Physics of Nuclear Fusion

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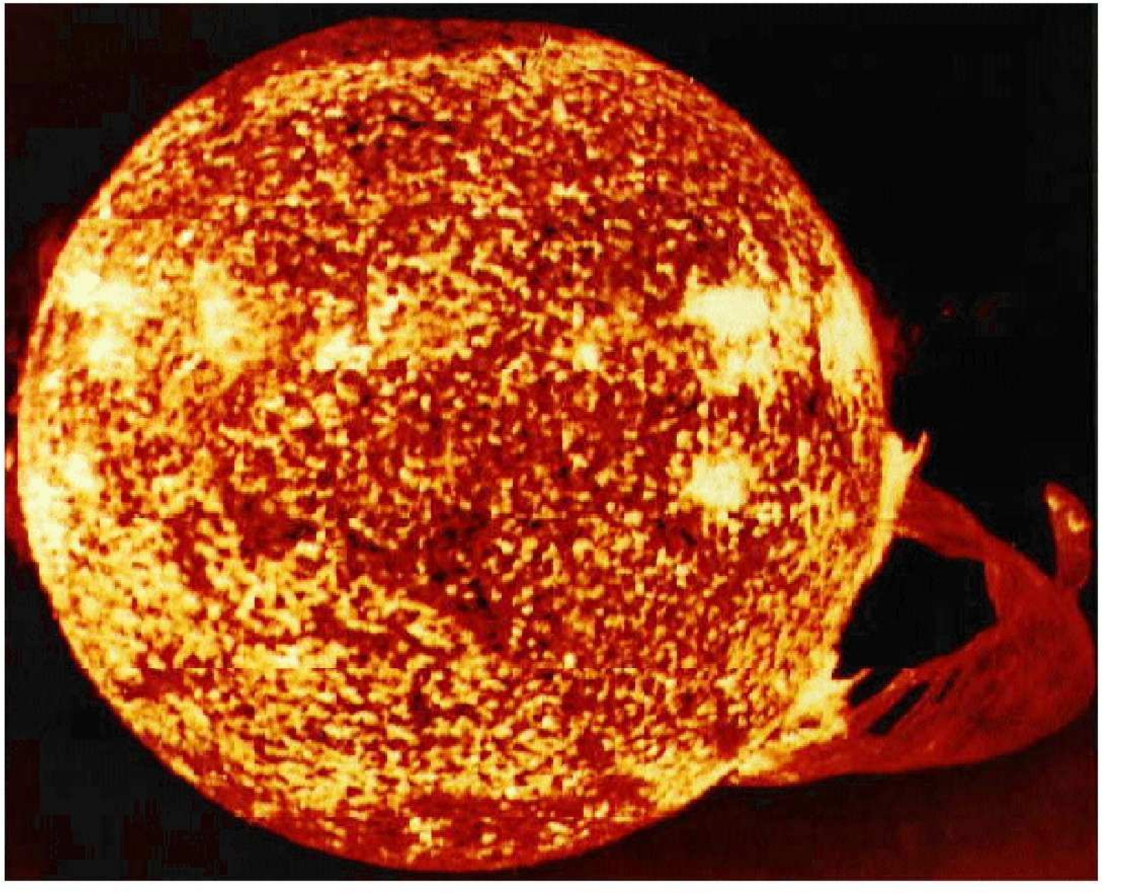
- Fusion in the stars
- Fusion research on earth
  - Inertial Confinement Fusion (ICF)
  - Magnetic Confinement Fusion (MCF)
- Status of fusion research and outlook

Summer University on Plasma Physics, Garching, 17-21 September 2012

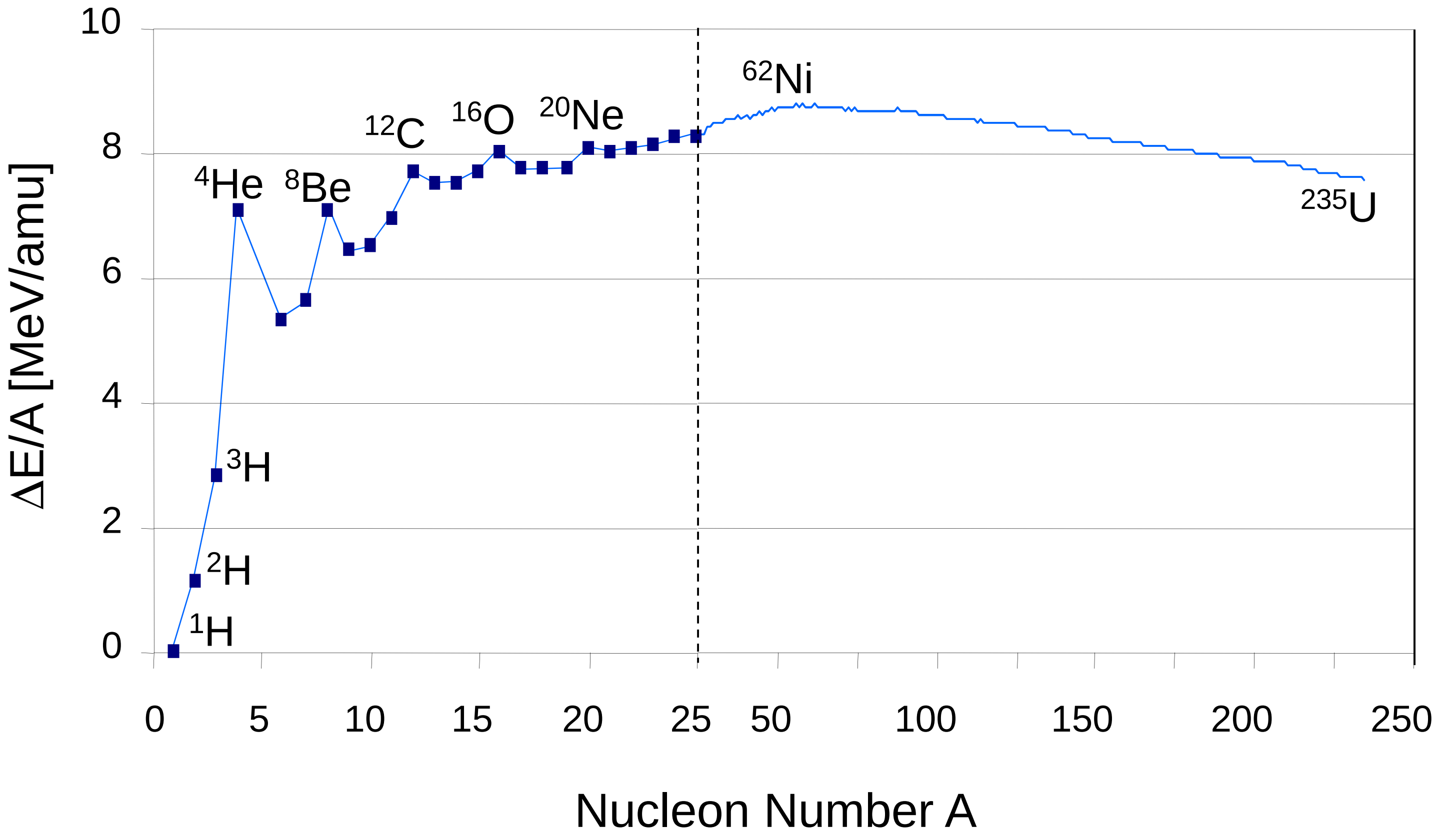
The energy source of the stars

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



NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

Nuclear energy: Fission/Fusion



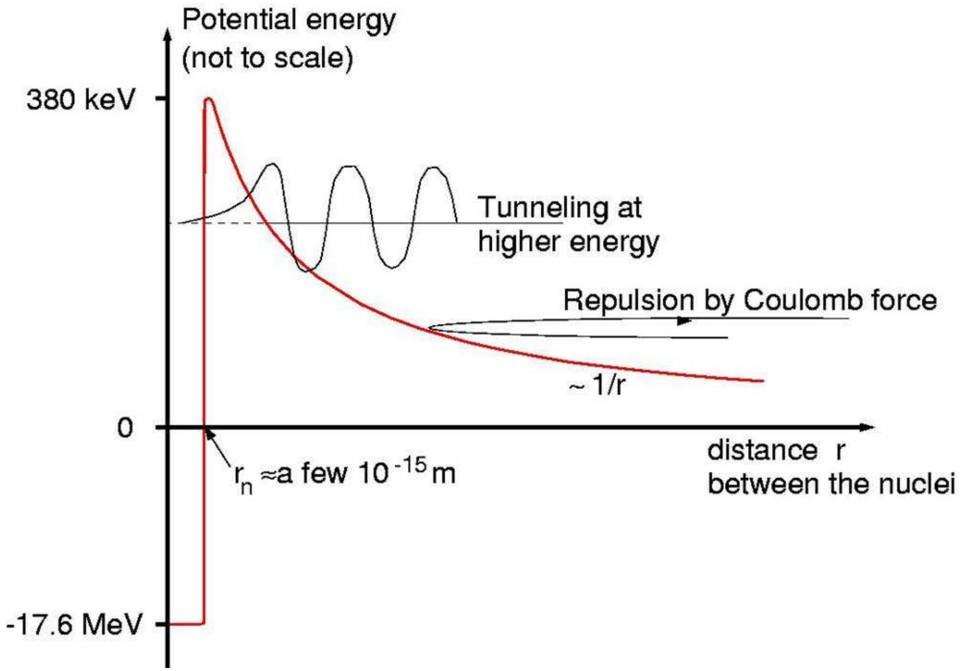
1) Binding energy of nuclei: **MeV**, not eV as in chemistry (electrons binding molecules)

2) Energy gain possible from - fission of heavy nuclei or

- fusion of light nuclei.

Advantages of fusion: fuel resources, safety aspects, reduced waste produktion

Nuclear reactions: potential energy



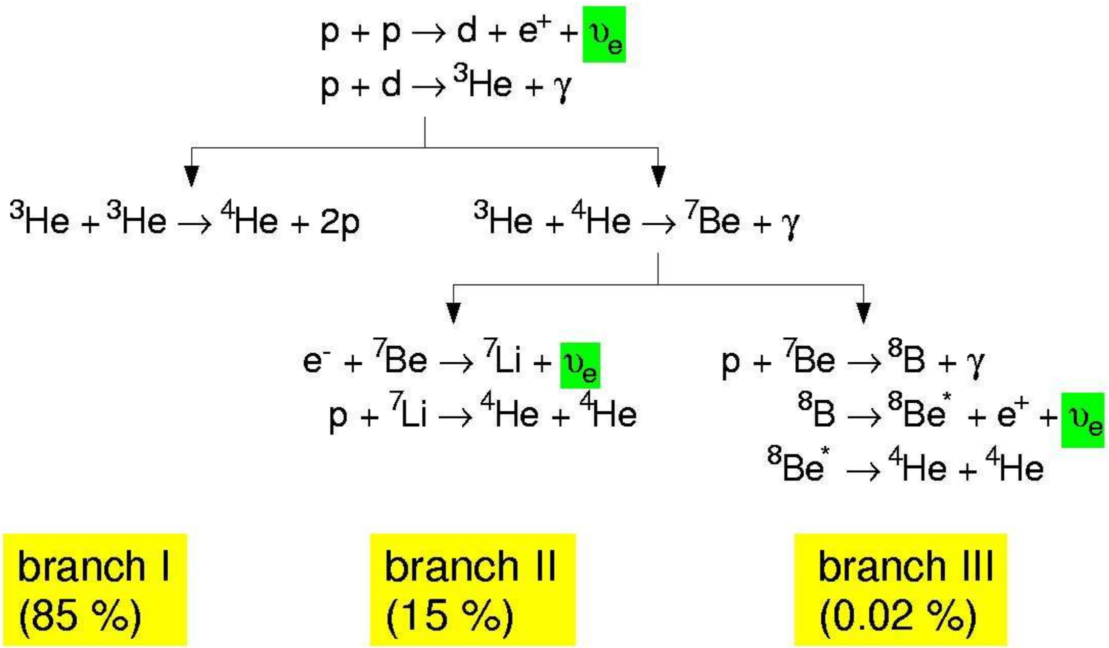
- Nuclear forces (strong interaction) act only over distances in the order of the nucleus dimensions (fm).
- Otherwise, the repulsive Coulomb force dominates
  ⇒ Potential wall: some 100 keV, impossible to overcome!

- 1928, Gamov explained α-decay with tunneling-effect (Q.M.):
  probability function is a spatially decaying wave funtion with finite values for $r < r_n$,
  ⇒ finite probability for tunneling
  through the Coulomb wall:

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

- Highest reaction probability for light nuclei at high relative velocity!

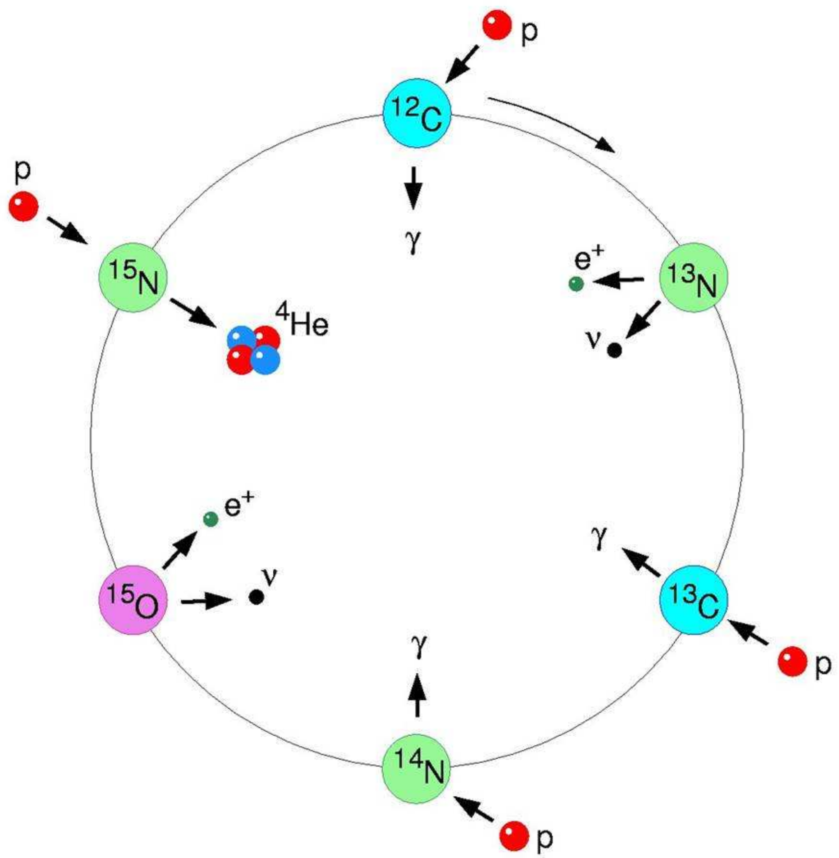
Solar fusion reactions: The pp-chain



- The first step involves the weak interaction, trans-forming 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.

