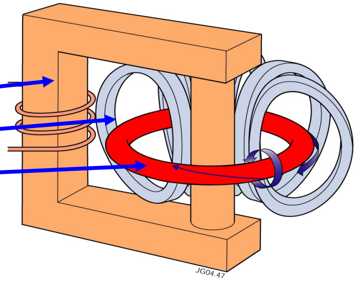
Tokamak – Summary

- **Tokamak**, from the Russian words:

тороидальная камера с магнитными катушками
(**to**roidalnaya **ka**mera, s **ma**gnitnimi **k**atushkami)
meaning "**toroidal chamber**" with "**magnetic coils**"

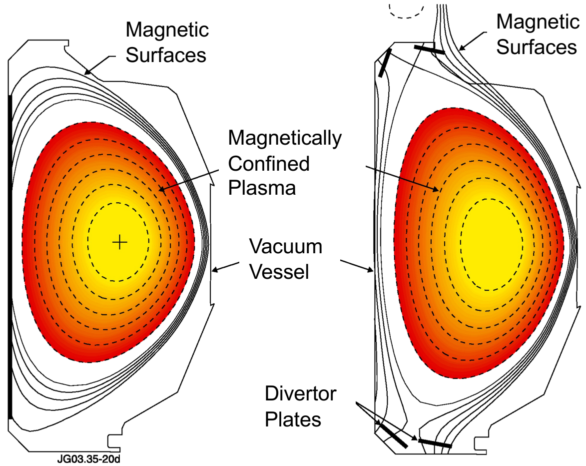
- Invented by : Andrei Sacharov and Igor Tamm
(both Noble Prize Winners)
at the Kurchatov Institute in Moscow in 1950

- Essentially a tokamak consists of :
  — large transformer
  — coils for magnetic fields
  — plasma ring with large plasma current



Two tokamak configurations in use

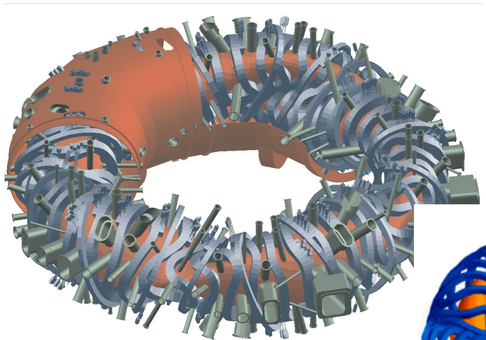
Limiter Configuration | **Divertor Configuration**

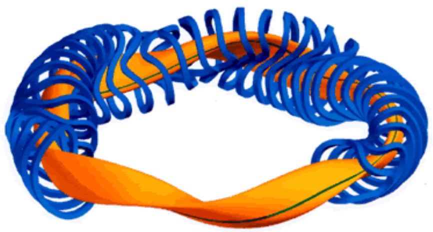


Realizing a helicoidal magnetic field : Option 2

Stellarator

Complex 3D coils create directly a helicoidal magnetic field





No plasma current
⇒ no transformer
⇒ continuous operation

Wendelstein 7-X: Overview

Physics goals

Fusion product should be about 1/50 of a fusion reactor

Major, average minor radius:	*R=5.5 m, <a>=0.53 m*
Magnetic field on plasma axis:	*B=2.5 T*

