# Physics of Nuclear Fusion

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- fusion in the stars
- fusion research on earth
  - Inertial Confinement Fusion (ICF)
  - Magnetic Confinement Fusion (MCF)
- status of fusion research and outlook

(compiled by H.-S. Bosch / edited by O. Grulke, J. Riemann)

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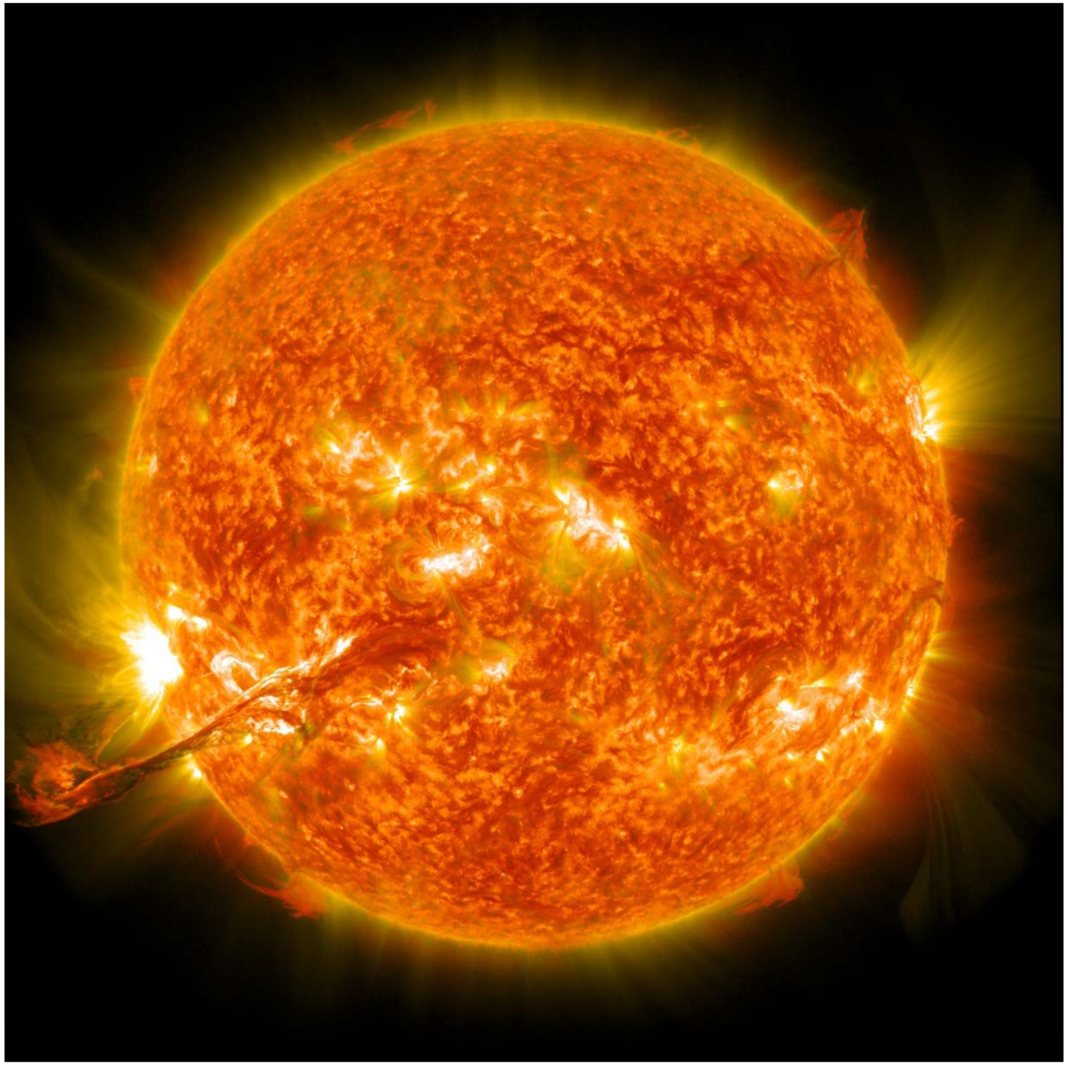
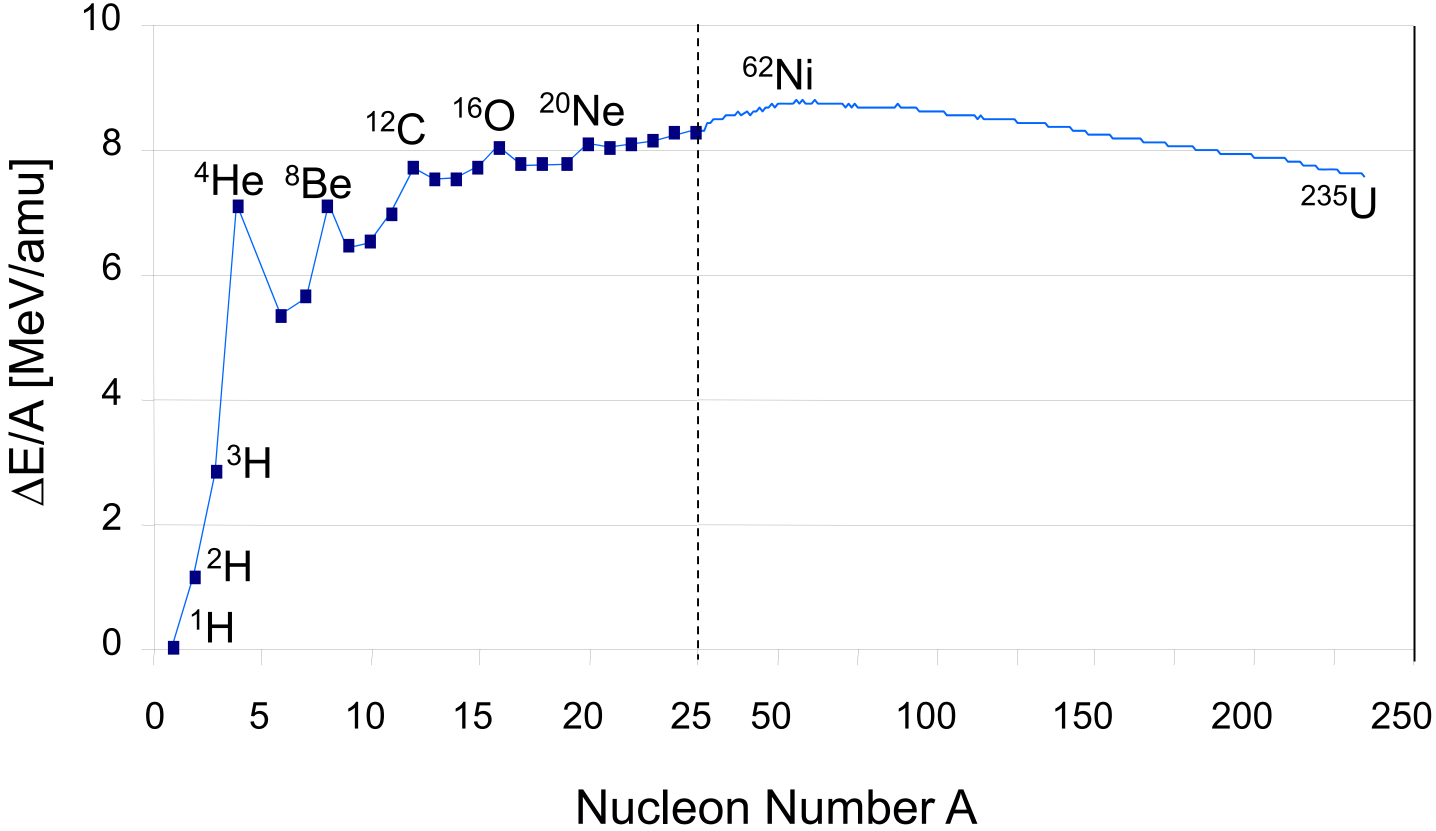
# The energy source of the stars

- The sun continuously releases energy, with a total power of $3.6 \cdot 10^{17}$ GW.
- In doing so, it converts 600 Mio. tons of hydrogen into 596 Mio. tons of helium – each second!
- The power flux arriving on earth is 1.4 kW/m$^2$ (above the atmosphere, without absoprtion).



**NASA, August 31, 2012 observation of a massive CME**

# Nuclear energy: Fission & Fusion

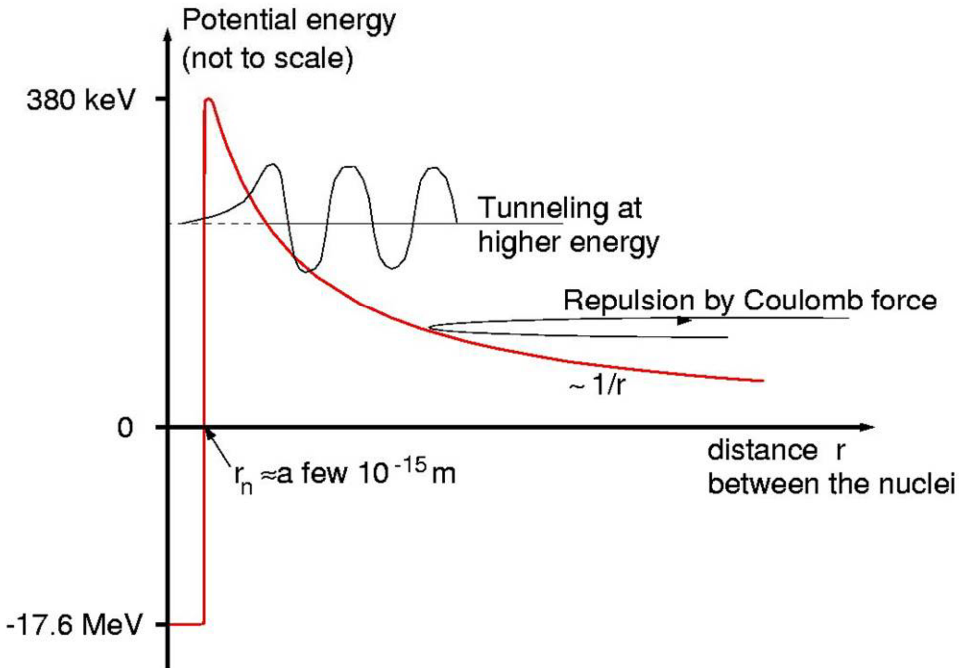



1) binding energy per nucleon **~MeV** (not eV as in chemistry → electrons bind molecules)

2) energy gain possible from: either **fission of heavy nuclei** or **fusion of light nuclei**

advantages of fusion: fuel resources, safety aspects, reduced waste production

# Nuclear reactions: Potential energy




- Nuclear forces (strong interaction) act only over distances on the order of the nucleus dimensions (fm).
- Otherwise, the repulsive Coulomb force dominates. potential wall ~ some 100 keV, impossible to overcome!

- 1928, Gamov explained $\alpha$-decay with tunneling-effect (Q.M.): probability function is a spatially decaying wave function with finite values for $r < r_n$,

  $\Rightarrow$ finite probability for tunneling through the Coulomb wall:

$$P_{tunnel} \sim e^{-\frac{2\pi Z_1 Z_2}{h v_{rel}}}$$

- reaction probability highest for light nuclei at high relative velocities!

# Solar fusion reactions: The pp-chain

$$p + p \rightarrow d + e^+ + \nu_e$$
$$p + d \rightarrow {}^3He + \gamma$$

$${}^3He + {}^3He \rightarrow {}^4He + 2p \qquad {}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

$$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$$
$$p + {}^7Li \rightarrow {}^4He + {}^4He$$

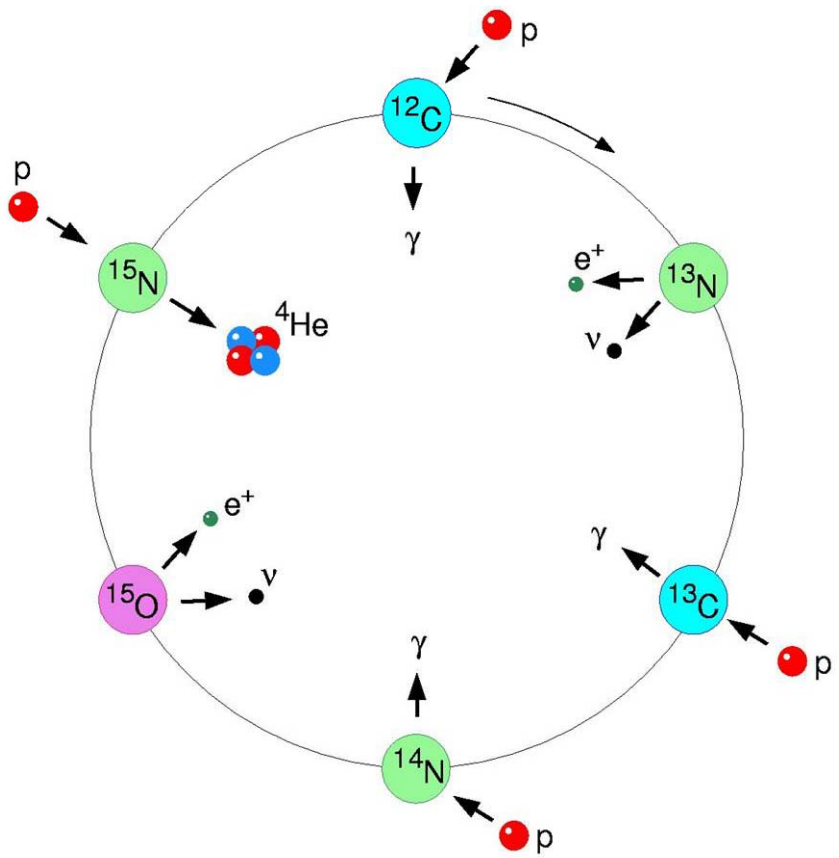
$$p + {}^7Be \rightarrow {}^8B + \gamma$$
$${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$$
$${}^8Be^* \rightarrow {}^4He + {}^4He$$

| branch I | branch II | branch III |
|---|---|---|
| (83.30%) | (16.68%) | (0.02%) |
| 0.86keV <T<1.2keV | 1.2keV <T<2.0keV | 2.0keV <T |

- The first step involves the weak interaction, transforming a proton into a neutron, resulting in a very long time scale, i.e. small reaction rates.
- This is the reason for the long life time of stars.

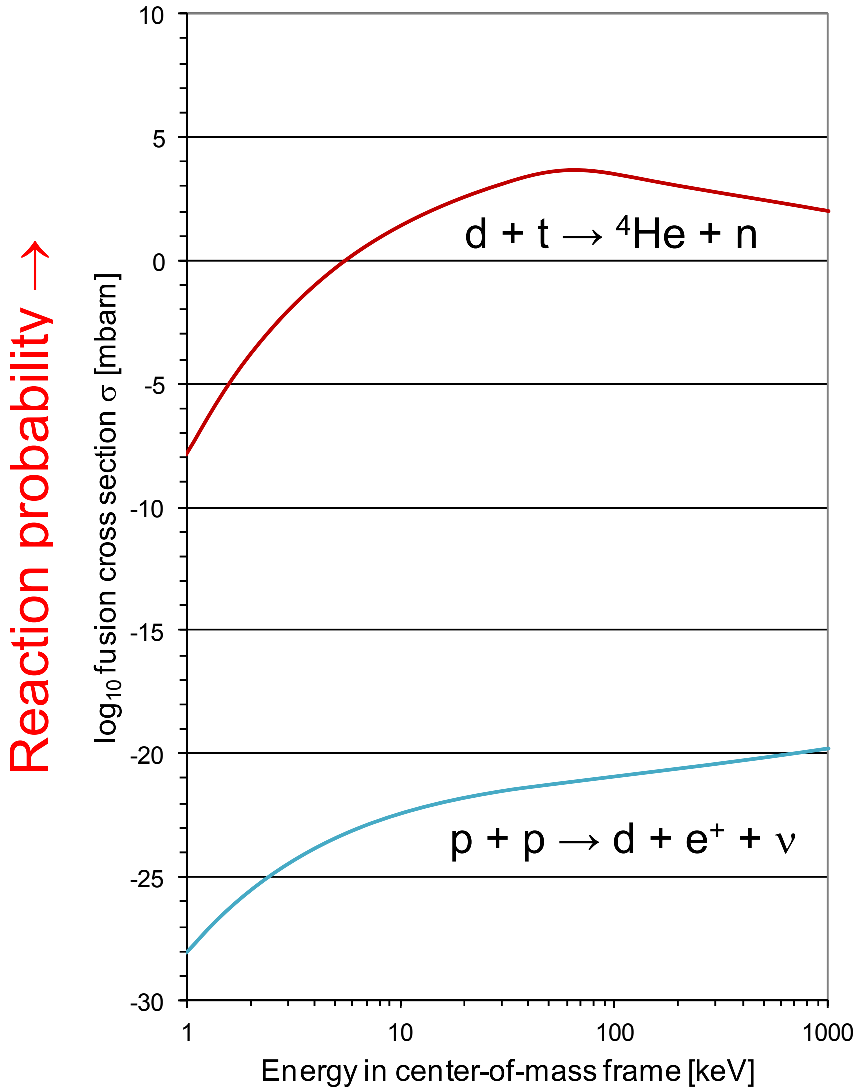
- An alternative path to the first step involves 3-body collisions, and is therefore very rare: $p + p + e^- \Rightarrow d + \nu_e$
- Fusion reactions also create the heavier nuclei in the stars.
  $\Rightarrow$ stellar nucleosynthesis
- The neutrinos from this reaction are the only particles to be observed on earth.

# The CNO-cycle
# (Bethe-Weizsäcker-cycle)




- independently discovered in 1938 by Hans Bethe (Cornell University) and Carl-Friedrich von Weizsäcker
- catalytic process at temperatures above 1.5 keV, based on $^{12}$C
- not important in the sun, but for all larger (i.e. hotter) stars
- This process requires the presence of carbon!
- net reaction:
  $4\ p \Rightarrow {}^{4}He + 2\ e^{+} + 2\ \nu + 3\ \gamma$ (27 MeV)

# For a terrestial energy source we have to rely on different fusion reactions!




- The weak interaction makes the pp-chain a rather slow reaction.

  → explains long lifetime of stars

- The huge mass of the sun makes up for that easily, still resulting in a large power production.

- However, for power production on earth, the weak interaction has to be avoided.

- For the small volume we can afford, we need faster fusion reactions.

