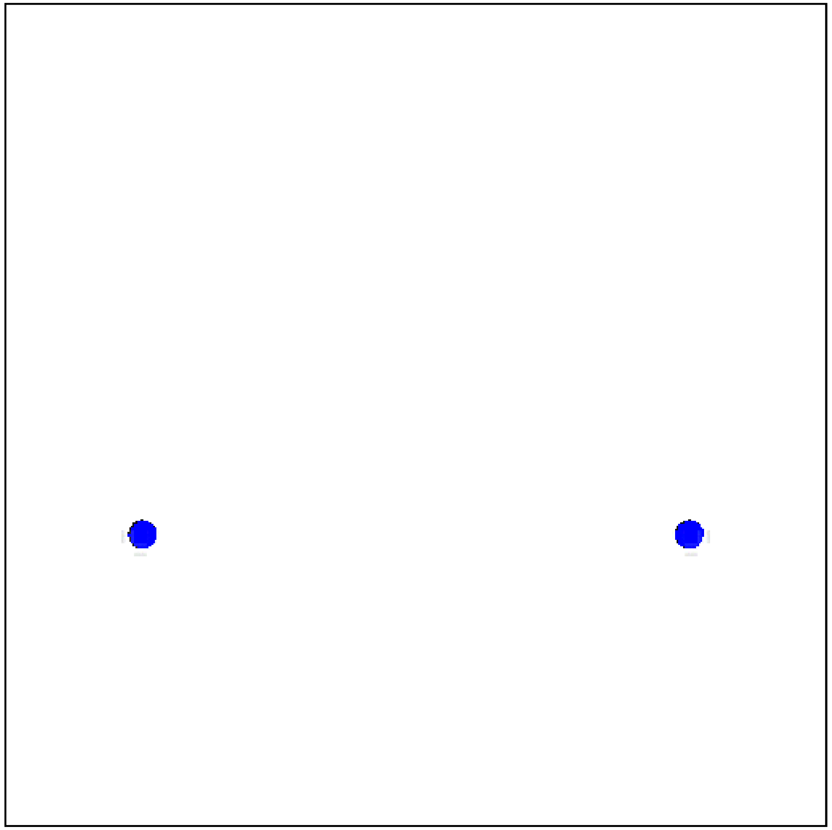
Energy from nuclear fusion



With increasing number of nuclei, electric repulsion starts to dominate

- binding energy has a maximum at A = 56 (iron)

Fusion needs close encounter of nuclei

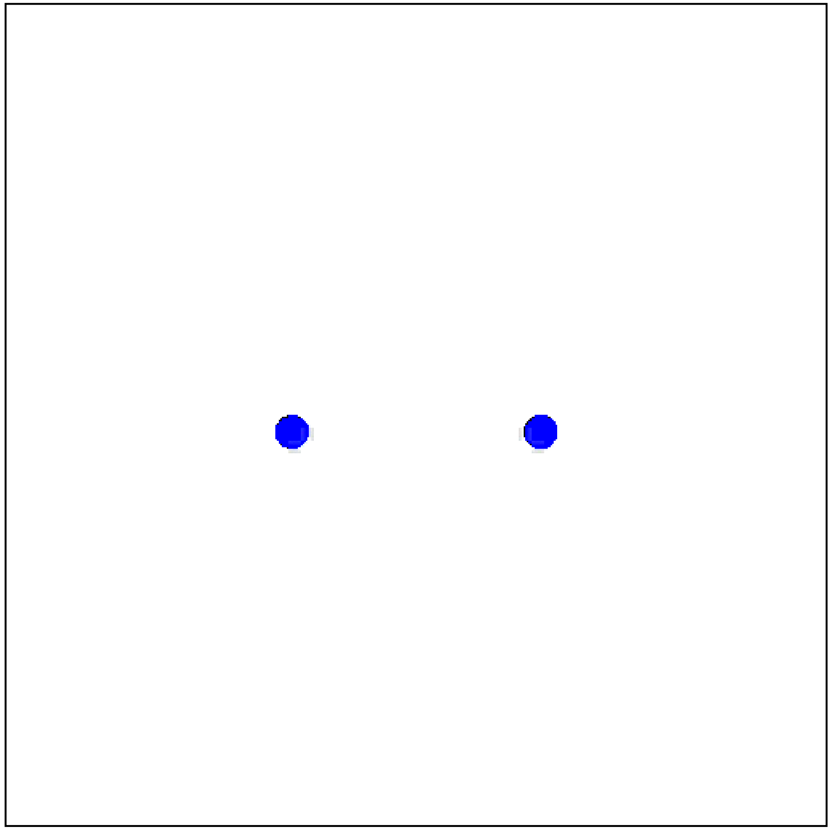


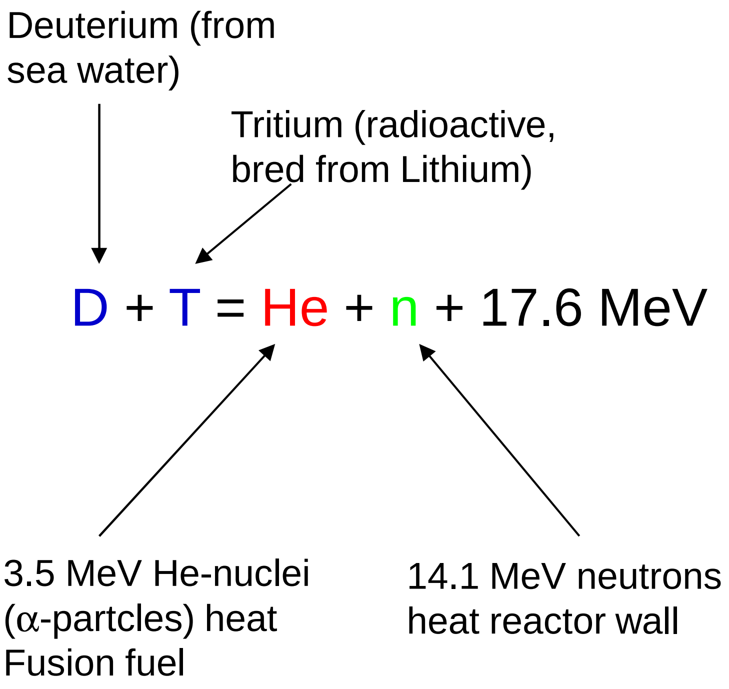
D + T = D' + T'

Particles have to ‚touch‘ (10^{-15} m) in order to feel attractive strong force

- repulsive coulomb energy at that point around 400 keV
- due to quantum mechanics (tunneling), minimum energy is several 10 keV

Fusion needs close encounter of nuclei





Deuterium (from sea water)

Tritium (radioactive, bred from Lithium)