Test magnetic field optimization

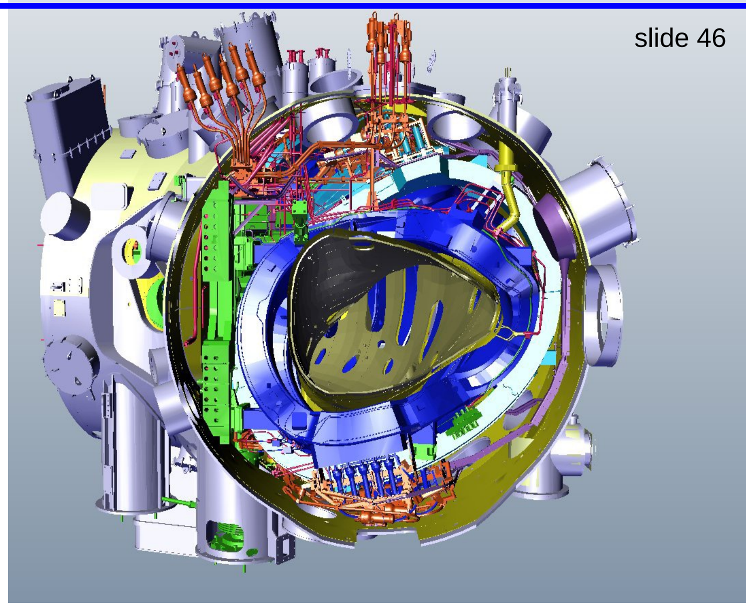
physics experiment:	*H, D plasmas only, additional planar coils*
heating systems	10*MW ECRH, 20 MW NBI, ICRH*
mimic α-particle heating:	ICRH, *NBI*

Technological goals

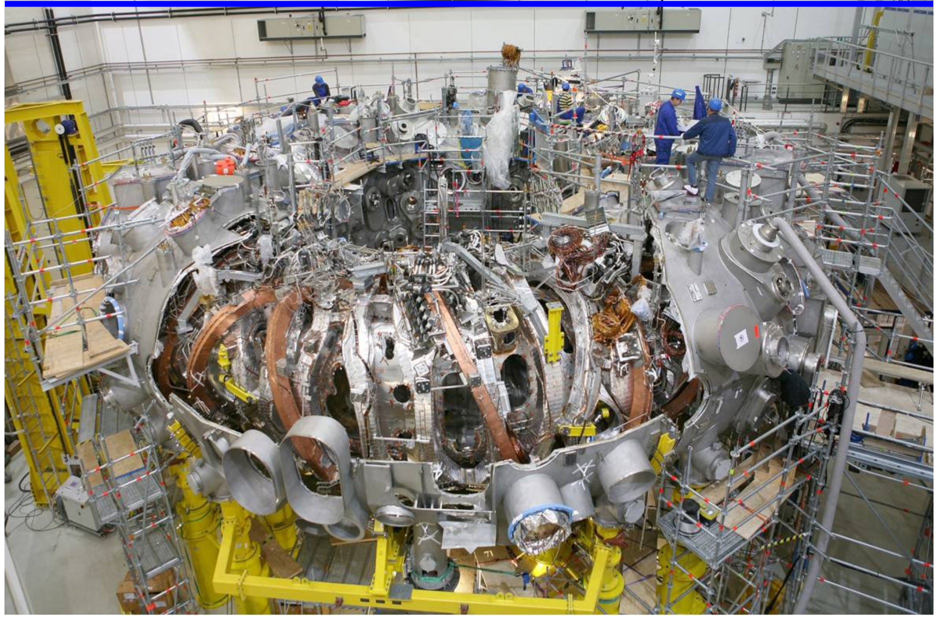
Reactor feasability of stellarators

steady-state operation	*30 minute plasma heating with ECRH*
	superconducting coils
	active cooling of plasma facing components

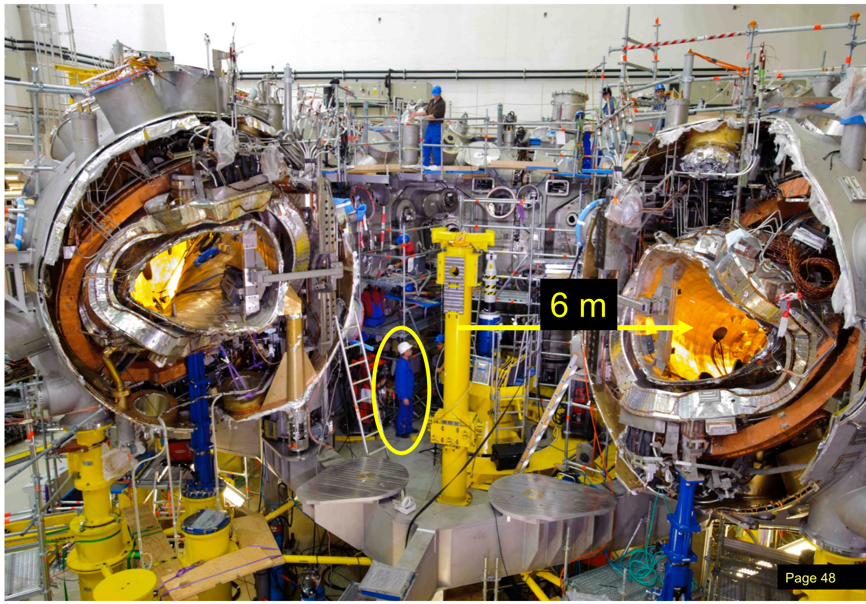
Wendelstein 7-X : Largest Stellarator in the world