# Fusion reactions on earth

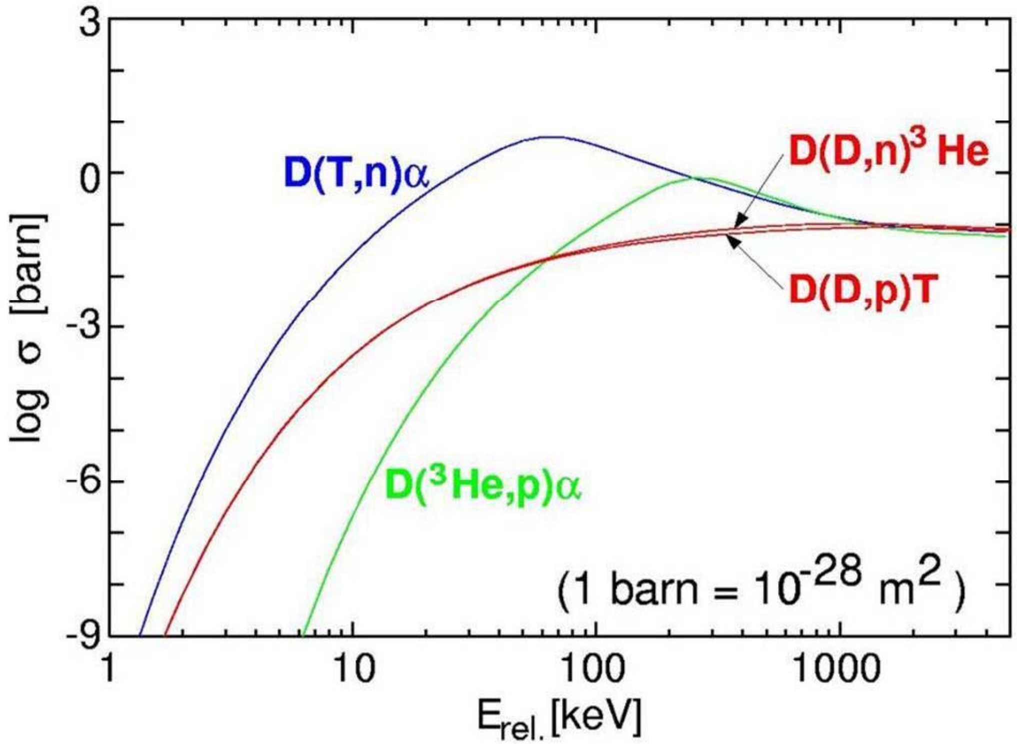
$d + d \Rightarrow {}^3He + n + 3.27$ MeV (50%)

or $t + p + 4.03$ MeV (50%)

$d + t \Rightarrow {}^4He + n + 17.59$ MeV

$d + {}^3He \Rightarrow {}^4He + p + 18.35$ MeV

- d = $^2$H, deuterium
  t = $^3$H, tritium
  (heavy hydrogen isotopes)
- best choice: DT-reaction



# Fusion reactions: The nuclear part

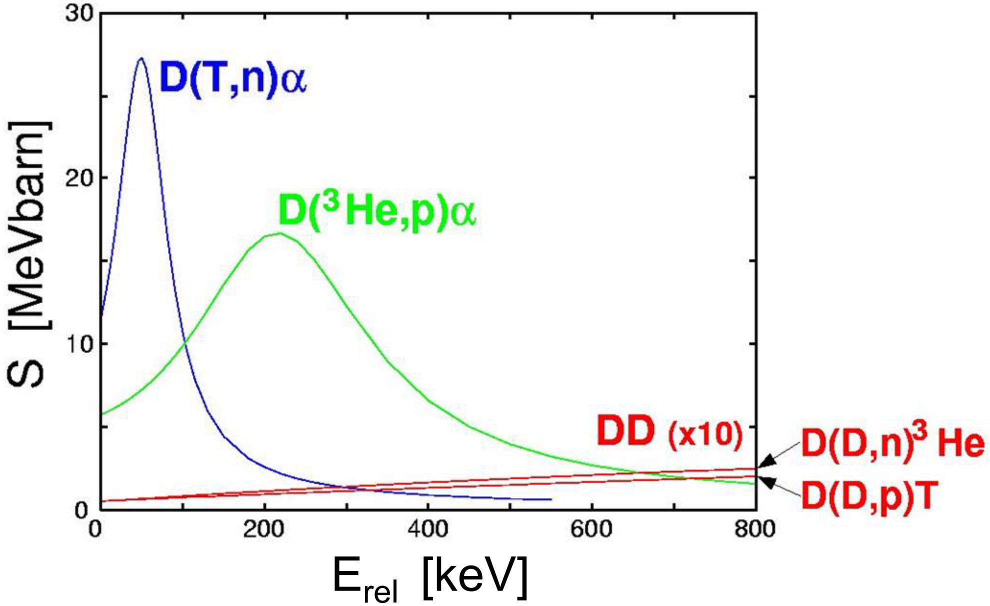
The fusion cross section can be written as:

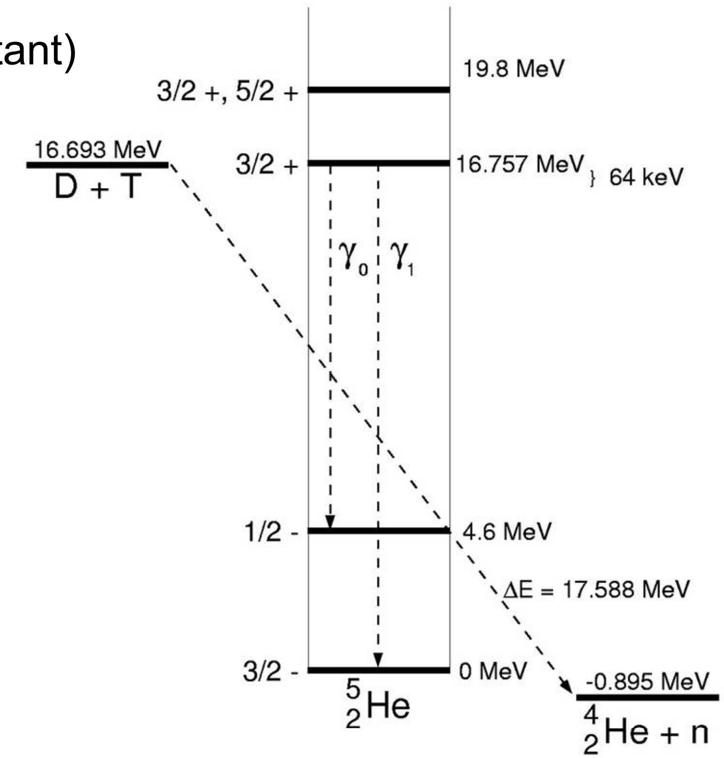
$$\sigma = S(E) \cdot 1/E \cdot \exp\{-B_G / \sqrt{E}\}$$

astrophysical S-function, (describes the nuclear physics of the reaction)

quantum-mechanical geometry factor

tunneling probability, ($B_G$ is the Gamov constant)



# Fusion fuels

- **Deuterium** exists with a weight fraction of $3.3 \cdot 10^{-5}$ in water
  $\Rightarrow$ static range of billions of years.

- **Tritium** is a radioactive isotope and decays with a half life of 12.33 years:

  $$T \rightarrow He + e^{-} + \nu_e$$

  $\Rightarrow$ no natural tritium available, but production with fusion-produced neutrons is possible:

  $$n + {}^{6}Li \rightarrow {}^{4}He + T \quad + 4.8\ \mathrm{MeV}$$

  $$n + {}^{7}Li \rightarrow {}^{4}He + T + n' \quad - 2.5\ \mathrm{MeV}$$

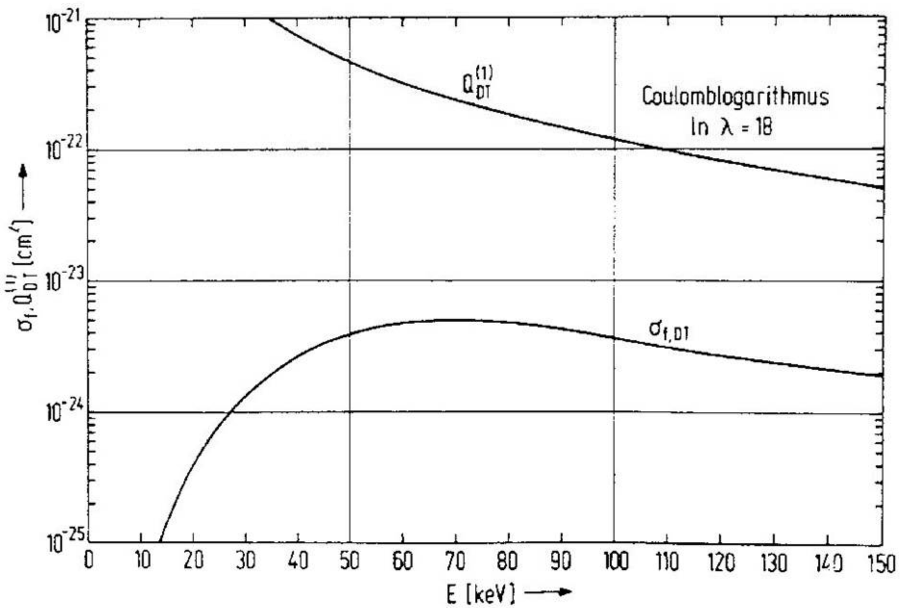
  The latter reaction allows self-sufficient tritium breeding.

- **Lithium** is very abundant and widespread (in the earth‘s crust and in the ocean water), sufficient for at least 30 000 years.

# Thermonuclear fusion

High relative velocity of the nuclei is necessary. $\Rightarrow$ Do we need an accelerator?

No! Coulomb scattering makes the beams diverge and thus inefficient.




Comparison of D-T fusion cross-section and cross-section for momentum exchange by Coulomb scattering $Q_{DT}$

Thermalised mixture of deuterium and tritium at temperatures of some 10 keV is needed. $\Rightarrow$ plasma!

energy distribution of particles in a thermal plasma: Maxwell distribution

$$f(v) = \left(\frac{m}{2\pi\, kT}\right)^{3/2} \cdot \exp\left(-\frac{mv^2}{2\, kT}\right)$$

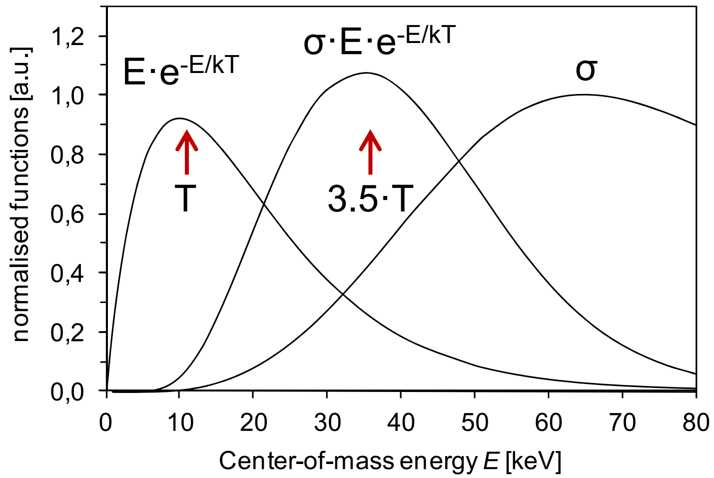
where f(v) is the number of particles in the velocity interval [v, v+dv].

# Reaction parameter

reaction rate per unit volume:

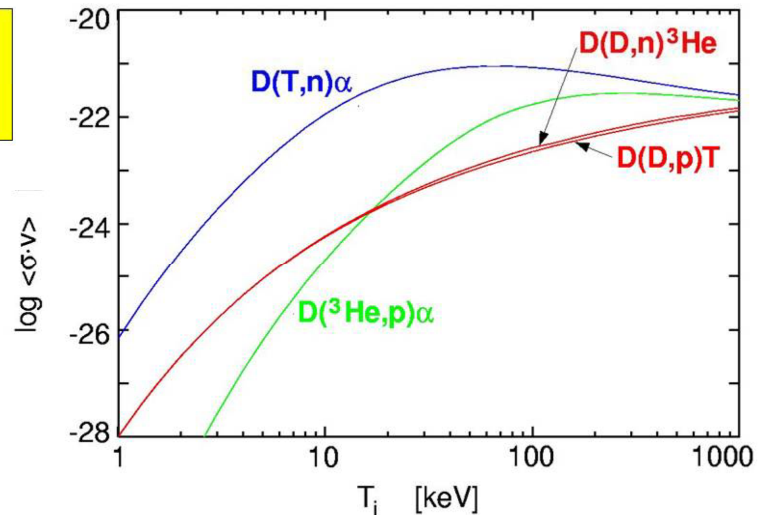
$$R = n_1 \cdot n_2 \cdot \langle\sigma \cdot v\rangle ,$$

where $\langle\sigma \cdot v\rangle$ is the average of $\sigma \cdot v$ over the velocity distribution, and v is the relative velocity




Transforming the integration into the center-of-mass sytem yields

$$\langle\sigma \cdot v\rangle = \frac{4}{(2\pi\, m_r)^{1/2} (kT)^{3/2}} \cdot \int \sigma(E_r) \cdot E_r \cdot \exp\left(-\frac{E_r}{kT}\right)$$




with $E_r$ the relative kinetic energy and $m_r$ the reduced mass

$$1/m_r = 1/m_1 + 1/m_2 .$$

# Lawson criterion

In 1957 Lawson analyzed power balances:

**break-even**: The fusion power

$$P_{fus} = n_D \cdot n_T \cdot \langle\sigma \cdot v\rangle \cdot E_{fus}$$

equals the loss due to radiation,

$$P_{bremsstrahlung} = c_1 \cdot n_e^2 \cdot Z_{eff} \cdot (kT)^{1/2}$$

(where $c_1 = 5.4 \cdot 10^{-37}$ $Wm^3keV^{-1/2}$, and $Z_{eff} = \Sigma n_i Z_i^2/n$ is the effective plasma charge),
and transport (diffusion, convection, charge-exchange):

$$P_{loss} = 3\,n\,kT / \tau_E$$

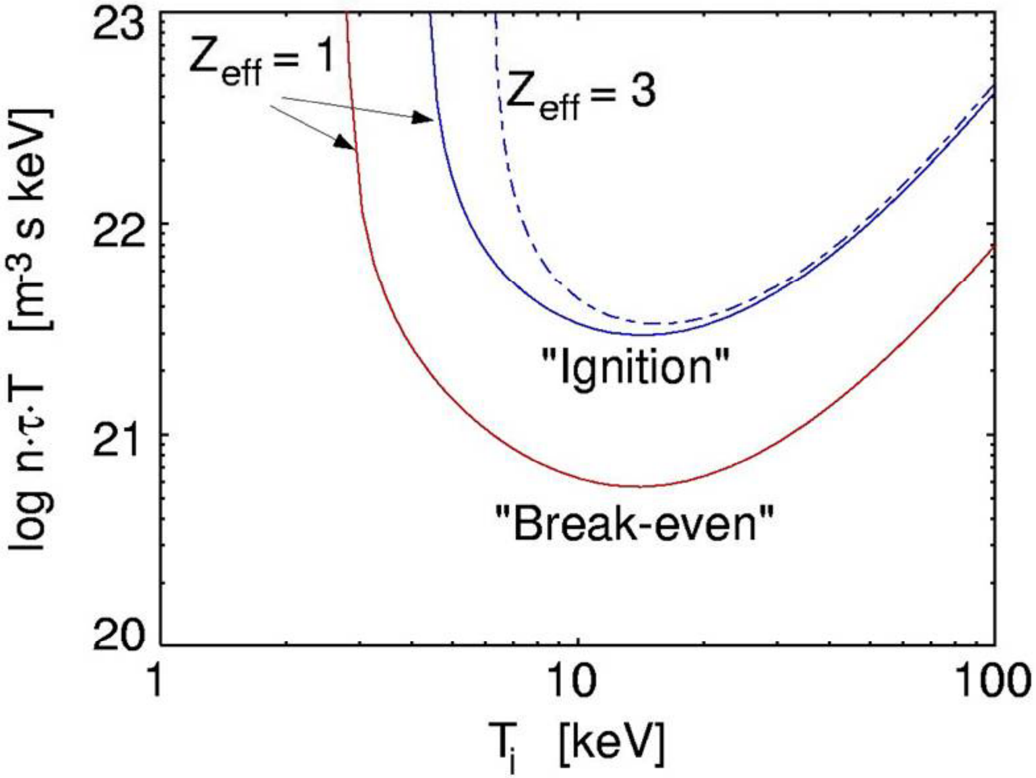
With $n_D = n_T = n/2$, $T_i = T_e = T$ we find a condition for the fusion product $n\tau T$.

fusion product (or triple product):

$$n\,\tau\,T = \frac{12\,(kT)^2}{\langle\sigma \cdot v\rangle \cdot E_{fus} - 4\,c_1\,Z_{eff}\,(kT)^{1/2}}$$

**ignition**: Neutrons leave the plasma, while the $\alpha$-particles are confined and heat it. Only their energy should enter the balance! $E_{fus} \rightarrow E_\alpha$

# Ignition Criteria




A more refined analysis also takes into account the $\alpha$-particles produced in the fusion reactions, as their production is intrinsically coupled to fusion power ($3.53\cdot10^{11}$ atoms/Ws).

$\Rightarrow$ closed curves parametrized by the normalized He-confinement time $\rho_{He} = \tau^*_{He}/\tau_E$

# Fusion concepts

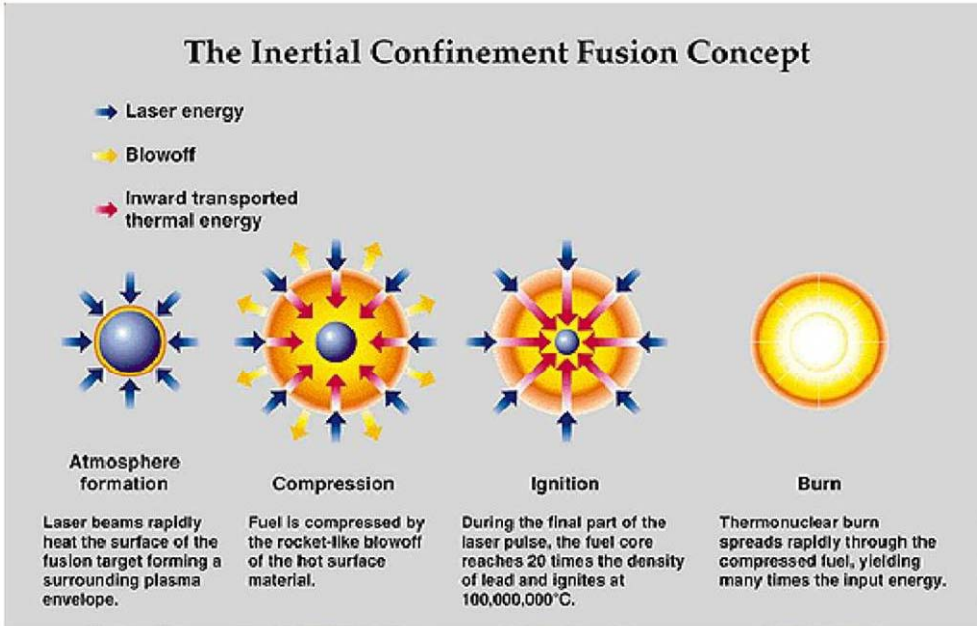
requirement for triple product $n\tau T \Rightarrow$ 2 concepts possible:

**1) high $\tau \Rightarrow$ magnetic confinement:**

A thermal plasma is confined by magnetic fields and heated to high temperature.

**2) high $n \Rightarrow$ inertial confinement:**

A small frozen fuel pellet is heated and compressed by high power beams: Ignition and burn while its „inertia“ keeps it together.

