Max-Planck-Institut für Plasmaphysik

Nuclear Fusion

Research for the energy of the future

IPP Greifswald

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Overview

- Max-Planck-Institut für Plasmaphysik (IPP)
- why do we need nuclear fusion?
- physical basics of nuclear fusion
- what is a plasma?
- the path to fusion: Tokamaks and Stellarators
- fusion experiment Wendelstein 7-X
- ITER and the path to a power plant

The Max-Planck-Institut für Plasmaphysik (IPP)

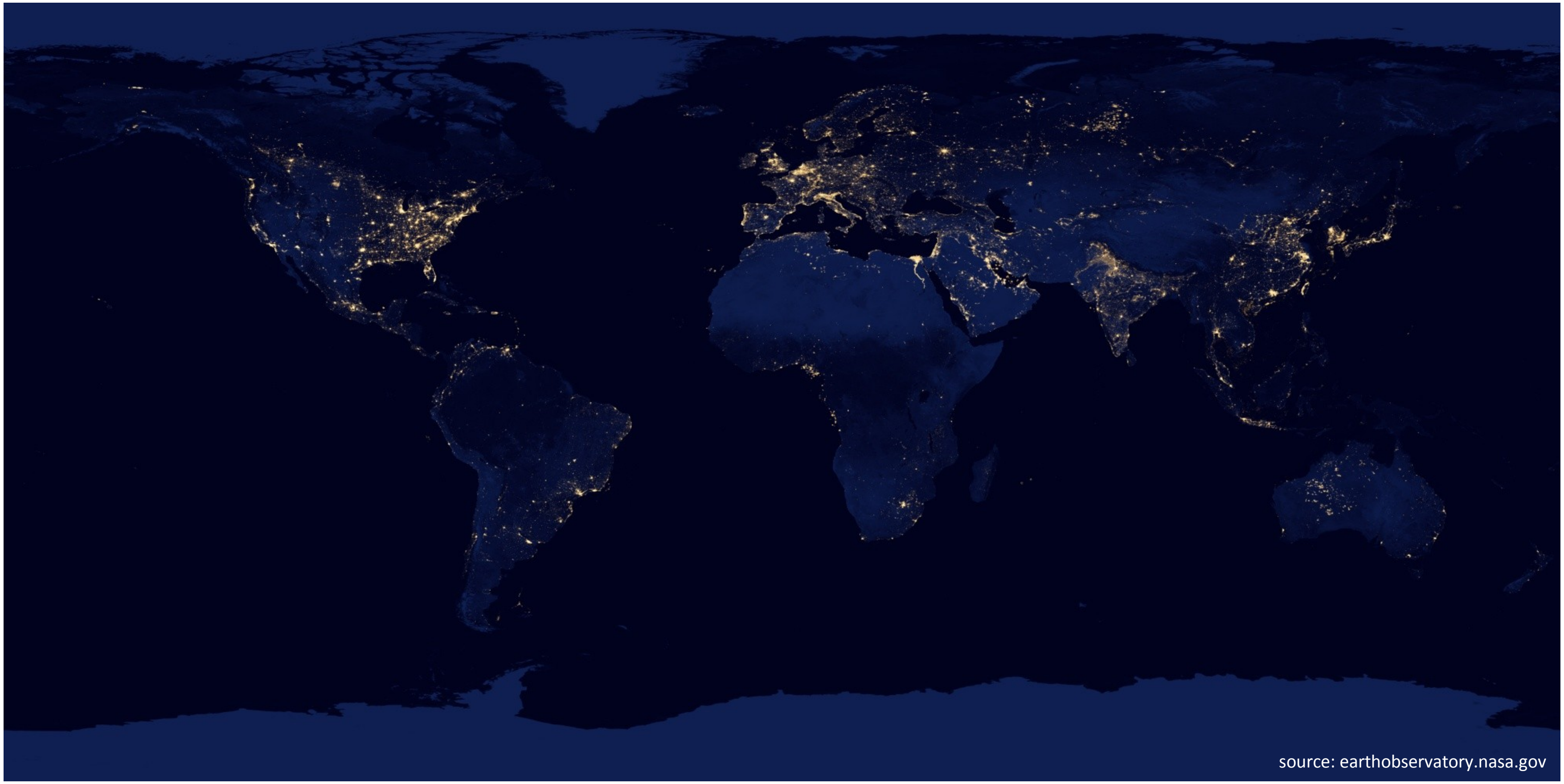
- institute of the Max-Planck-Gesellschaft (MPG)
- national research laboratory (Helmholtz-Gemeinschaft)
- located in Garching and Greifswald
- 1994: foundation of the Greifswald branch
- 2000: completion of building
- Staff: approximately 450 people
- construction and operation of the fusion experiment W7-X (one of Germany’s biggest research projects)
- 10.12.2015: first plasma

Mission of the IPP

Experimental and theoretical basic research for utilising controlled nuclear fusion based on magnetic confinement for the production of energy

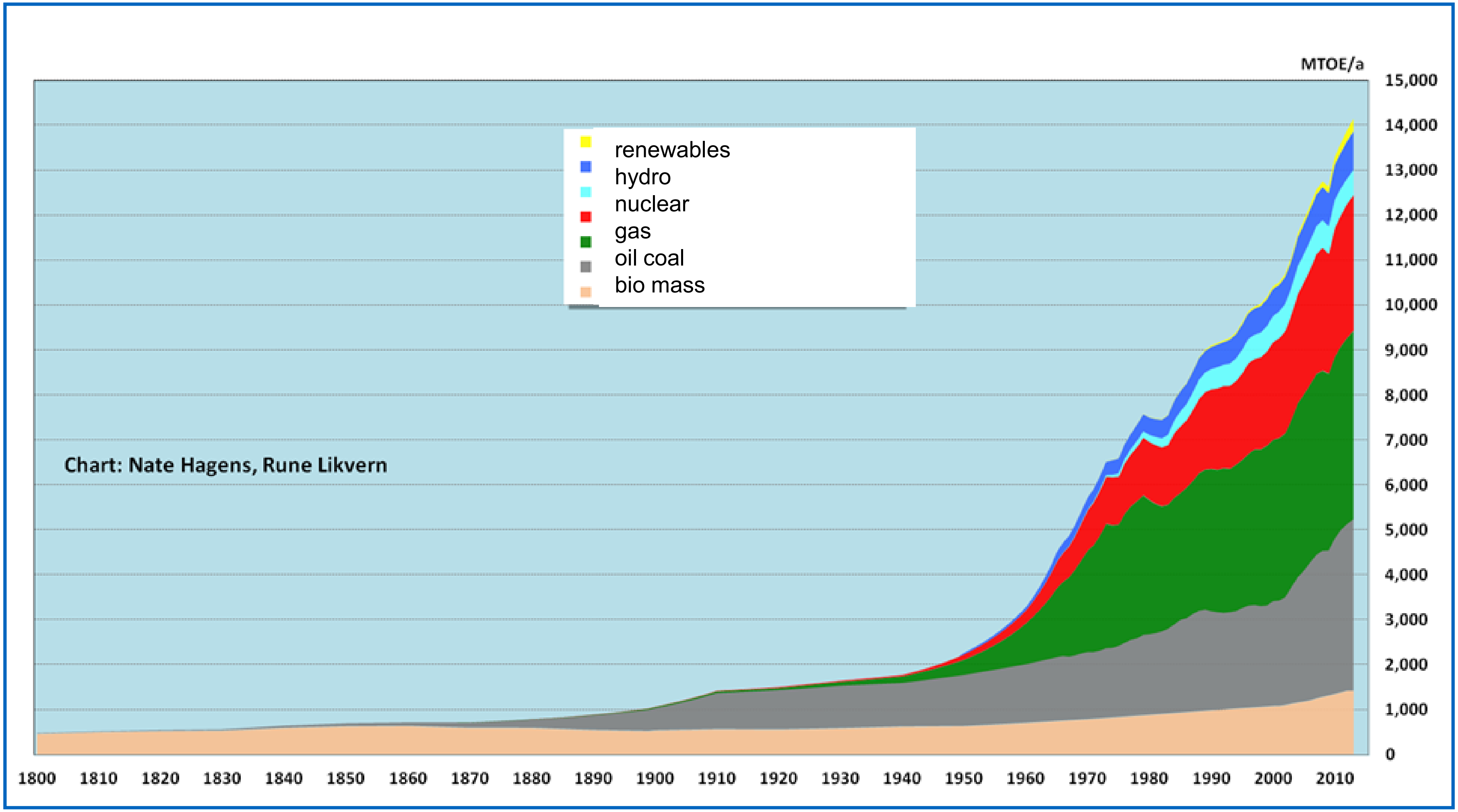
- design, construction and operation of fusion experiments (ASDEX-Upgrade, Wendelstein 7-X)
- development of diagnostic methods
- obtaining data relevant for fusion
- theoretical research in plasma physics
- numerical modelling of fusion plasmas
- research of materials and technology
- contributions to the first fusion reactor (ITER)

WHY DO WE NEED NEW SOURCES OF ENERGY?



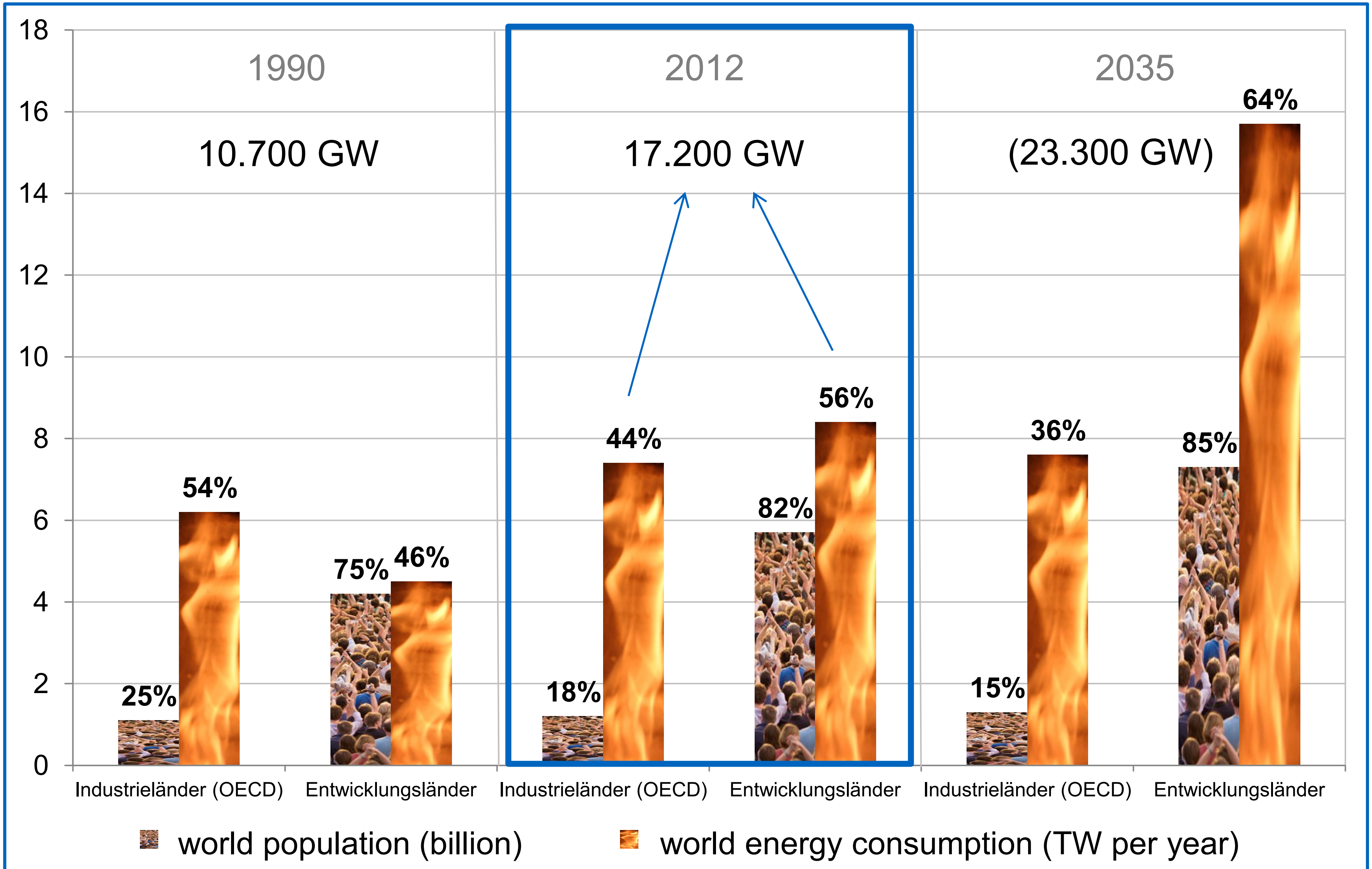
World Primary Energy Consumption 1860-2010

Electricity consumption ≈ 1/6 of primary energy consumption



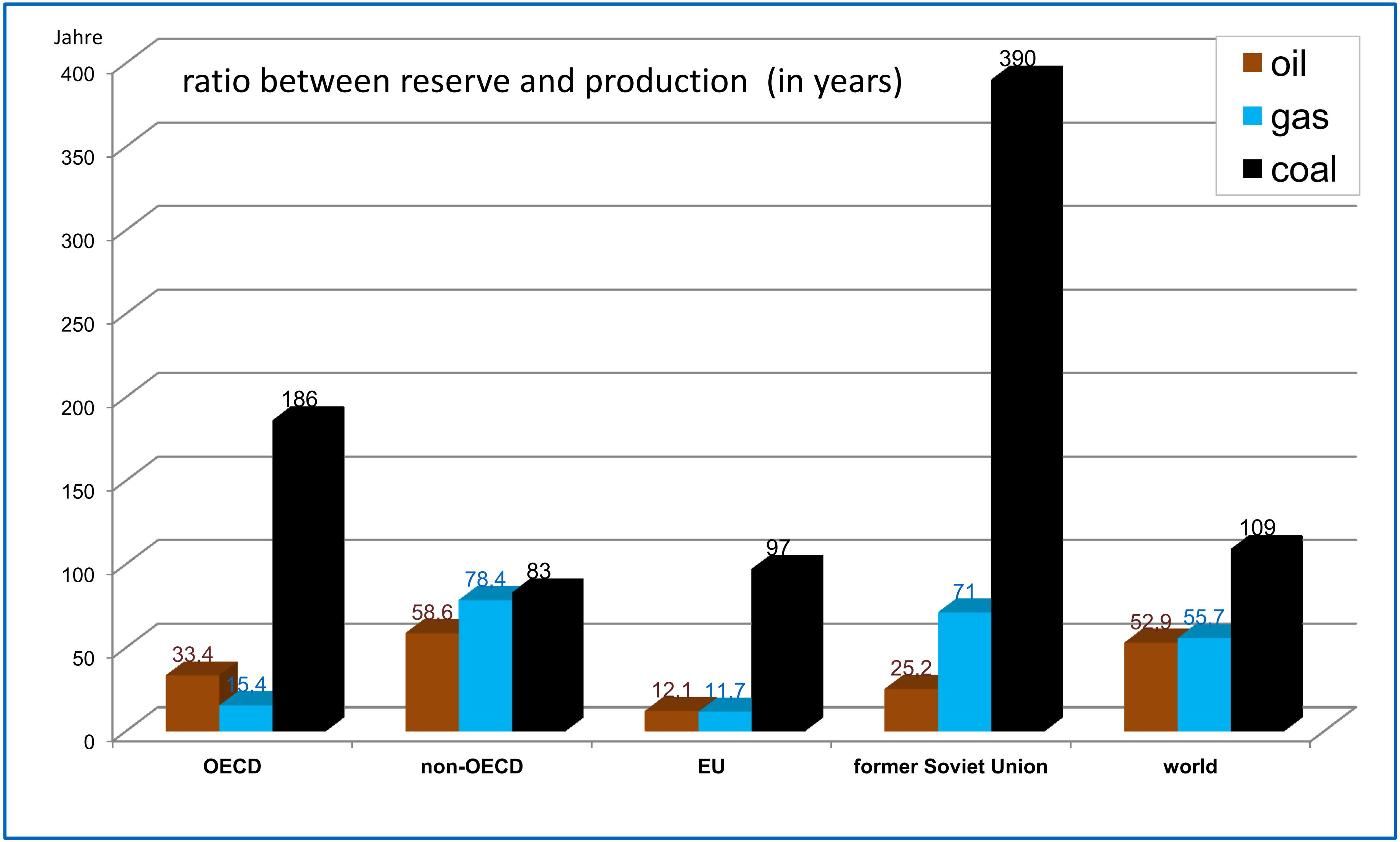
source: Nate Hagens, Rune Likvern

Energy Consumption and World Population



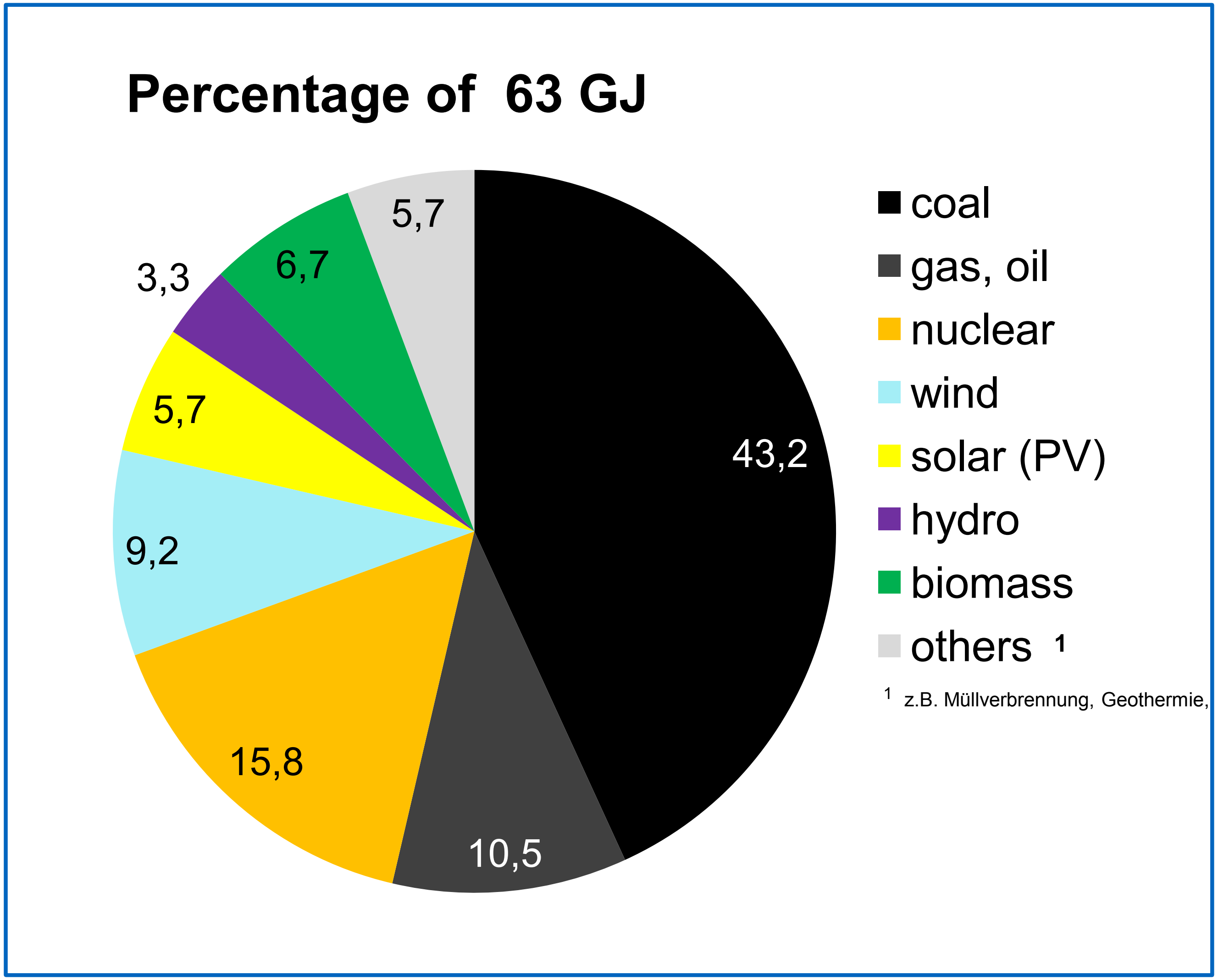
source: BP Energy Outlook 2035, January 2014; UN World Population Prospects, 2010 Revision; A. Kleiber 2014

Availability of Fossile Energy Resources



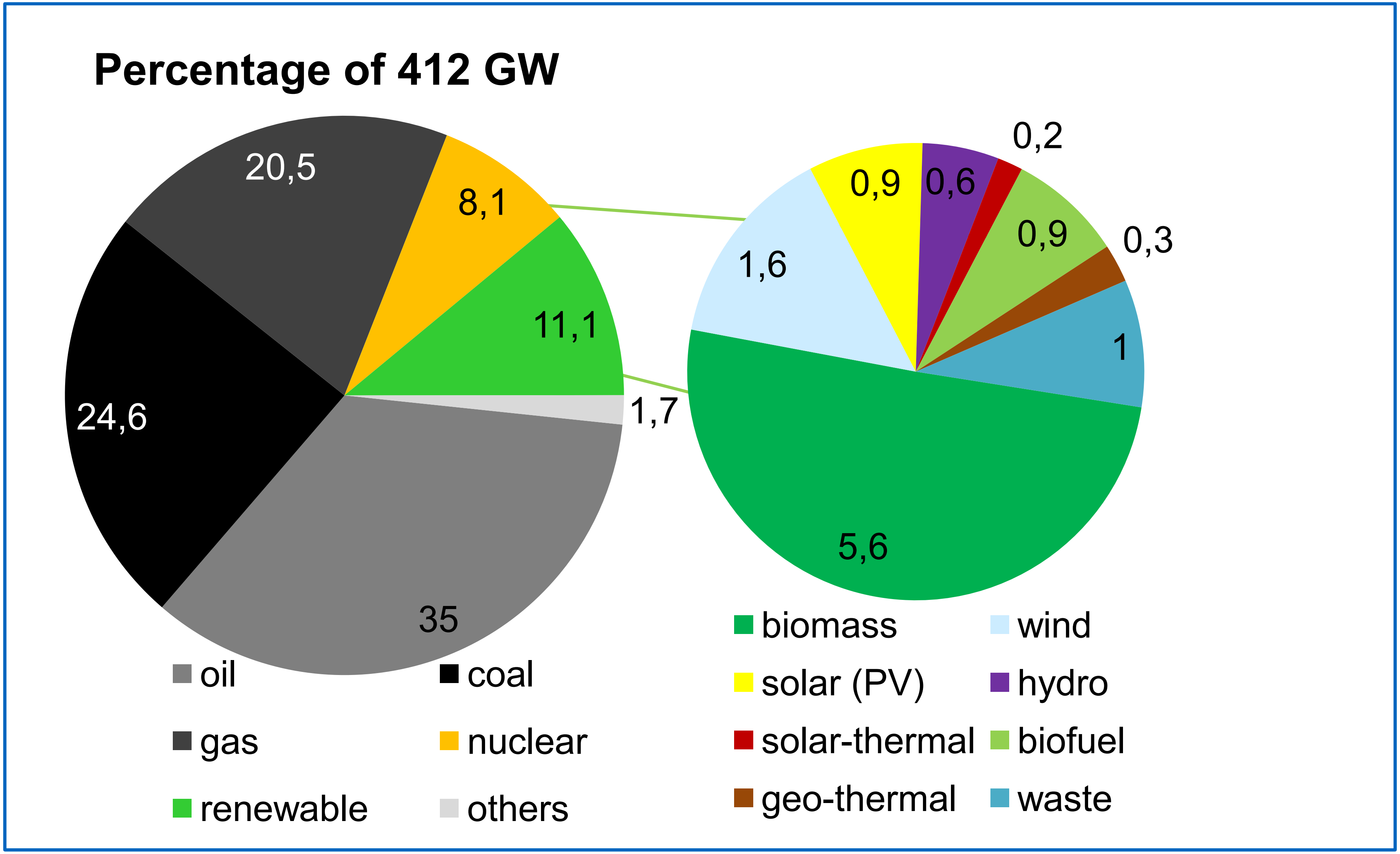
Reserve-zu-Produktions-Verhältnis (R/P) für die fossilen Energieträger Öl, Gas und Kohle Ende 2012; source: BP Statistical Review of World Energy June 2013, A. Kleiber 2014