Wendelstein 7-X : November 2011



Wendelstein 7-X in construction (2013)



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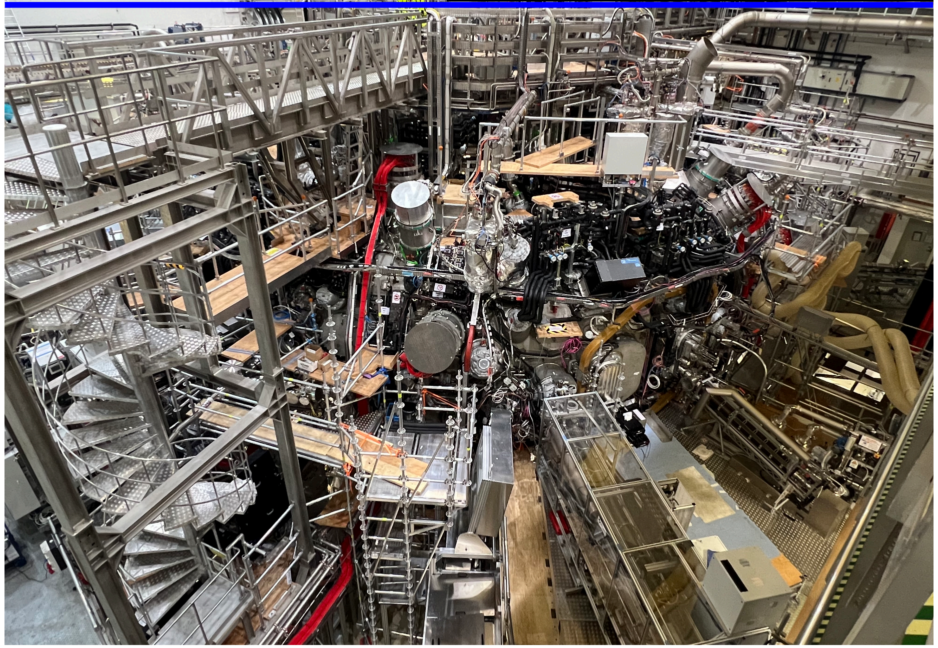
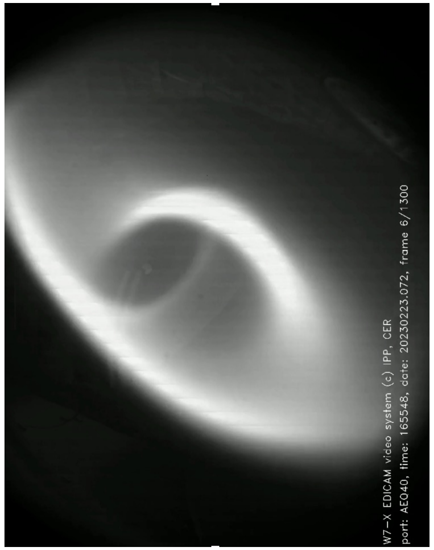
Wendelstein 7-X : April 2026



Example of a plasma in Wendelstein 7-X

slide 50



How to create the ultra high temperatures needed ?

