MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Prospects For Fusion Energy Using Magnetic Confinement

Part I: Introduction

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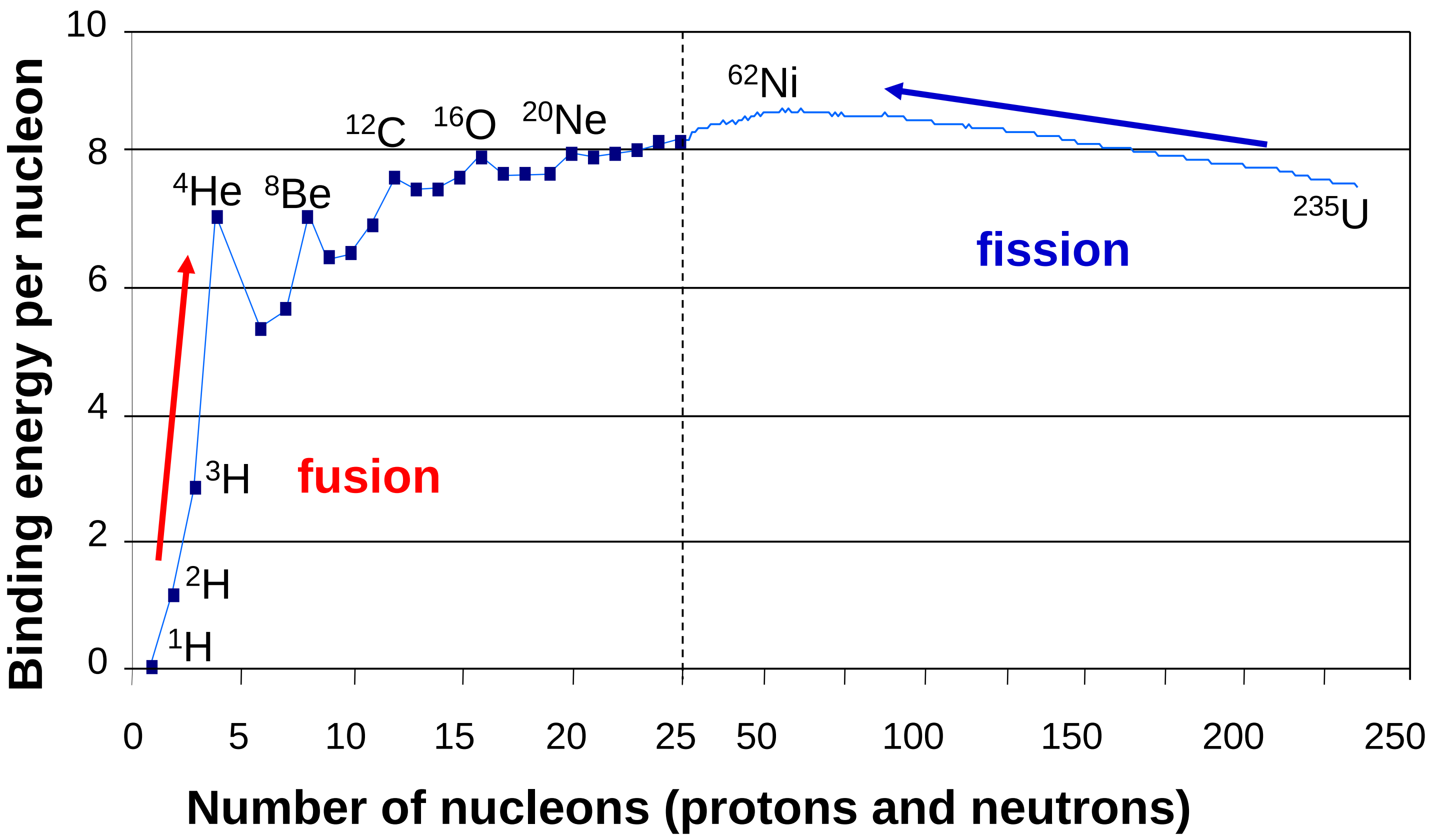
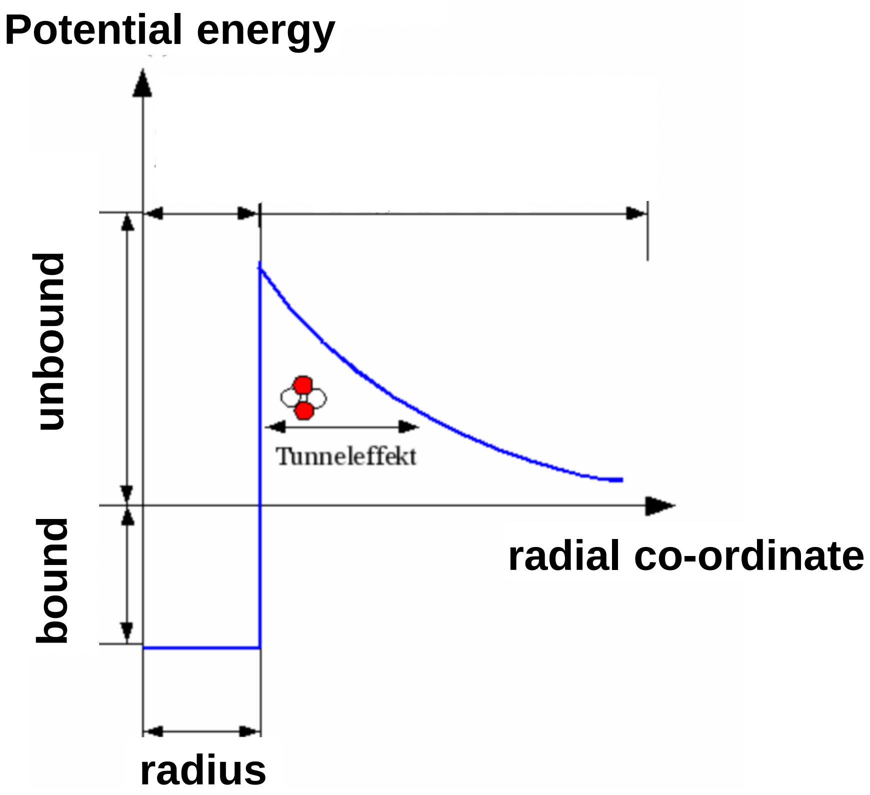
Energy Gain From Nuclear Fusion

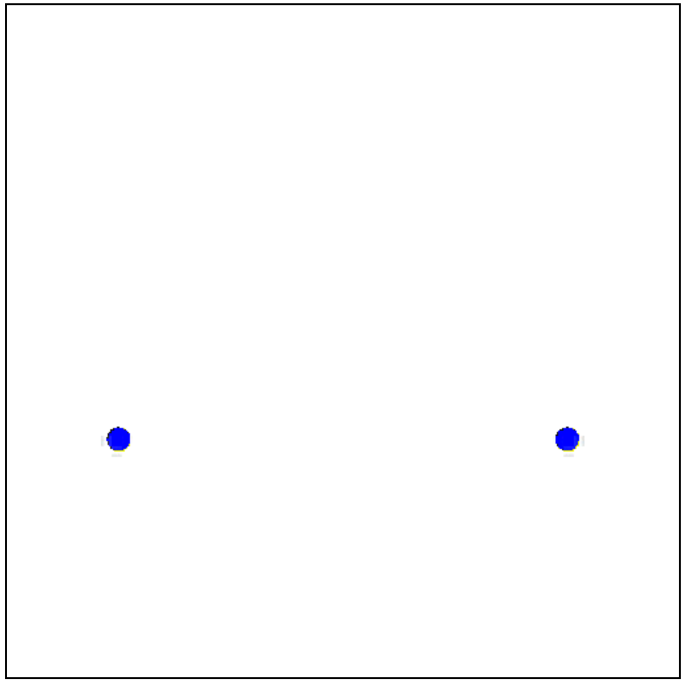


With increasing proton number, electrostatic repulsion dominates – curve has a maximuml

- energy gain by fusion of light nuclei or fission of heavy nuclei

How Can You Fuse Nuclei?

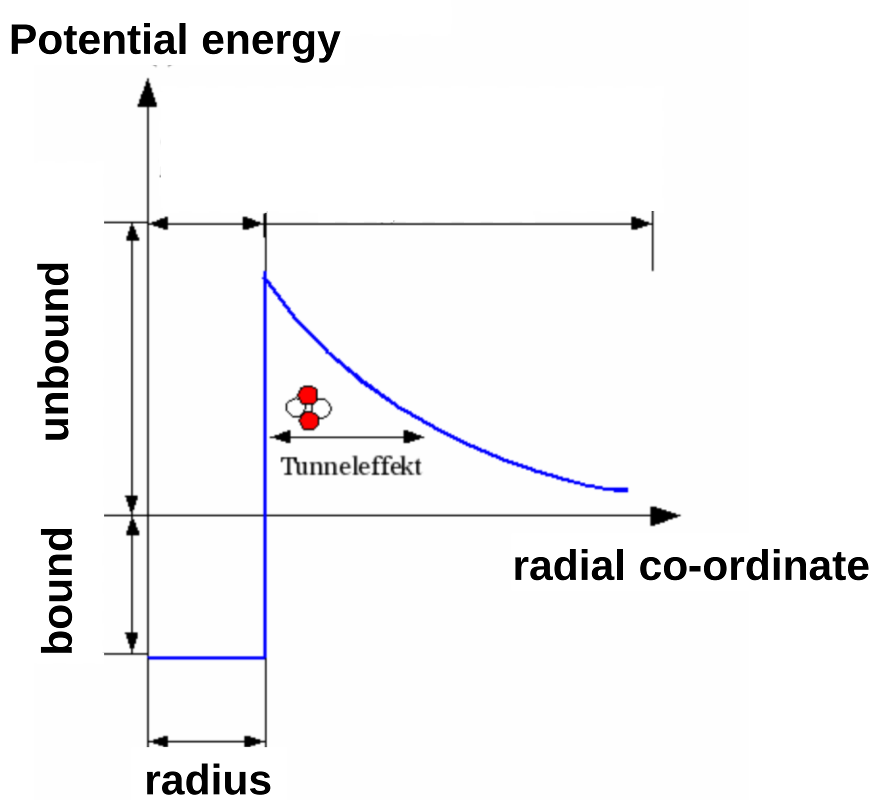


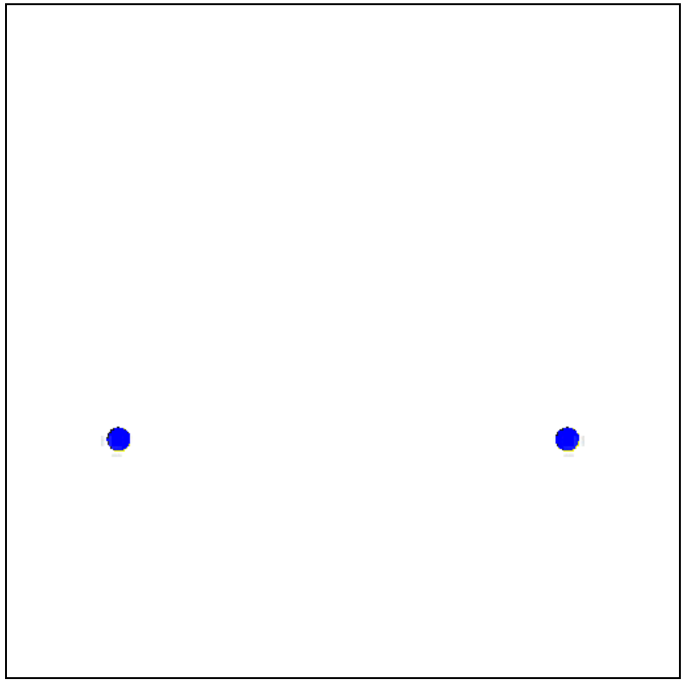


Nuclei have to ‚touch' in order to fuse

- need enough energy to overcome electrostatic repulsion

How Can You Fuse Nuclei?



