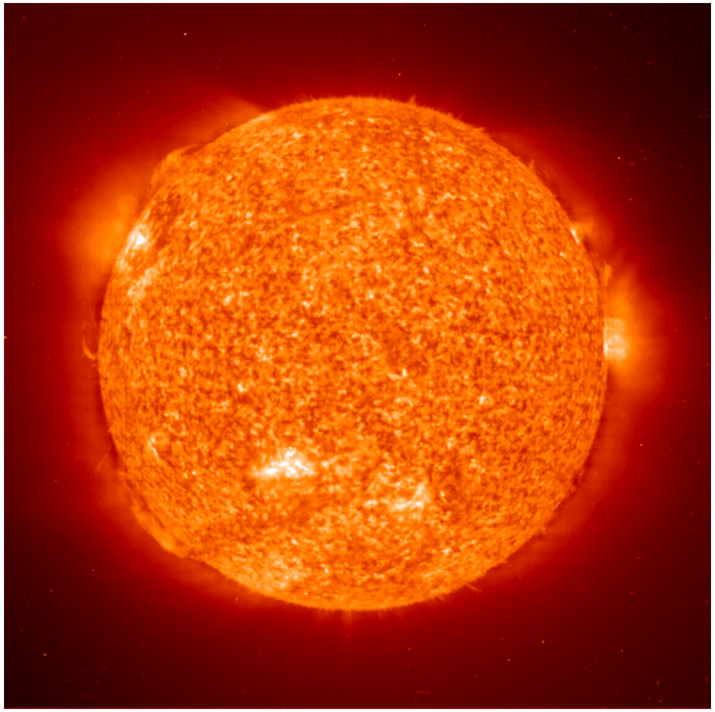
The tokamak principle – magnetic fusion



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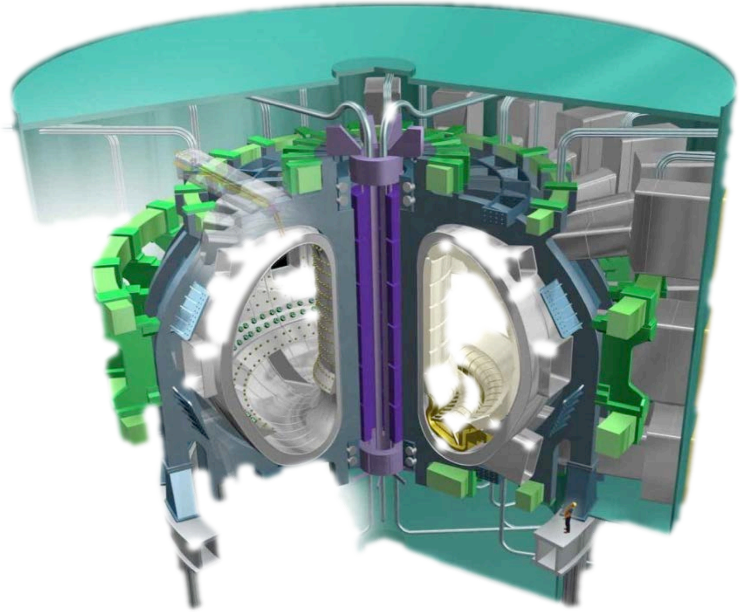


Joint ICTP-IAEA College on Advanced Plasma Physics, Triest, Italy, 2016

Based on lectures given by Hartmut Zohm, Ursel Fantz, Sebastijan Brezinsek, Sibylle Günter and additional material

Outline

Introduction: The inspiration

Nuclear Fusion - The tokamak principle – magnetic fusion (~60 min)

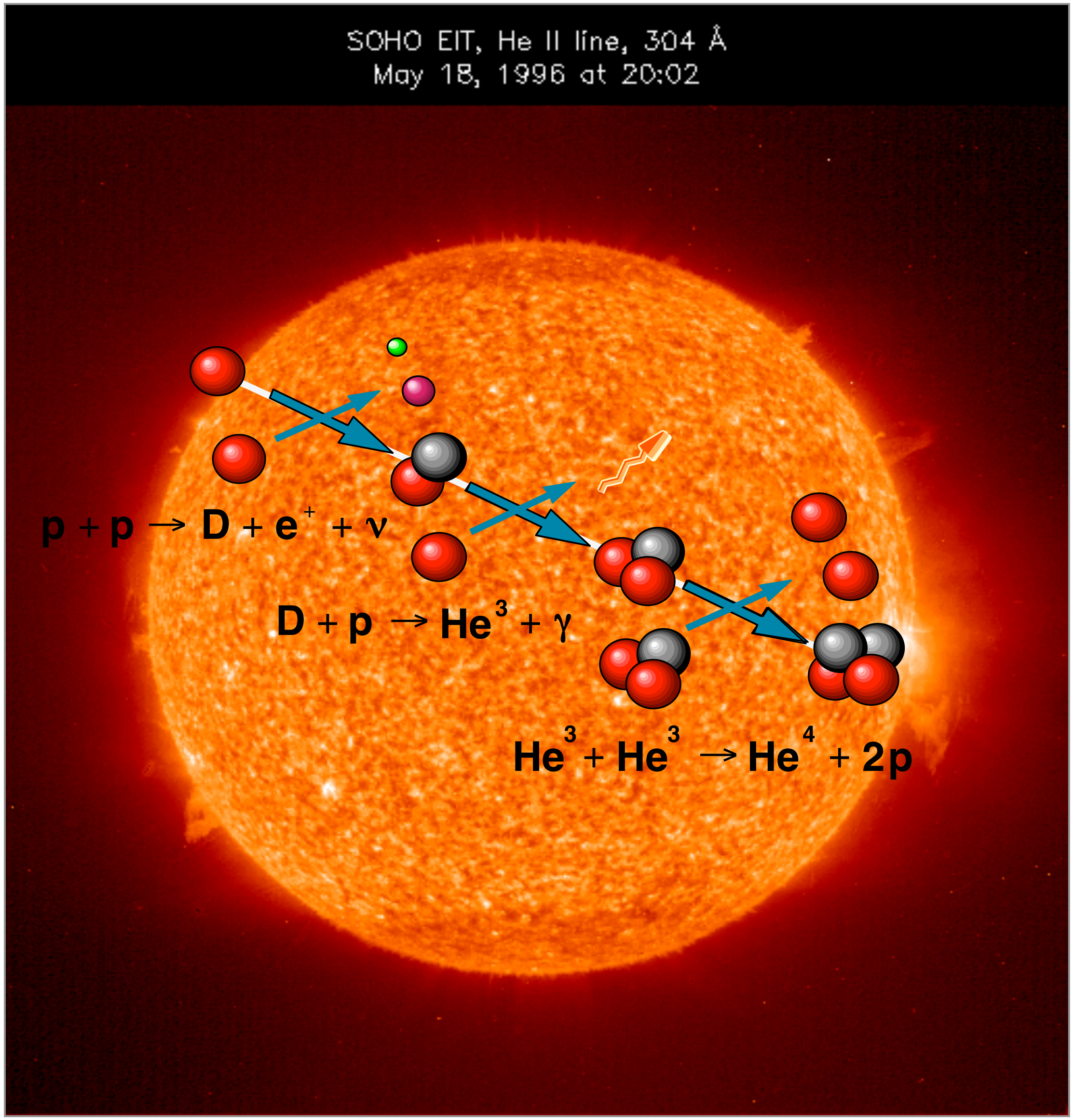
Progressing Performance – Tokamaks Core physics (~60 min)

Power Exhaust – Materials for Tokamaks (~60 min)

The inspiration

Particles fuse inside the sun

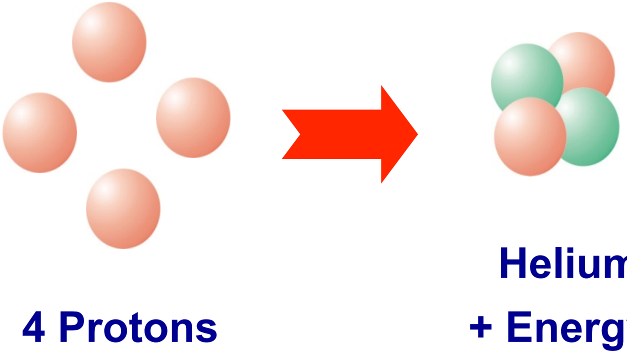
Nuclear fusion - the energy source of the sun and the stars



Energy set free by fusion of light nucleii, in the sun:

pp-cycle

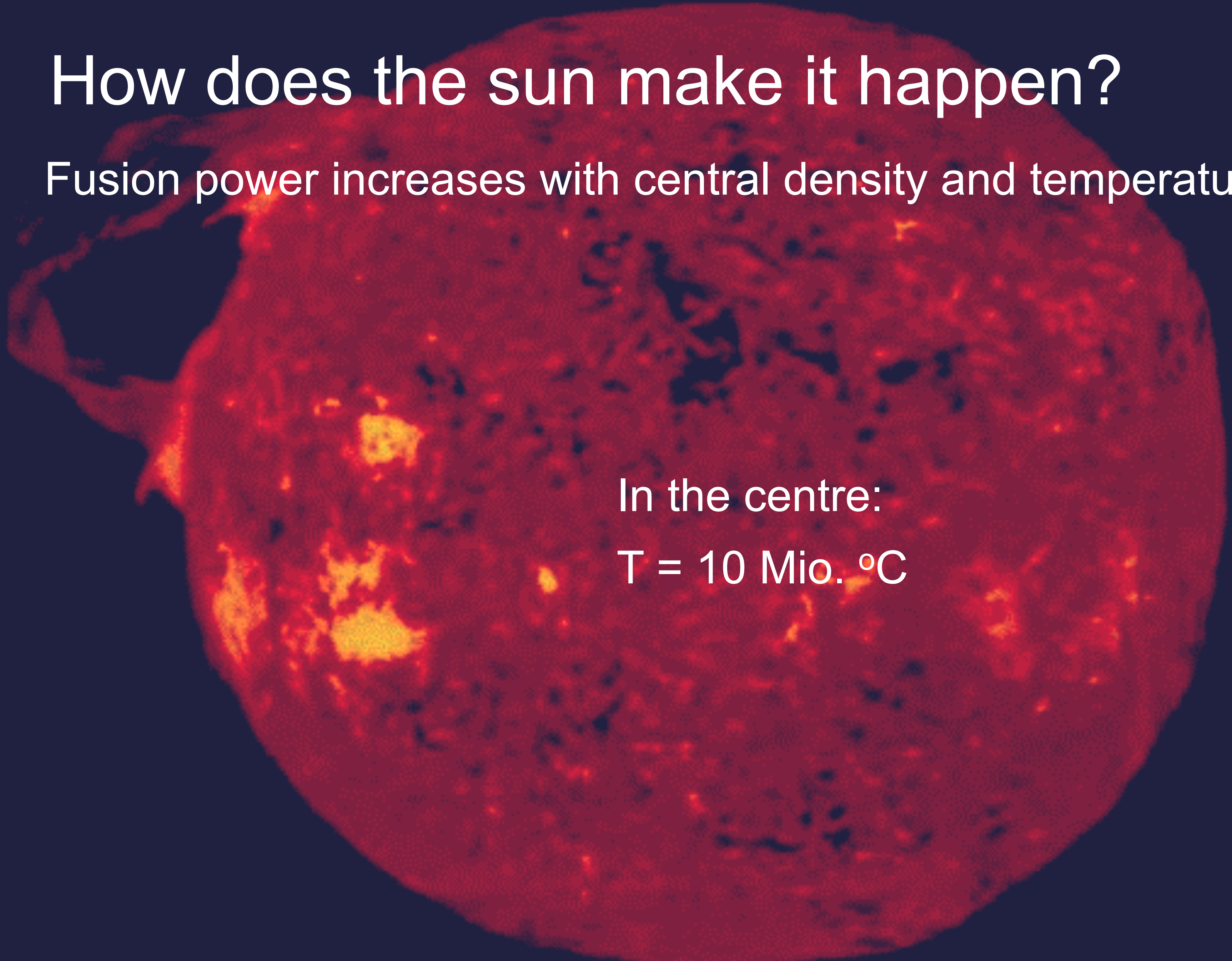
Essentially:



weak interaction involved, thus small fusion rates, on earth: 10^{27} times larger fusion rates required

How does the sun make it happen?

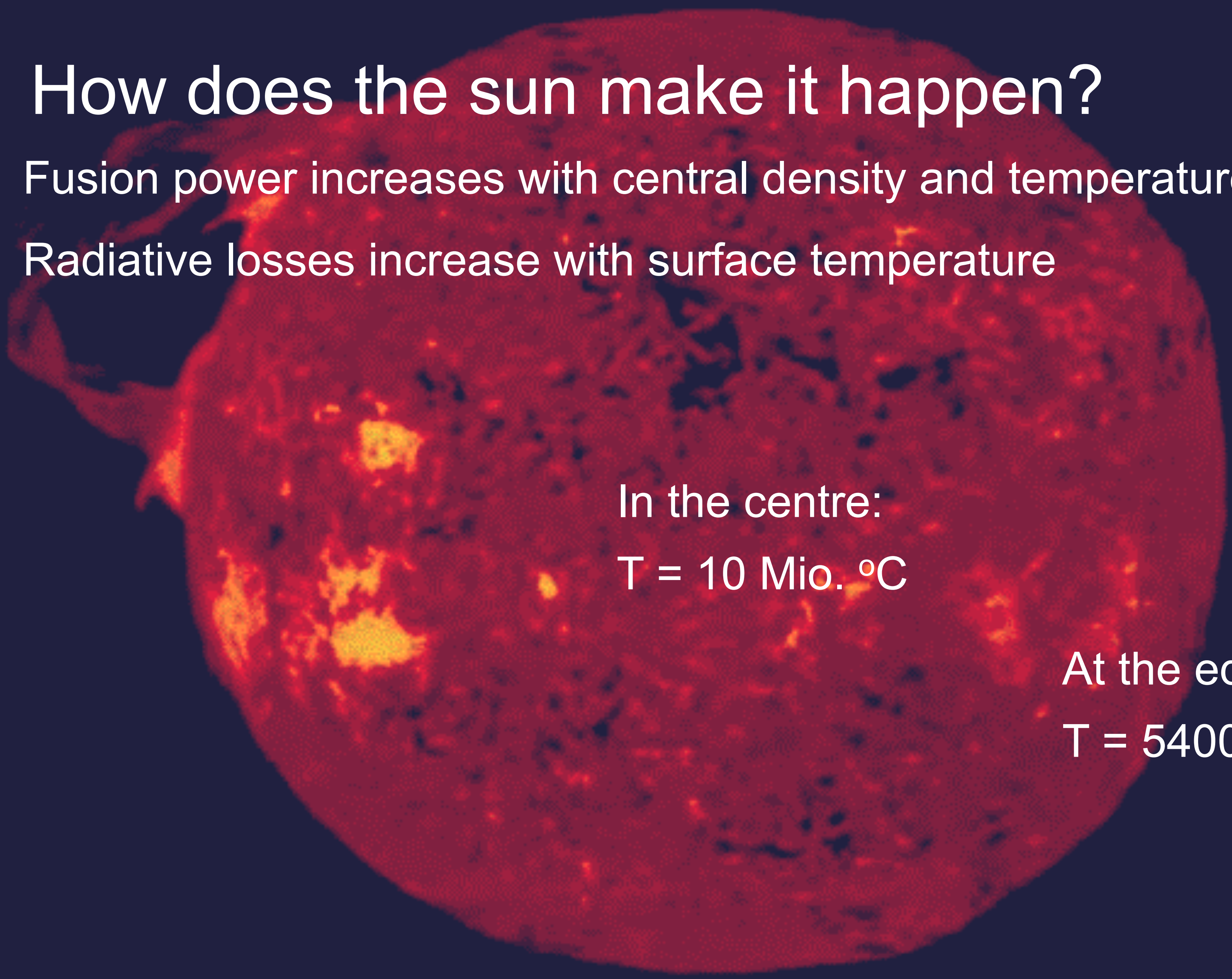
Fusion power increases with central density and temperature



In the centre:

T = 10 Mio. ºC

How does the sun make it happen?



Fusion power increases with central density and temperature

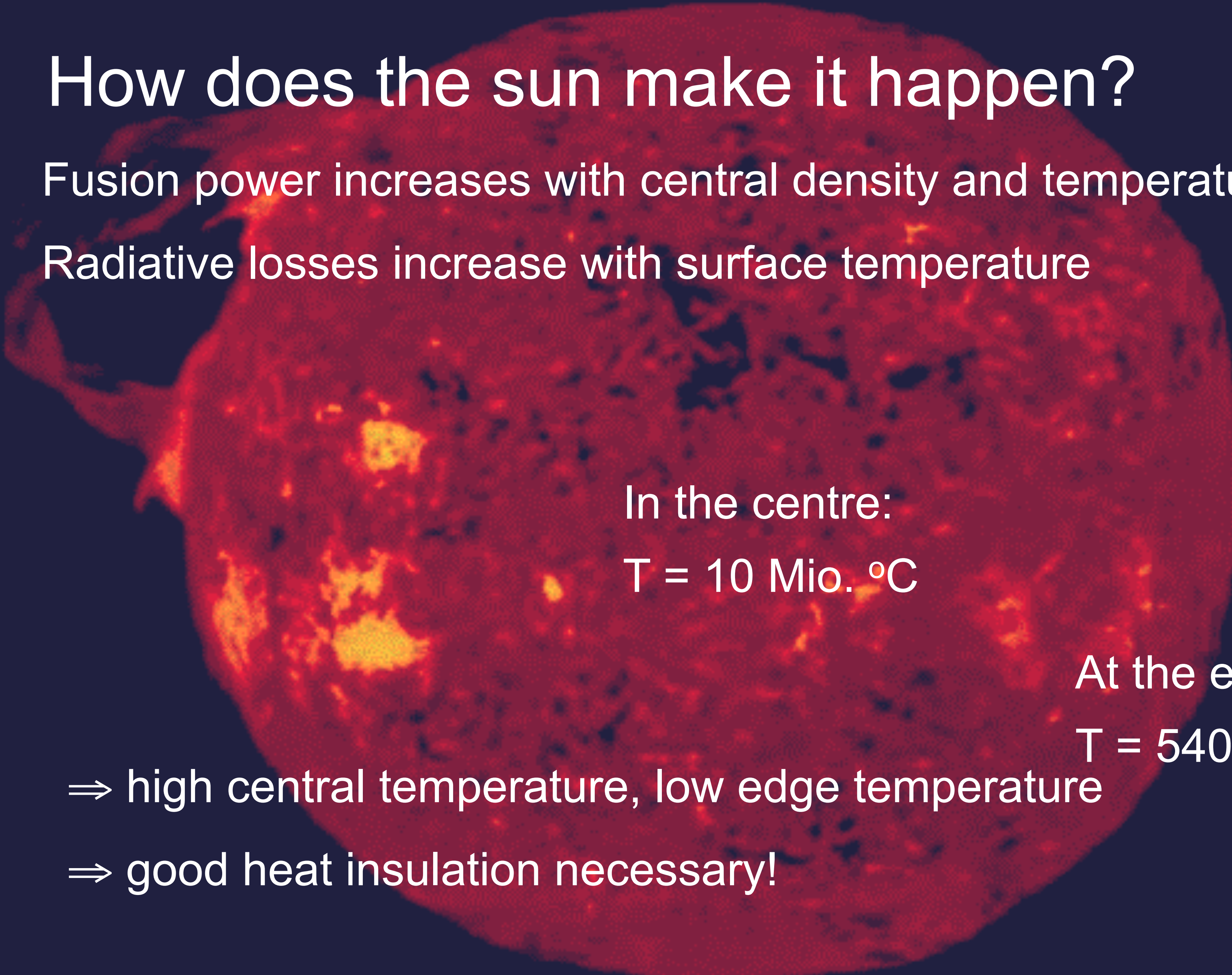
Radiative losses increase with surface temperature

In the centre:

T = 10 Mio. °C

At the edge:

T = 5400 °C



How does the sun make it happen?

Fusion power increases with central density and temperature

Radiative losses increase with surface temperature

In the centre:

T = 10 Mio. °C

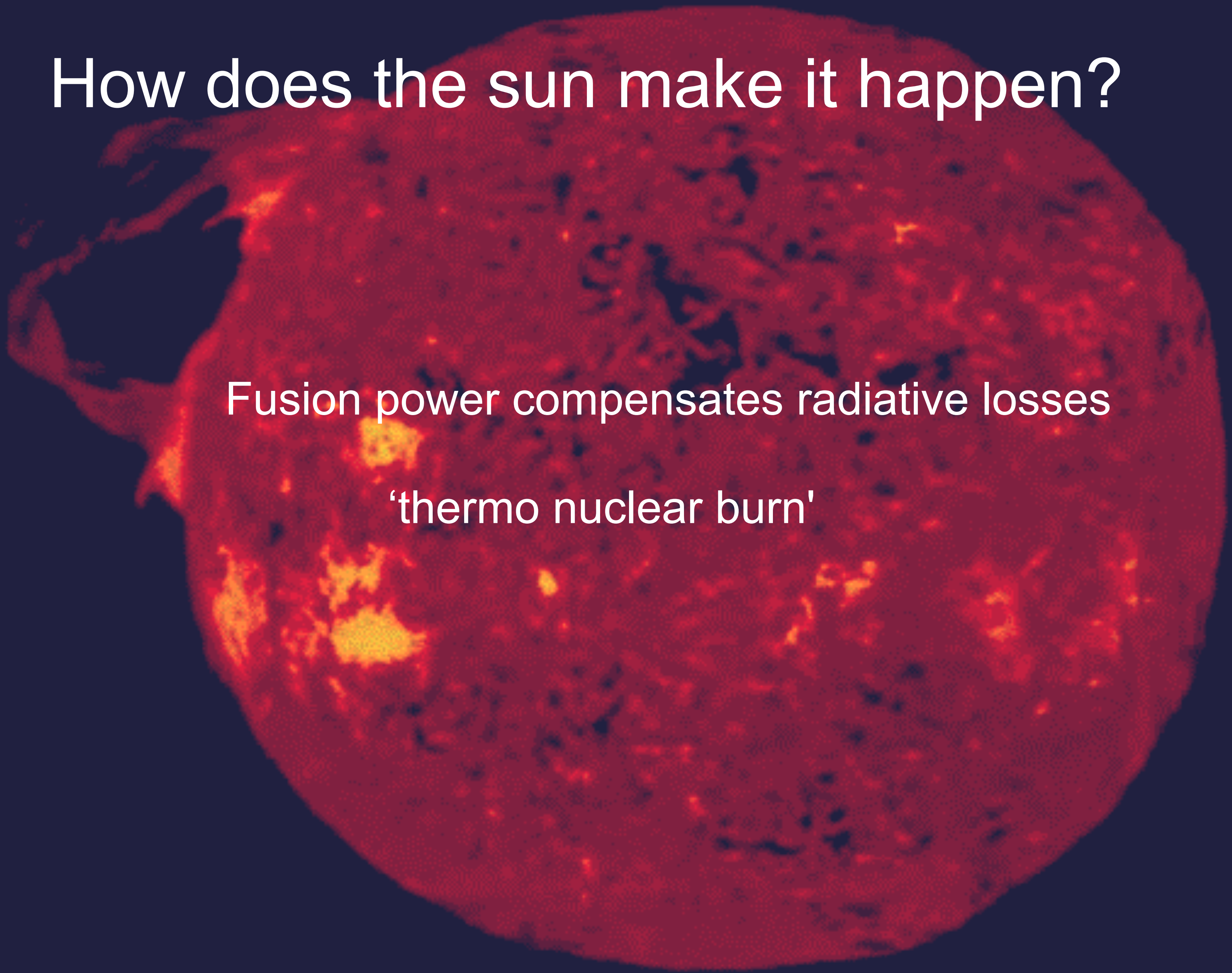
At the edge:

T = 5400 °C

⇒ high central temperature, low edge temperature

⇒ good heat insulation necessary!

How does the sun make it happen?