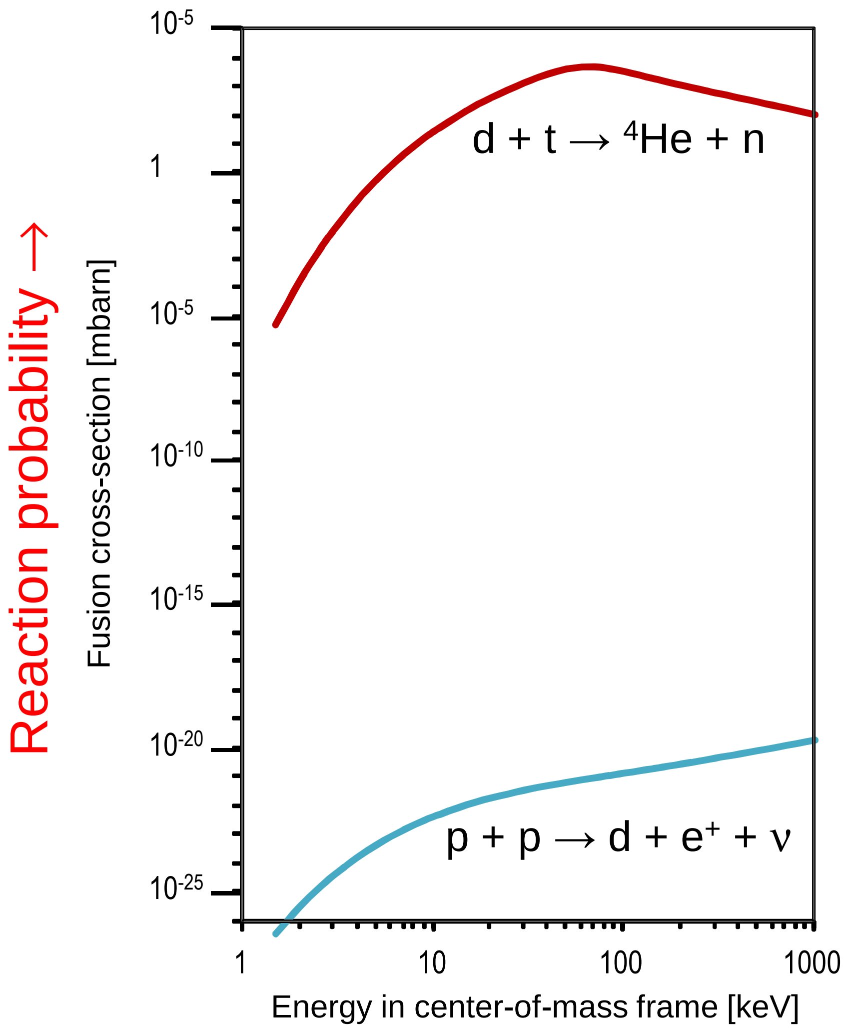
- An alternative to this first step involves 3 body collisions, and is therefore very rare: $p + p + e^- \Rightarrow d + \nu_e$
- Fusion reactions also create the heavier nuclei in the stars
  $\Rightarrow$ stellar Nucleosynthesis
- The neutrinos from this reaction are the only particles to be observed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

The CNO-cycle
(Bethe-Weizsäcker-cycle)



- Discovered in 1938, independently 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 existence of carbon!
- Net reaction:
  $4\ p \Rightarrow {}^{4}He + 2\ e^{+} + 2\ \nu + 3\ \gamma$

For a terrestial energy source we need different fusion reactions!



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

  => 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 on earth

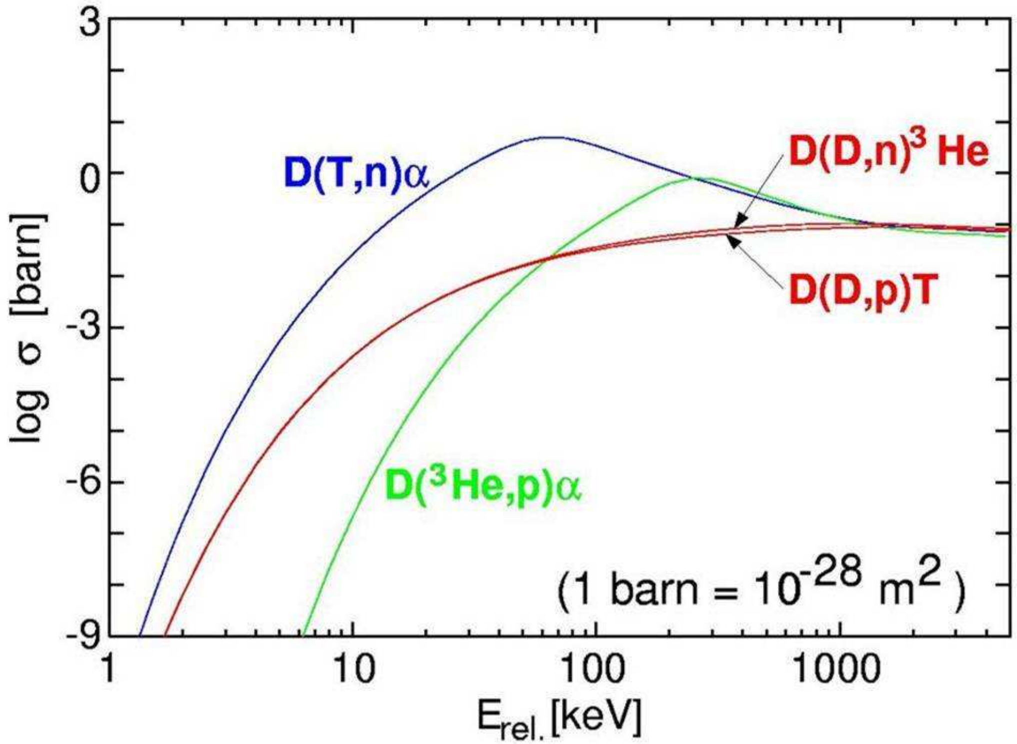
d + d $\Rightarrow$ ^{3}He + n + 3.27 MeV (50%)

or t + p + 4.03 MeV (50%)

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

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

- d = ^{2}H, Deuterium
  t = ^{3}H, Tritium
  the heavy hydrogen isotopes.
- Best choice: the DT-reaction



Fusion reactions, the nuclear part

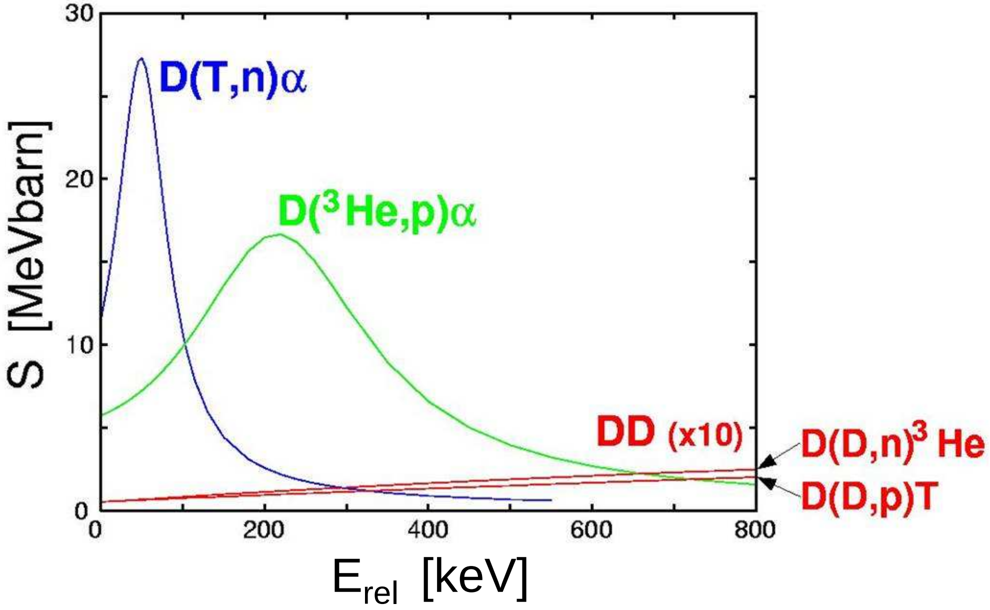
The fusion cross section can be written as

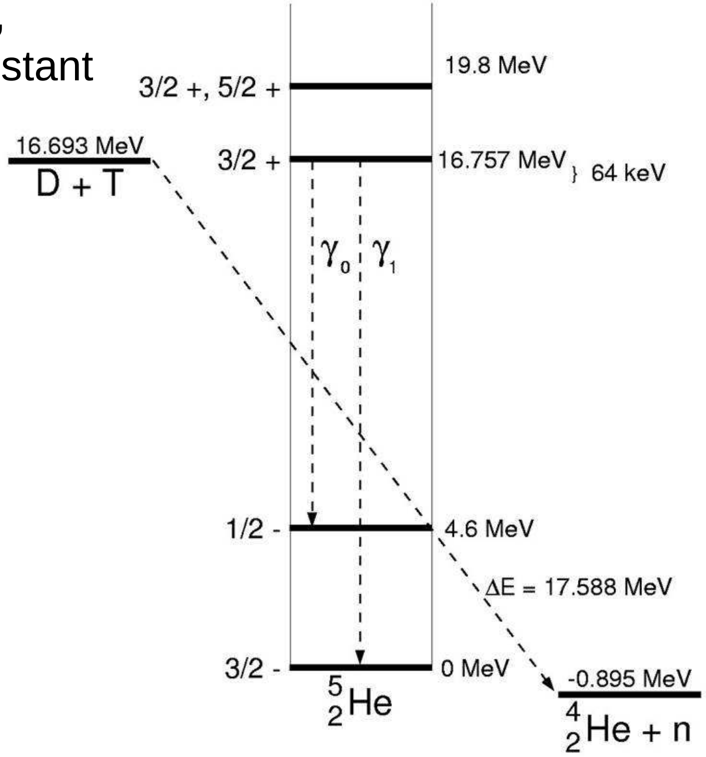
$$\sigma = S(E) \bullet 1/E \bullet \exp\{-B_G/\sqrt{E}\}$$

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:

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

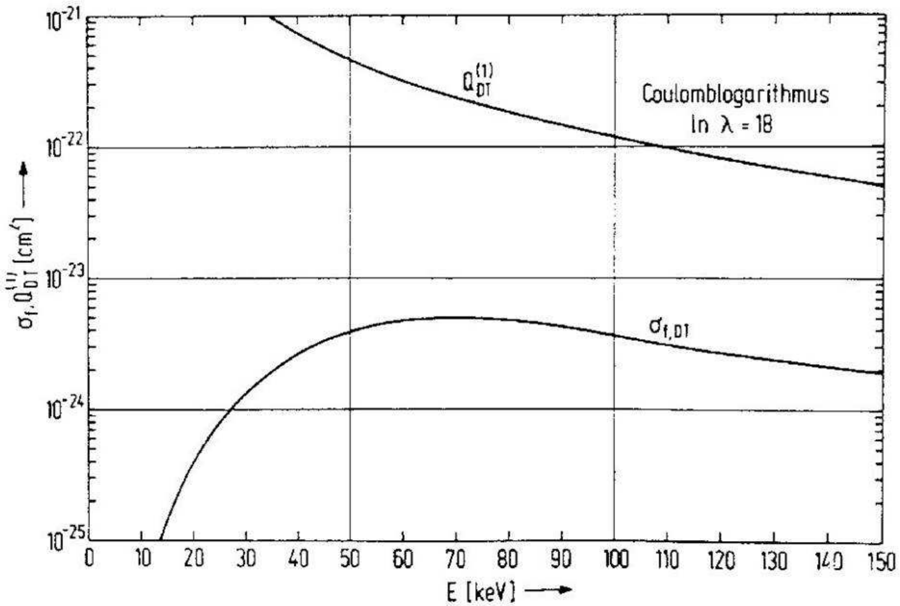
  $$n + {}^{7}Li \rightarrow {}^{4}He + T + n' \quad - 2.5\ MeV$$

  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 0000 years.

Thermonuclear fusion

High relative velocity of the nuclei is necessary ⇒ accelerator?
No! Coulomb scattering makes the beams diverge ⇒ not efficient



Thermalised mixture of deuterium and tritium at temperatures of some 10 keV is needed ⇒ plasma.

Energy distribution of particles in a thermal plasma: Maxwell distribution

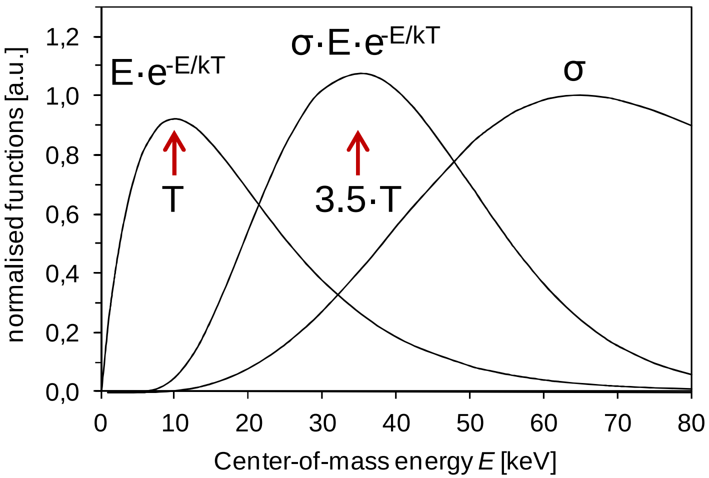
$$f(v) = \left(\frac{m}{2\pi\, kT}\right)^{3/2} \cdot \exp\left(-\frac{mv^2}{2\, kT}\right)$$

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

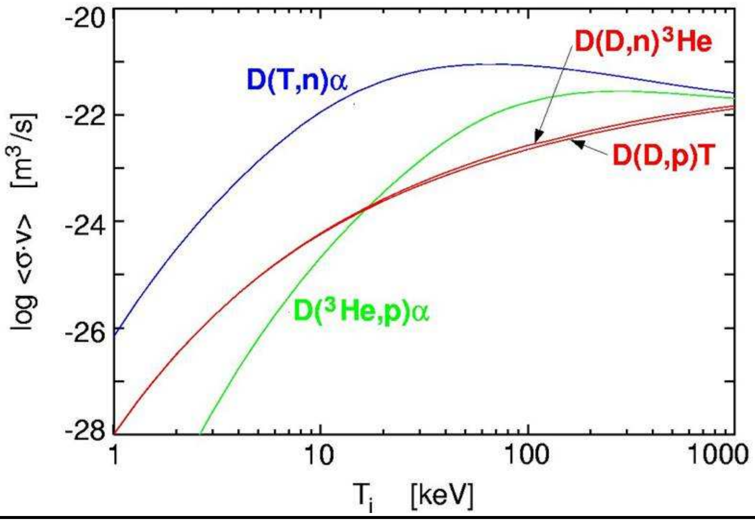
Reaction parameter

Reaction rate per unit volume: R = $n_1 \bullet n_2 \bullet \langle\sigma \bullet v\rangle$
when $\langle\sigma \bullet v\rangle$ is the average of $\sigma \bullet v$ over the velocity distribution, and v is the relative velocity
⇒ Transforming the integration into the center-of-mass sytem yields

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



when E_r is the rel. kinetic energy
and m_r is the reduced mass,
$1/m_r = 1/m_1 + 1/m_2$.



Lawson Criterion

In 1957 Lawson introduced 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 by radiation,

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

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

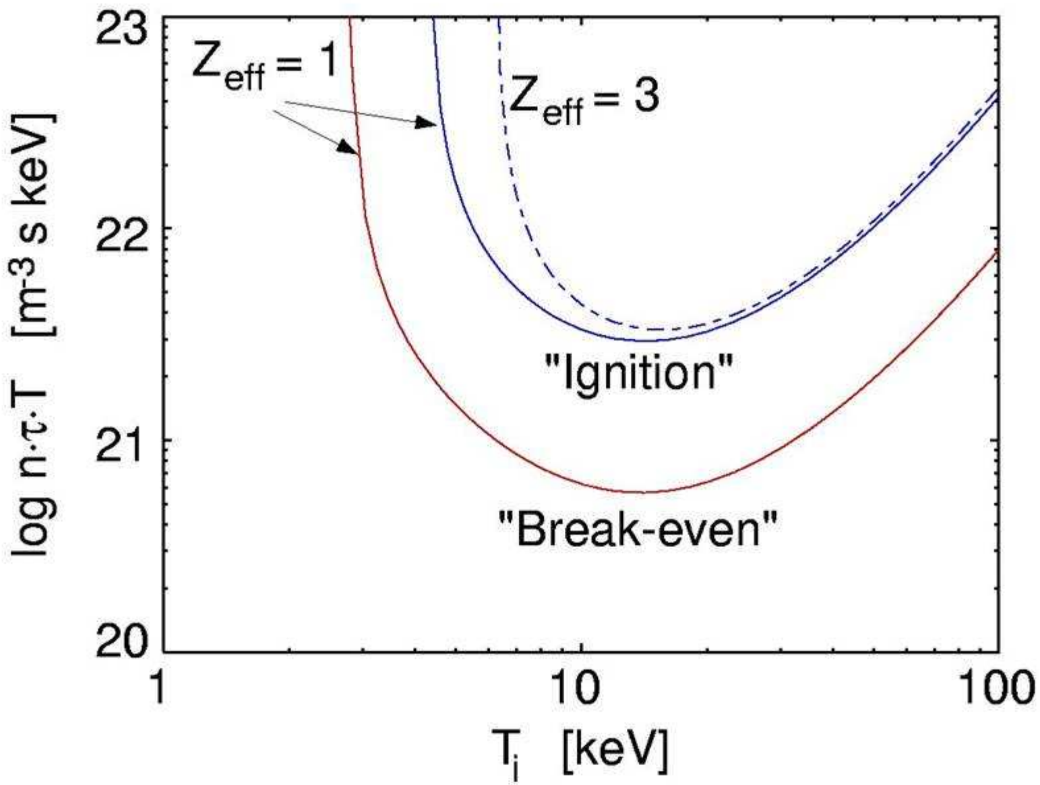
$$P_{loss} = 3\, n\, kT / \tau_E$$

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

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

Ignition: The neutrons leave the plasma, the α-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 α-particles produced in the fusion reactions, as their production is intrinsically coupled to fusion power ($3.53 \cdot 10^{11}$ atoms/s/W).