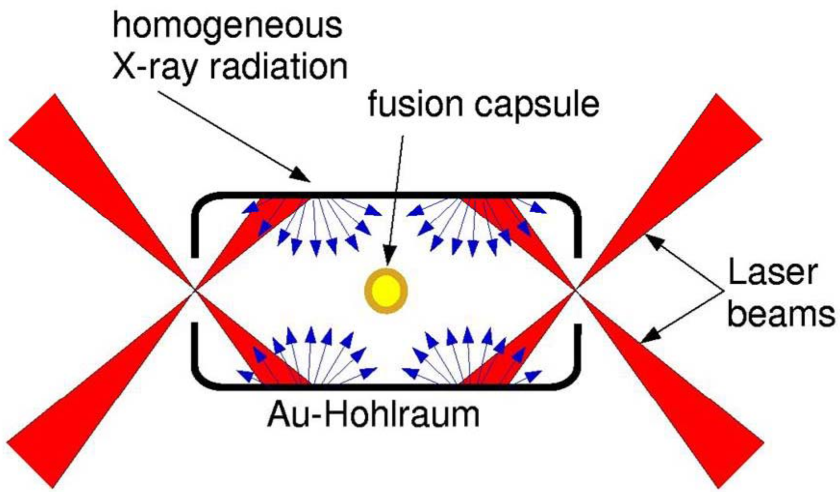


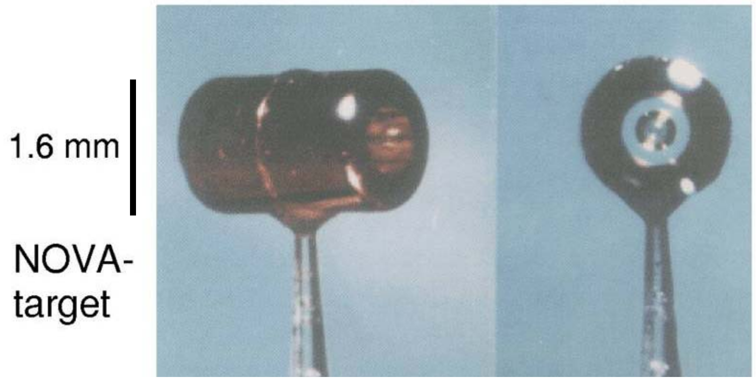

ignition in a small, central spot (low n), propagating outward into area of high n (low T), spark ignition (Nuckolls et al. 1972)

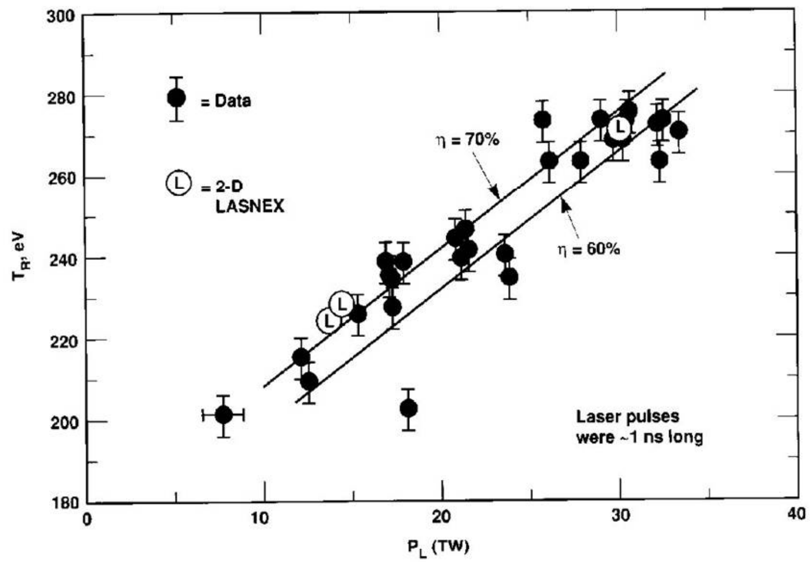
problems:
- uniformity of irradiation and compression,
- Rayleigh-Taylor-instabilities
- drivers

# Hohlraum targets & indirect drive

Uniformity of the target irradiation can be achieved in so-called Hohlraums:




The laser heats the inside of a high-Z hohlraum, which then emits thermal radiation (X-rays), which is absorbed with high efficiency.

Lindl et al.
Phys. Plasmas, 1995

# Drivers I (Lasers)

general requirements: - pulse energy: 2-10 MJ
- pulse duration: 10 ns
- repetition rate: 1-10 Hz
- energy gain of the pellet burn should be > 1000

LASER:

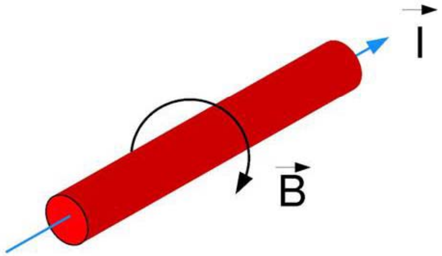
1) Neodym glass laser:
- at $\lambda$= 1.06 $\mu$m, absorption is too small. Improvement by frequency conversion to 530 nm (70%) or 350 nm (50%) in potassium dihydrogen phosphate (KDP) crystals .
- $\varepsilon_{driver}$ < 1% (pumping presently by flashlamps, i.e. white light),
$\Rightarrow$ Solid State Diode Pumped Lasers (Yb:S-FAP crystals) with efficiencies up to 20% under development (LLNL, : 50J, 10 Hz, 15ns).
- repetition rate about 1 pulse/2 hrs.
- achievements:

| | | | |
|---|---|---|---|
| NOVA | (Livermore) | 125 kJ, | 10 beams |
| NIF | (Livermore) | 1.4 MJ, | 192 beams |

2) KrF gas laser:
- $\lambda$= 248 nm
- $\varepsilon_{driver}$ ~ 1%, potenial for development,
- AURORA, Los Alamos: 10 kJ in 500 ns.

# Drivers II (X-Rays from Z-Pinches)

Generally, Z-Pinches
are unstable
(sausage-instability):




However,
- they generate strong X-Rays during the collapse,
- multi-wire arrays are more stable and generate
  even more X-Rays!

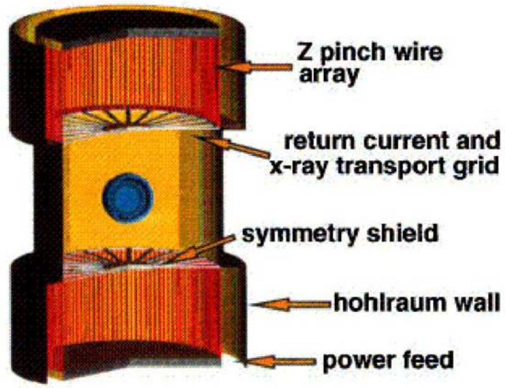
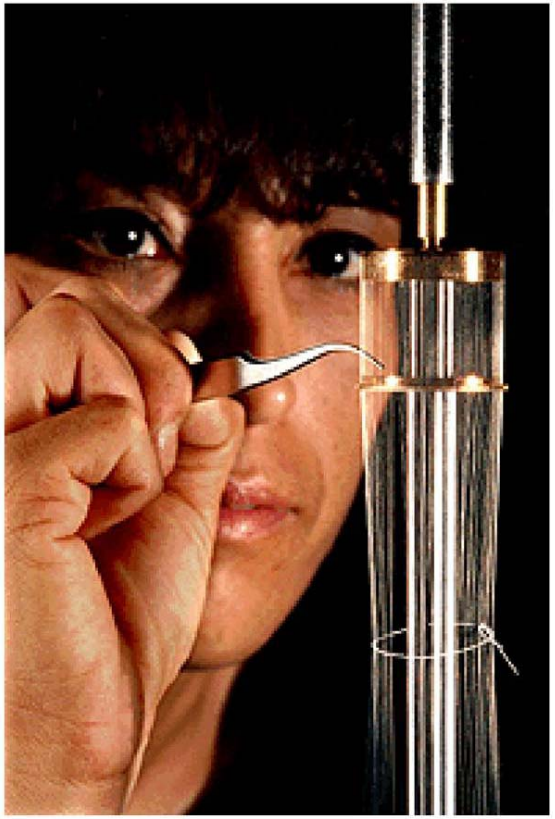
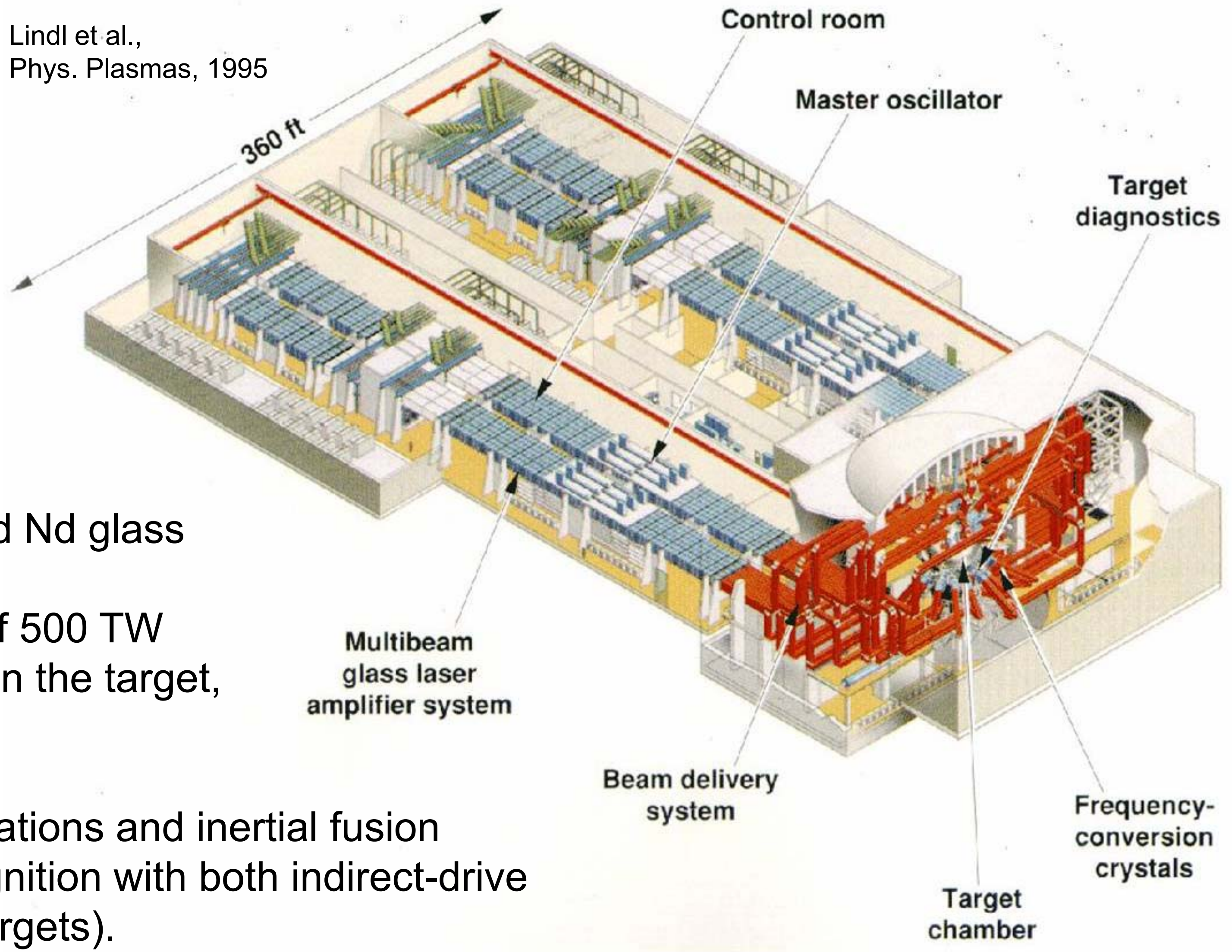



FIG. 1. Z-pinch-driven hohlraum ICF concept. Primary hohlraums 1 cm tall with 2.4 cm diam are placed on the ends of a secondary hohlraum 1.6 cm tall containing the capsule. The primary hohlraums have annular power feeds 0.2 cm in width, and are separated from the secondary hohlraum by transport grids. Shine shields of 0.9 cm diam prevent direct pinch illumination of the capsule.



# National Ignition Facility (NIF)
# Lawrence Livermore National Laboratory (LLNL)

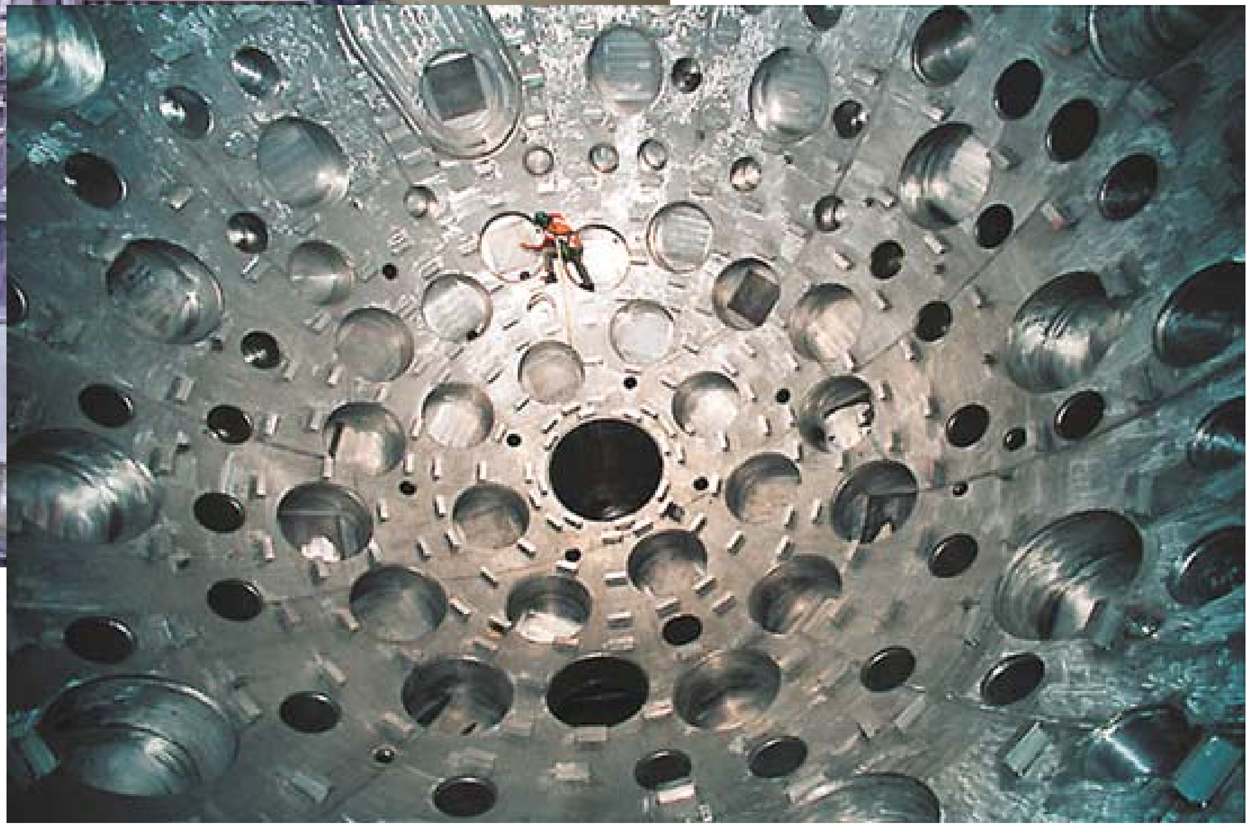
Lindl et al.,
Phys. Plasmas, 1995



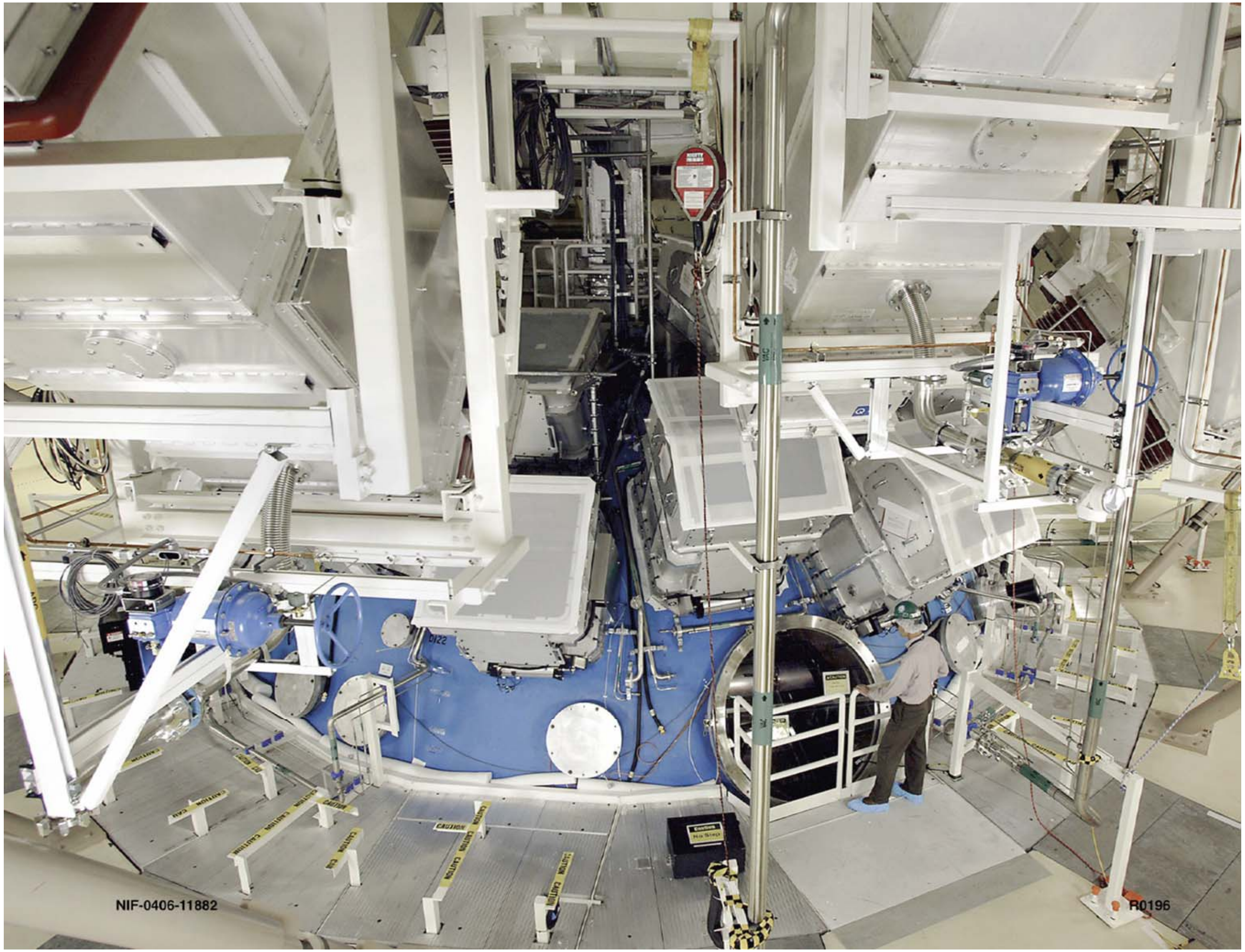

- 192 lasers,
- frequency-tripled Nd glass laser at 350 nm,
- with an output of 500 TW
- 1.8 MJ energy on the target,

**official mission:**
for defense applications and inertial fusion ignition (explore ignition with both indirect-drive and direct-drive targets).