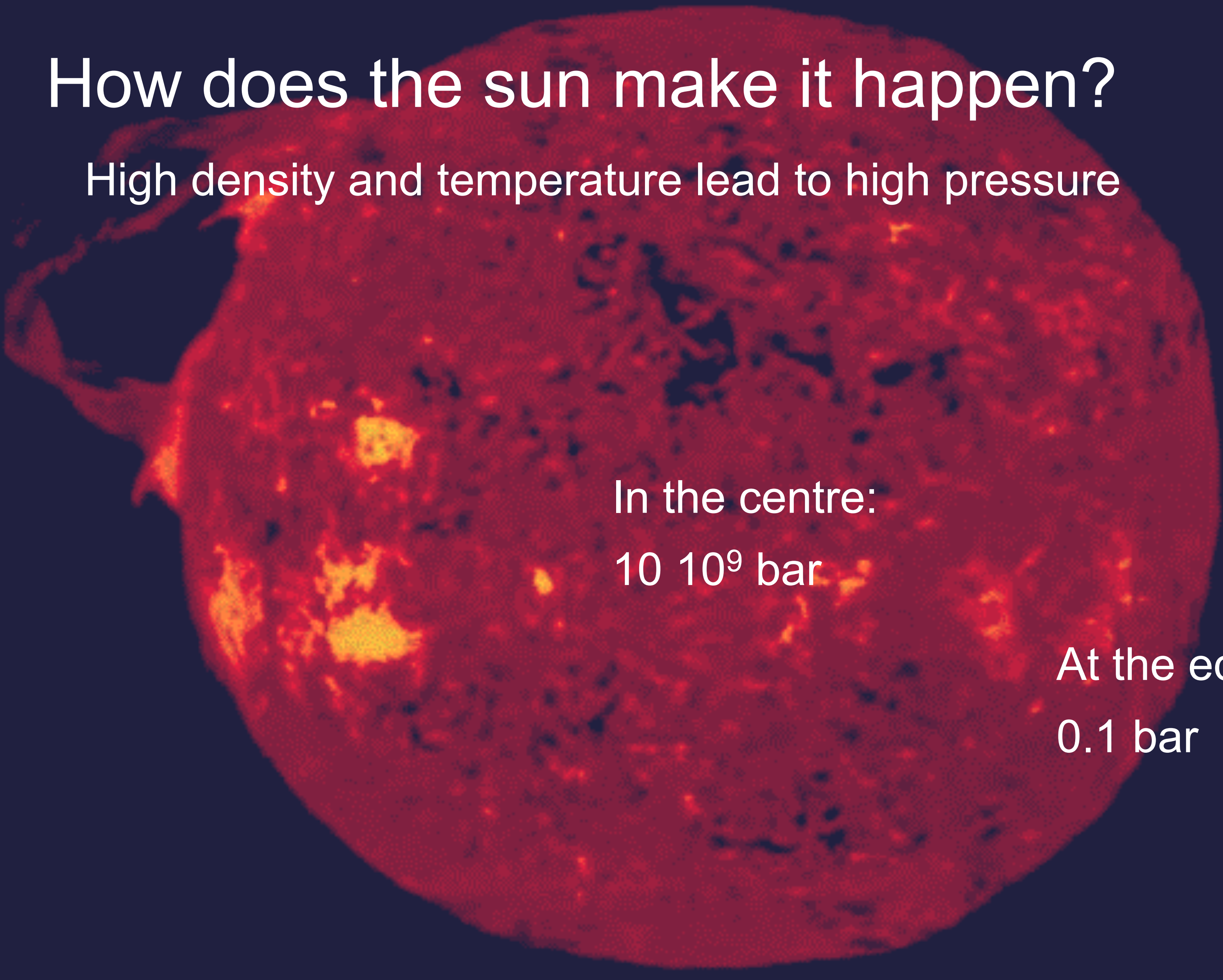


Fusion power compensates radiative losses

‘thermo nuclear burn'

How does the sun make it happen?

High density and temperature lead to high pressure



In the centre:

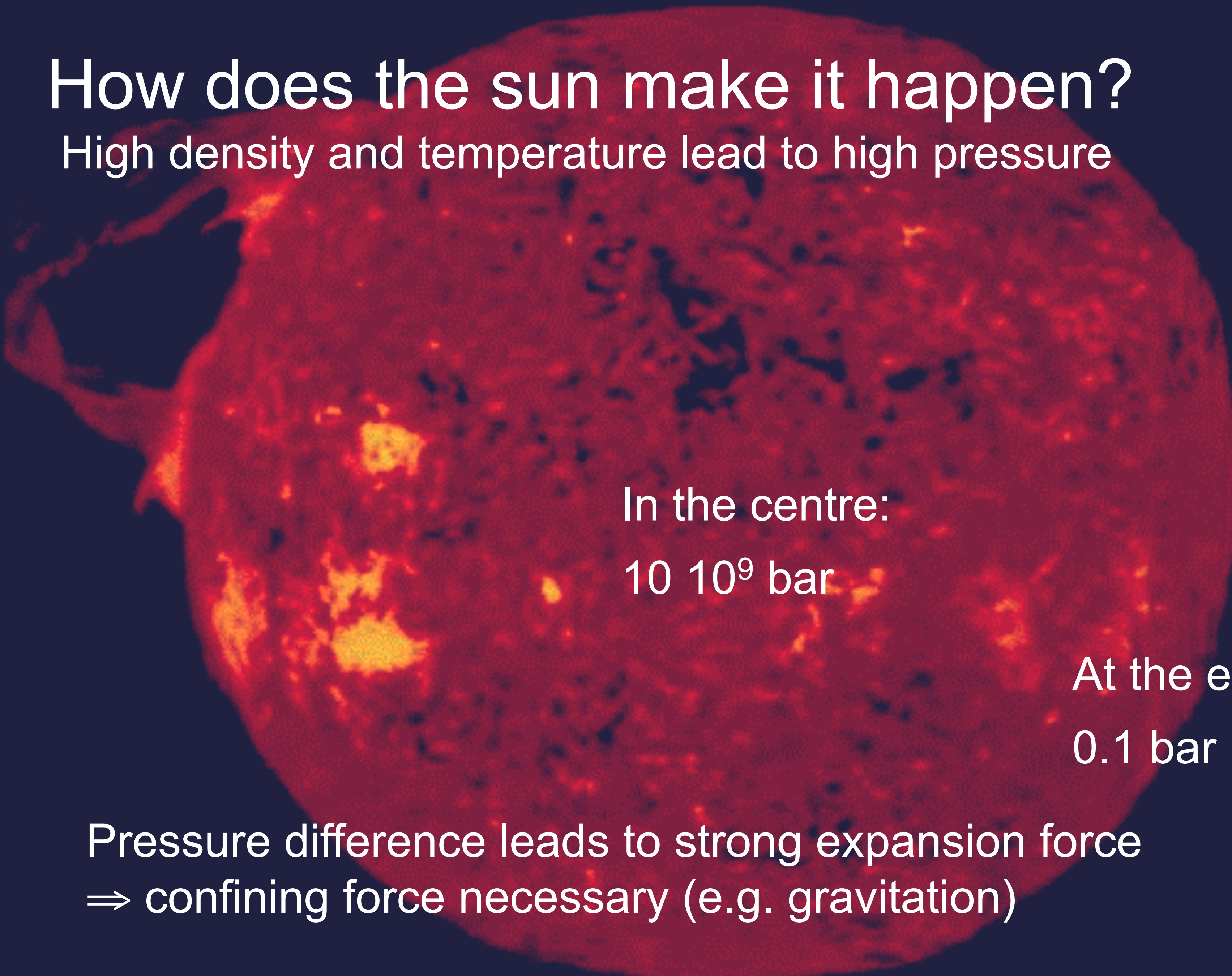
$10\ 10^9$ bar

At the edge:

0.1 bar

How does the sun make it happen?

High density and temperature lead to high pressure



In the centre:

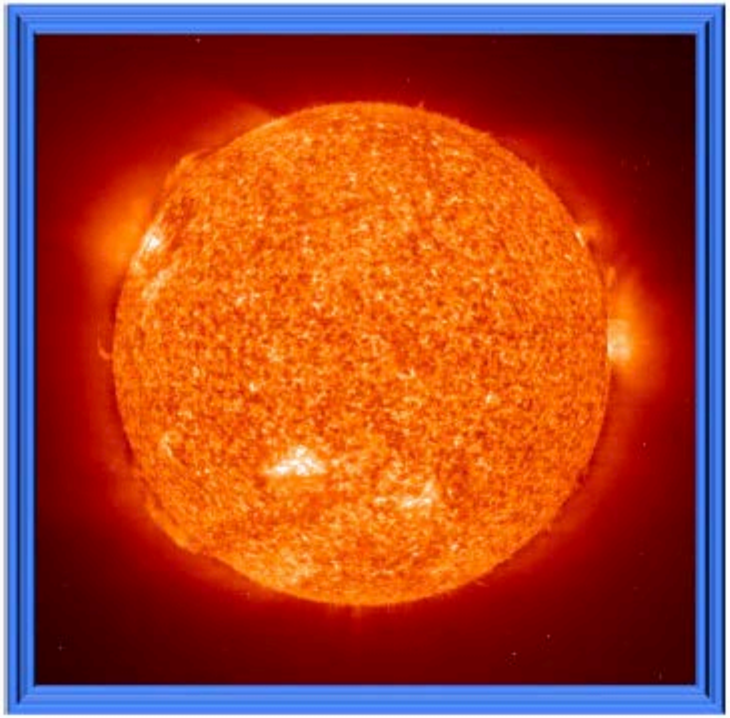
$10\ 10^9$ bar

At the edge:

0.1 bar

Pressure difference leads to strong expansion force
⇒ confining force necessary (e.g. gravitation)

Aim of nuclear fusion research



We say we want to put the sun into a box.
The idea is great. The problem is, that we
don't know how to build the box.

Sébastien Balibar, research director at CNRS

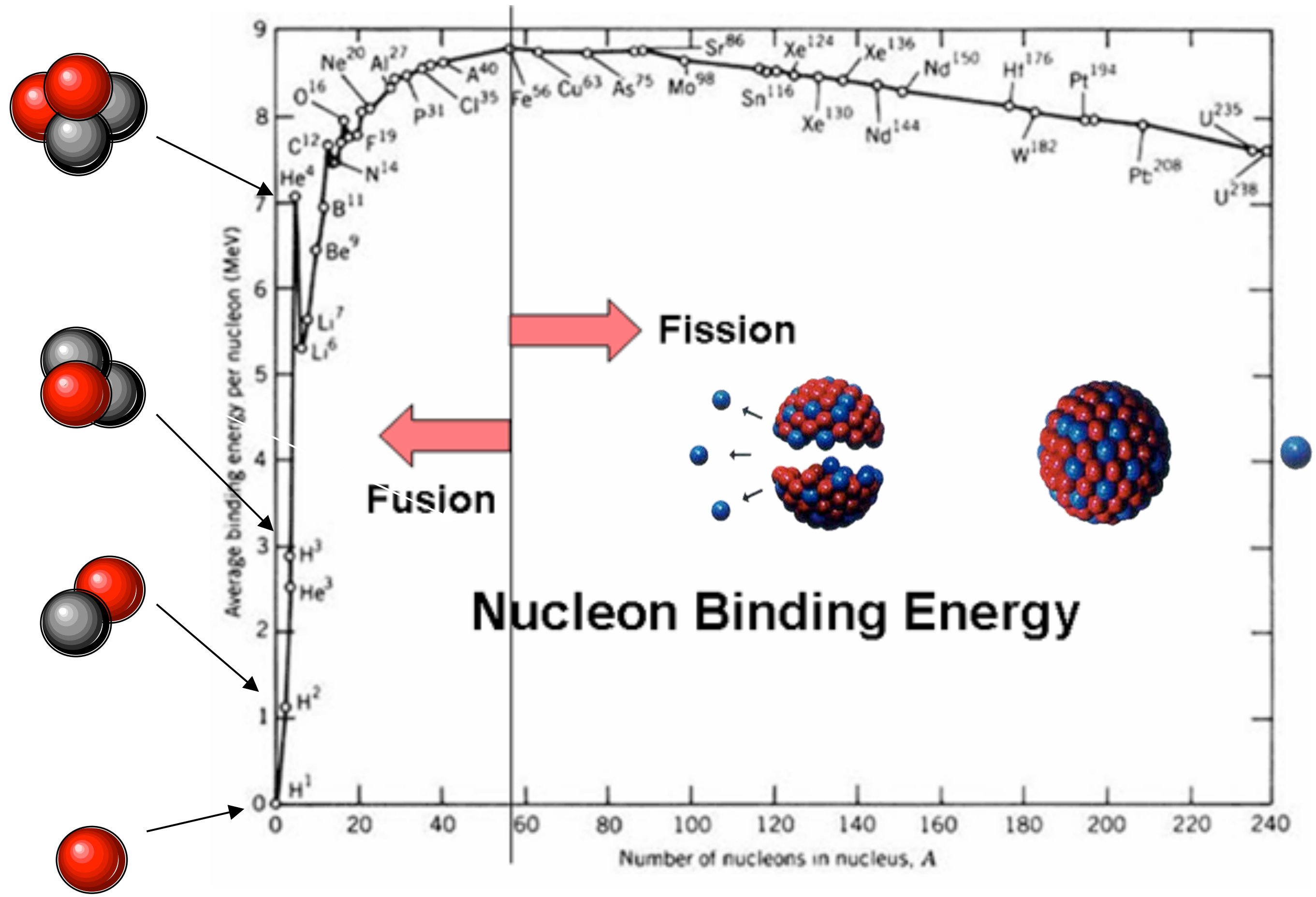
Methods for energy production

Helium

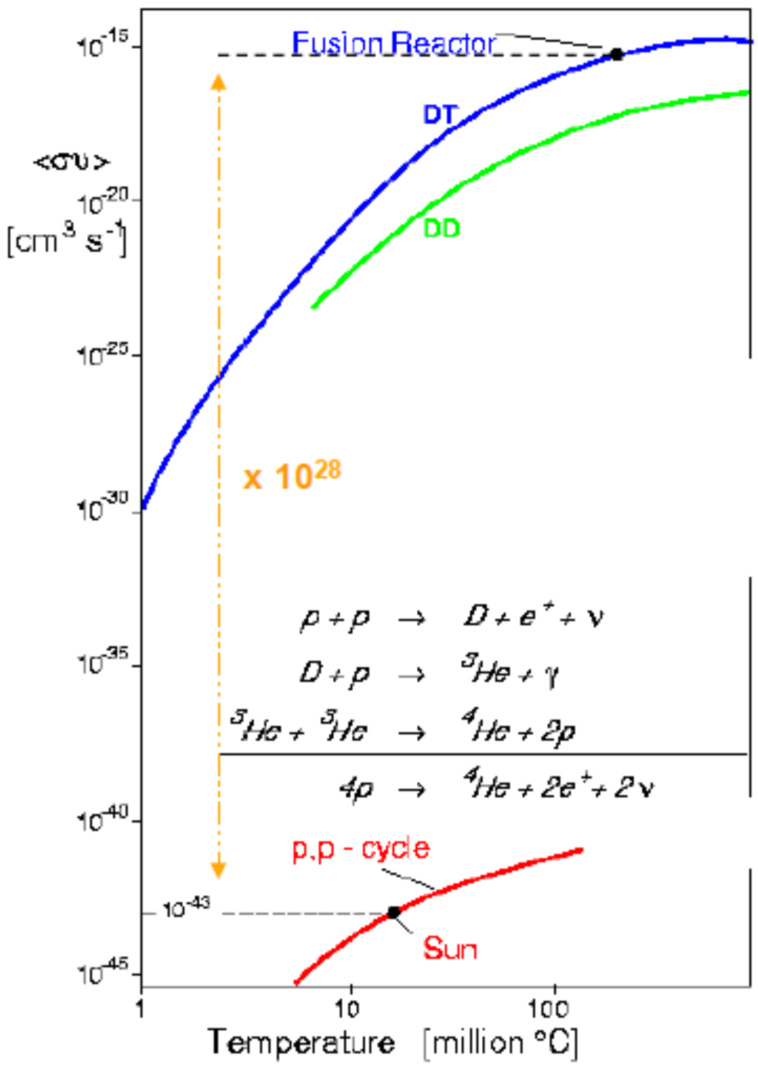
Tritium

Deuterium

Proton



Nuclear fusion on earth – the right reaction

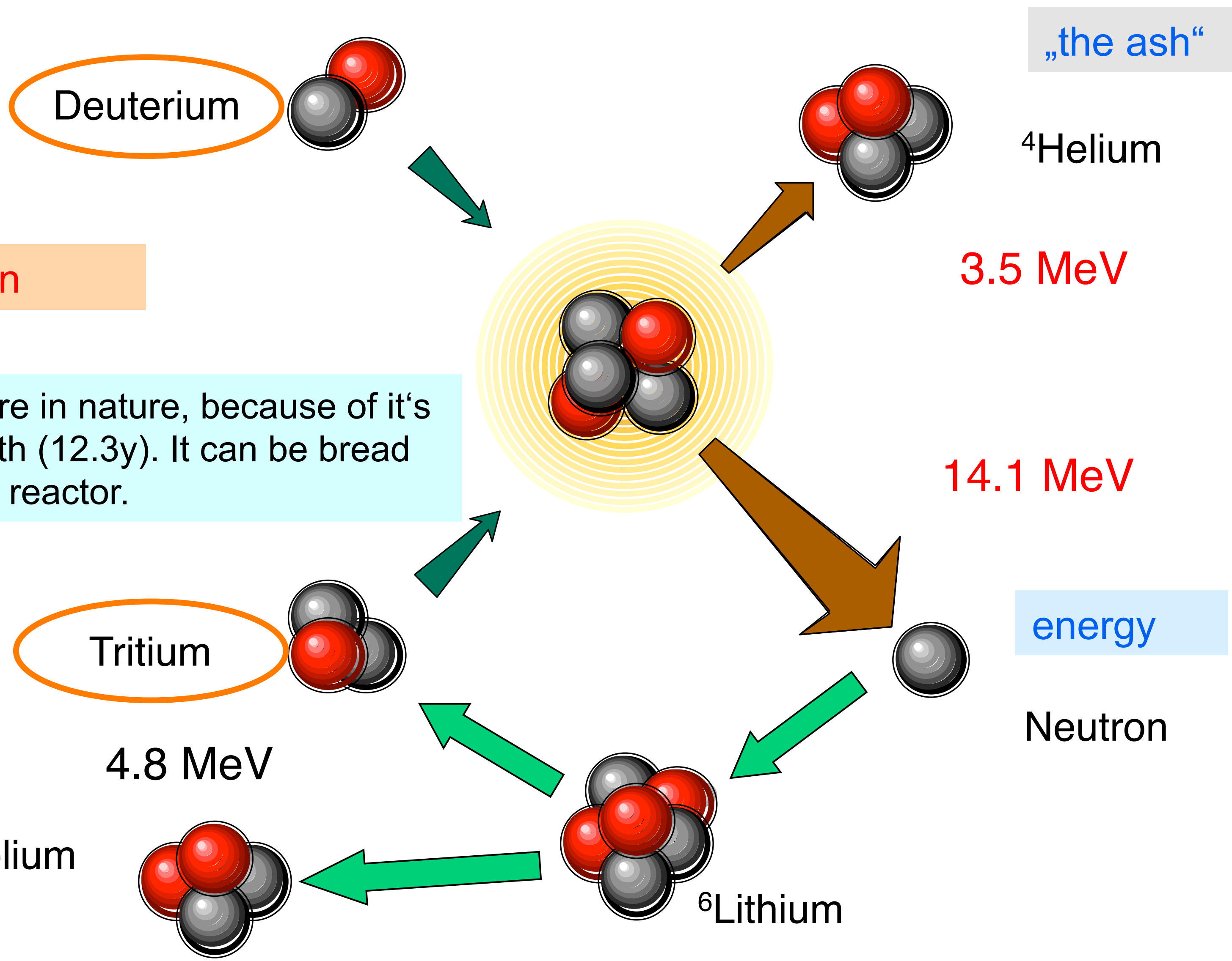


- ➢ Rate for DD and DT reactions is much larger than pp reaction
- ➢ DT plasma is a candidate for fusion reactor
- ➢ Problems:
  - ❖ high temperature (100Mio C)
  - ❖ T is radioactive: t ½ = 12.3 y
  - ❖ T is not easily accessible and must be bread from Li

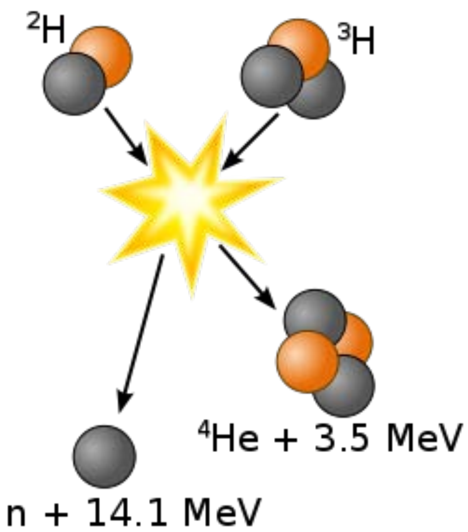
In a power plant: fusion of deuterium and tritium

Fuel for fusion

Tritium is very rare in nature, because of it‘s short decay length (12.3y). It can be bread from Lithium in a reactor.



Energy gain in a D-T-fusion reaction



Very high energy density and availability:

10000 t	coal corresponds to
800 g	D-T

Deuterium is contained in water to 0.015%.

Tritium must be generated in situ:

$^{6}Li + n \rightarrow {}^{4}He + {}^{3}T$

One bathtub of water
Li in a battery

↓

Energy for 50 years for an average family

Nuclear fusion on earth – energy balance

Easiest idea for fusion is:
collide to particle beams against each other

Energy needed for accelaration ~0.1MeV
Energy gain from fusion reaction: 17.6 MeV

Good deal!

Nuclear fusion on earth – energy balance

Easiest idea for fusion is:
collide to particle beams against each other

Energy needed for accelaration ~0.1MeV
Energy gain from fusion reaction: 17.6 MeV

Good deal!

Problem:

Particles are deflected by coulomb forces (nearly always)

Nuclear fusion on earth – energy balance

Fusion reaction:

- Difficult obstacle
- Very deep hole

Solution:

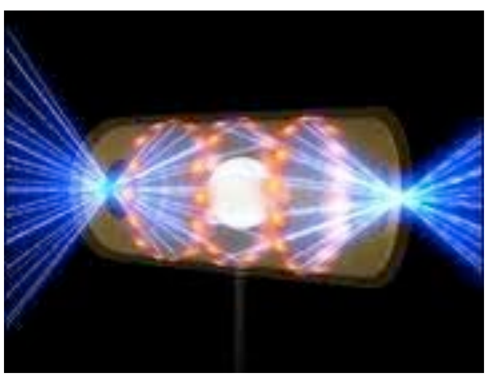
- Many attempts without having to accelerate the particles for each attempt
- Confining a DT mixture at high temperature (200Mio C)
- Every gas becomes a plasma at these temperatures

Two ways to fusion energy

D-T fusion needs temperatures 10 times larges than in the solar interior: ~150 Mio degrees

Inertial fusion:

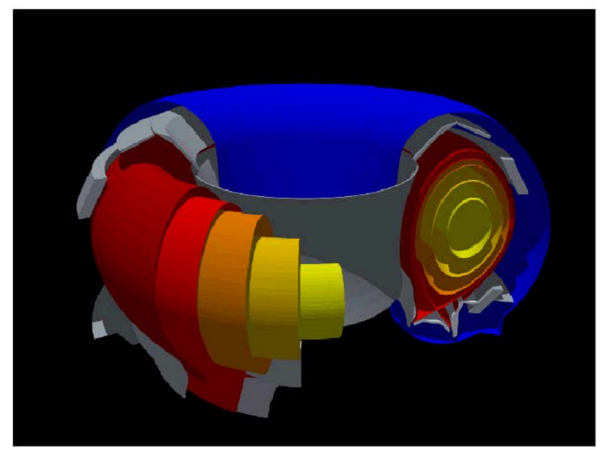
- fast heating (e.g. laser) of small pellets, minor explosions
- pressure comparable to solar interior ($n \sim 10^{31}\ m^{-3}$)
- confinement time $\sim 10^{-10}$



Mainly in the US and Japan, keep-in-touch activities in Europe

Magnetic fusion:

- confinement through magnetic fields
- very low pressure
- confinement time: a few seconds



Outline

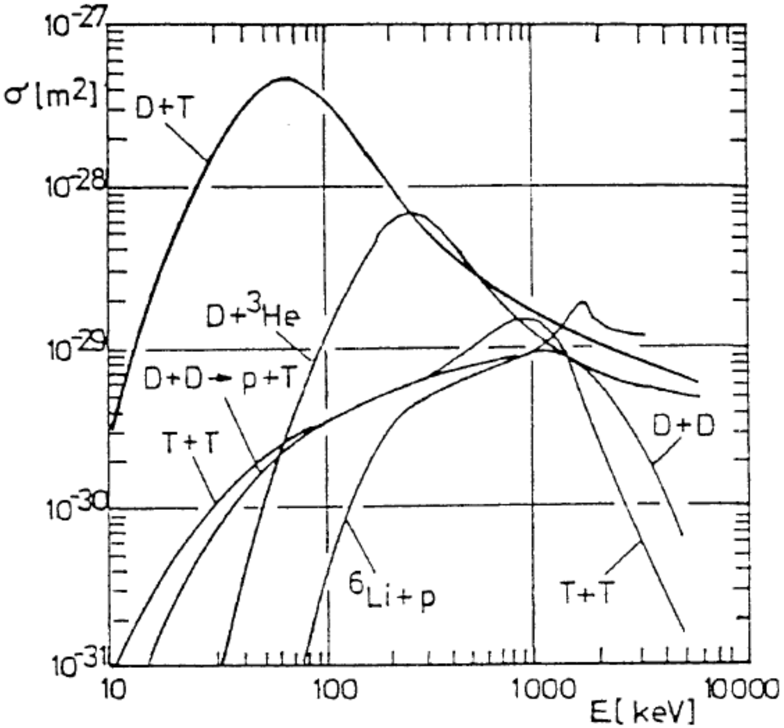
The tokamak principle – magnetic fusion (~60 min)