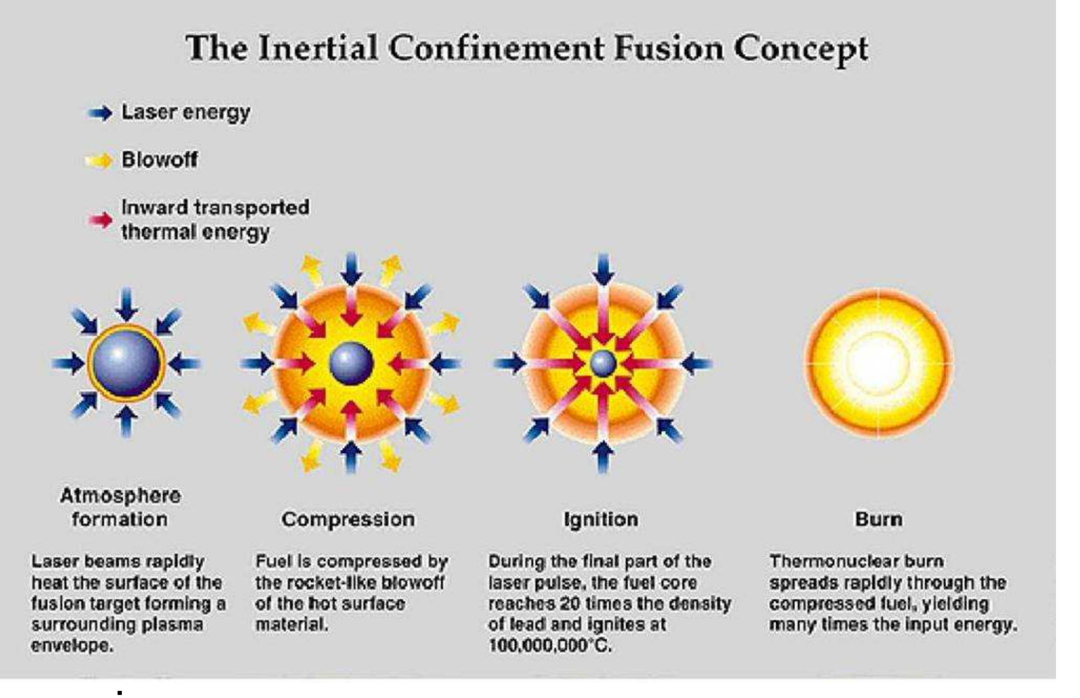
⇒ Closed curves parametrized by the normalized He-confinement time $\rho_{He} = \tau^*_{He} / \tau_E$

Fusion Concepts

Requirement for $n\tau T \Rightarrow$ 2 concepts:

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.

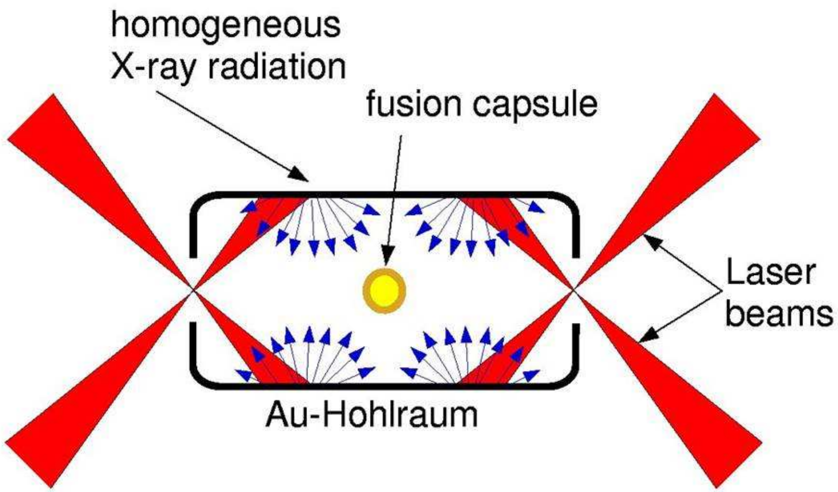


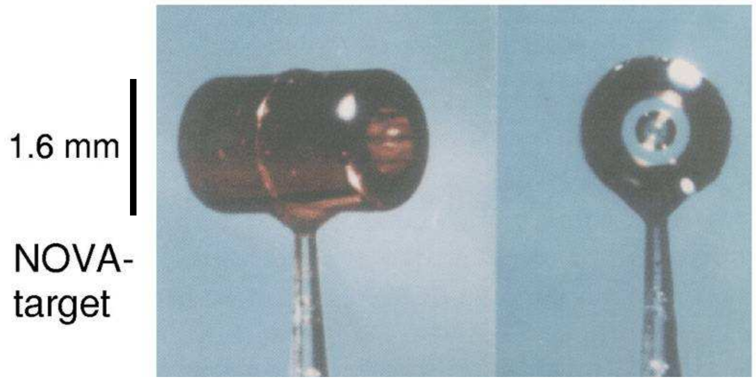
Ignition in a small, central spot (low n), propagating outward into area of high n (low T), spark ignition (Nuckolls et al. 1972)

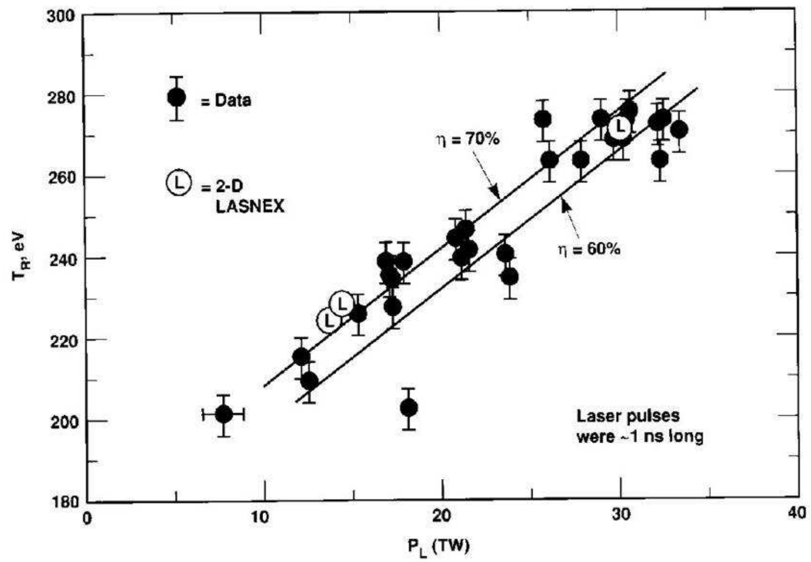
Problems:
- Uniformity of irradiation and compression,
- Rayleigh-Taylor-Instabilities
- Drivers

Hohlraum targets, Indirect drive

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







Lindl et al.
Phys. Plasmas, 1995

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

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:

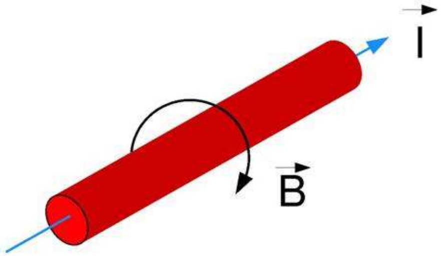
1) Neodym glass laser:
- at λ= 1.06 μm, absorption is too small. Improvement by frequency conversion to 530 nm (70%) or 350 nm (50%) in potassium dihydrogen phosphate (KDP) crystals .
- ε_{driver} < 1% (pumping presently by flashlamps, i.e. white light),
$\Rightarrow$ Solid State Diode Pumped Lasers (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:
- λ= 248 nm
- ε_{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,
- mult-wire arrays are more stable, generate even more X-Rays!

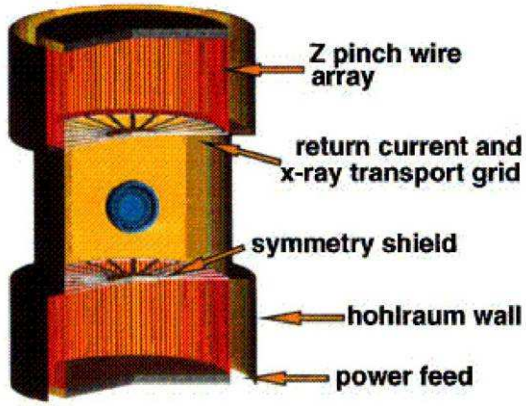
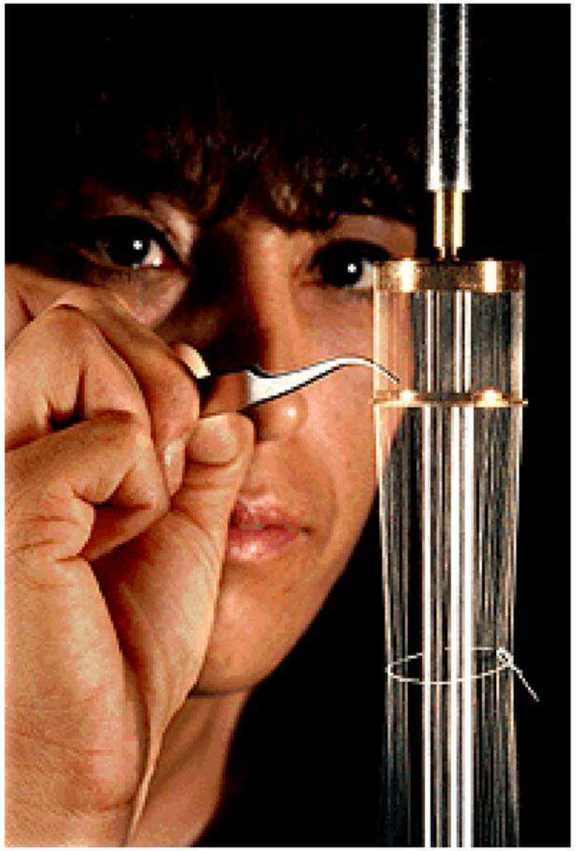
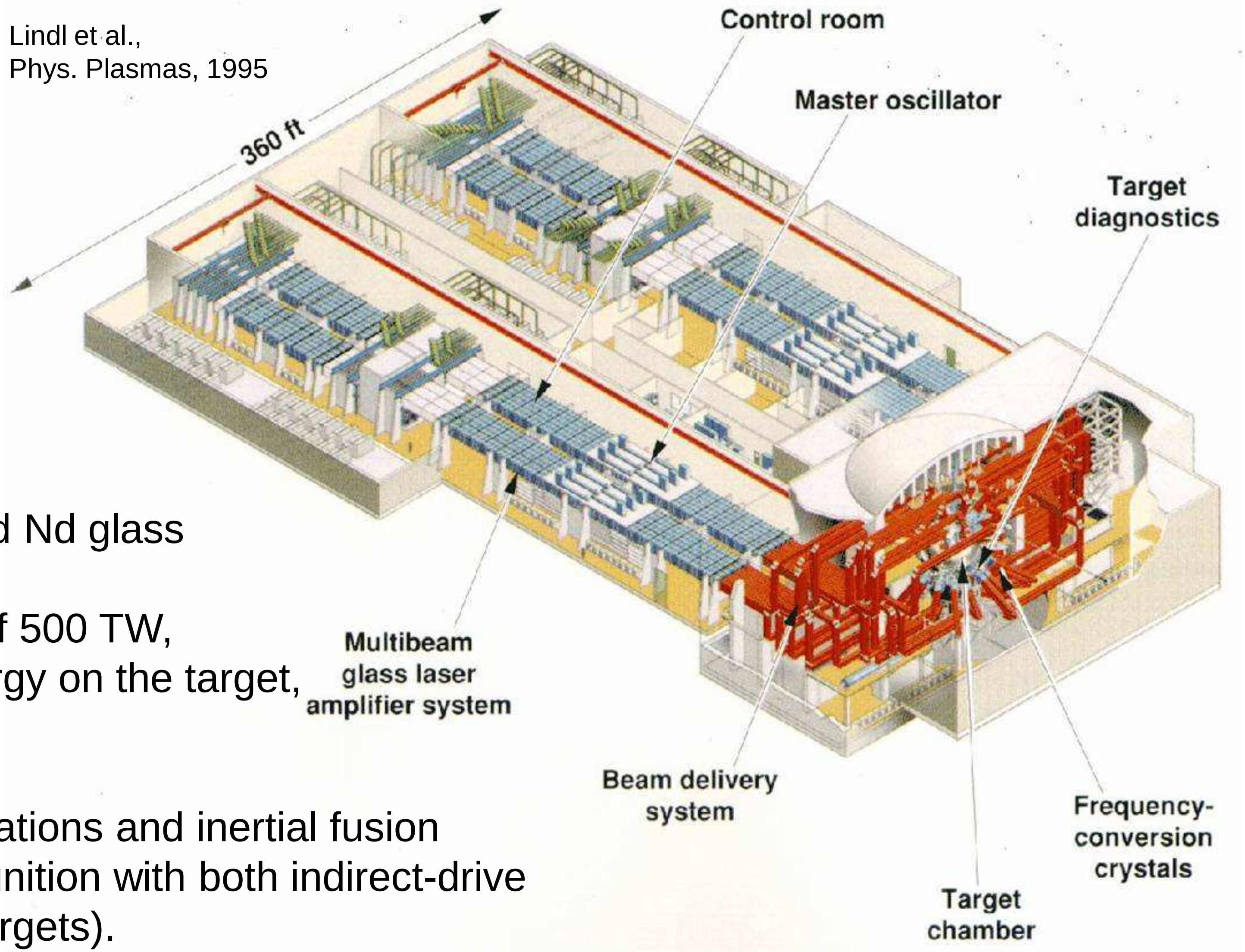


FIG. 1. Z-pinch-driven hohlraum ICF concept. Primary hohlraums 1 cm ta with 2.4 cm diam are placed on the ends of a secondary hohlraum 1.6 c tall containing the capsule. The primary hohlraums have annular pow feeds 0.2 cm in width, and are separated from the secondary hohlraum t transport grids. Shine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