$$D + T = He + n + 17.6\ \mathrm{MeV}$$

3.5 MeV He-nuclei (α-partcles) heat Fusion fuel

14.1 MeV neutrons heat reactor wall

Particles have to ‚touch‘ (10^{-15} m) in order to feel attractive strong force

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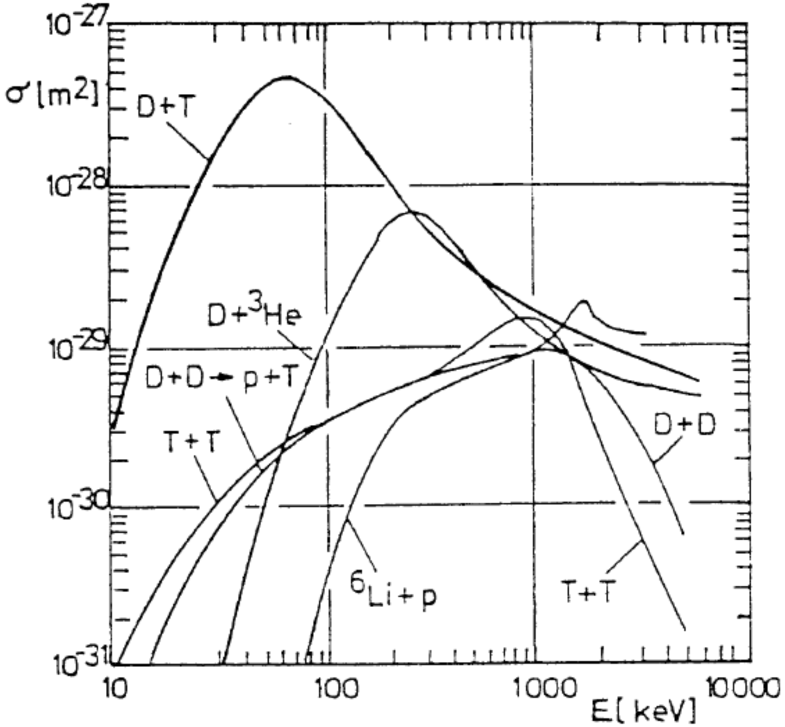
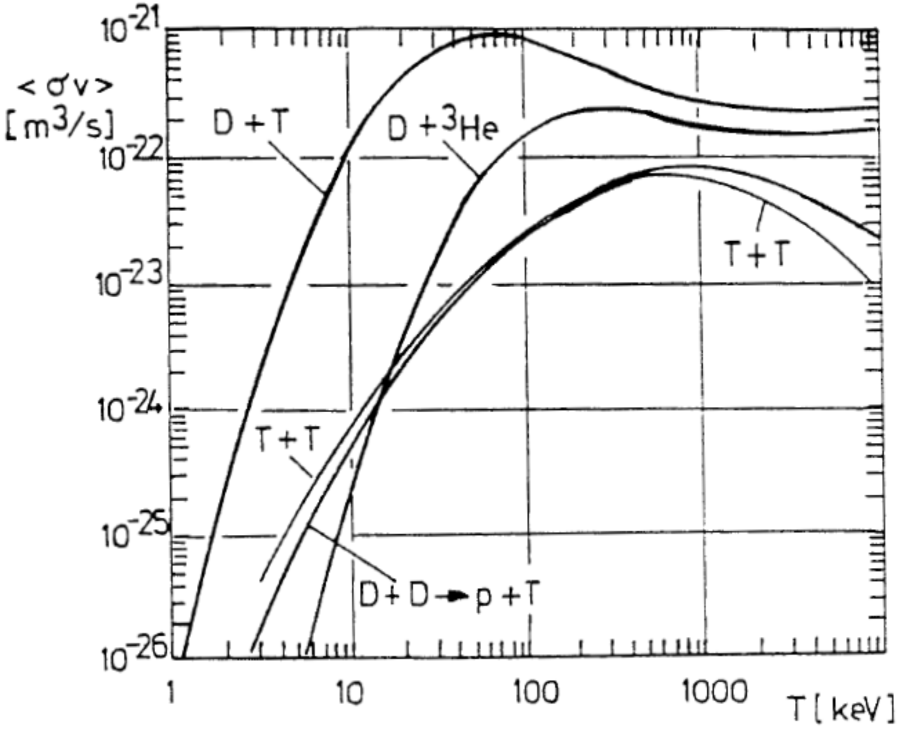
D-T reaction most favorable for energy gain





Highest cross section with maximum at lowest energy

At these energies, elastic collision still 100 x more likely than fusion

- crossed beam configurations would not be efficient enough
- have to confine the particles to allow many collisions – thermal plasma

Reactor energetics: the ‚Lawson‘ criterion for $n\tau_E$

α-heating compensates losses:

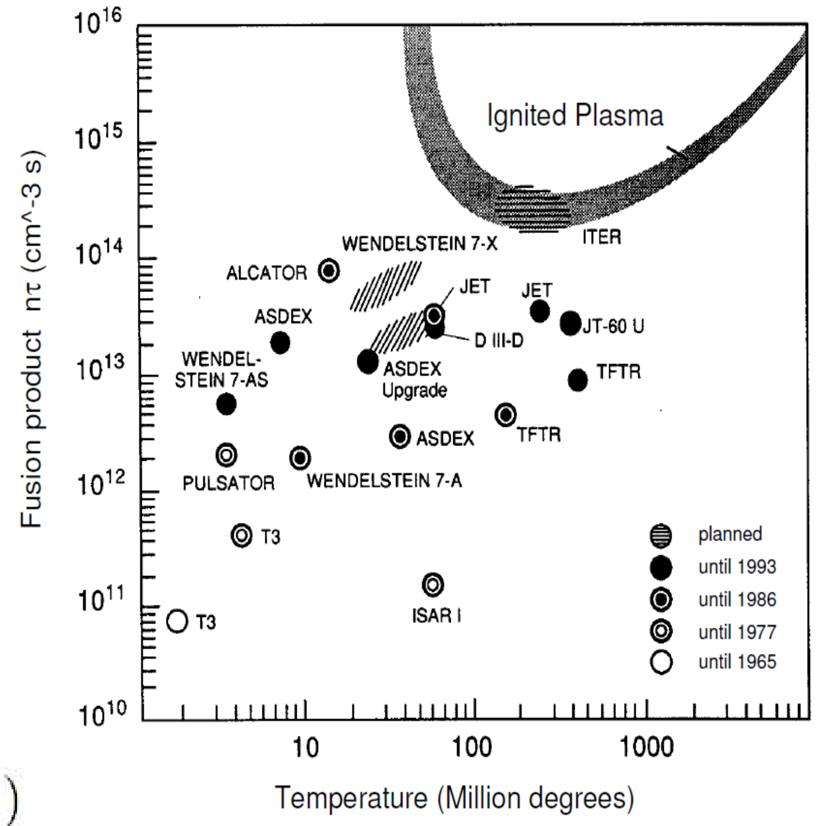
- radiative losses (Bremsstrahlung)
- heat conduction and convection

$$\frac{n_e^2}{4}\langle\sigma u\rangle E_\alpha > c_{Br} n_e^2 Z_{eff}\sqrt{k_B T} + \frac{3 n_e k_B T}{\tau_E}$$

$\tau_E = W_{plasma}/P_{loss}$ **(‘energy confinement time’)**

leads to

$$n_e\tau_E > \frac{3k_B T}{\langle\sigma u\rangle E_\alpha/4 - c_{Br} Z_{eff}\sqrt{k_B T}} = f(T)$$



which has a minimum for $n\tau_E = 2 \times 10^{20}\ \mathrm{m}^{-3}\ \mathrm{s}$ at $T = 20$ keV

Note: can be fulfilled quite differently (magnetic versus inertial fusion)

Figure of merit for fusion performance $nT\tau$

Power P_{loss} needed to sustain plasma

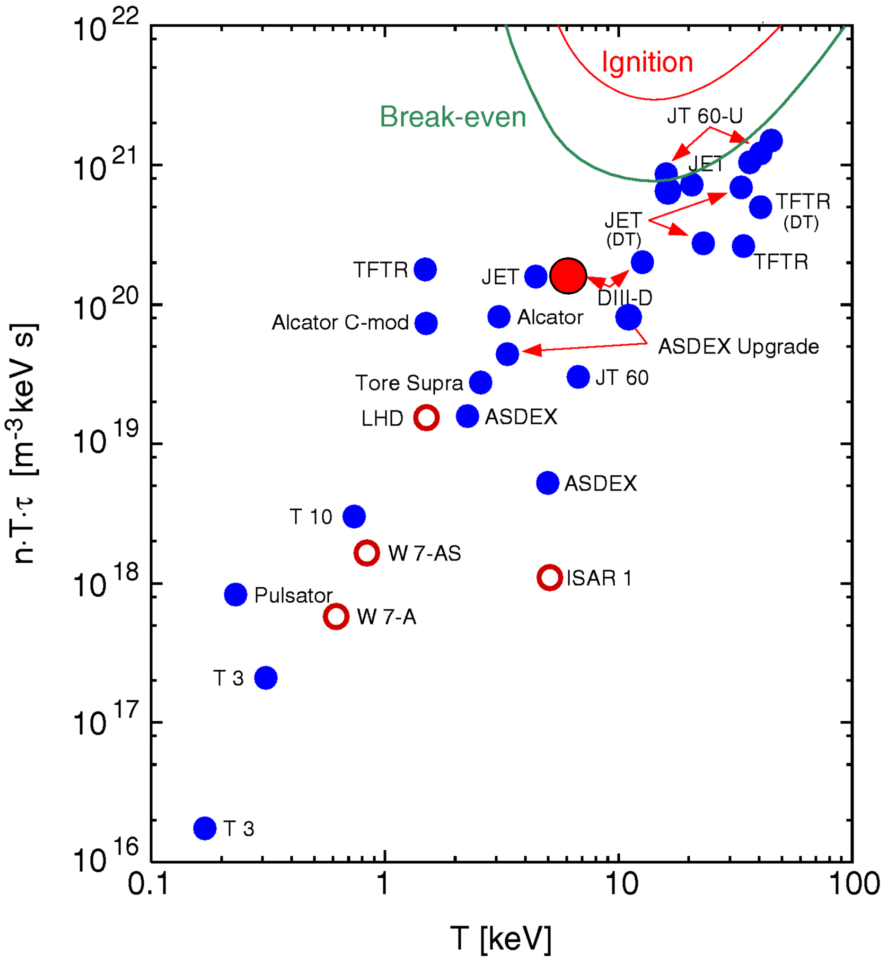
- determined by thermal insulation: $\tau_E = W_{plasma}/P_{loss}$ **('energy confinement time')**