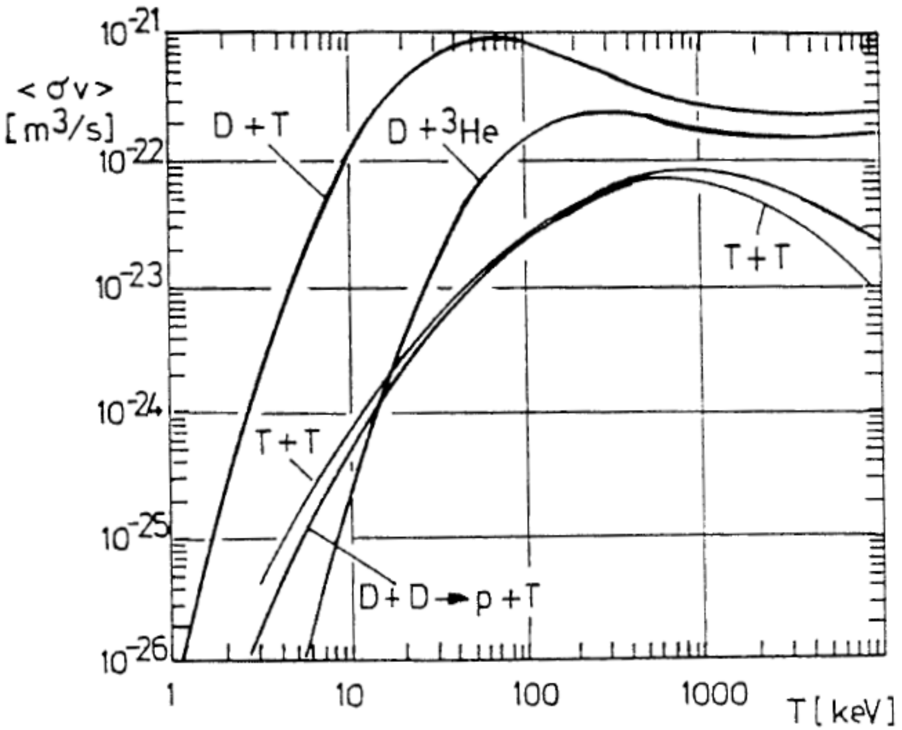
Progressing Performance – Tokamaks Core physics (~60 min)

Power Exhaust – Materials for Tokamaks (~60 min)

Basic Fusion Physics

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:

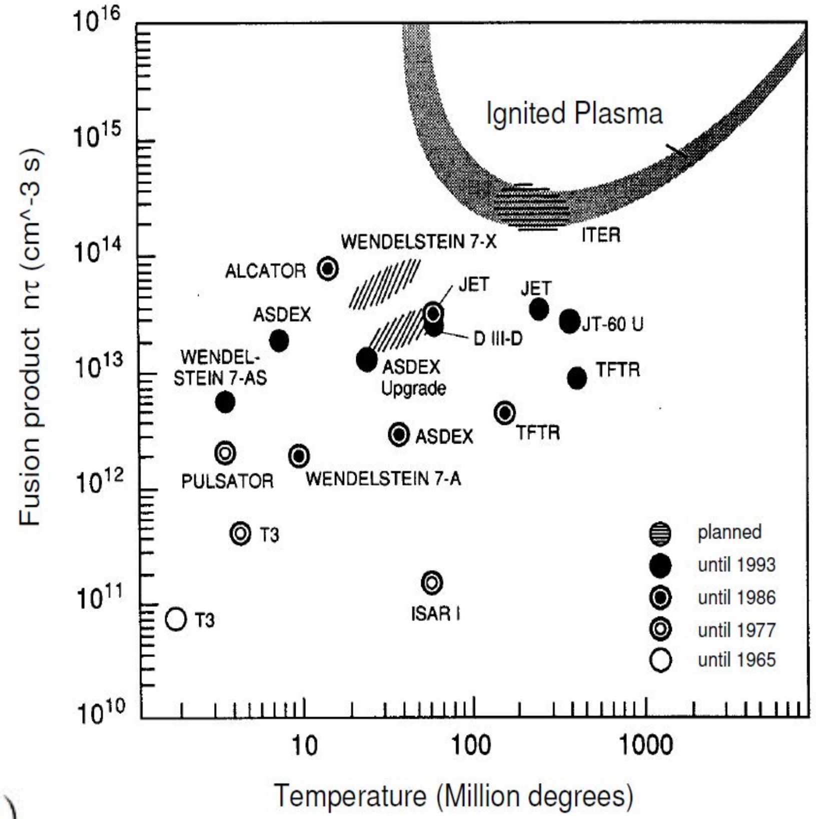
- radiative losses (Bremsstrahlung)
- heat conduction and convection

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

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

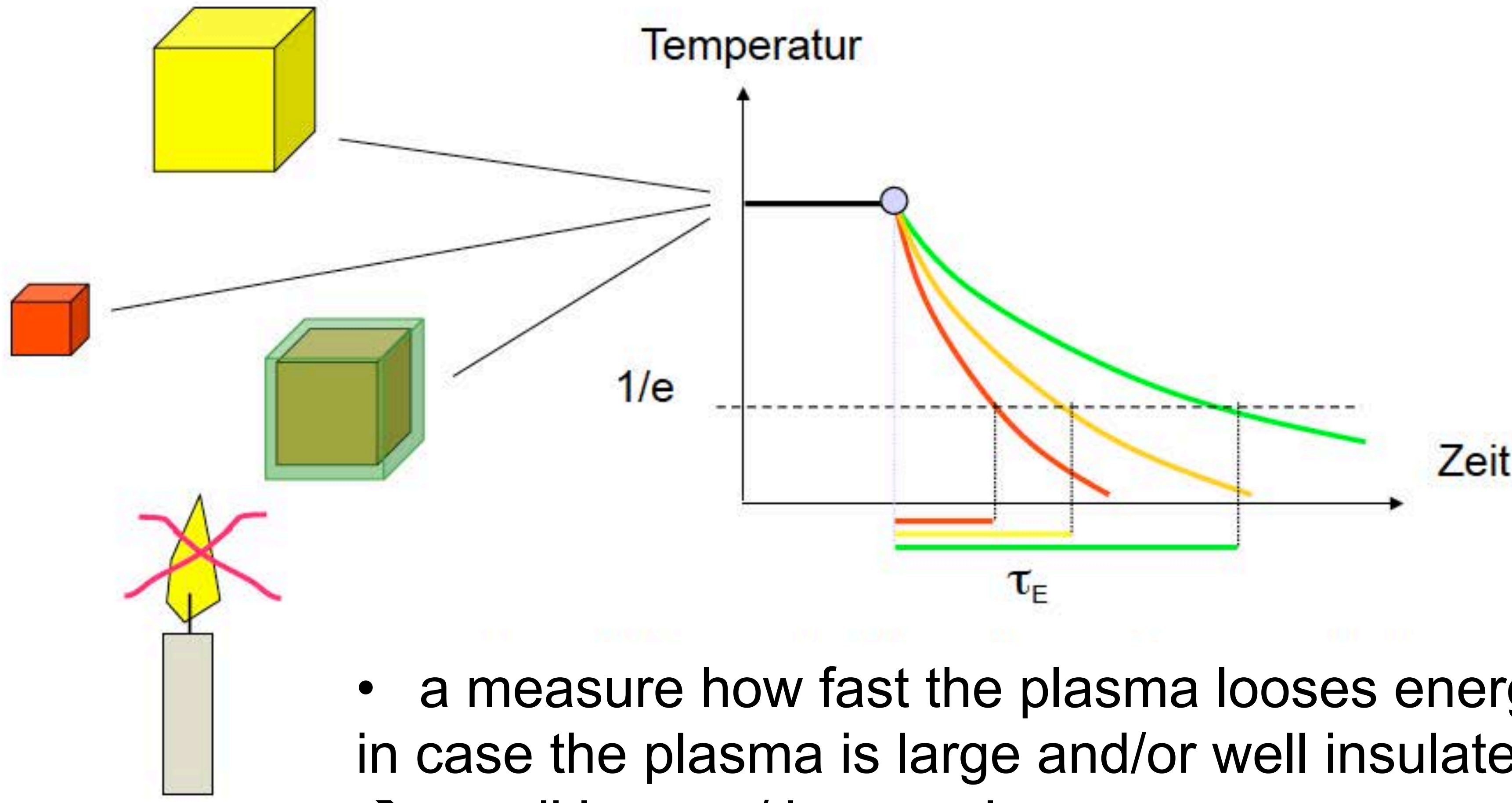
leads to

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



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

Confinement time



- a measure how fast the plasma looses energy, in case the plasma is large and/or well insulated ➔ small losses / large value,

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’)**

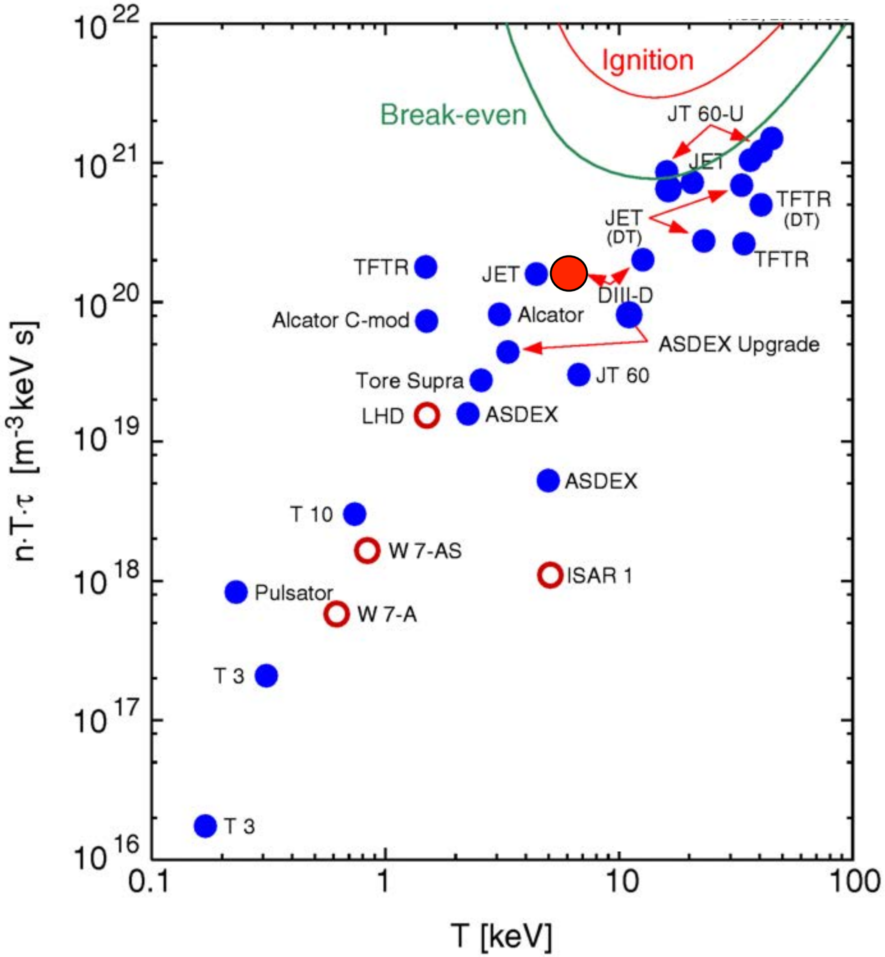
Fusion power increases with W_{plasma}

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

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

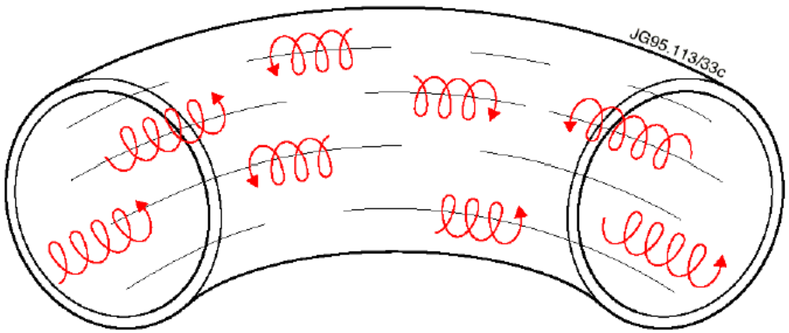
- $Q = P_{fus}/P_{ext} \approx P_{fus}/P_{loss} \sim nT\tau_E$

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

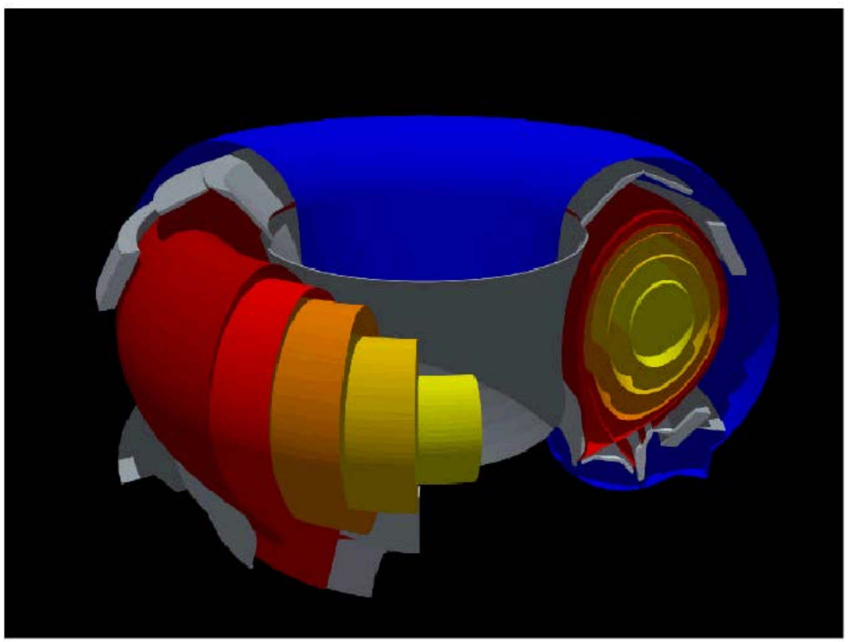


- $Q = P_{fus}/P_{ext} = P_{fus}/(P_{loss} - P_\alpha) \rightarrow \infty$ (ignited plasma)

Magnetic confinement of fusion plasmas



Magnetic field:
- reduces perpendicular particle motion (particle and energy confinement)
- balances plasma pressure (~ 10 atm)



No end losses in torus
Field lines on magnetic surfaces

System with low power per volume

ITER: 0.5 kW/l

Combustion engine: 50 kW/l

Fission reactor: 100 kW/l

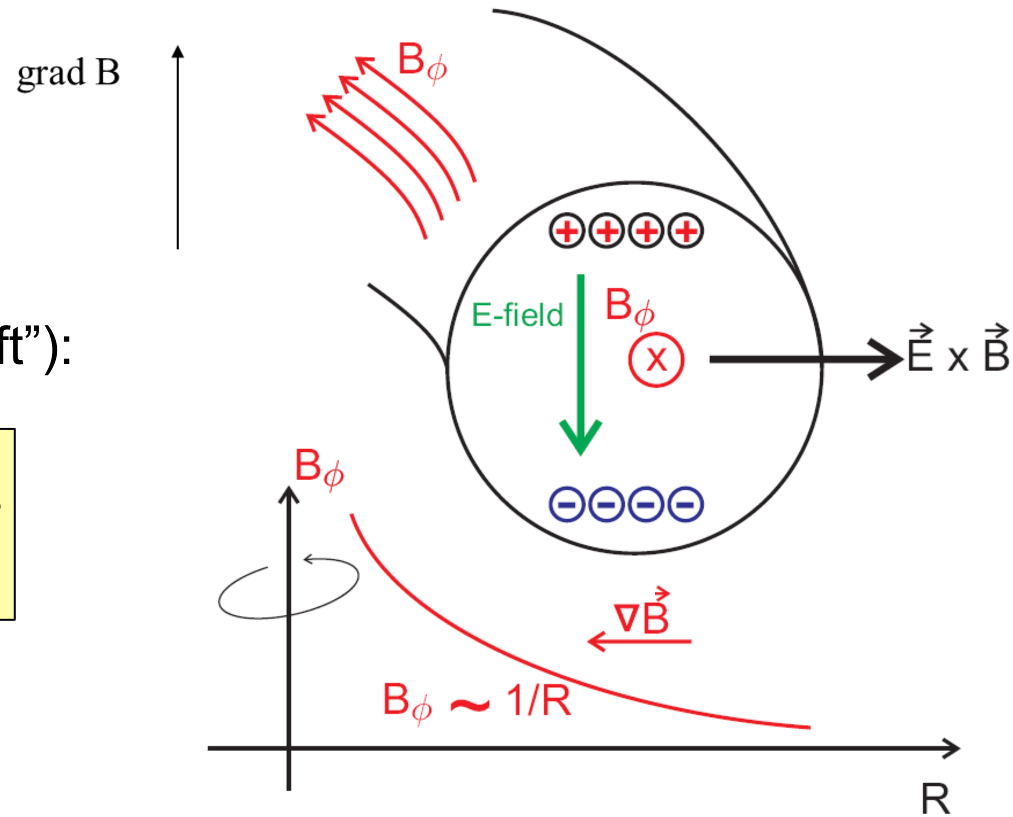
Is a simple toroidal confinement sufficient?

Drift of particles due to forces:

$$\vec{v}_D = \frac{\vec{F} \times \vec{B}}{qB^2} \Rightarrow$$

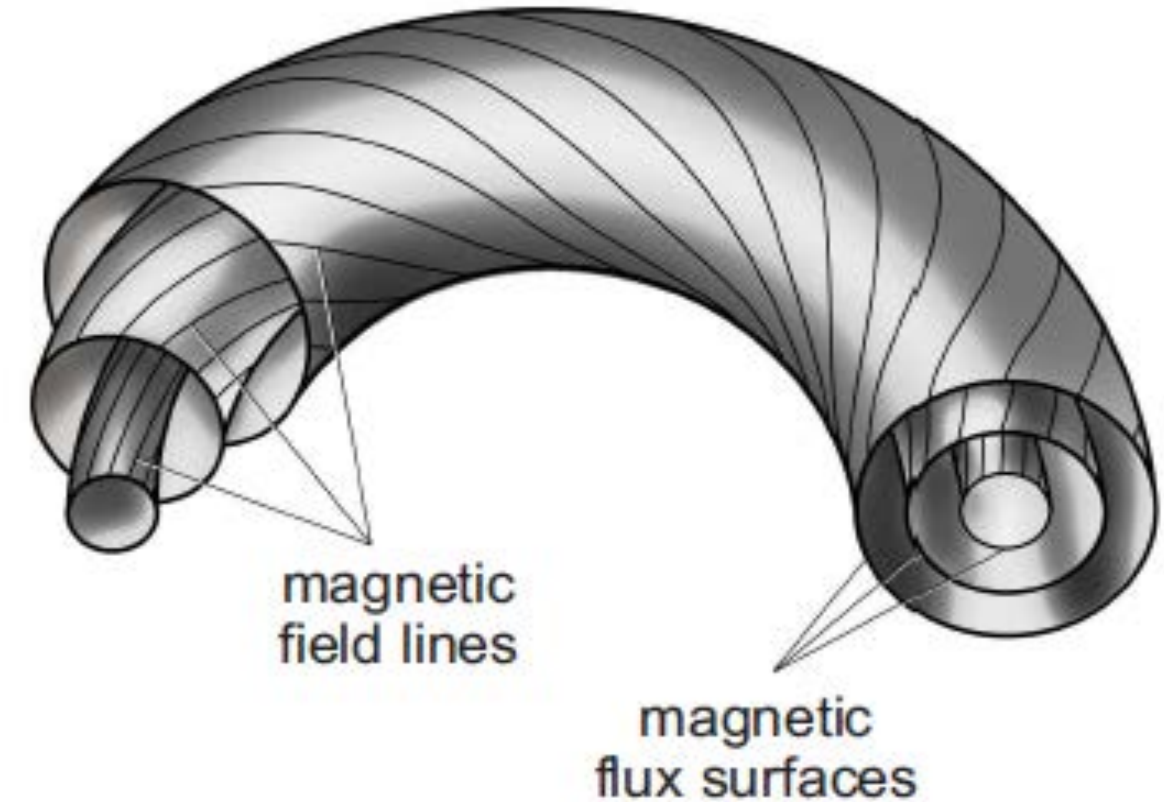
∇B and curvature drift ("torus drift"):

$$\vec{v}_D = \frac{m}{qB^3}\left(v_{\parallel}^2 + \frac{1}{2}v_{\perp}^2\right)\vec{B} \times \nabla B$$



Pure toroidal magnetic field ➔ charge separation via ∇B drift and curvature drift lead to a vertical E-field.
ExB drift would drive all charged particles towards the outboard side
➔ Need helical magnetic field structure

Plasma can be confined in a magnetic field



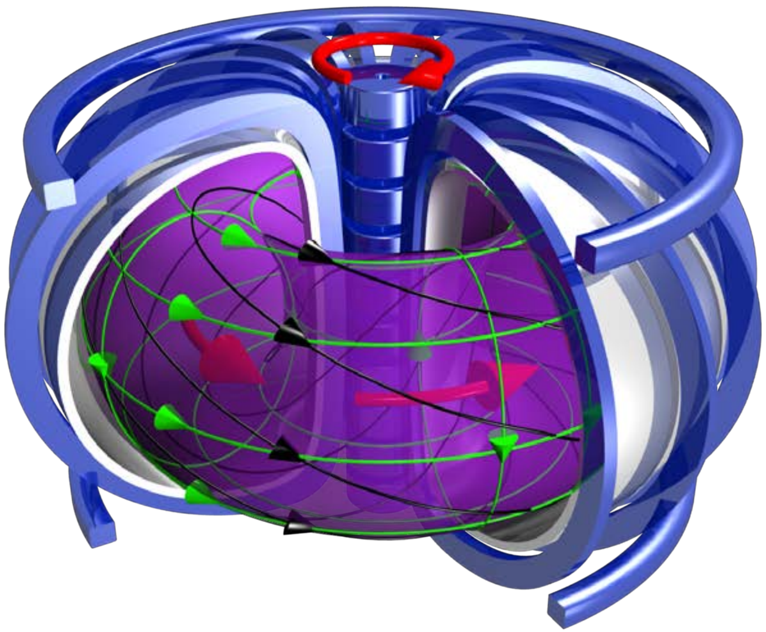
Toroidal systems avoid end losses along magnetic field

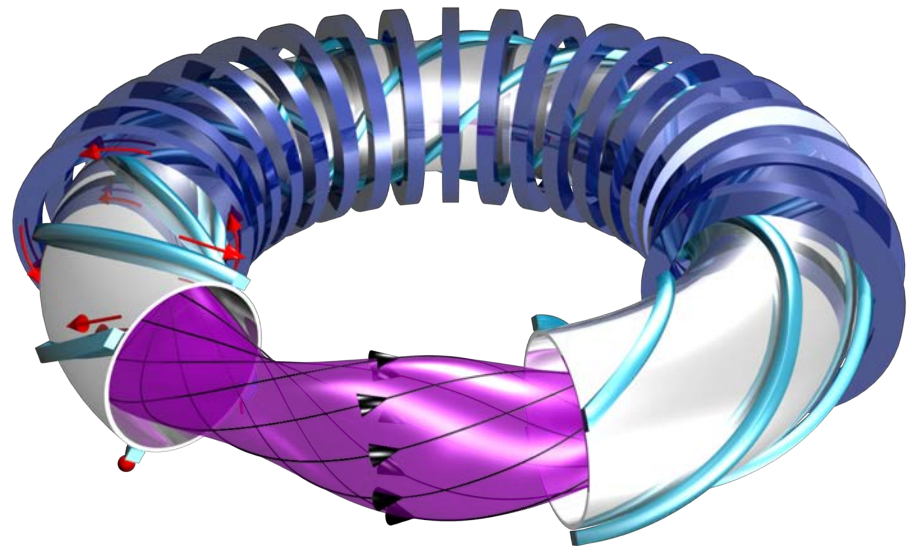
⇒ Need to twist field lines helically to compensate particle drifts

Concepts of magnetic confinement

Tokamak (axis symmetric)

Stellarator (3D)





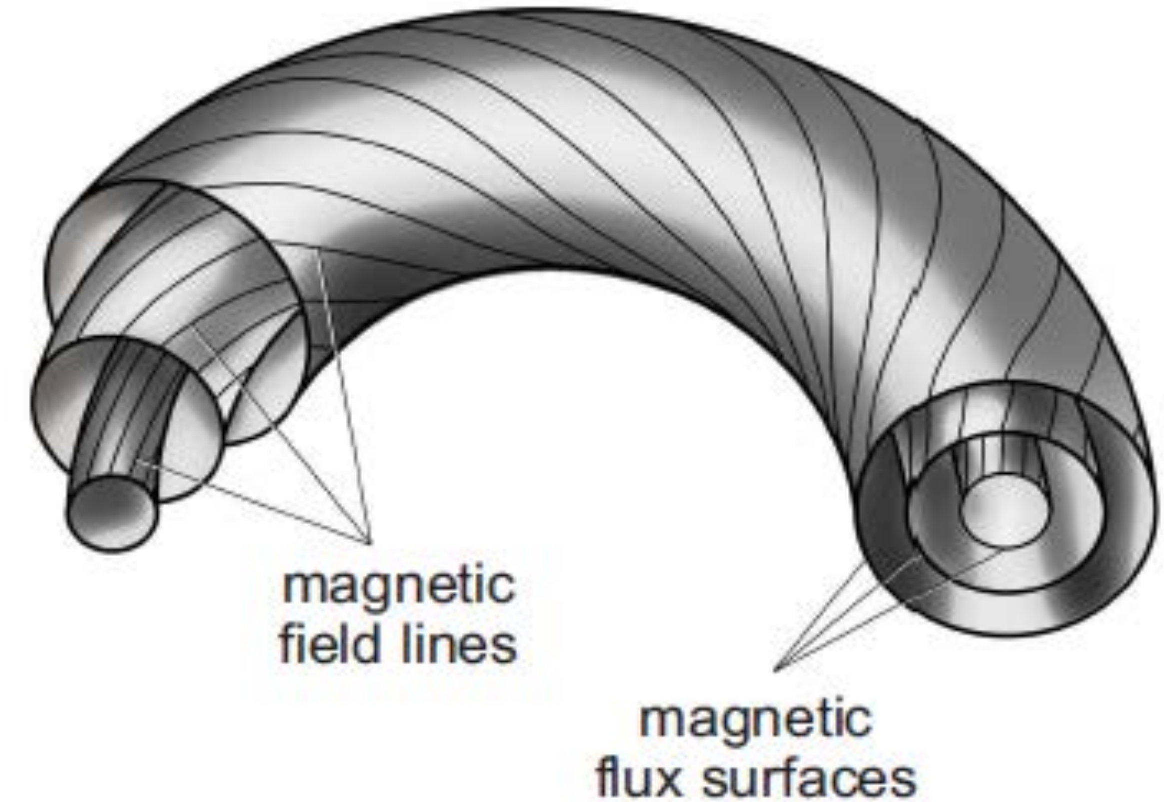
Magnetic field by external coils and plasma current