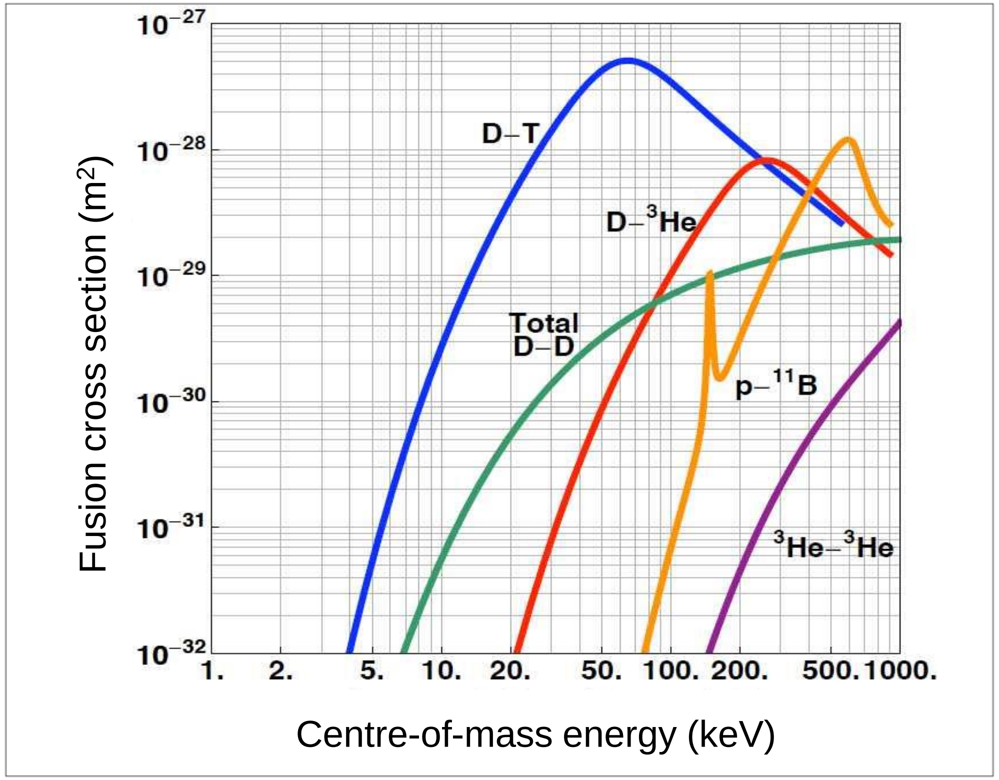


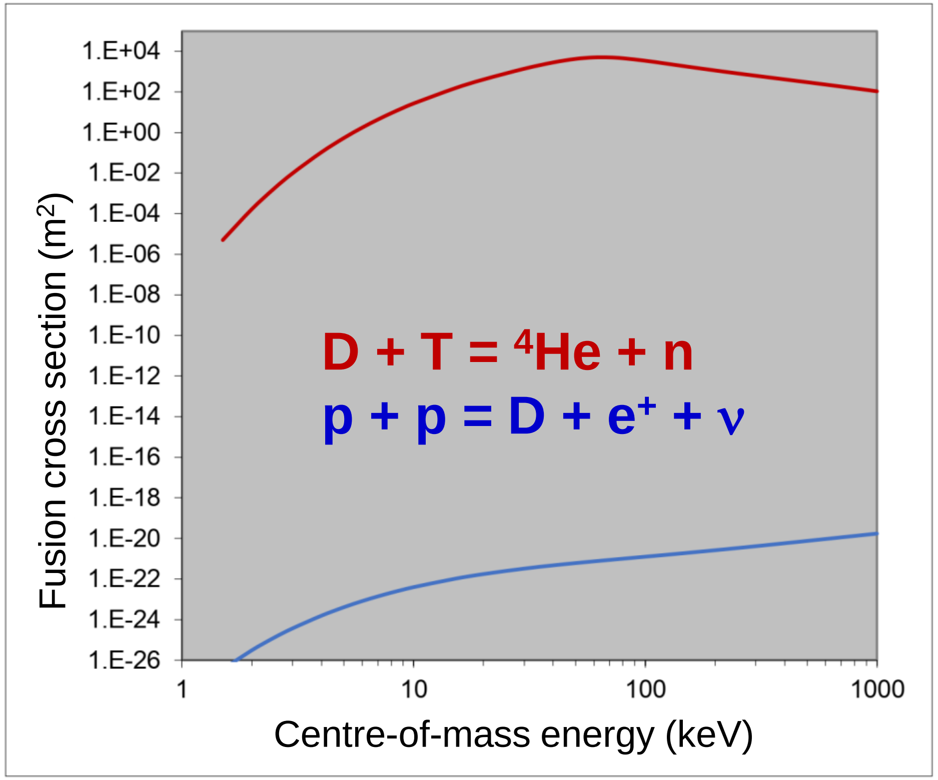
Nuclei have to ‚touch' in order to fuse

- need enough energy to overcome electrostatic repulsion

Required energy for fusion of hydrogen nuclei: some 10 keV

Fusing Hydrogen to Helium





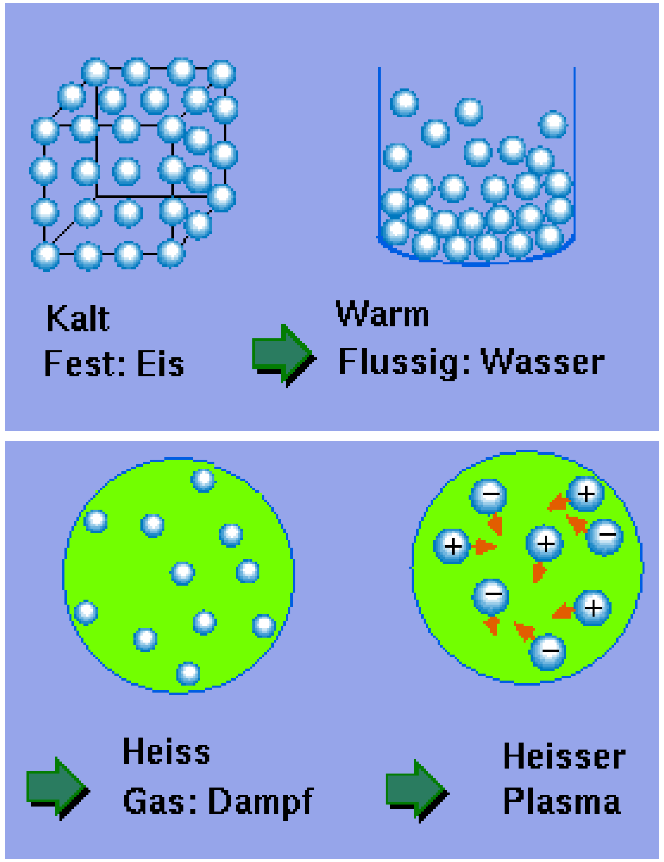
Fusion cross section varies strongly between different fusion reactions

- D-T fusion: highest cross-section, lowest activation energy
- cross-section for proton-chain (sun) lower by a factor of 10^{24} (!)

Fusion Reactors: the Challenge

In order to gain energy from fusion reactions, one has to confine a hydrogen gas and heat it up such that the thermal energy is of the order of ~ 20 keV (equivalent to 200 Mio degrees(!))

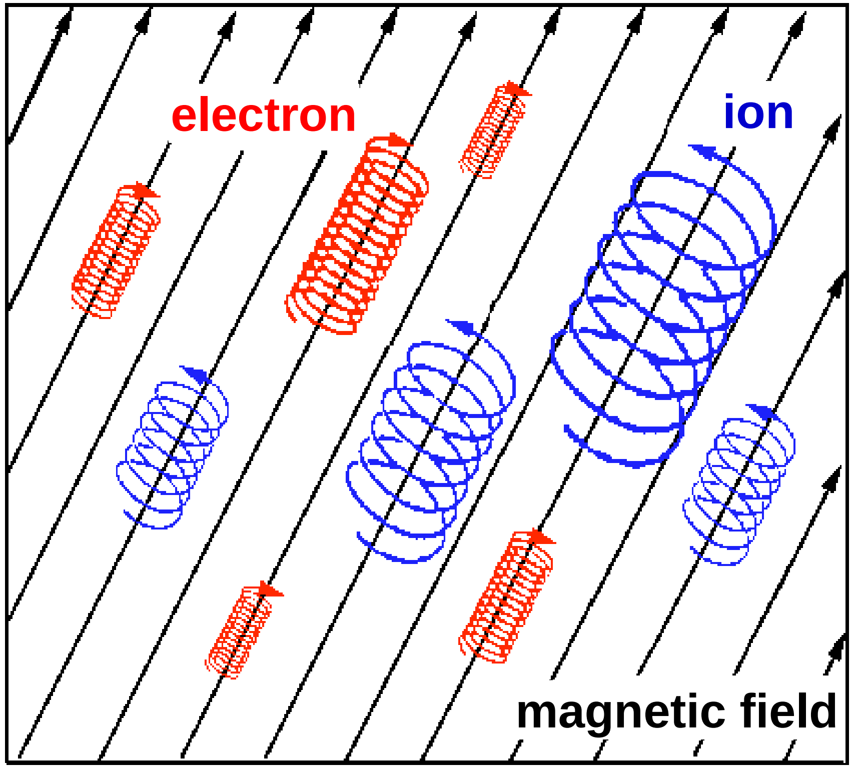
Fusion Physics is Plasma Physics



At these temperatures, hydrogen gas becomes a *Plasma* (gas consisting of charged particles)

- more than 99% of visible matter in the Universe is in the plasma state

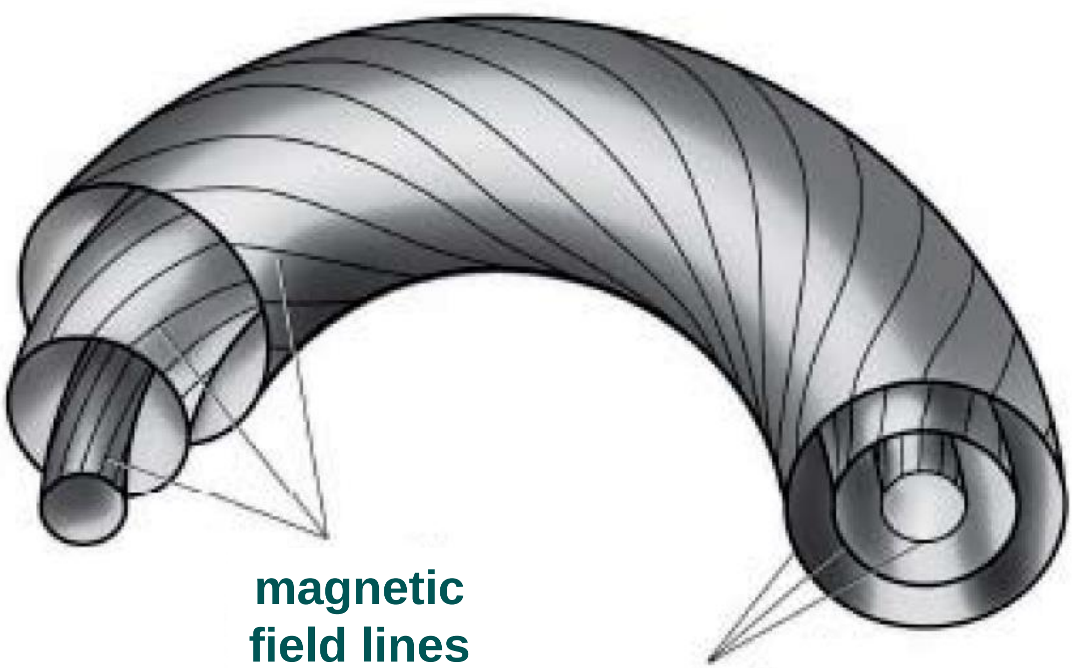
Magnetic Confinement of Fusion Plasmas



Charged particles gyrate around magnetic field lines, move freely along them

- for strong enough field, particles follow the field lines
- ‚magnetic confinement' of fusion plasmas