German Electricity Production 2014



Quelle: AGEB 2015, A. Kleiber 2016

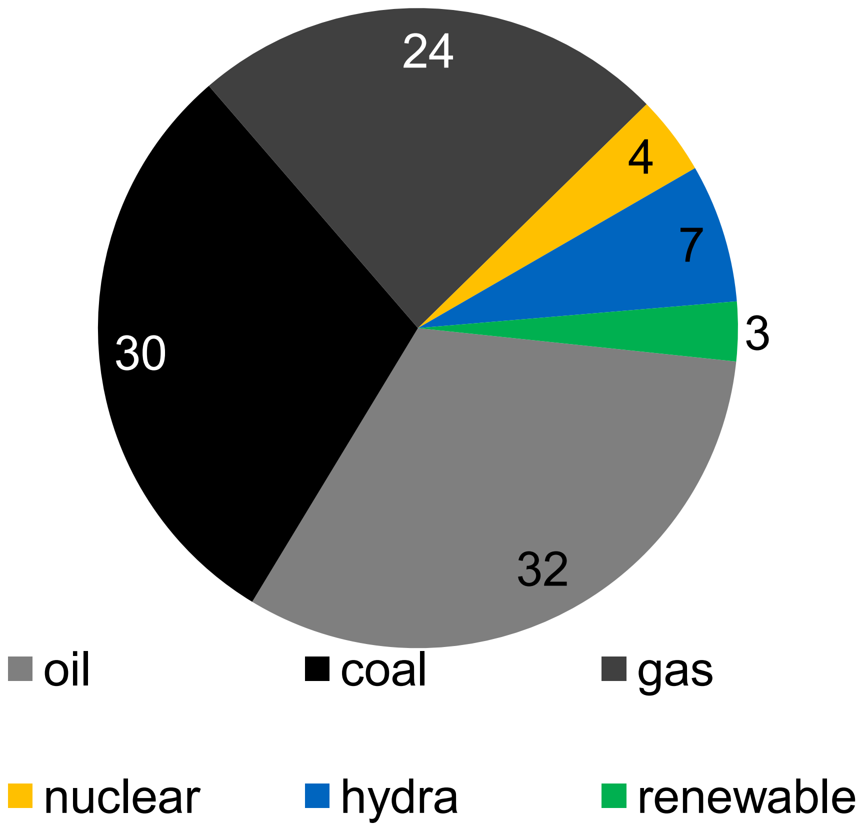
German Primary Energy Consumption 2014



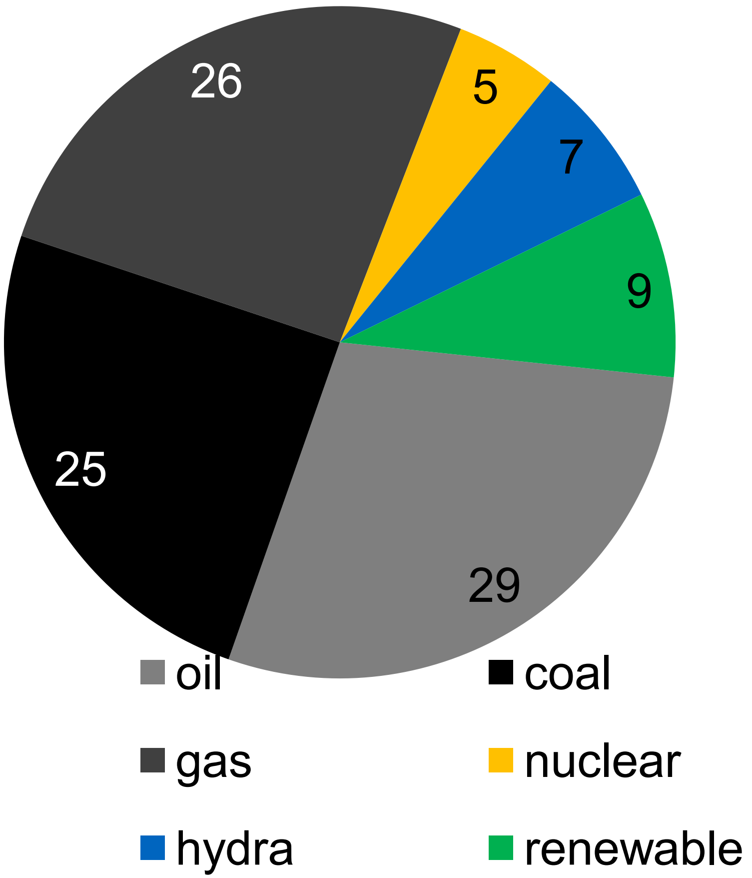
Quelle: AGEB 2015, A. Kleiber 2016

World Energy Consumption

2014: Percentage of 17 200 GW

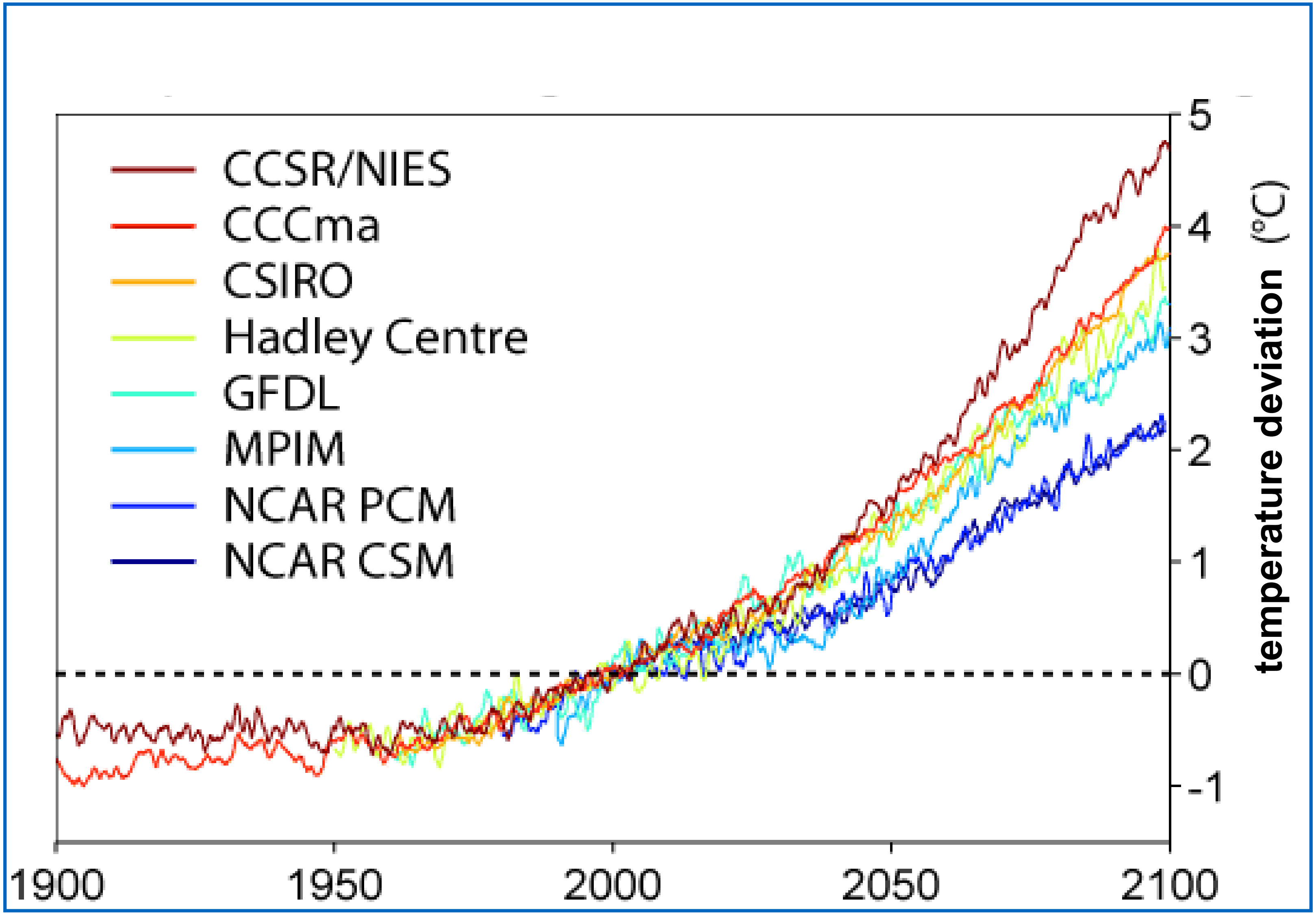


2035: Percentage of 23 000 GW



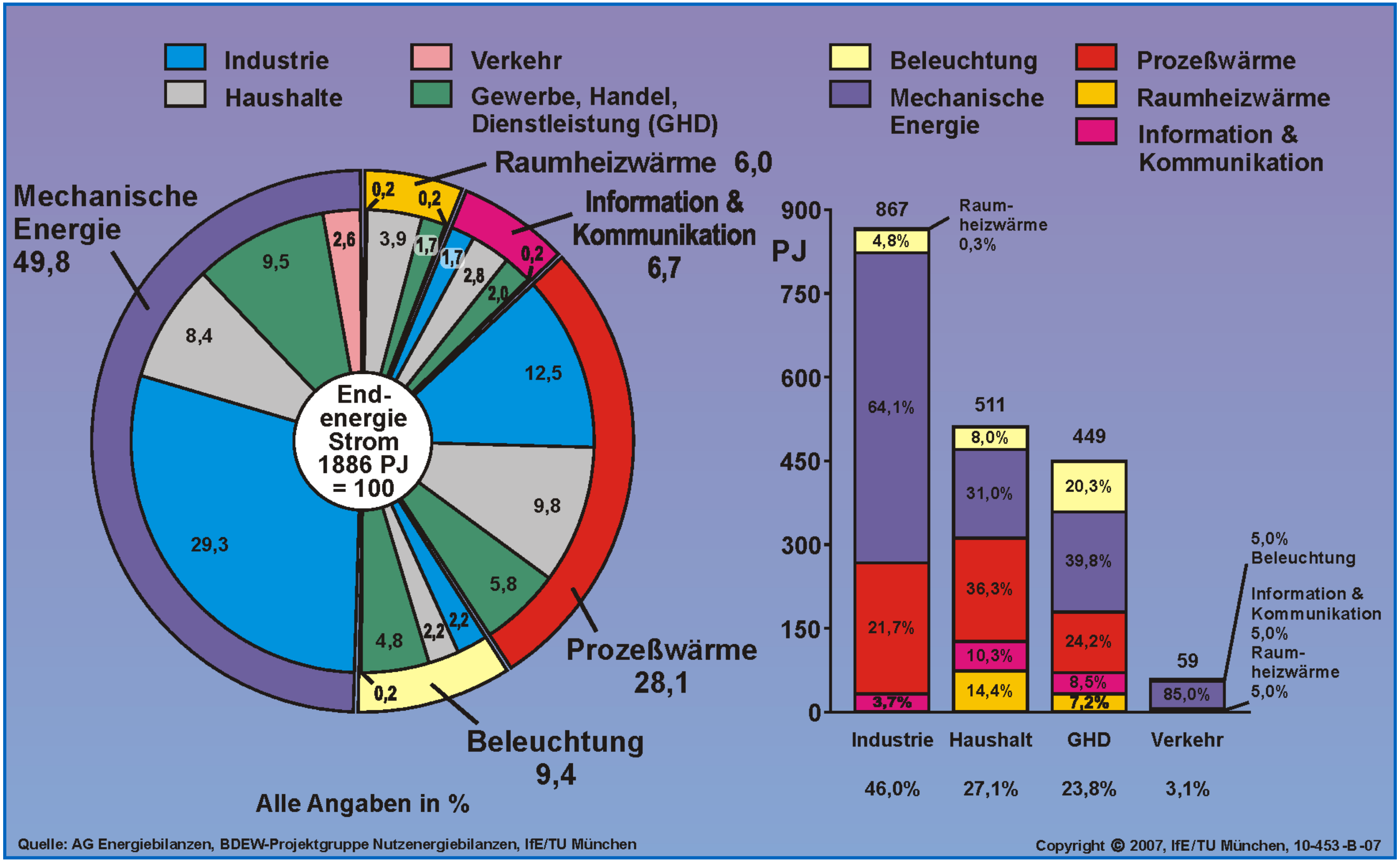
Quelle: BP Energy Outlook 2035, Feb. 2016, A. Kleiber 2016

Predictions of Global Warming due to CO_2-Emissions



sources: de.wikipedia „Globale Erwärmung“

Electricity Consumption in Germany



source: IfE/TU München 10-453-B-07, 2007

Future Energy Production

Challenges:

- rising energy consumption
- secure energy supply
- limitations of fossile energy (possible substitute?)
- curbing of global warming (CO_2-reduction)

Strategy for minimising risk:

- parallel development of different concepts as part of a future energy supply concept

  (solar, wind, storage of energy, nuclear fusion, …)⇧

Energy Sources Compared

Example: Berlin

- population: 3,5 million
- area: 900 km^2
- electricity demand (2010): 1,5 GW

  (10 GW total primary energy)

- wind power (2 W/m^2): 80 % city area
- solar power (15 W/m^2): 10 % city area
- anthracite: 5 Mt (4 Olympia stadia)
- nuclear fission: 260 t natural Uranium (14 m^3)
- nuclear fusion: 0,6 t Deuterium (D) and Tritium (T)

fusion: electricity demand of a family for one year (3000 kWh) covered by 0,08 g D and 0,2 g ^{6}Li.

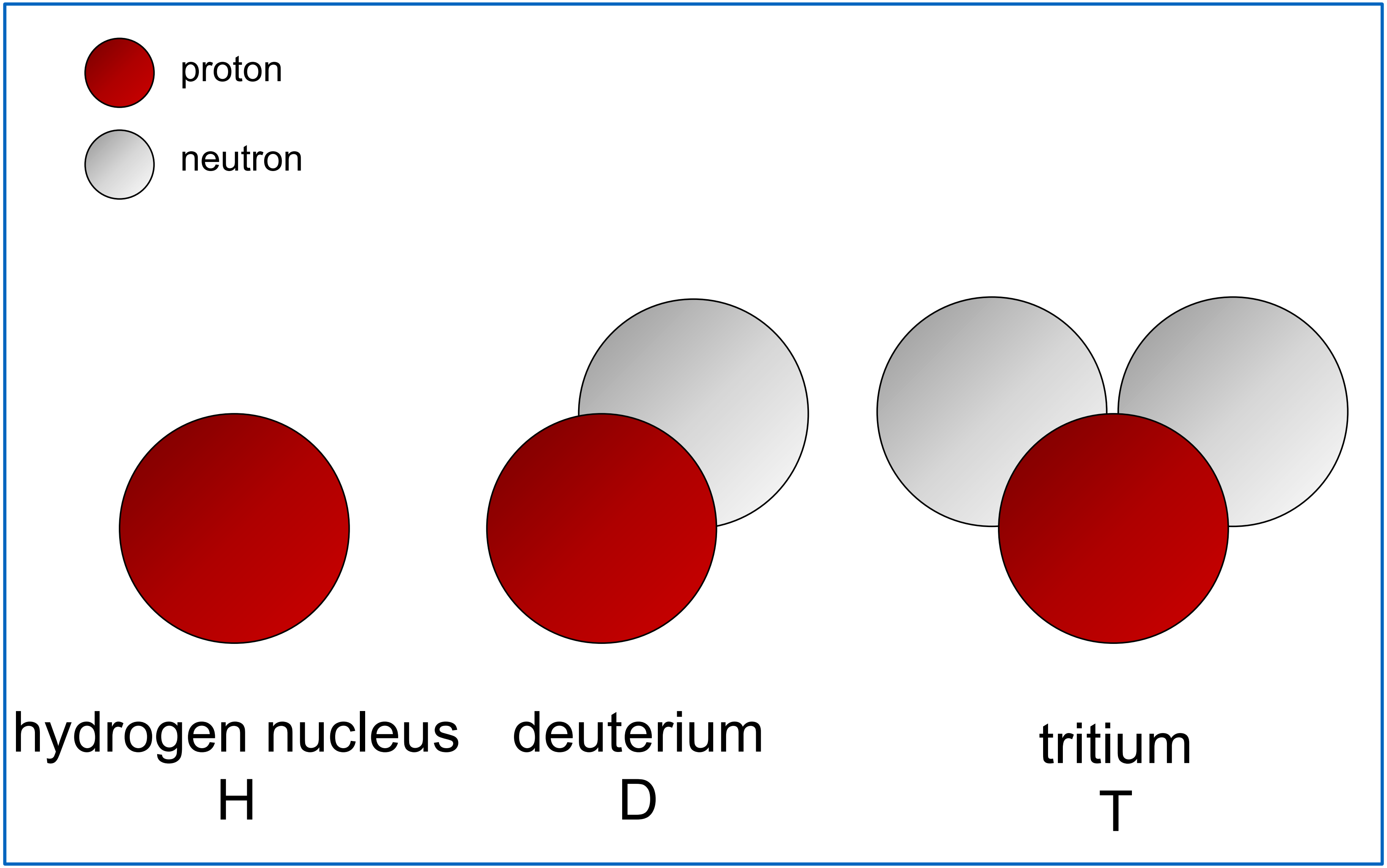
source: M. Borchardt 2014

D in 4,5 l water and Lithium (^{6}Li) in an old laptop battery can supply a family with electricity for 3 years.

PHYSICAL BASICS

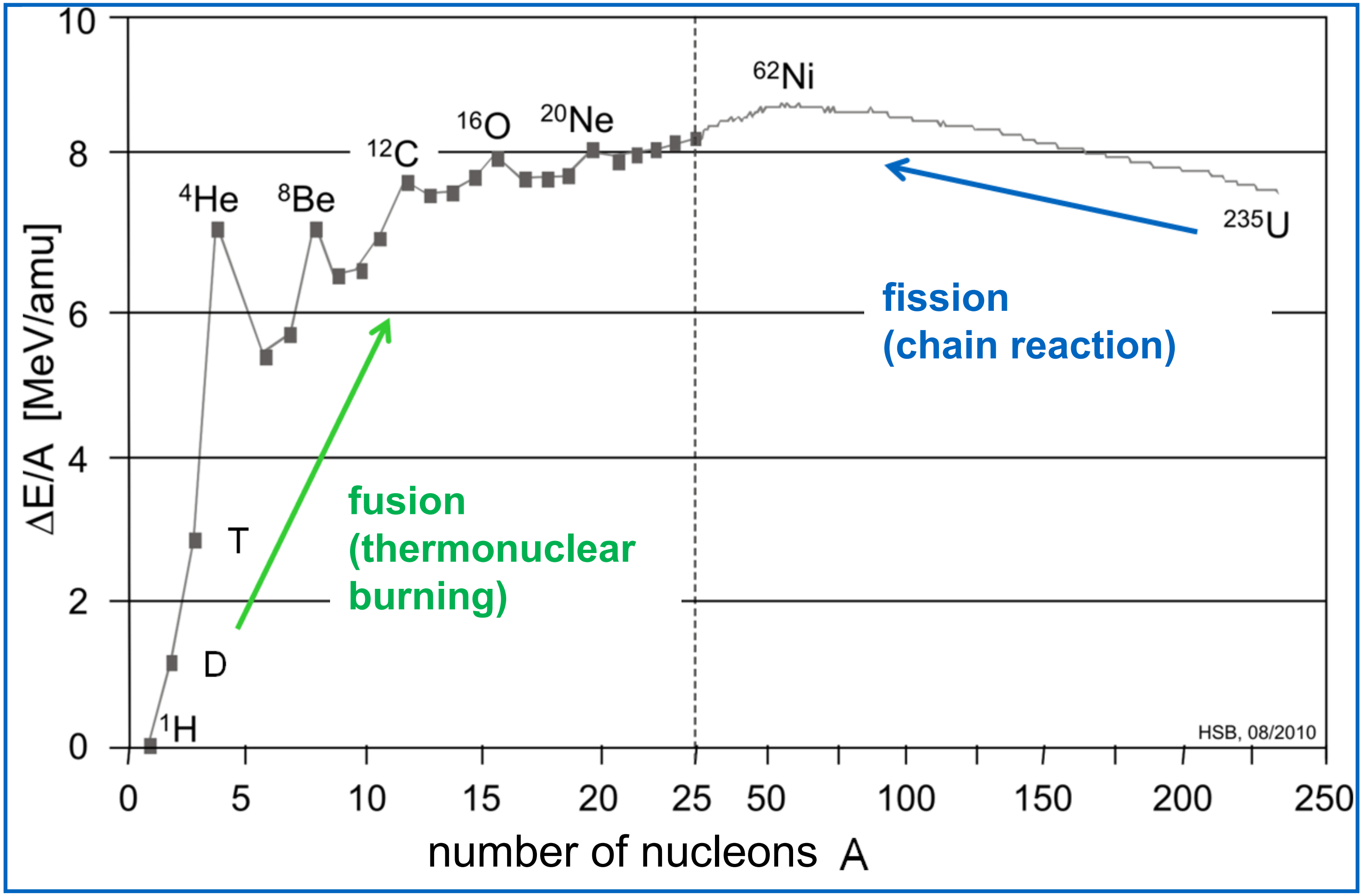
$$
\begin{aligned}
\nabla \vec{E} &= \frac{1}{\varepsilon_0} \varrho \\
\nabla \times \vec{B} &= \mu_0 \vec{j} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \\
\nabla \vec{B} &= 0 \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t}
\end{aligned}
$$