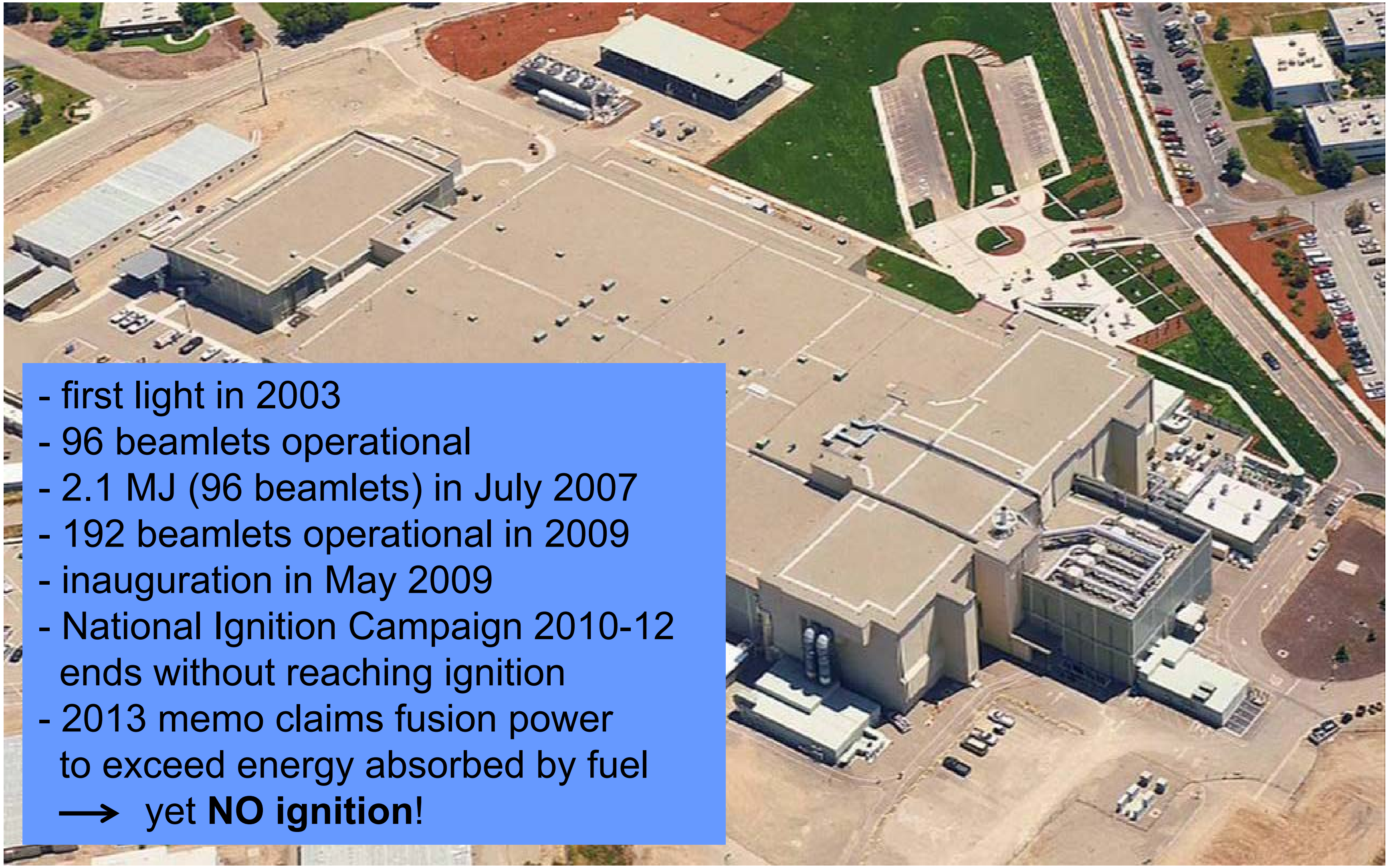
# NIF Construction I



# NIF Construction II



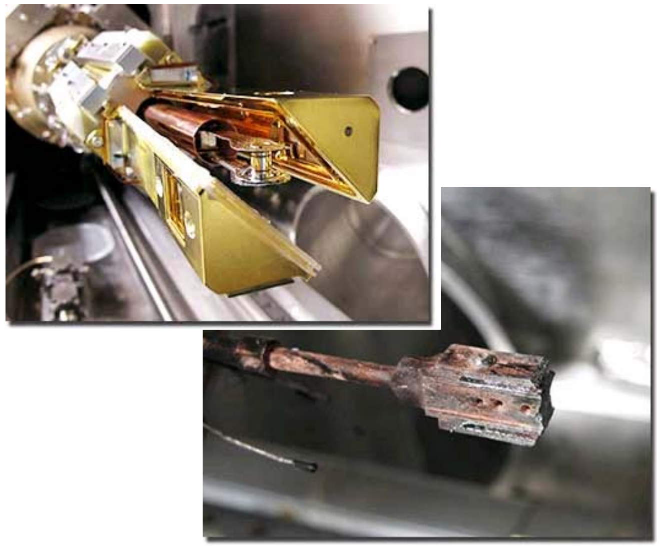
# NIF Construction III



- first light in 2003
- 96 beamlets operational
- 2.1 MJ (96 beamlets) in July 2007
- 192 beamlets operational in 2009
- inauguration in May 2009
- National Ignition Campaign 2010-12
  ends without reaching ignition
- 2013 memo claims fusion power
  to exceed energy absorbed by fuel
  ⟶ yet **NO ignition**!

# National Ignition Campaign NIC 2011-2012

**High-Energy Deuterium-Tritium Experiments Resume**
On Aug. 27, 2011, the NIC team began a new round of high-energy experiments on NIF using cryogenically cooled equimolar (50-50) deuterium-tritium (DT) fuel. In the fourth layered DT experiment, all 192 NIF beams delivered 1.41 MJ of ultraviolet light to the target. Preliminary estimates indicate that the neutron yield was about 2 x $10^{14}$ (200 trillion) and the x-ray emission data showed a small, round core, consistent with earlier symmetry tuning results.



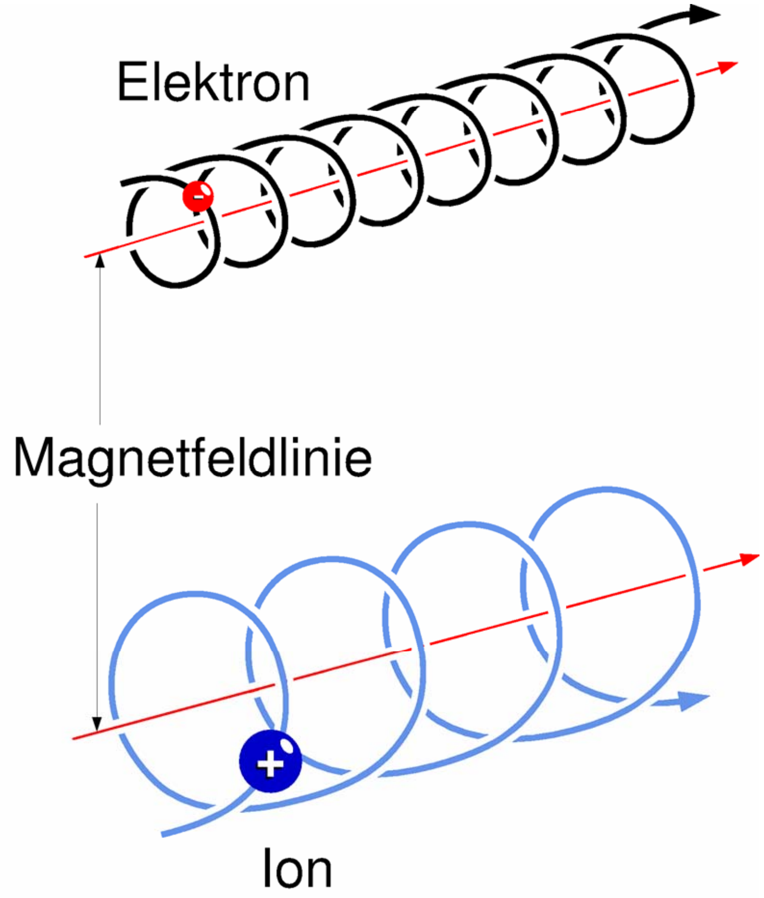
**NIC Team Fires First 500-Terawatt Shot on NIF**
A major milestone in the National Ignition Campaign (NIC) was reached July 5 as the NIC team conducted the highest-power experiment to date, firing a 23-nanosecond ignition-shaped pulse with a peak power initially measured at 522.6 TW. All 192 NIF lasers fired an estimated 2.02 MJ of 3ω (ultraviolet) light into the final optics assembly and delivered 1.855 MJ to the target after some energy was diverted to diagnostic equipment.

**Sept. 28, 2013 shot claims to have produced 51015 neutrons**
This corresponds to 75% more than in any previous shot. Alpha heating was said to be seen and fusion energy released exceeded the energy absorbed by the fuel. Though this was no fundamental breakthrough as conditions achieved were yet far below those required for ignition.

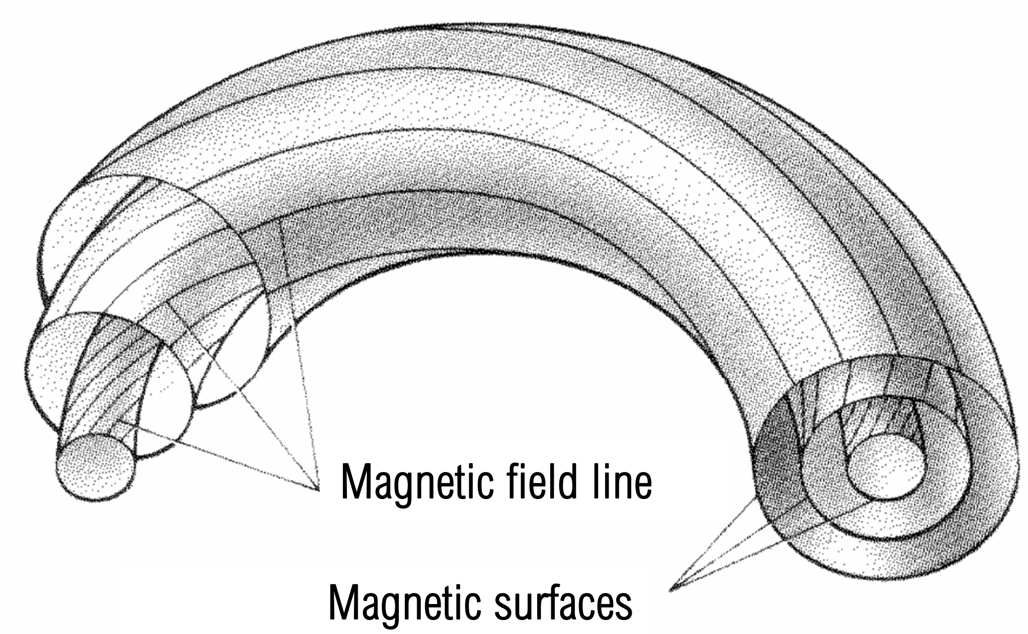
**NIF continues with material science research**

# Magnetic confinement

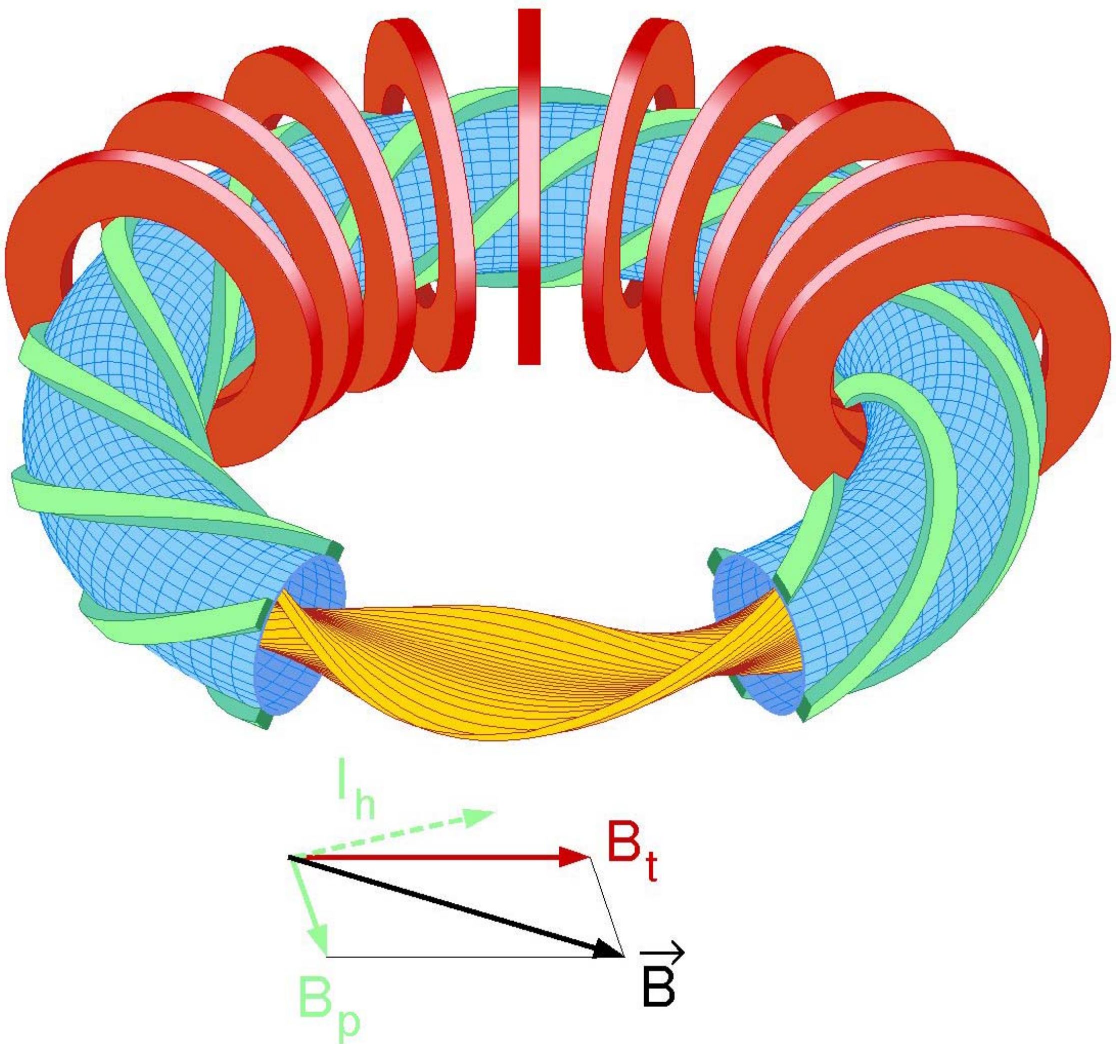
Charged particles can be confined by magnetic fields (Lorentz force).




Transport perpendicular to B only due to collisions. Particles escape only parallell to B, i.e. at the ends.
⇒ remedy: bend it into a torus.
gradient drift requires rotational transform of the magnetic field
⇒ magnetic surfaces



# Classical stellarator



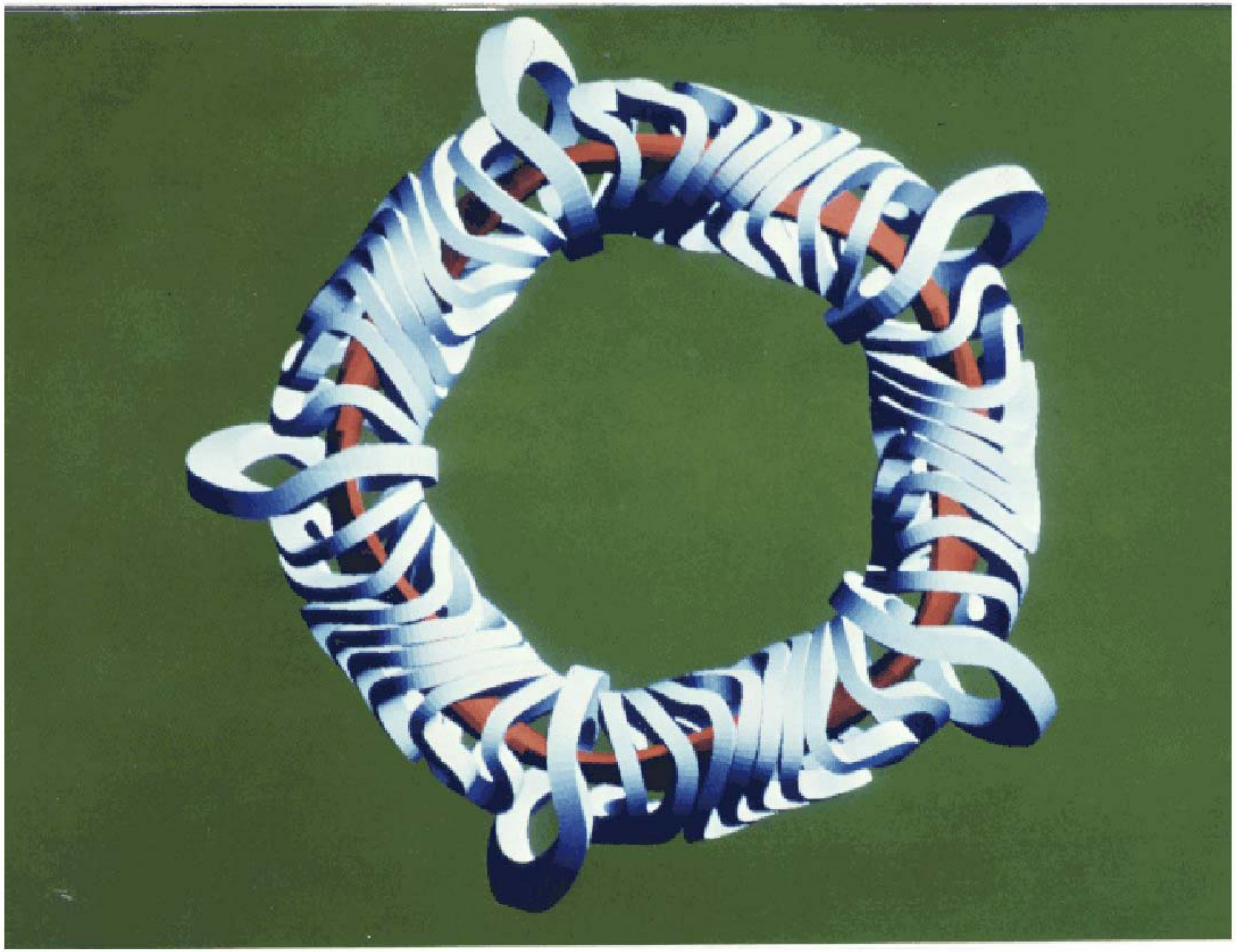

- invented in the 1950s by L. Spitzer jr. (PPPL)
- toroidal field from ring coils
- poloidal field from helical windings (alternating current)

+ only external currents
+ well controllable
+ intrinsically stationary

- problem of nested coils,
- trapped particles not confined

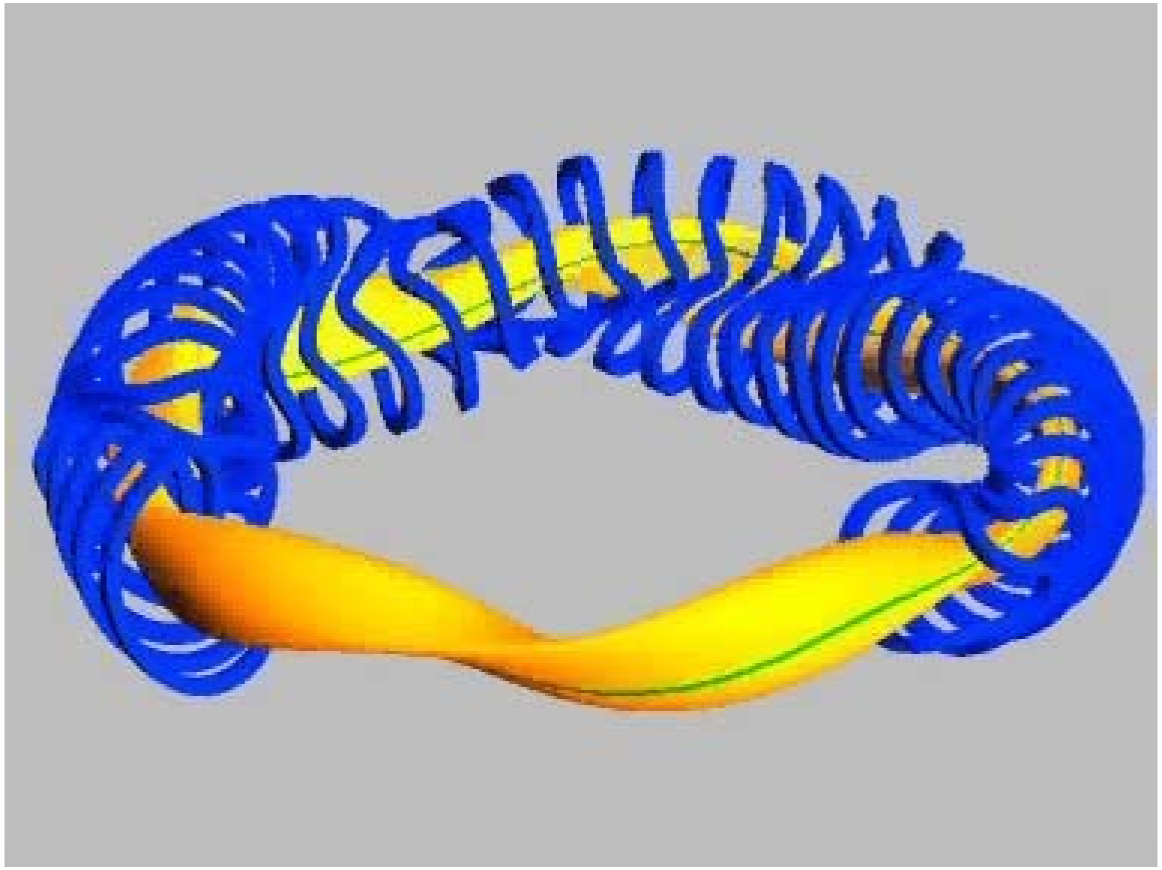
$\Rightarrow$ need and potential for further optimization
$\Rightarrow$ modular stellarators