Magnetic field only by external coils

pulsed

intrinsically stationary

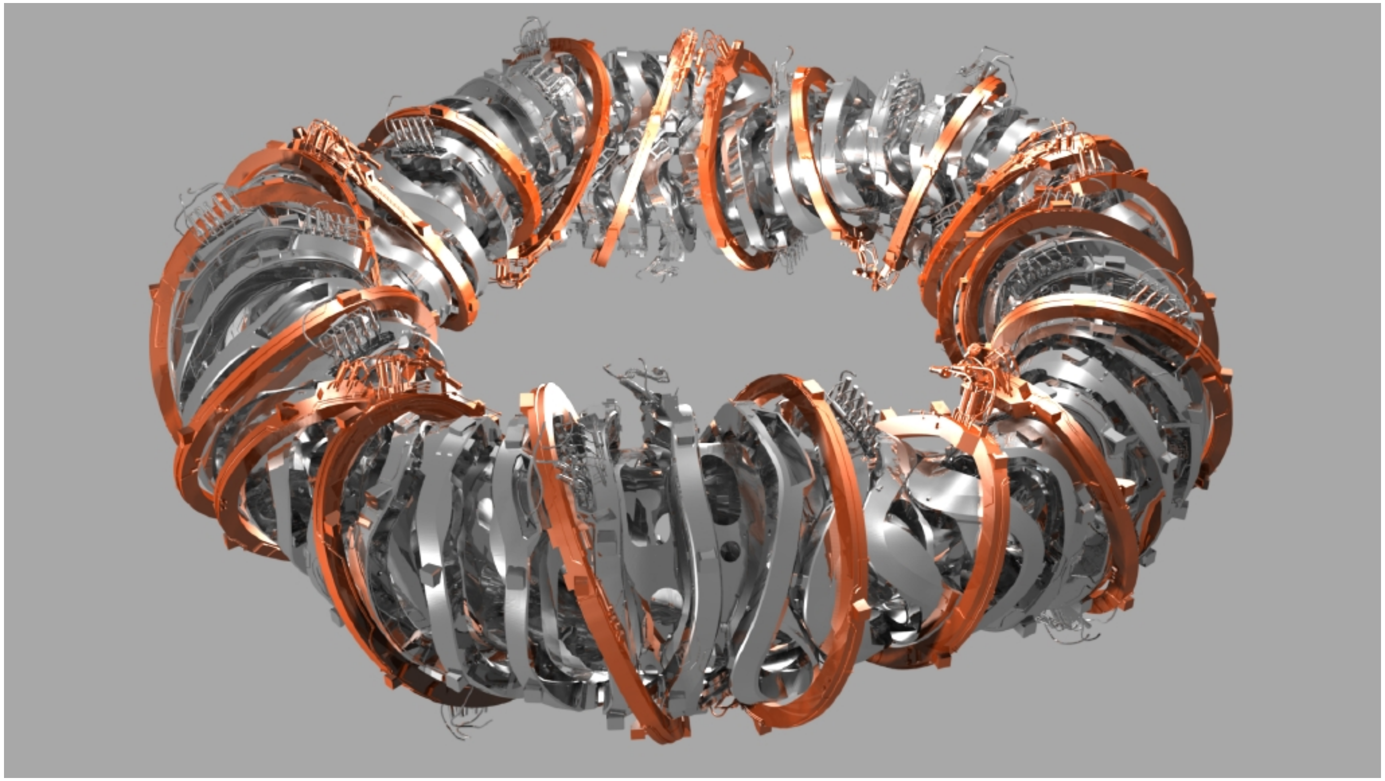
Field line geometry described by safety factor q



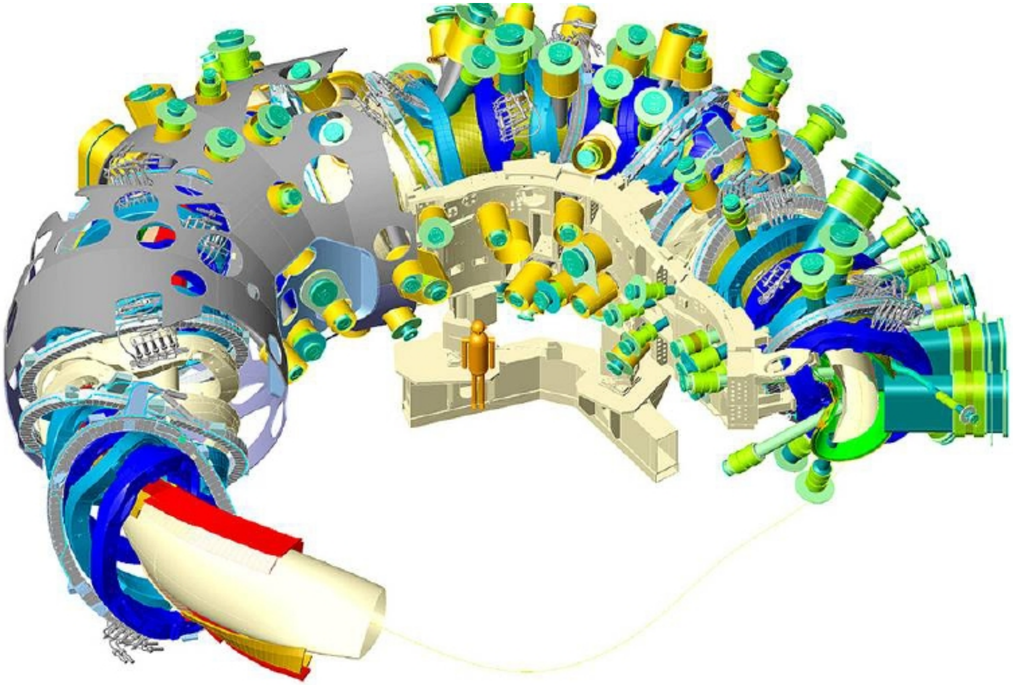
$$q = \frac{\text{number of toroidal windings}}{\text{number of poloidal windings}}$$

Plasma can be confined in a magnetic field

'Stellarator': magnetic field exclusively produced by coils

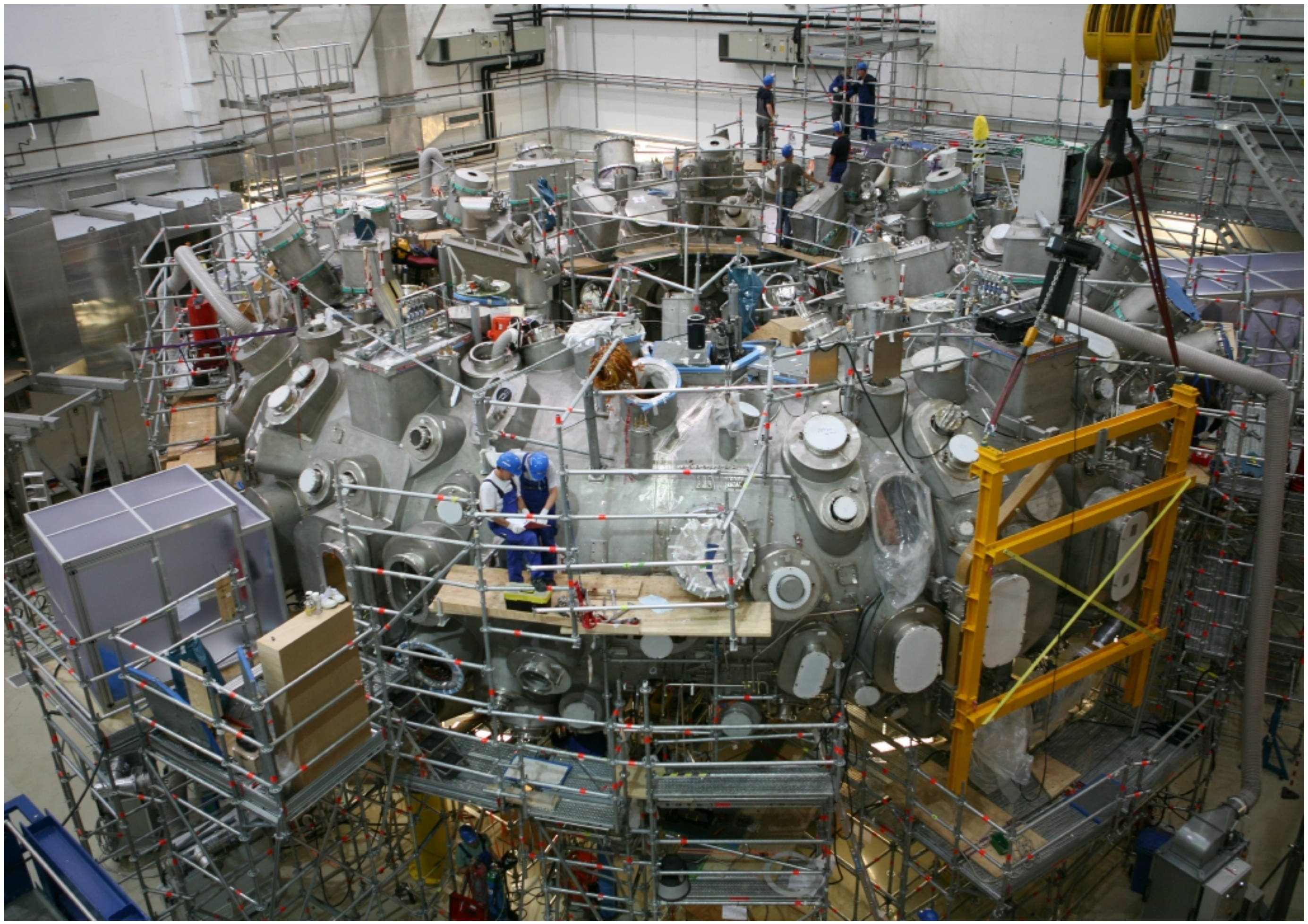


Example: Wendelstein 7-X (IPP Greifswald)



CAD design of Wendelstein 7-X including ports and magnetic flux surfaces

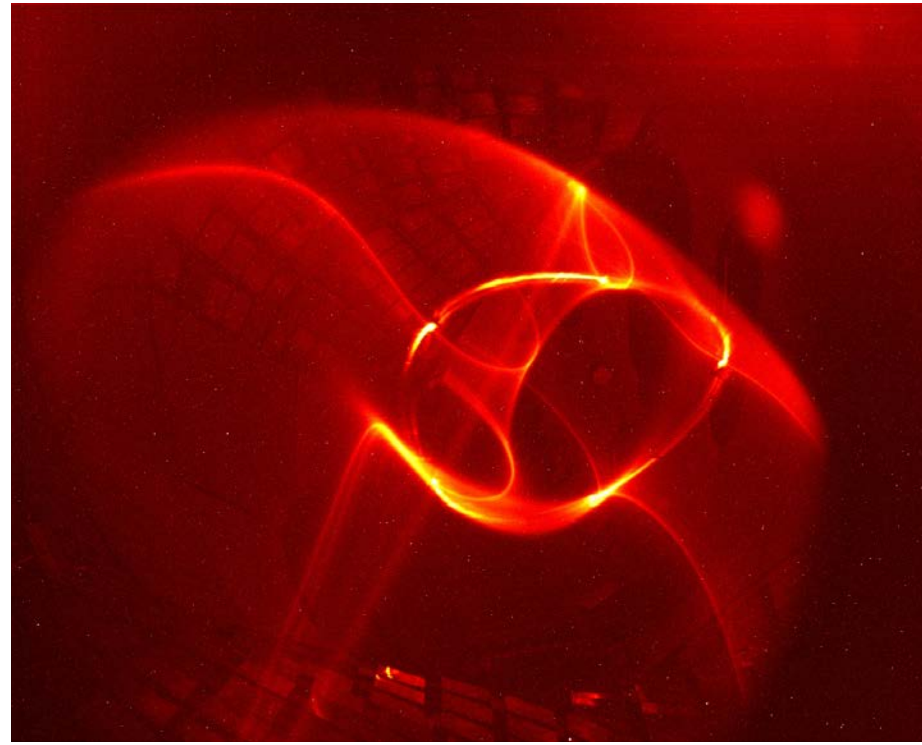
Stellarator (II)



Wendelstein 7-X, May 2014

Magnetic field tests at full field sucessful

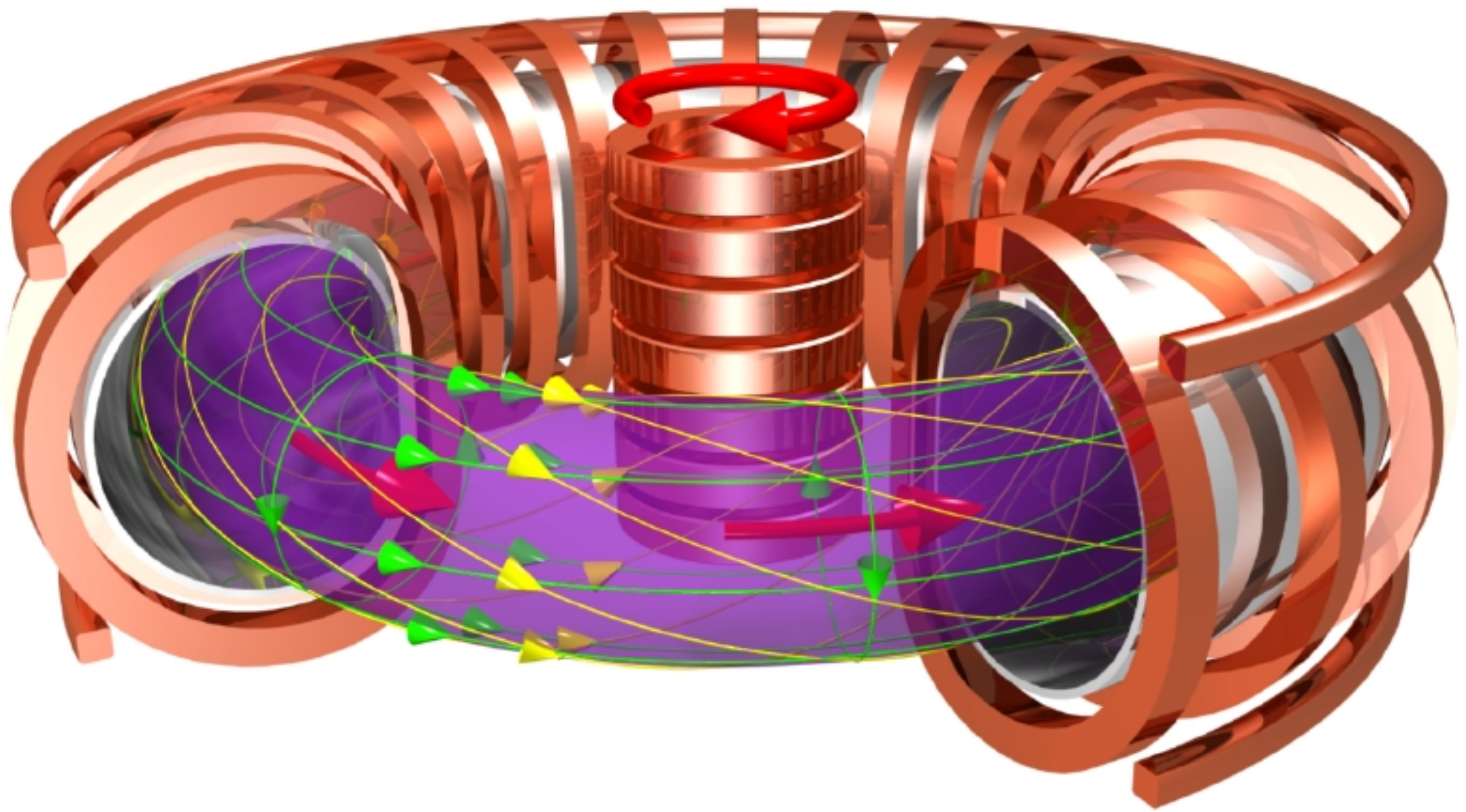
temperature
12.5 kA



First plasma in He in December 2015
First plasma in H in February 2016
➔ Currently under maintenance

Plasma can be confined in a magnetic field

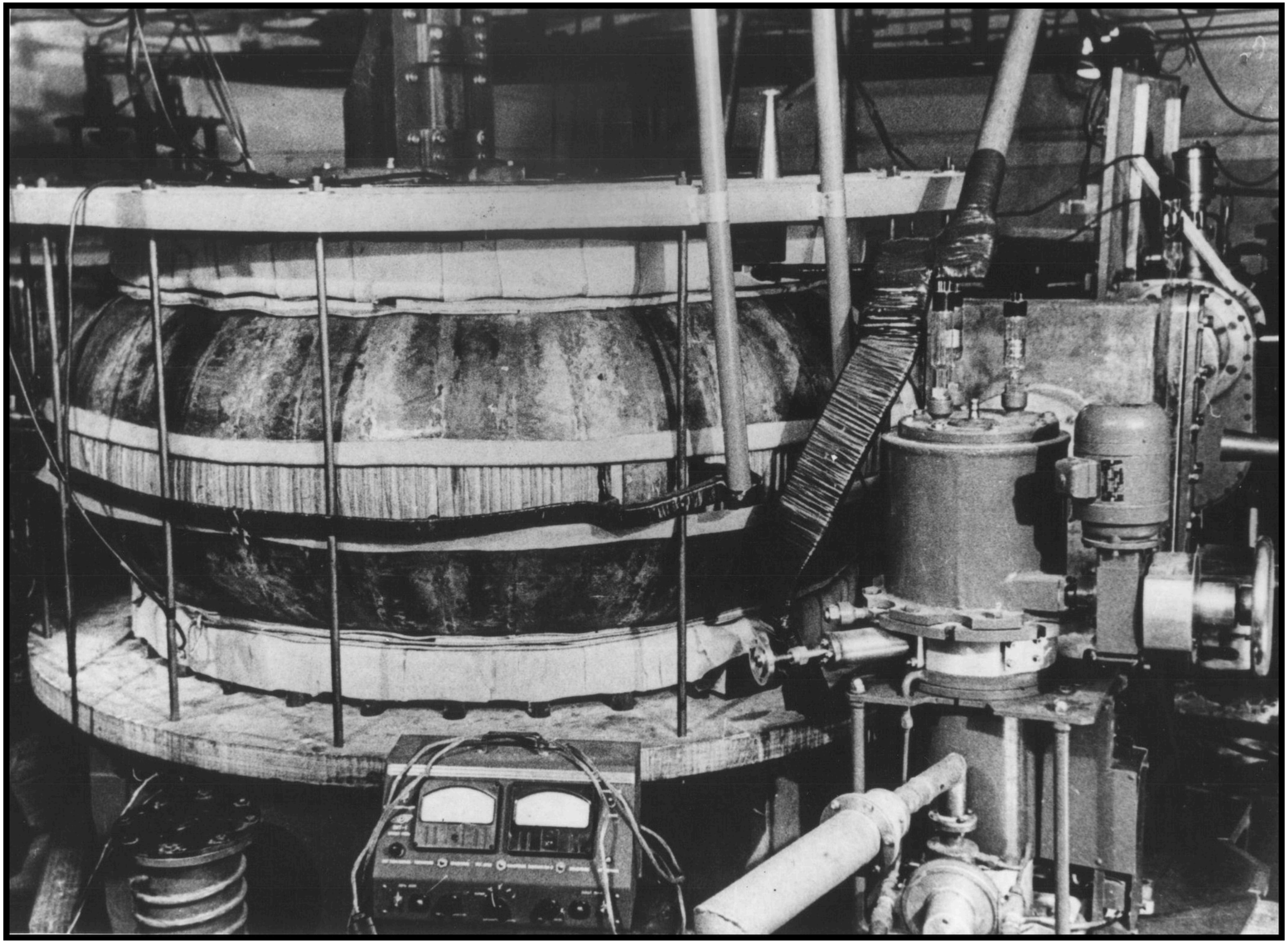
'Tokamak': poloidal field component from current in plasma



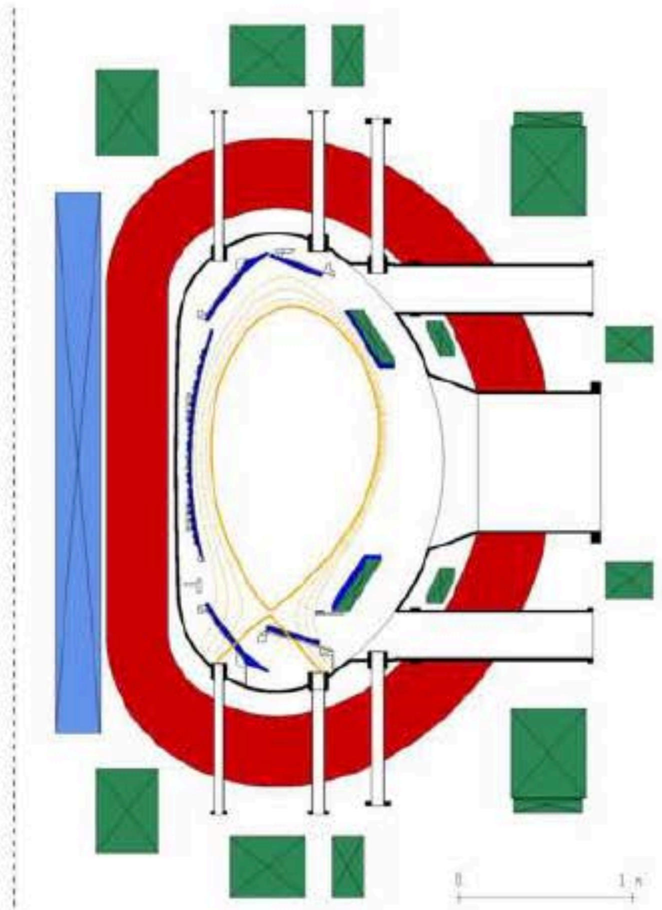
Simple concept, but not inherently stationary!