The Three Isotopes of Hydrogen



source: J. Riemann 2013

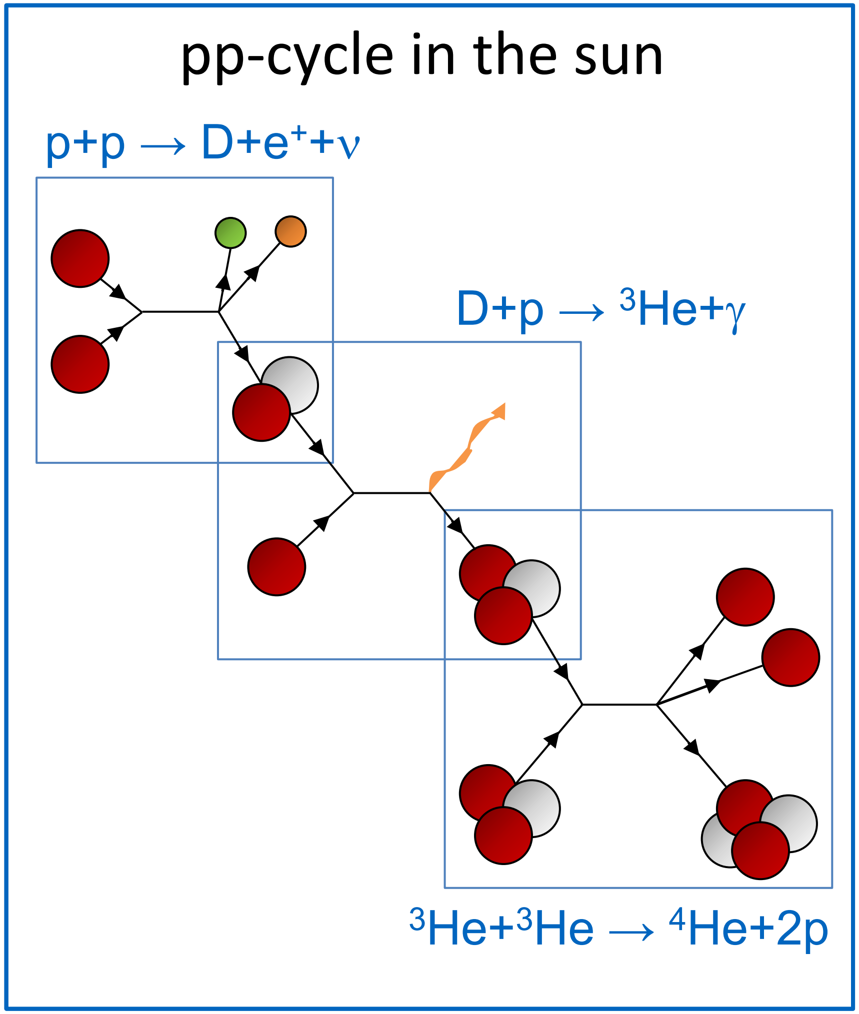
Nuclear Energy: Fusion or Fission



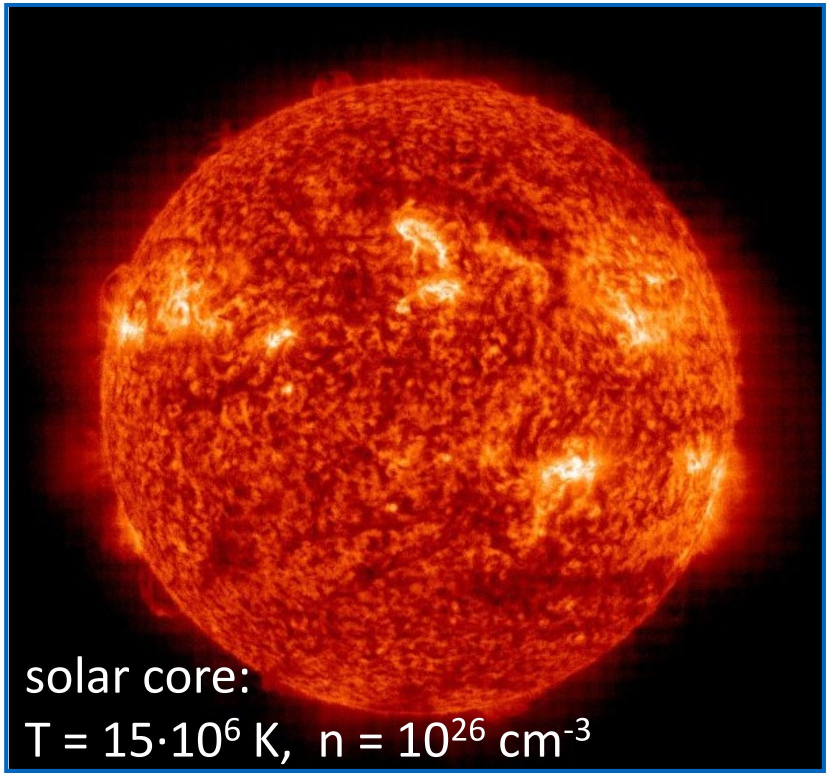
source: H.S. Bosch 2010

Energy can be produced by **fusion of light nuclei** **or by** **fission of heavy nuclei**

Nuclear Fusion in the Sun



source: A. Kleiber 2014



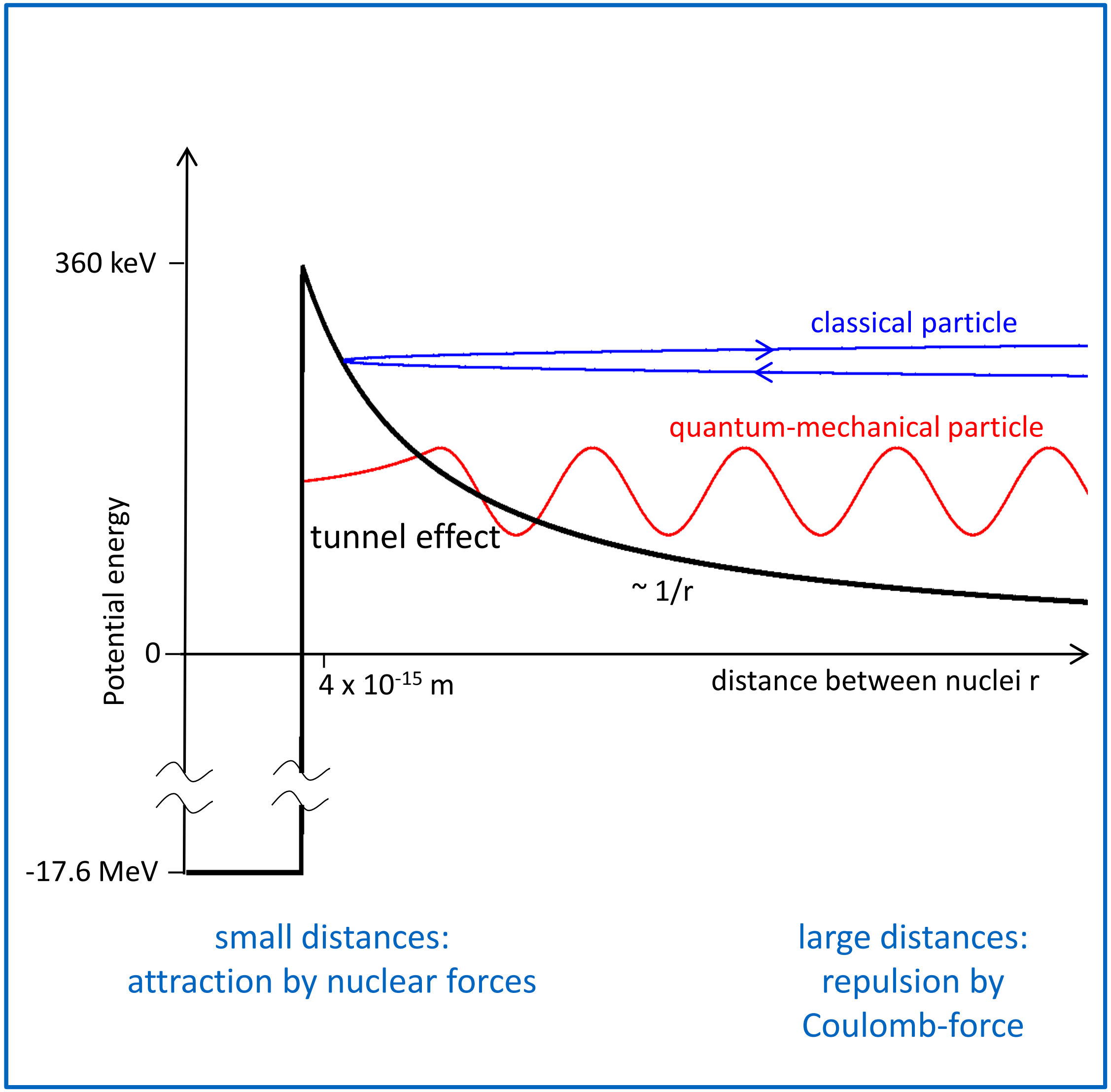
source: SOHO, ESA & NASA (EIT 304) 12. März 2013 um 13.19 UT

Every second 600 Mio. t of hydrogen are transformed into 596 Mio. t of helium according to $E = mc^2$.
This yields a power of $3{,}6 \cdot 10^{17}$ GW.

Important: Gravitational force overcomes repulsive forces

Potential Energy in Nuclear Fusion

- potential well: difficult to overcome
- finite probability for tunneling through the barrier
- probability highest for light nuclei with high velocity



source: R. Kleiber 2014

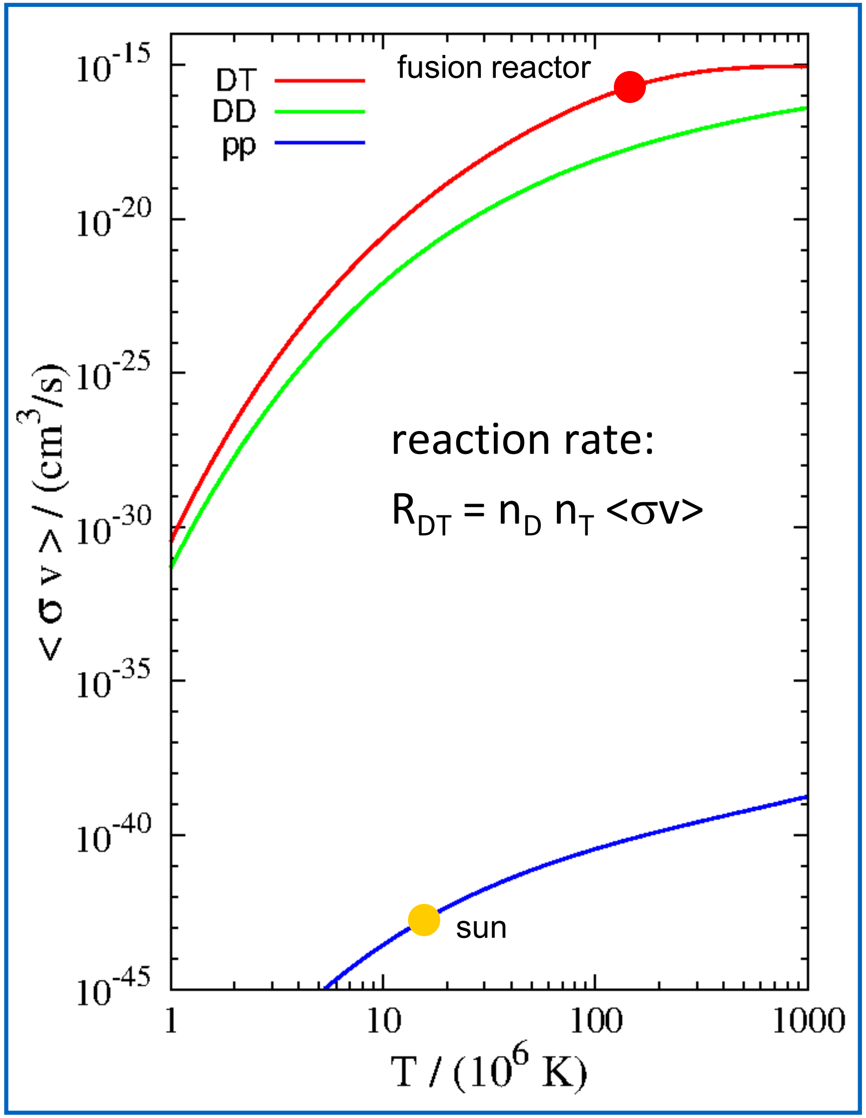
Controlled Nuclear Fusion on Earth

- low cross-section of pp-cycle
  - very slow ($\tau = 3{\cdot}10^9$ a)
  - very unlikely
  - long life-time of the stars
  - not feasible on earth!

- more likely reaction:

  Deuterium-Tritium (DT)
  - faster than pp-cycle (τ = 100 s)
  - required temperature:

    approx. 150 Mio K (15 keV)



source: IPP

Fusion Reactions on Earth

Fuels

Deuterium (D)

- part of seawater (0,15 ‰)

Tritium (T)

- can be "bred" from lithium
- radioactive (half-life period 12 a)
- only small amount in reactor due to breeding

Lithium (Li)

- contained in rocks (0,05 ‰)

→ resources (D, Li) available for many millenniums

"Ash"

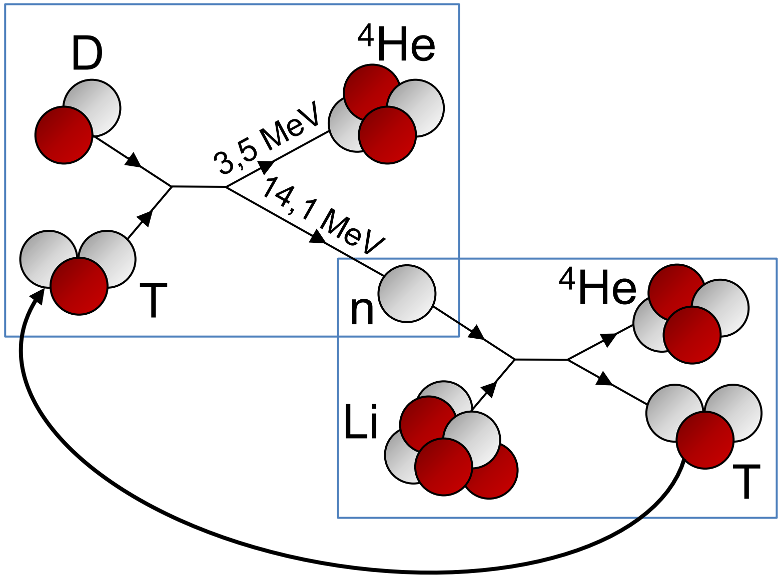
Helium (He)

Energy

kinetic energy of neutrons → heat

DT-cycle on earth

$D+T \rightarrow {}^4He+n$



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

$n+{}^7Li \rightarrow T+{}^4He+n$

DT-fusion reactions, source: A. Kleiber 2014

Excursion: Energy Equivalents

calory content of a whole
milk chocolate bar (100 g)

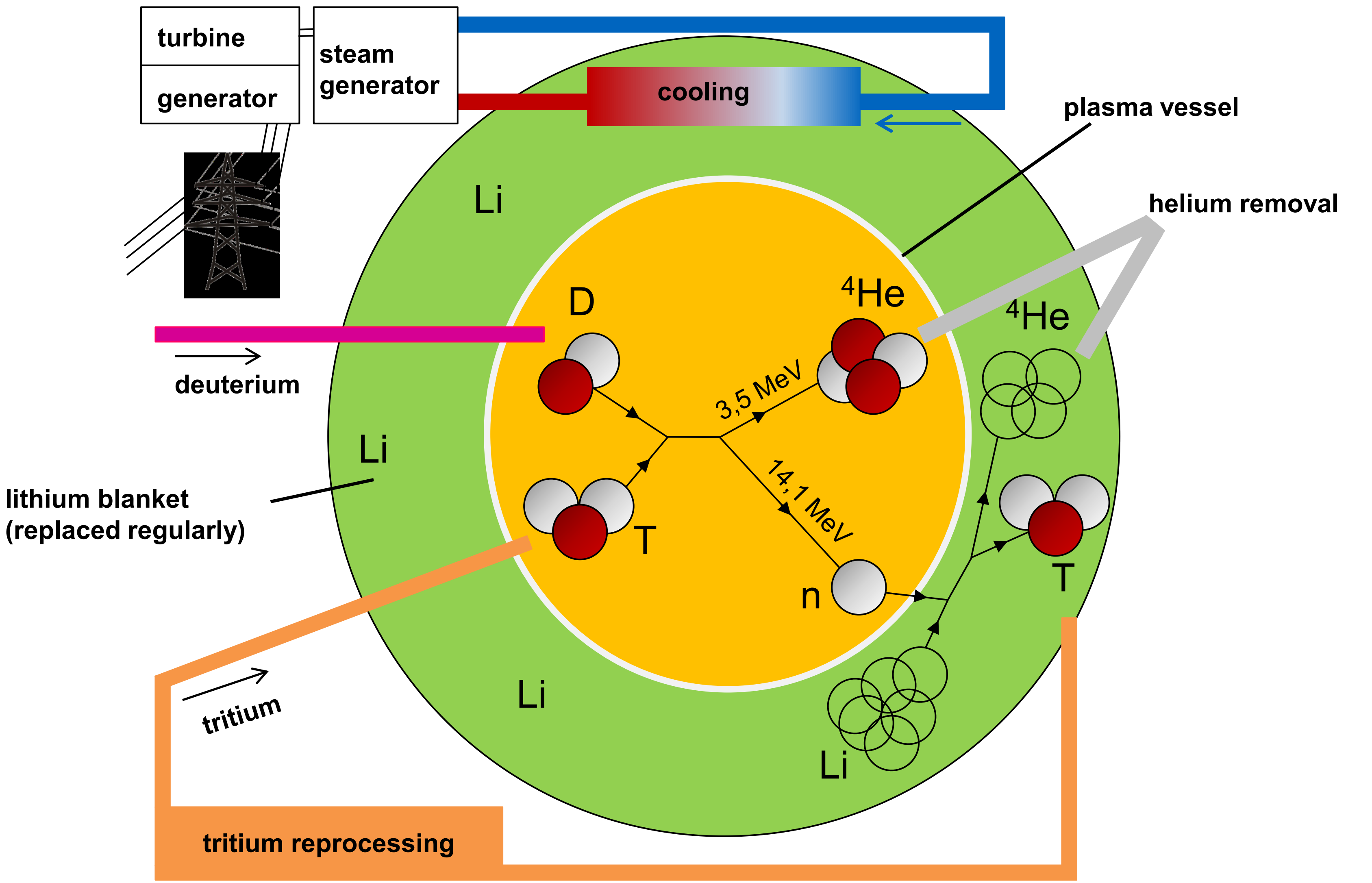
⇨ 527 kcal = $1{,}4 \cdot 10^{19}$ MeV =
1 chocolate unit (CU)

kinetic energy of a car
m = 1 t, v = 100 km/h

⇨ 1/6 CU

source: R. Kleiber 2012

Schematic Diagram of a Fusion Reactor



uel

source: A. Kleiber 2014

Requirements for a Fusion Reactor

- high temperature

  ➡ $T \approx 150$ Mio K

- sufficient number of particles per volume (density)

  ➡ $n \approx 10^{20}\, m^{-3}$

  (equivalent to 1/500.000 of the atmospheric density)

- good confinement(= heat insulation) confinement time

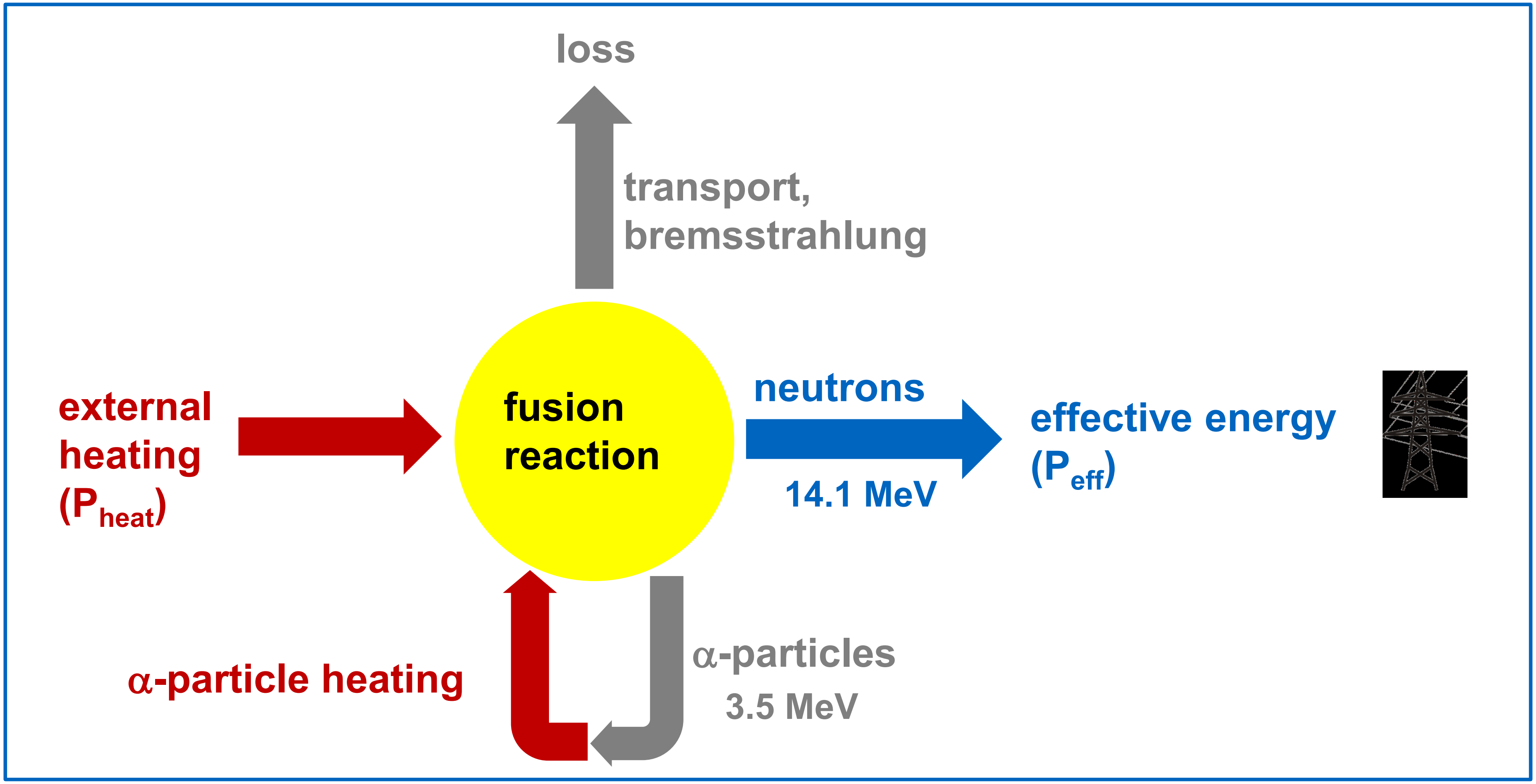
  (time of cooling down of the plasma after heating)