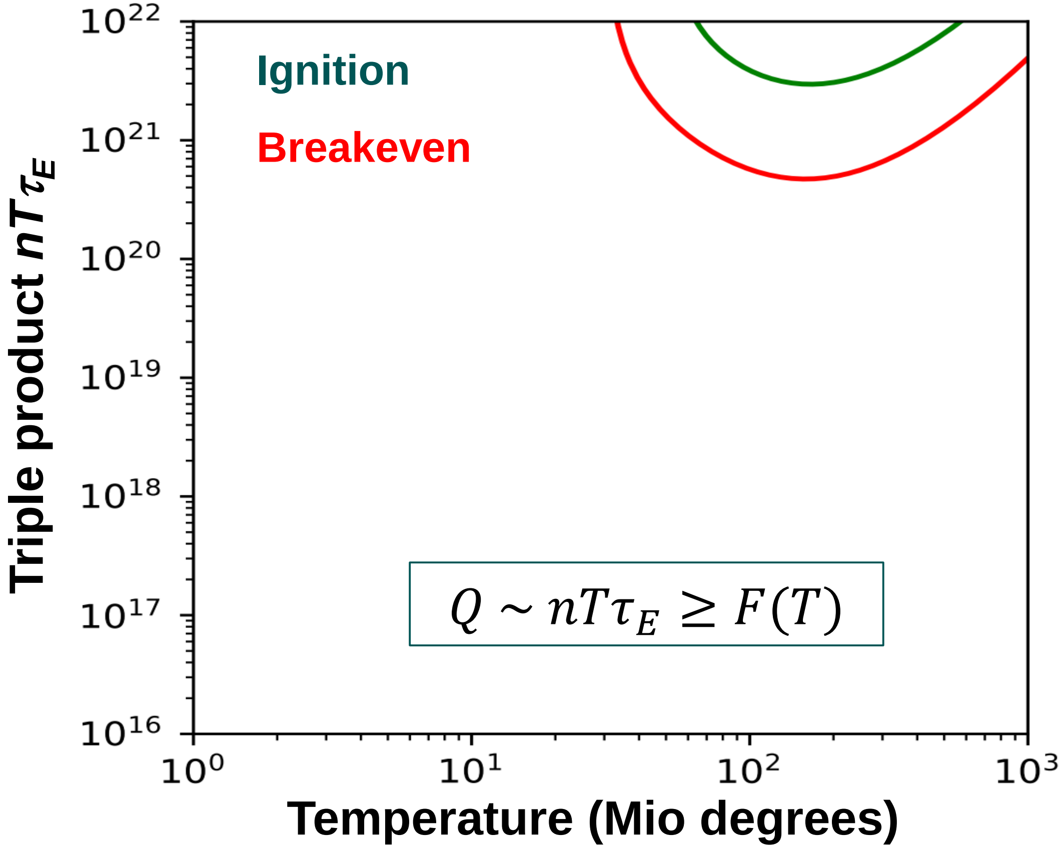
Magnetic Confinement of Fusion Plasmas



In order to avoid end losses, confinement is acheived in toroidal geometry

- helical field lines minimise particle drifts and allow for stationary confinement

Energy Balance: the Lawson Criterion



‚Lawson diagramm' for D-T fusion:

Plasma heating by external power

$$Q = \frac{P_{Fusion}}{P_{extern}}$$

- Q = 1: ‚Breakeven'
- $Q \rightarrow \infty$: ‚Ignition'

(self-heating by the α-particles born in the fusion reaction, ‚thermonuclear burn')

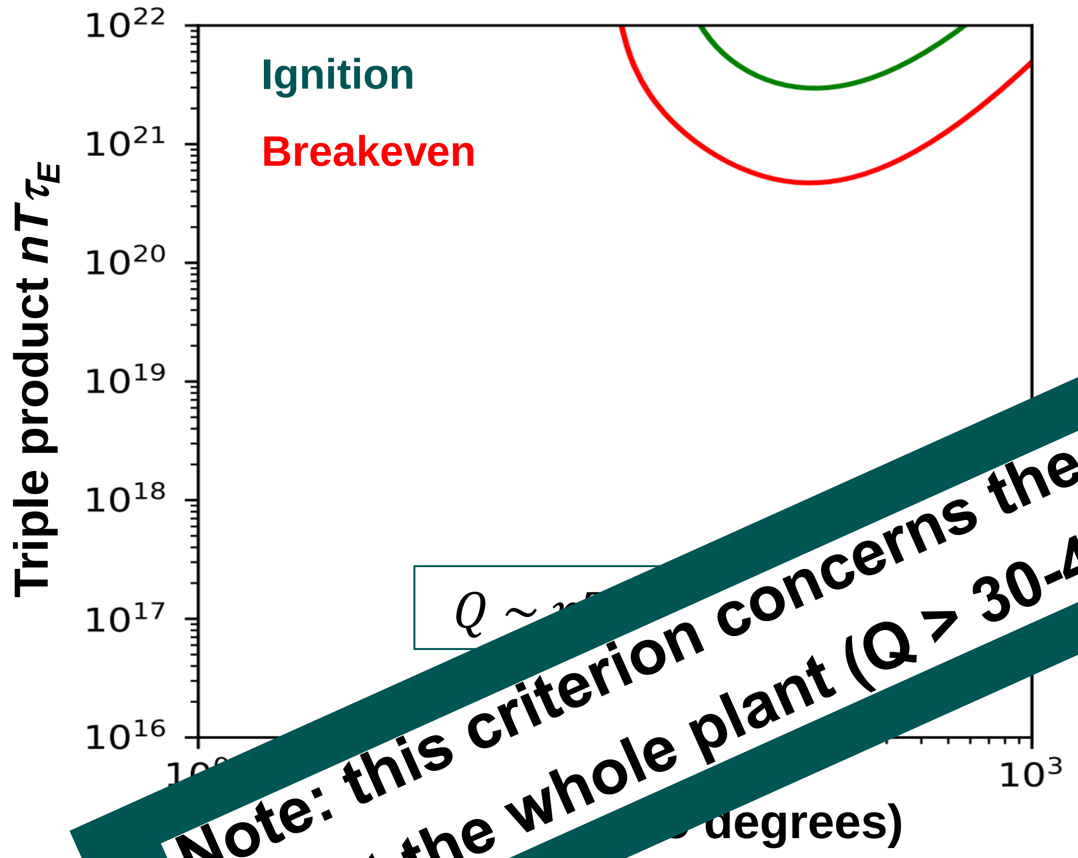
Energy confinement time τ_E is a measure for the heat insulation:

- ‚after τ_E seconds, the coffee is cold'
- target parameters: $n = 10^{20}$ particles/m^3, τ_E some seconds

τ_E = 10 Minuten

τ_E = 10 Stunden

Energy Balance: the Lawson Criterion



'Lawson diagramm' for D-T

Plasma heating by

ven'

'ignition'

(self-heating by the α-particles born in the fusion reaction, 'thermonuclear burn')

Note: this criterion concerns the energy/power balance of the plasma, not the whole plant (Q > 30-40 needed for net energy production)

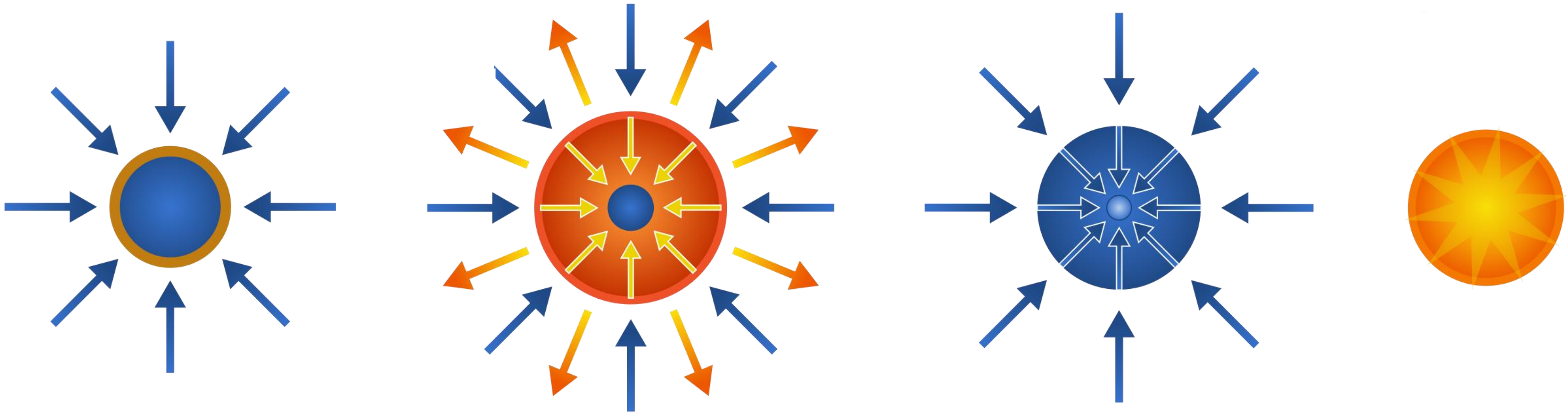
Ene time τ_E is a measure for the heat insulation:

- 'a seconds, the coffee is cold'
- target parameters: $n = 10^{20}$ particles/m^3, τ_E some seconds

τ_E = 10 Minuten

τ_E = 10 Stunden

An Alternative: Inertial Confinement of Fusion Plasmas



fast heating by laser irradiation | **ablating material compresses pellet** | **fusions conditions are reached in the centre** | **thermonuclear burn-up of ignited pellet**

The whole process takes place in a few nanoseconds

In inertial fusion, ignition and burn happen faster than expansion of the hot plasma

- same principle as the hydrogen bomb, but with manageable explosion energy (~ 1 mm pellets)
- target parameters: n = 10^{31} particles/m^3, τ_E some 10^{-10} seconds

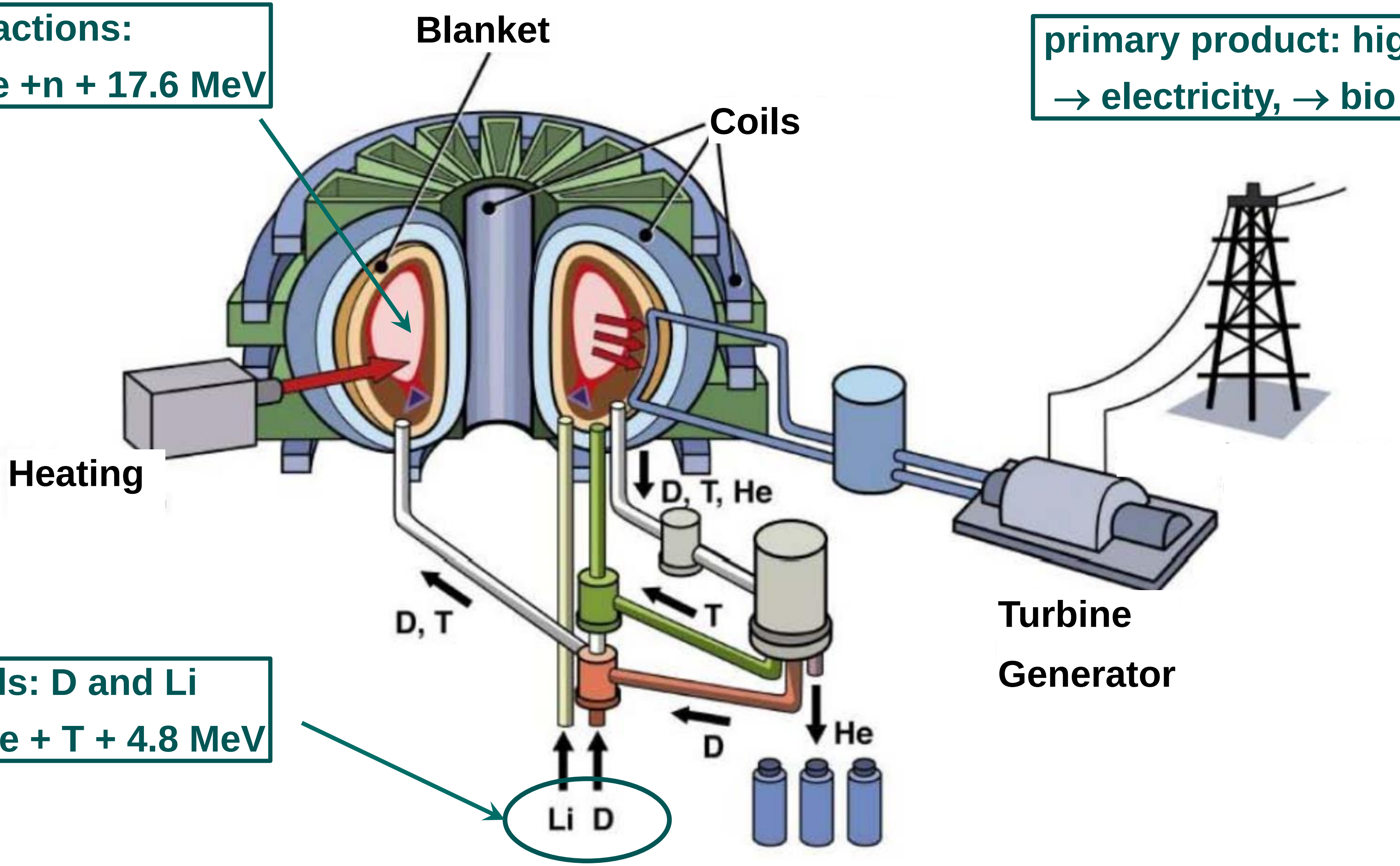
Schematic of a Fusion Power Plant Using Magnetic Confinement

Fusion reactions:

D+T → He +n + 17.6 MeV

primary product: high grade heat

→ electricity, → bio fuels...