National Ignition Facility, NIF
Lawrence Livermore National Laboratory

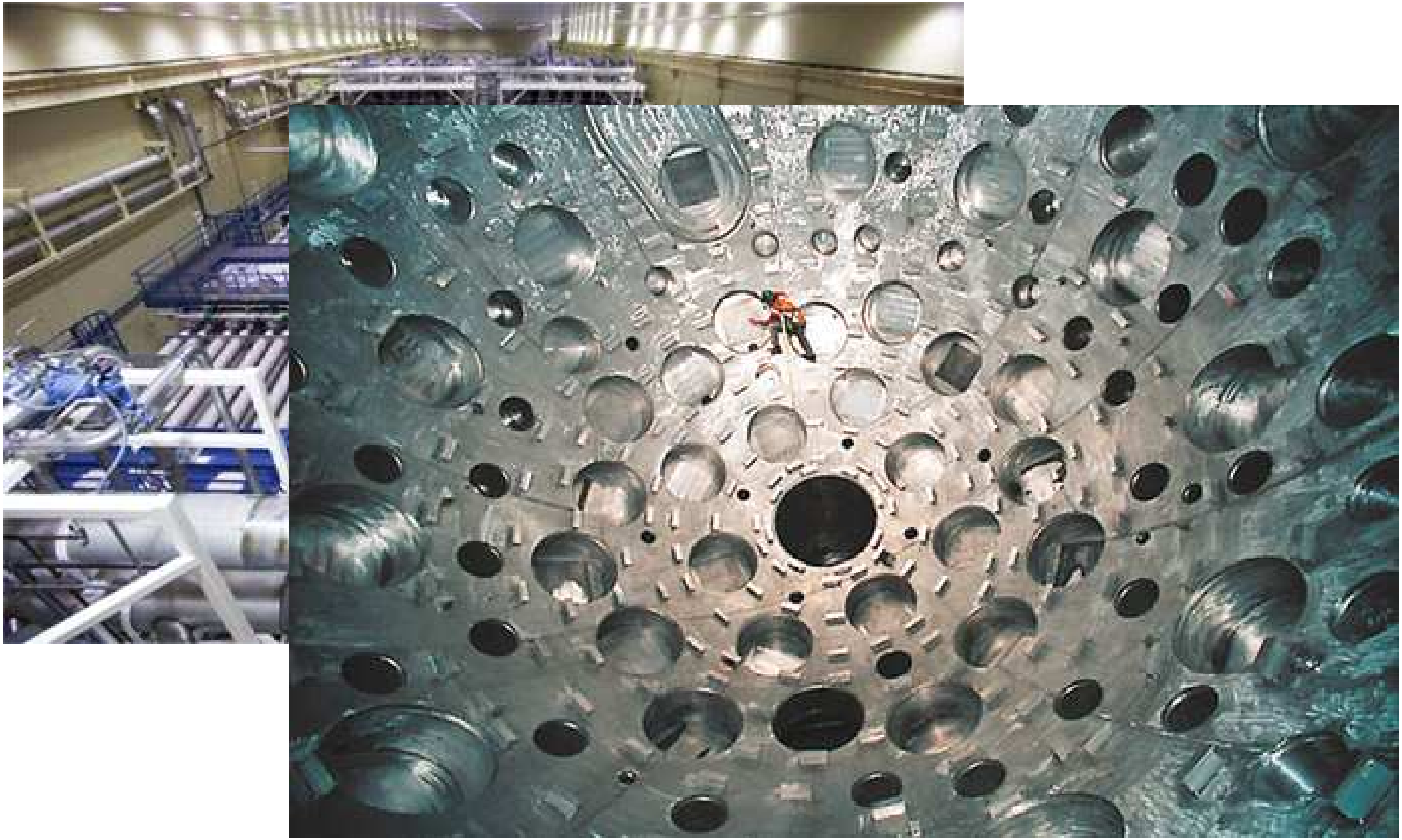
Lindl et al.,
Phys. Plasmas, 1995



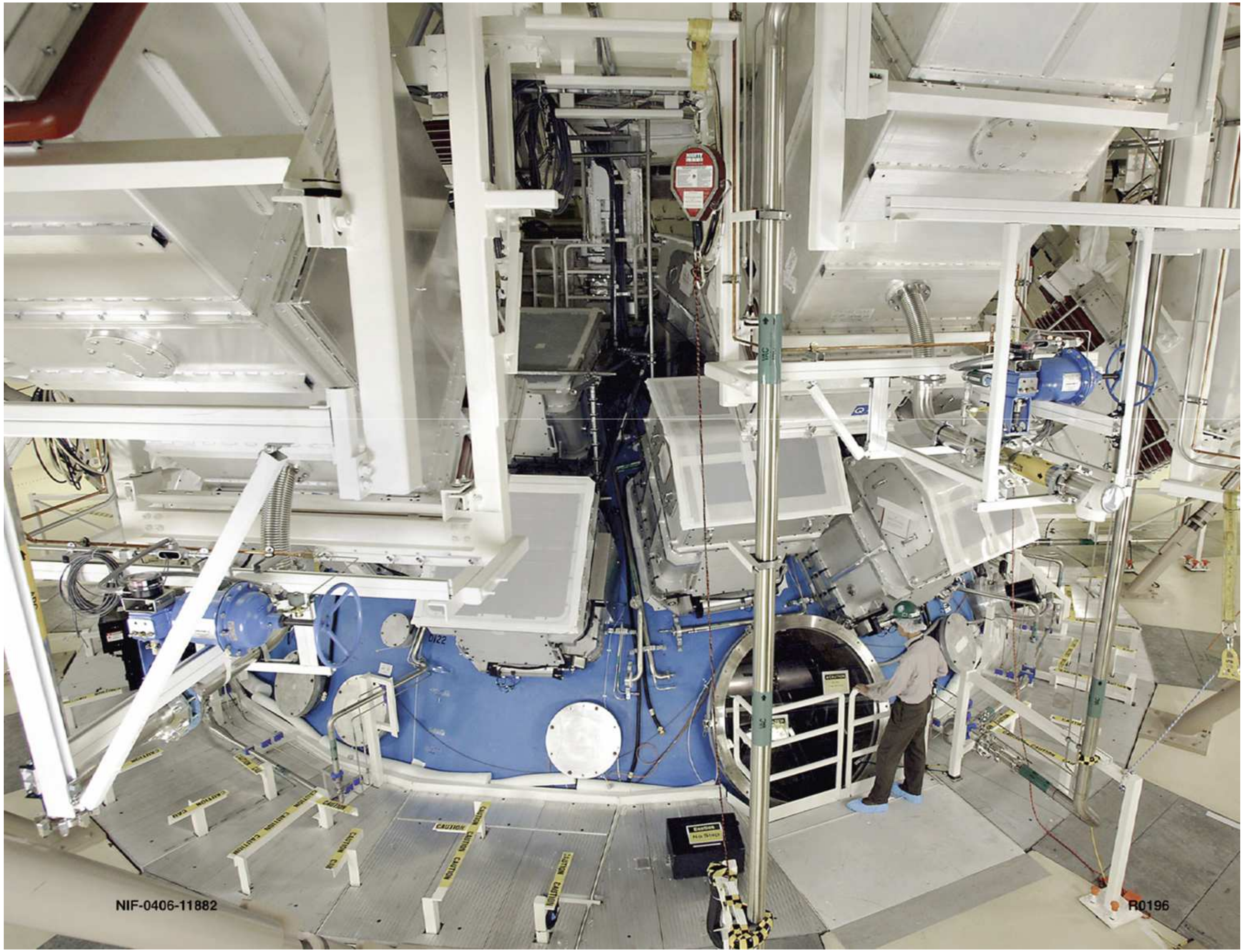
- 192 lasers,
- frequency-tripled Nd glass laser at 350 nm,
- with an output of 500 TW,
- and 1.8 MJ energy on the target,

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

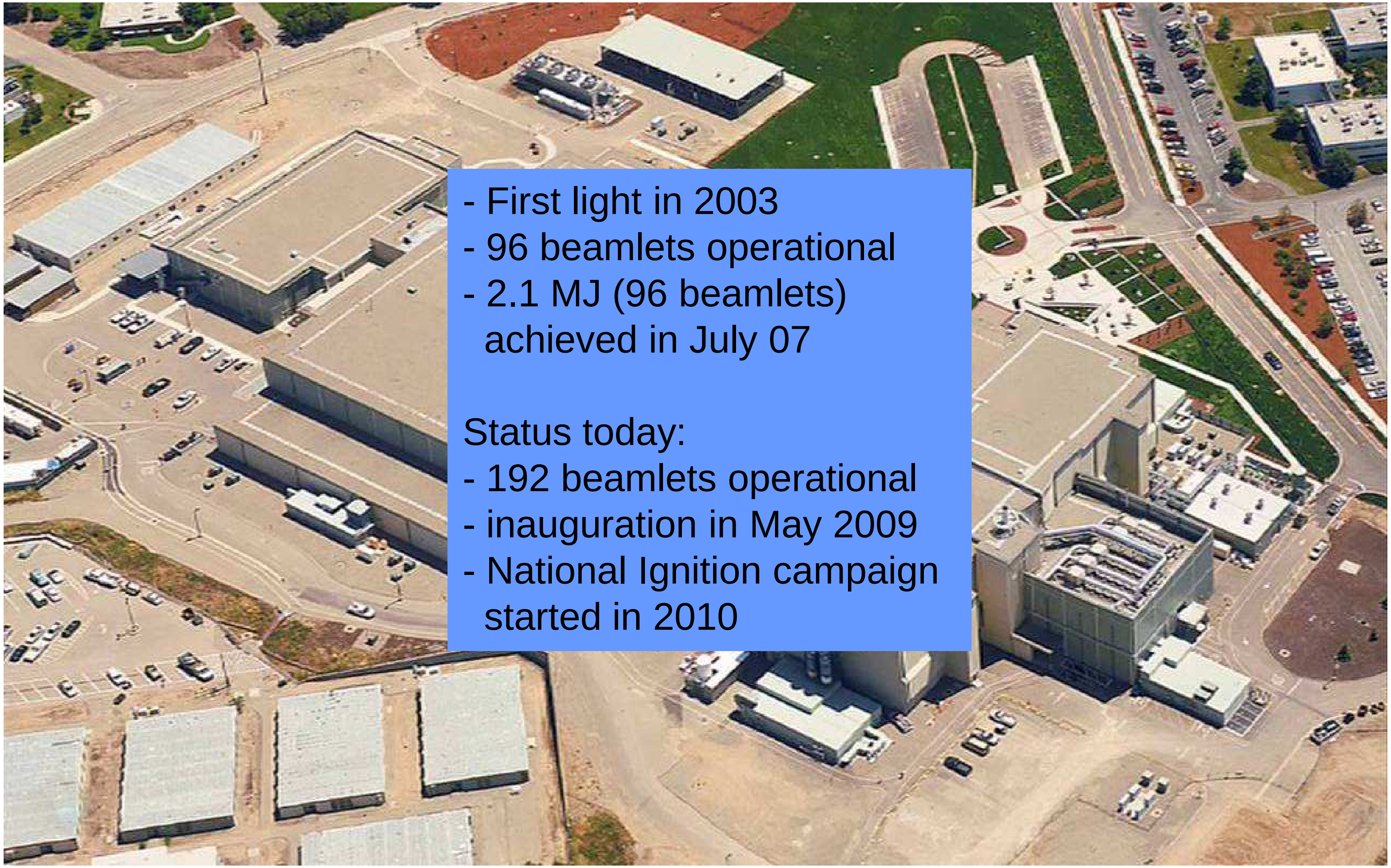
NIF Construction I



NIF Construction II



NIF Construction III



- First light in 2003
- 96 beamlets operational
- 2.1 MJ (96 beamlets) achieved in July 07

Status today:
- 192 beamlets operational
- inauguration in May 2009
- National Ignition campaign started in 2010

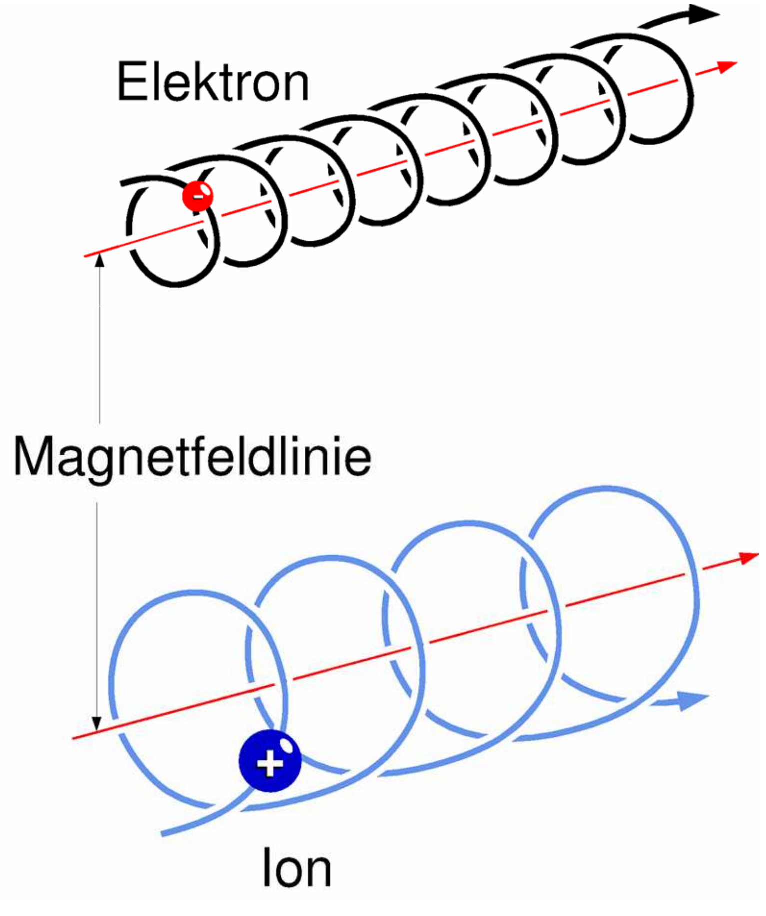
National Ignition Campaign

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 using a modified pulse based on the results of the recent re-emit and shock-timing experiments. Preliminary estimates indicate that the neutron yield was about 2×10^{14} (200 trillion) and the x-ray emission data showed a small, round core, consistent with earlier symmetry tuning results.
… experiments with laser energies of up to 1.6 MJ in the coming weeks.

Magnetic Confinement

Plasma Physics Poli previous talk

Charged particles are confined by magnetic fields

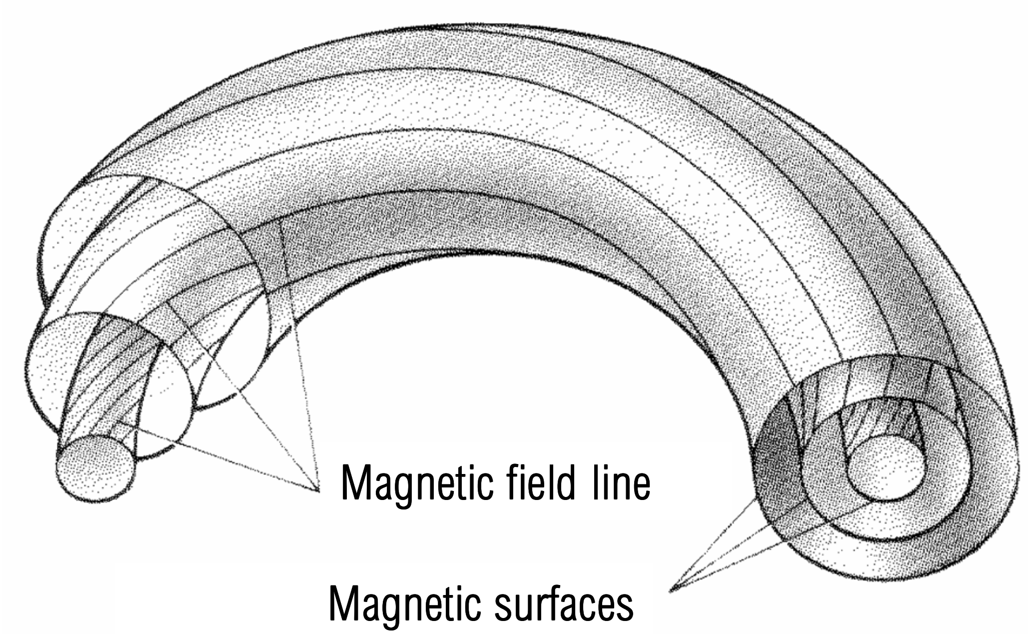


Transport perpendicular to B only from collisions. Particles escape only parallell to B, i.e. at the ends.

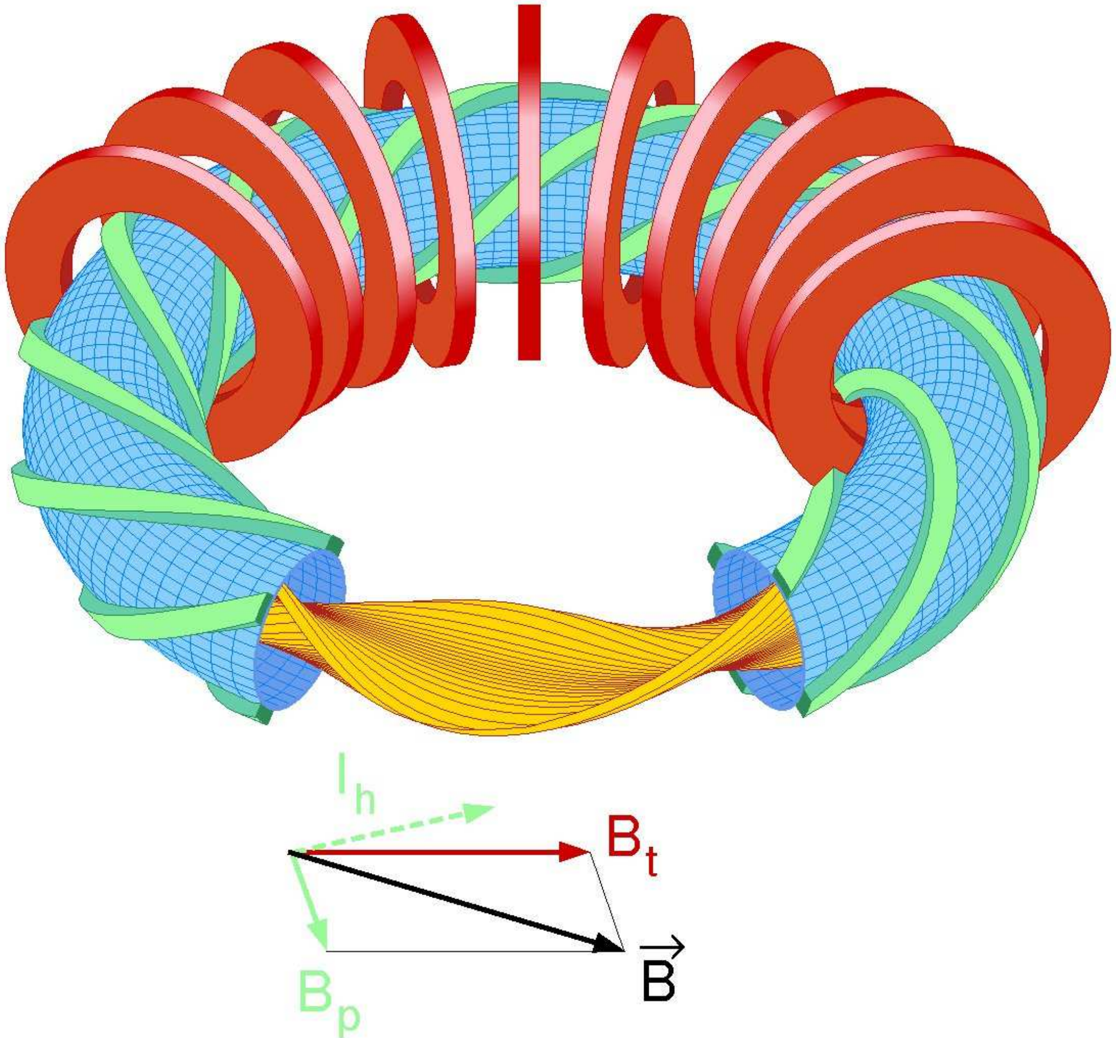
$\Rightarrow$ bend it to a torus.