  ➡ $\tau_E \approx 5$ s

source: M. Borchardt 2014

triple product ($n\tau_E T$) has to be sufficiently large to ignite the plasma

Power Balance of Nuclear Fusion

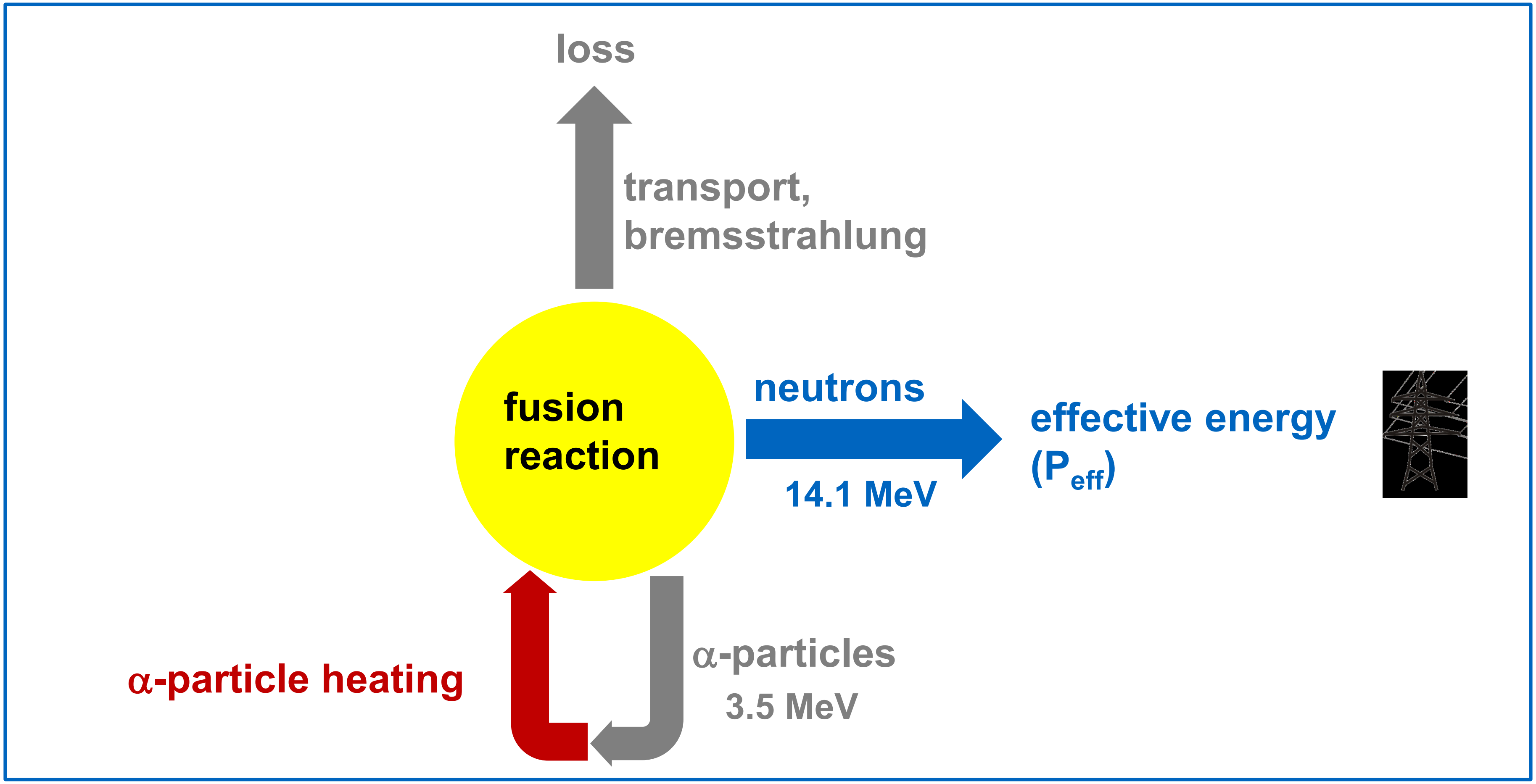


source: R. Kleiber 2012

power gain factor: $Q = P_{eff} / P_{heat}$

energy gain: $Q > 1$

Power Balance of Nuclear Fusion

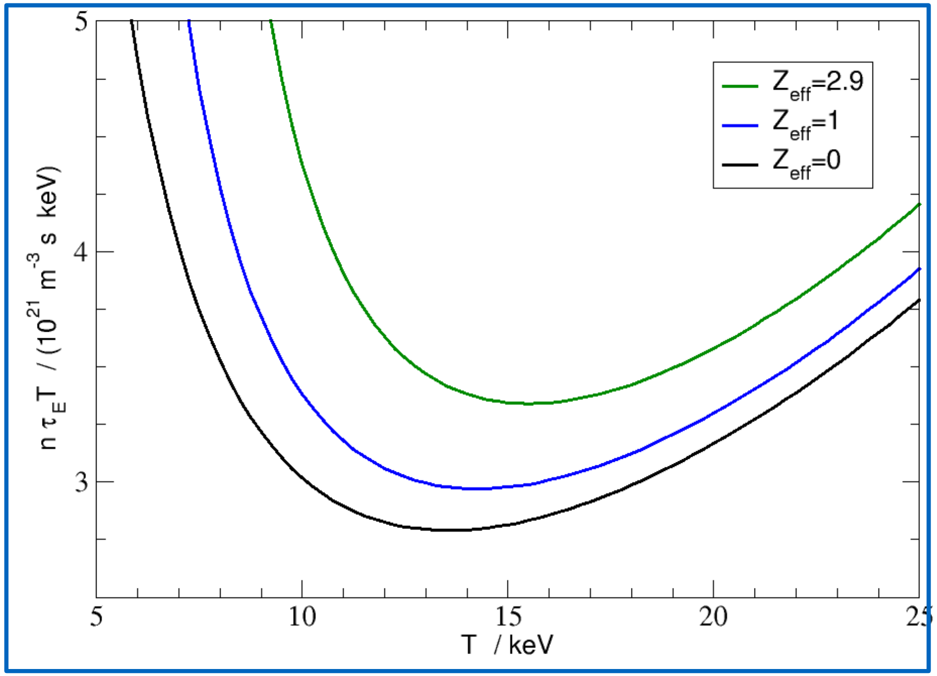


source: R. Kleiber 2012

nτT large enough → burning plasma: Q = ∞

Lawson Criterion (Triple Product)

- neutrons leave the plasma
  ➡ power generation
- α-particles confined
  ➡ heating



source: R. Kleiber 2014

- heating:

$$P_{\mathrm{Fusion}} = \frac{1}{4} n^2 \langle \sigma v \rangle E_\alpha$$

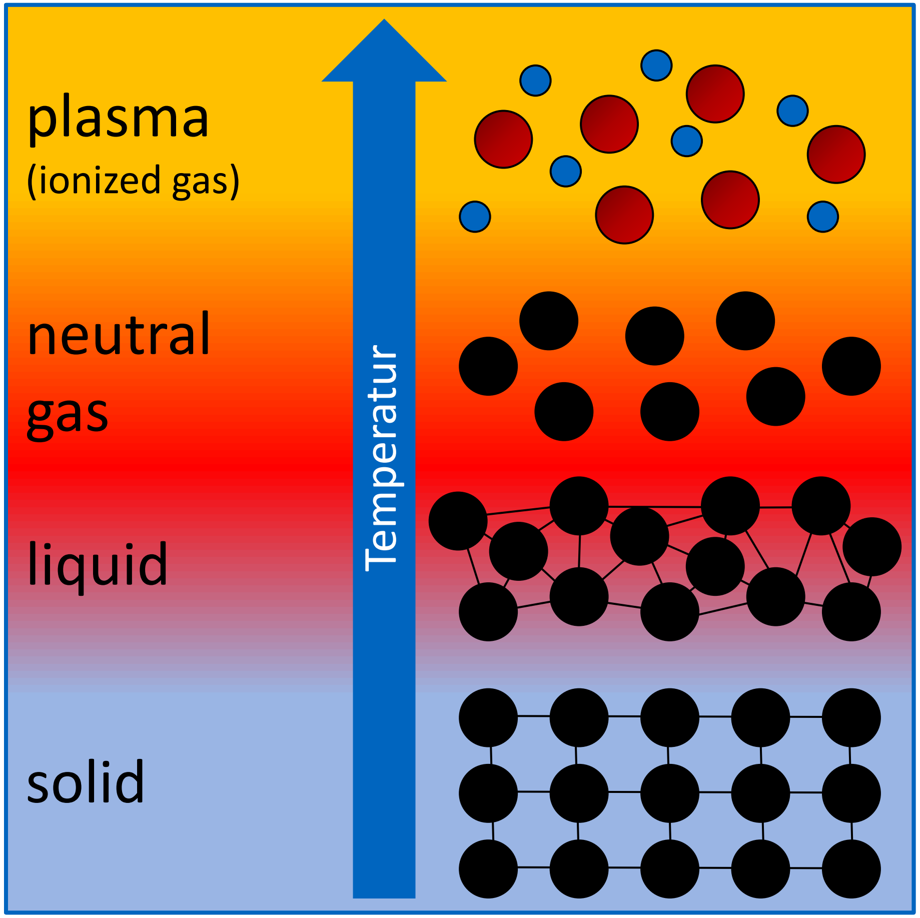
- loss due to radiation: $P_{\mathrm{Bremsstrahlung}} = c_1 n_{\mathrm{e}}^2 Z_{\mathrm{eff}} \sqrt{T}$
- loss due to transport: $P_{\mathrm{Transport}} = \frac{3nkT}{\tau_E}$
- (diffusion, turbulence)

➡ $$n\, \tau_{\mathrm{E}}\, T = \frac{12 k T^2}{\langle \sigma v \rangle E_\alpha - 4 c_1 Z_{\mathrm{eff}} \sqrt{T}}$$

The Plasma State of Matter

properties of a plasma

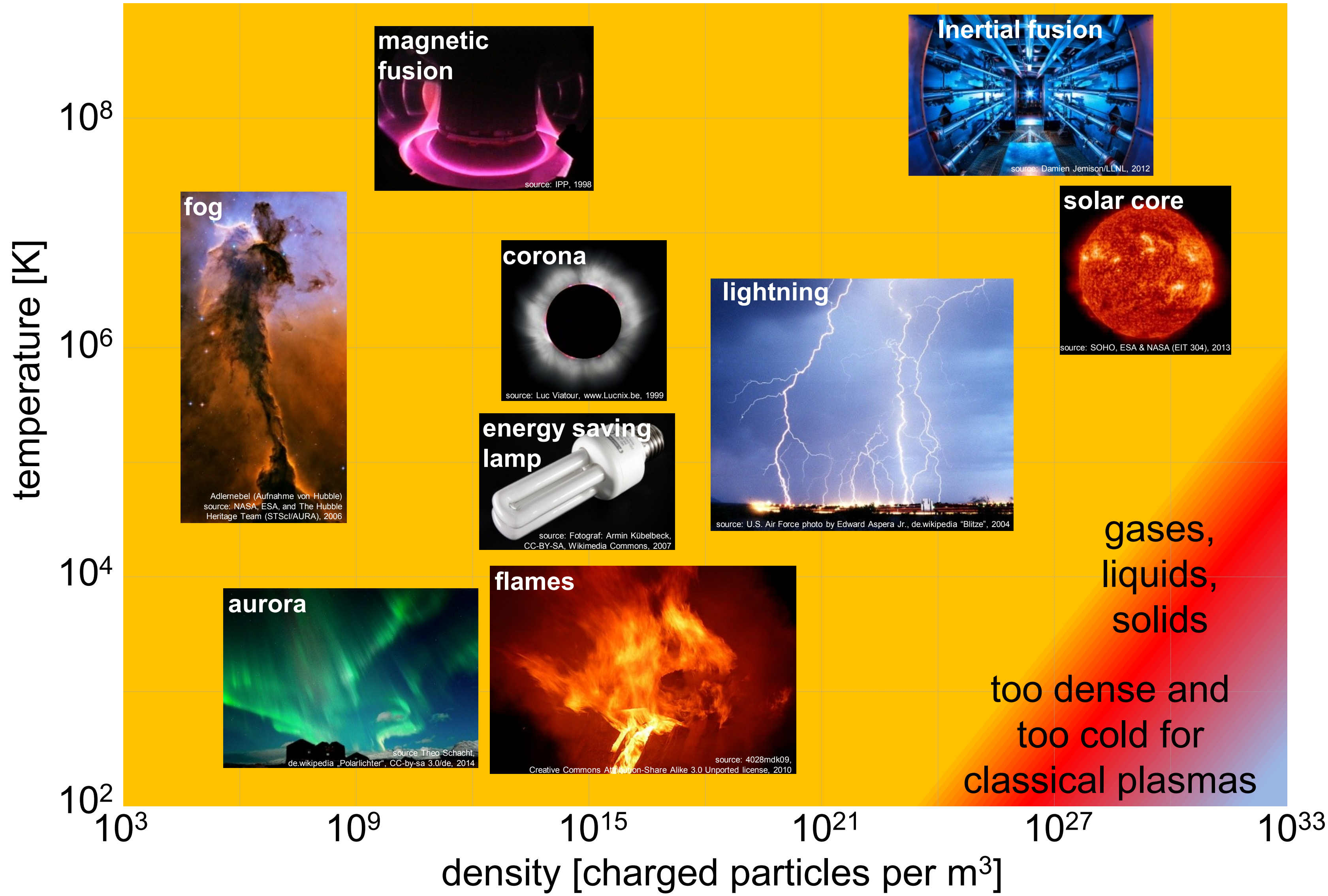
- neutral und charged particles
- free electric charge
  - ➡ electric conductivity
- interaction by Coulomb force
  - ➡ collective effects, shielding
- local concentration of charges
  - ➡ oscillations and waves
- no thermodynamical phase transition



source: A. Kleiber 2014

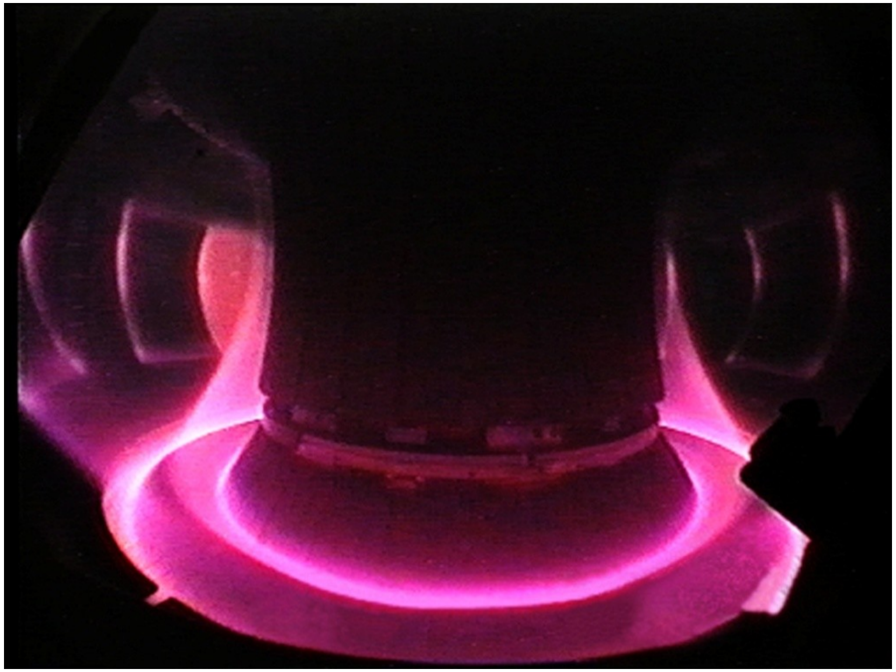
A vast fraction of matter in the universe is in the plasma state.

Plasma in the n-T-Diagram



source: A. Kleiber 2014

Thermal Energy in a Fusion Reactor



source: IPP 1998

source: A. Ullmann 2012

T = 150 million °C

$n = 10^{20}\ m^{-3}$

→ 150 CU

Safety Aspects of Nuclear Fusion

- no problems with criticality (no chain reaction)
- small energy reservoir in the plasma
  - fusion reactor contains only fuel for some seconds (fission reactor contains fuel for more than one year)
- low energy density in the plasma
  - high temperature, but low density
  - plasma cannot breach the vessel
- tritium (half-life period $T_{1/2}$ = 12,3 years)
  - about 1 g fuel inside a reactor and about 2 kg bound in the wall
  - low radiotoxicity
  - radiation does not penetrate the skin
- neutrons from fusion reaction (14,1 MeV)
  - adequate shielding necessary
  - activation of structure components (waste ➡ materials research)

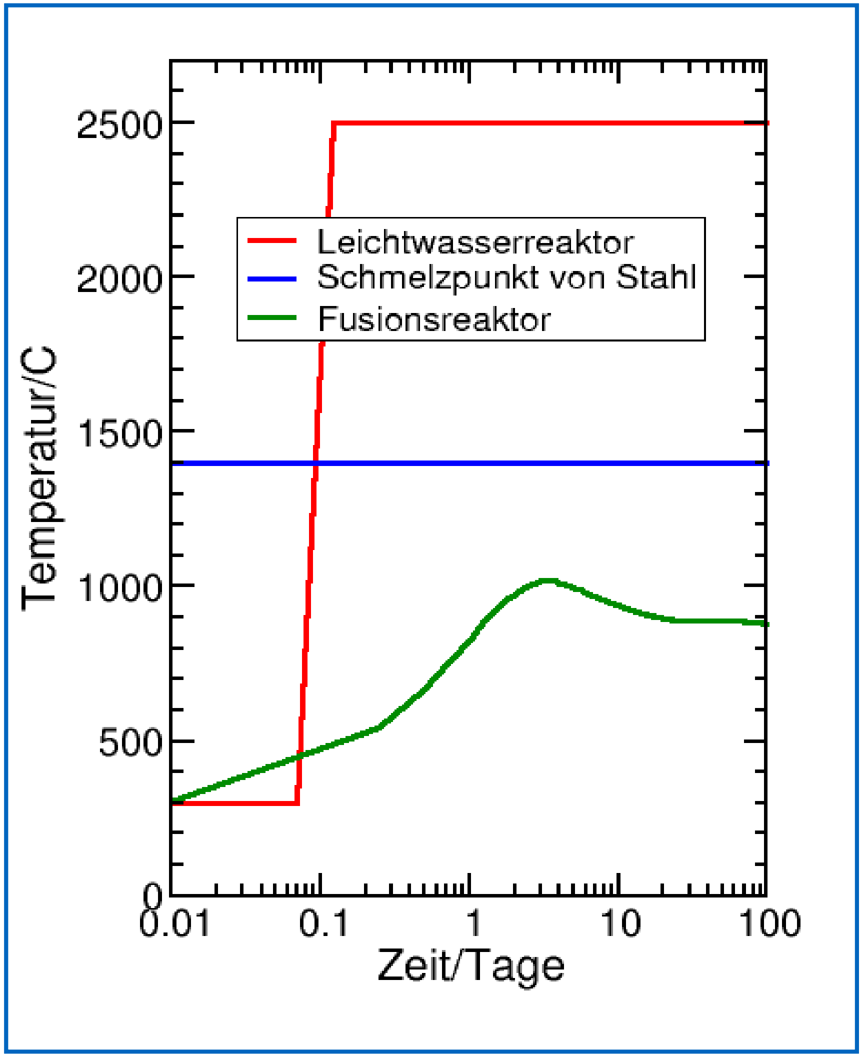
Safety of Fusion in Case of an Accident

study of possible accident scenarios

e.g. loss of cooling liquid:

- fusion process will stop immediately
- further warming only through decay heat of activated components
- temperature never reaches melting point of steel

- no meltdown of the reactor
- longer response time for possible intervention

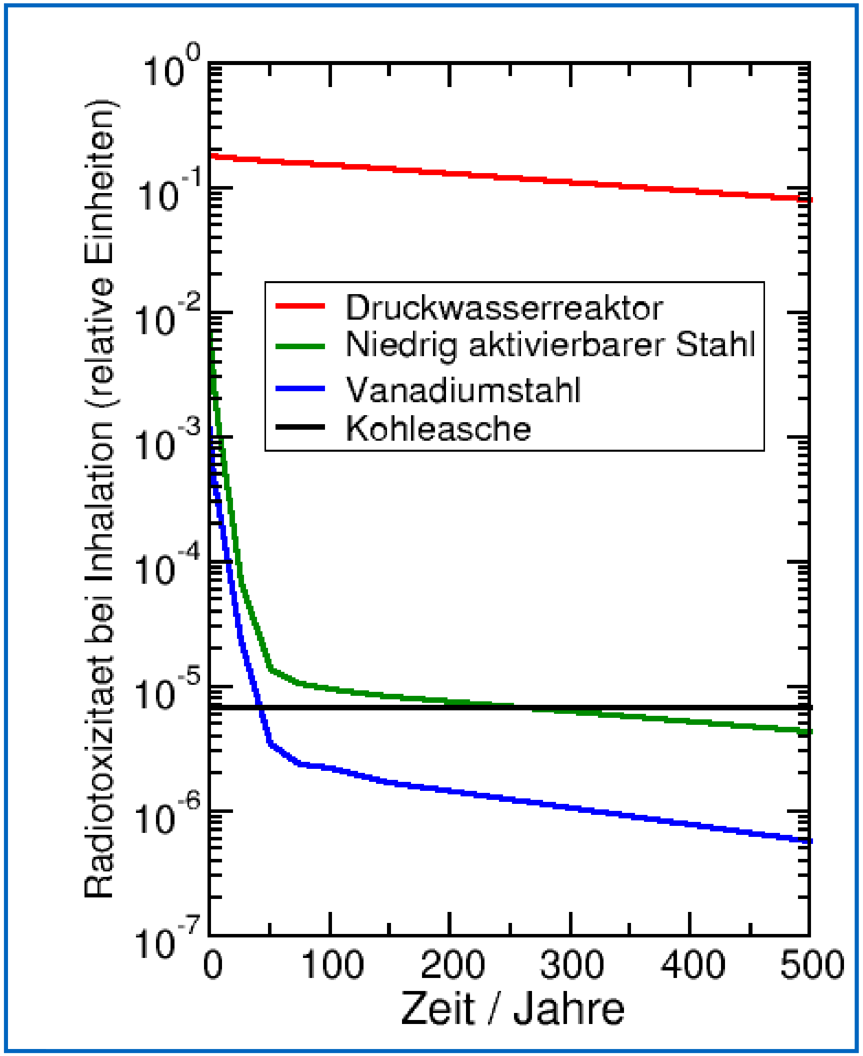


source: EFDA Power Plant Conceptual Study (PPCS), 2005, R. Kleiber, M. Borchardt 2014.