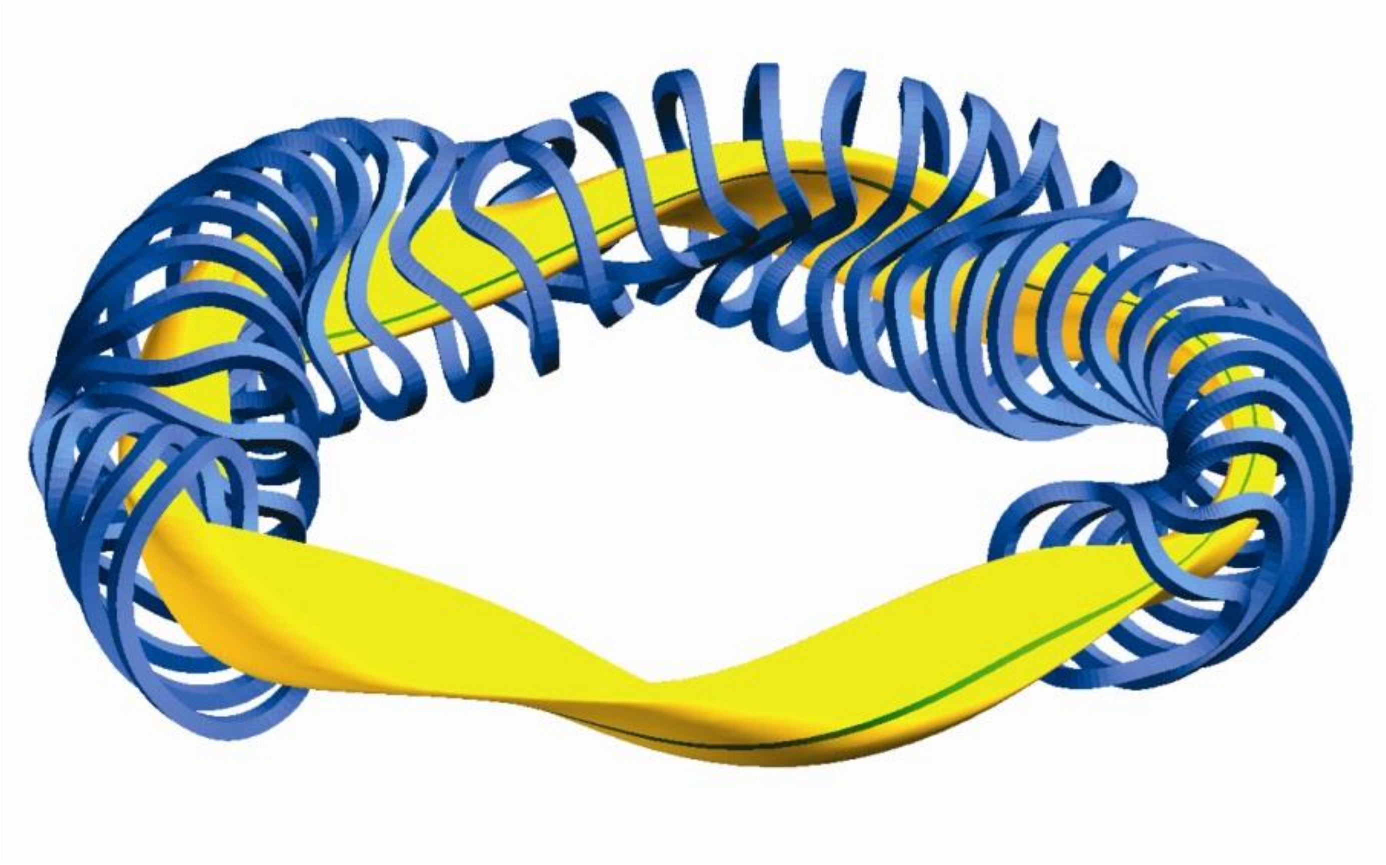


Primary fuels: D and Li

n + ^{6}Li → He + T + 4.8 MeV

Magnetic Confinement of Fusion Plasmas

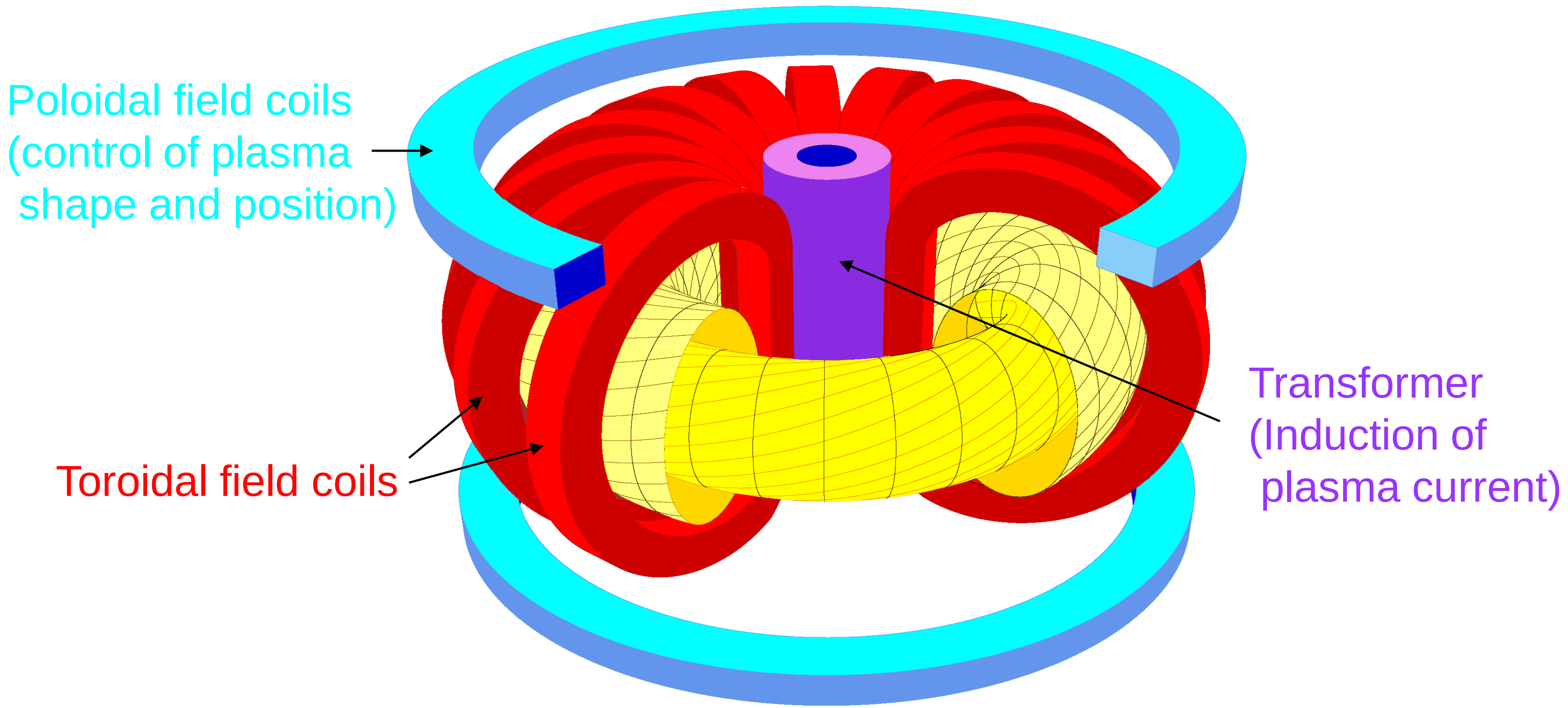
'Stellarator': (complex) magnetic field structure generated by external coils only



Example: Wendelstein 7-X (MPI Greifswald)

Magnetic Confinement of Fusion Plasmas

'Tokamak': magnetic field partly generated by toroidal plasma current (Transformer)



Example: ASDEX Upgrade (MPI Garching), ITER (Cadarache, France)…

Magnetic Confinement of Fusion Plasmas

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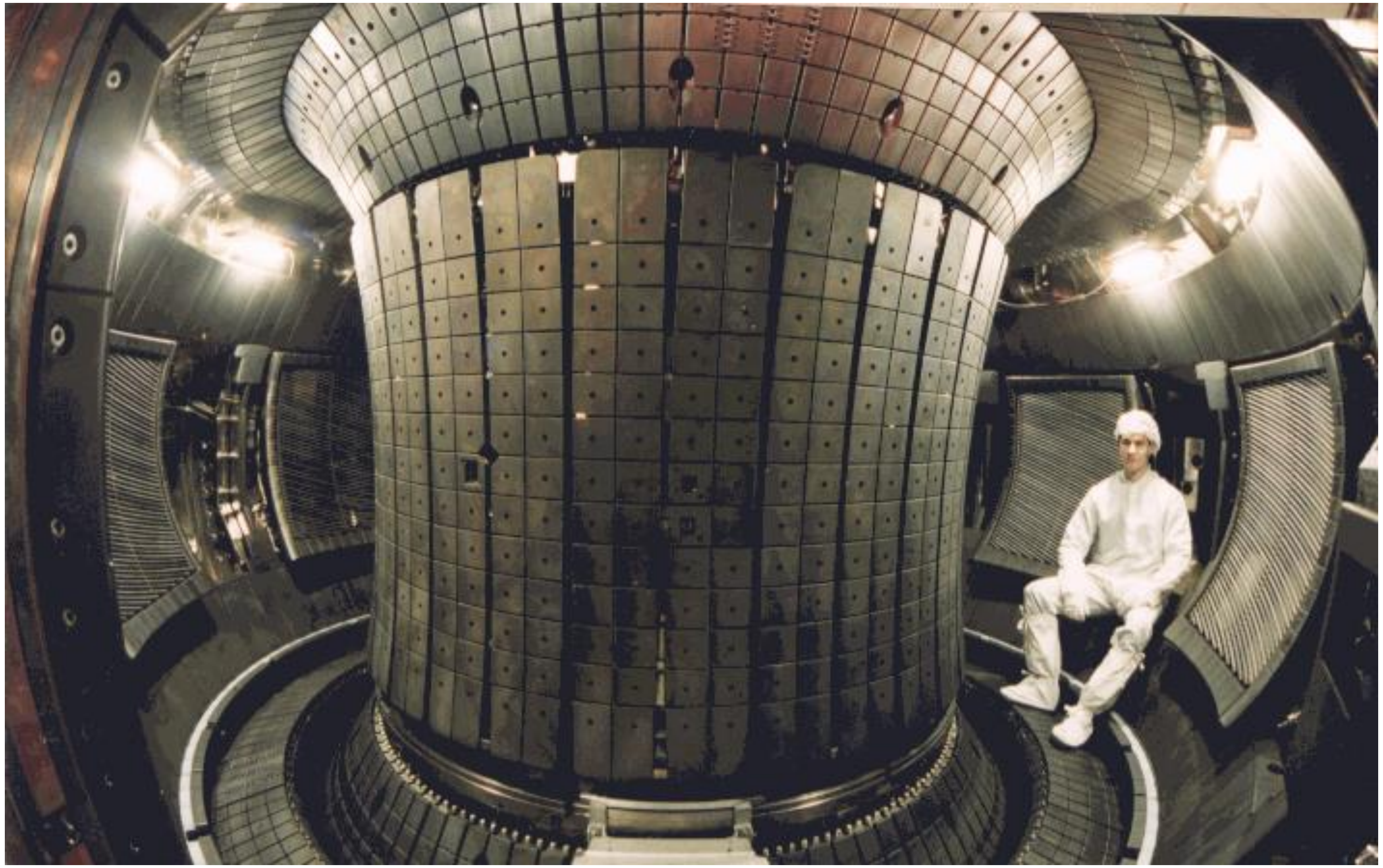

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Magnetic Confinement of Fusion Plasmas