Gradient drift requires a rotation of the magnetic field lines

$\Rightarrow$ magnetic surfaces



Stellarators



- A poloidal field is created by helical, external.
- Invented in the 50‘s by L. Spitzer jr. At Princeton.

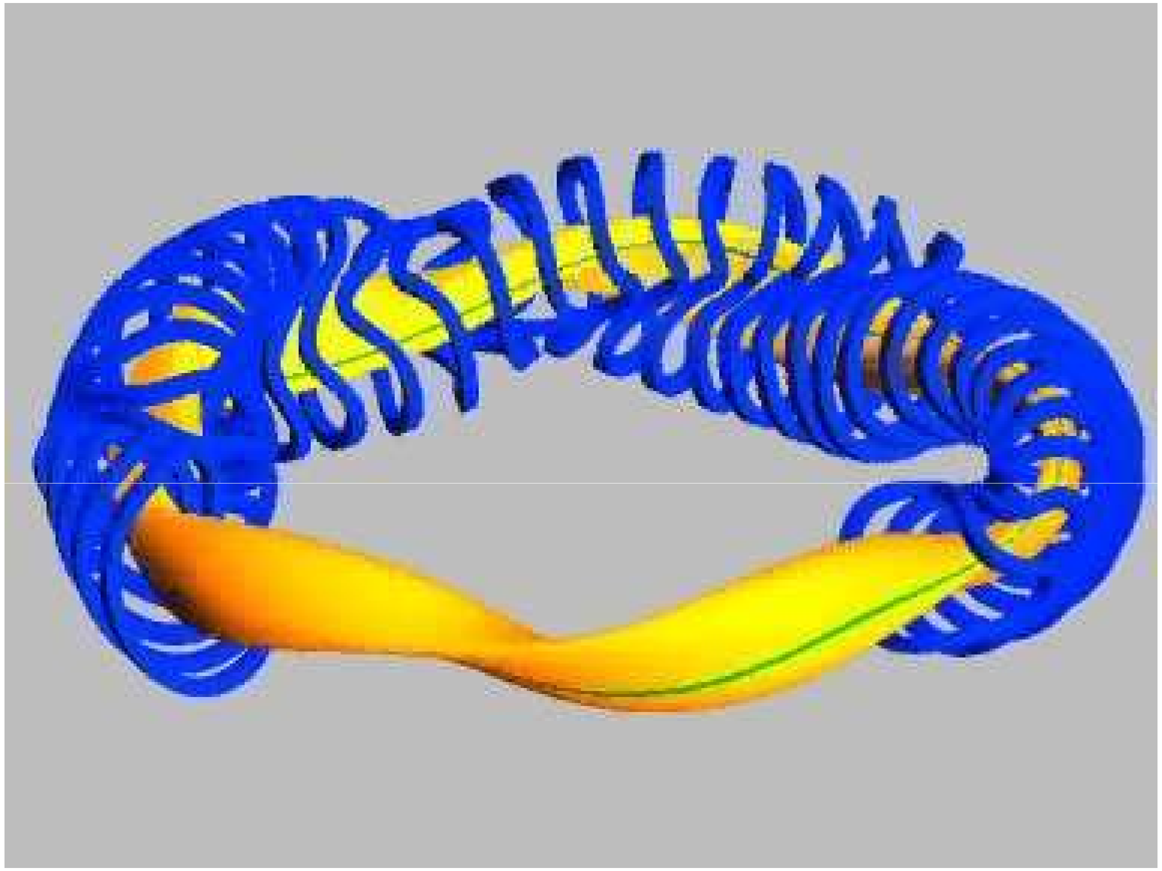
\+ Only external currents,
\+ well controllable,
\+ stationary operation intrinsic

\- problem of nested coils,
\- trapped particles unconfined

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

Development of Stellarators

Stellarator WENDELSTEIN 7-X



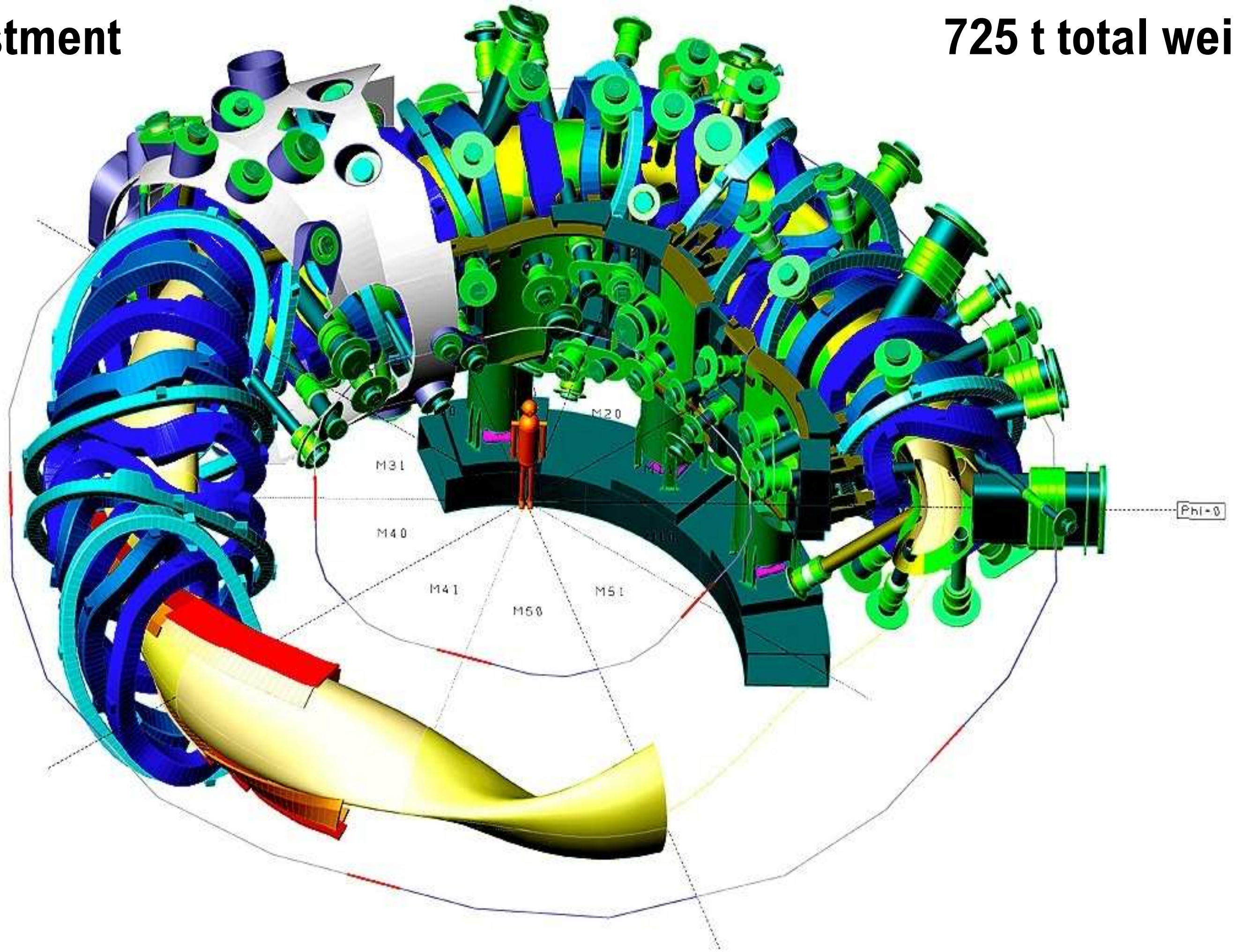
Major radius: 5.5 m
av. Minor radius: 0.53 m
Magnetic field: 3 T, superconducting

EURATOM approval in March 1996,
start of the project: summer 1997,
start of assembly: spring 2005,
start of operation: 2014/5.