Fusion power increases with W_{plasma}

- $P_{fus} \sim n_D n_T \langle\sigma v\rangle \sim n_e^2 T^2 \sim W_{plasma}^2$

Present day experiments: P_{loss} compensated by external heating

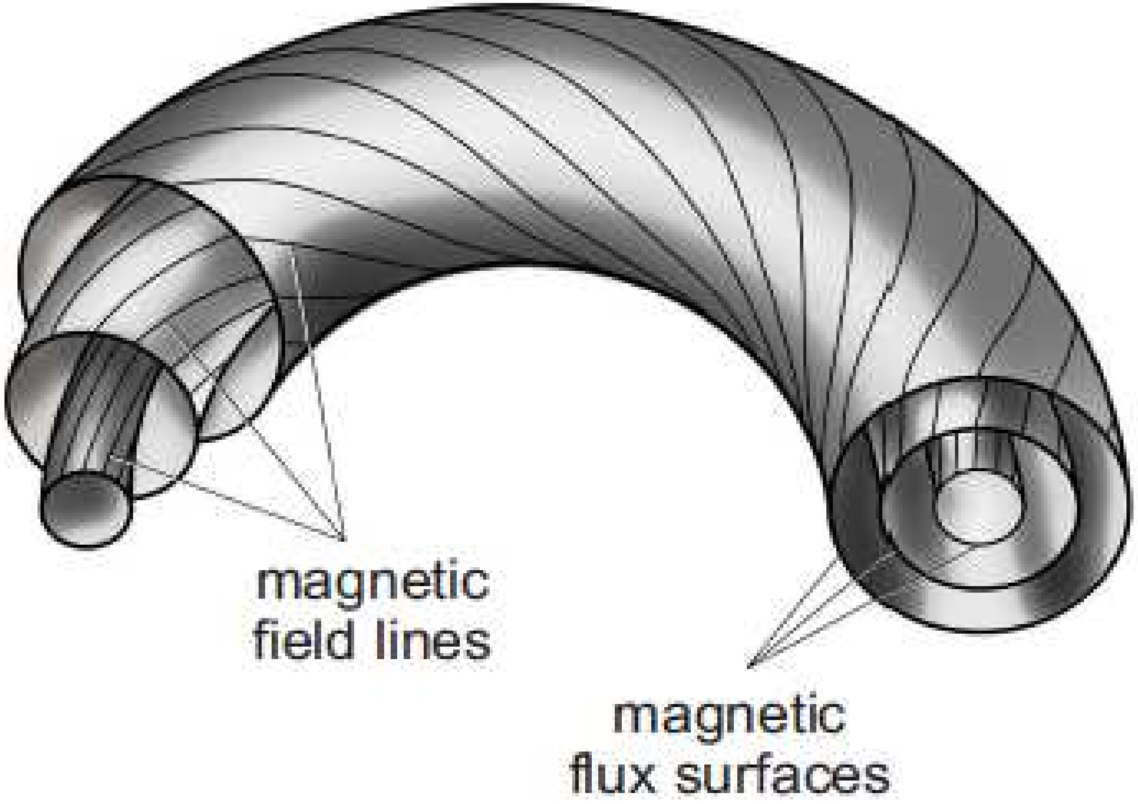
- $Q = P_{fus}/P_{ext} \approx P_{fus}/P_{loss} \sim nT\tau_E$



Reactor: P_{loss} compensated by α-(self)heating

- $Q = P_{fus}/P_{ext} = P_{fus}/(P_{loss}-P_\alpha) \to \infty$ (ignited plasma)

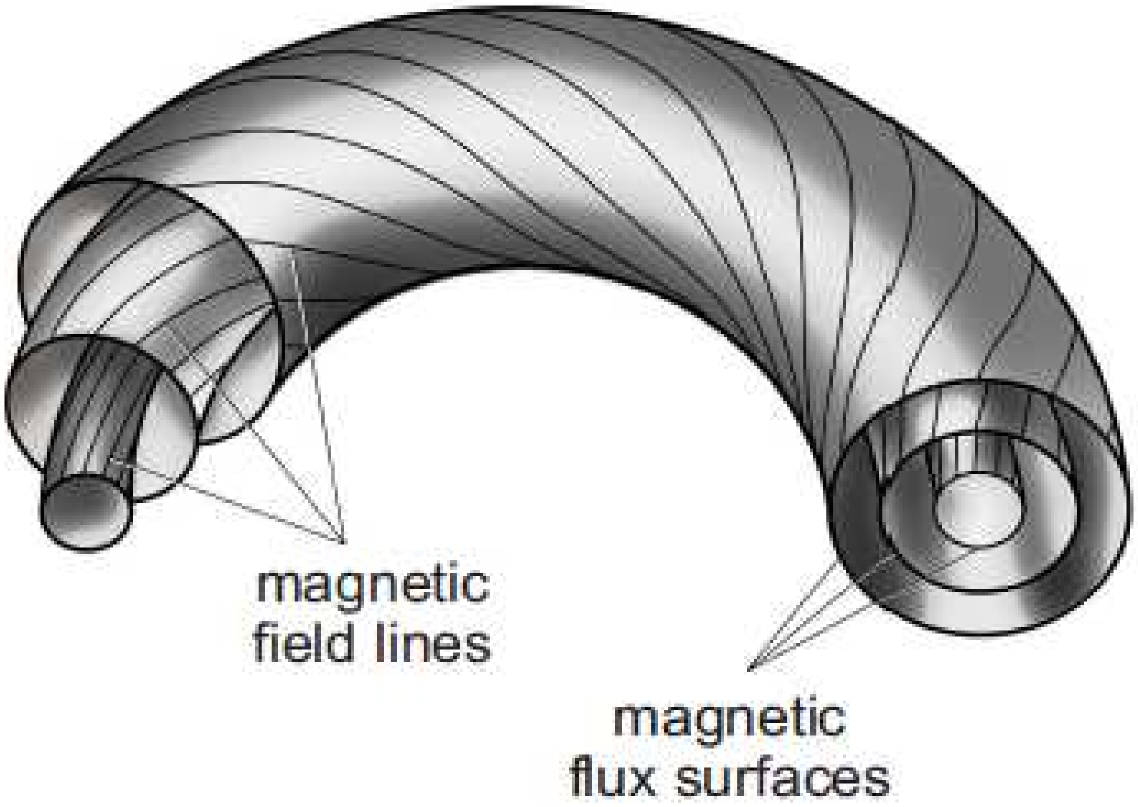
Plasma can be confined in a magnetic field



Toroidal systems avoid end losses along magnetic field

⇒ Need to twist field lines helically to compensate particle drifts

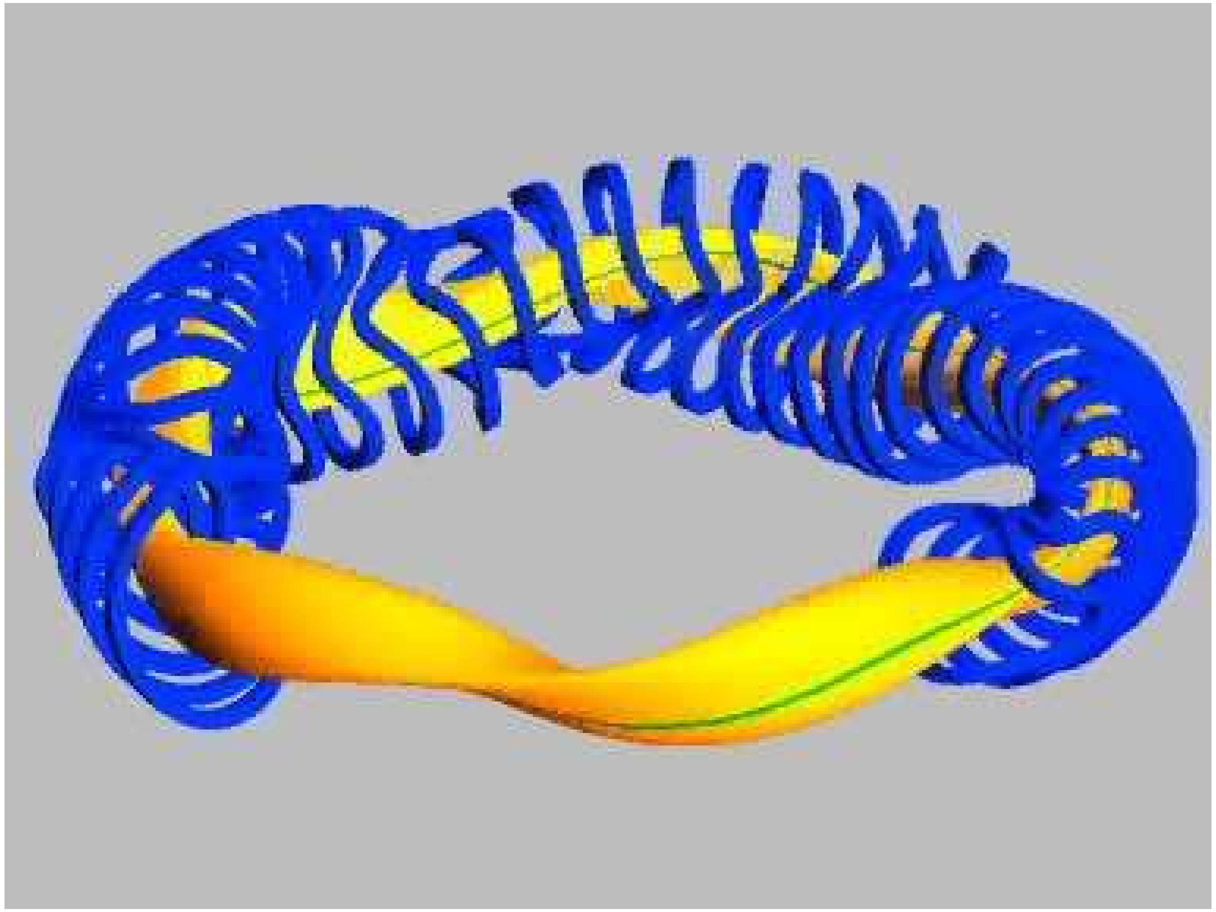
Field line geometry described by safety factor q



$$q = \frac{\text{number of toroidal windings}}{\text{number of poloidal windings}}$$