Example: ASDEX Upgrade (IPP Garching)

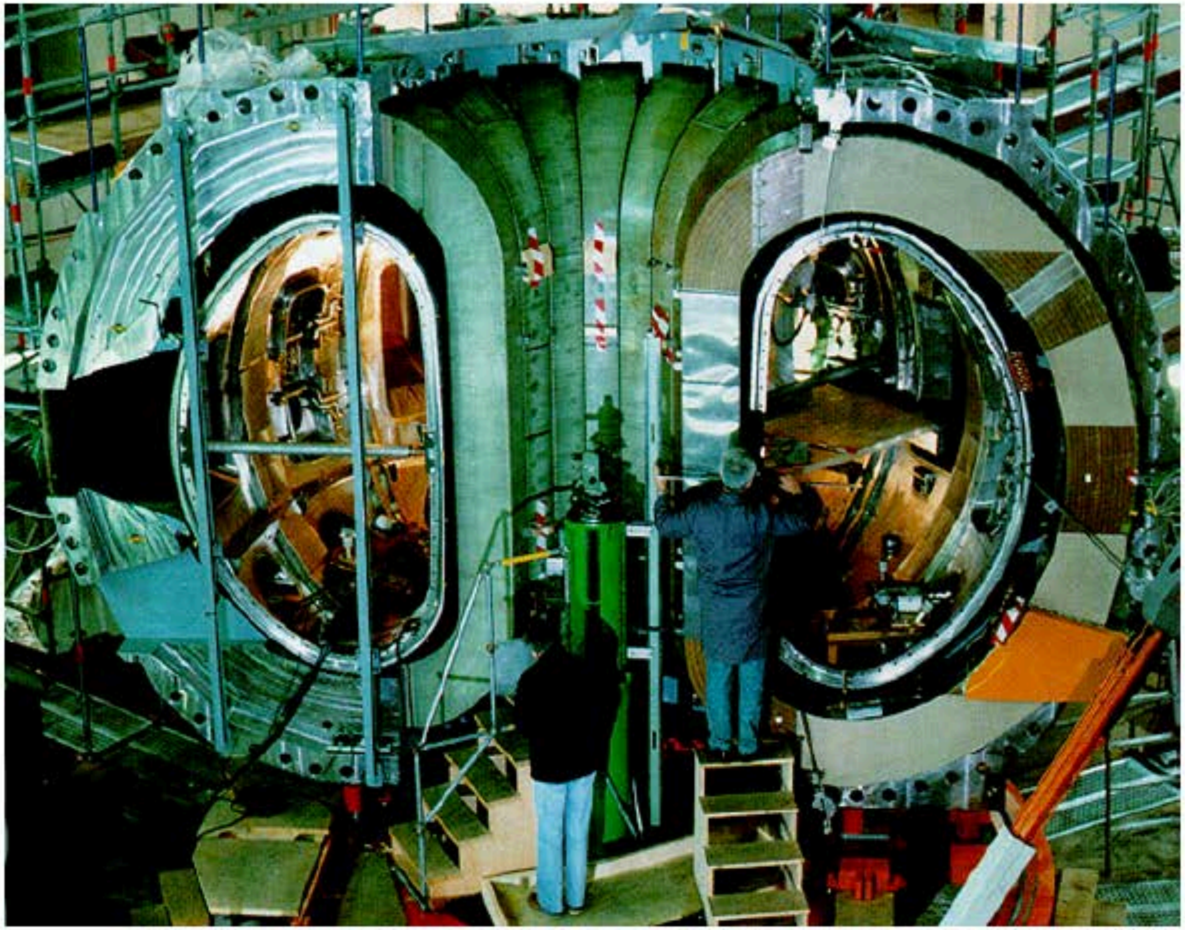
Tokamak T1



ASDEX Upgrade – Largest German tokamak



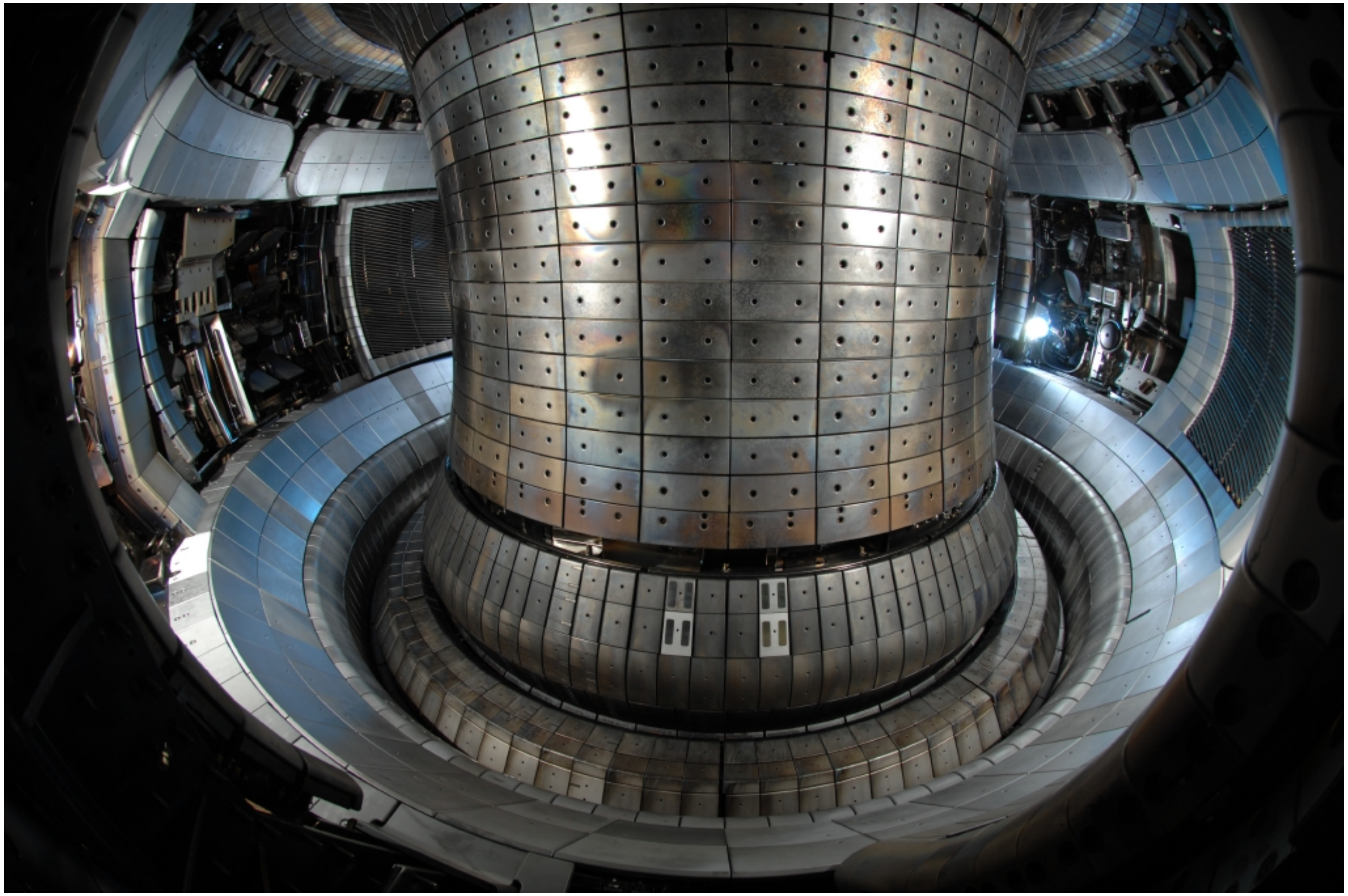
Großer Radius = 1.65 m, $B_t \leq 3{,}5$ T
Kleiner Radius = 0.5 m, $I_p \leq 1{,}4$ MA
$P_{Heiz} \leq 28$ MW,



Start des Betriebs in 1991;
hier während der Konstruktion in 1989

Plasma can be confined in a magnetic field

'Tokamak': poloidal field component from current in plasma



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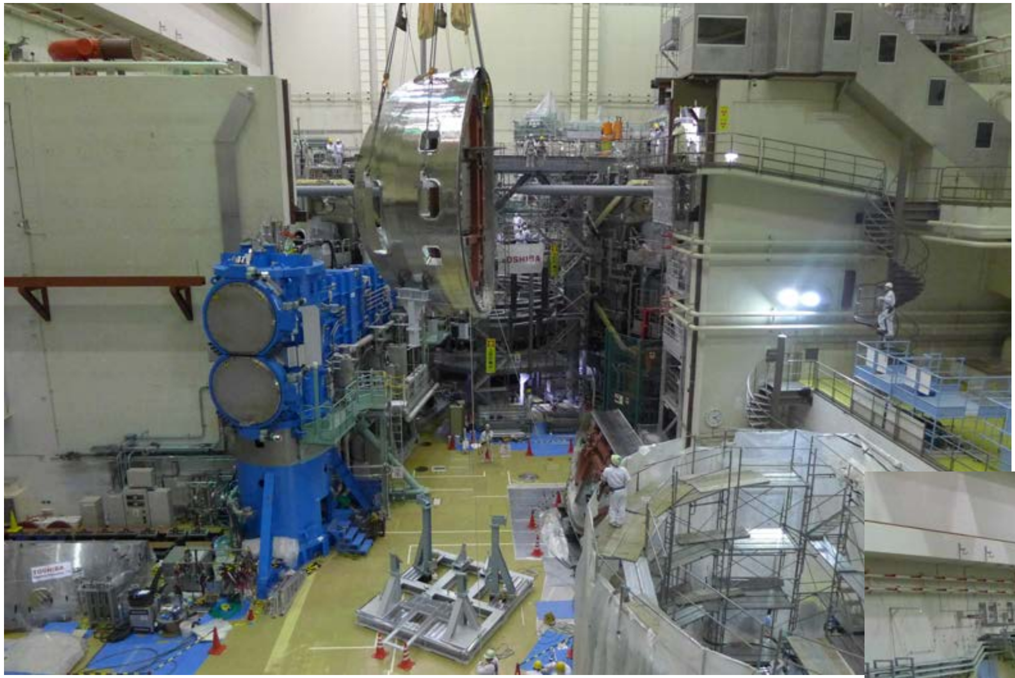
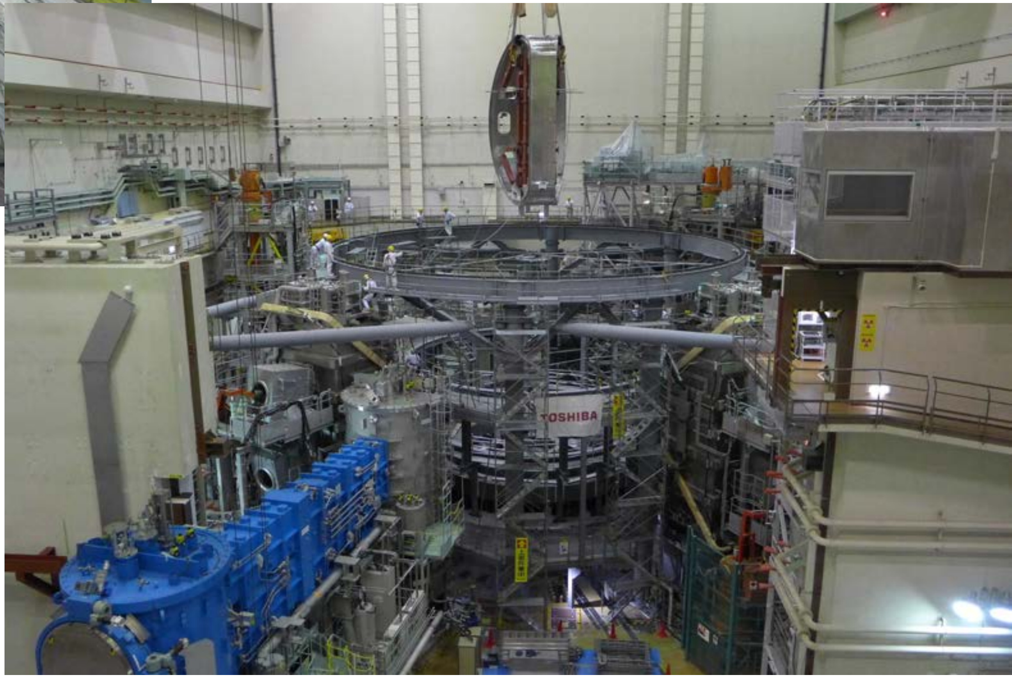
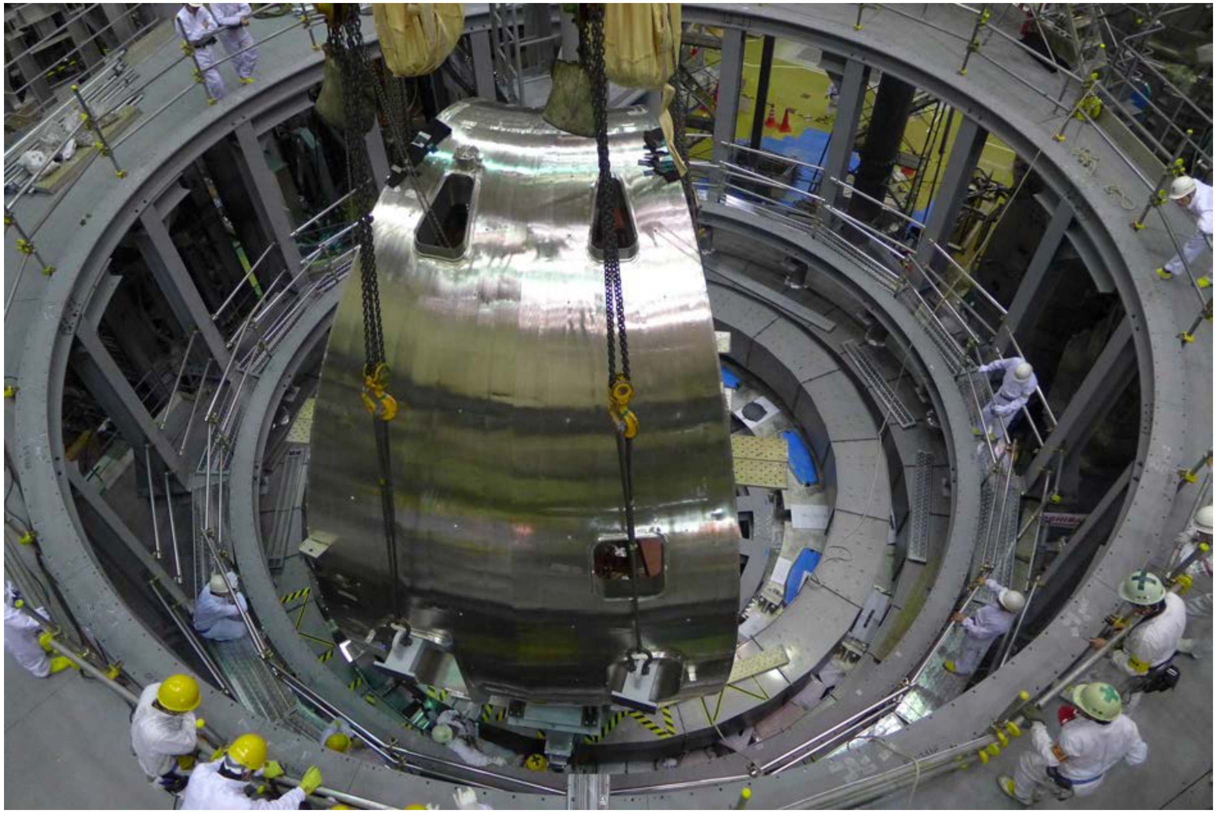
Example: ASDEX Upgrade (IPP Garching)

Tokamak under construction – JT60-SA Japan





Tokamak under construction (II) – JT60-SA Japan

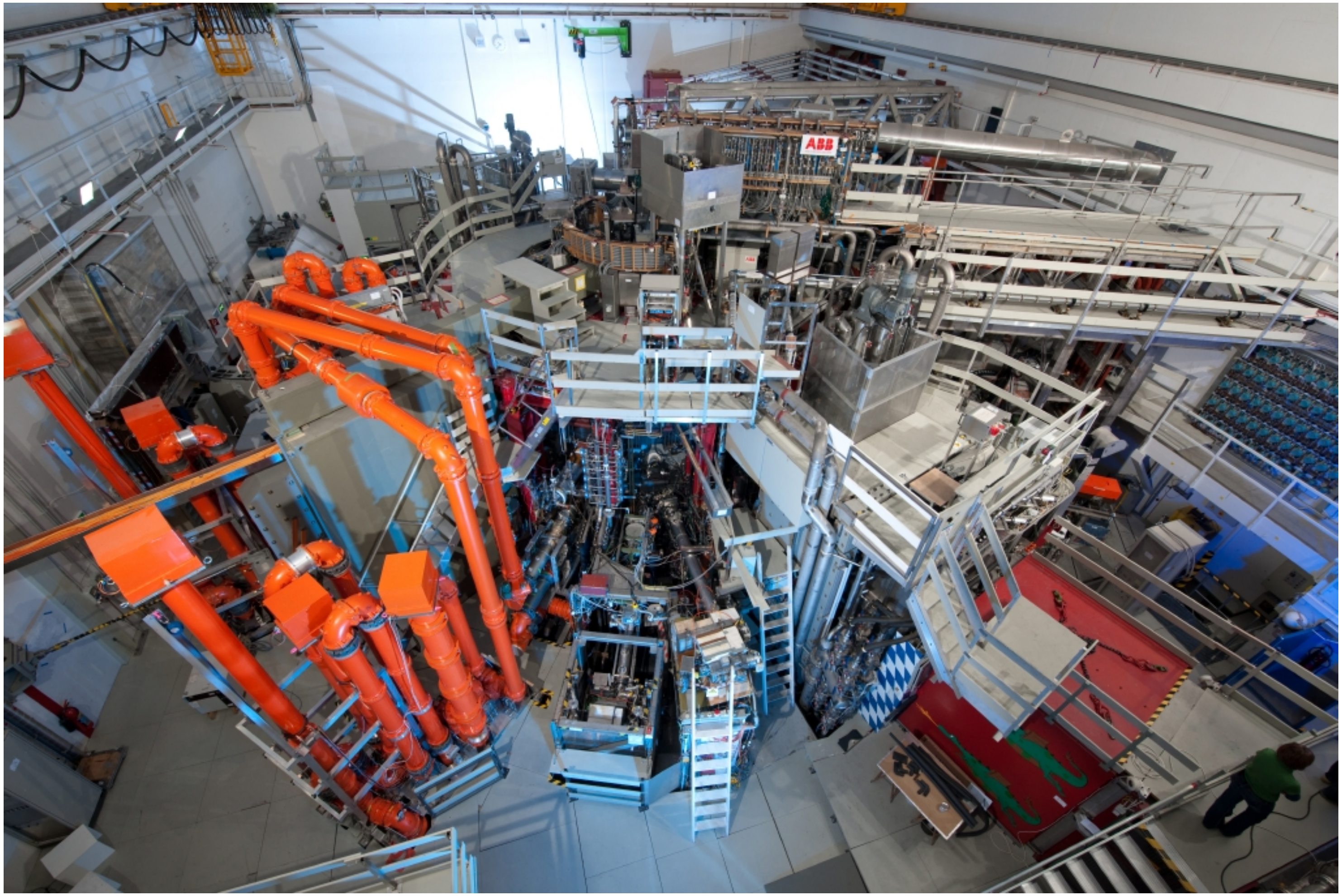


Spring 2014

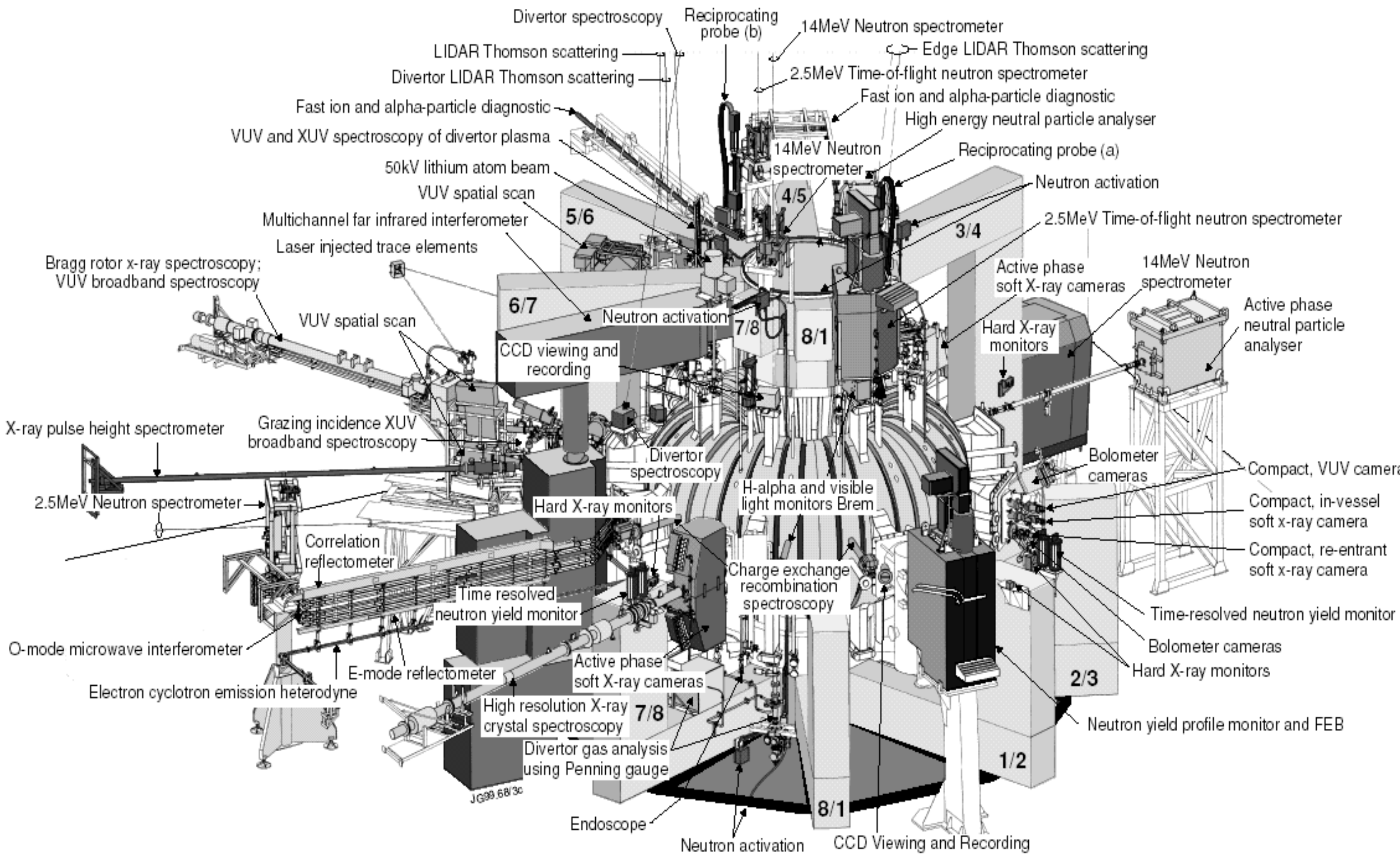
Tokamak under construction (III) – JT60-SA Japan

Spring 2016

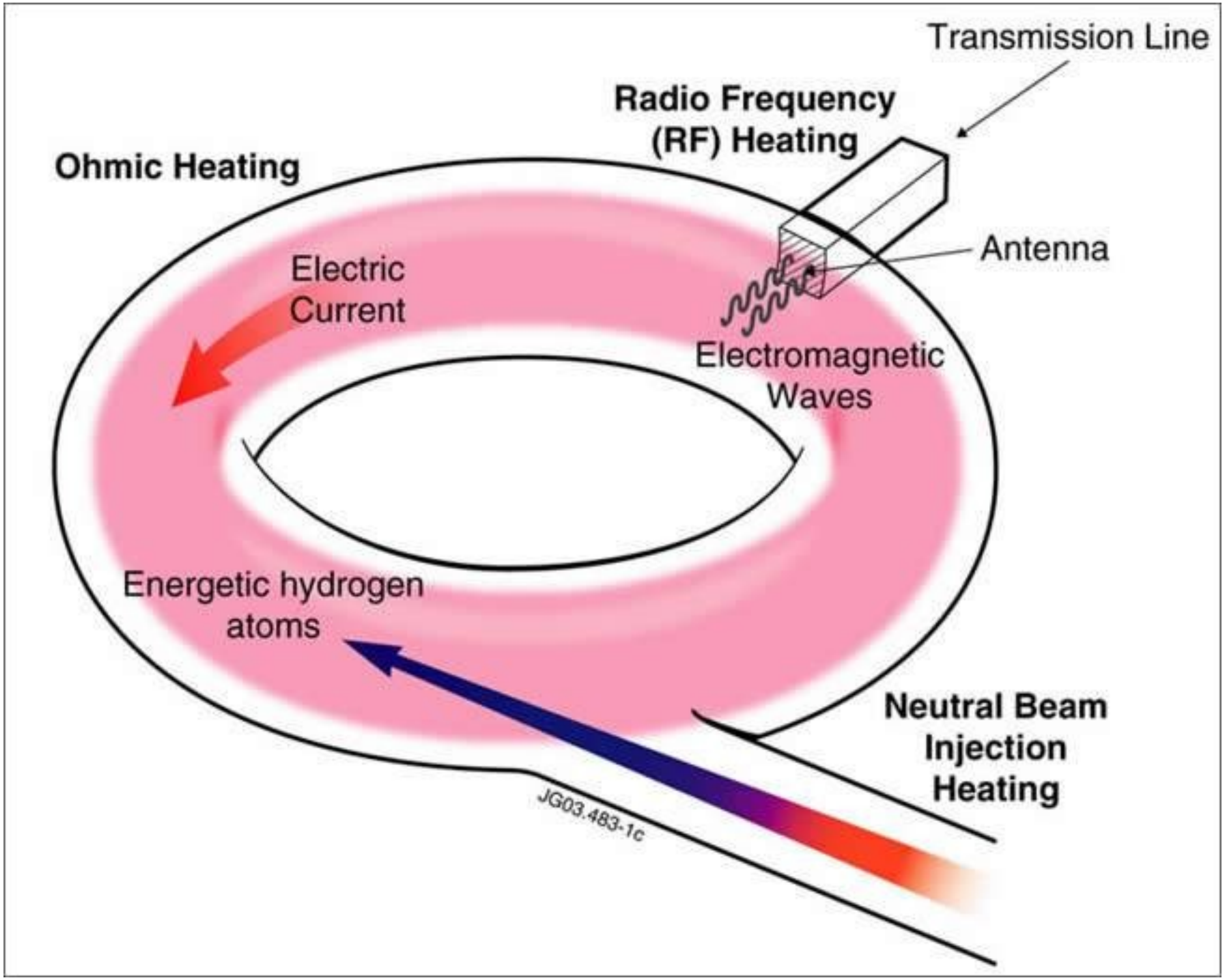
ASDEX Upgrade viewed inside torus hall



Diagnostics of Fusion Plasmas: JET-Design



Tokamak plasma heating systems



Methods for plasma heating

Ohmic heating (only tokamaks)

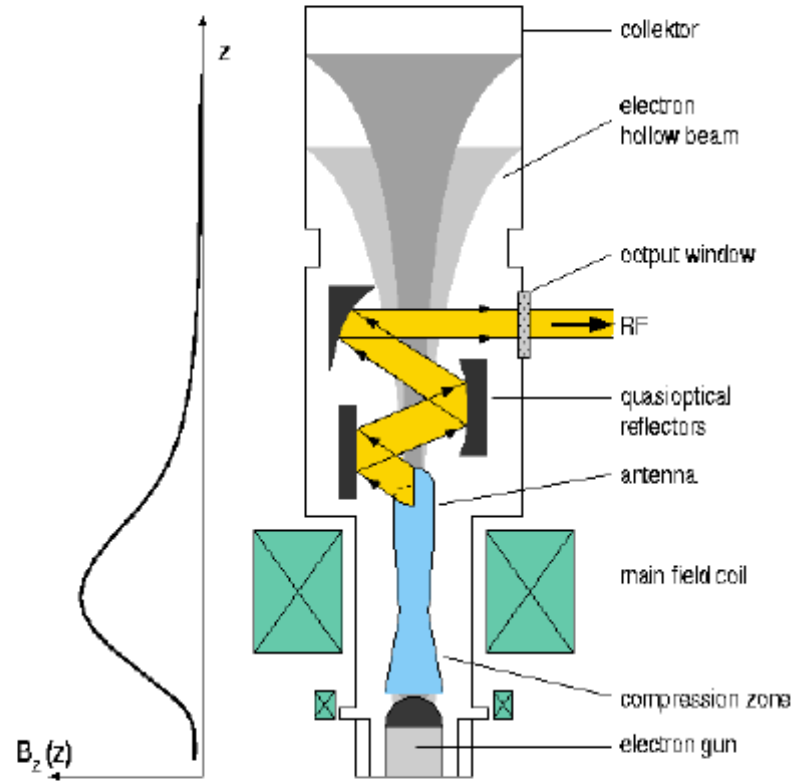
$P_{OH} = I_P^2 \cdot R_P$ mit $R_P \sim 1/T^{3/2}$