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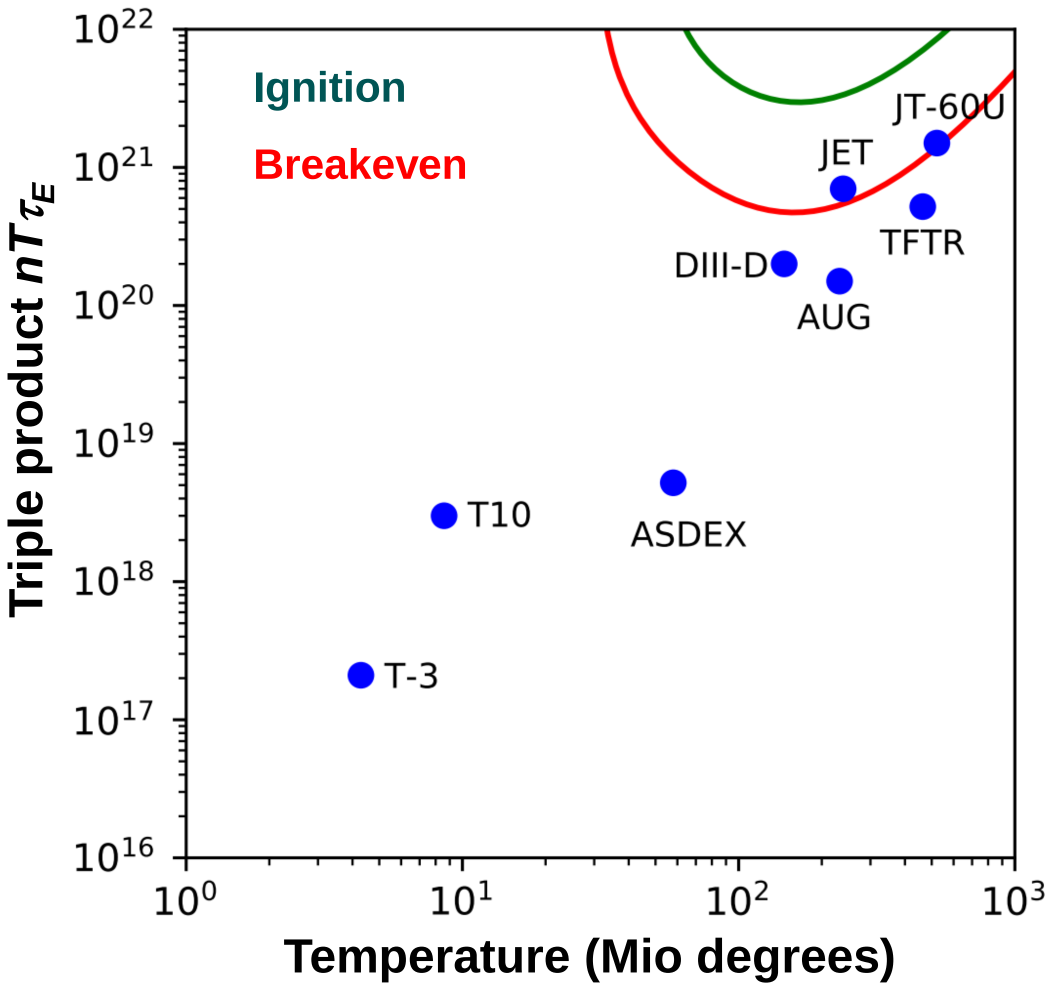
Magnetic Confinement – Target Parameters



Needed for ignition:

- high temperature:

  reached 400 Mio. degrees ☺

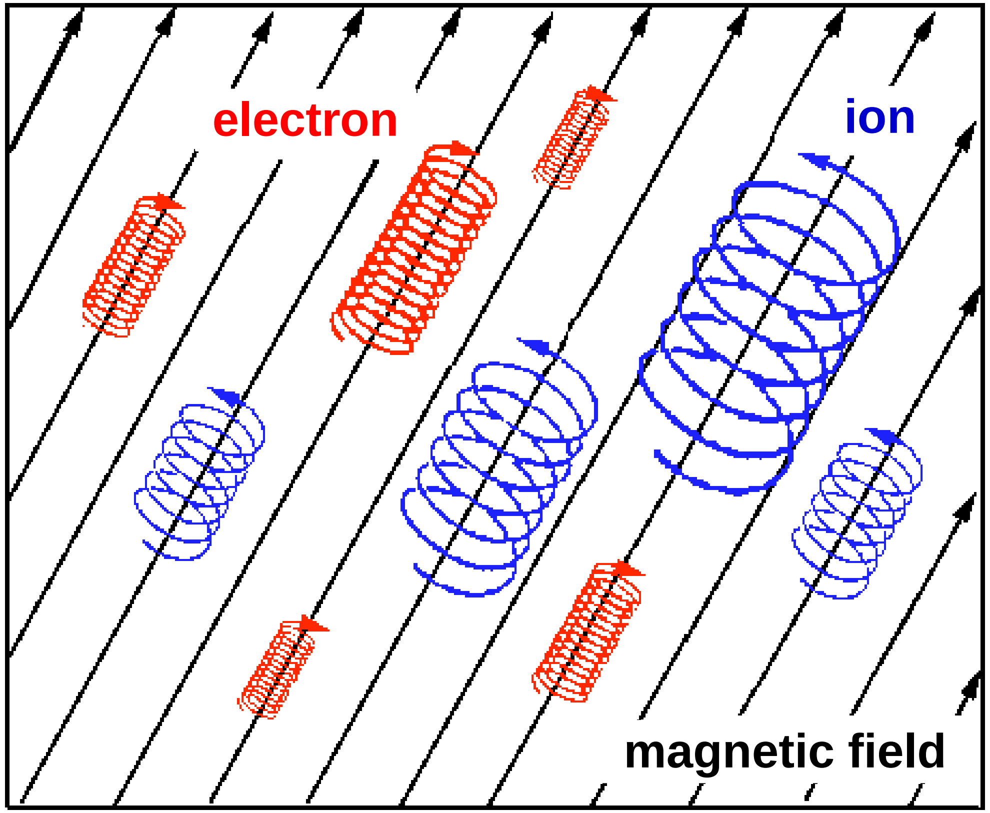
- ‚high' particle density:

  reached 10^{20} / m^3 ☺

- good heat insulation:

  reached $\tau_E < 1$ s ☹

Energy Transport in Magnetically Confined Fusion Plasmas



Simple Ansatz:

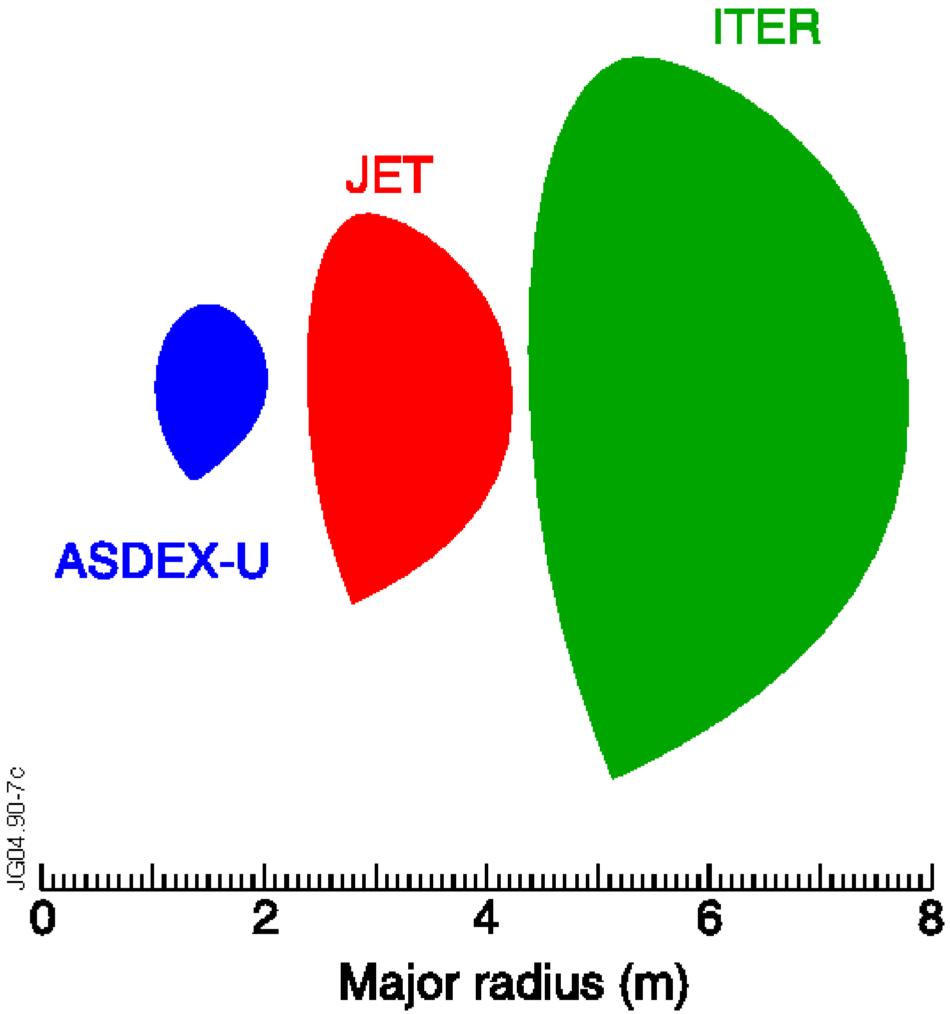
- losses due to binary collisions of particle
- ignition should be achieved at *R* = 0.15 m (!)

In reality:

- igntion for R > 6-7 m
- energy transport dominated by turbulence

Understanding of the (nonlinear) turbulent heat transport is a central subject of fusion plasma physics!

Energy Transport in Magnetically Confined Fusion Plasmas



For diffusive process

- heat insulation improves with plasma cross section

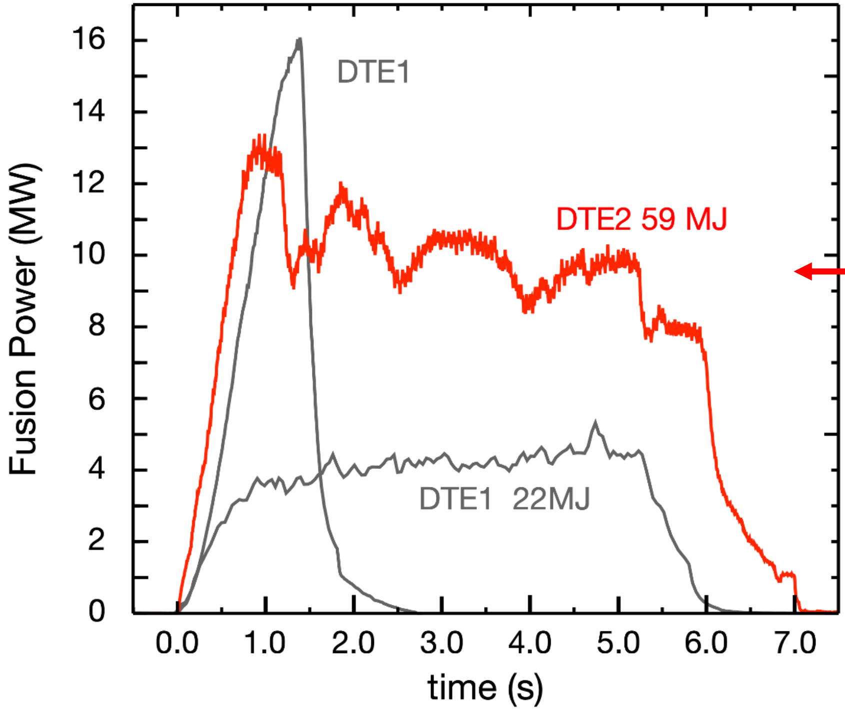
ASDEX Upgrade (D):
R = 1.65 m, τ_E = 100 ms