Plasma can be confined in a magnetic field

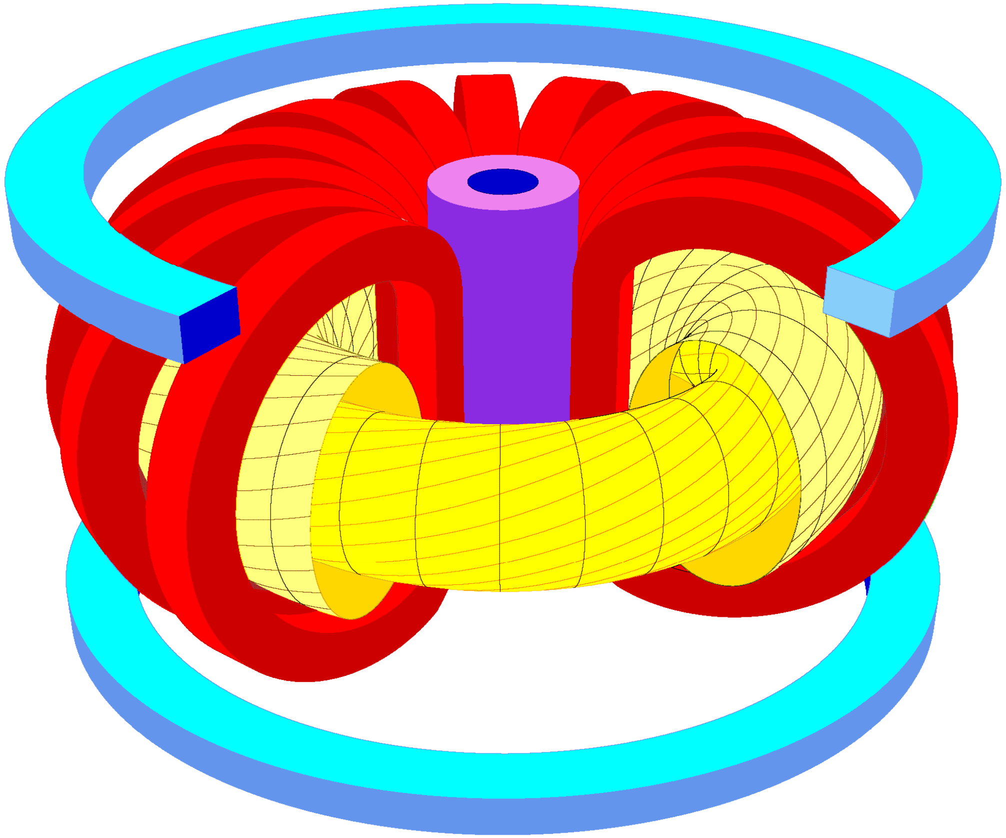
'Stellarator': magnetic field exclusively produced by coils



Example: Wendelstein 7-X (IPP Greifswald)

Plasma can be confined in a magnetic field

'Tokamak': poloidal field component from current in plasma

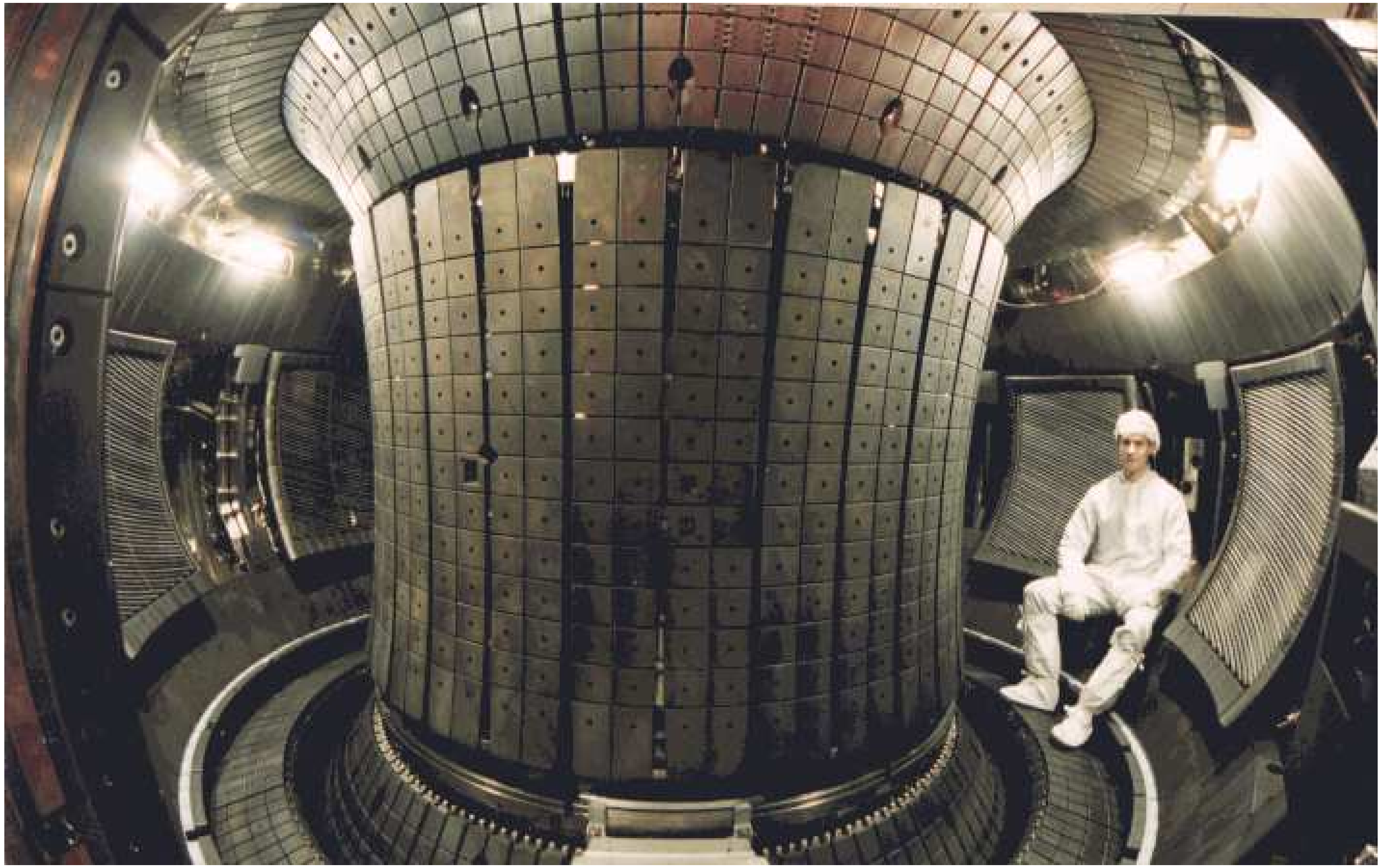


Simple concept, but not inherently stationary!