# Development of Stellarators



**Wendelstein 7-AS (advanced stellarator, IPP)**

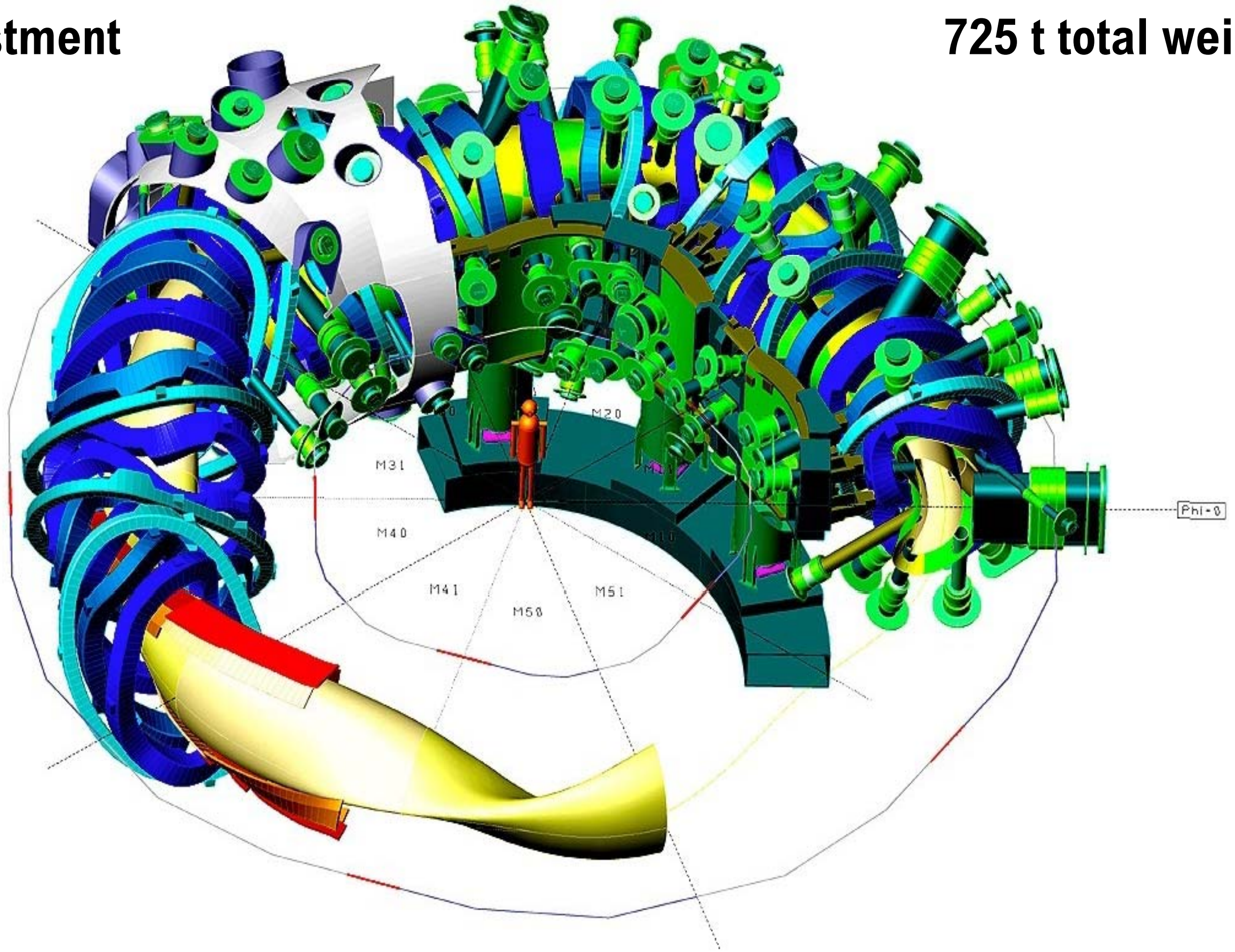
# Optimized stellarator WENDELSTEIN 7-X



| | | | |
|---|---|---|---|
| major radius: | 5.5 m | EURATOM approval: | March 1996 |
| av. minor radius: | 0.53 m | start of the project: | summer 1997 |
| magnetic field (on axis): | 2.5 T | start of assembly: | spring 2005 |
| superconducting field coils | | 1st plasma: | XII/2015 |

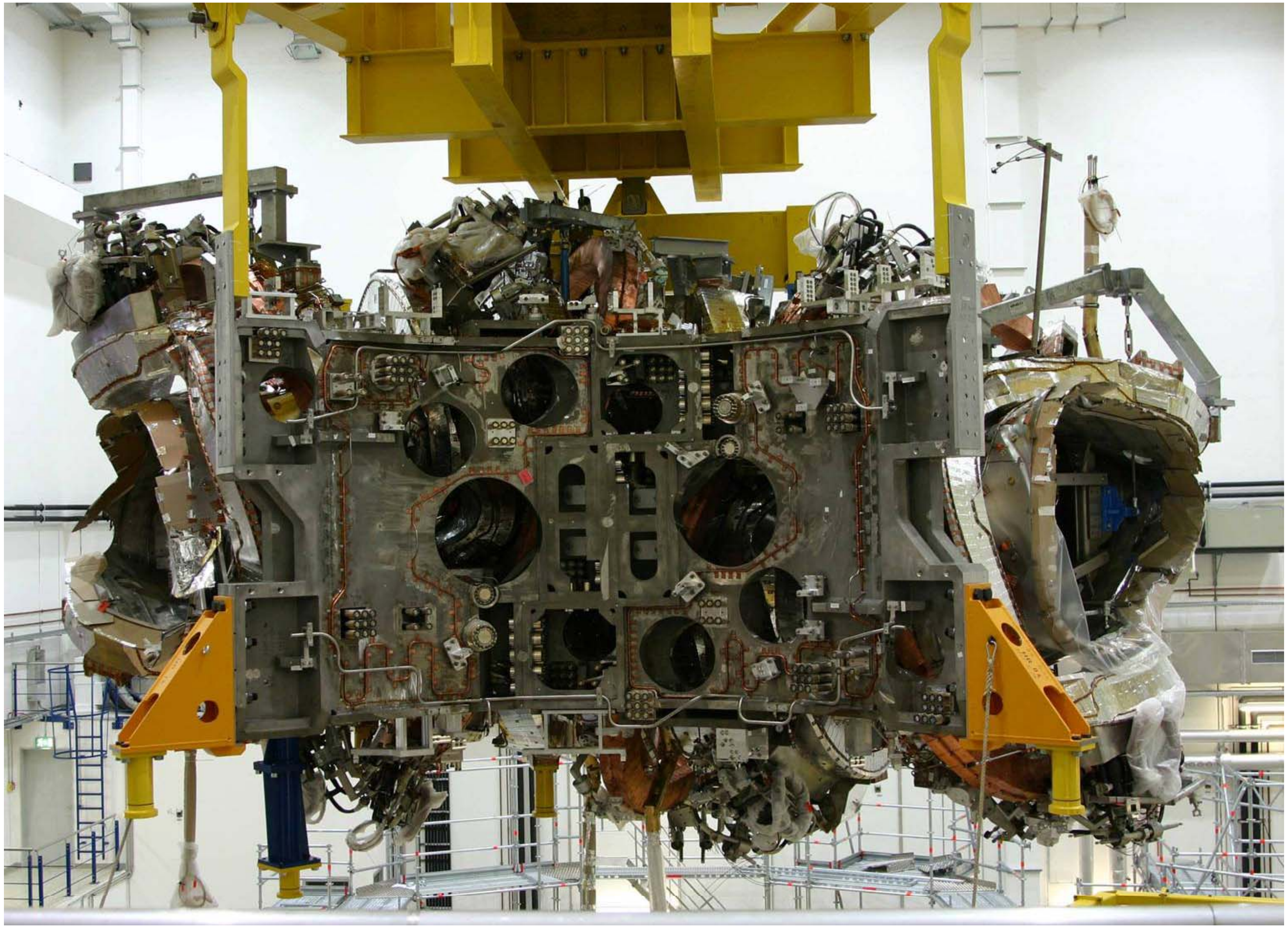
# WENDELSTEIN 7-X
## the engineers version

**370 M€ investment** **725 t total weight**

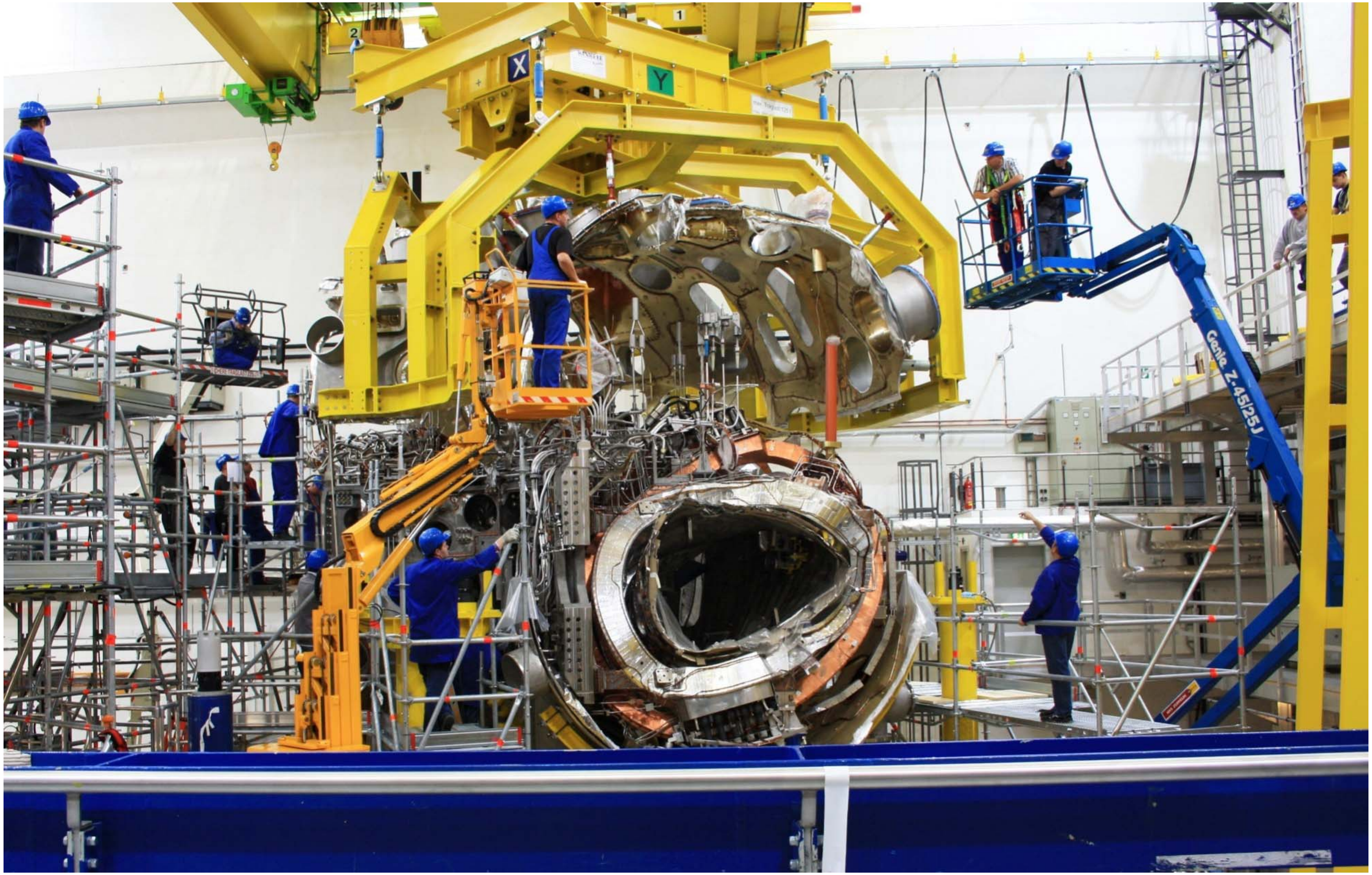



**~1m plasma diameter** **11m torus diameter**

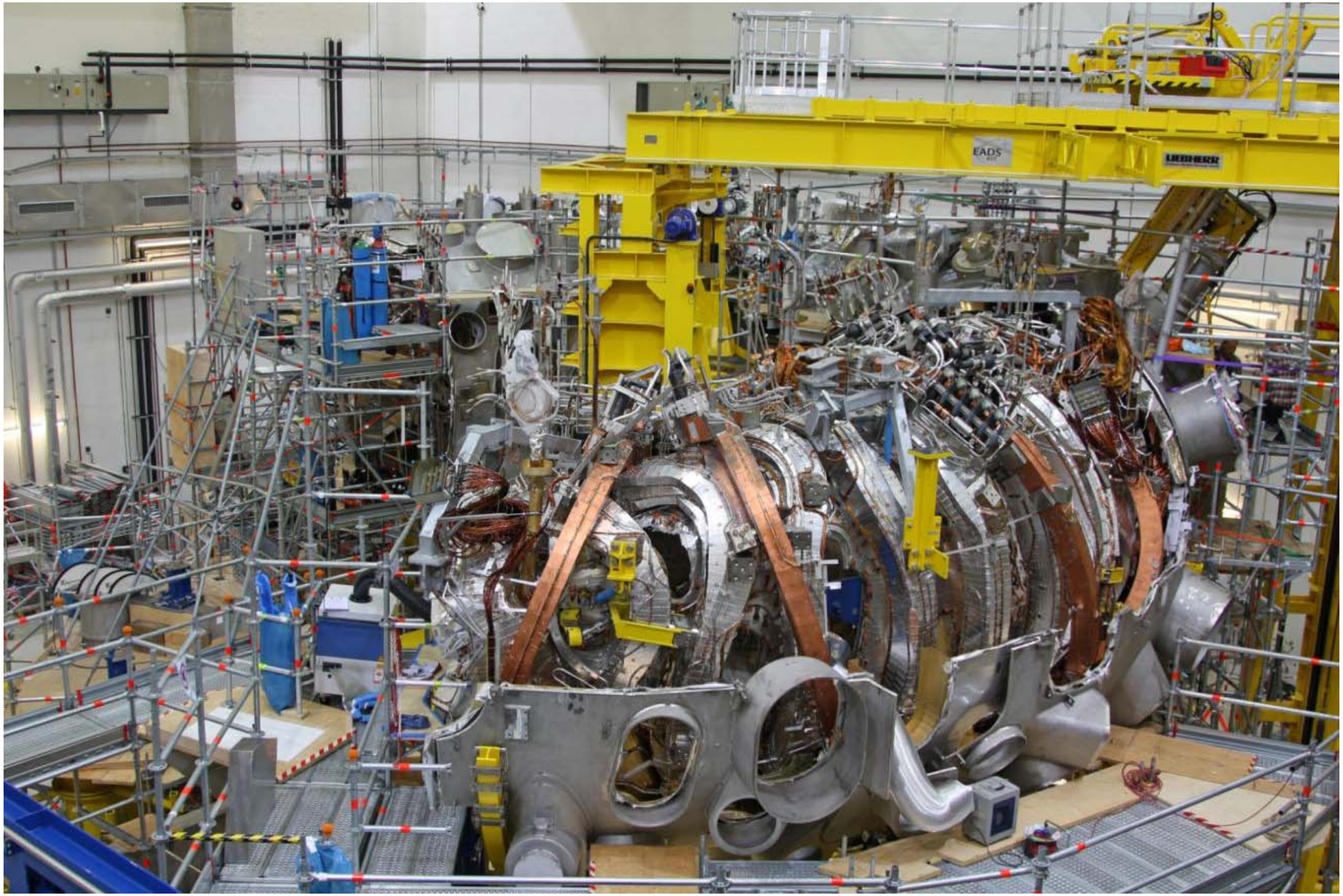
# WENDELSTEIN 7-X assembly
# first magnet module  (VIII/2008)



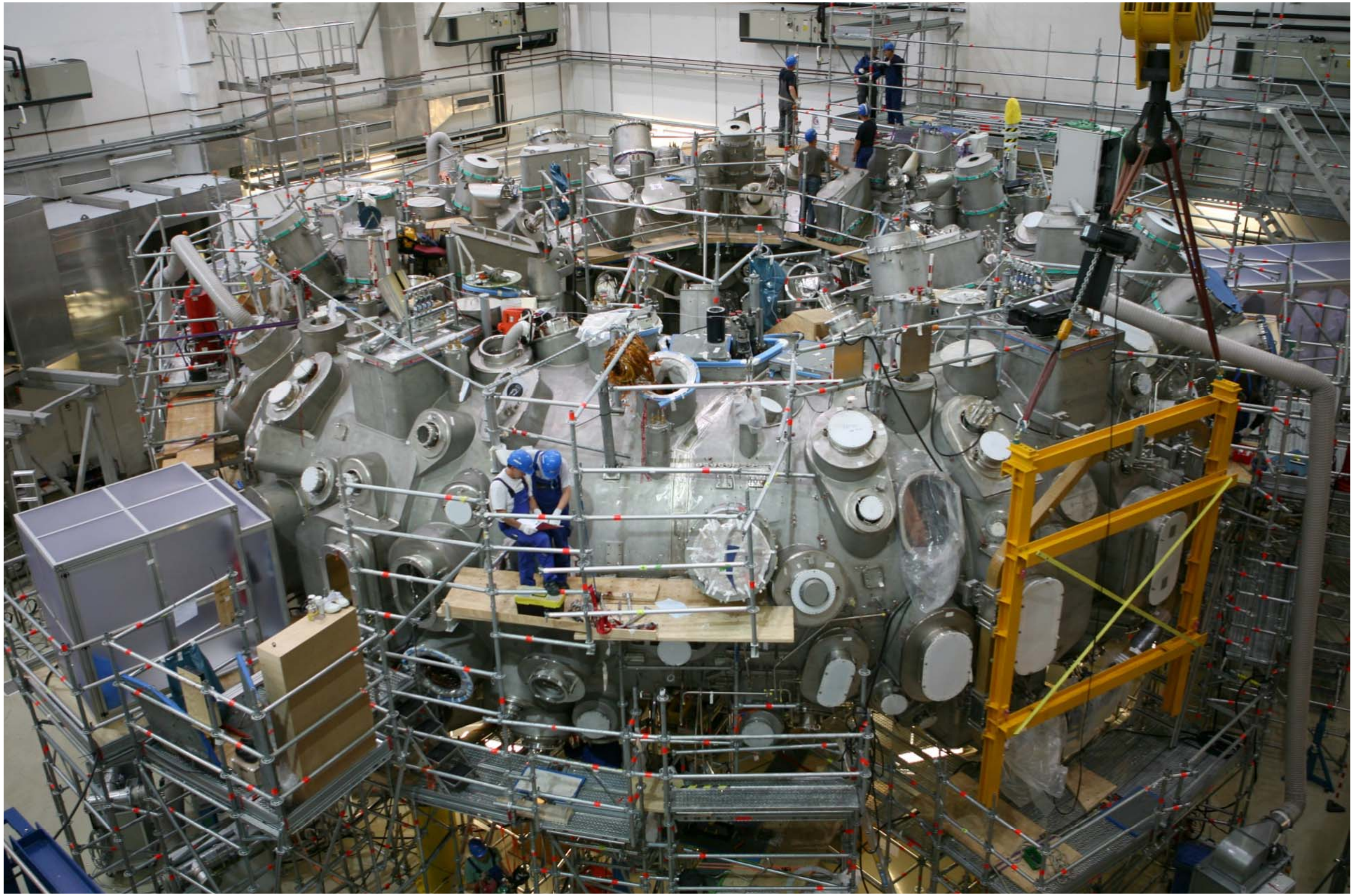
# WENDELSTEIN 7-X assembly
# first module in cryostat (IX/2009)