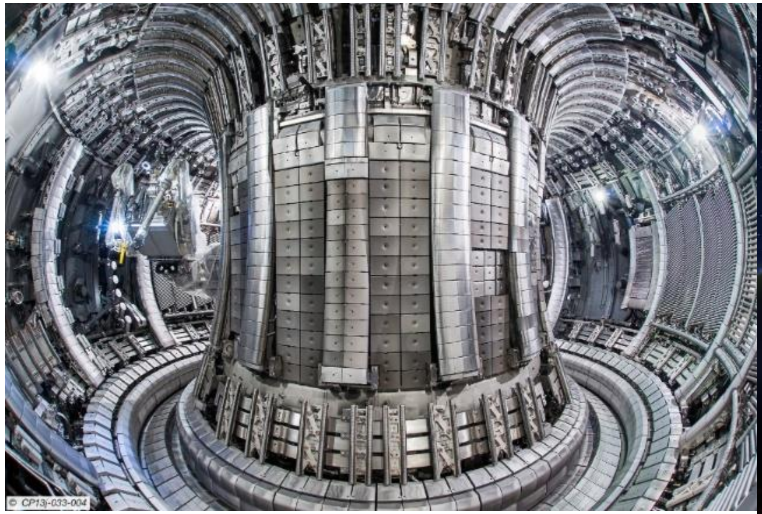
JET (GB):
R = 3 m, τ_E = 500 ms

ITER (F):
R = 6.2 m, τ_E = 3 s

Recent Success in Tokamaks by using D-T fuel

Late 2021: world record for fusion energy set up by JET tokamak

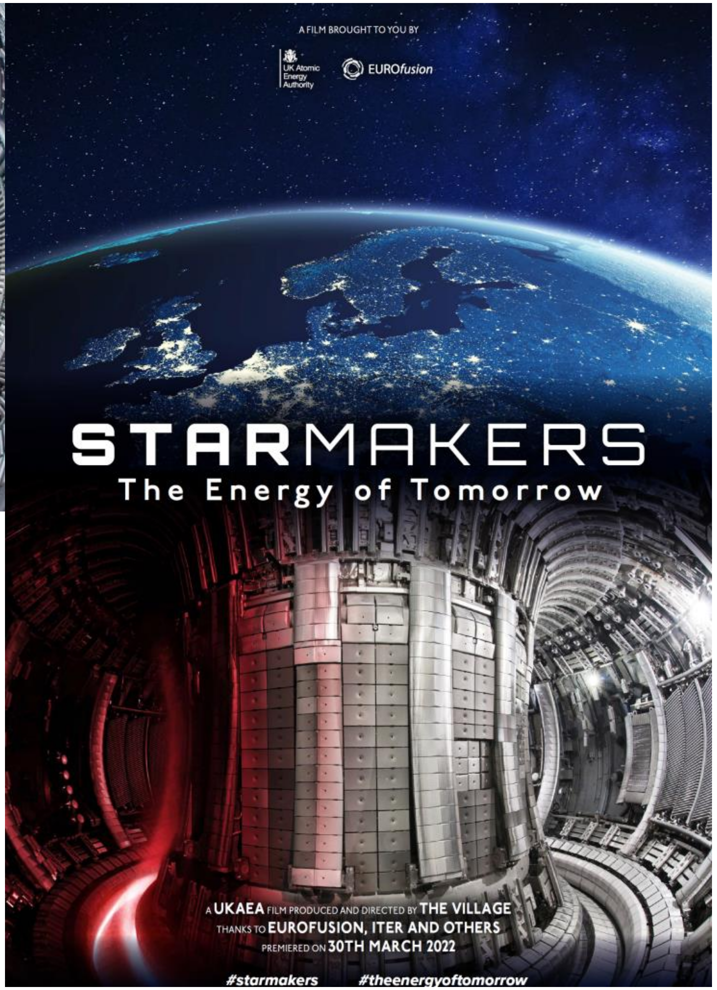




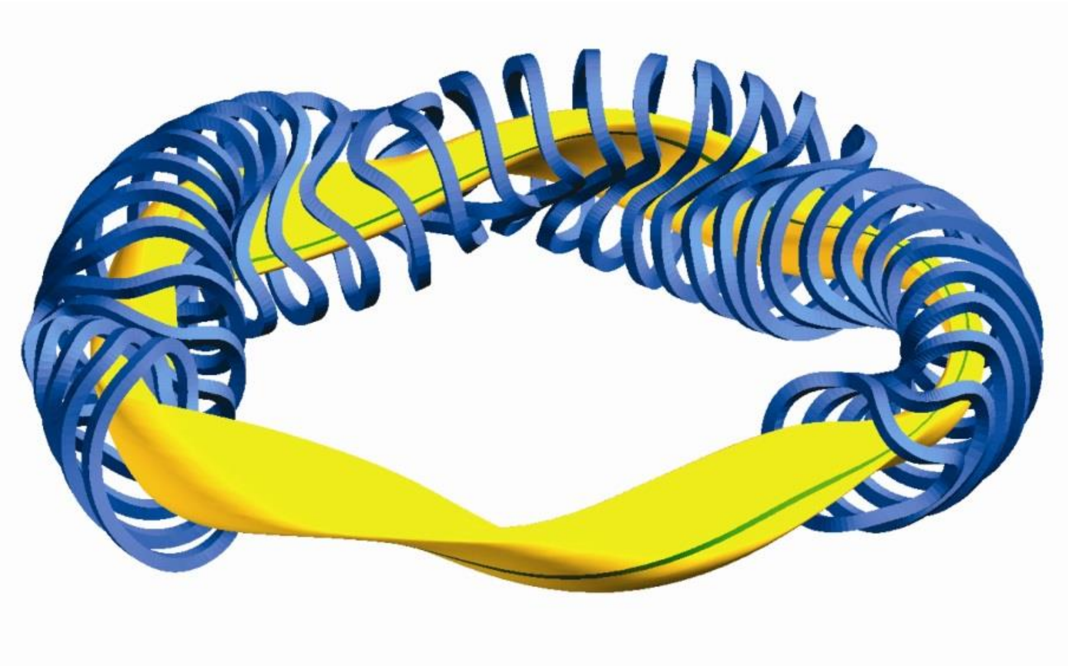
100 μg Tritium and
70 μg Deuterium

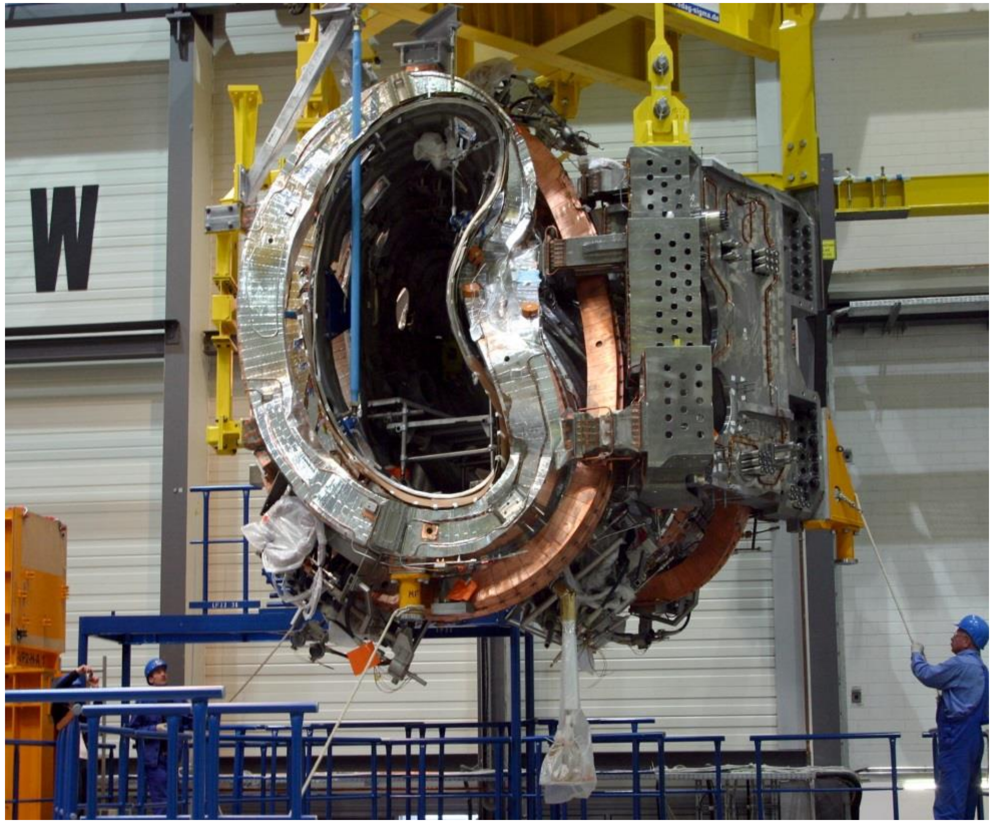
Using fossil fules:

- 1.06 kg natural gas or
- 3.9 kg lignite coal



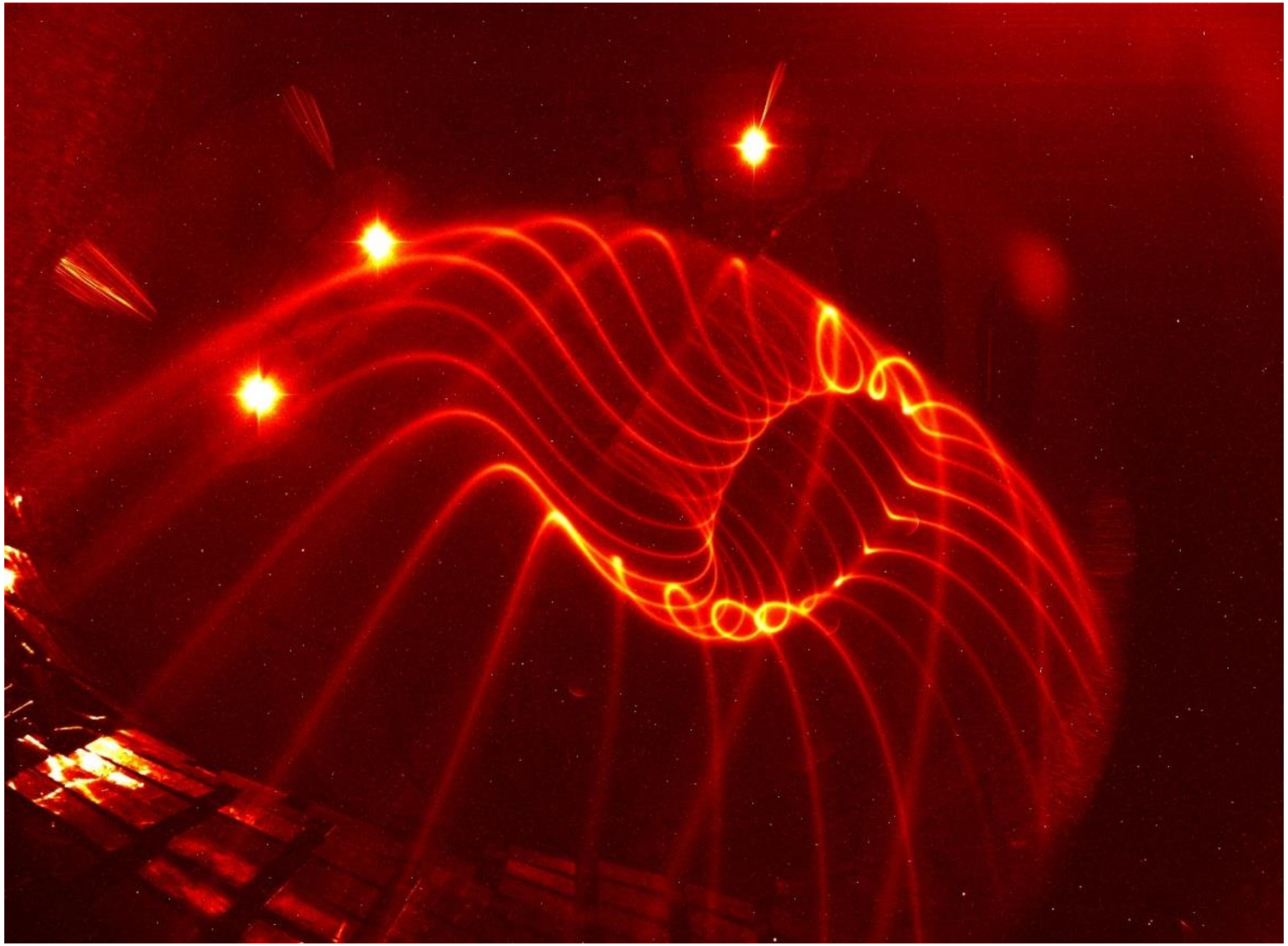
With W7-X the Stellarator is Catching Up