Example: ASDEX Upgrade (IPP Garching)

Plasma can be confined in a magnetic field

'Tokamak': poloidal field component from current in plasma

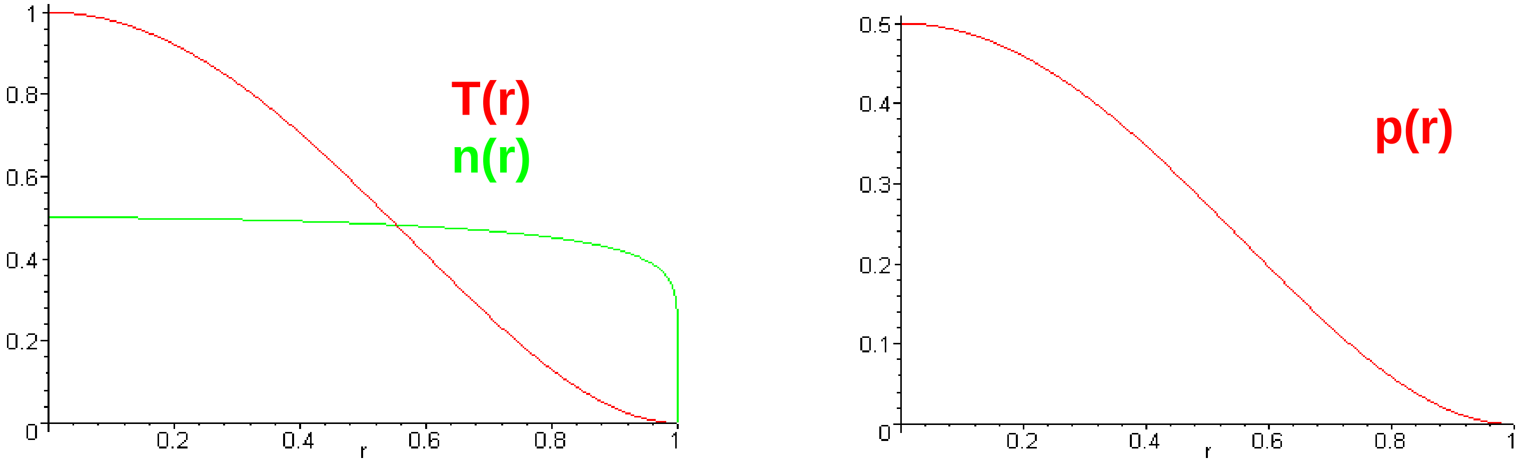


Simple concept, but not inherently stationary!

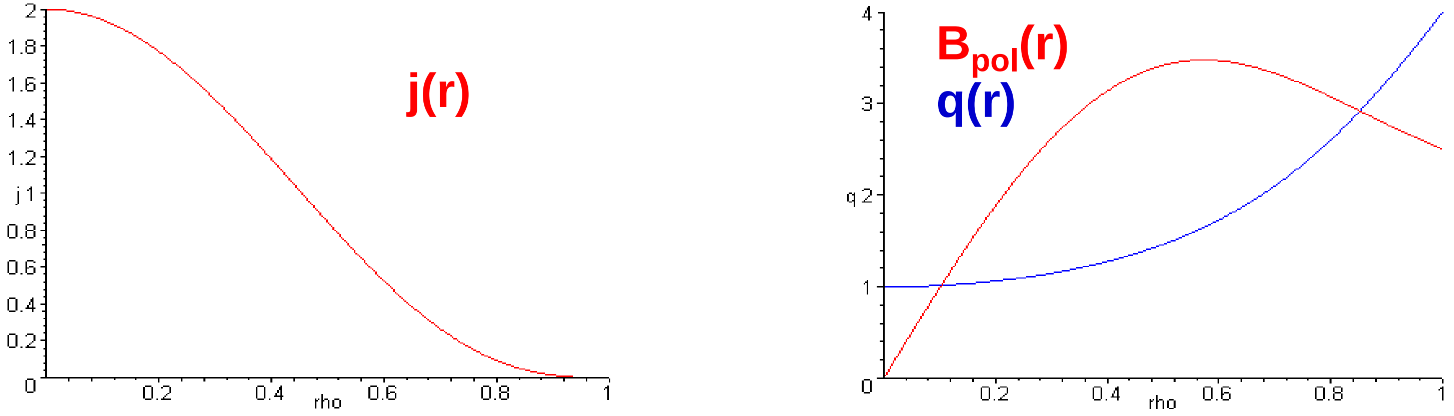
Example: ASDEX Upgrade (IPP Garching)

Plasma can be confined in a magnetic field

Typical radial profiles in fusion experiments (schematic)



Temperature profiles peaked on axis, density usually flatter, $p = n\ k_B T$

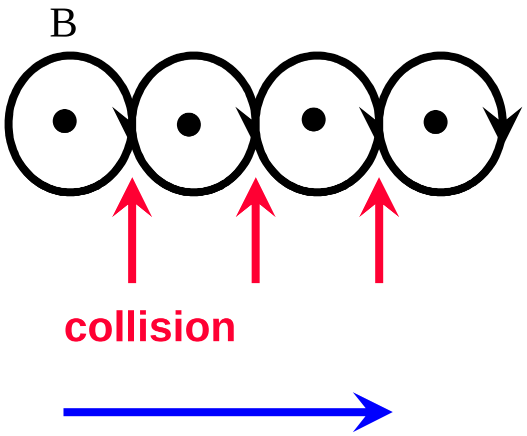


Tokamak current profiles peaked on axis ($\sigma \sim T^{3/2}$ is highest) – B_{pol} and safety factor q increase from centre to the edge

Energy confinement time determined by transport

Simplest ansatz for heat transport:

- Diffusion due to binary collisions
- table top device (R ≈ 0.6 m) should ignite

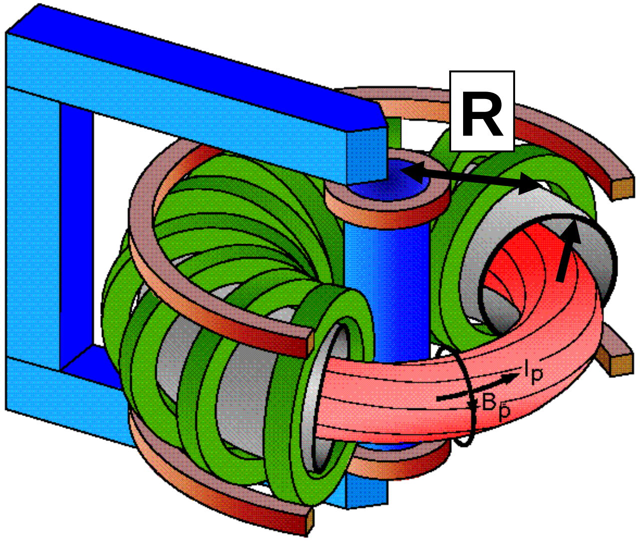


collision

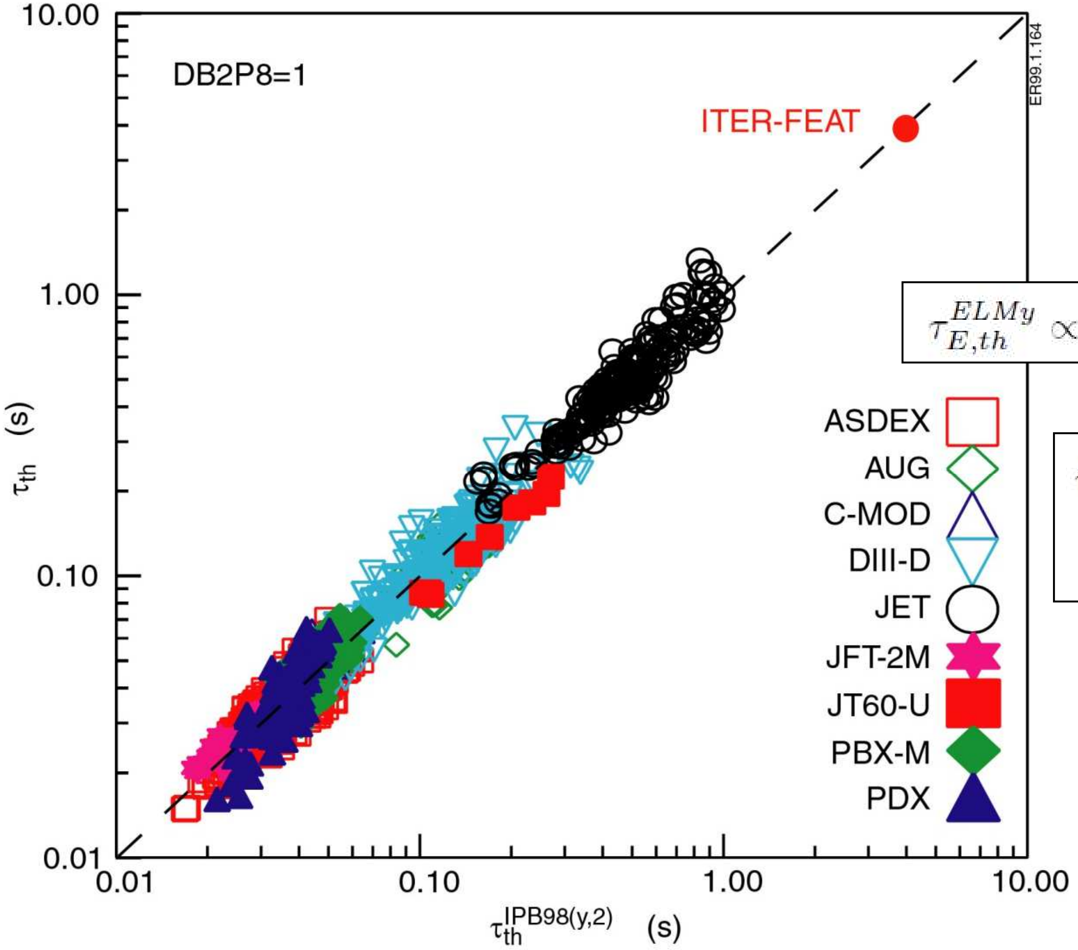
Transport to the edge

Experimental finding:

- ‚Anomalous‘ transport, much larger heat losses
- Tokamaks: Ignition expected for R = 7.5 m



Energy confinement: empirical scaling laws



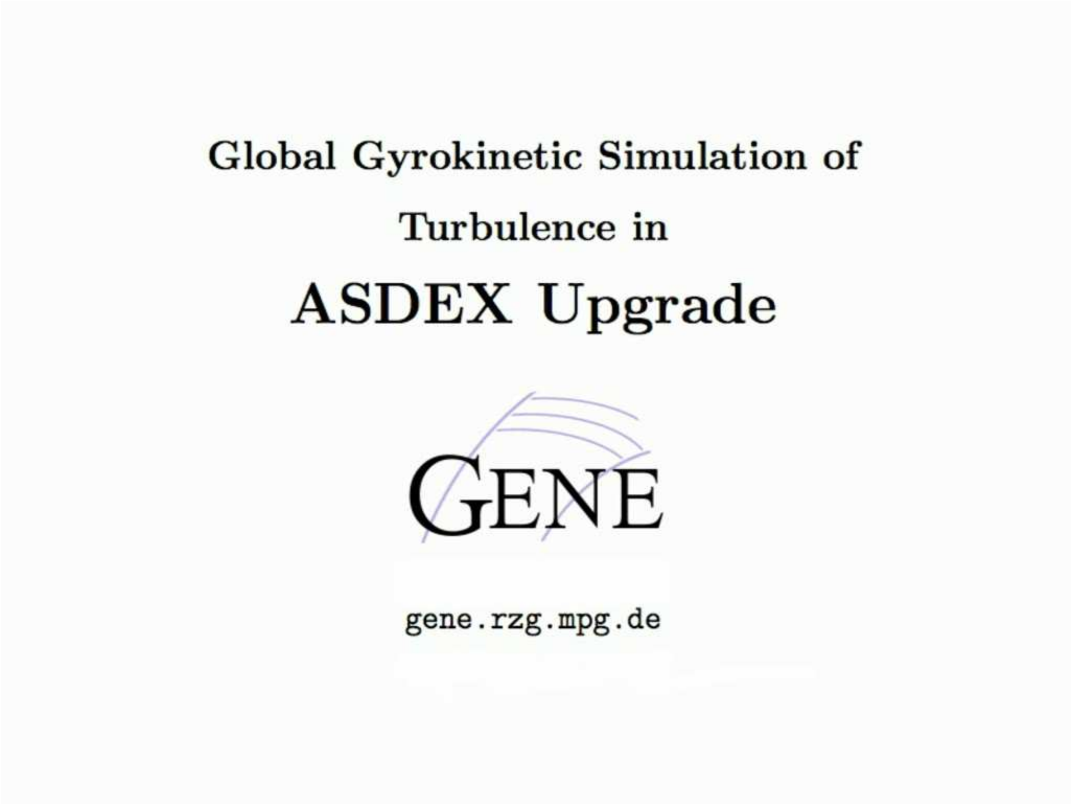
$$\tau_{E,th}^{ELMy} \propto \tau_B \rho_*^{-0.70} \beta^{-0.90} \nu_*^{-0.01} M^{0.96} q^{-3.0} \varepsilon^{0.73} \kappa_a^{2.3}$$

$$\tau_{E,th}^{ELMy} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} \times M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78}$$

In lack of a first principles physics model, ITER has been designed on the basis of an empirical scaling law

- very limited predictive capability, need first principles model

Energy Transport in Fusion Plasmas



Global Gyrokinetic Simulation of
Turbulence in
ASDEX Upgrade

GENE

gene.rzg.mpg.de

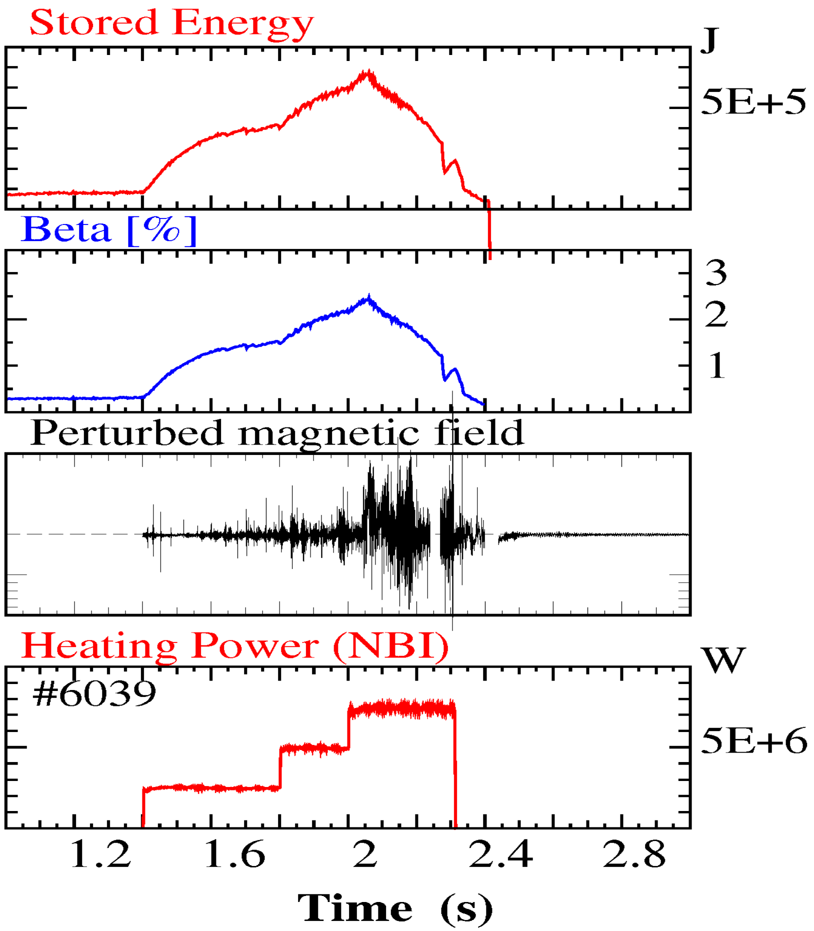
Anomalous transport determined by gradient driven turbulence

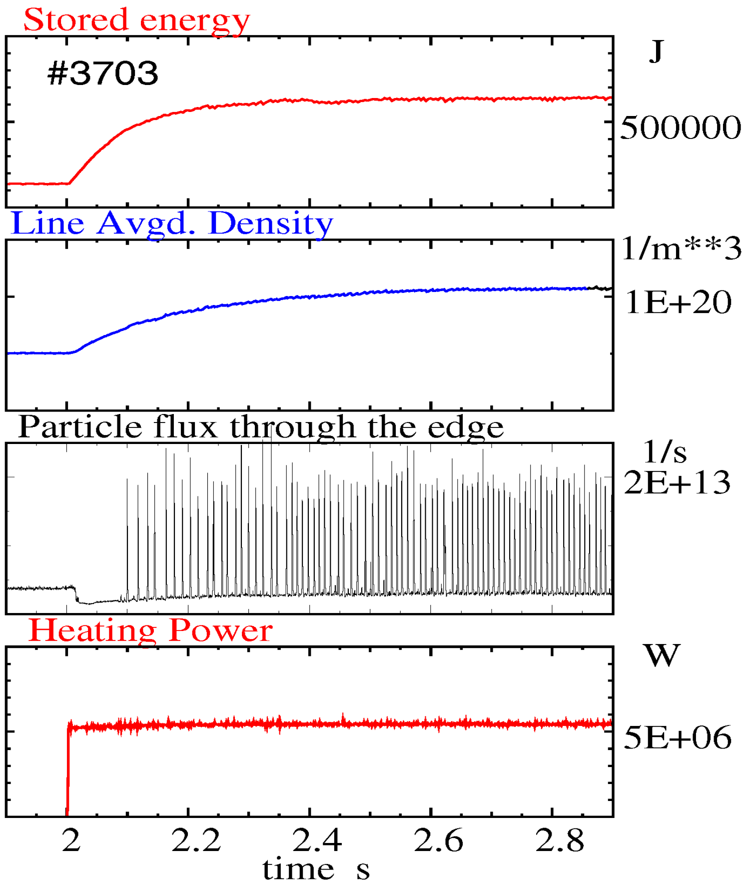
- (eddy size)^2 / (eddy lifetime) is of the order of experimental χ–values