➔ Very inefficient at high T *T*

RF heating:
Injecting waves at cyclotron frequency

$$\omega_C = qB/m$$

Ionen (ICRH): < 100 MHz
Elektr. (ECRH): < 180 GHz



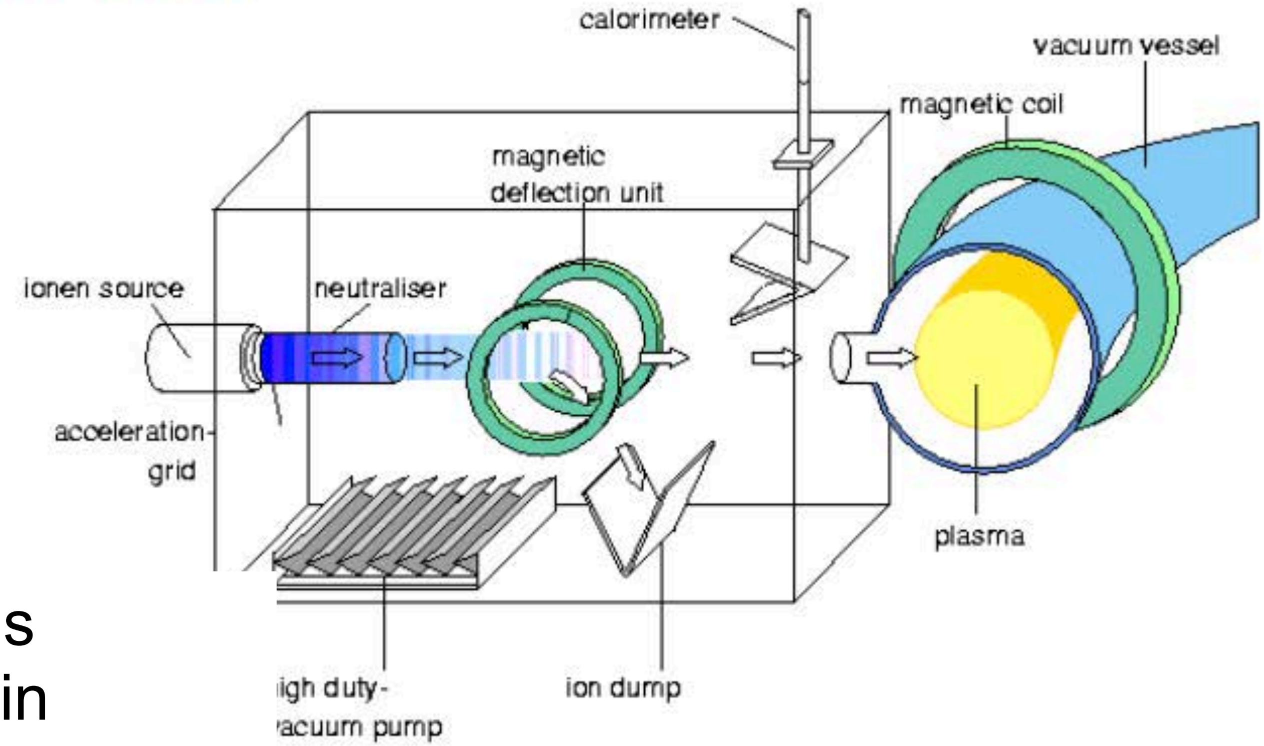
Schematic of a high frequency amplifier

Gyrotron (f ≈ 80 – 180 GHz)

Methods for plasma heating

- Neutral beam injection

$P_{NBI} = U_B \cdot I_B$

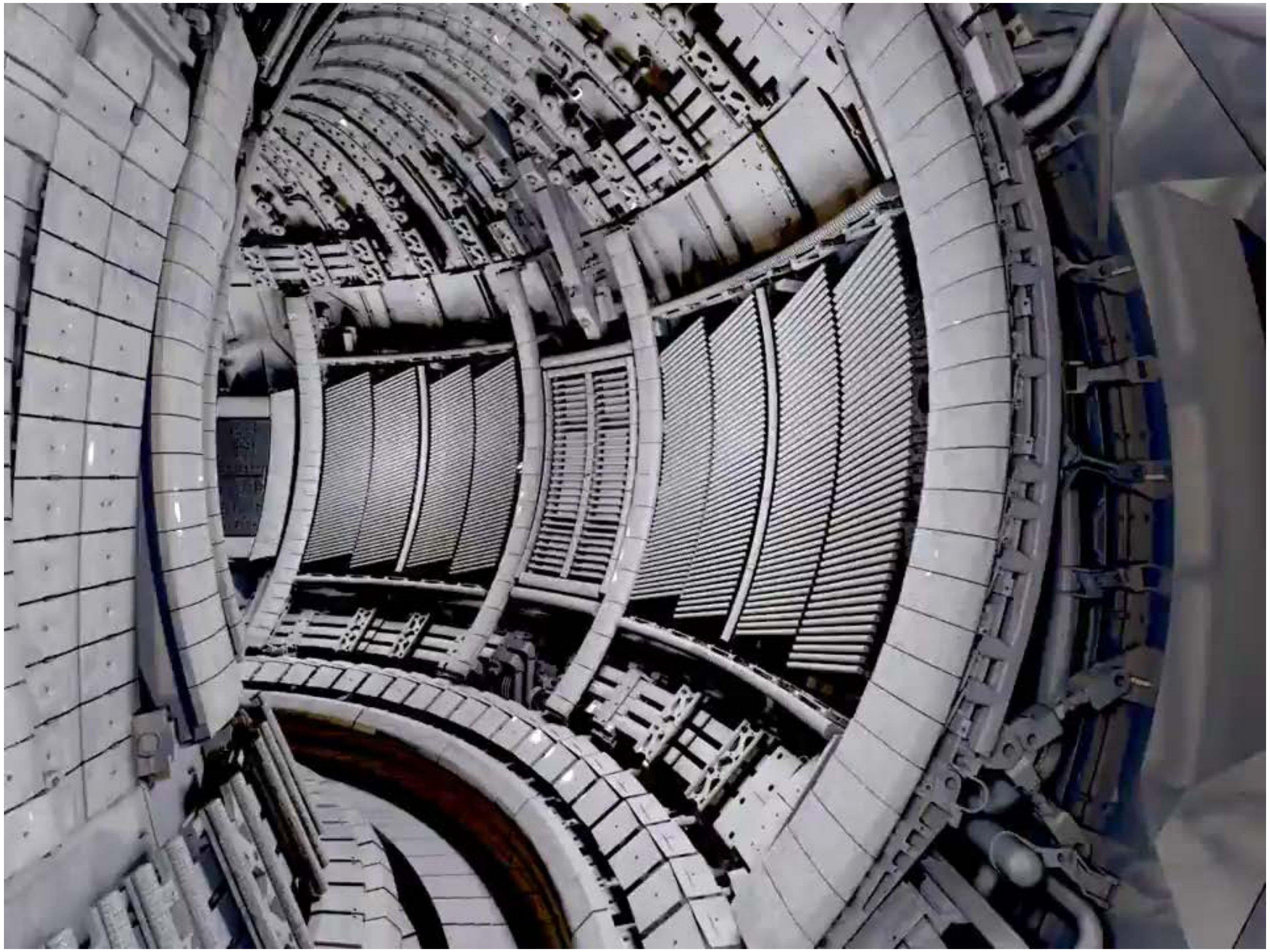


- Acceleration of ions
- Charge exchange in neutral gas
- Negative ions necessary for

$E_{beam} >> 100$ keV

Periphery of non super conducting tokamak: Power supply

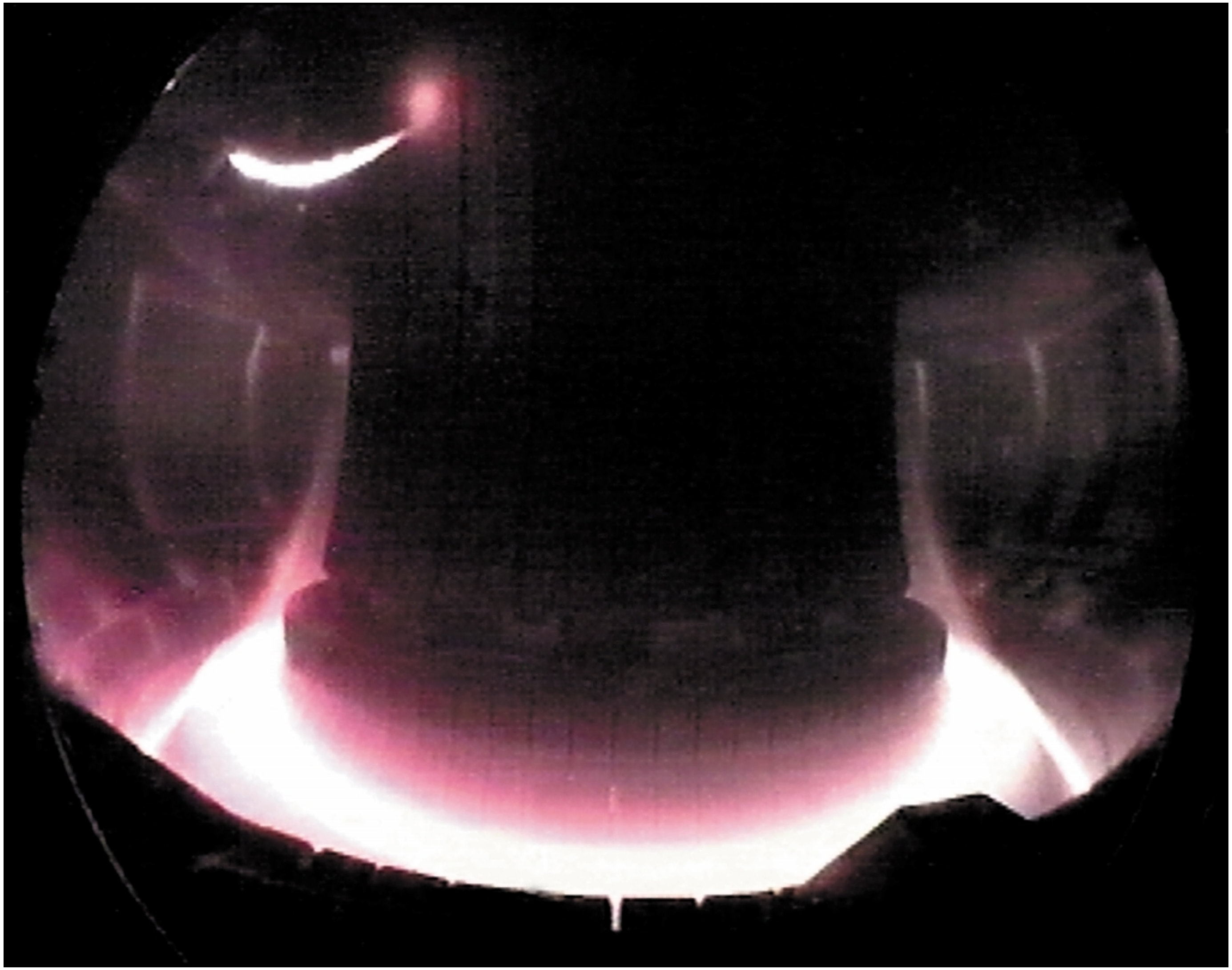
Inside the torus of the JET tokamak



A discharge at JET (movie)

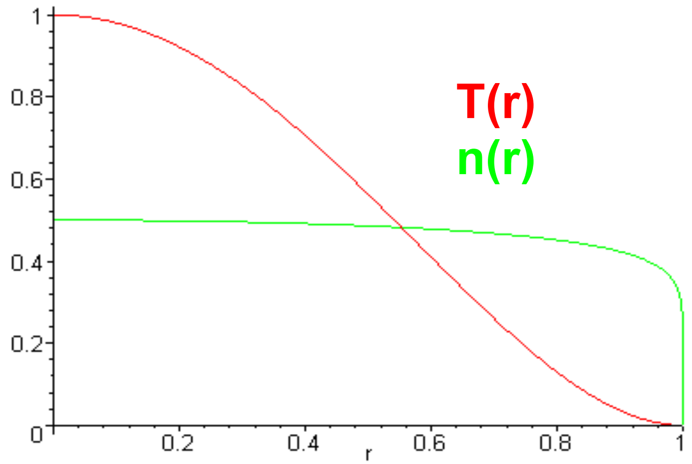
A discharge at JET with the ILW – can find it on youtube

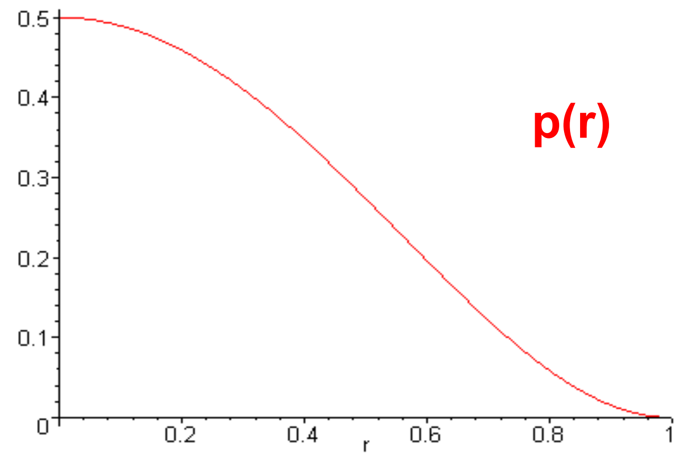
Plasma can be confined in a magnetic field



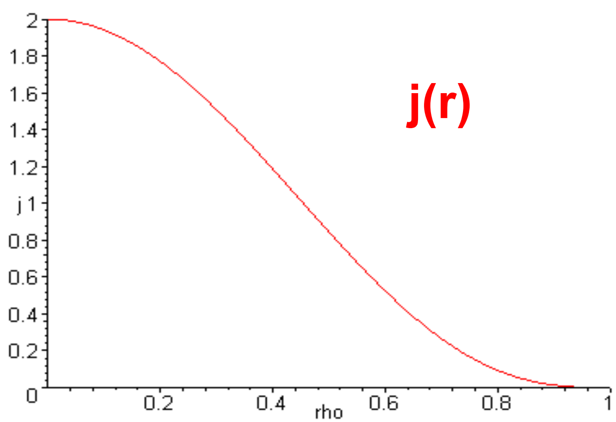
ASDEX Upgrade (with trace of a pellet)

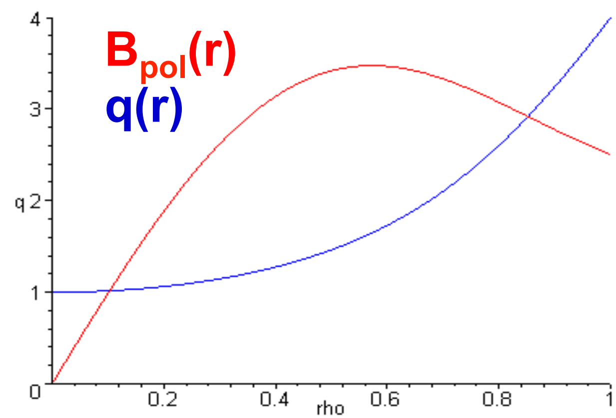
Typical radial profiles in fusion experiments (schematic)





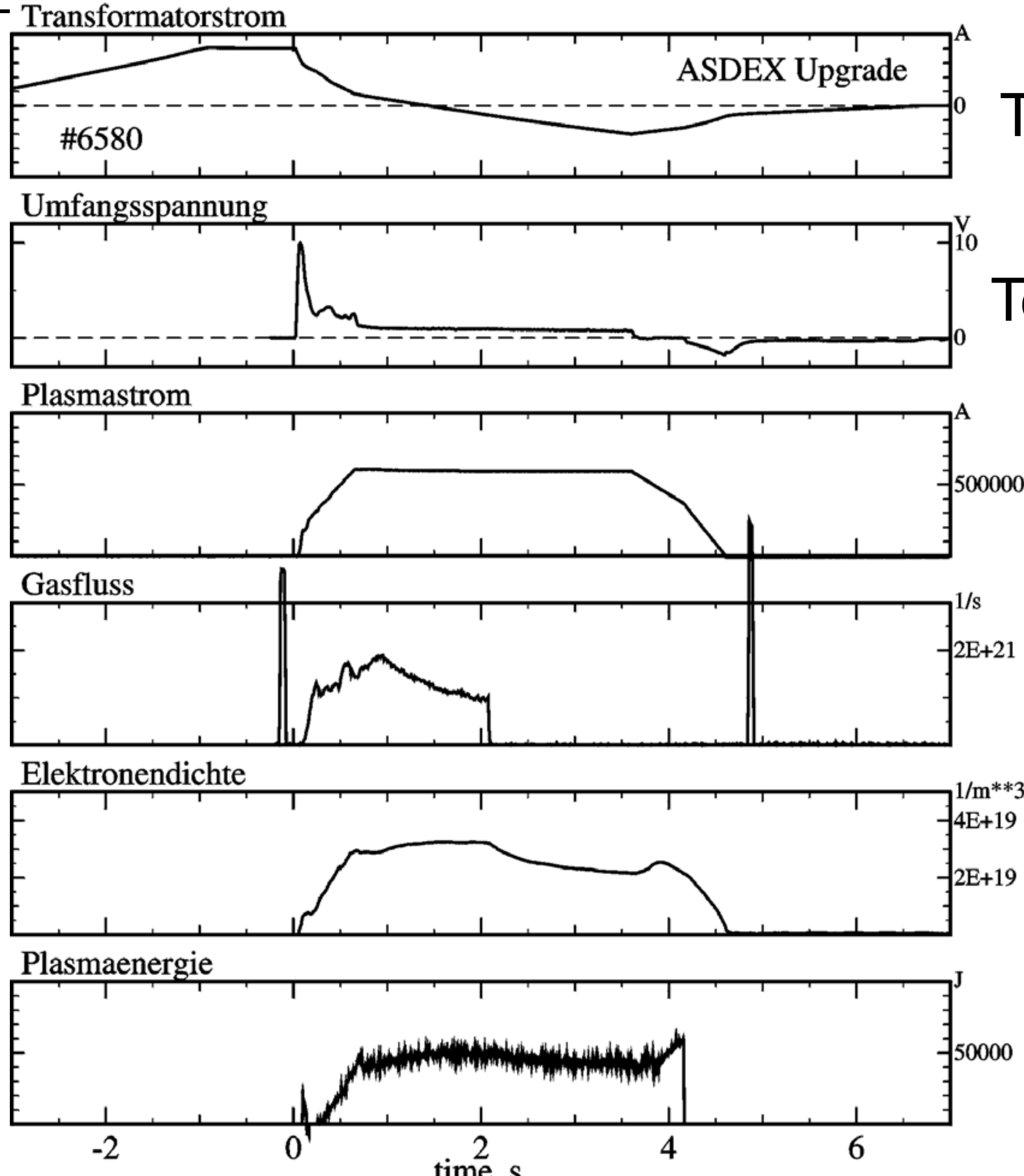
Temperature profiles peaked on axis, density usually flatter, $p = n\,k_B T$