Complex technological problems were solved – W7-X in operation since 2016

Magnetic Field in W7-X Precisely Matches Target Configuration



Stationary Plasma Discharges in W7-X

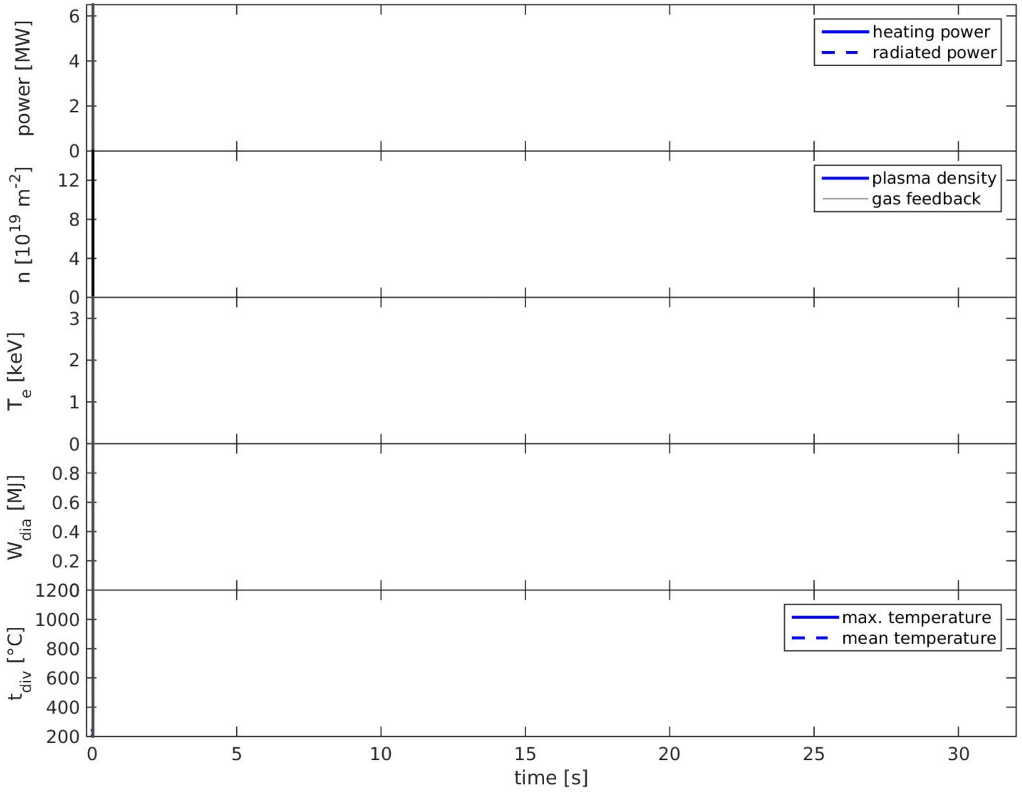
Heating power

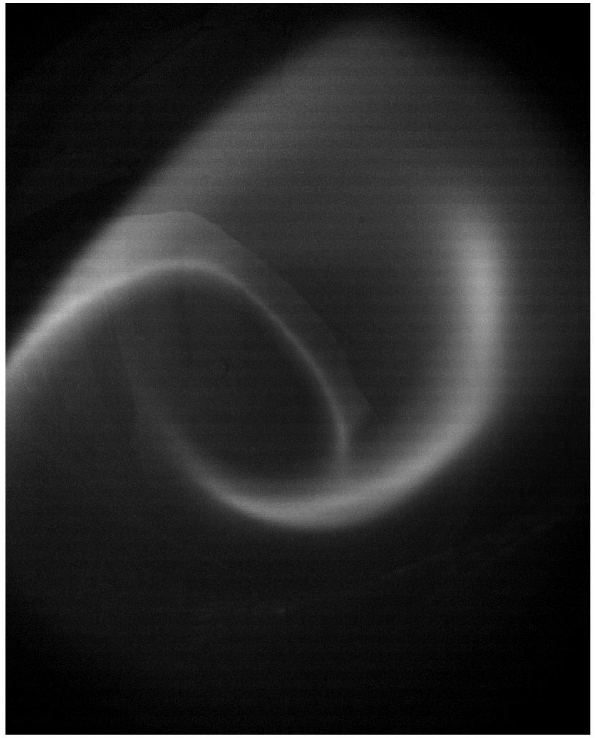
Plasma density

Electron temperature

Plasma energy

Divertor temperature

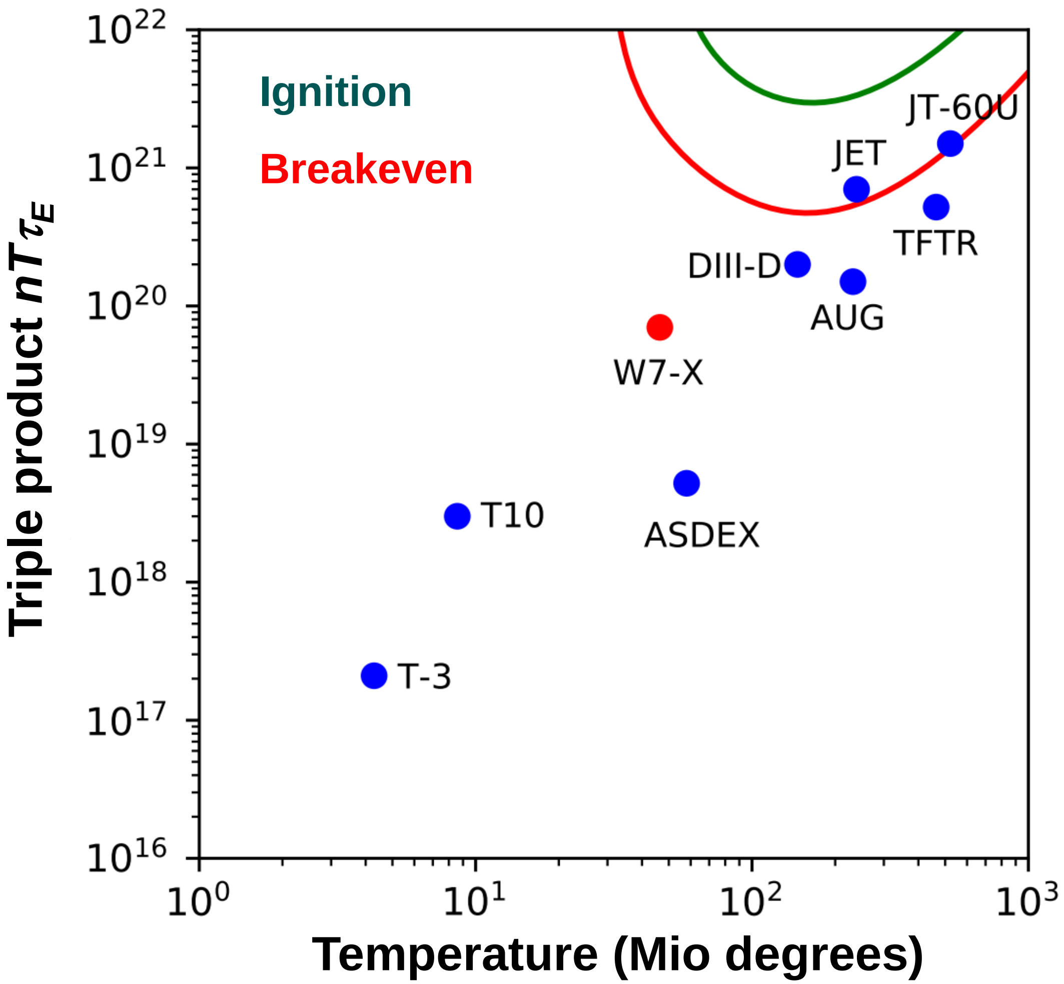




In the first operational campaign, long discharges were obtained without problems

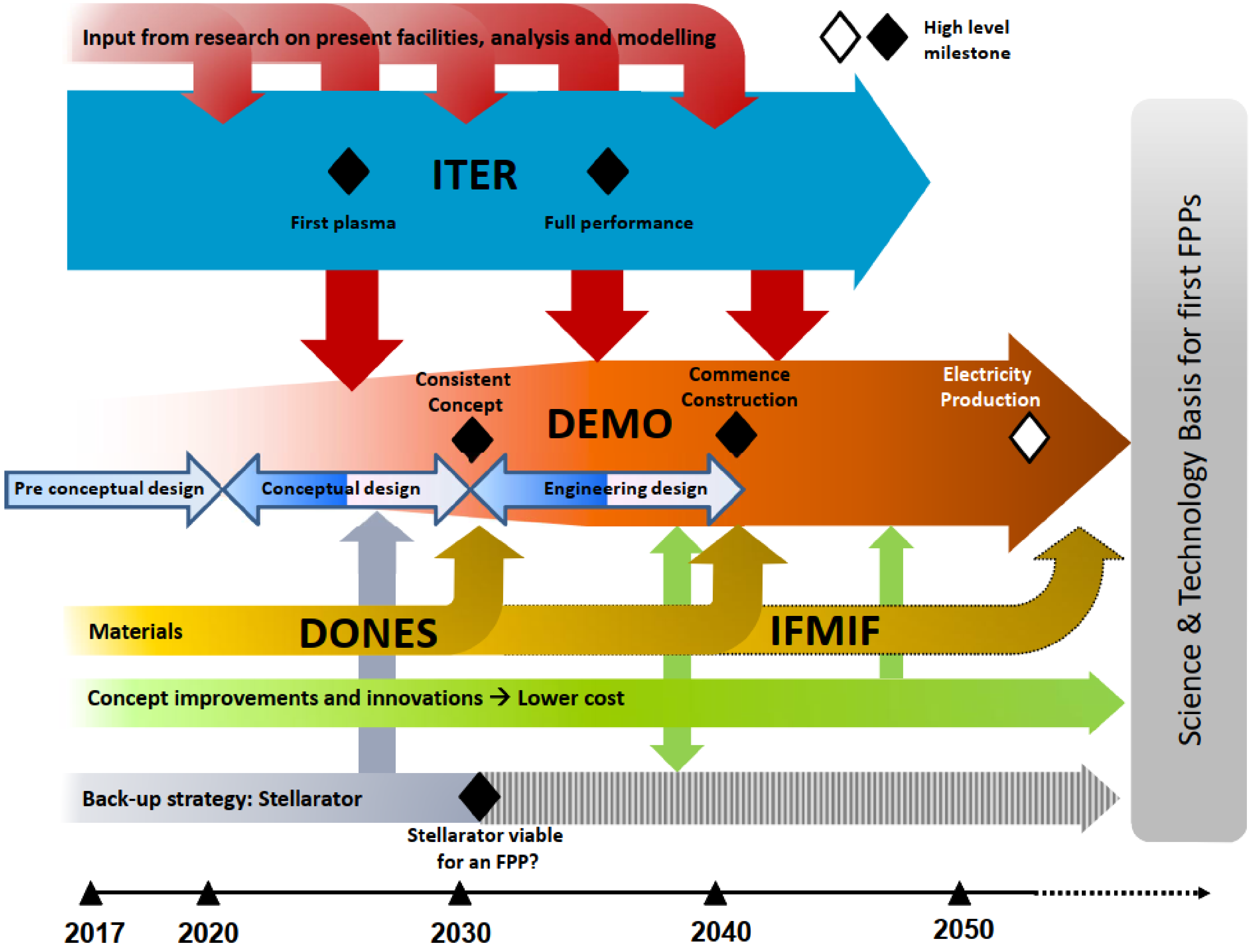
- limited by inertial cooling of wall elements (first experimental campaign until 2019)
- machine now actively cooled and resumed operation (as of October 2022)

With W7-X the Stellarator is Catching Up

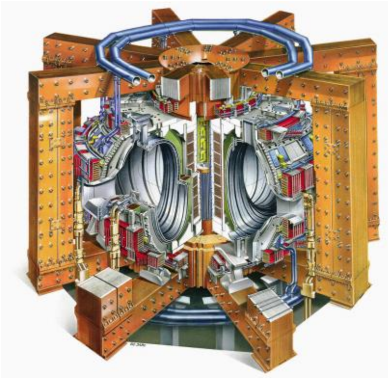


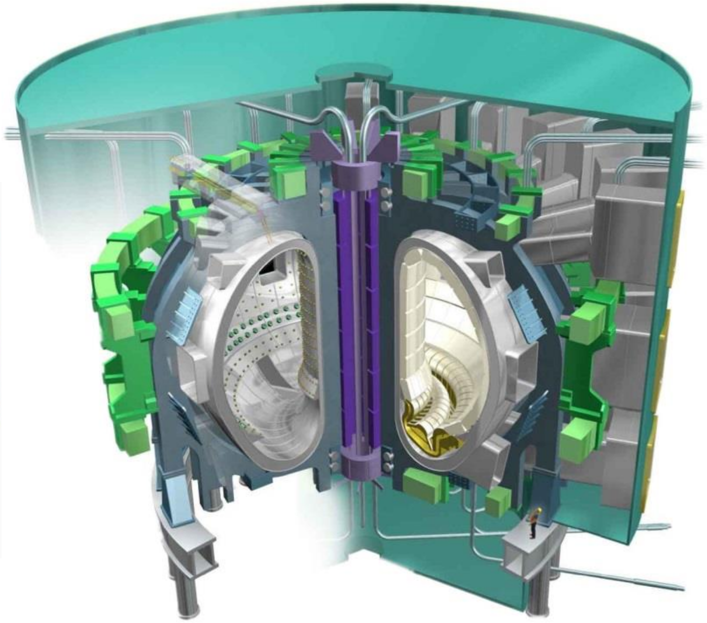
2018: record values in $nT\tau_E$ for a stellarator