WENDELSTEIN 7-X, the engineers version

235 M€ investment

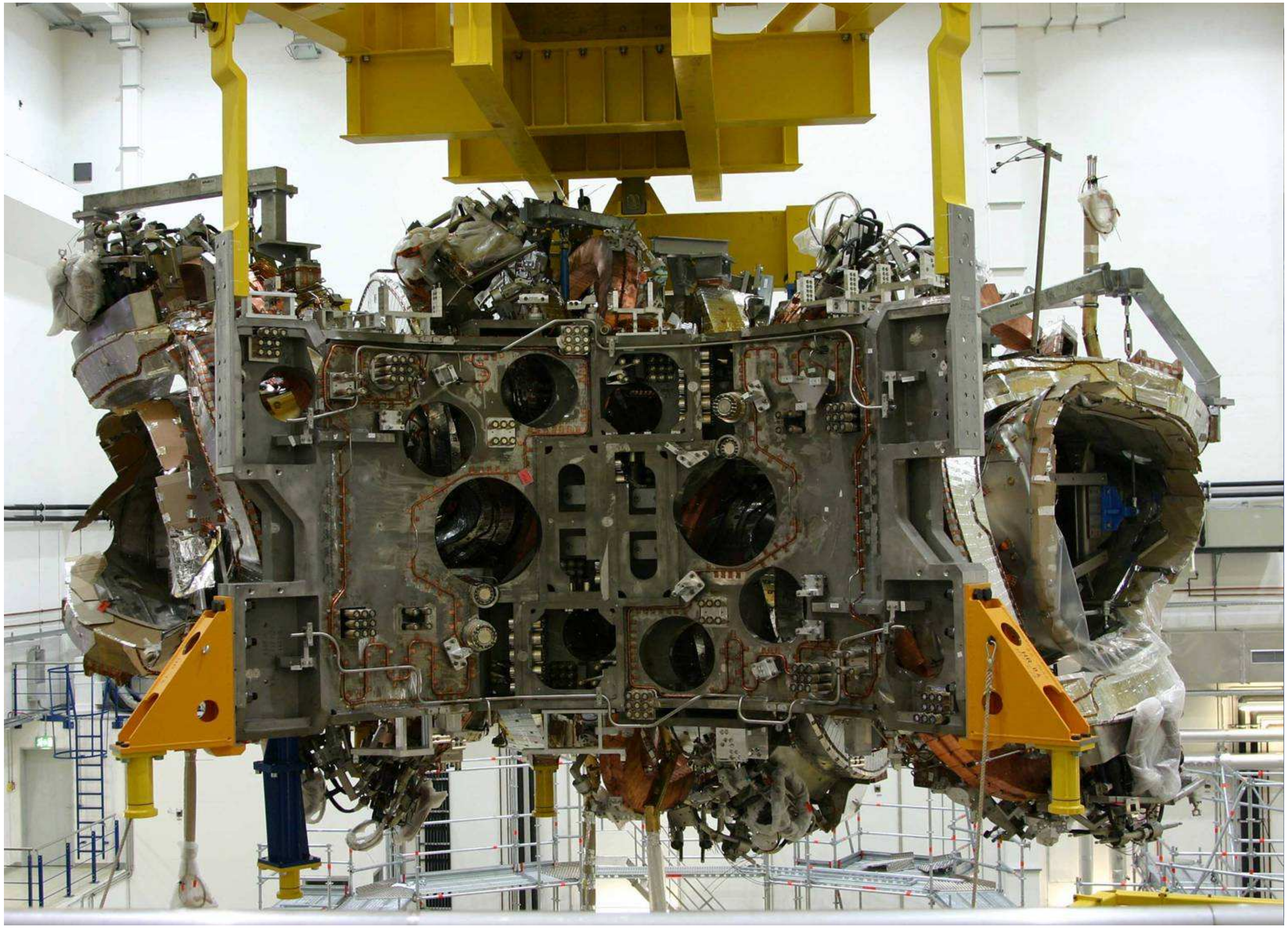
725 t total weight



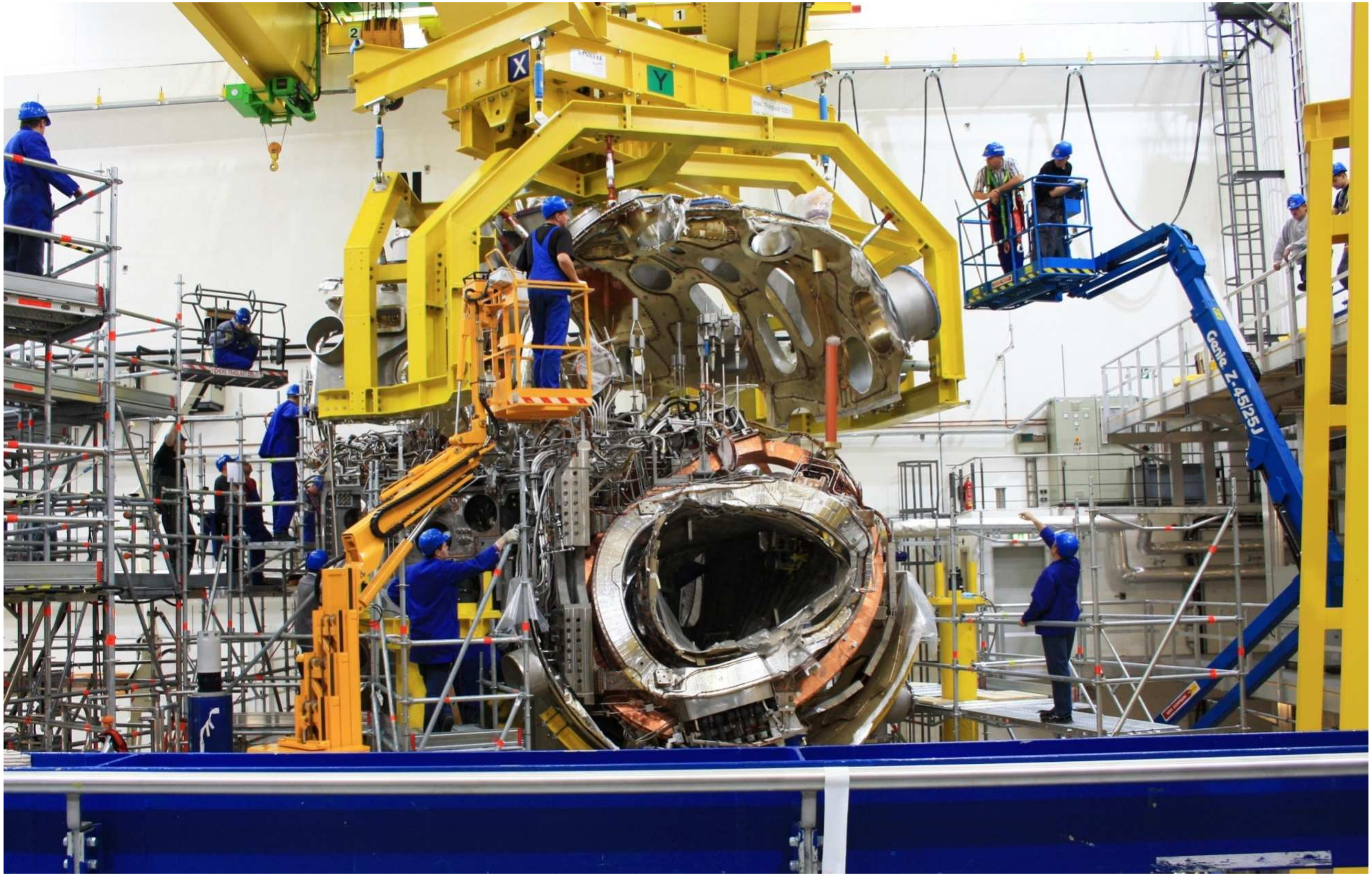
~1m plasma diameter

11m torus diameter

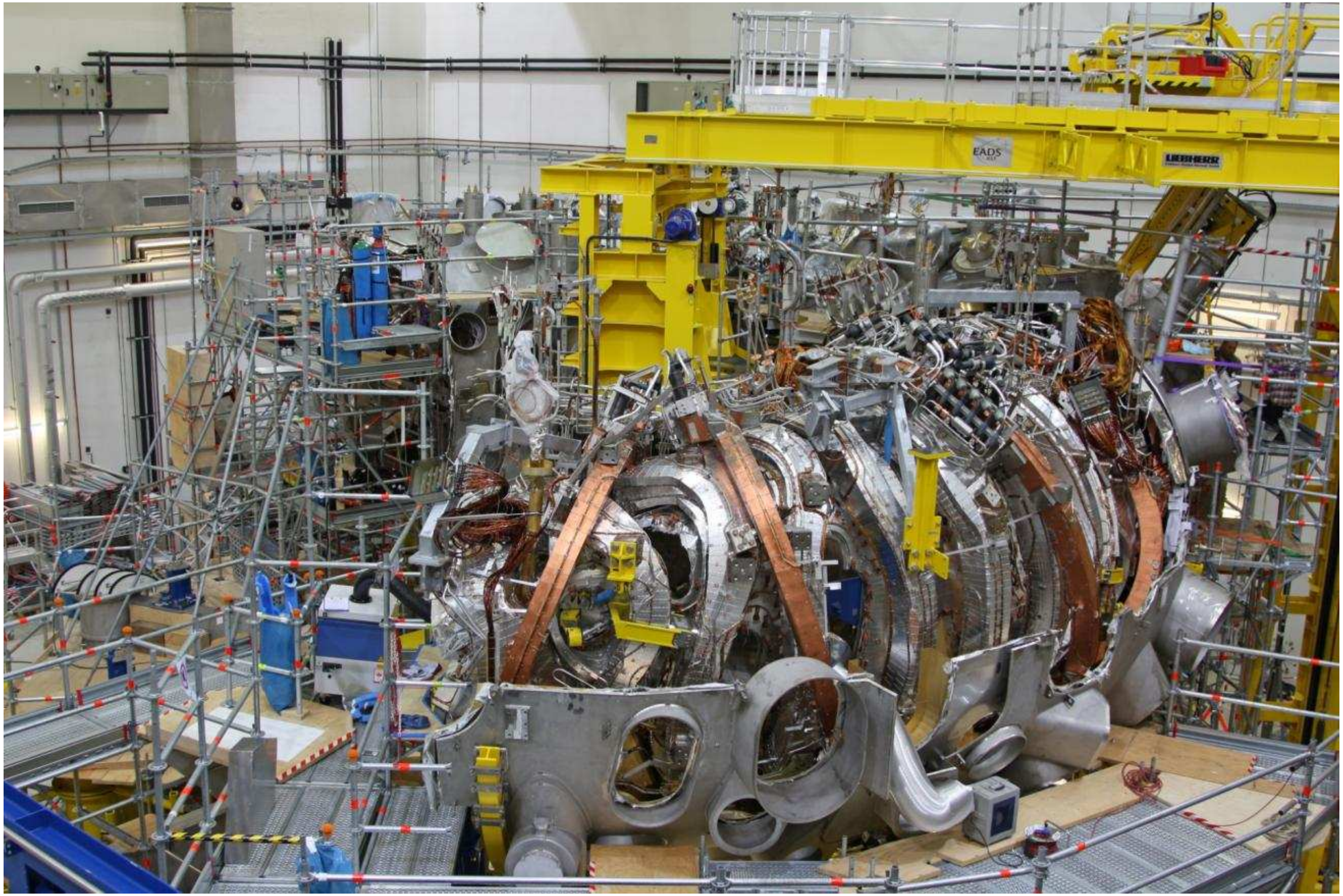
WENDELSTEIN 7-X assembly
first magnet module, August 2008



WENDELSTEIN 7-X assembly
First module in cryostat, November 2009



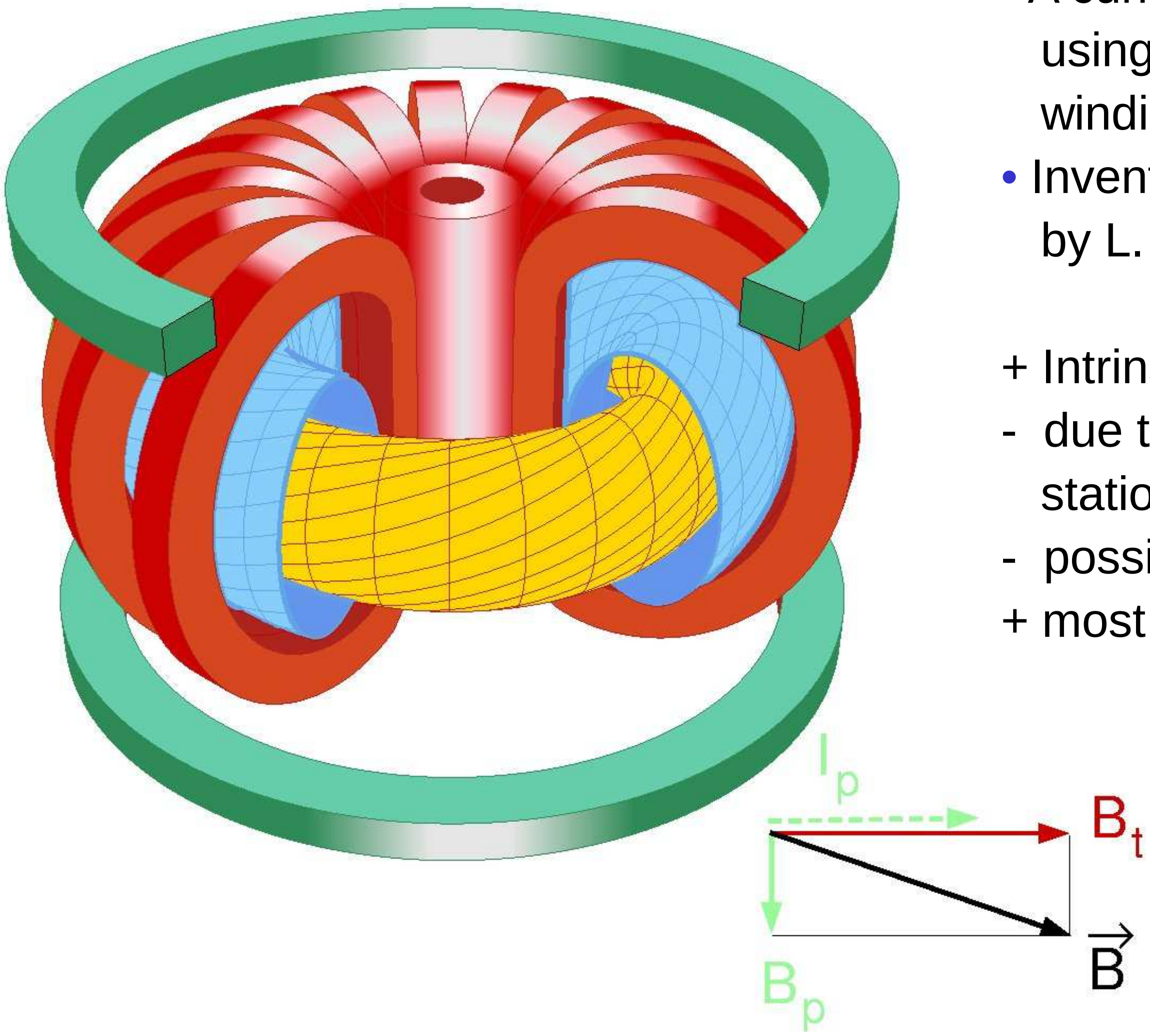
WENDELSTEIN 7-X assembly
Port assembly in 1st module, September 2010



Tokamaks

- A current in the plasma is induced, using the plasma as secondary winding of a transformer.
- Invented in the 50‘s in Moscow, by L. Artsimovich and Sacharov.

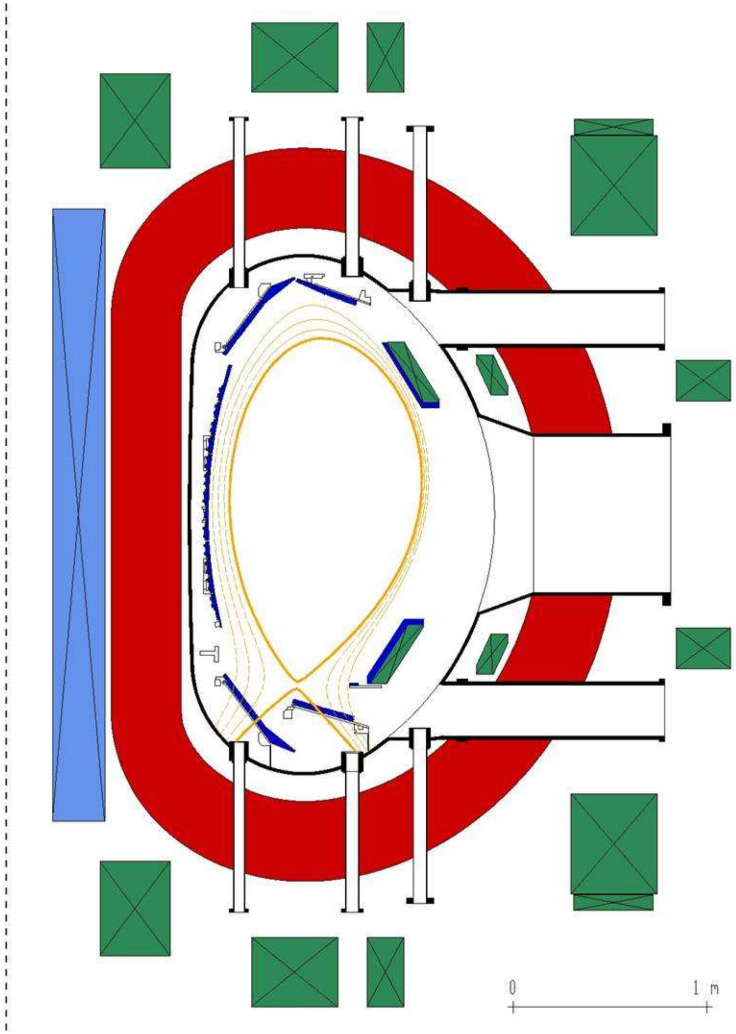
+ Intrinsic heating,
- due to the transformer not stationary ⇒ current drive
- possibility of current disruptions
+ most advanced fusion concept

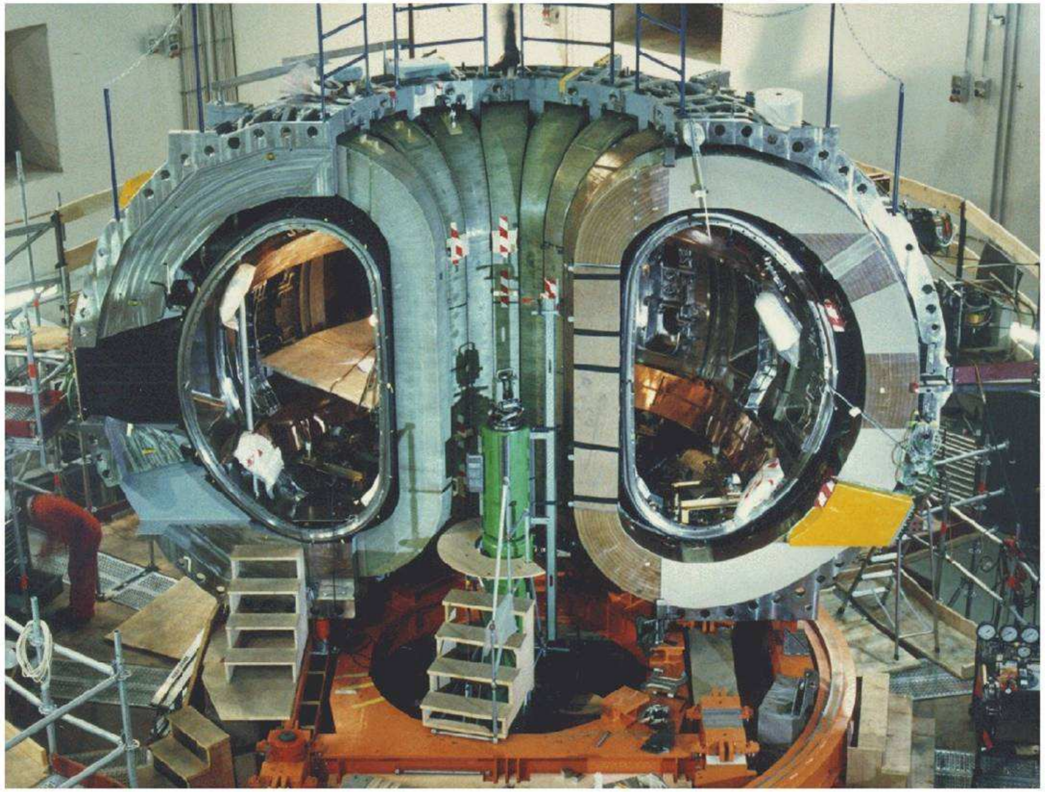


ASDEX Upgrade

R = 1.65 m	a = 0.5 m	κ = 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

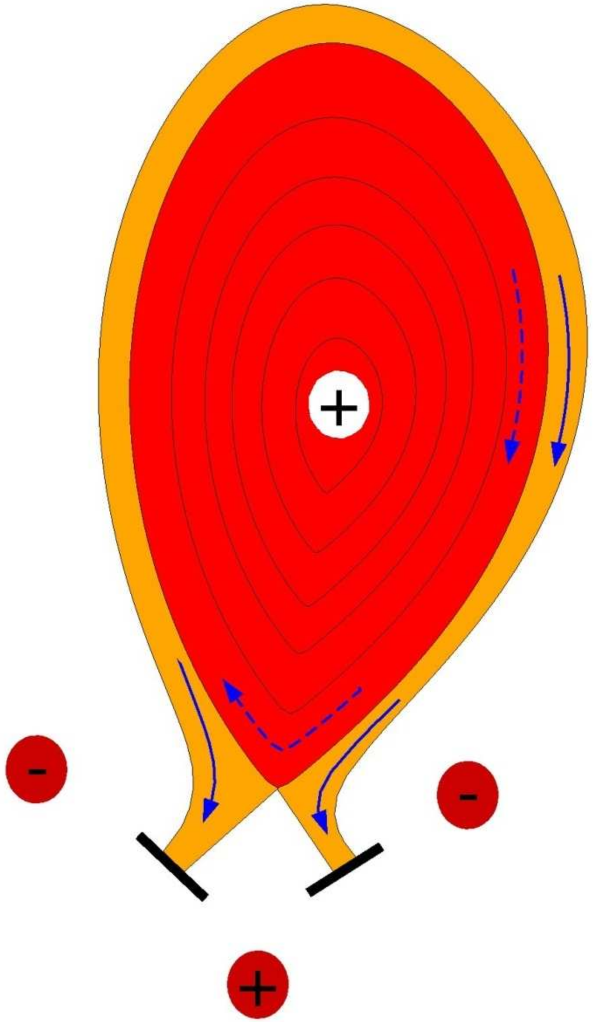
- plasma confinement with nested, closed magnetic surfaces, but
- plasma edge has to be defined either
  - physically by a material limiter, or
  - magnetically by additional poloidal fields, defining a last closed flux surface, the separatrix.