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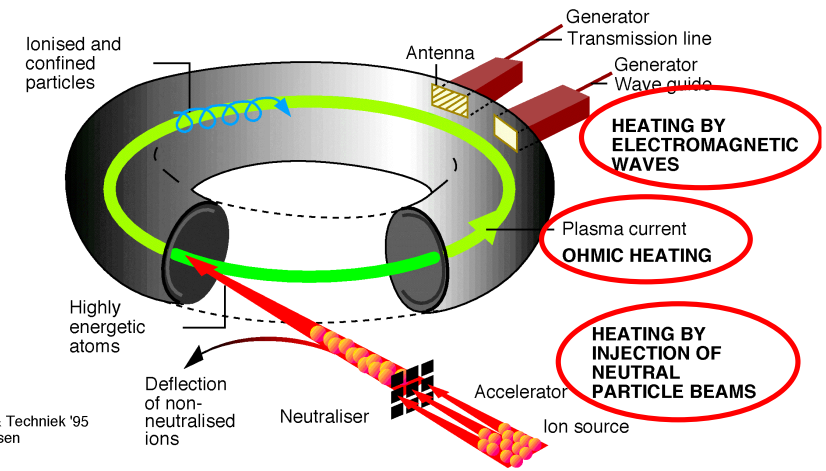
In a future fusion reactor: α-particle heating



The main difficulty of magnetic fusion: keep a huge T gradient

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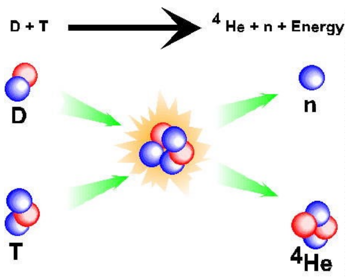
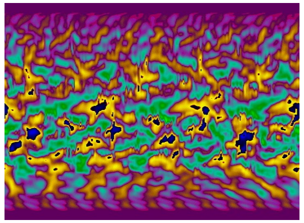


- Two positive nuclei (D^+ and T^+) at short distance
  — strong repulsion
  EXTREMELY HIGH temperatures needed to bring the nuclei close enough together : ~200 000 000 K
- Special methods needed to heat and confine the fuel



- Very large gradient in temperature (~ 200 000 000K/m)
  — gradients limited by turbulence
  ⇒ TURBULENT medium : very complex physics

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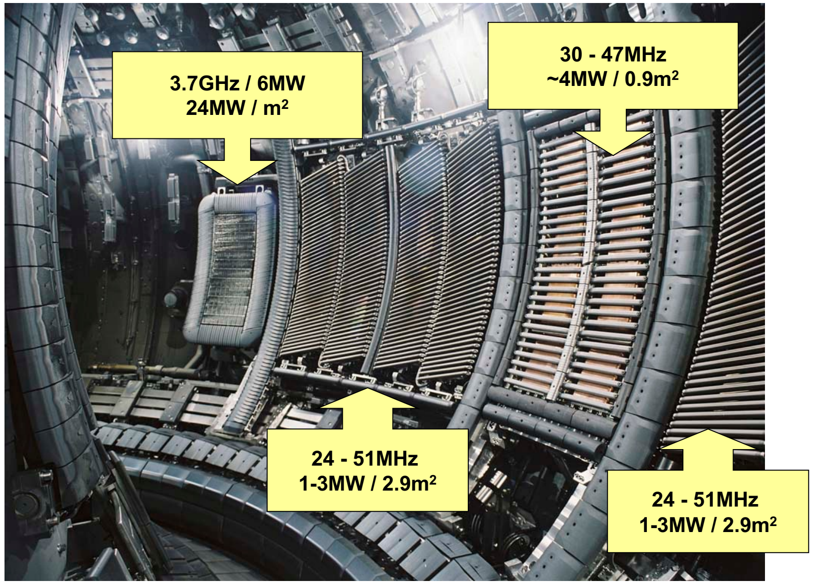
Example of RF heating systems (in JET)