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

Typical evolution of a tokamak discharge



Transformer Current

Toroidal loop voltage

Plasma current

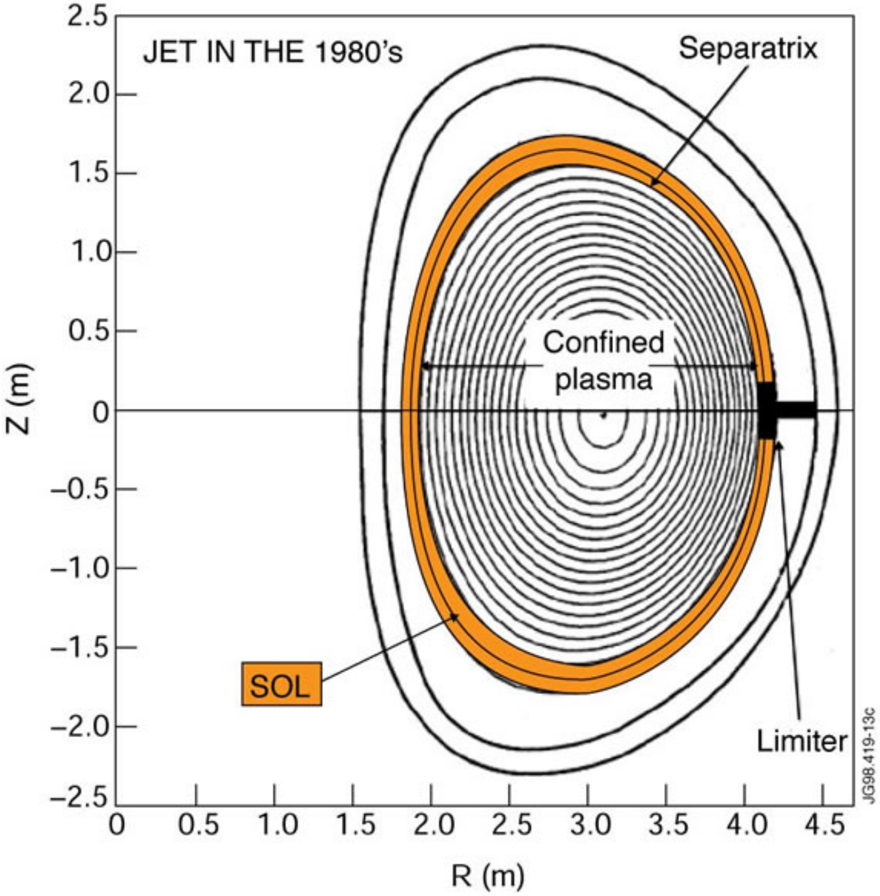
Gas inlet

Electron density

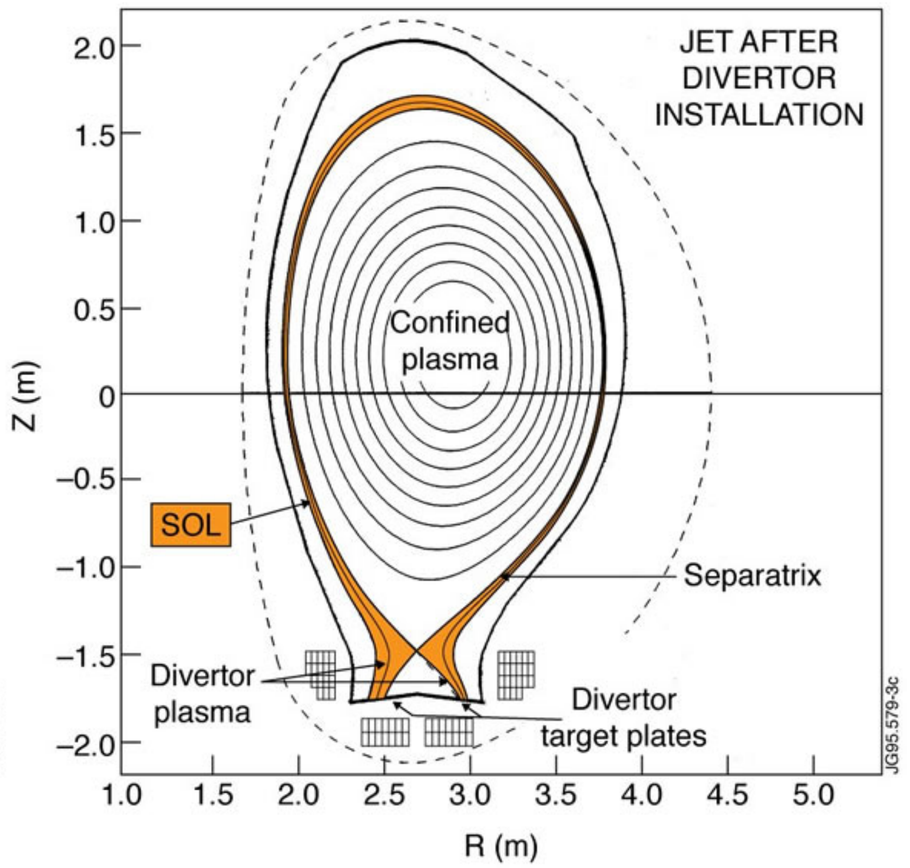
Plasma stored energy

Tokamak configurations

Limiter

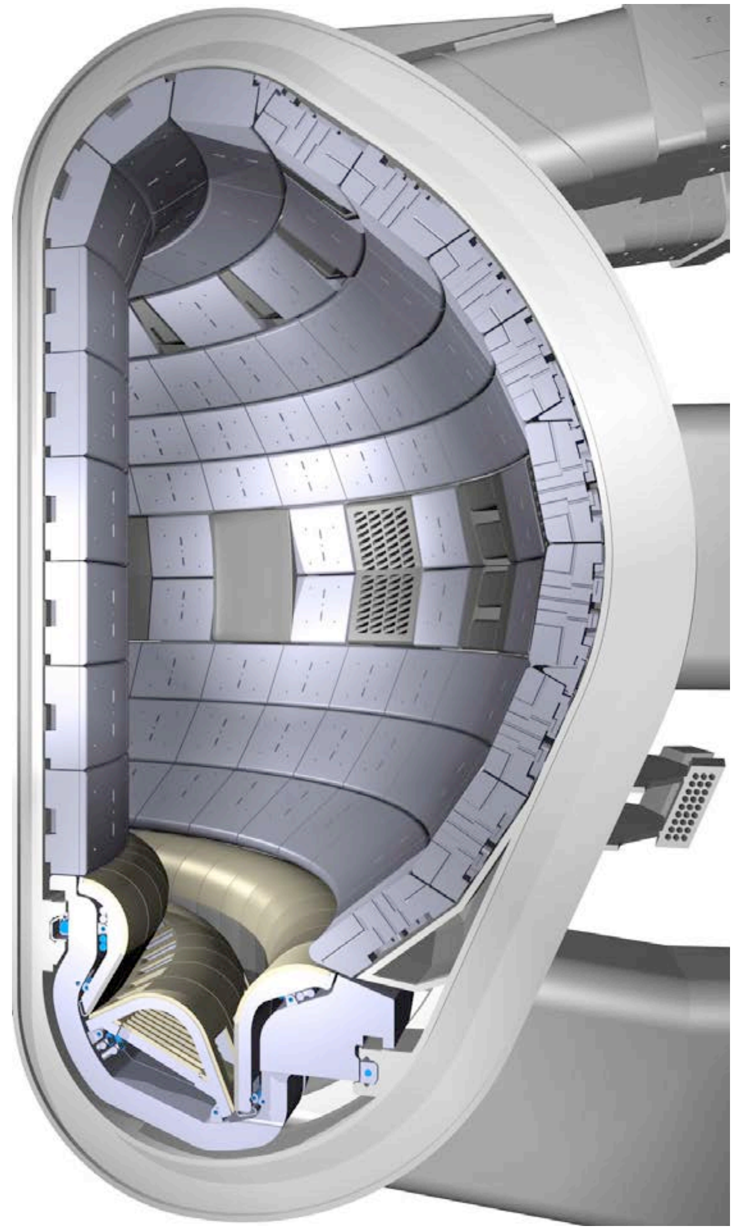


Divertor

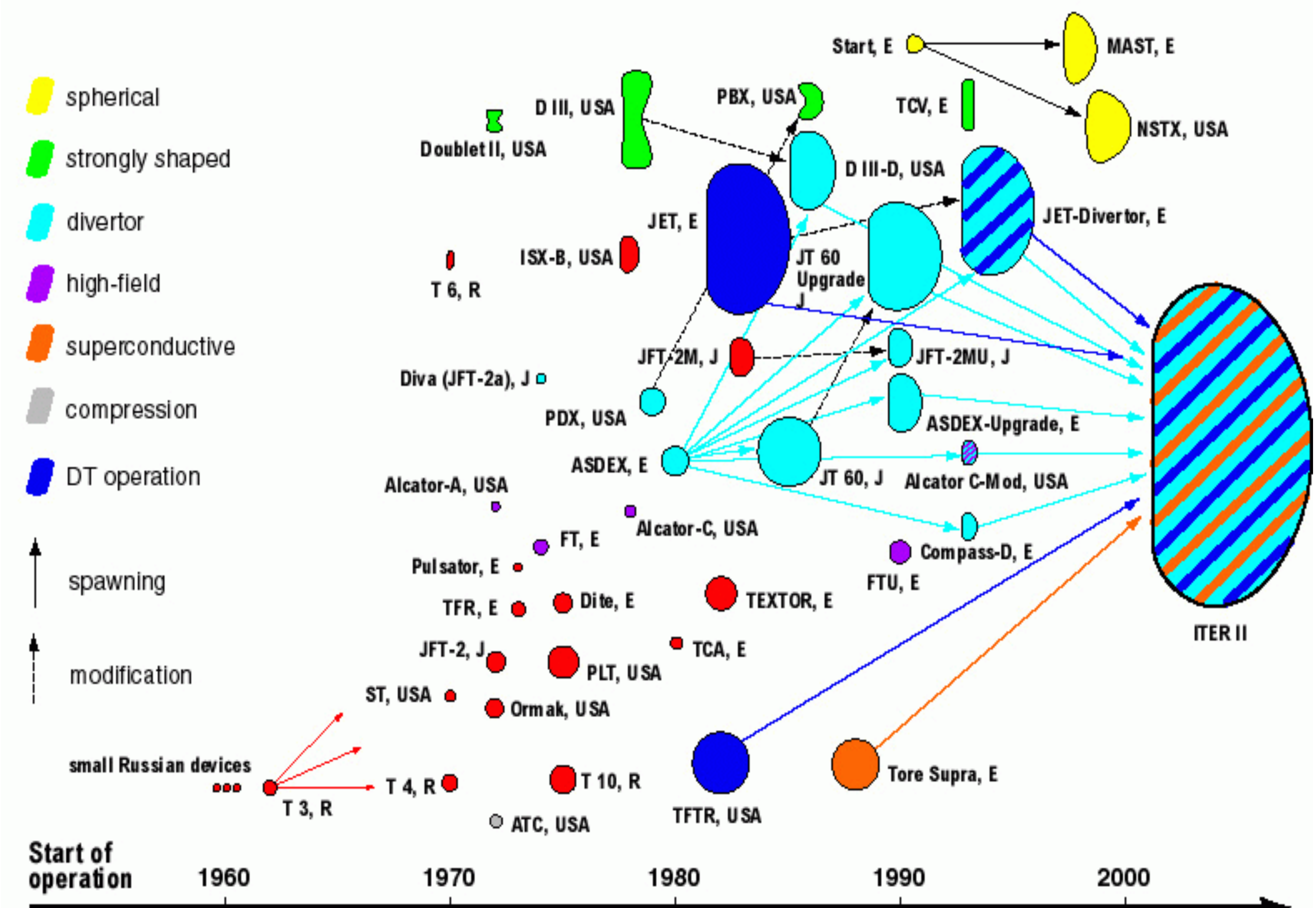


ITER divertor

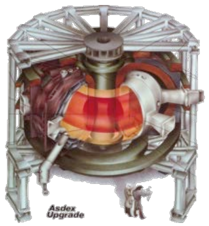
www.iter.org



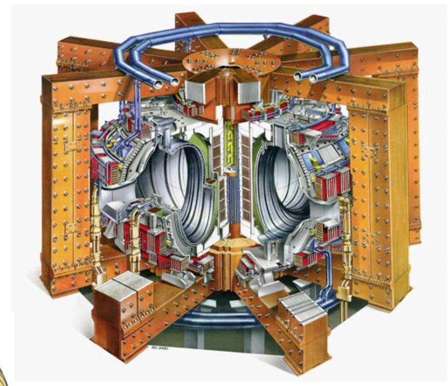
Tokamak Evolution



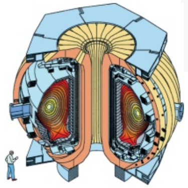
Tokamak experiments worldwide



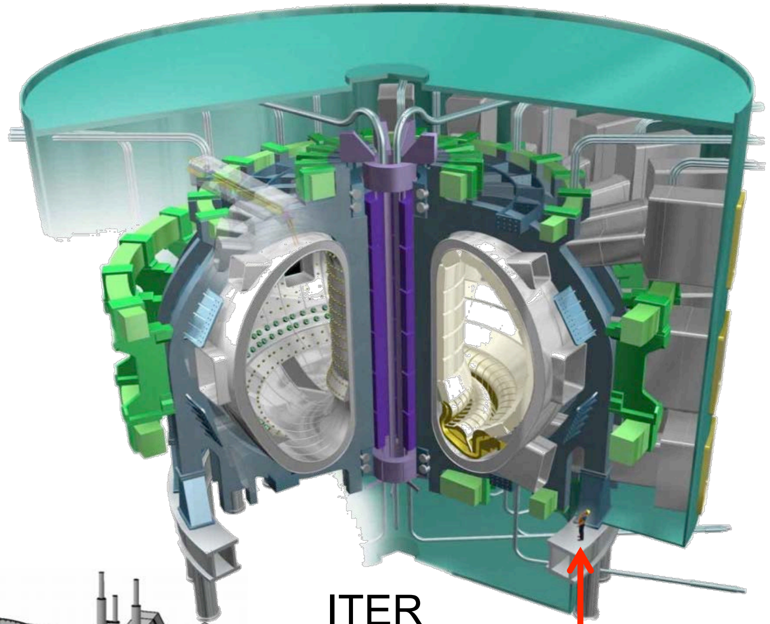
ASDEX
Upgrade
Garching (D)



JET
Culham (GB)

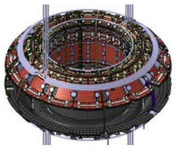


DIIID
San Diego
(USA)

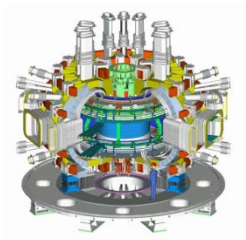


ITER
Cadarache (F)

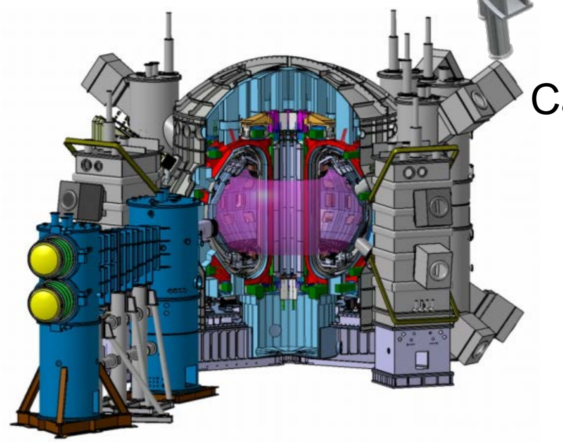
person



EAST
Chengdu (C)



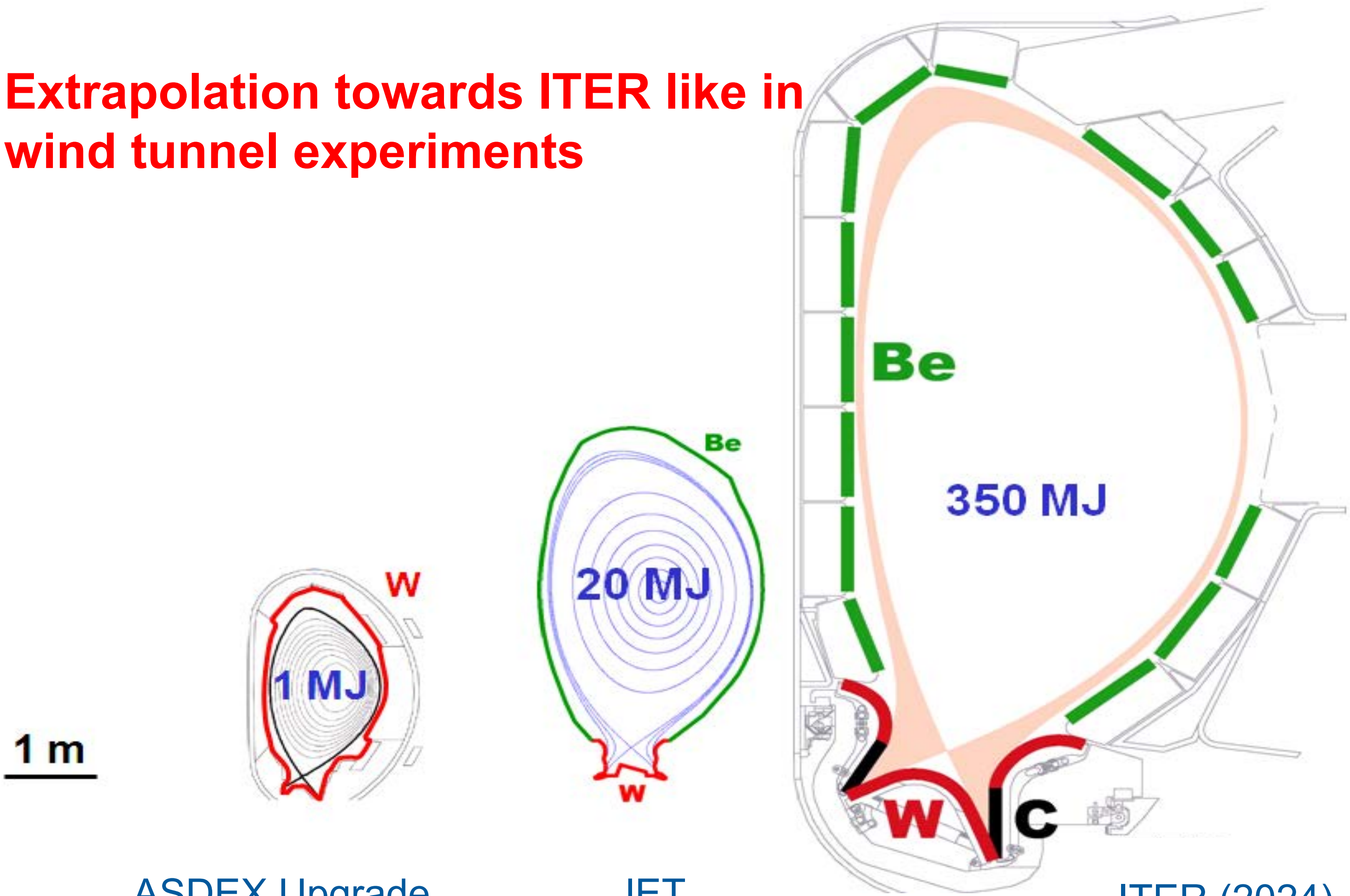
KSTAR
Daejon (KR)



JT-60SA
Naka (JA)

Planing ITER based on existing devices

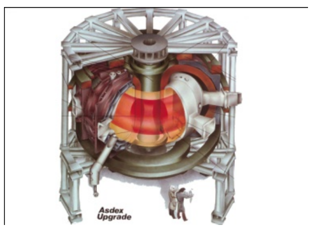
Extrapolation towards ITER like in wind tunnel experiments



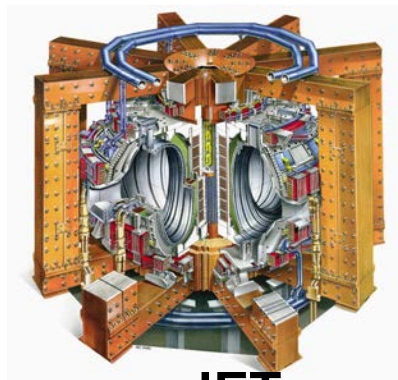
ASDEX Upgrade (Germany) | JET (EU) | ITER (2024) (international)

Development...

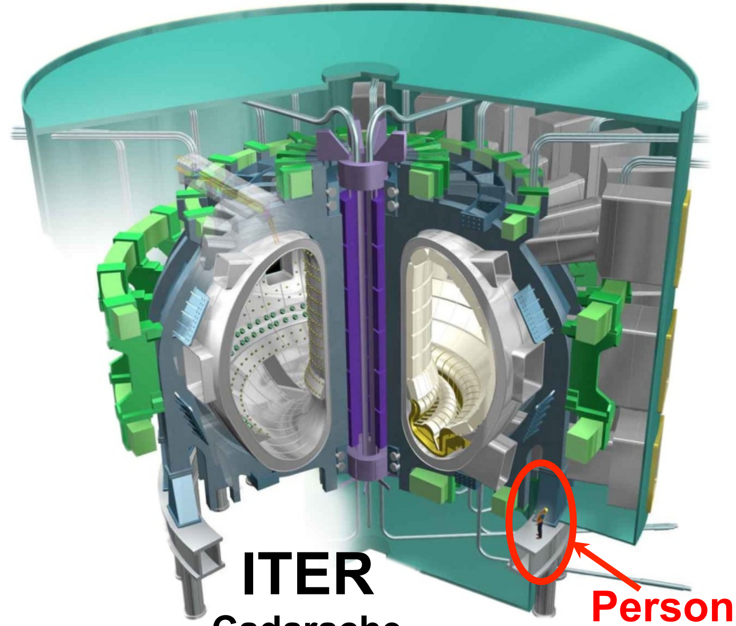
Tokamaks



ASDEX Upgrade
Garching



JET
Culham

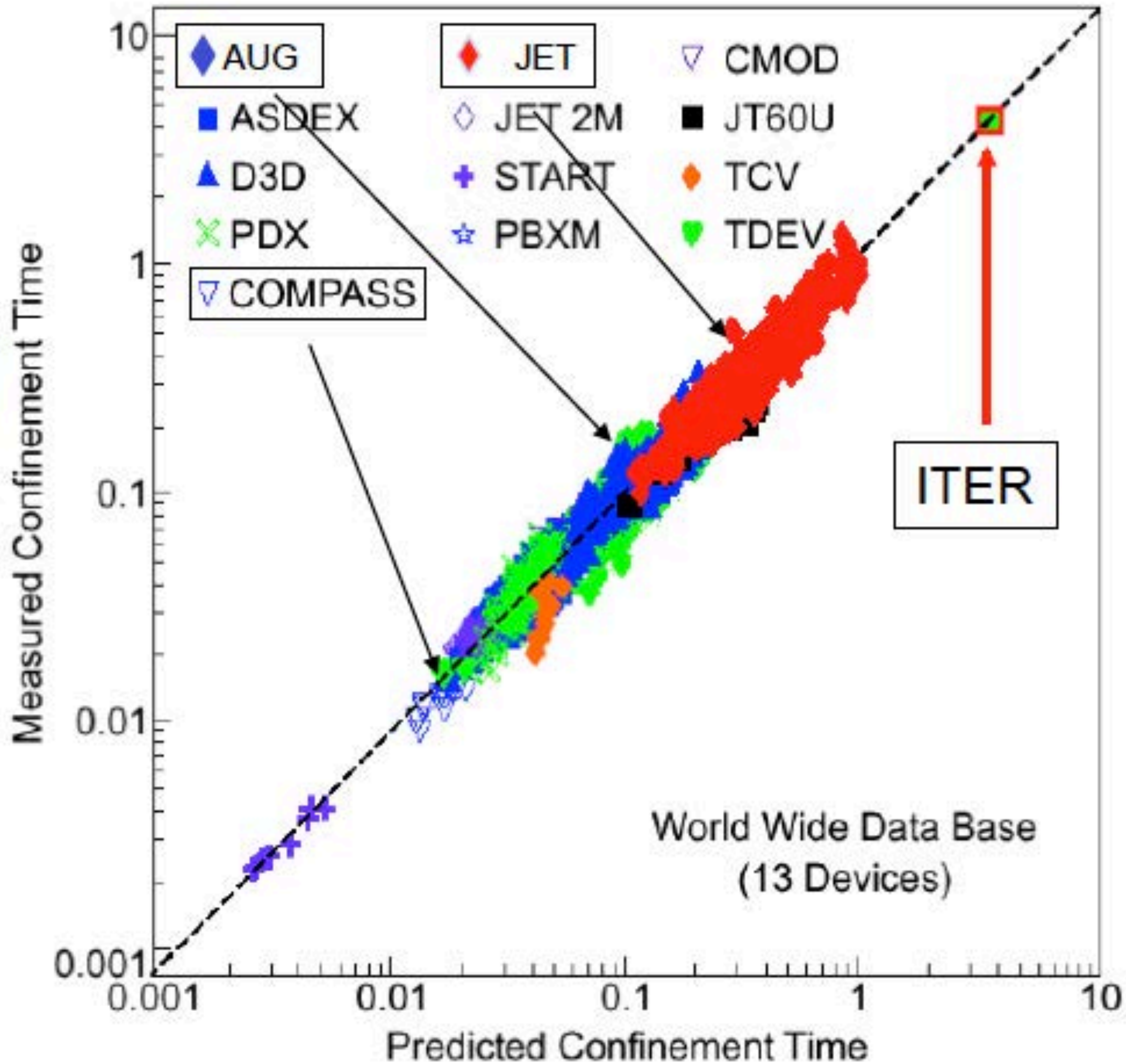


ITER
Cadarache

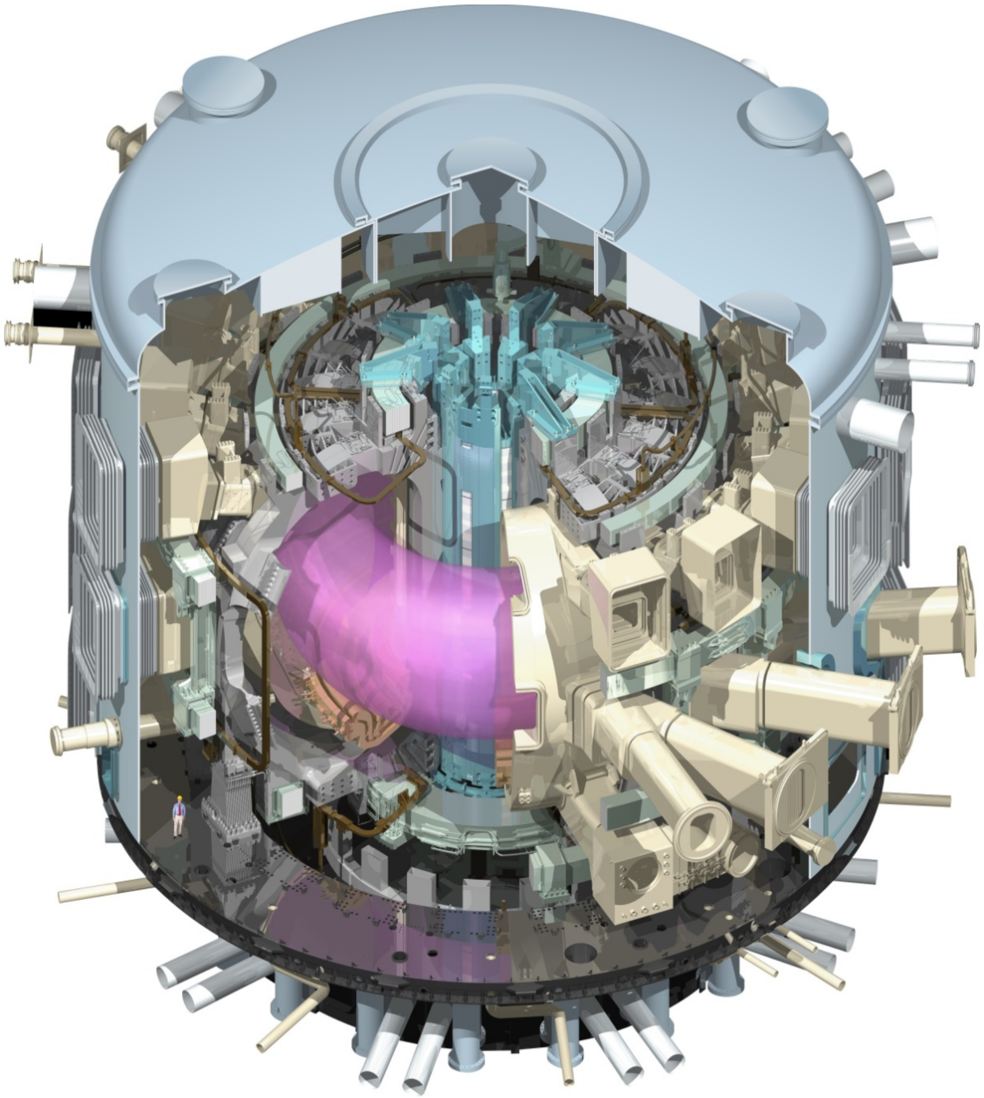
Erreichte Kennzahlen:

- Temperatur T 400 Mio.°C ✓
- Dichte n $10^{20}\,m^{-3}$ ✓
- Energie Einschlusszeit τ_E ~1 s, ist noch zu klein (etwa 4s benötigt)

ITER:
Due to larger volumes and higher confinement time Q=10 is expected



The ITER Design



	ITER
Major Radius	6.2 m
Minor Radius	2.0 m
Plasma current	15 MA
Magnetic field	5.3 T (Supercond.)
Power amplification Q	≥ 10
Fusion power	400 (800)MW
Duration of burn	400 (3000) s
External heating	73 (110) MW

Cost: ~ 15 Billion €
Requires world-wide effort

ITER will be built in Cadarache (F) as joint effort – Cn, EU, In, Jp, Ko, RF, US

ITER site – artists vision

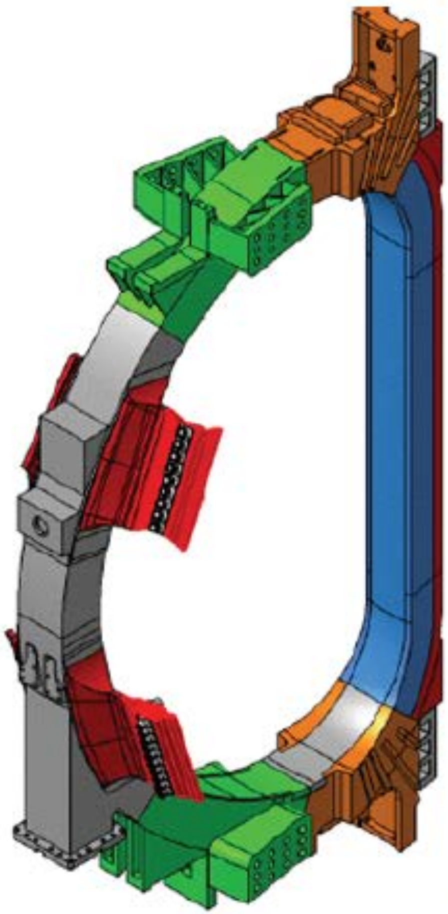
ITER site – artists vision

First Plasma slipped from 2019 – 2025 and 2027/28

Energy gain Q = 10 (~2037 − 2039)