- First successful experiments inASDEX:
  - cleaner plasmas
  - steep edge gradients

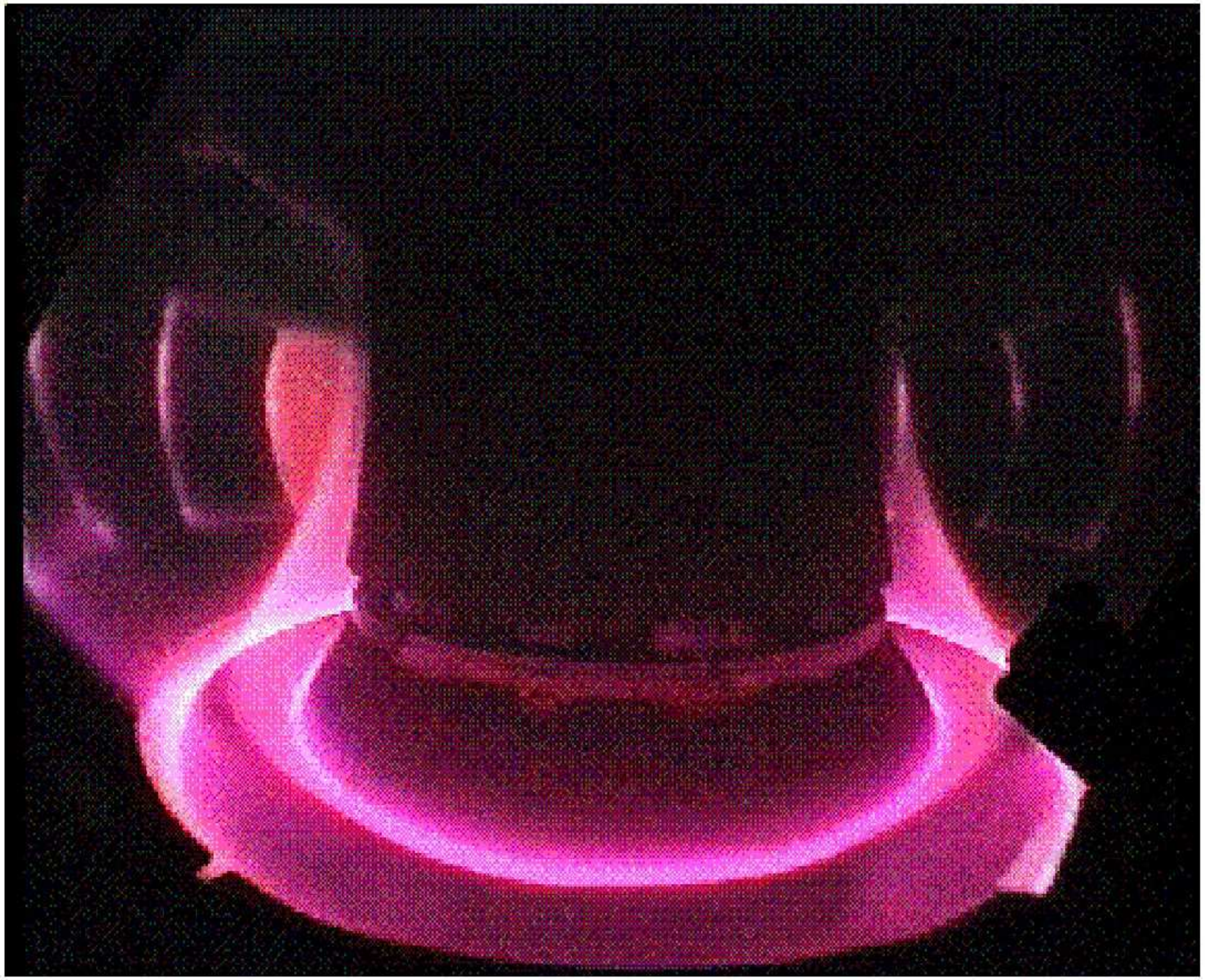
  ⇒ H-mode with improved confinement

- Meanwhile the divertor is a standard for for power and particle exhaust.

- Stellarators have an intrinsic separatrix



ASDEX Upgrade plasma



Plasma interior at some keV, $\Rightarrow$ X-Rays

Outside the separatrix, some eV, $\Rightarrow$ Hα

steep gradients at the separatrix

strong radiation in the divertor

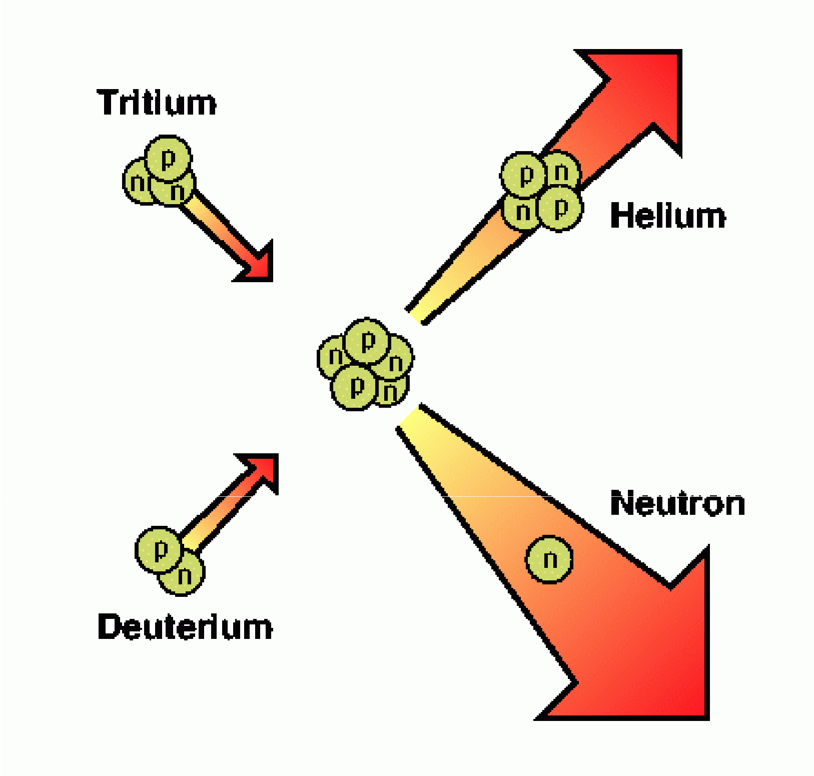
Quantitative criteria

Power balance of a fusion plasma:

Alpha-particle heating balance losses

⇒ criteria for

- T ≈ 100 Mio K = 10 keV



Quantitative criteria

Power balance of a fusion plasma:

Alpha-particle heating balance losses

$\Rightarrow$ criteria for

- T $\approx$ 100 Mio K = 10 keV ✓

- $n \approx 10^{20}$ m^{-3} ✓

- $\tau \approx$ 5-10 s

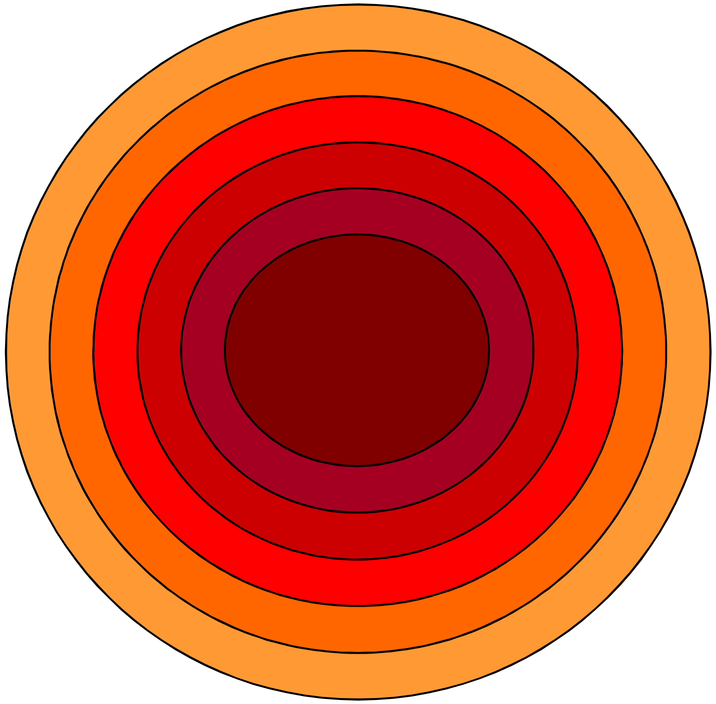
Energy loss in a magnetically confined plasmas

„Classical" picture:

- Energy- and Particletransport
  on magnetic surfaces free

- Transport perpendicular to magnetic
  field only through collisions.

- but losses are about 100 x
  higher than expected!

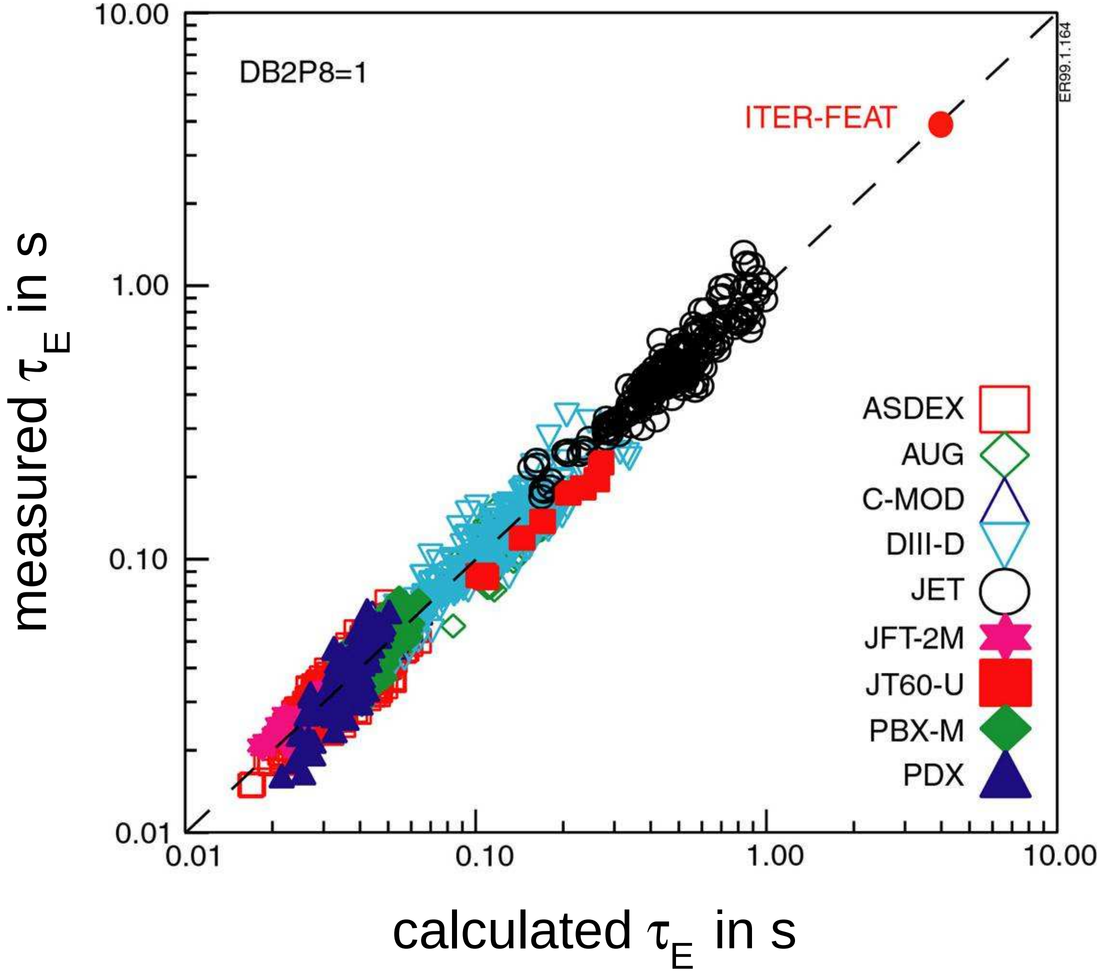


$\Rightarrow$ 1. Larger experiments (longer isolation path)

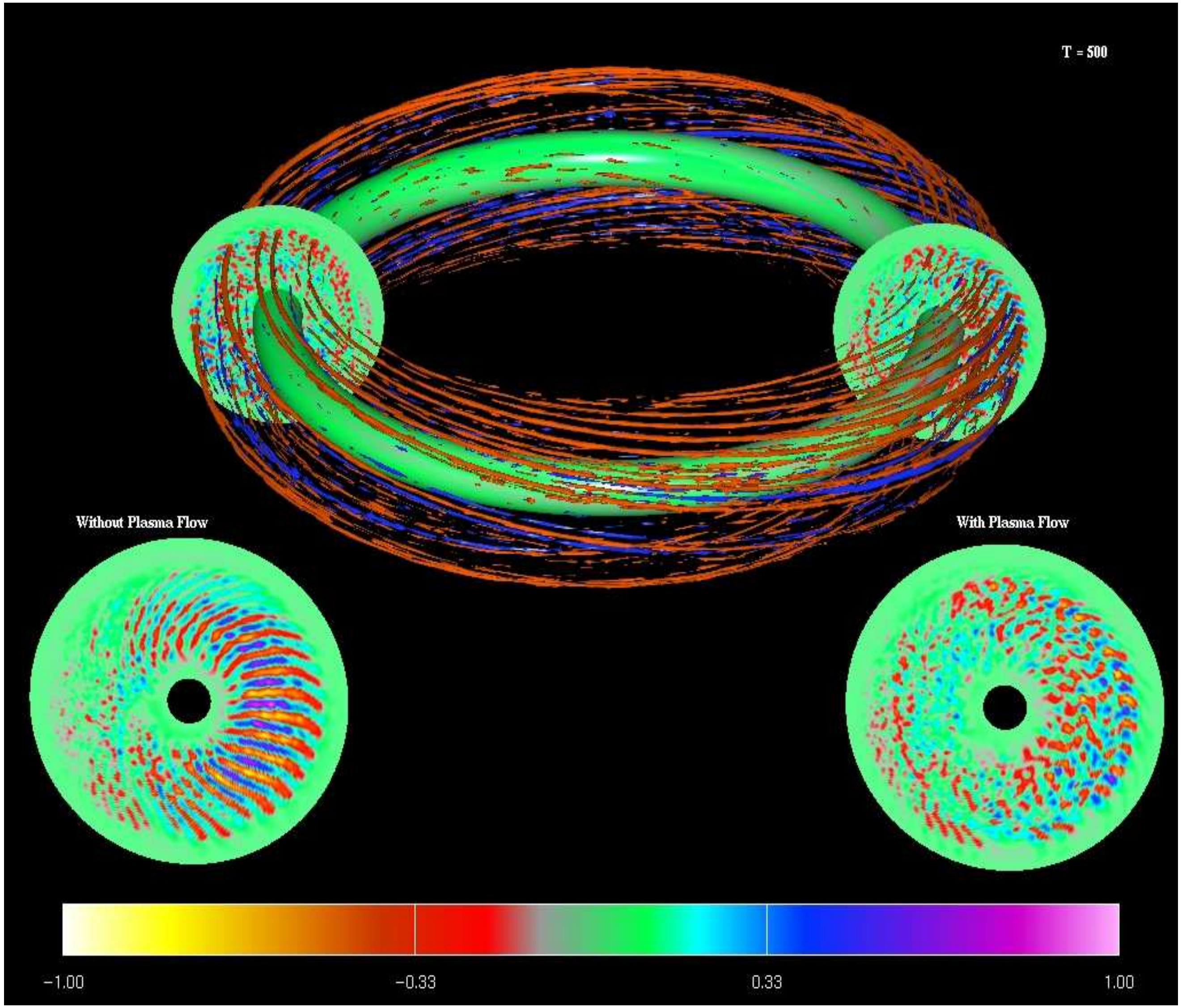
2. "Intelligent experiments" (understand problems and modify)