Fusion expertise at the Royal Military Academy

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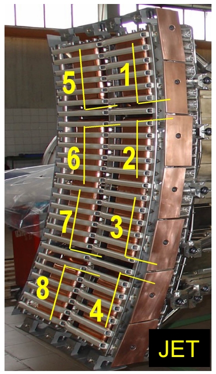
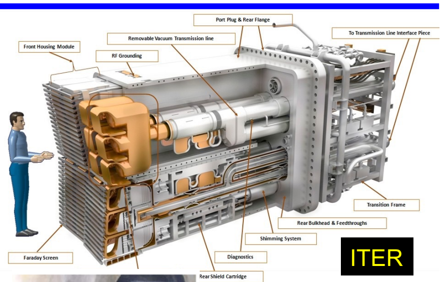
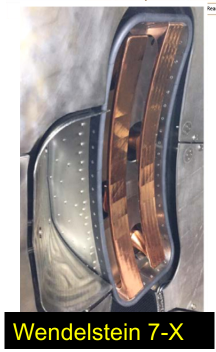
Laboratory voor Plasmaphysics of the
Ecole Royale Militaire – Koninklijke Militaire School
(LPP/ERM-KMS)

Heating with radio waves (short wave – FM frequencies)
20 – 90 Mhz at MW level

LPP-ERM/KMS designs heating antenna's for machines worldwide







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Recent international recognition for LPP/ERM-KMS

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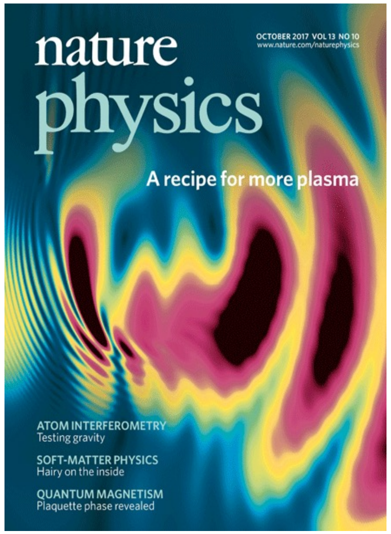
Front page Nature Physics (2017)



Most cited paper in US journal Physics of Plasmas (2021)

slide 57 **Landau-Spitzer Prize (American Physical Society)**

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Status of Magnetic Fusion Research

slide 59 **Power Amplification Factor Q, Break-even, Ignition**

$$Q = \frac{P_{fusion}}{P_{external\ heating}}$$

Breakeven Q=1

when $P_{fusion} = P_{external\ heating}$

Ignition Q = ∞

when $P_{external\ heating} = 0$: no external heating needed
Selfsustained fusion reaction

Note:

Q relates to the balance between fusion and external heating power **only**

It is **not** representative for the balance between total power consumption (magnetic fields, additional systems) and fusion power output

Plasma Energy and Energy Confinement Time slide 60

$$W_p = 1.5 \int_V k\,[n_e(r)\,T_e(r) + n_i(r)\,T_i(r)]\,dV$$

$$\frac{dW_p}{dt} = P - \frac{W_p}{\tau_E} \qquad \text{If } P = 0 \Rightarrow W_p(t) = W_p(0)\,e^{-t/\tau_E}$$

Transport losses by conduction and convection

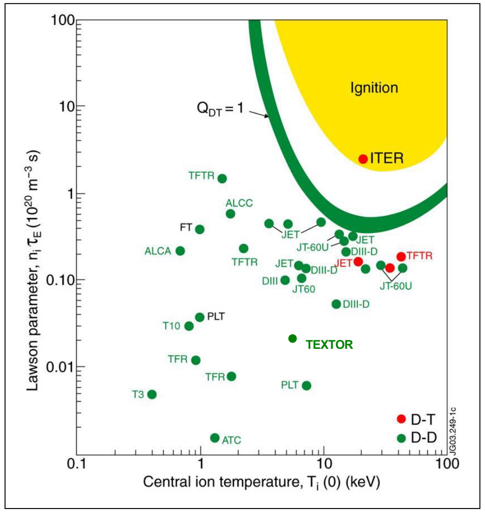
τ_E **measures how fast the plasma looses its energy**
τ_E **is a measure for the thermal insulation of the plasma**