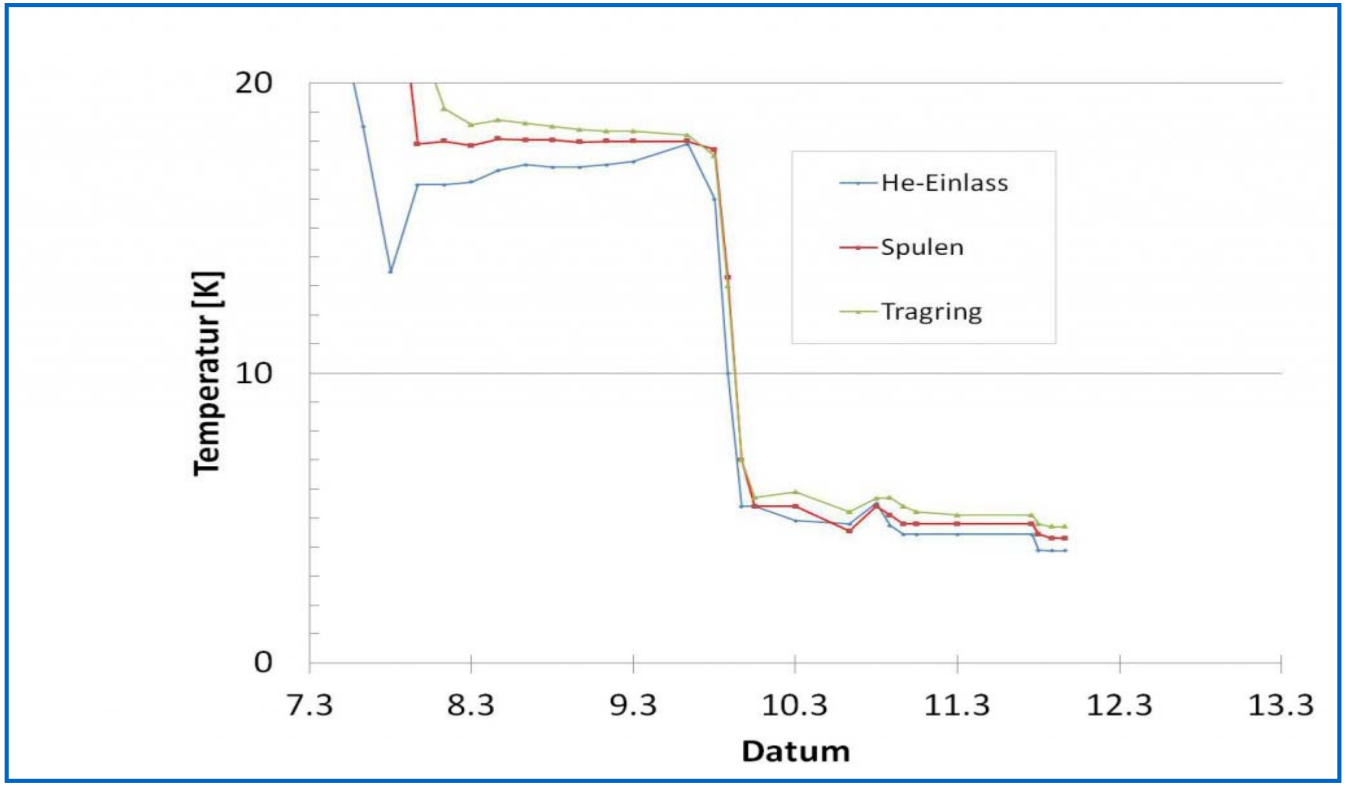
# WENDELSTEIN 7-X assembly
# port assembly in 1st module (IX/2010)



# WENDELSTEIN 7-X assembly
# torus welded (VI/ 2013)



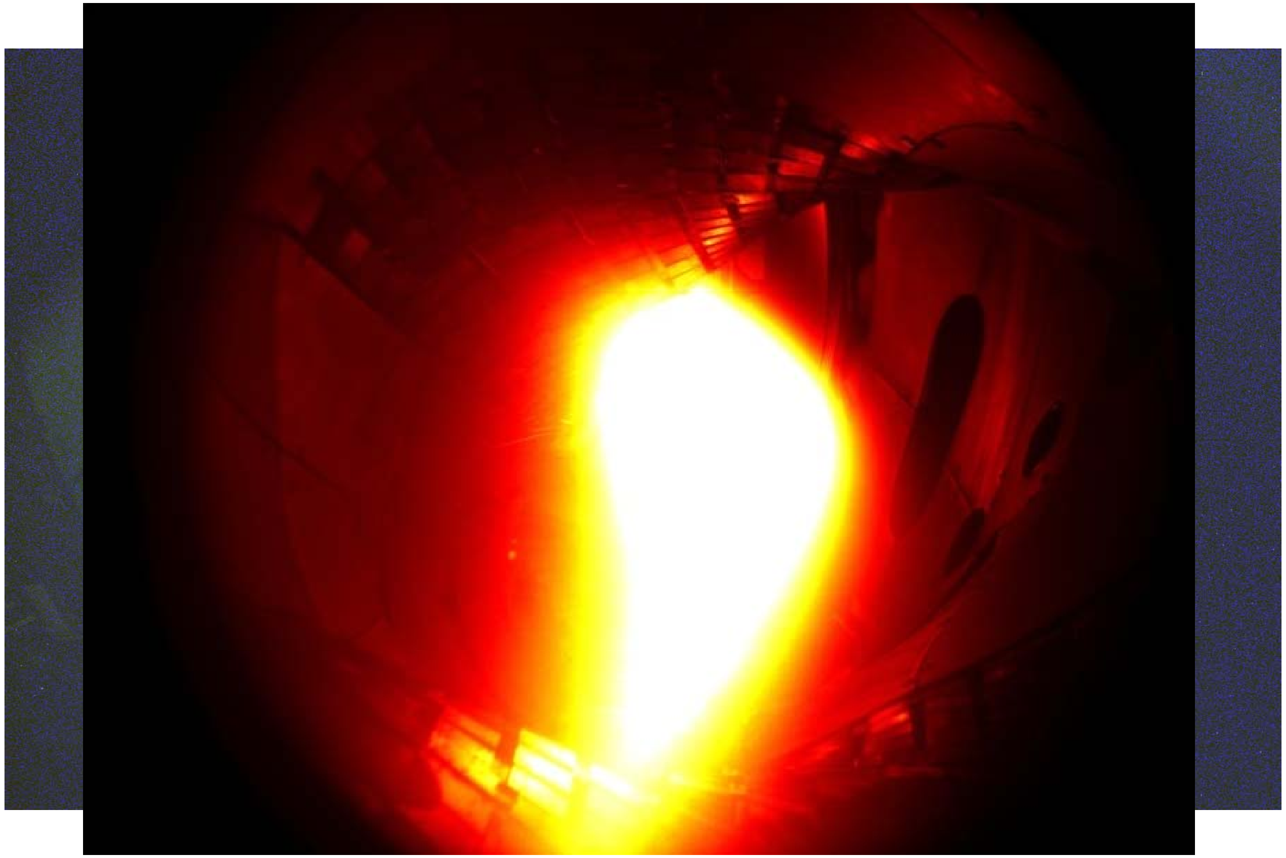
# WENDELSTEIN 7-X commissioning milestones




source: H.S. Bosch (IPP)

- **successful cool down of cryostat** **(III/2015)**
- **successful test of magnet system** **(VI/2015)**
- **successful pump out of plasma vessel** **(VI/2015)**

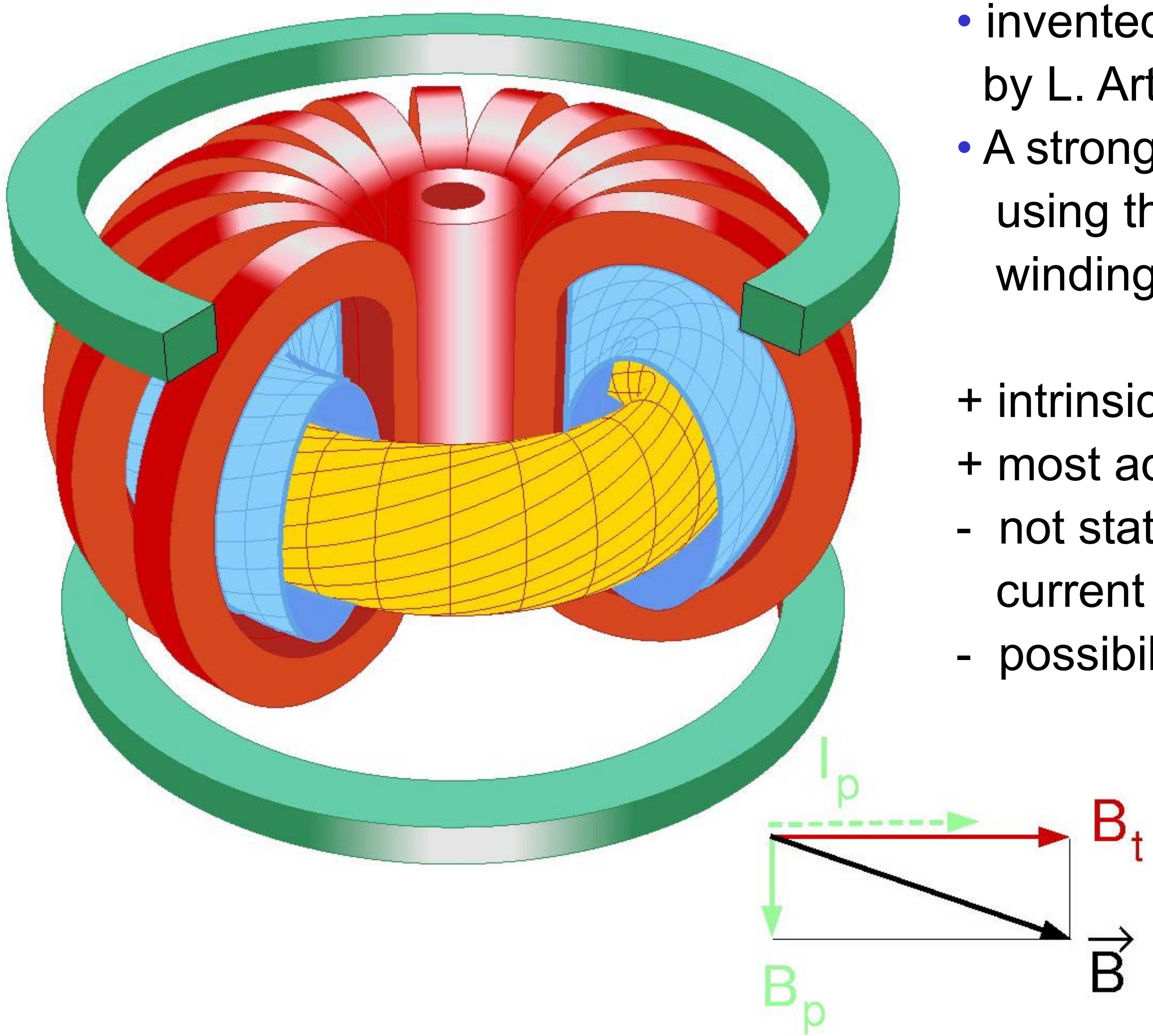
## WENDELSTEIN 7-X commissioning milestones



source: IPP

- 1st flux surface measurement (VII/2015)
- 1st plasma (XII/2015)

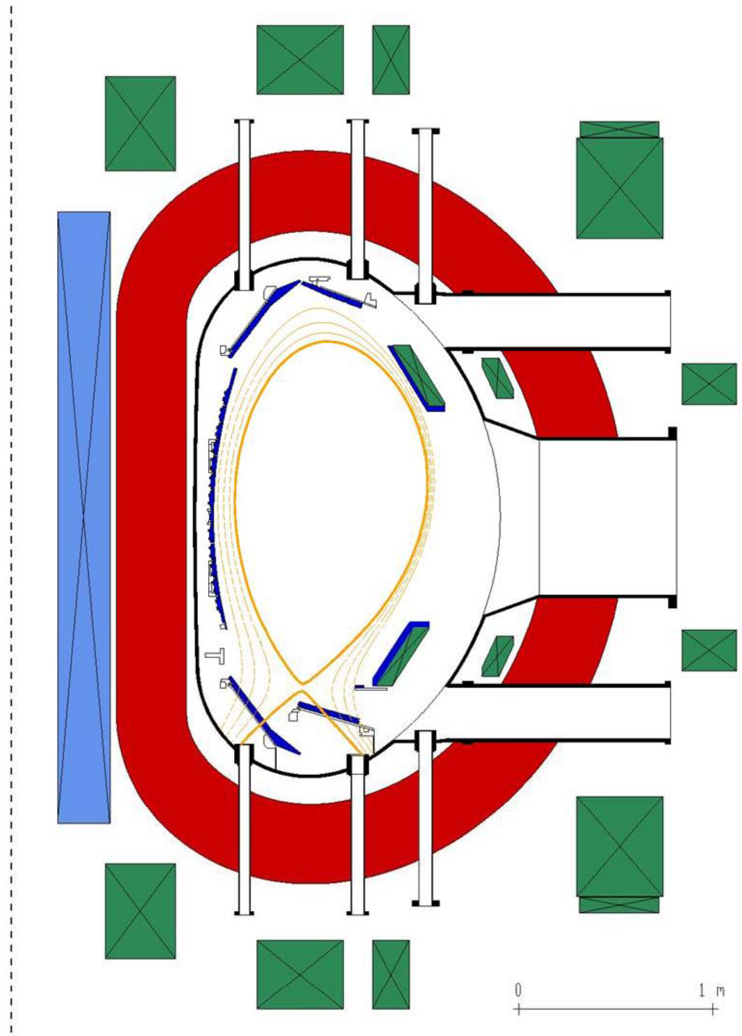
# Tokamaks




- invented in the 1950s in Moscow by L. Artsimovich and A. N. Sakharov
- A strong plasma current is induced, using the plasma as the secondary winding of a transformer.

\+ intrinsic heating,
\+ most advanced fusion concept
\- not stationary due to transformer current drive required
\- possibility of current disruptions