Empirical scaling of energy confinement

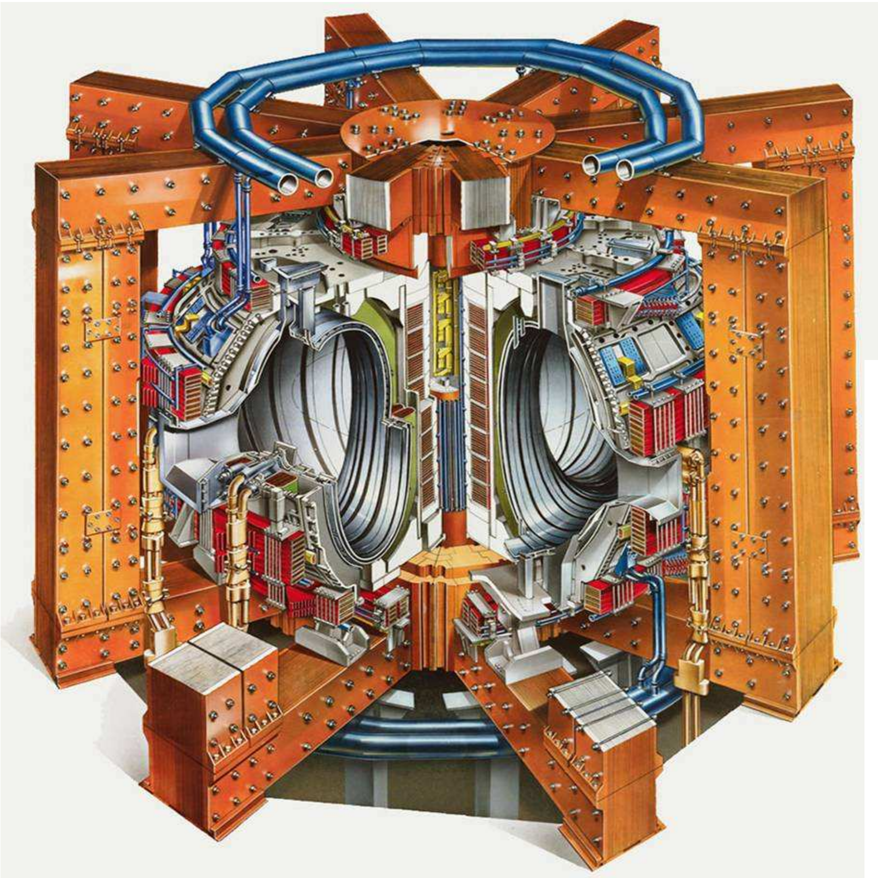
Scaling of experimental data: $\tau_E \propto R^3 \cdot B_t / P_{Heiz}^{0.65}$



Turbulence-dominated energy loss



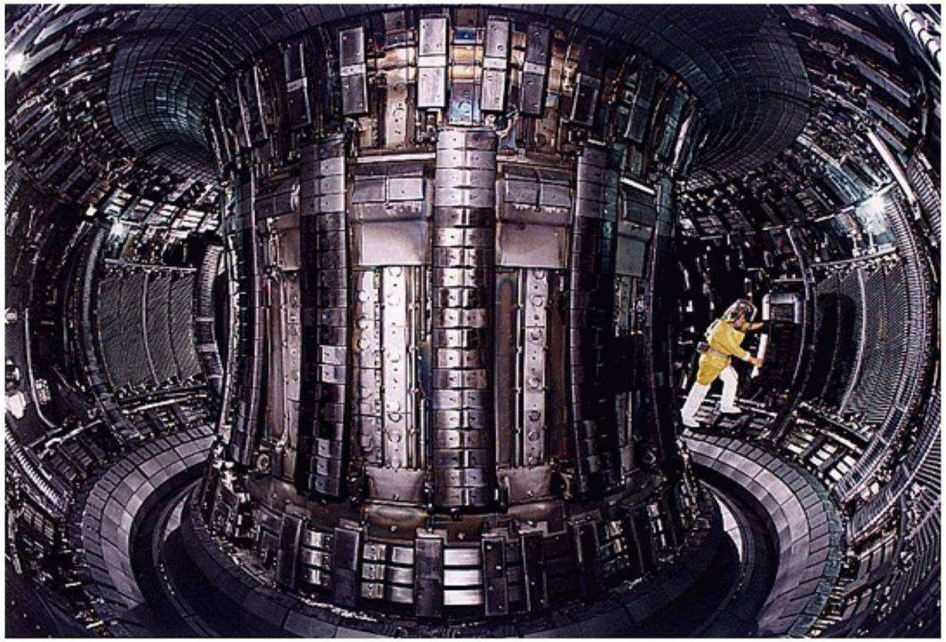
Joint European Undertaking



$R = 2.95$ 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

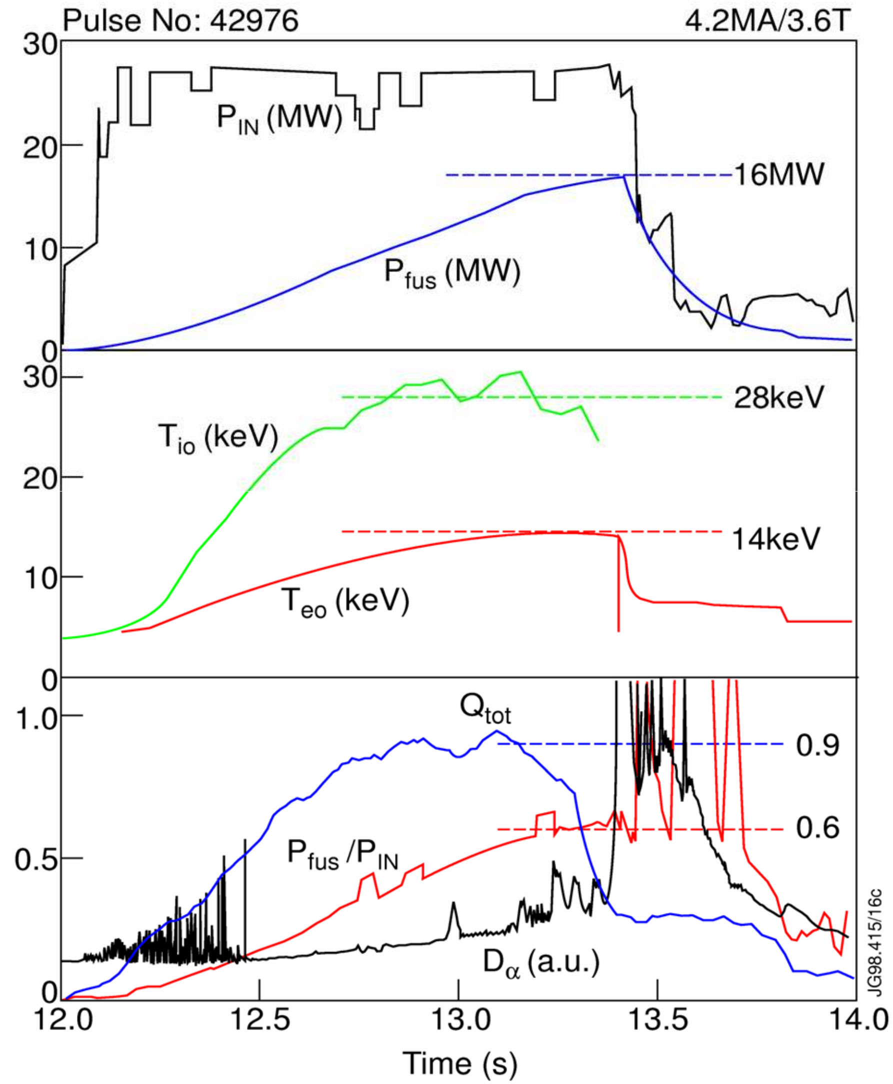
JET DT-Experiments

DT-Experiments only in
- JET
- TFTR, Princeton

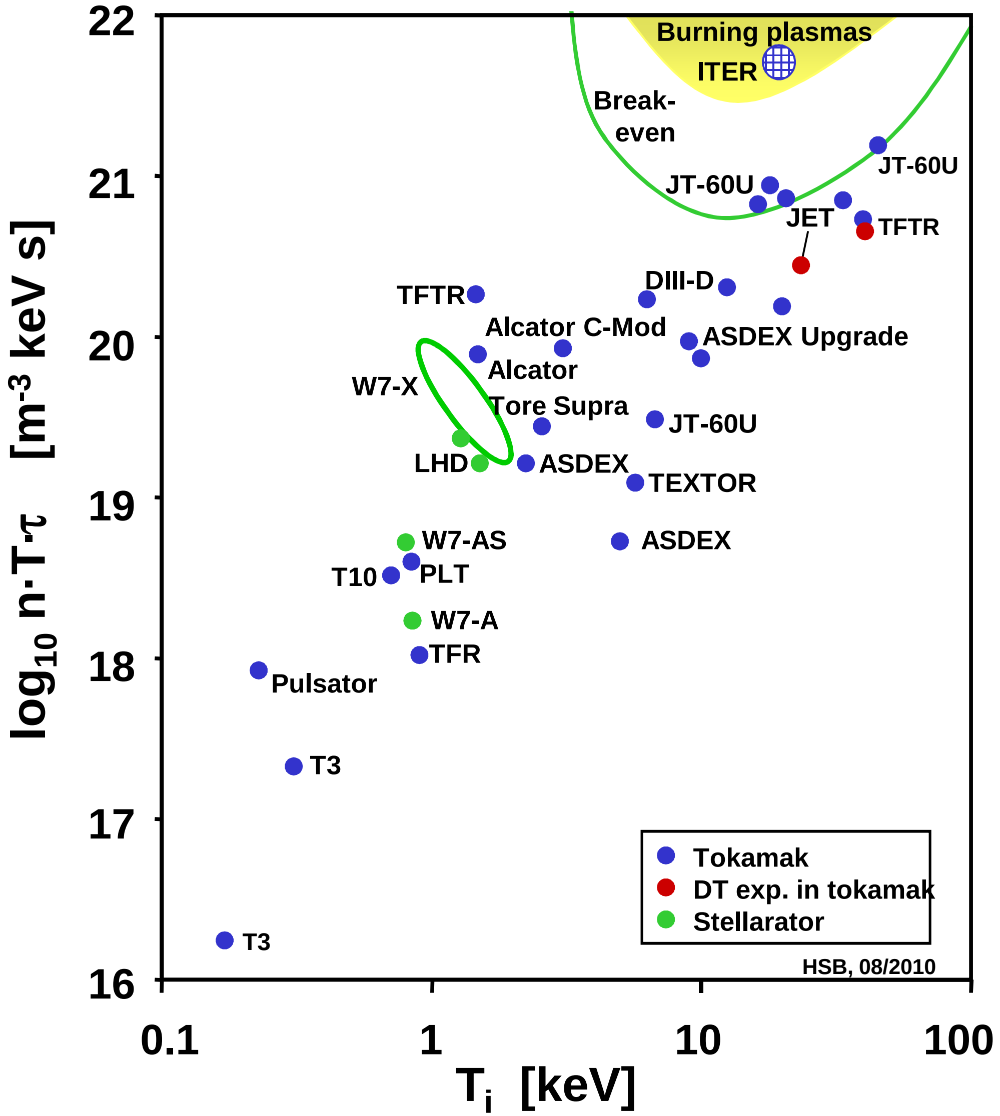
with world records in JET:

P_{fusion} = 16 MW

Q = 0.65

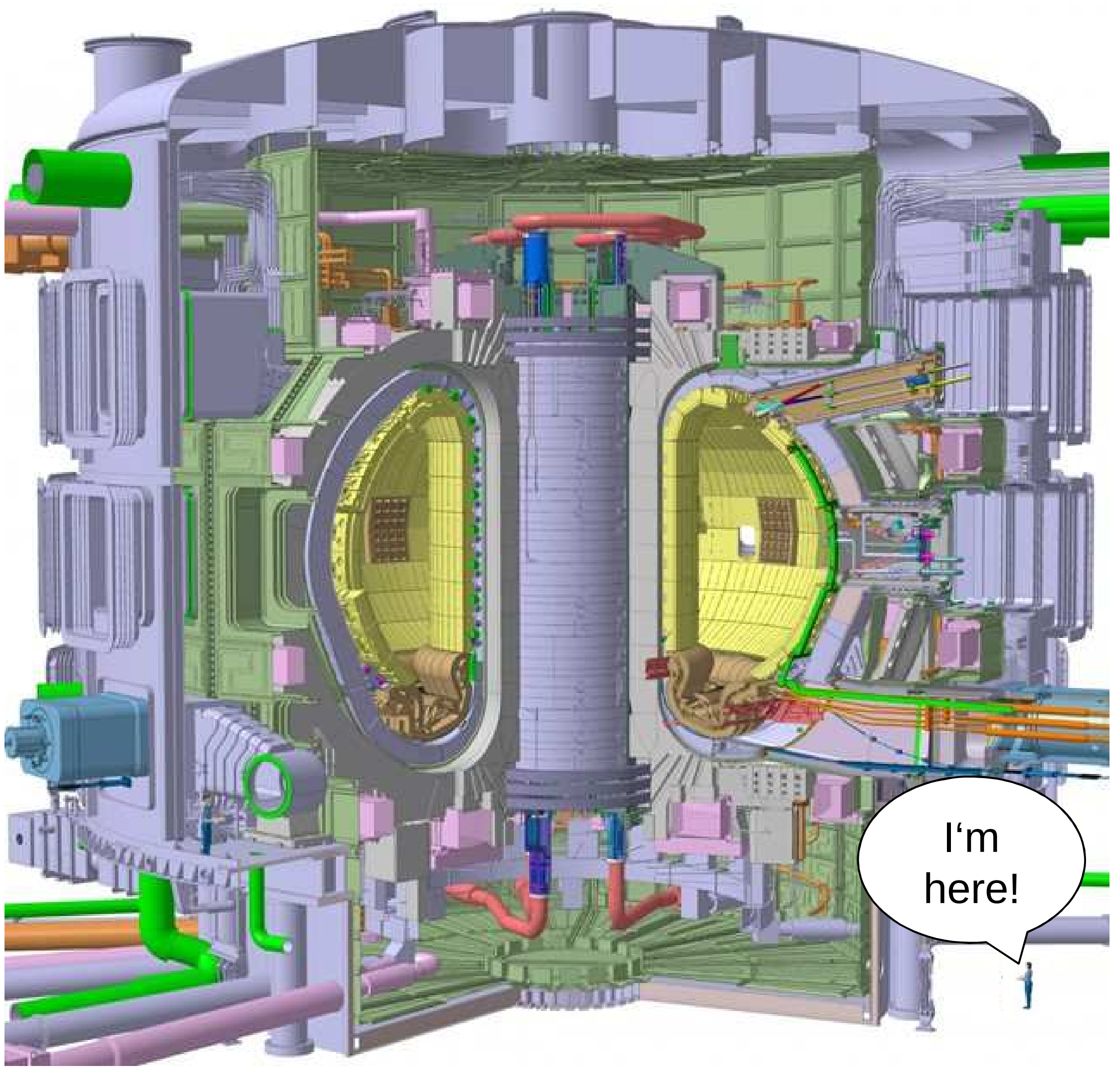


Status of Fusion Research



- 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

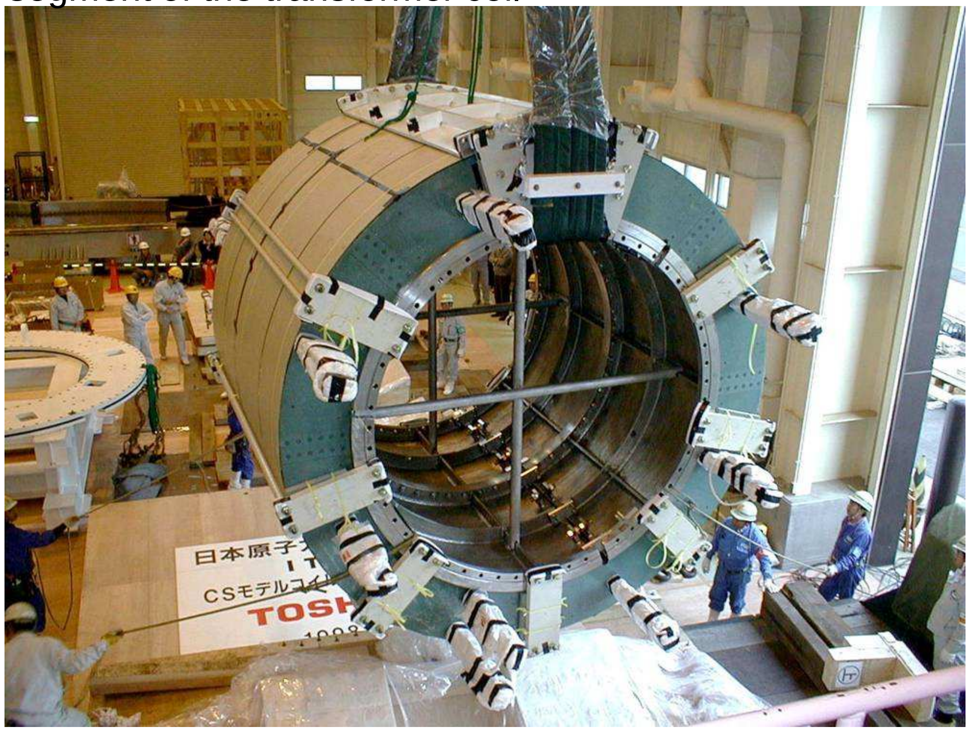
24.10.2007 : official start of the ITER project

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 we get started

ITER
… finally we get started

Schematic fusion reactor

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