Waste from Fusion

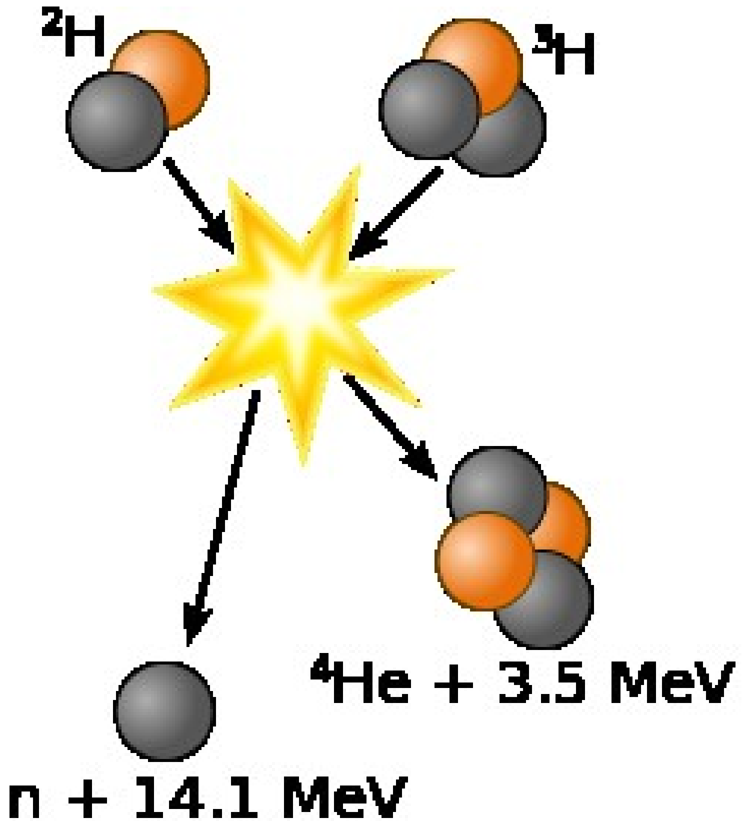
- radioactive waste results from steel activated by neutrons
- optimisation by improved materials (materials research)
- no long-living isotopes produced (e.g. U, Pu, Th)
- after 100 years 90 % of the waste is recyclable
- after 500 years the remaining 10 % of the waste is comparable with coal ash

➡ no final storage necessary



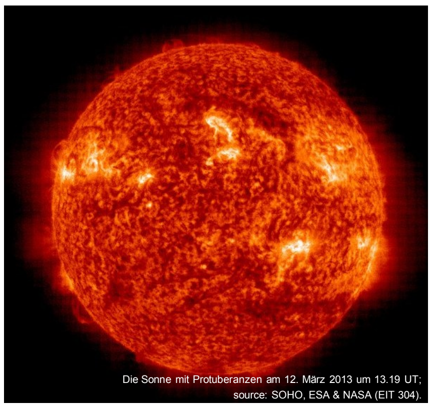
source: EFDA Safety and Environmental Impact of Fusion (SEIF), 2001, R. Kleiber, M. Borchardt 2014

BASIC CONCEPTS OF NUCLEAR FUSION



source: de.wikipedia "Kernfusion", Wykis, 2007

Main Approaches in Fusion Research


Die Sonne mit Protuberanzen am 12. März 2013 um 13.19 UT; source: SOHO, ESA & NASA (EIT 304).

gravitation
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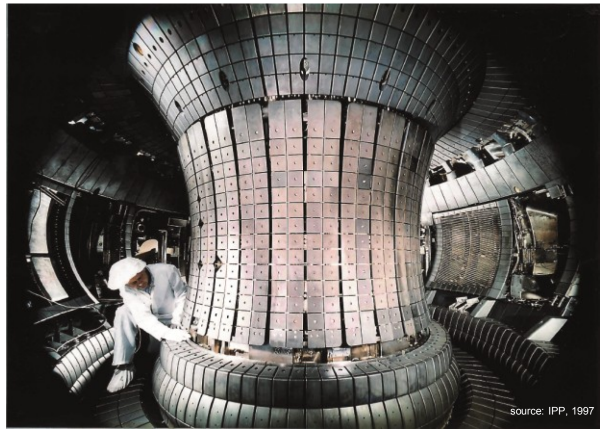
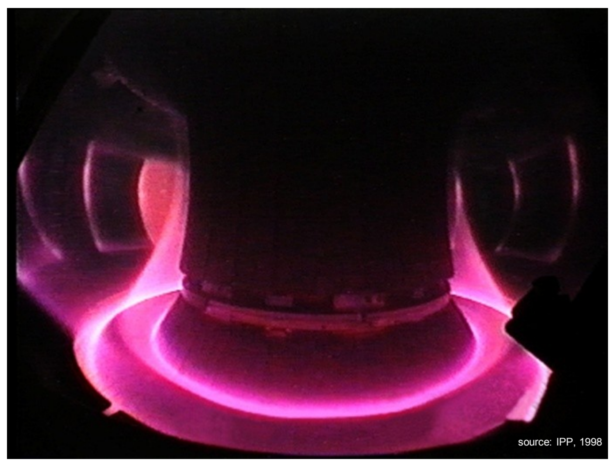
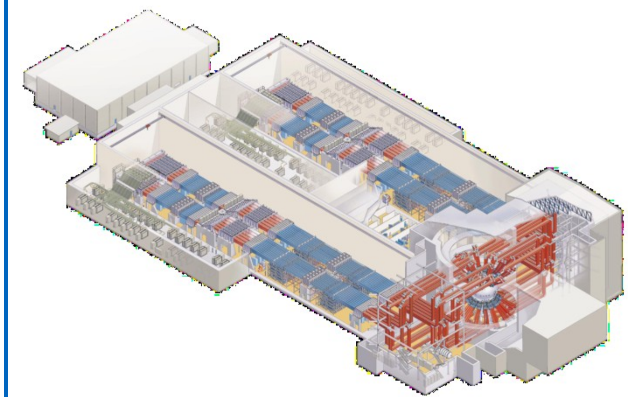
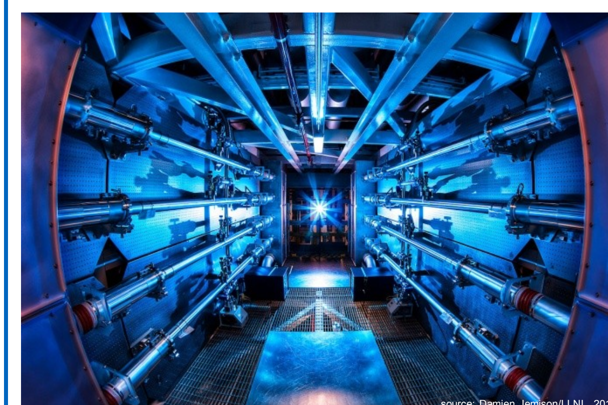

source: IPP, 1997


source: IPP, 1998

magnetic confinement

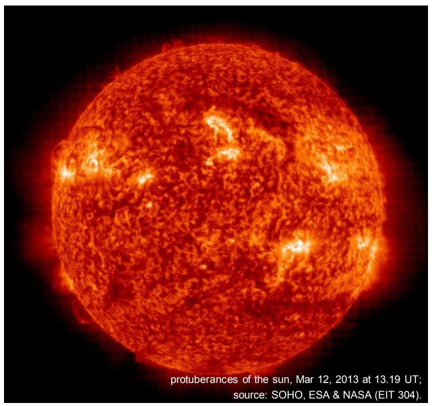
source: Sfan00_IMG, Layout of the National Ignition Facility. Image taken from a LLNL publication, en.wikipedia, 2010.




source: Damien Jemison/LLNL, 2012

inertial fusion

Ways to Confine a Plasma


protuberances of the sun, Mar 12, 2013 at 13.19 UT; source: SOHO, ESA & NASA (EIT 304).

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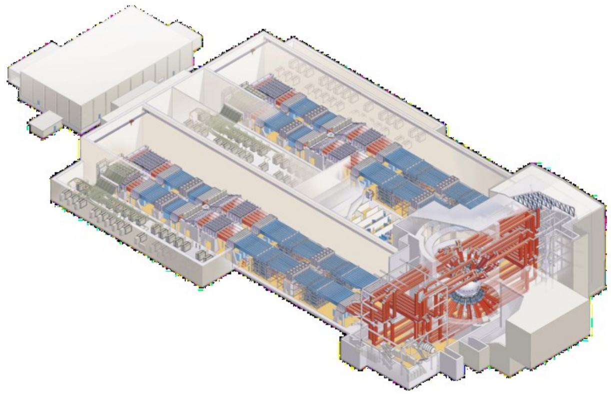
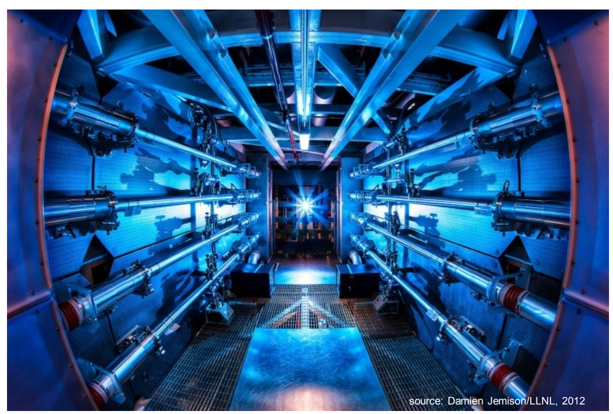
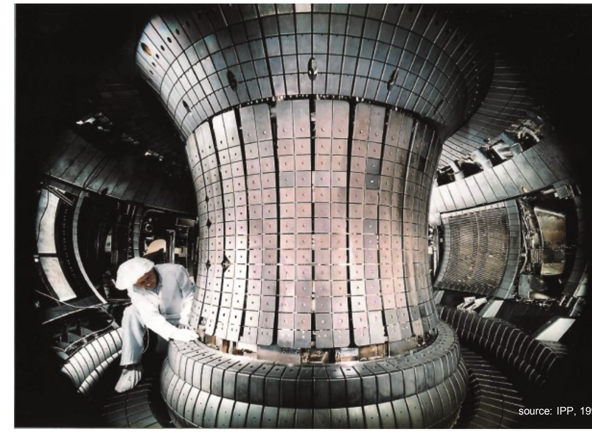
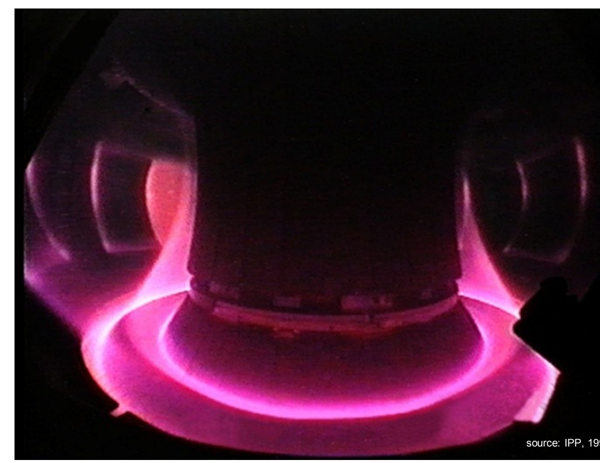
source: Sfan00_IMG, Layout of the National Ignition Facility. Image taken from a LLNL publication, en.wikipedia, 2010.




source: Damien Jemison/LLNL, 2012

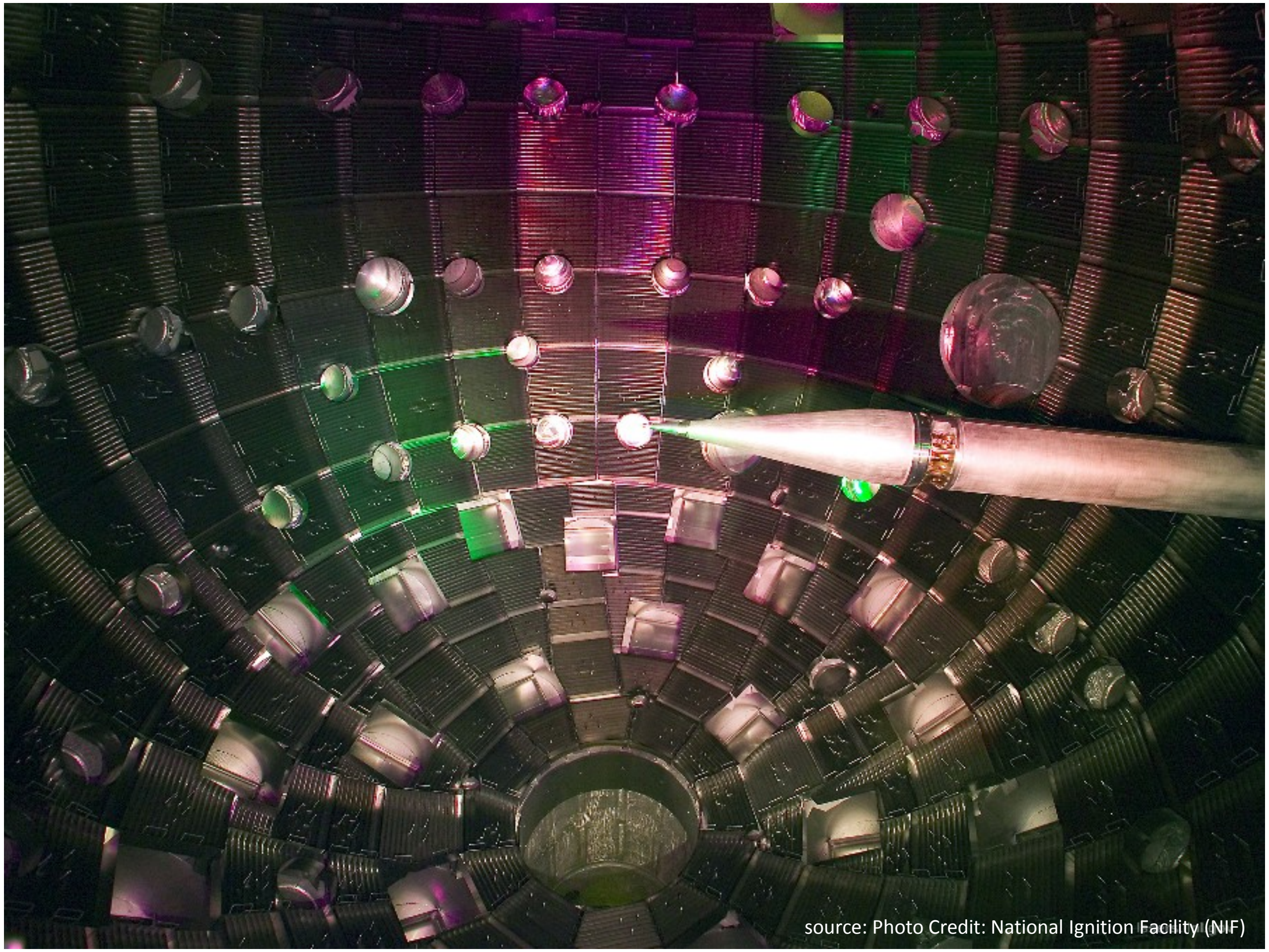
inertial confinement


source: IPP, 1997


source: IPP, 1998

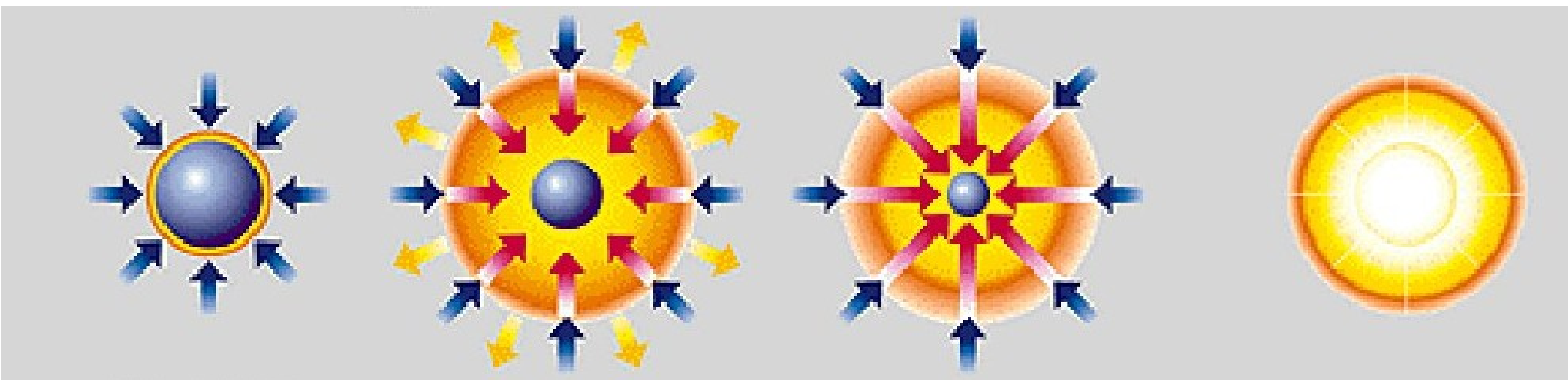
magnetic confinement

INERTIAL FUSION



Principle of Inertial Confinement Fusion

laser energy
blow-off
energy transported inwards



1. heating
by laser beams, plasma layer on the surface

2. compression
by ablation of surface material

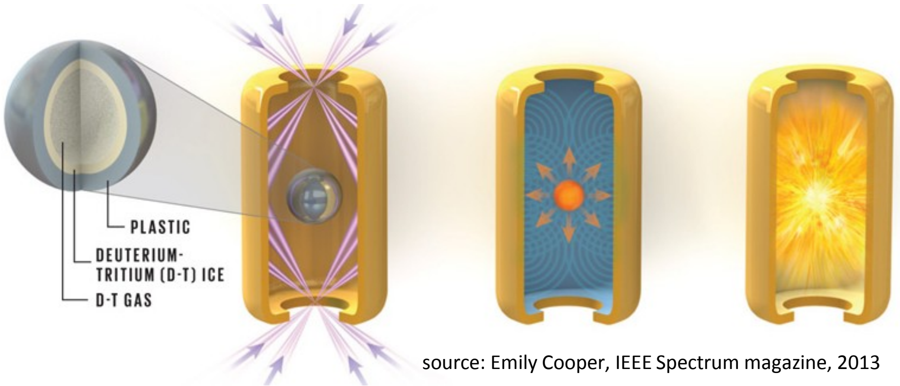
3. ignition
at the end of the laser pulse the centre reaches 100 times the mass density of lead and 100 million °C

4. burning
rapid spreading of thermonuclear burn
→ energy gain

source: NIF, A. Pulss 2005.

Hohlraum Targets

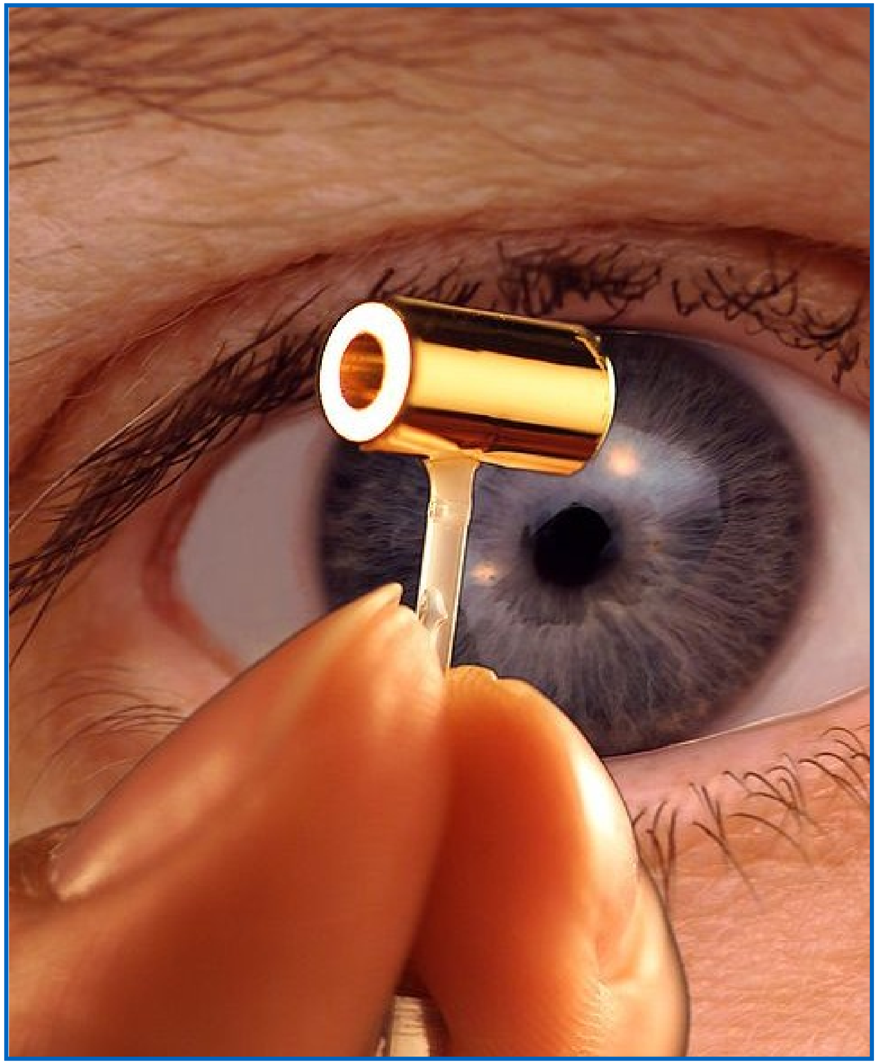
metallic hohlraum of high atomic number (e.g. gold) contains a microcapsule with fuel (target)



source: Emily Cooper, IEEE Spectrum magazine, 2013

- lasers heat the inside
- thermal X-rays are emitted

homogeneous radiation causes a uniform compression of the fuel

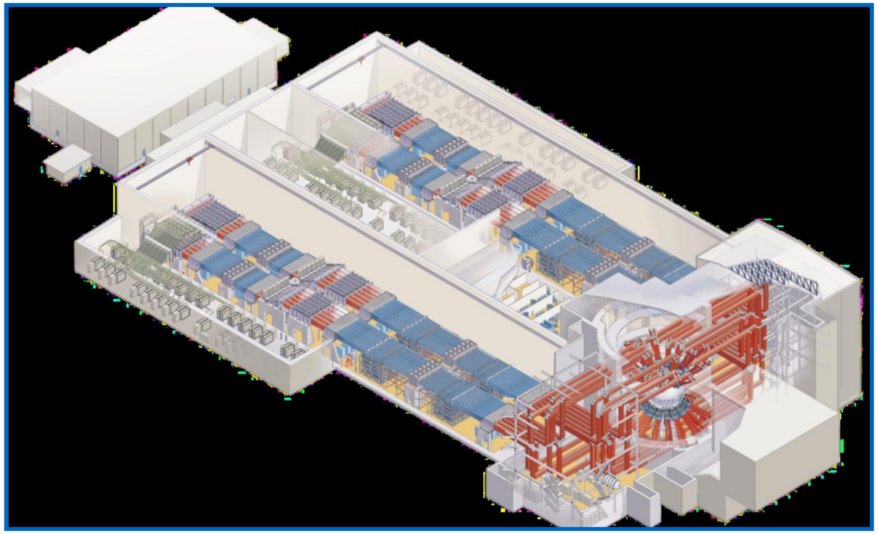


source: Croquant, en.wikipedia „inertial fusion“, llnl.gov, 2006

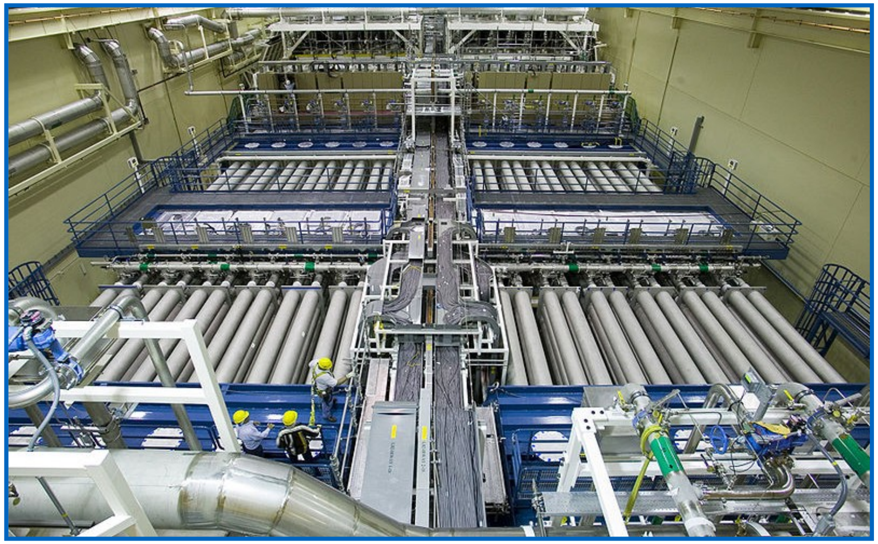
National Ignition Facility (NIF), Livermore, USA