Under stationary conditions (dW/dt=0) : $\tau_E = \frac{W_p}{P}$

slide 61 **Present tokamak devices close to Break-Even**

Present machines are close to produce fusion energy comparable with the energy required to sustain the plasma (breakeven : Q=1)

Next step devices (ITER) are expected to produce significantly more fusion energy than the energy required to sustain the plasma (close to Ignition Q=∞)



slide 62

The largest fusion machine in the world

JET

Joint European Torus

(Oxford, UK)

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slide 63

Joint European Torus (JET). Largest tokamak* in the world (in Culham, 10km from Oxford)

*Russisch Acronym:
тороидальная камера с магнитными катушками
Toroidal chamber with magnet coils

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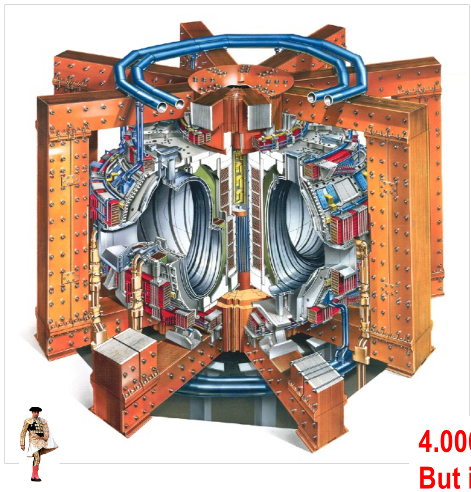
Joint European Torus (JET) - Largest and best fusion machine worldwide