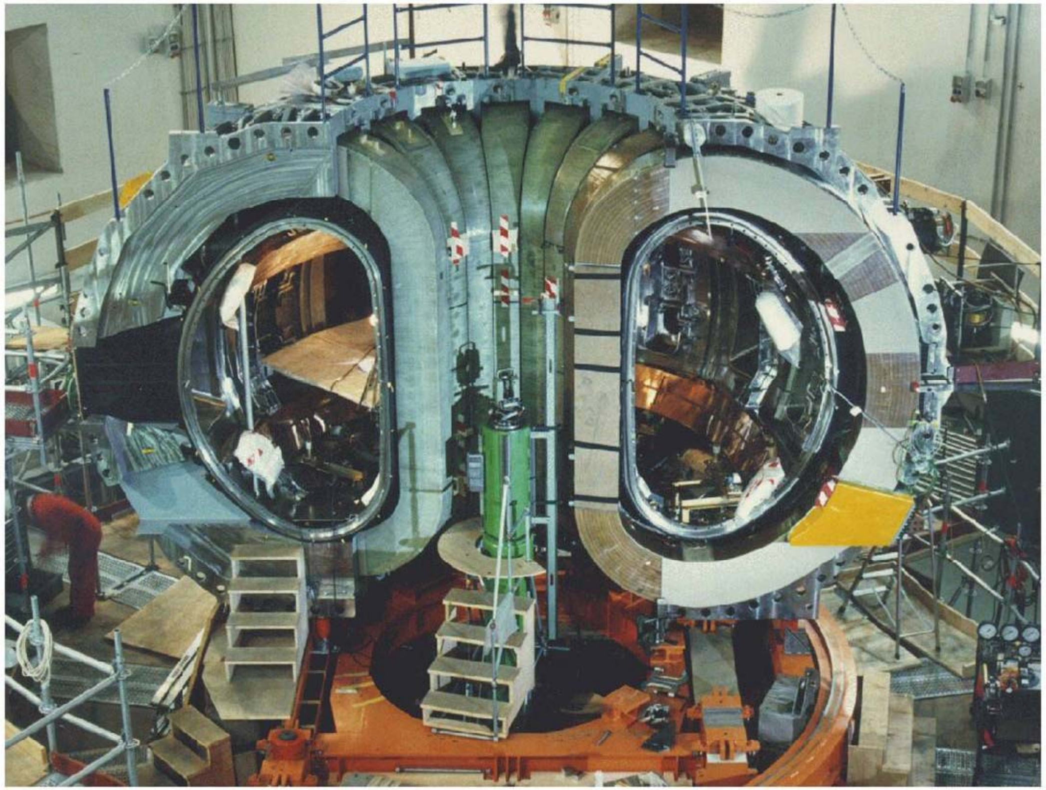
# ASDEX Upgrade




$R = 1.65$ m  $a = 0.5$ m  $\kappa = 1.6$

$B_t \leq 3.5$ T  $I_p \leq 1.4$ MA  $P_H \leq 28$ MW

start of operation in 1991



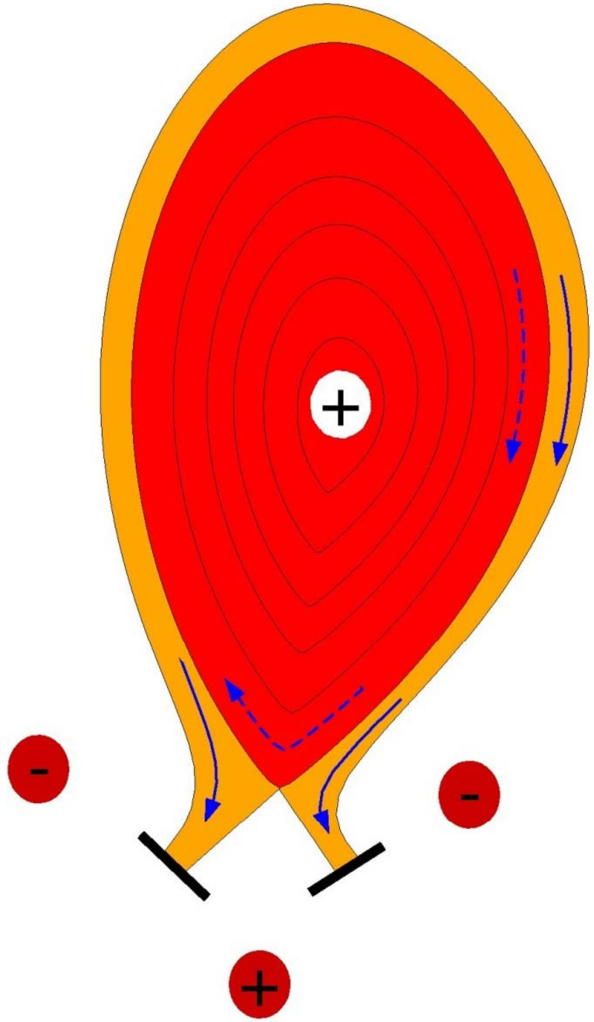
2/1989

# Divertor

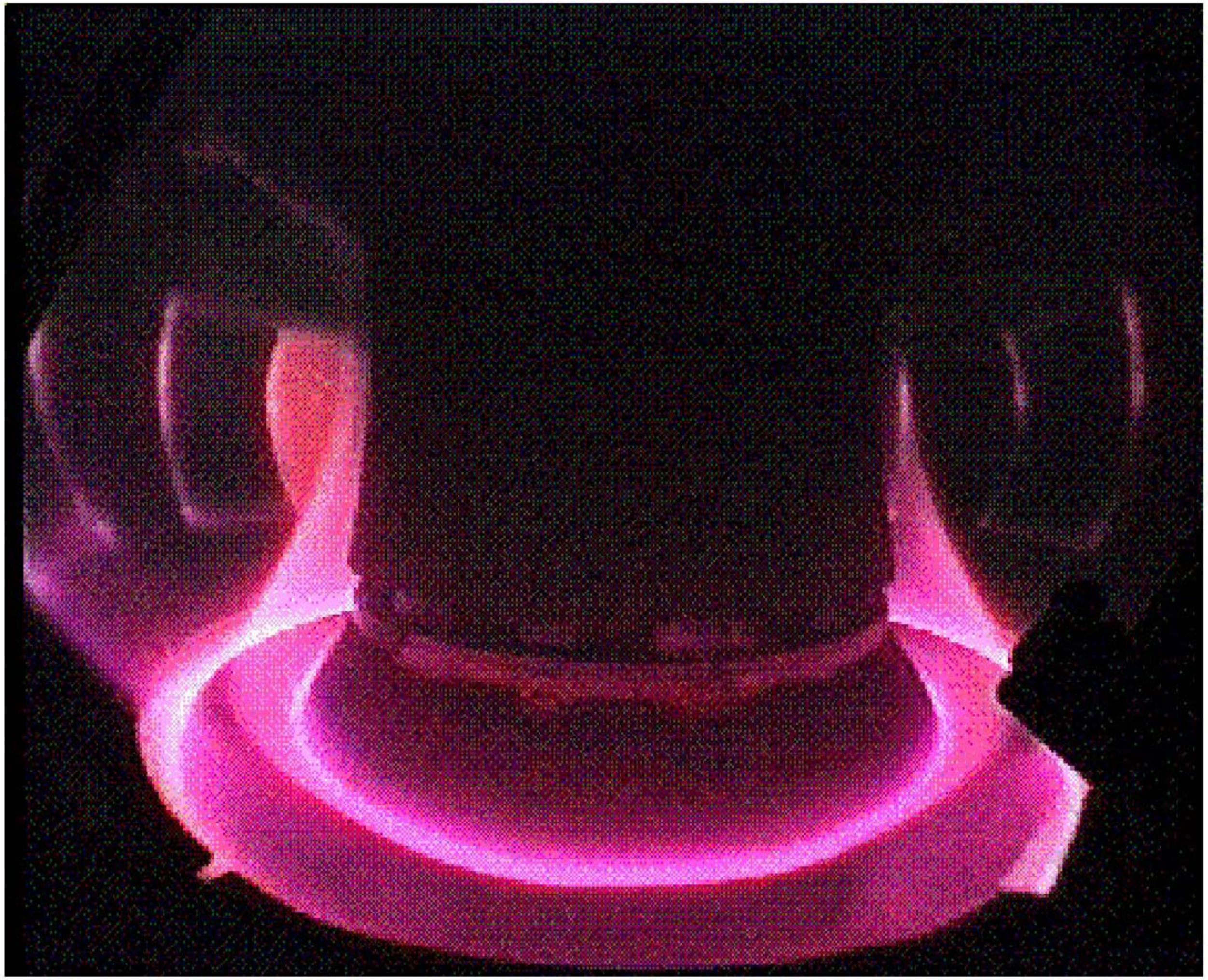
- plasma confinement with nested, closed magnetic surfaces
- plasma edge has to be defined either
  - physically by a material limiter or
  - magnetically by additional poloidal fields, defining a last closed flux surface - the separatrix.
- first successful experiments in ASDEX:
  - cleaner plasmas
  - steep edge gradients
  - $\Rightarrow$ H-mode with improved confinement

- Meanwhile, the divertor has become a standard for power and particle exhaust.

- Stellarators have an intrinsic separatrix due to the 3D-magnetic field



## ASDEX Upgrade plasma



plasma interior at
some keV $\Rightarrow$ X-rays

outside the separatrix,
some eV $\Rightarrow$ H$\alpha$ light

steep gradients at
the separatrix

strong radiation in the
divertor region

# Quantitative criteria

power balance of a fusion plasma:

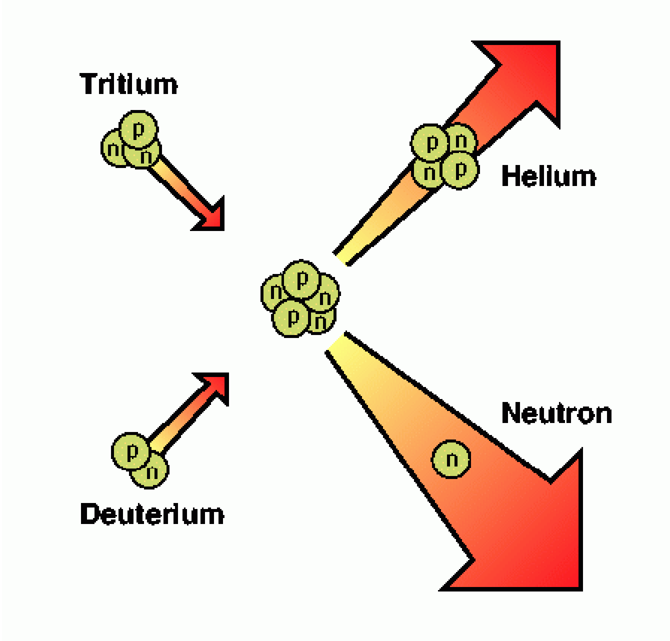
Alpha-particle heating balances losses

$\Rightarrow$ criteria for:

- $T \approx 100$ Mio K = 10 keV ✓

- $n \approx 10^{20}$ m$^{-3}$ ✓

- $\tau_E \approx 5$ -10 s ?



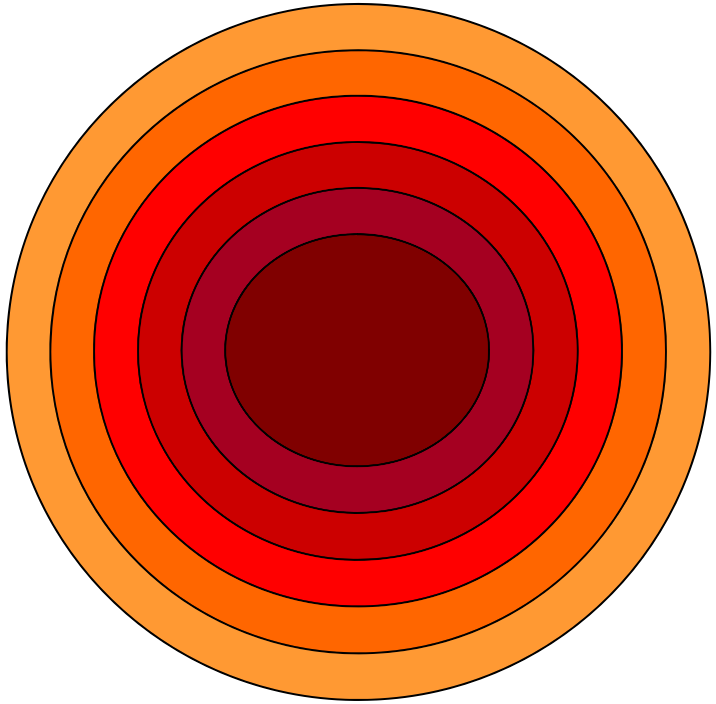
# Energy loss in a magnetically confined plasmas

the „classical“ picture:

- free transport of energy & particles on magnetic surfaces

- transport perpendicular to magnetic field only through collisions

- **but:** observed losses are about 100 times higher than expected! (turbulent transport?)

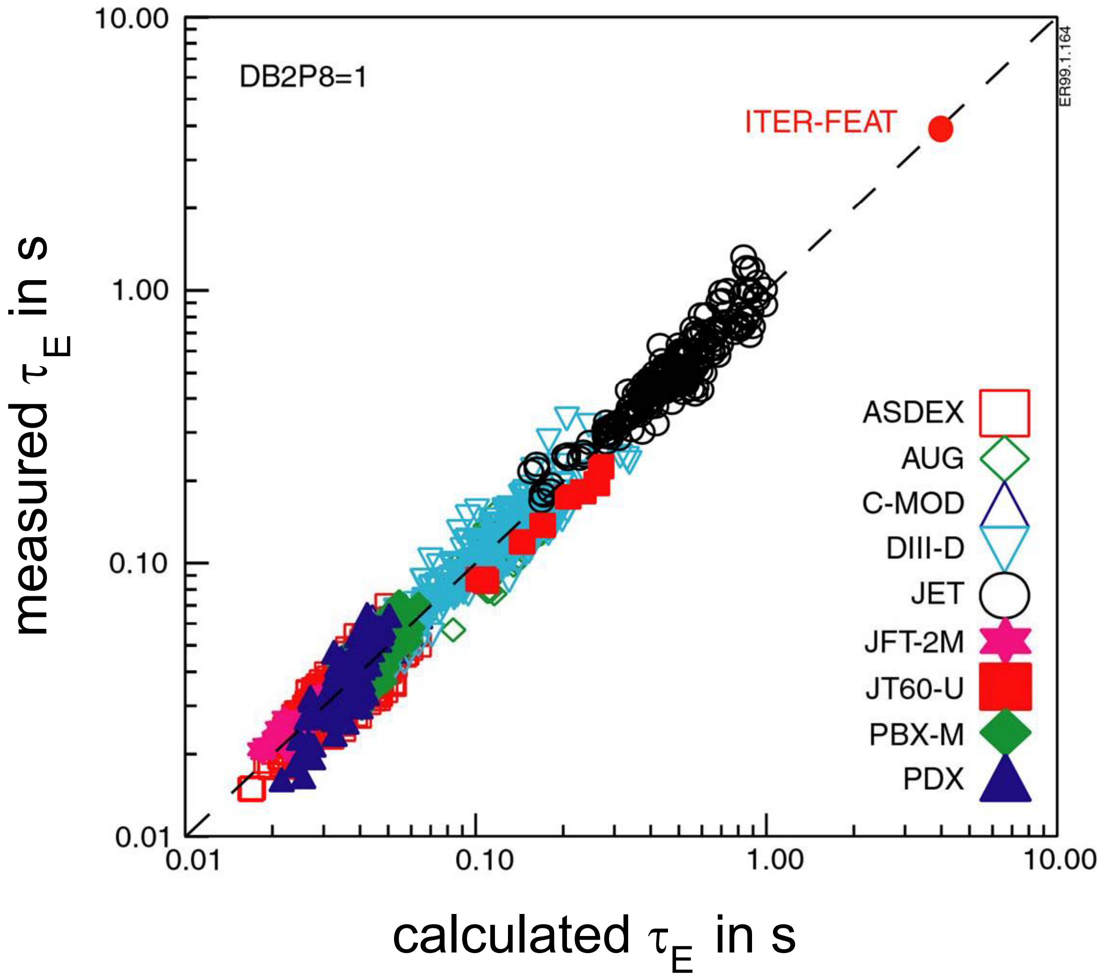


remedy: 1. larger experiments (longer isolation path)

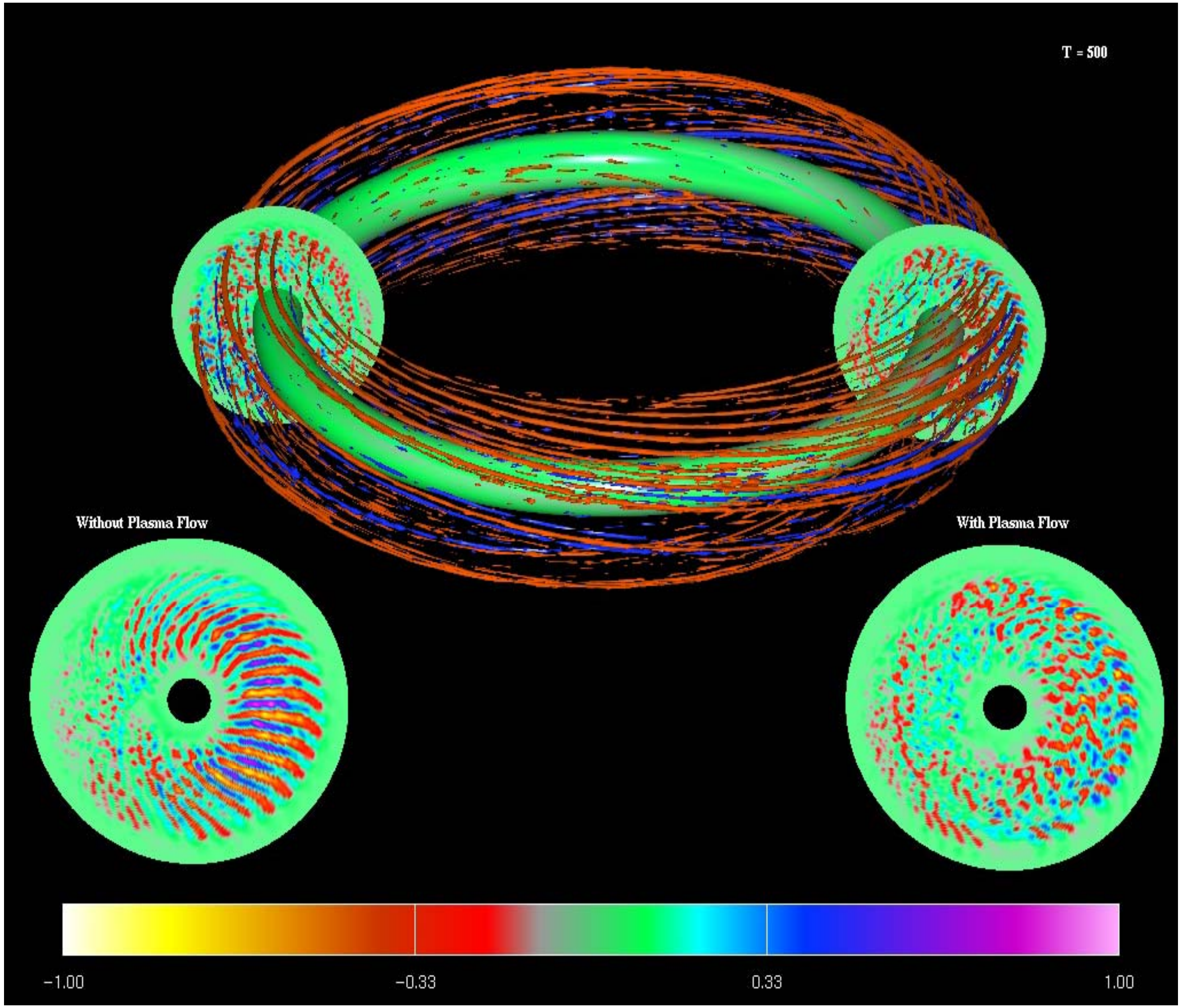
2. “intelligent experiments“ (understand problems and modify)

# Empirical scaling of energy confinement

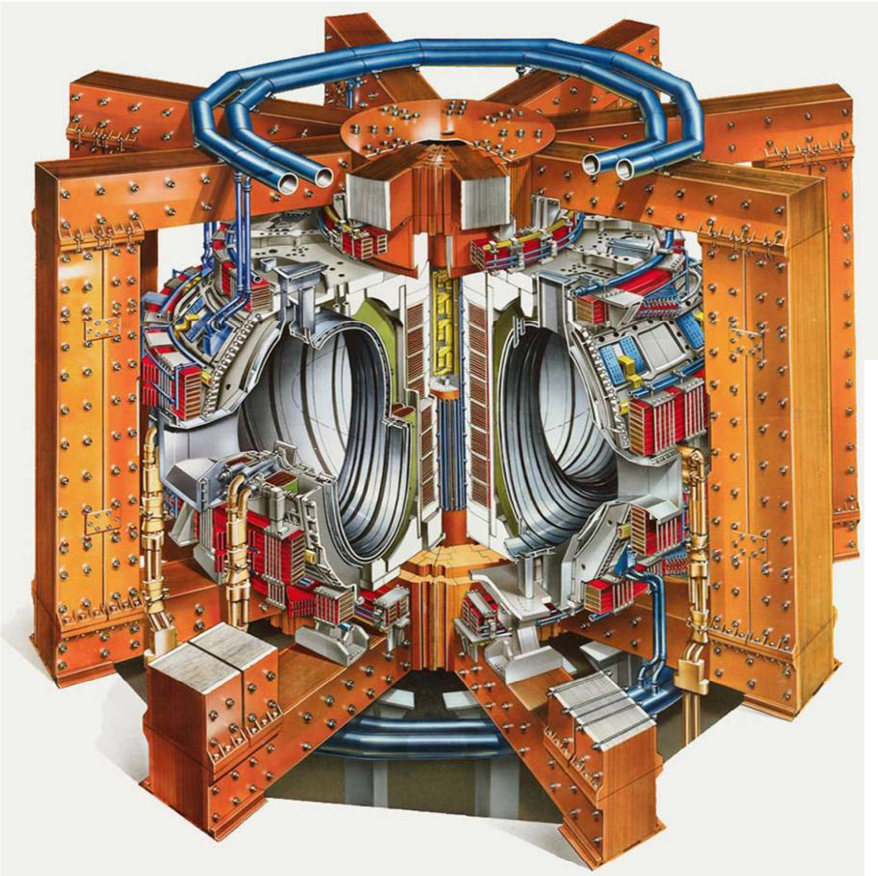
Scaling of experimental data: $\tau_E \propto R^3 \cdot B_t / P_{Heiz}^{0.65}$