Plasma can be confined in a magnetic field

Plasma discharges can be subject to instabilities

Plasma discharges can be subject to instabilities





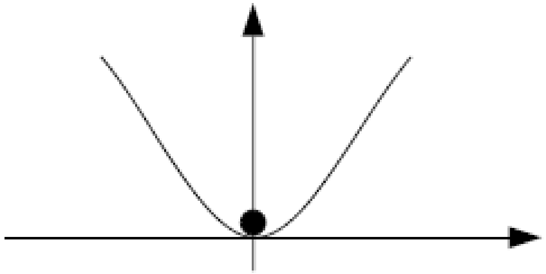
Desaster

β-limit, disruption

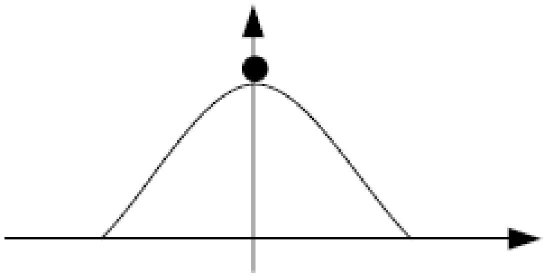
Self-organisation

sationarity of profiles *j(r)*, *p(r)*

Plasma discharges can be subject to instabilities



linearly stable



linearly unstable

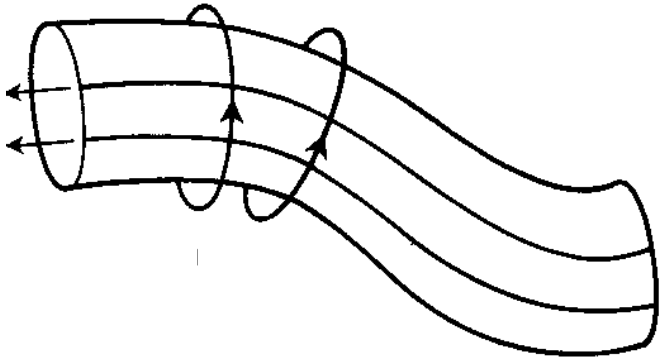
Equilibrium $\nabla p = j \times B$ means force balance, but not necessarily stability

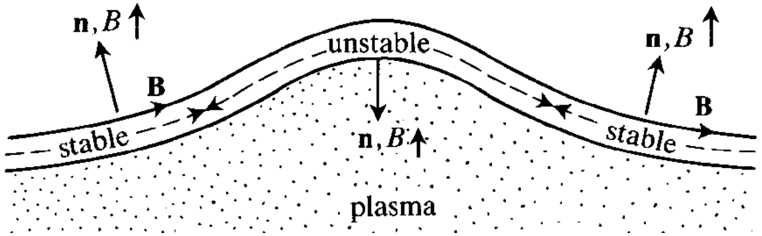
Stability against perturbation has to be evaluated by stability analysis

Mathematically: solve time dependent MHD equations

- linear stability: small perturbation, equilibrium unperturbed, exponentially growing eigenmodes
- nonlinear stability: finite peturbation, back reaction on equilibrium, final state can also be saturated instability

Free energies to drive MHD modes





current driven instabilities

Ex.: kink mode

(only tokamaks)

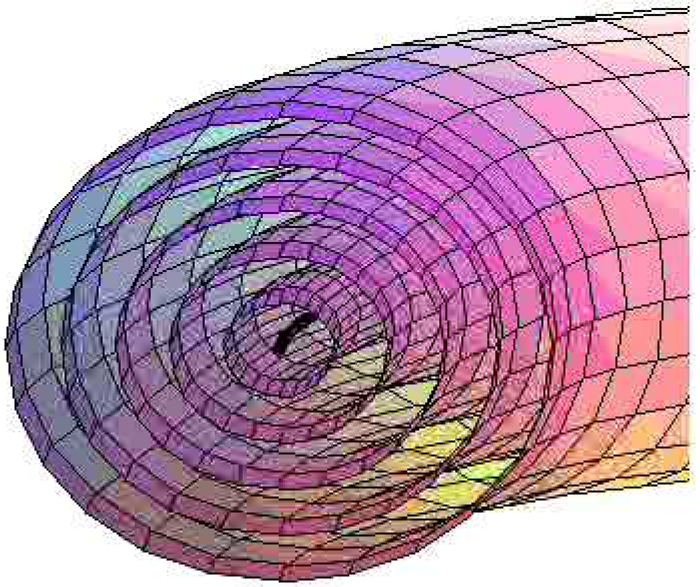
pressure driven instabilities

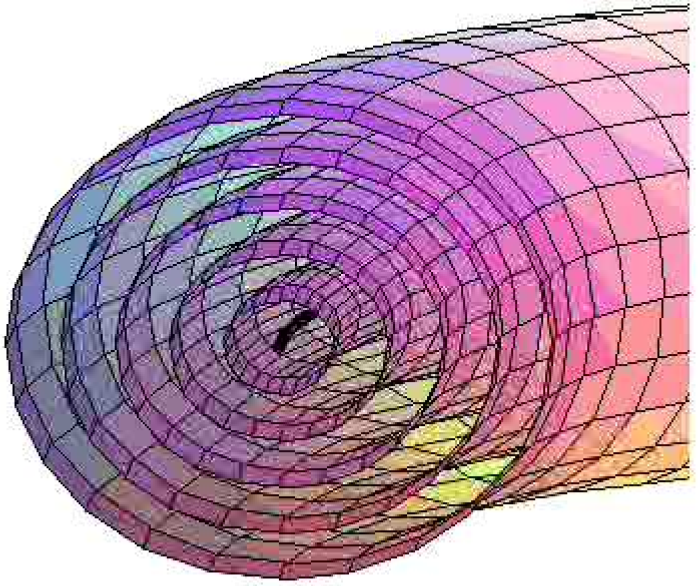
Ex.: interchange mode

(tokamak and stellarator)

N.B.: also fast particle
pressure (usually kinetic effects)!