- completed 2009
- 192 lasers
- 500 TW power
- 1.85 MJ of laser energy injected into target chamber
- milestone 2013:

  released more energy than absorbed by the fuel
- official mission:
  - defence research
  - basic research
  - inertial fusion

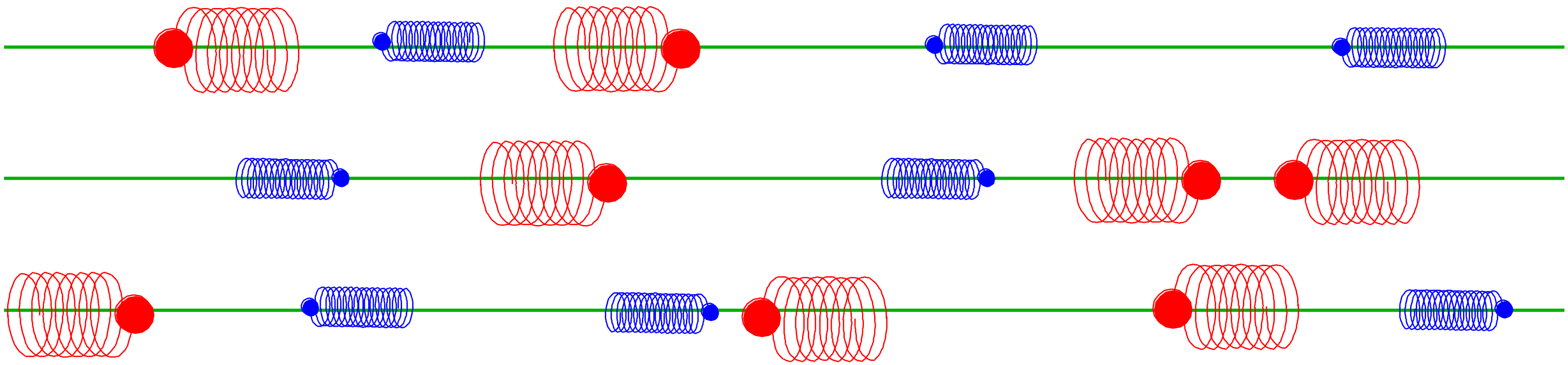


source: Sfan00_IMG, Layout of the National Ignition Facility. Image taken from a LLNL publication, en.wikipedia, 2010



source: Laser Bay 2, National Ignition Facility, Lawrence Livermore National Laboratory, 2007

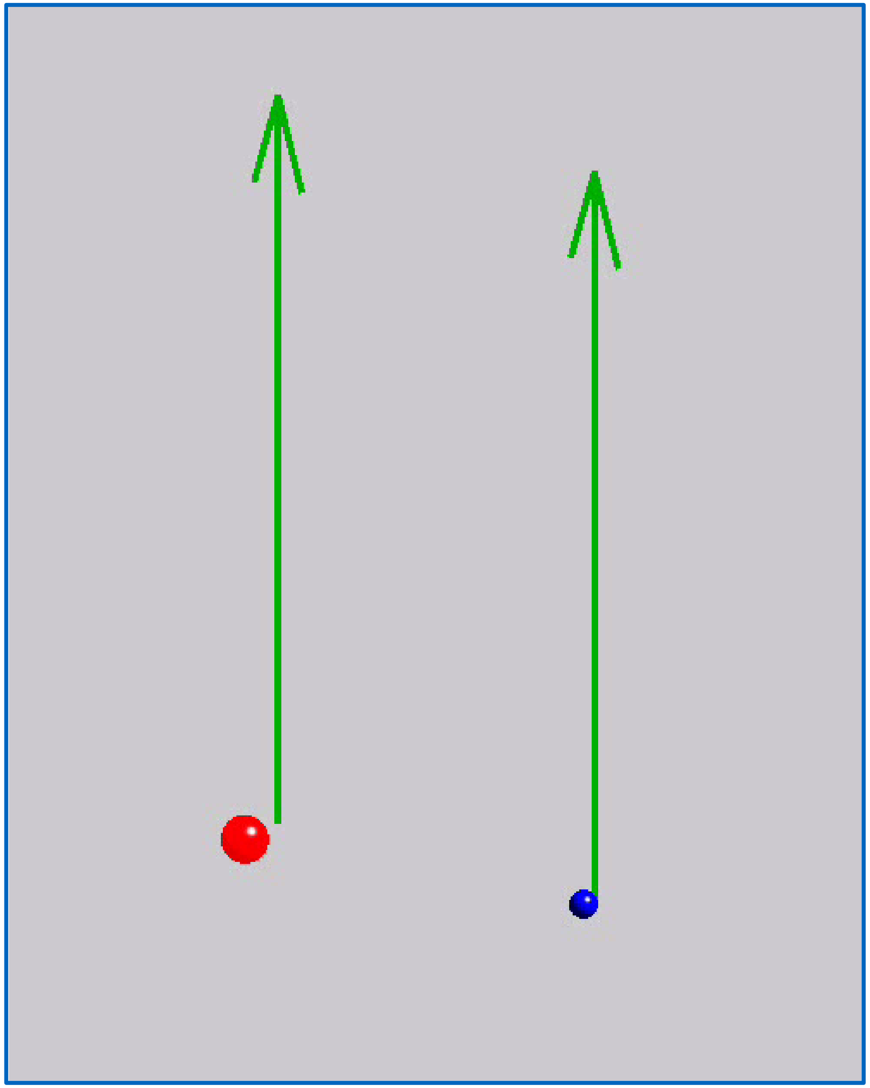
MAGNETIC CONFINEMENT



source: R. KLeiber 2012

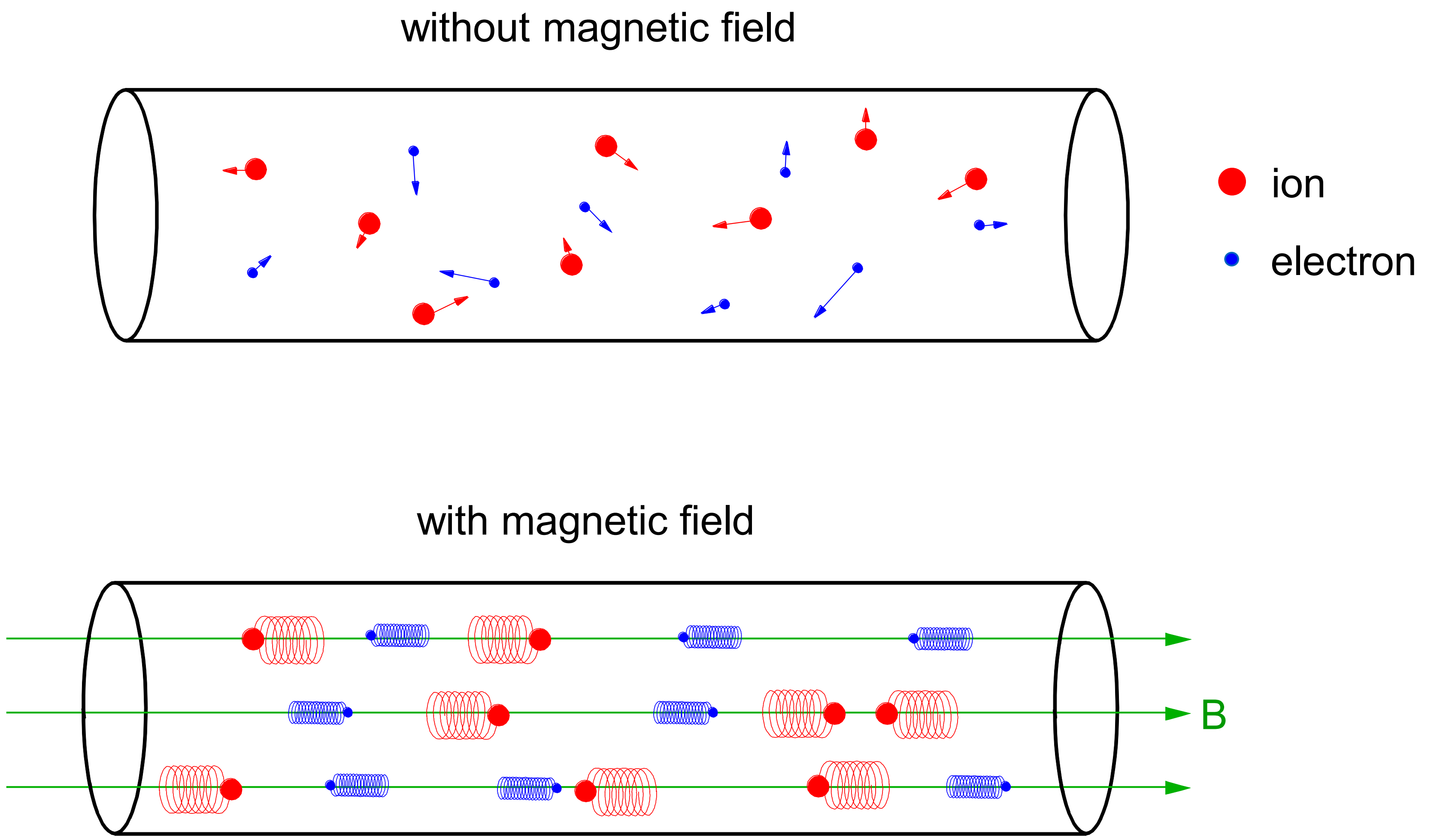
Magnetic Confinement

- a hot plasma cannot be confined by material walls
  ➡ use magnetic field (Lorentz force)
- magnetic field in fusion devices ca. 2.5 - 6 Tesla
  (earth magnetic field ≈ 50 μT)
- gyration radius:
  ions: 2 mm
  electrons: 45 μm
- gyration frequencies:
  ions: 90 MHz
  electrons: 170 GHz



source: R. Kleiber 2012

Magnetic Confinement



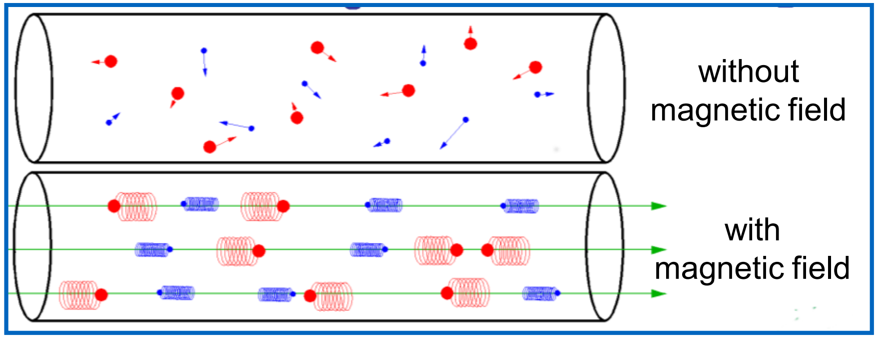
source: R. Kleiber 2012

Lorentz Force in Magnetic Field

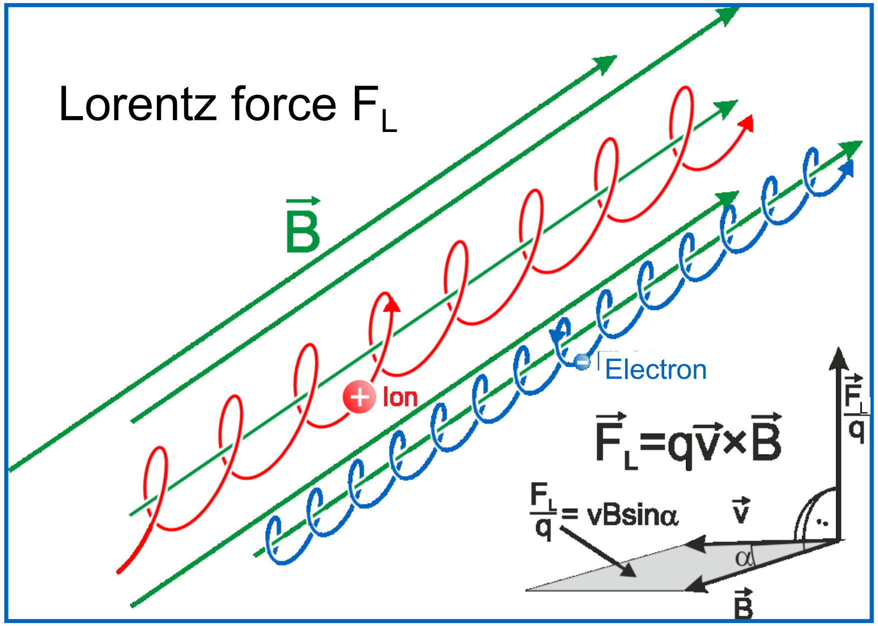
Hot plasmas cannot be confined by conventional material walls.

Force on electric charges in a magnetic field:

- motion perpendicular to field is modified
- particles forced on helical trajectories
- transport properties are changed
- fusion devices: ca. 2.5 - 6 Tesla (corresponds to ca. 10^5-times earth magnetic field strength)



source: R. Kleiber 2012

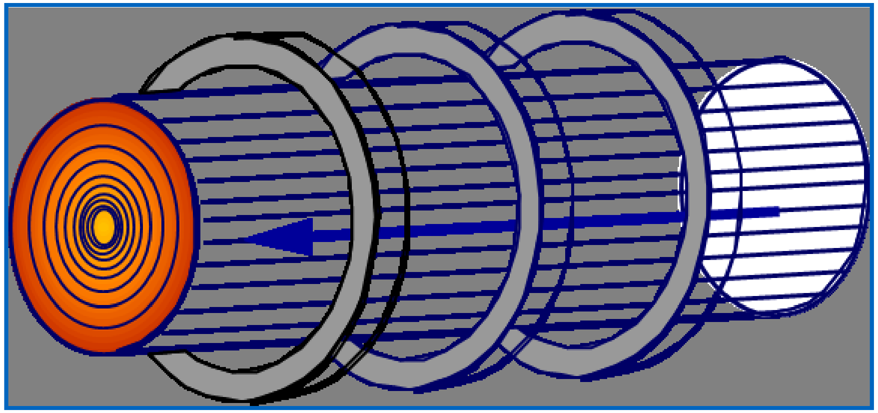


source: A. Kleiber 2014

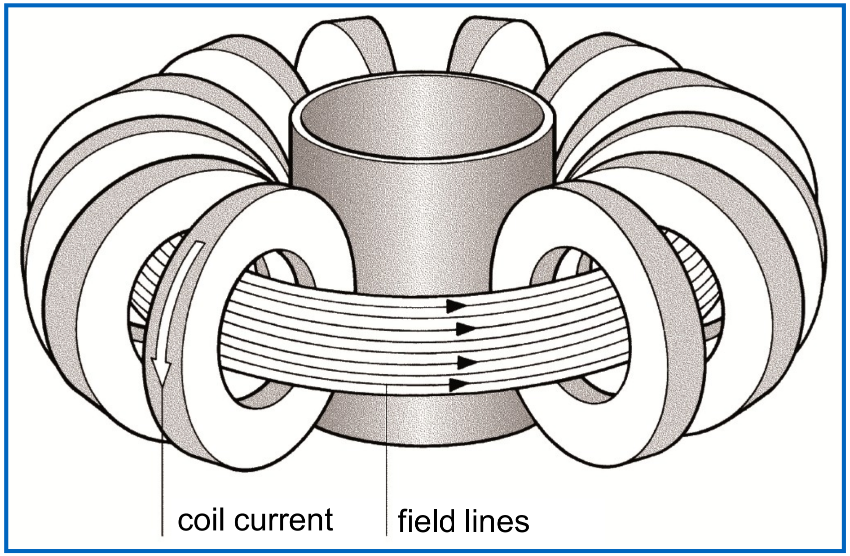
From a Cylinder towards a Torus

- cylindrical homogenous magnetic field
  - confinement perpendicular to axis
  - but: particles lost at the ends
- closing the field toroidally
  - quasi-endless configuration
  - but: particle losses due to drift motion

    (reason: inhomogenous field and curvature)



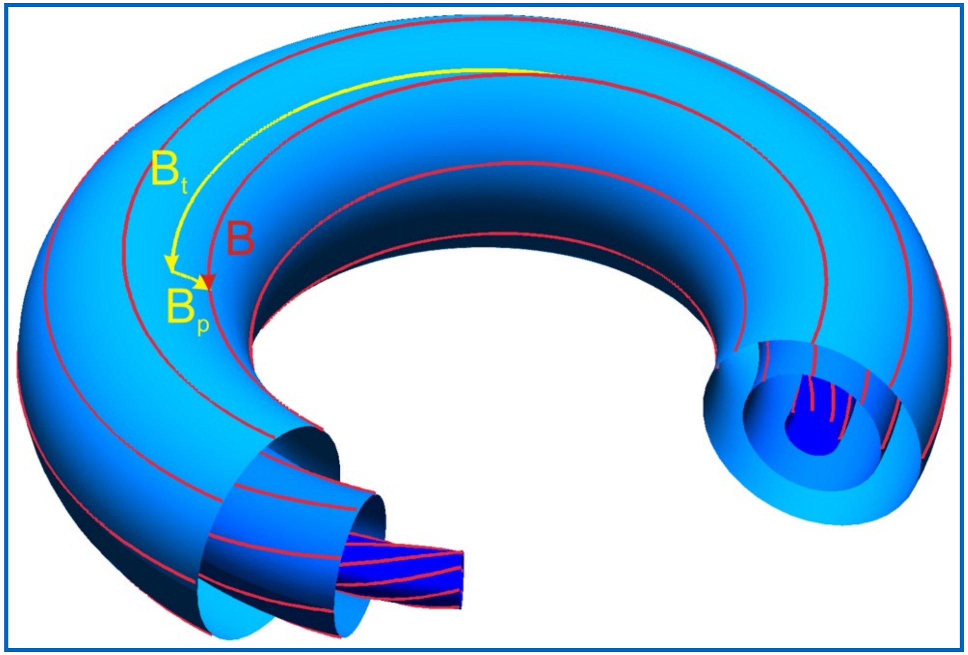
source: IPP



source: IPP 2002

Twisted Field Lines (Rotational Transform)

Twisted magnetic fields lead to confinement of particles.



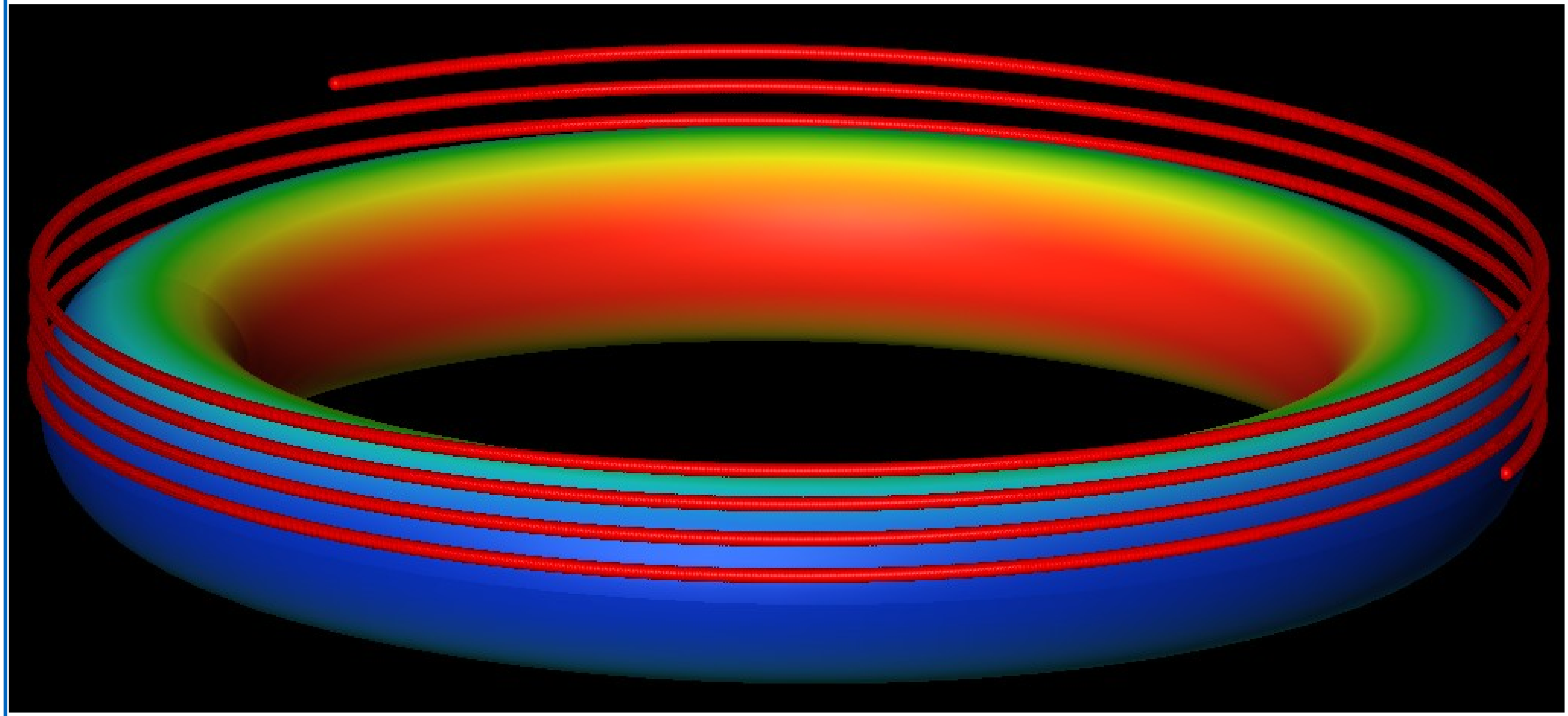
source: R. Kleiber, A. Pulss 2008

- two field components
  - B_t toroidal field
  - B_p poloidal field

  give rotational transform
- creation of magnetic flux surfaces
- rotational transform varies over radius

two possible concepts to generate rotational transform:
Tokamak & Stellarator

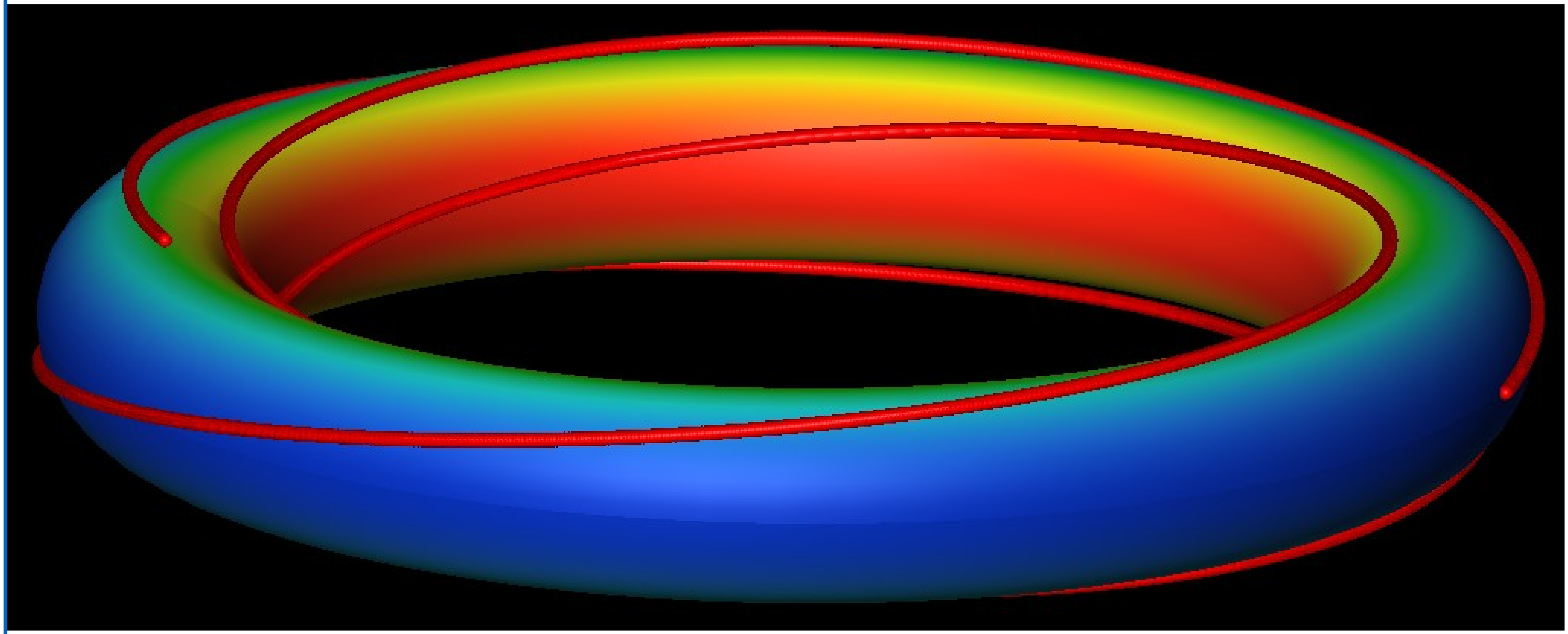
Particle Trajectories without Rotational Transform



source: M. Borchardt 2014

Plasma particles leave the torus.