# Turbulence-dominated energy loss



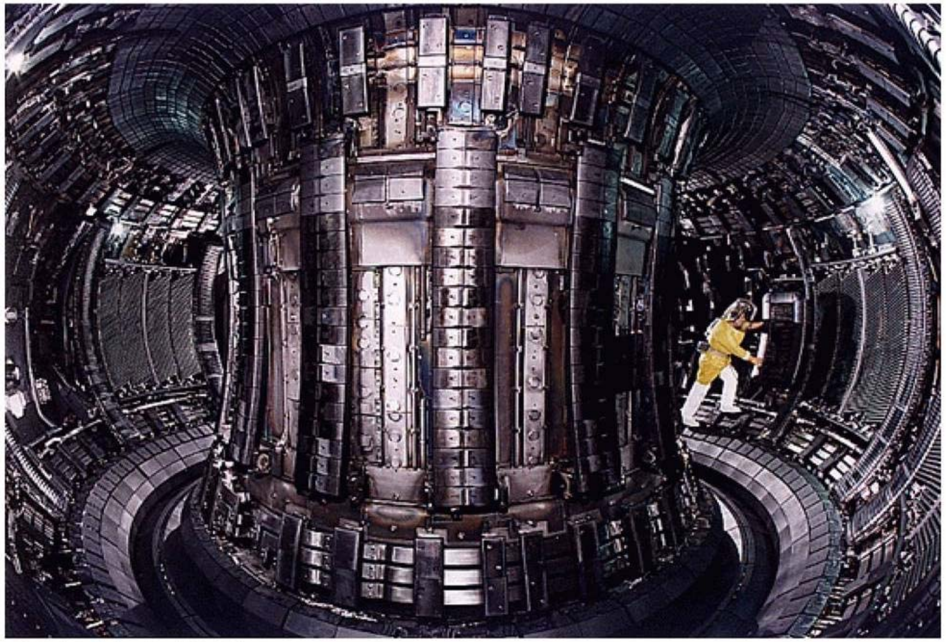
# Joint European Undertaking (JET, Culham/GB)



$R = 2.95$ m  $a = 1.25$ m  $\kappa = 1.6$

$B_t \leq 3.5$ T  $I_p \leq 7.0$ MA  $P_H \leq 30$ MW

start of operation in 1983



1997, Mark IIA Divertor

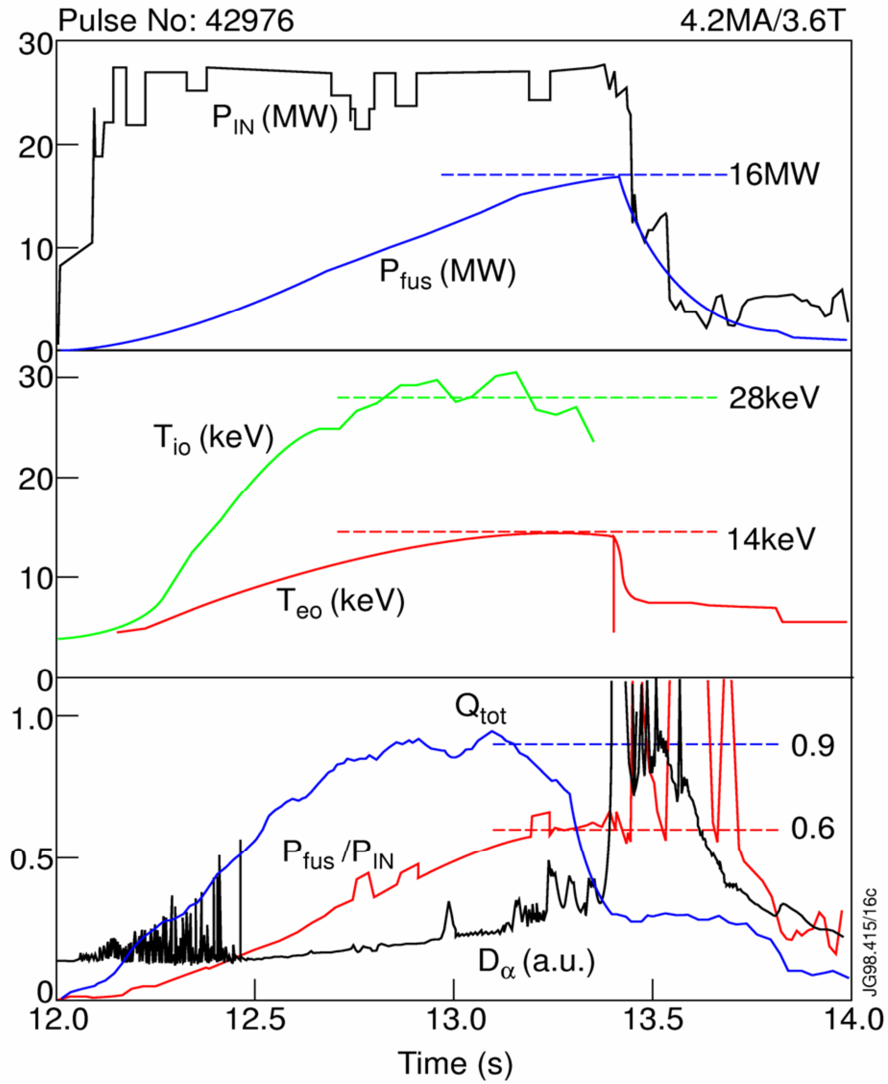
# JET DT-Experiments

DT-experiments only in
- JET
- TFTR, Princeton

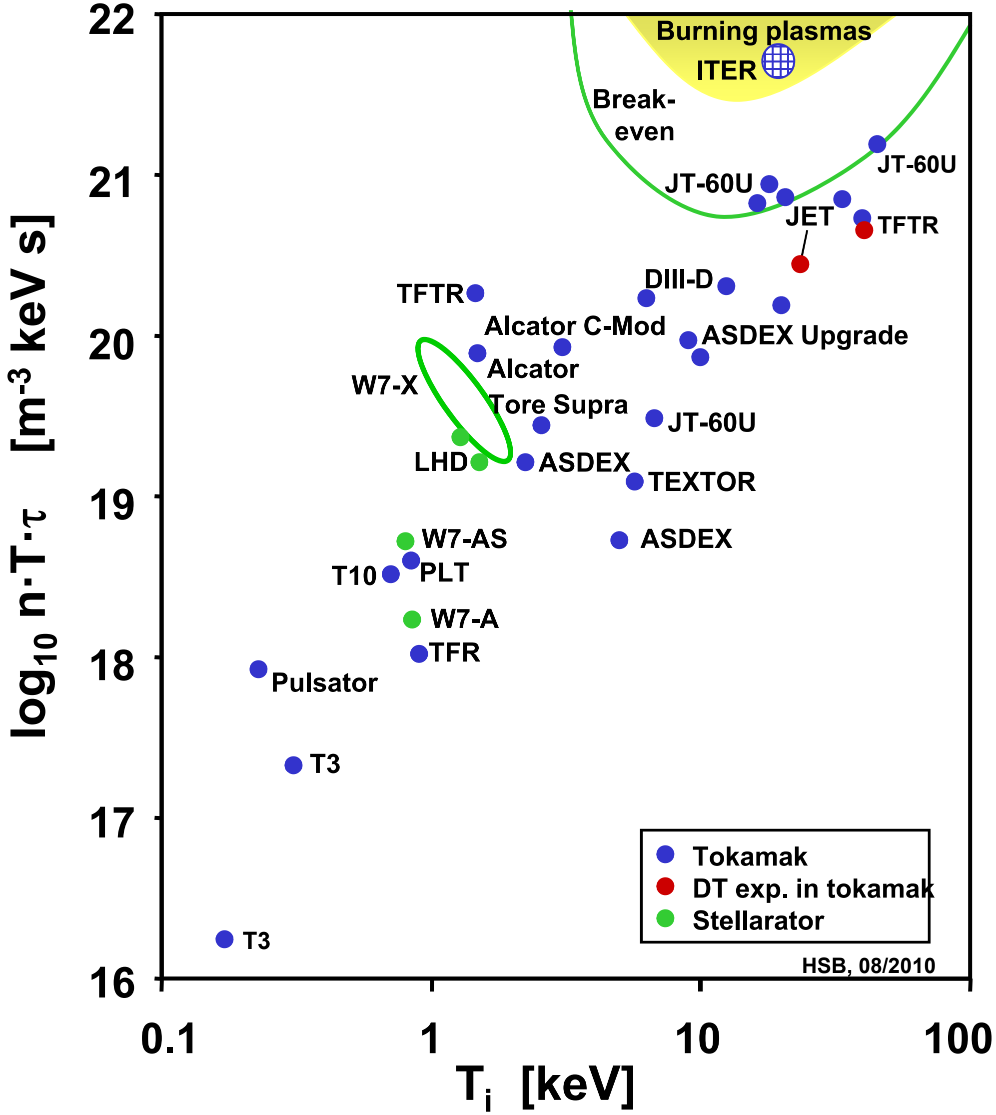
with world records in JET:

$P_{fusion}$ = 16 MW

Q = 0.65

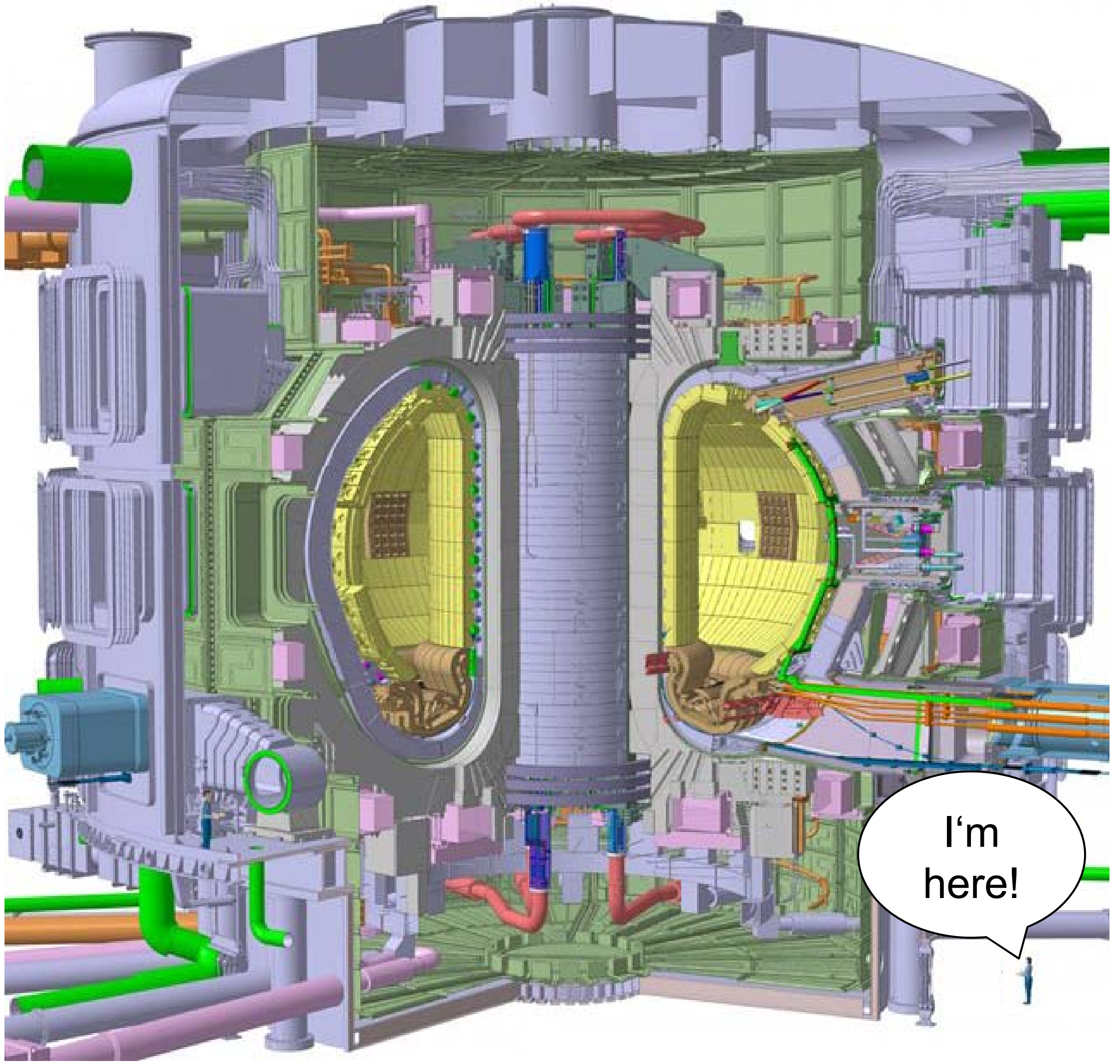


# Status of Fusion Research




- Todays tokamak plasmas are close to breakeven.
- The next step (ITER) will ignite or at least operate at high Q (≈10) …
- … and thereby prove the scientific and technological feasibility of fusion energy.

# ITER (latin: the way)




- international project since 1985, started by Europe, Japan, Russia, and the USA.

- final Design Report in July 2001

| | |
|---|---|
| R [m] | 6.2 |
| a [m] | 2.0 |
| k | 1.7 |
| d | 0.35 |
| $I_p$ [MA] | 15.1 |
| B [T] | 5.3 |
| $T_{puls}$ [s] | 400 |
| $P_{fusion}$ [MW] | 400 |

# The ITER project

November 1985: US President Reagan and General Secretary Gorbachev of the Soviet Union agreed to pursue an international effort to develop fusion energy for the benefit of all mankind (Geneva summit).

1988-1990: Conceptual Design Activity (Garching ITER site)

1990-2001: Engineering Design Activity (ITER sites in Garching, Naka, San Diego)

2001-2005: ITER negotiations (in parallel technical activities on low level)

2003: China and South Korea join ITER

Nov. 2003 Europe decides to offer Cadarache as ITER site

Dec. 2005: India joins ITER

21.11.2006: Signature of the ITER contract in the Elysée Place, Paris

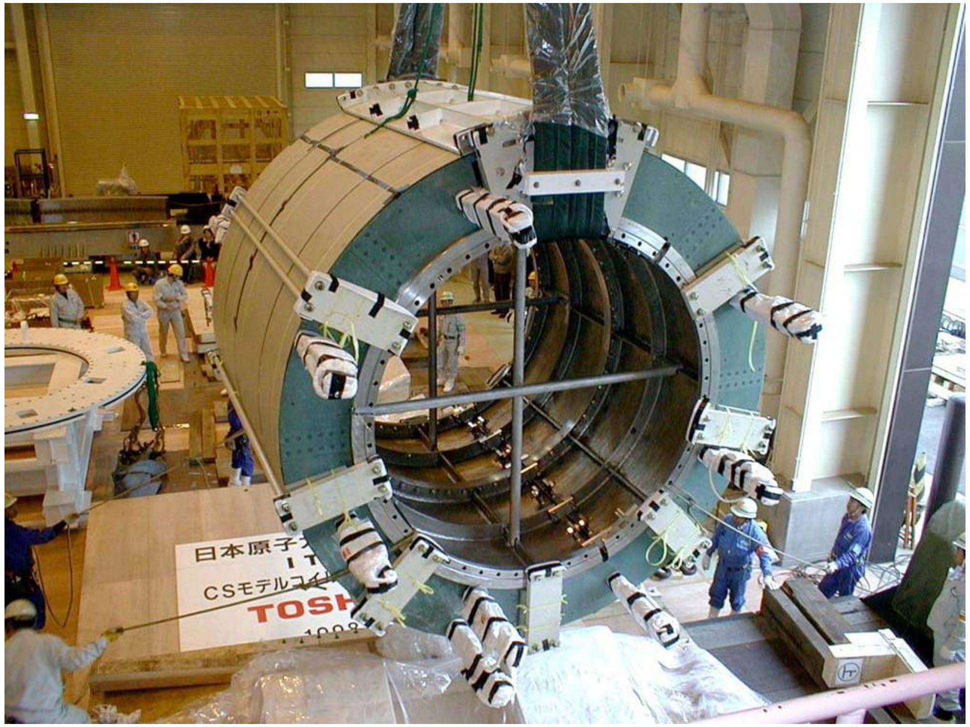
24.10.2007 : official start of the ITER project

# The ITER project

section of the vacuum vessel (1/20)

Prototypes of all major components have been built in the R&D program
- to prove the technologies
- to get a reliable costing.

segment of the transformer coil



# ITER
## … finally got started

# ITER
# … finally got started

September 2011

# ITER
## … is being built

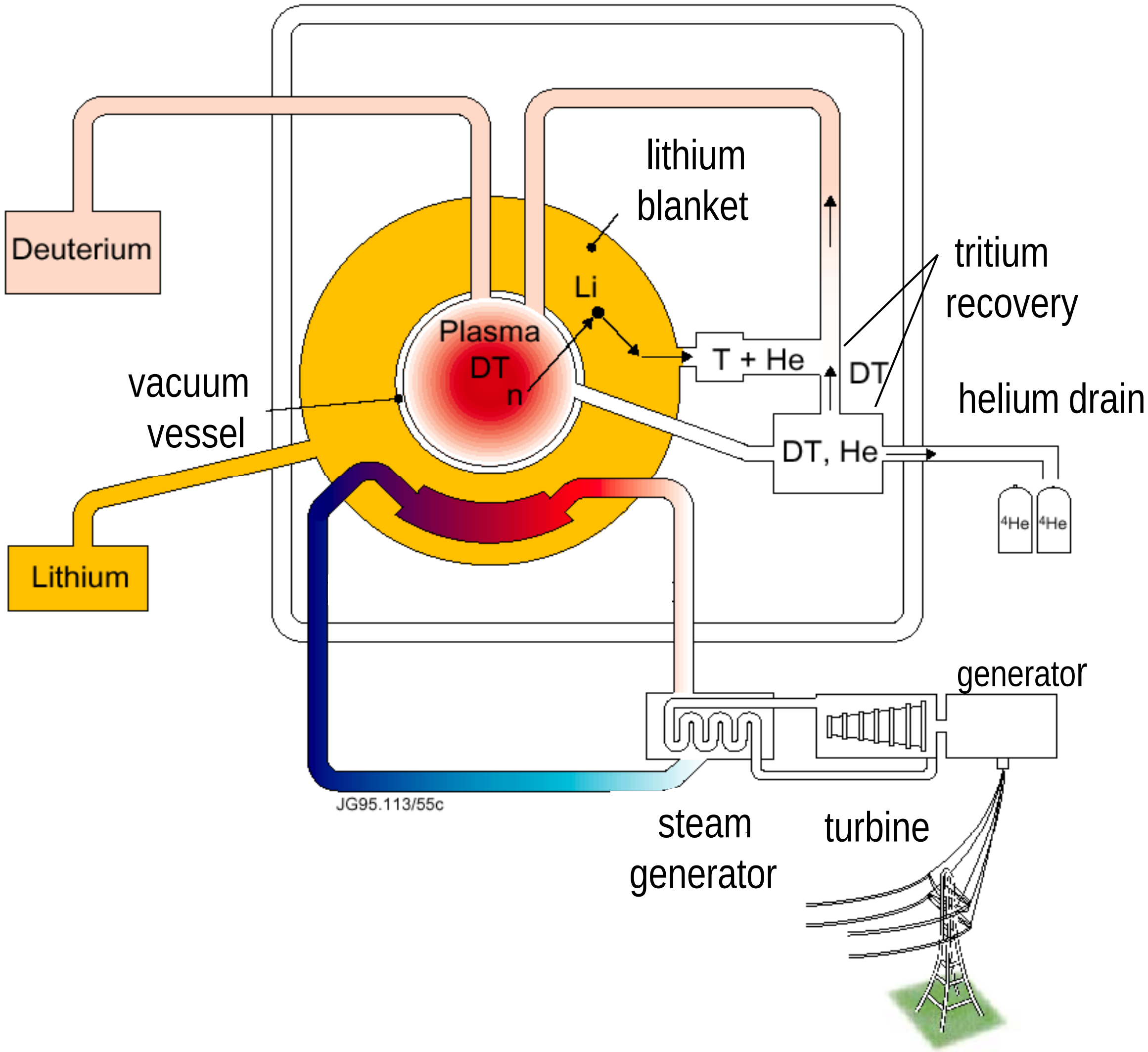
# ITER
# … is being built


**for more pictures visit:**

**http://www.iter.org/news/galleries**

# Schematic fusion reactor

Around 2025 one could start the design of a prototype reactor DEMO, operating in about 2035.



# The path to commercial fusion