Ideal and resistive MHD instabilities





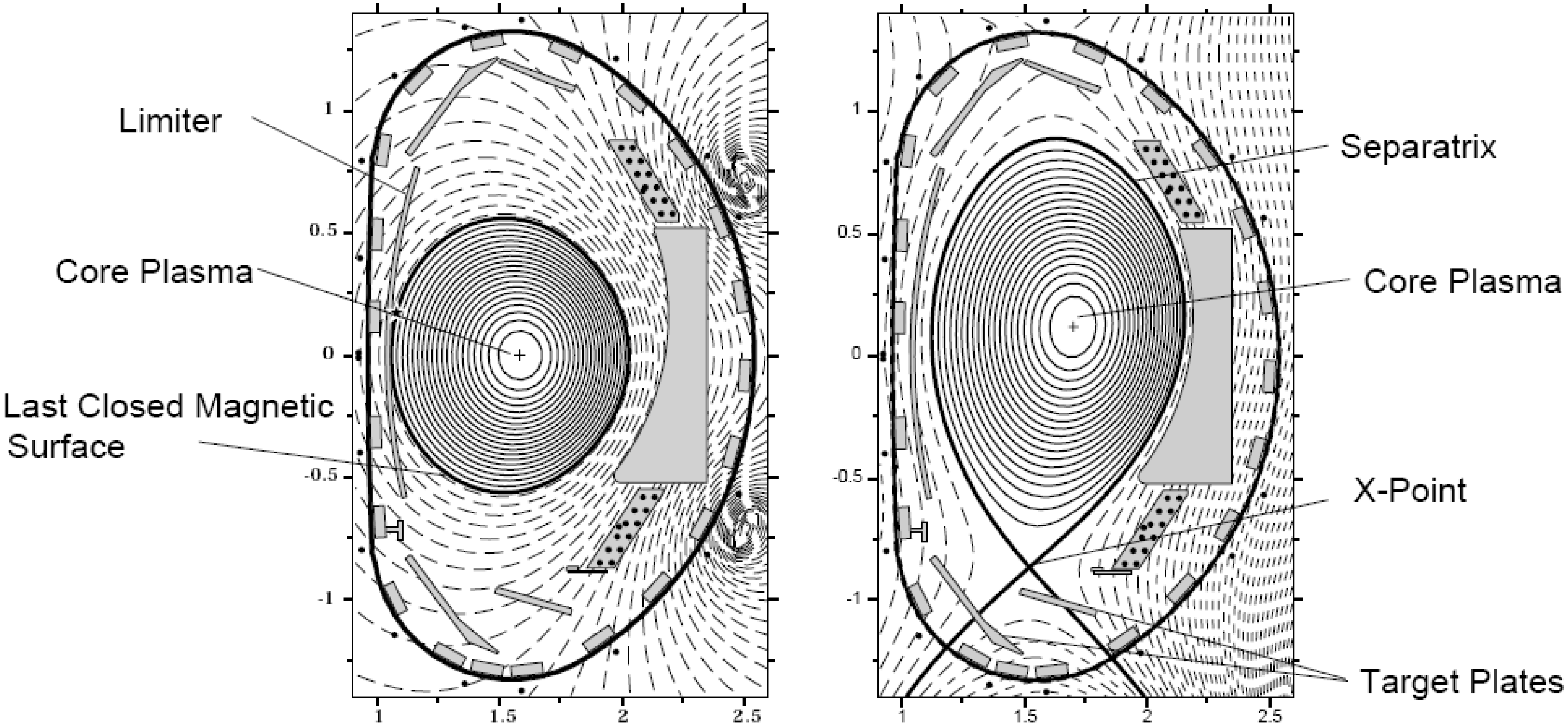
Ideal MHD: $\eta = 0$

- flux conservation
- topology unchanged

Resistive MHD: $\eta \neq 0$

- reconnection of field lines
- topology changes

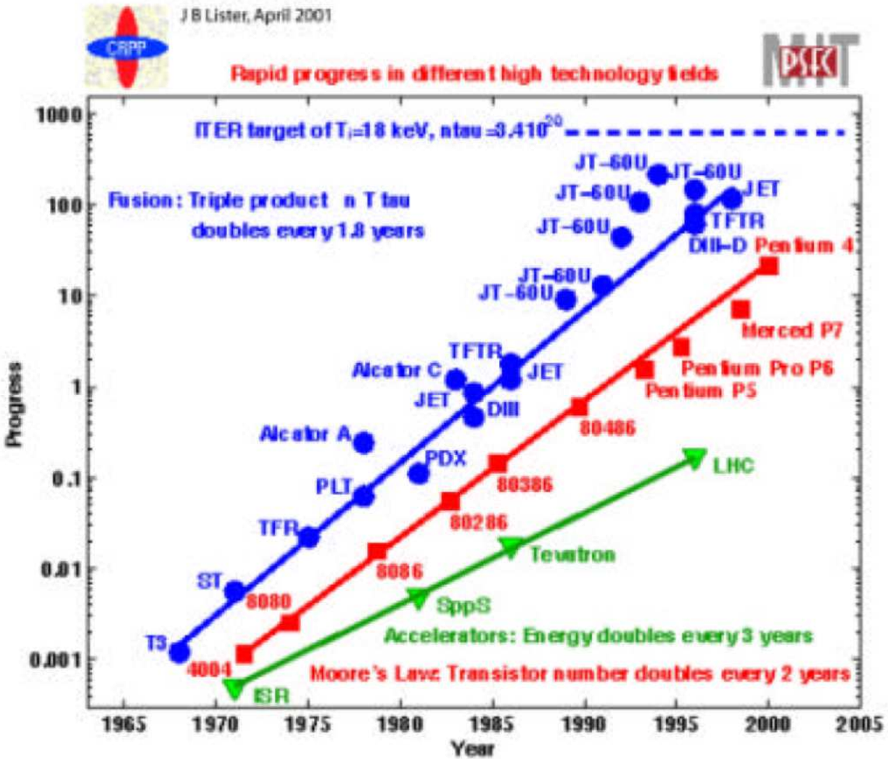
Plasma wall interface – from millions of K to 100s of K

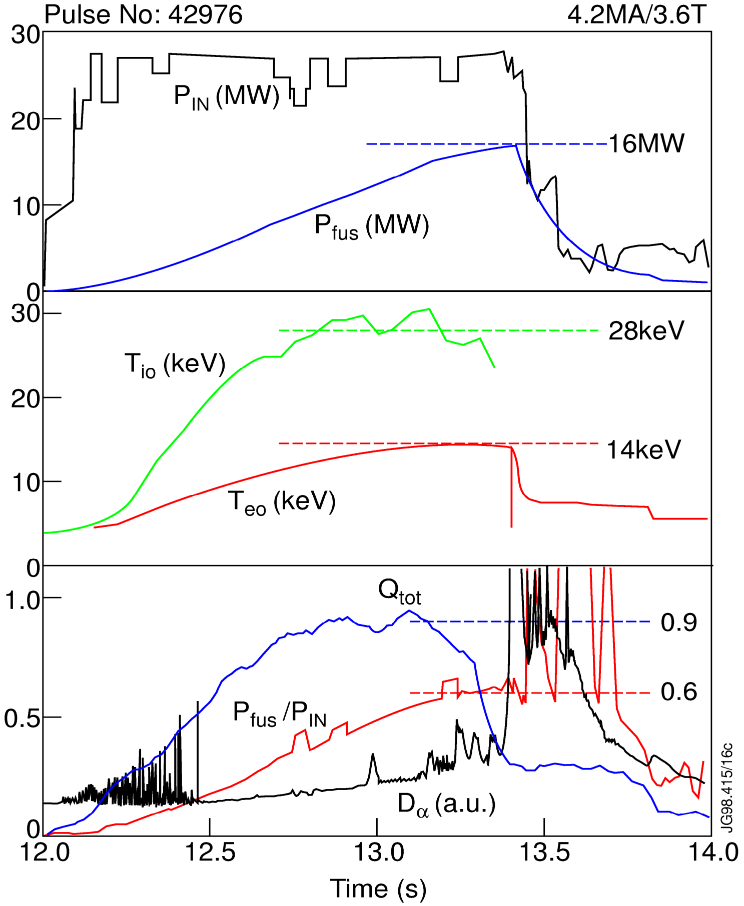


- plasma wall interaction in well defined zone further away from core plasma
- allows plasma wall contact without destroying the wall materials
- provides particle control (retention of impurities, pumping of He ash)

Plasma wall interface – from millions of K to 100s of K

Tokamaks have made Tremendous Progress



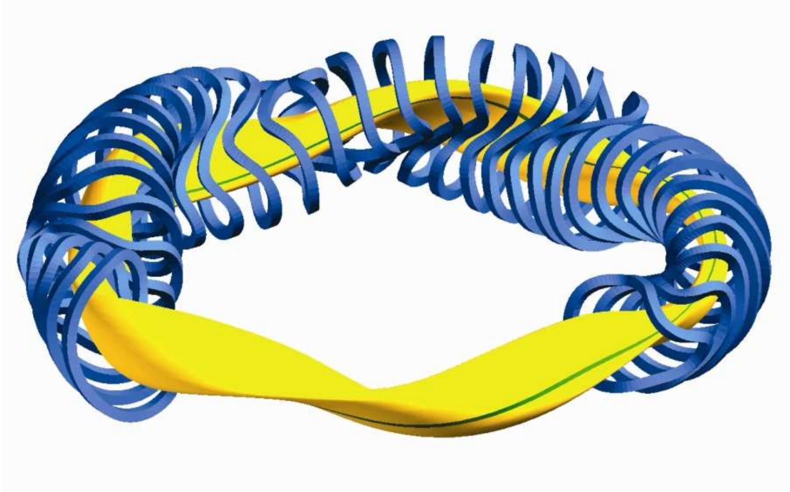


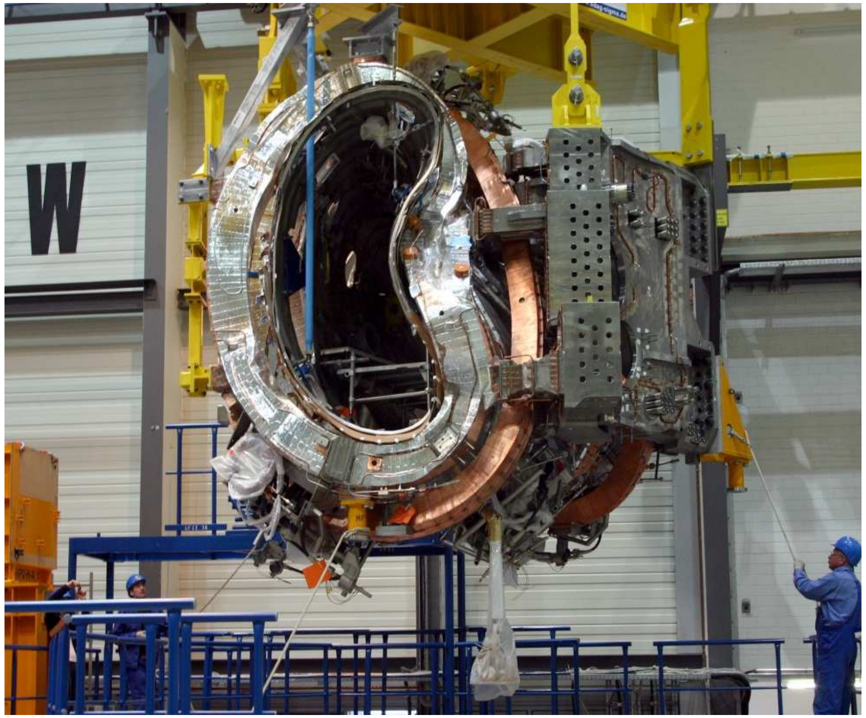
- figure of merit $nT\tau_E$ doubles every 1.8 years

•JET tokamak in Culham (UK) has produced 16 MW of fusion power

- present knowledge has allowed to design a next step tokamak to demonstrate large scale fusion power production: ITER

With Wendelstein-7X, stellarators are catching up





Complex technological problems have been solved

- operation of Wendelstein 7-X should demonstrate appropriate confinement (presently lagging behind that of tokamaks by ~ 1.5 generations)
- stellarators are intrinsically stationary (tokamaks are not)