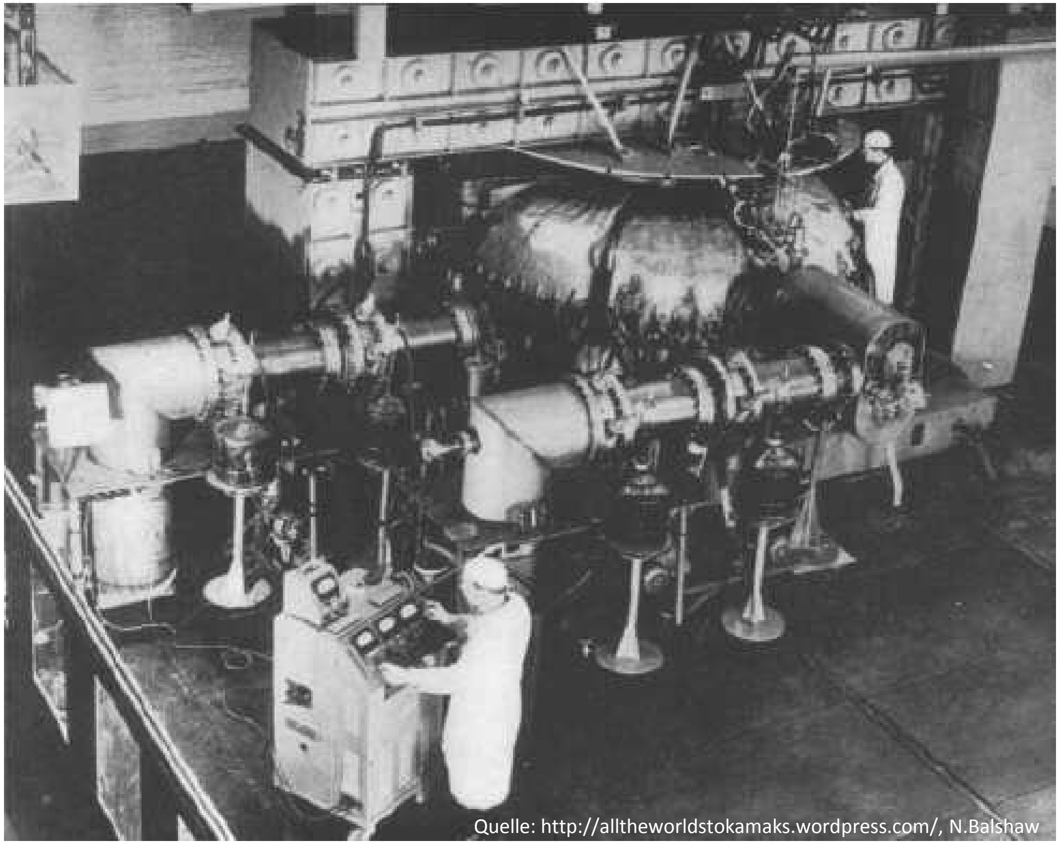
Particle Trajectories with Rotational Transform



source: M. Borchardt 2014

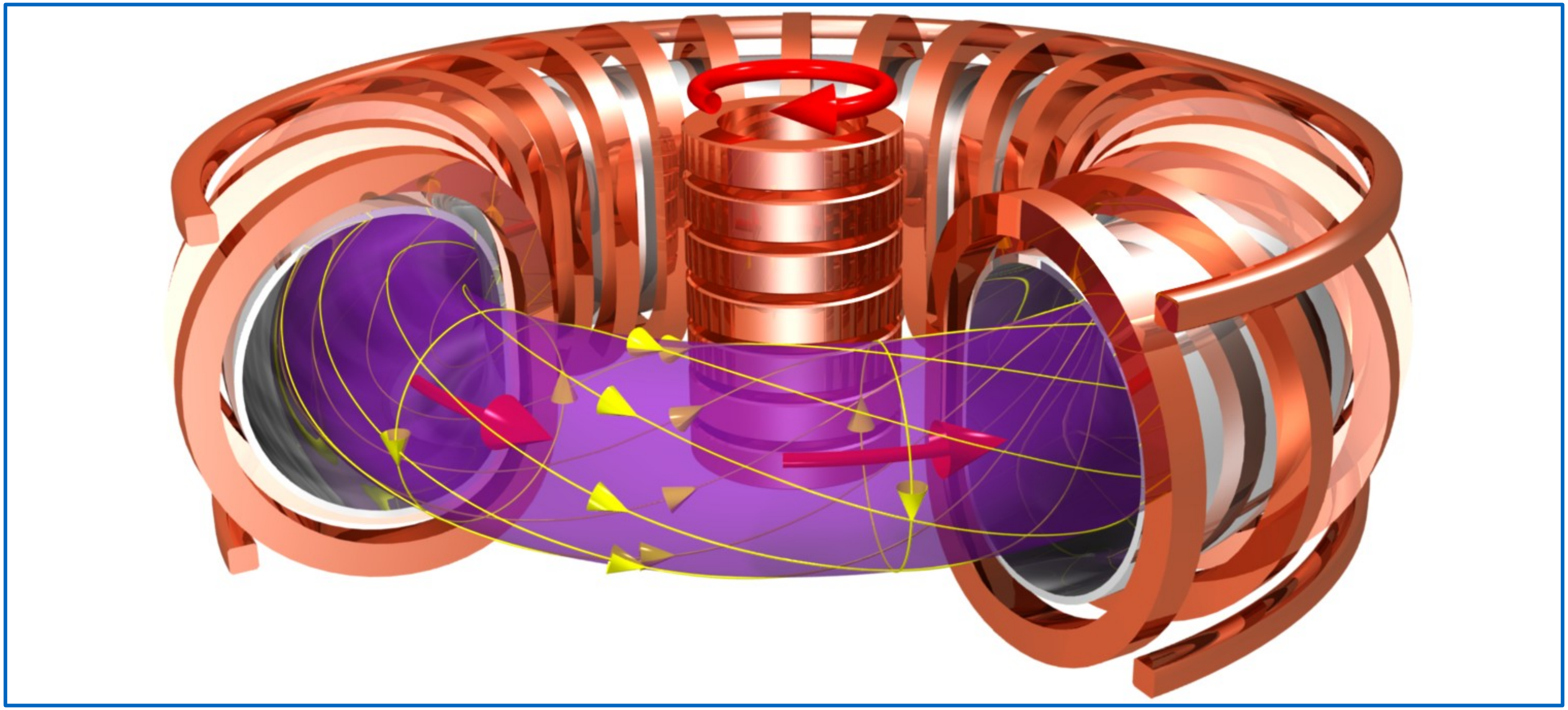
Plasma particles are confined to the torus.

THE TOKAMAK



T3-Tokamak, Kurchatov-Institute Moscow, USSR

Tokamak (тороидальная камера с магнитными катушками)

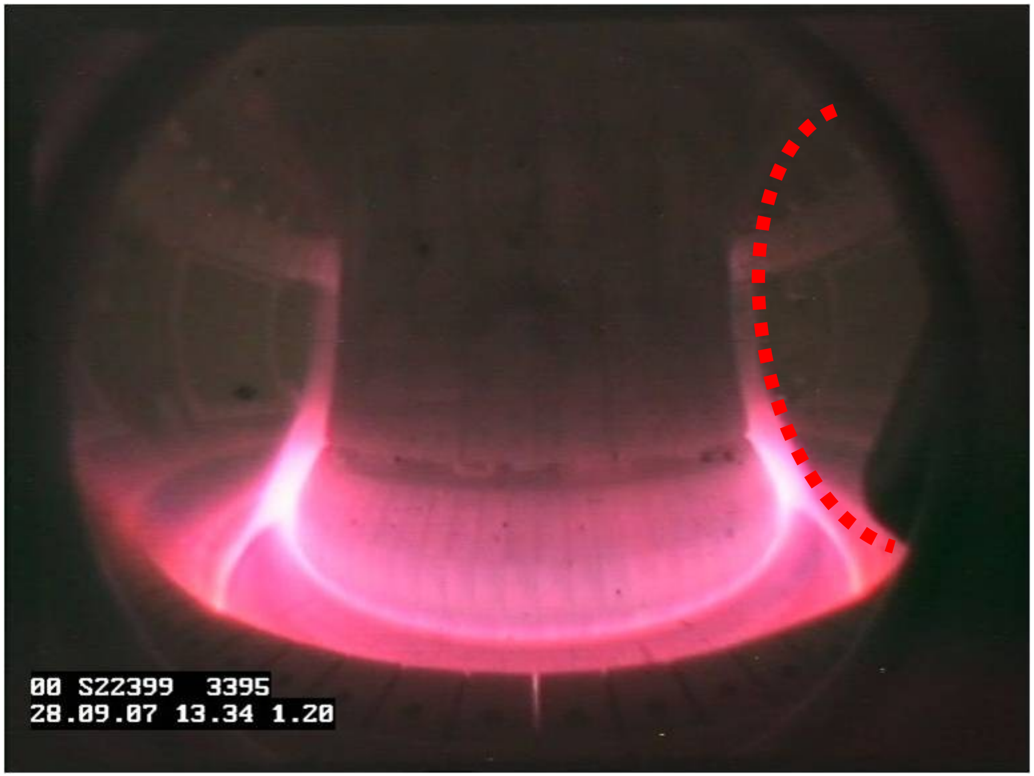


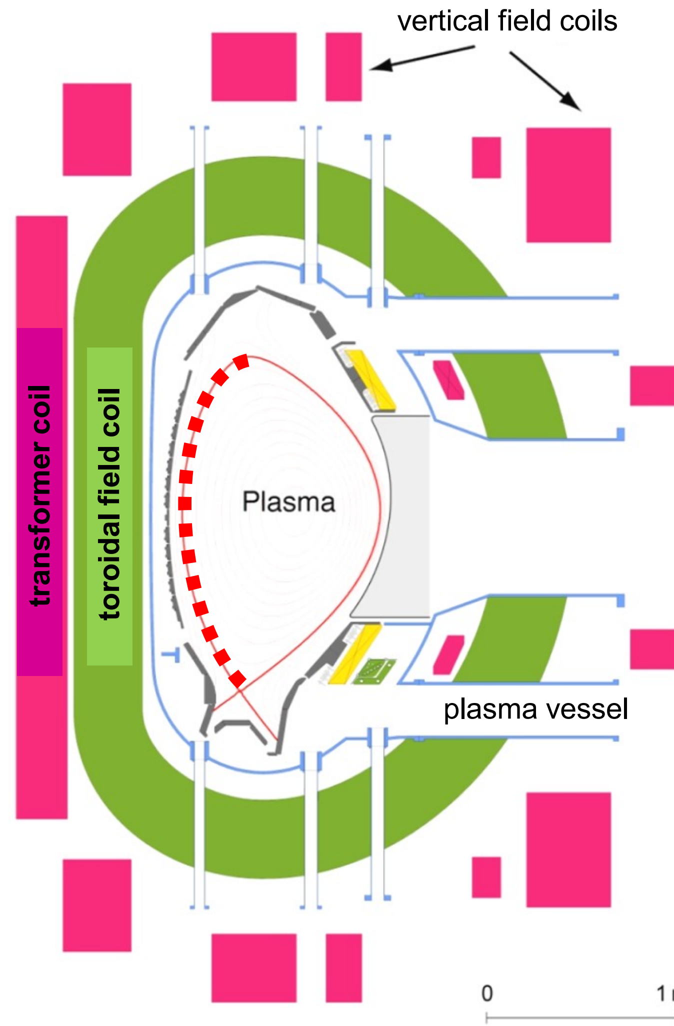
source: Christian Brandt, IPP 2011

developed around 1950 by Artsimovich and Sacharov in Moscow:

+ intrinsic heating
+ most advanced fusion concept
– no stationary operation (works like a transformer) ➡ current drive
– current quench possible (disruption)

ASDEX-UPGRADE (AUG), IPP Garching, Germany



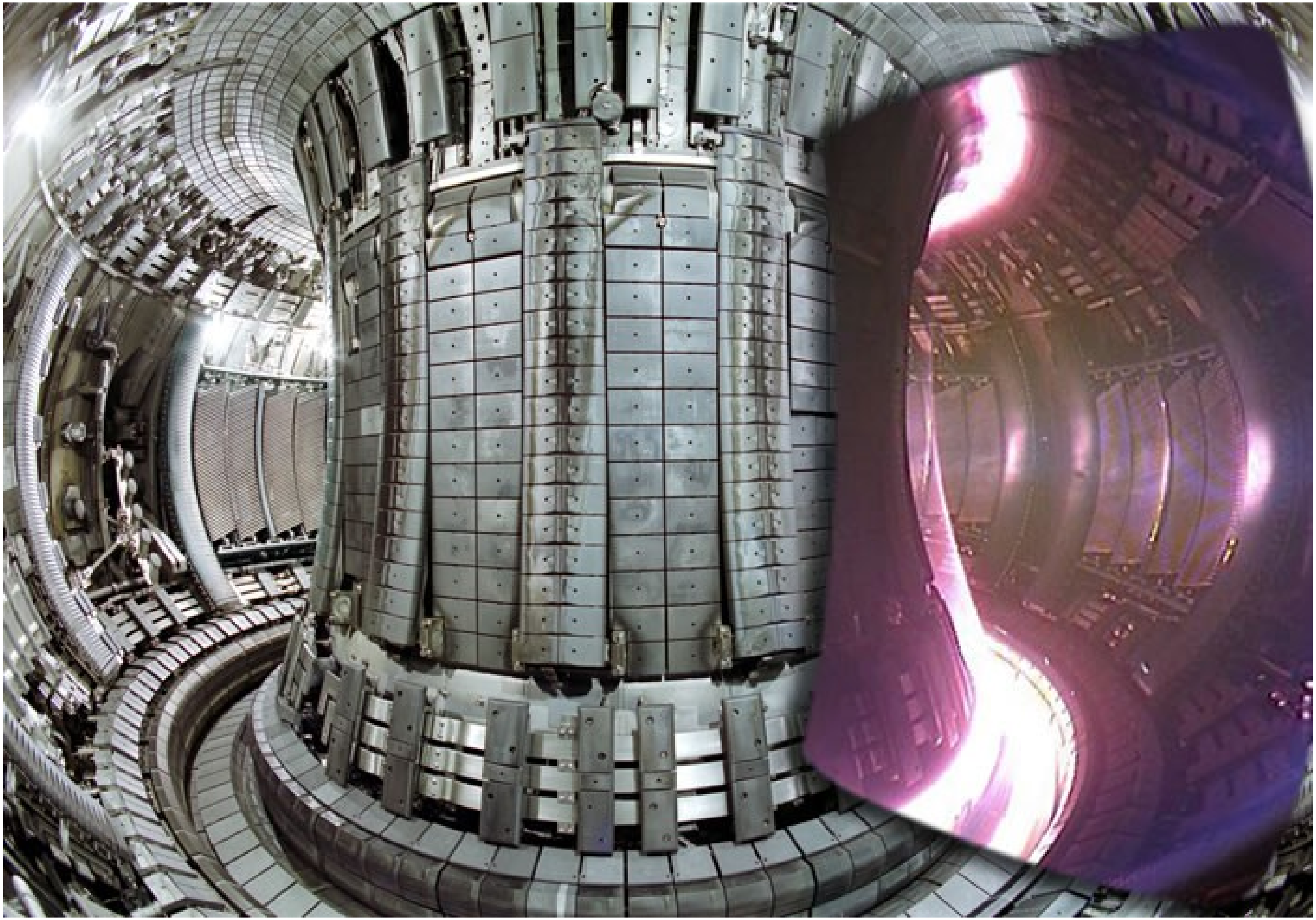


$R = 1.65$ m $a = 0.5$ m $\kappa = 1.6$

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

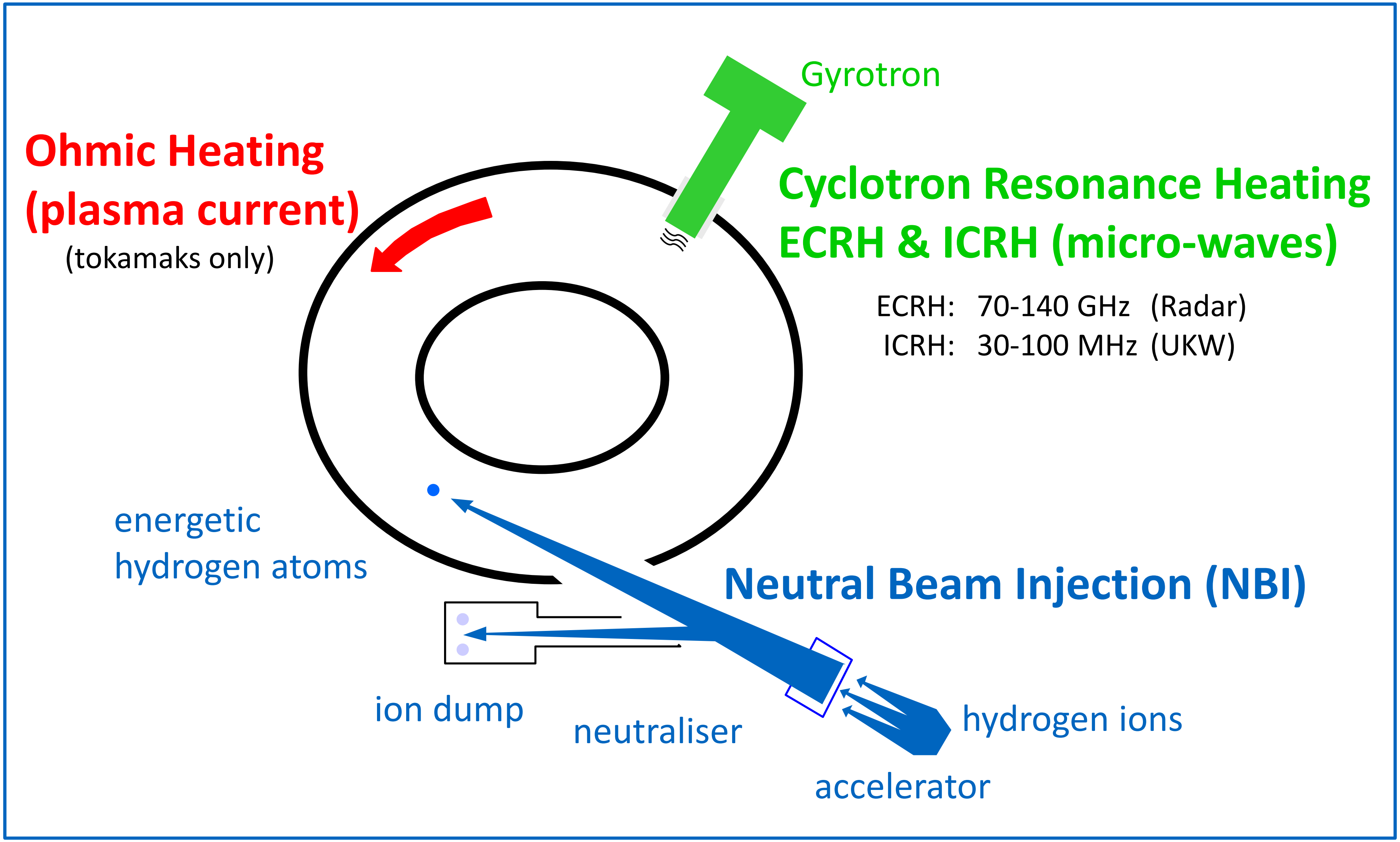
source: IPP 1993

Joint European Torus (JET), Culham, Great Britain



source: EFDA-JET public relations, en.wikipedia "JET"