slide 64



Vacuum vessel 3.96m x 2.4m

Plasma volume 80 m3 - 100 m3

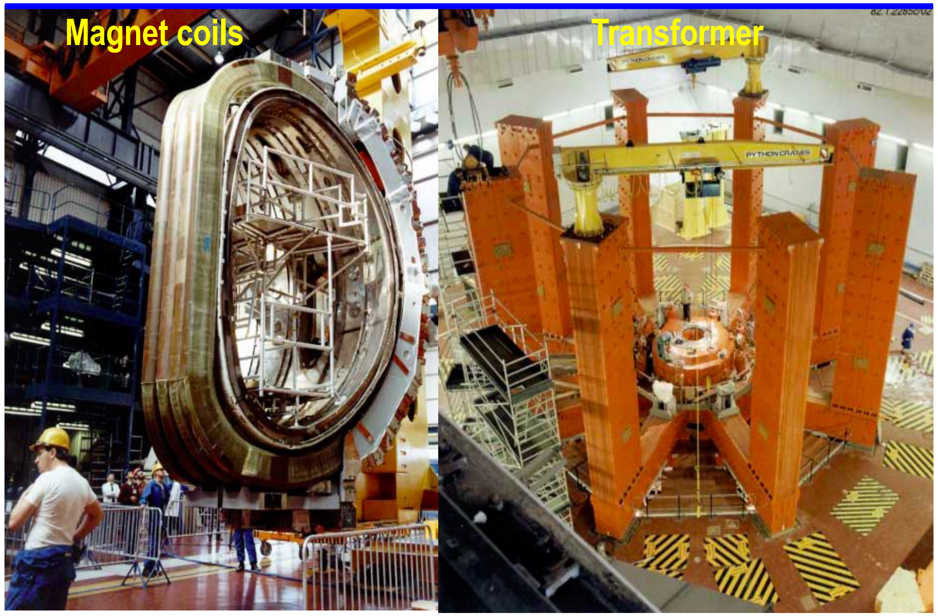
Plasma current max. 5 MA

Magnetic field max. ~4 Tesla

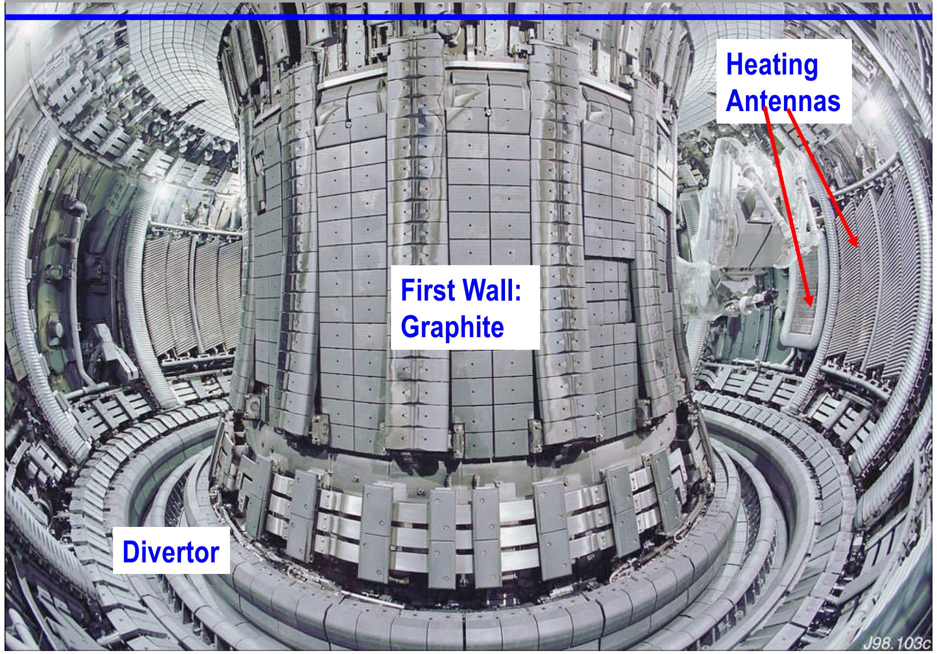
(80000 times as strong as the earth magnetic field)

4.000 000 000 Euro being destroyed.
But in perfect working order
Due to political (EU+UK) nonsense

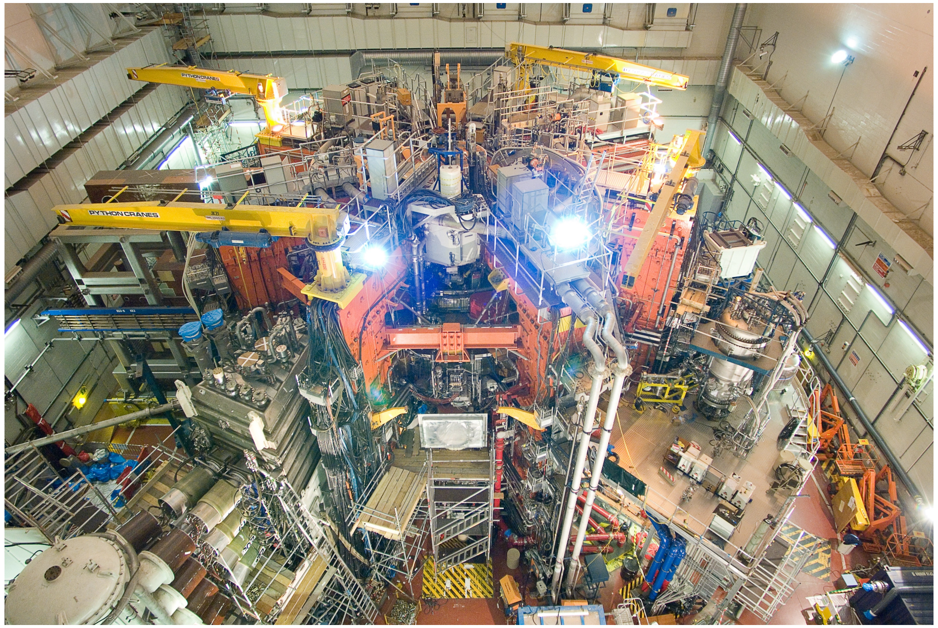
An impression of the dimensions of JET slide 65 65



Inside view of JET with graphite wall (until 2010)



JET: (it was) a cathedral of science



Inside view of JET with and without hot plasma