Demonstrate the physical feasability of nuclear fusion by magnetic confinement

Toroidal field coils

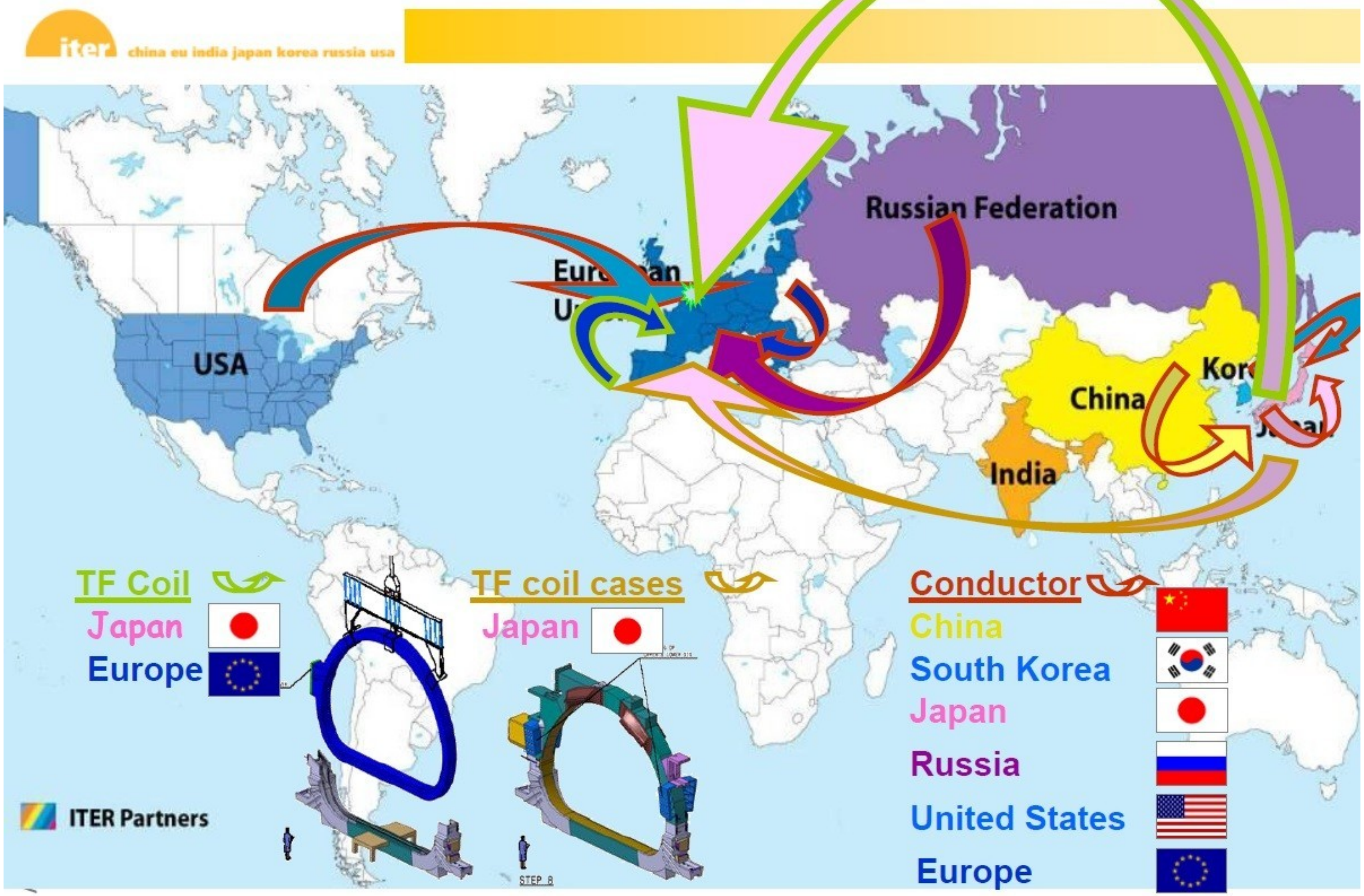


16 x 9 m, **~360 t**
(EU, JP – 18 coils)

Boeing 747-300
(maximum take-off weight **~377 t**)

Example: toroidal field coils

TF Coils – A Worldwide Collaboration

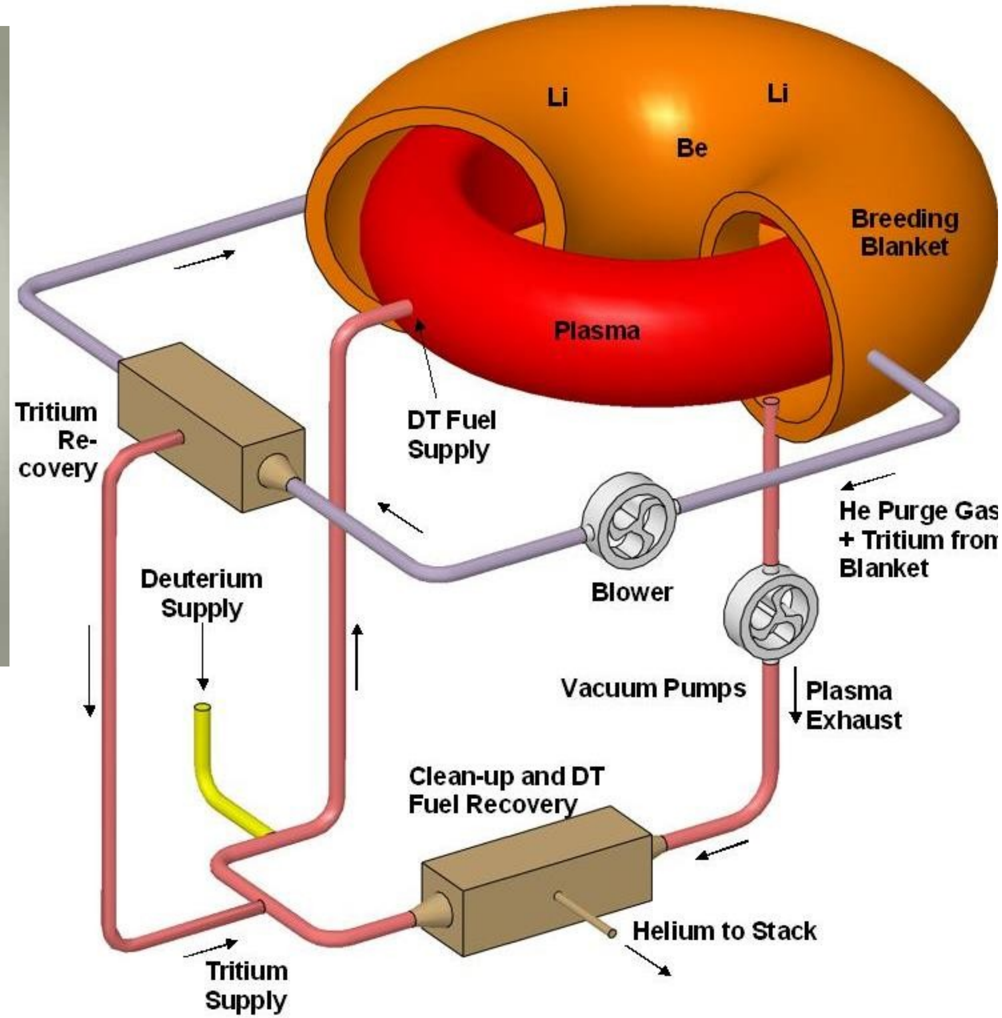


ITER site – aerial view 2014

ITER site 2015 – tokamak pit

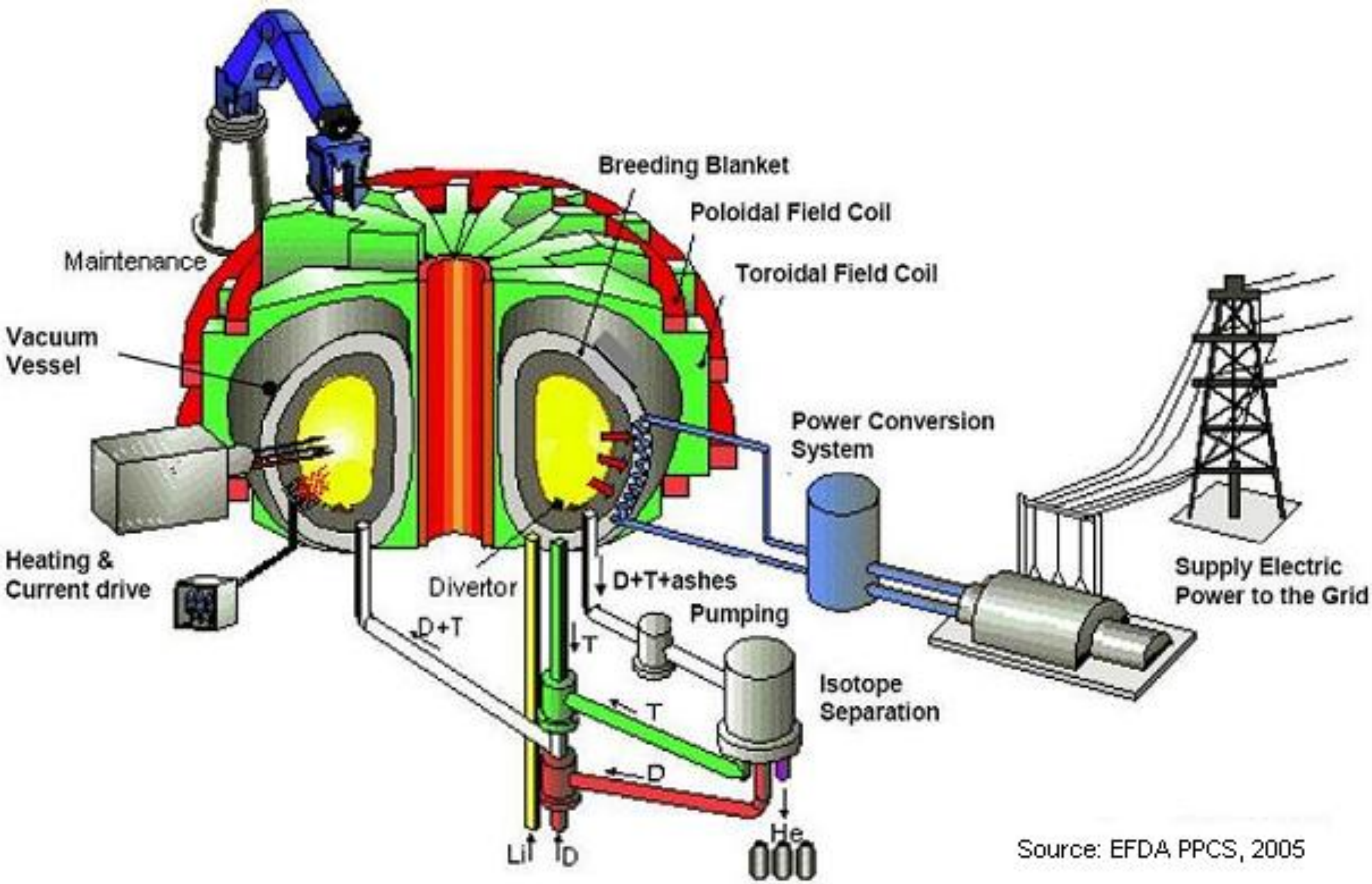
ITER site – aerial view 2016

Tritium breeding



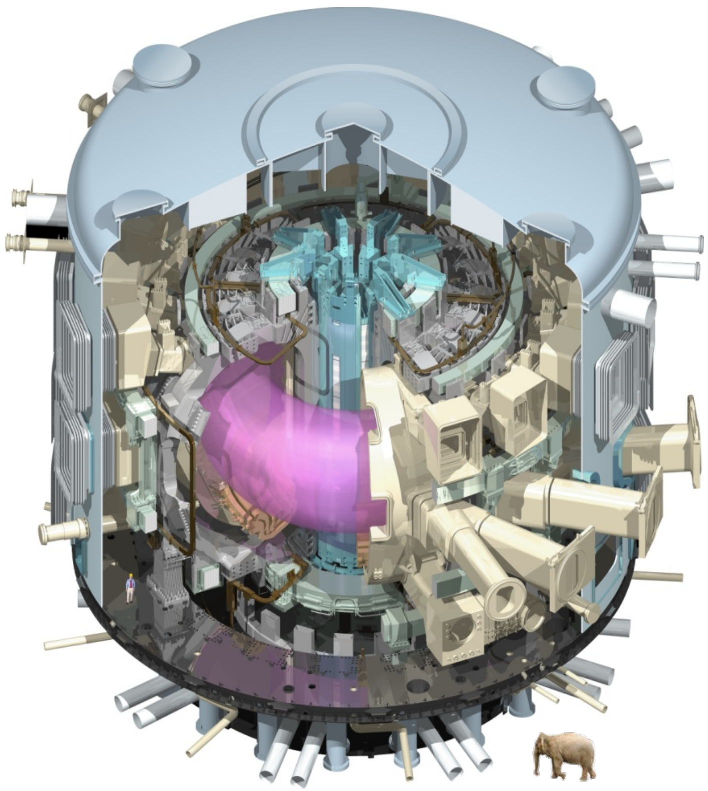
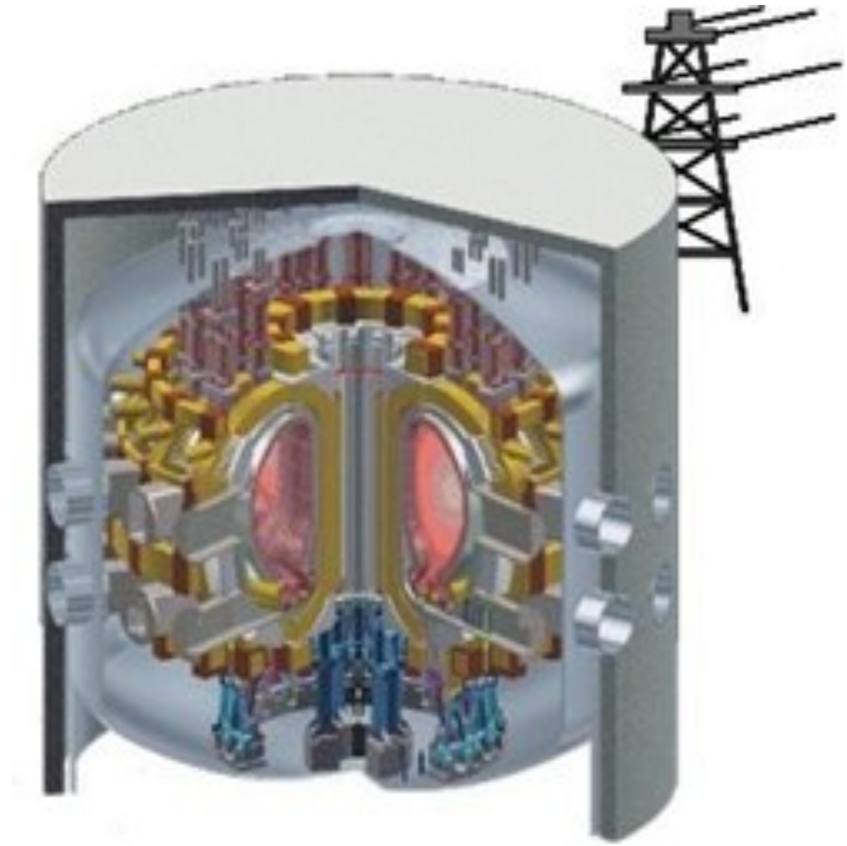
www.iter.org

Fusion power plant



Source: EFDA PPCS, 2005

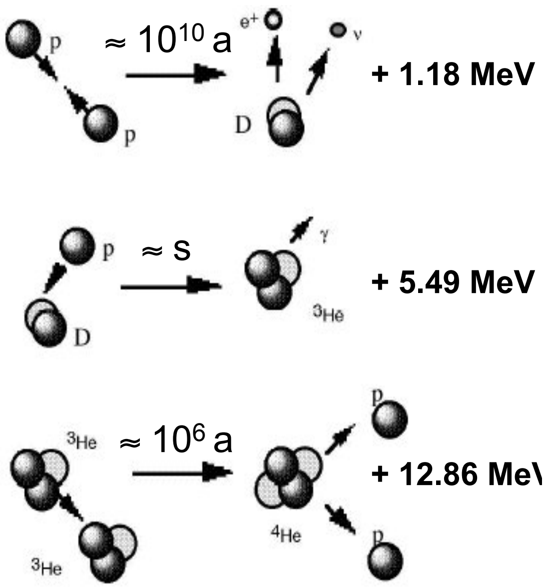
Path to a fusion power plant

ITER	DEMO
	
7min discharge Tritium supplied externally Experiment	Continuos operation Tritium bread from Lithium Net electricity output to the network

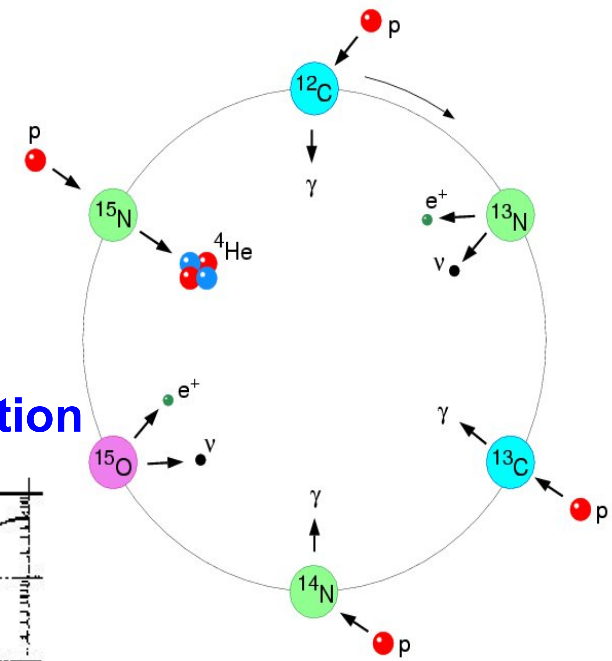
Fusion process in stars

$$4\,p \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_e$$

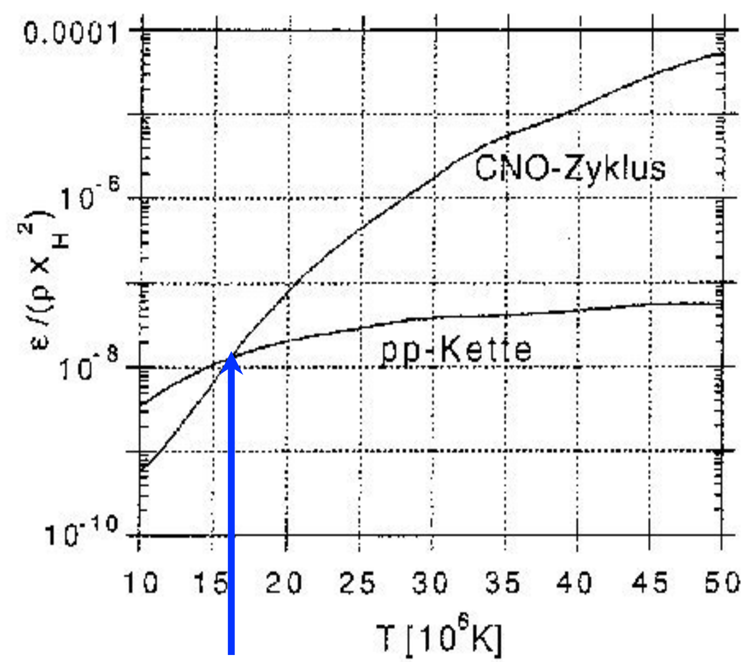
Protonen chain



CNO-Zyklus



Normalized energy production



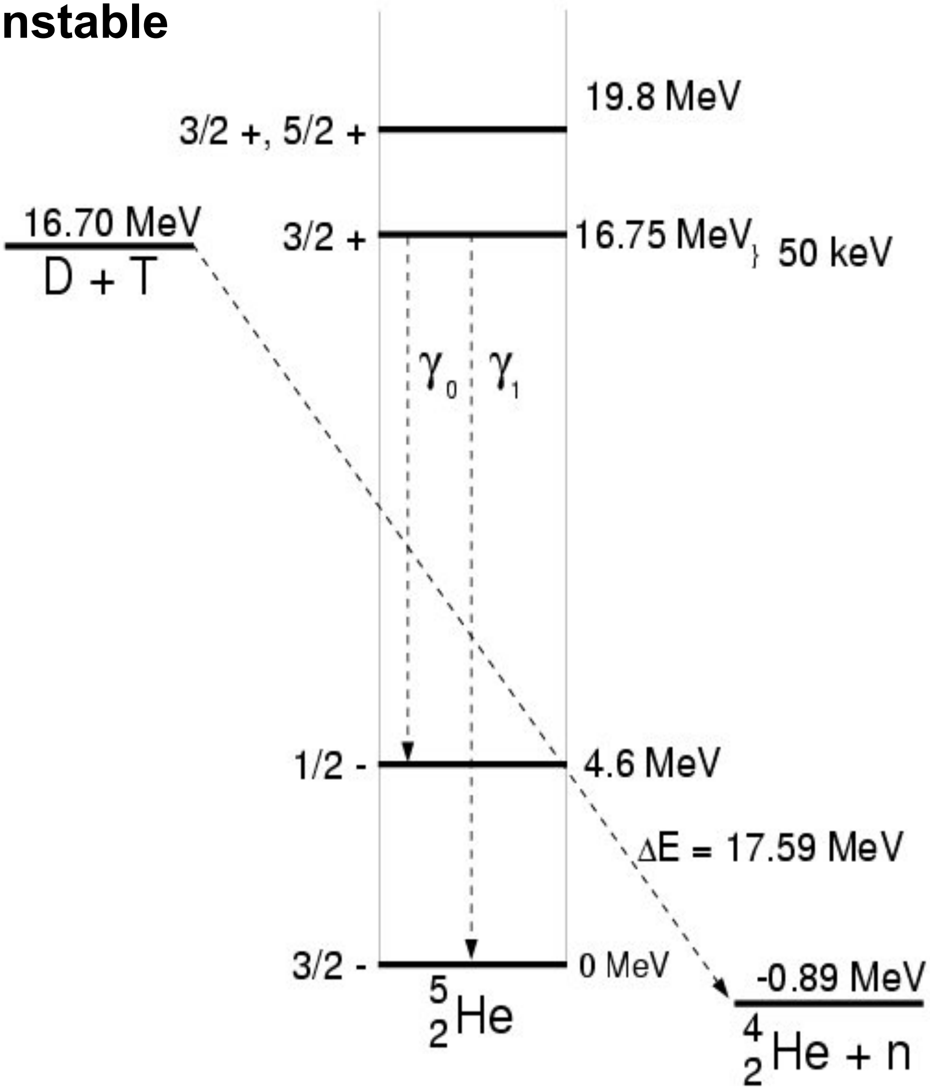
T ≈ 1.5 keV

Fusion process in laboratory

$$D + T \rightarrow {}^{4}_{2}He + n + 17.6\ MeV$$

Energy level diagram of the unstable He^{5}_{2}

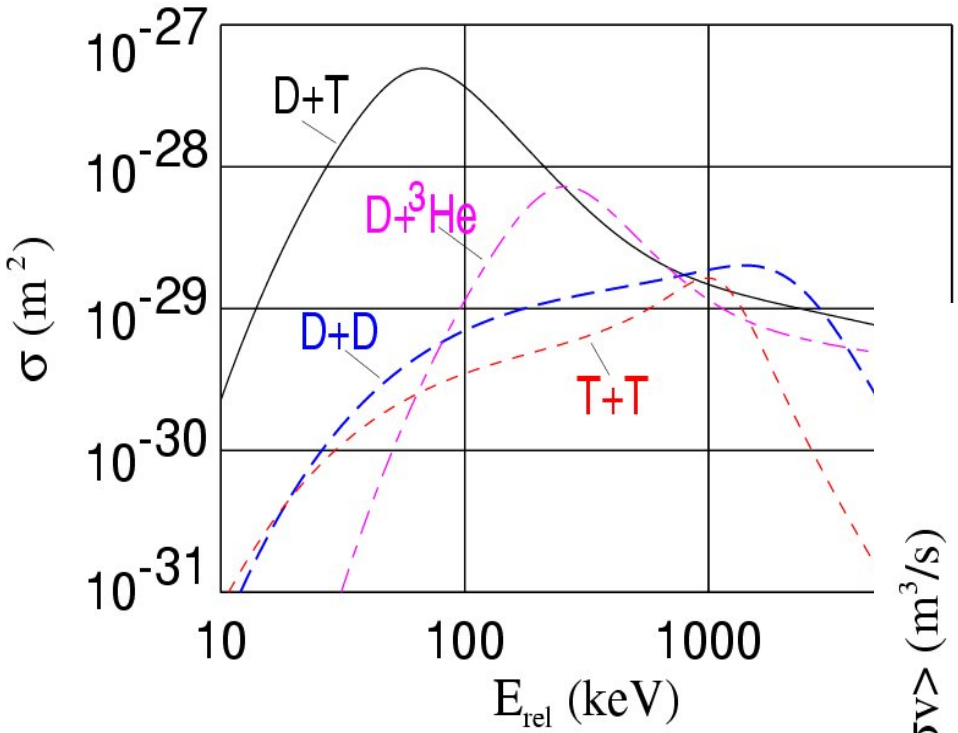
Resonance for E = 64 keV



Fusion processes in a laboratory

$$D + T \rightarrow {}^4_2He + n + 17.6\ MeV$$

Cross section



Reaction parameter − rate coefficient
Assuming a Maxwell distribution