EU Roadmap to Fusion Power



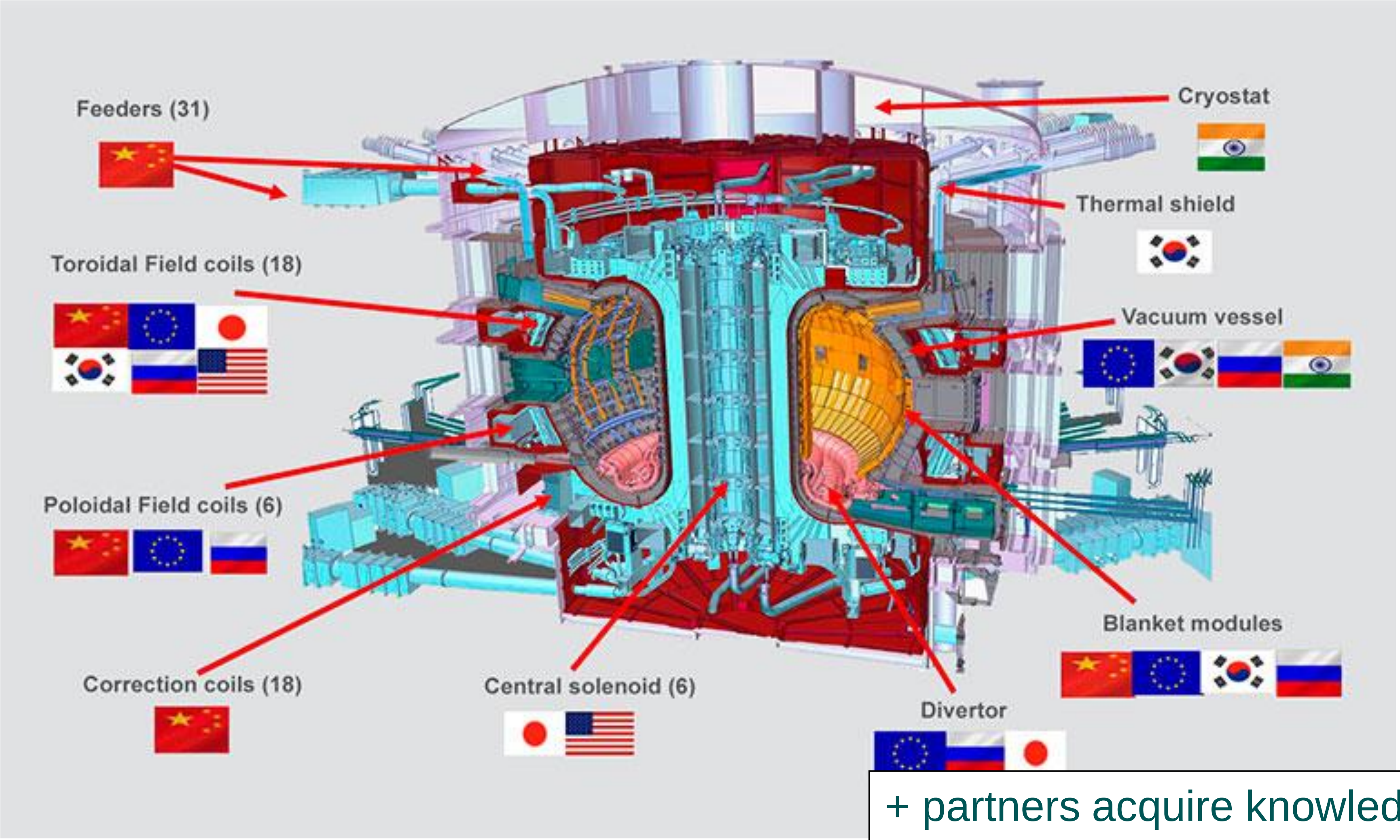
A ‚Step Ladder‘ Approach to Fusion Power





	ASDEX Upgrade	***JET***	***ITER***
Diameter	*3.3 m*	*6 m*	*12 m*
Volume	*14 m³*	*80 m³*	*800 m³*
Fusion Power	*1.5 MW*	*~ 10 MW*	*~ 500 MW*
	(D-T equivalent)	*(D-T)*	*(D-T)*

ITER Partner Build Machine by ‚in-kind' Contributions



ITER partners
- China
- Europe
- India
- Japan
- Korea
- Russia
- USA

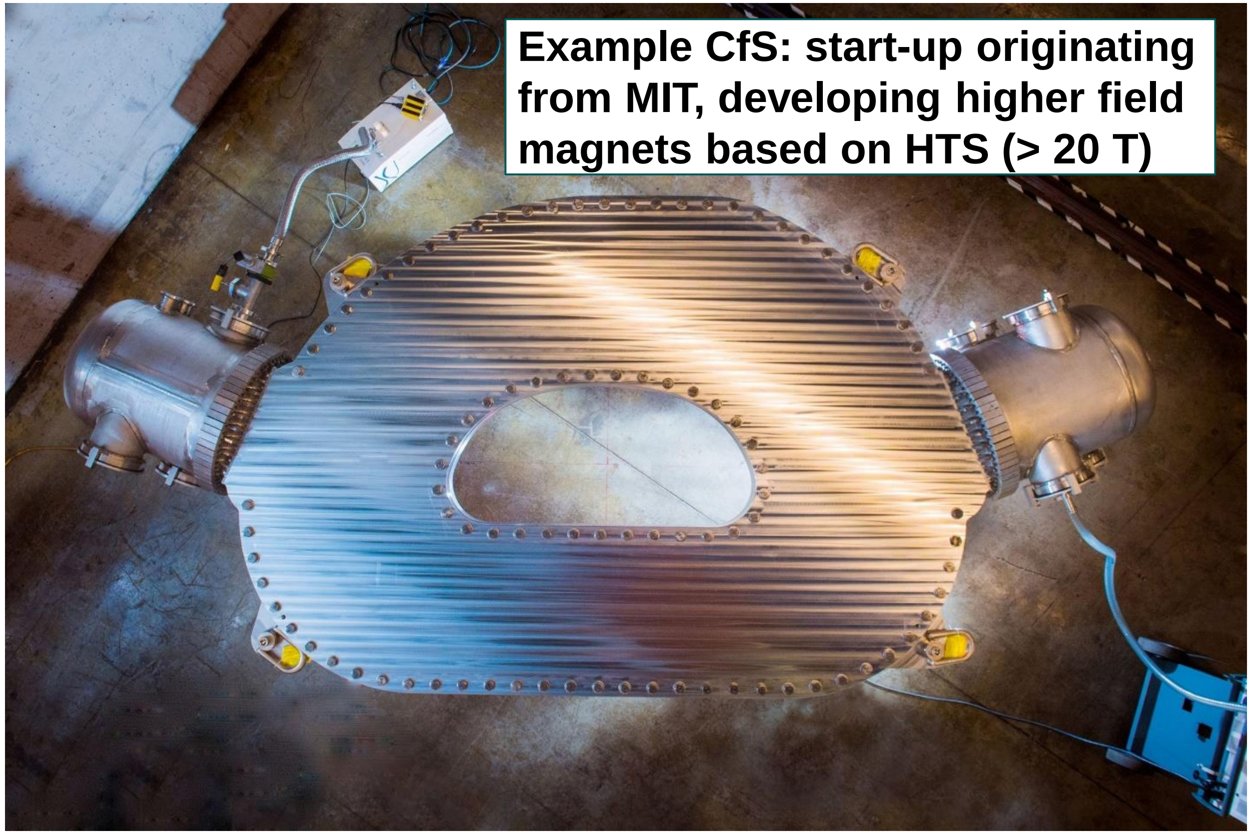
+ partners acquire knowledge in all technologies

- very complex project management

Faster by ‚Private-Public Partnership'?

Fusion Industry Association:

- **25 members**
- **> 4 Bio €**



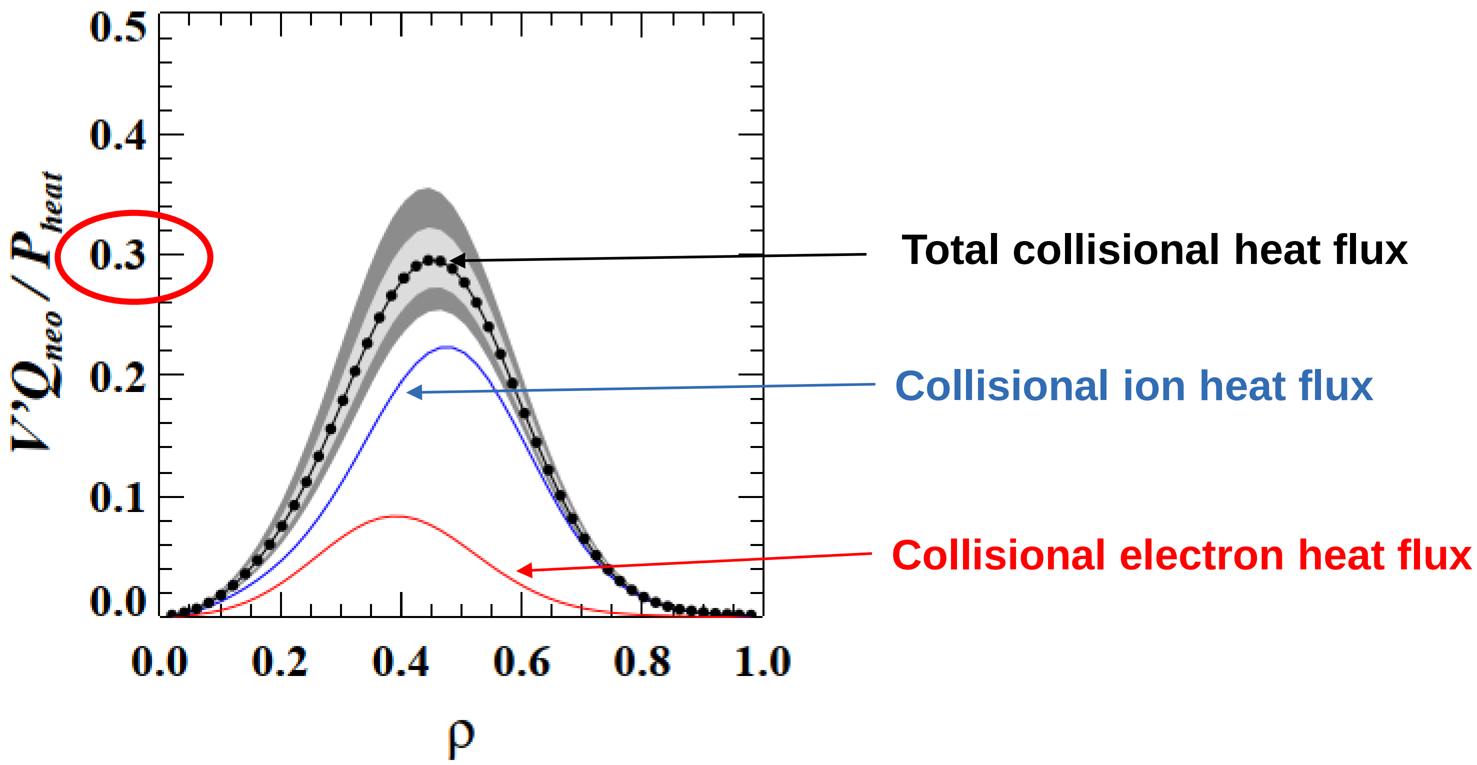
Example CfS: start-up originating from MIT, developing higher field magnets based on HTS (> 20 T)

Over the last ~ 5 years, significant private funding enabled a number of start-ups

- big chance: private companies willing to take greater risk in developing fusion technology
- big risk: scientific basis / time plans sometimes less carefully scrutinised than publicly funded ones

The end of part I

W7-X Results Validate Optimisation Strategy



One optimization criterion of W7-X was to reduce collisional transport (dominates w/o optimization)

- successful, transport now dominated by turbulence (as is the case in tokamaks)
- starting point for further optimization studies (turbulence optimised stellarators)