Plasma Heating



source: IPP

Plasma Heating

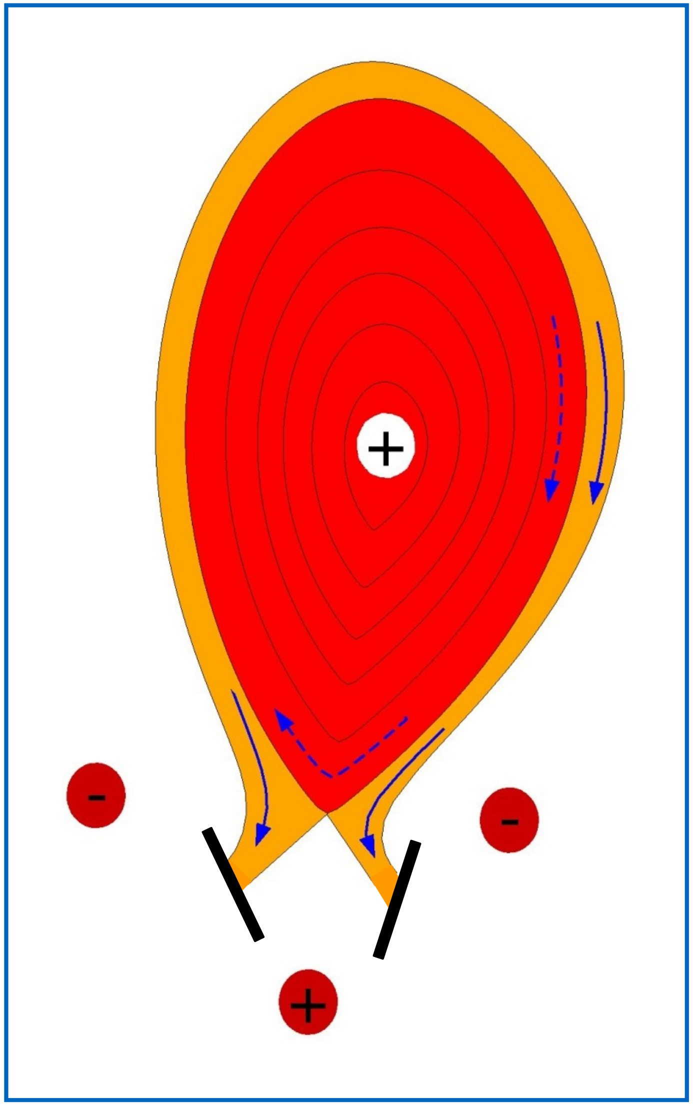
Heating methods in fusion research

- via plasma current (ohmic heating)
  applies to tokamaks
- neutral beam injection (NBI):
  fast particles dissipate their energy
- cyclotron resonance heating:
  accelerates the gyro-motion
  - of ions (ICRH):
    30 - 100 MHz (VHF)
  - of electrons (ECRH):
    70 - 140 GHz (Radar)

Gyrotron IPP Greifswald, source: M. Borchardt 2014

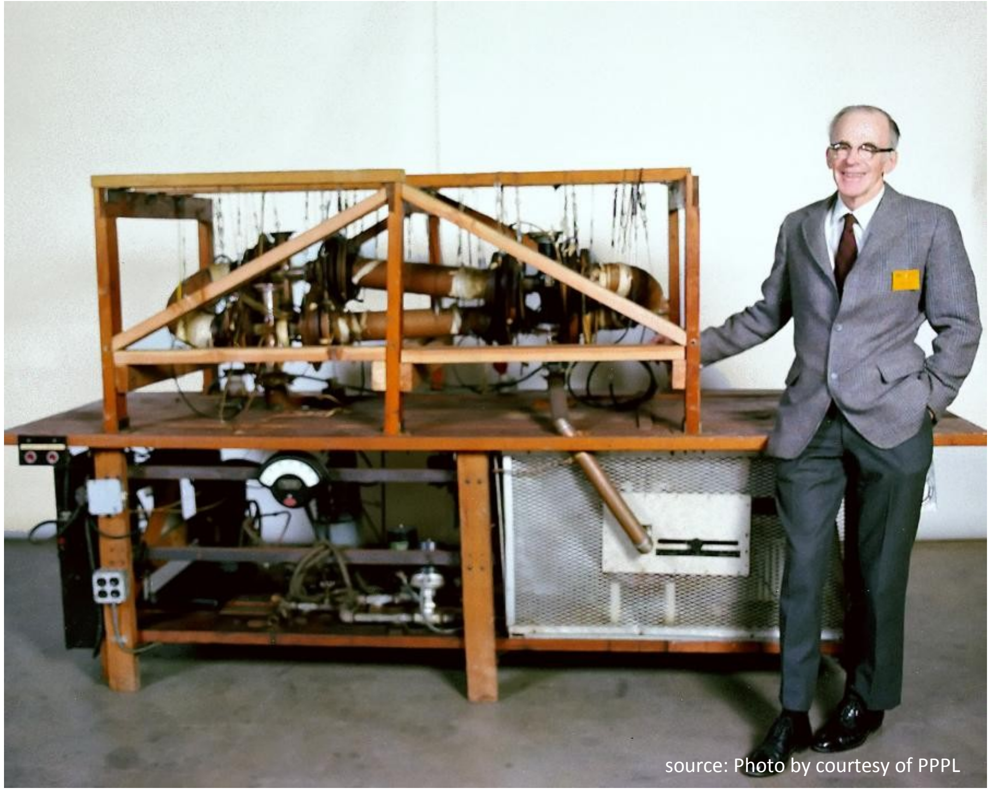
Divertor

- plasma confinement with nested and closed magnetic surfaces
- plasma edge needs to be defined magnetically by additional fields forming a last closed surface (separatrix)
- divertor for the first time successfully used at IPP (ASDEX):
  - clean plasma
  - enhanced confinement (H-mode)
- nowadays a standard element of all larger tokamaks and stellarators for well-defined wall contact



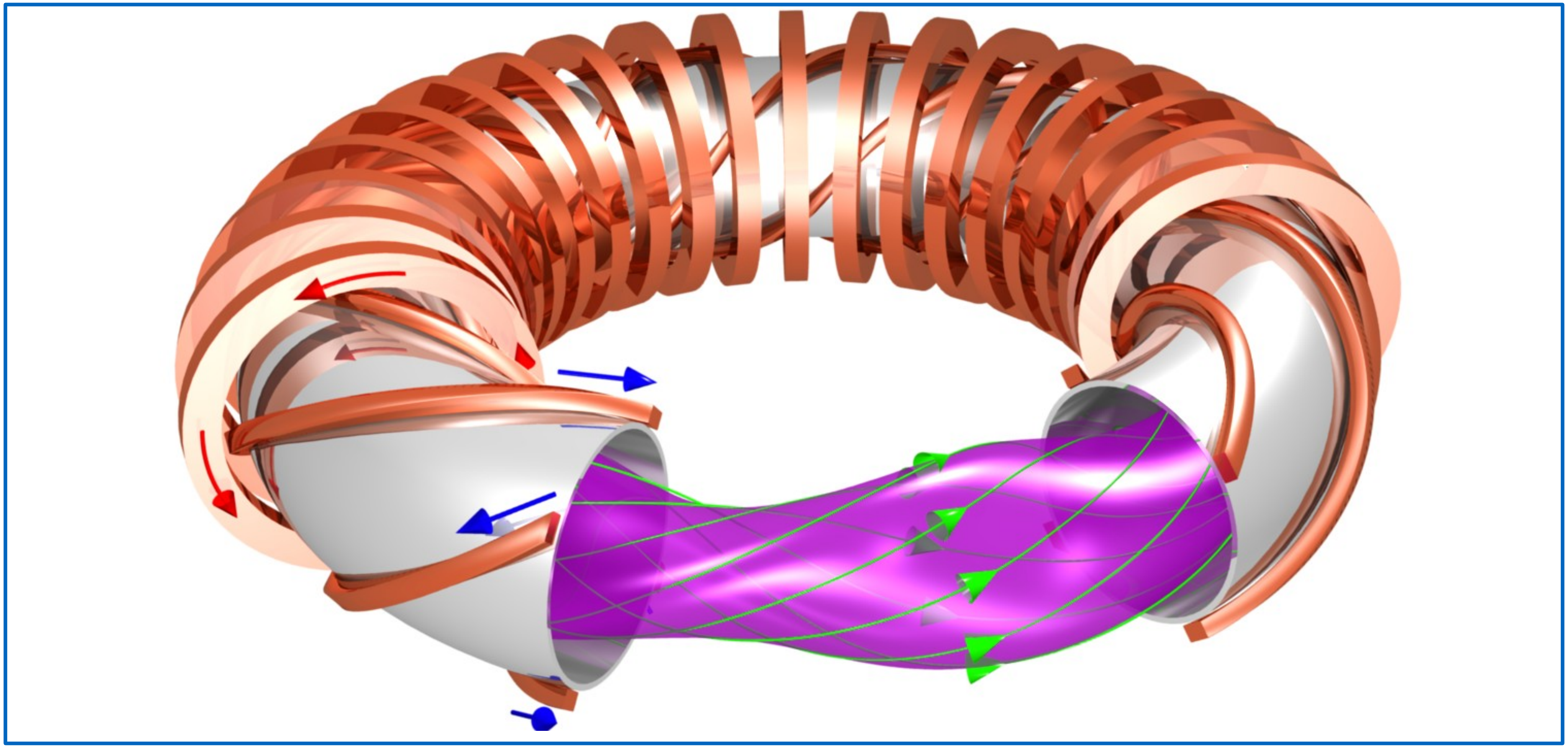
source: IPP

THE STELLARATOR



Stellarator A, Princeton Plasma Physics Laboratory (PPPL), USA

Classical Stellarator

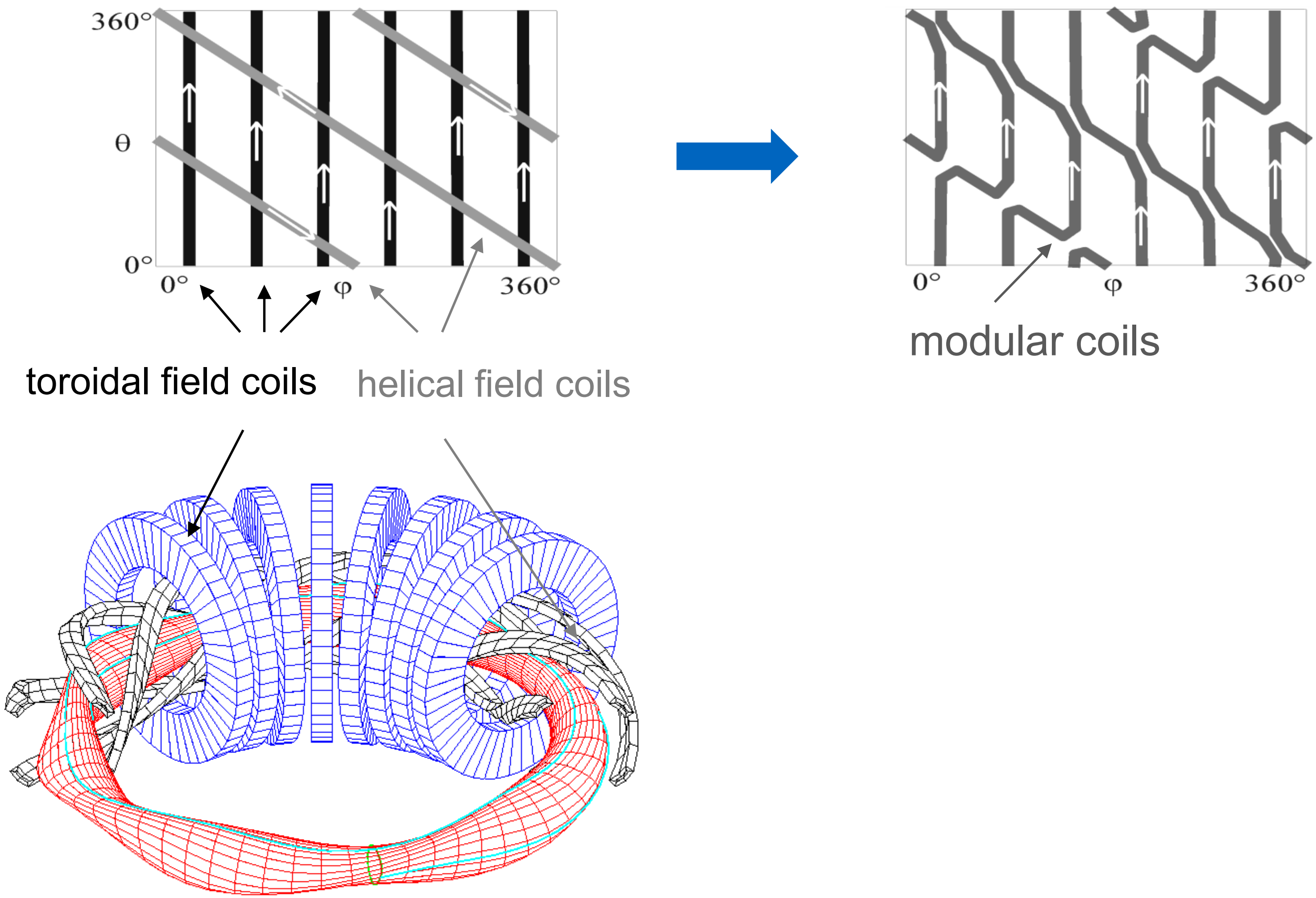


source: Christian Brandt, IPP 2011

- \+ external currents only
- \+ good controllability
- \+ stationary operation
- ⇒ need and potential for optimisation

- – complex three-dimensional geometry
- – reflected particles not confined

Modular Stellarator



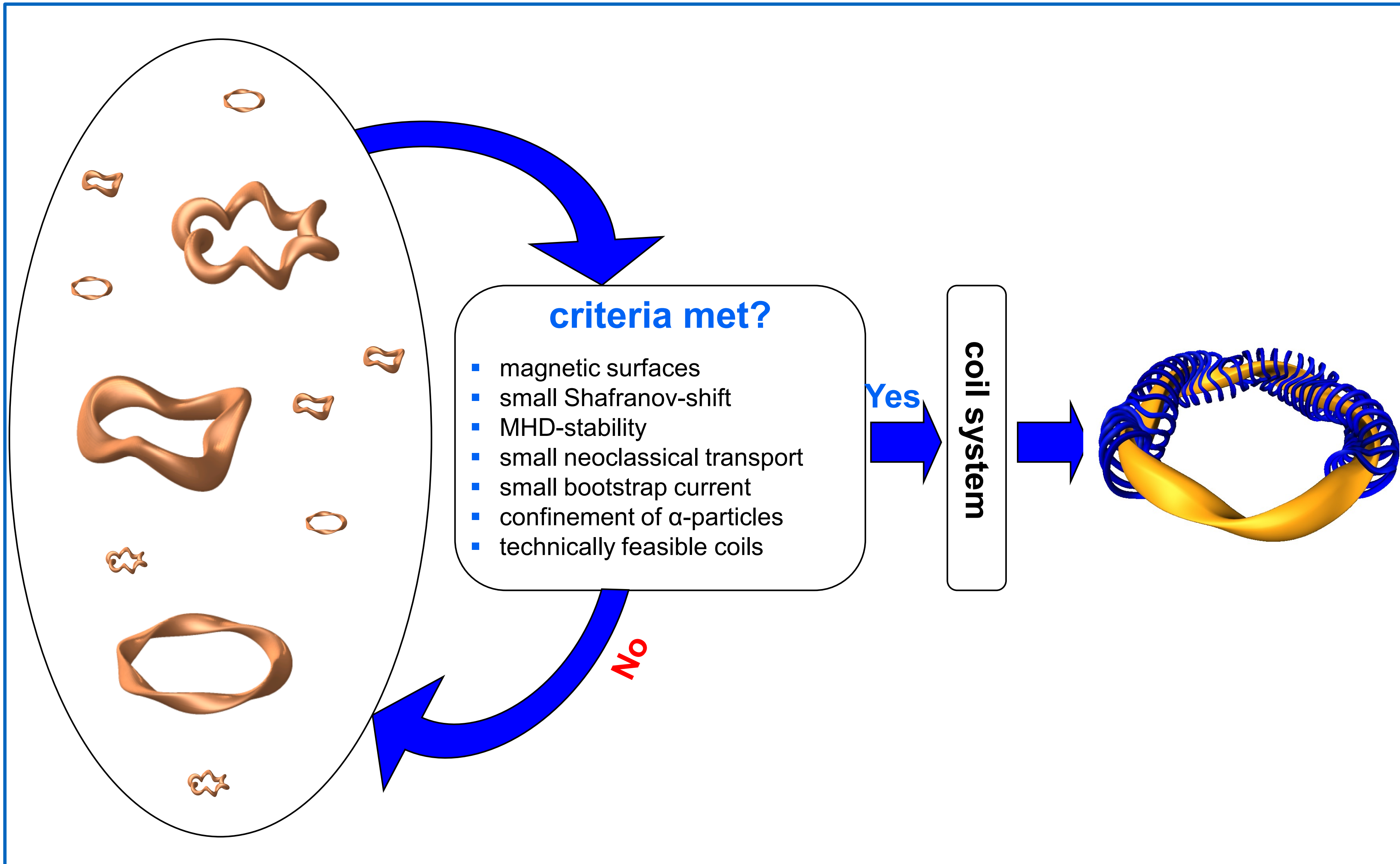
nested

source: IPP

FUSION EXPERIMENT WENDELSTEIN 7-X

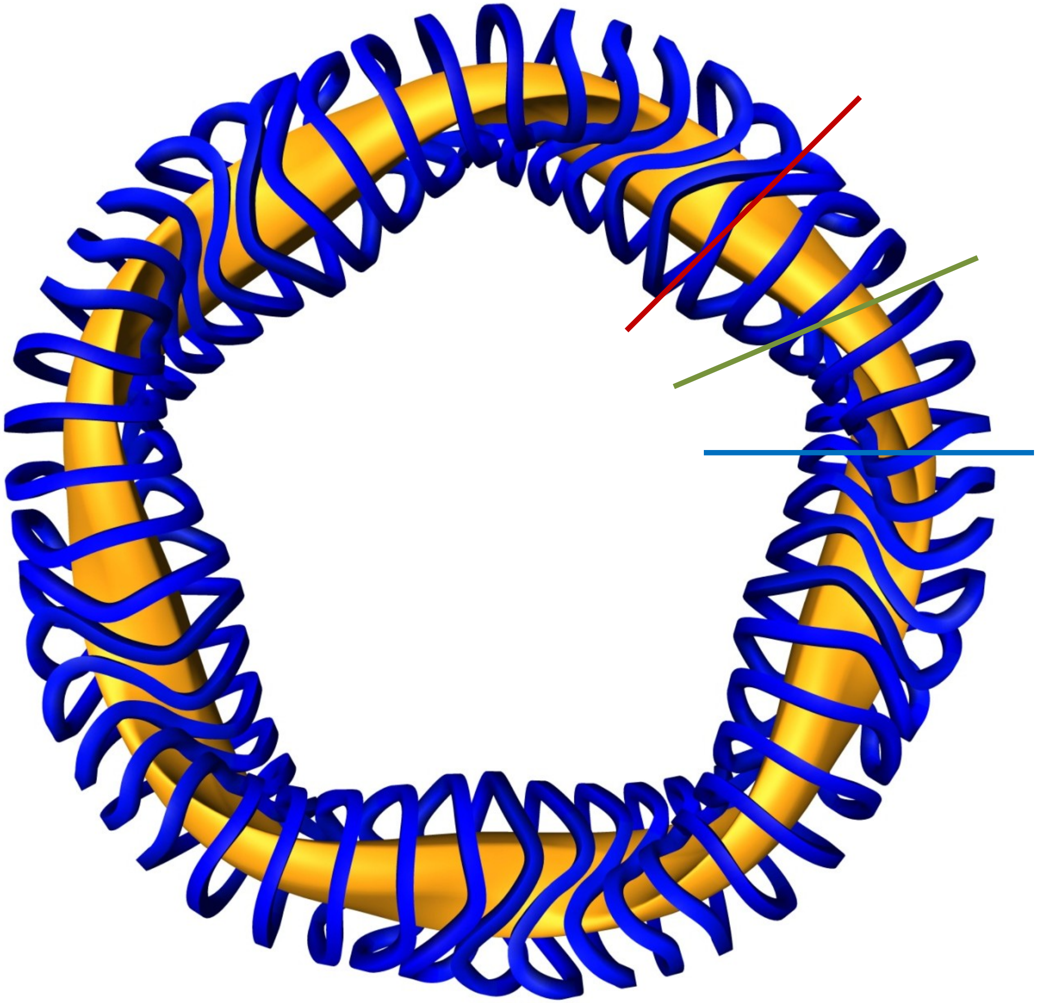
source: B. Kemnitz 2014

Optimised Stellarator

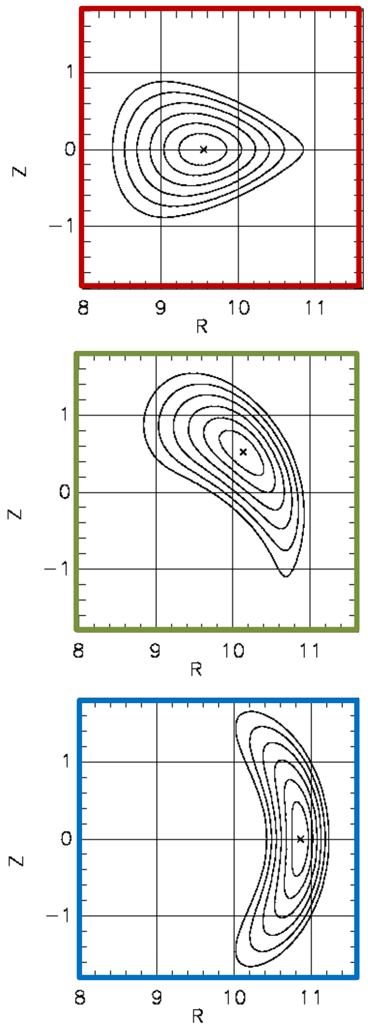


source: R. Kleiber, M. Borchardt 2012

Optimised Stellarator Wendelstein 7-X

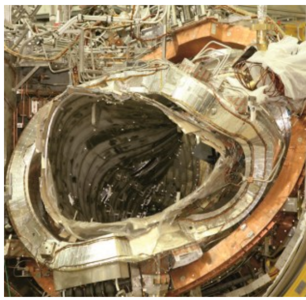
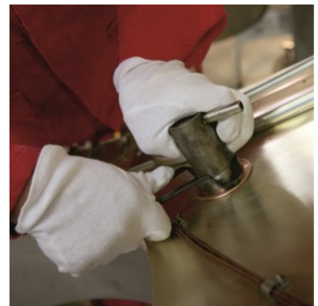
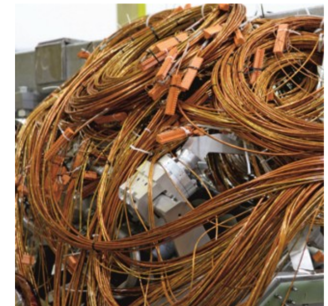


plasma cross section

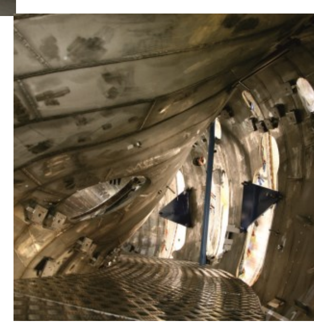
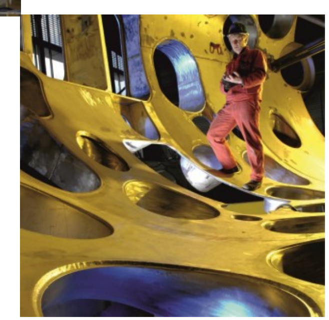


source: M. Borchardt, R. Kleiber 2012/2014

ASSEMBLY OF WENDELSTEIN 7-X

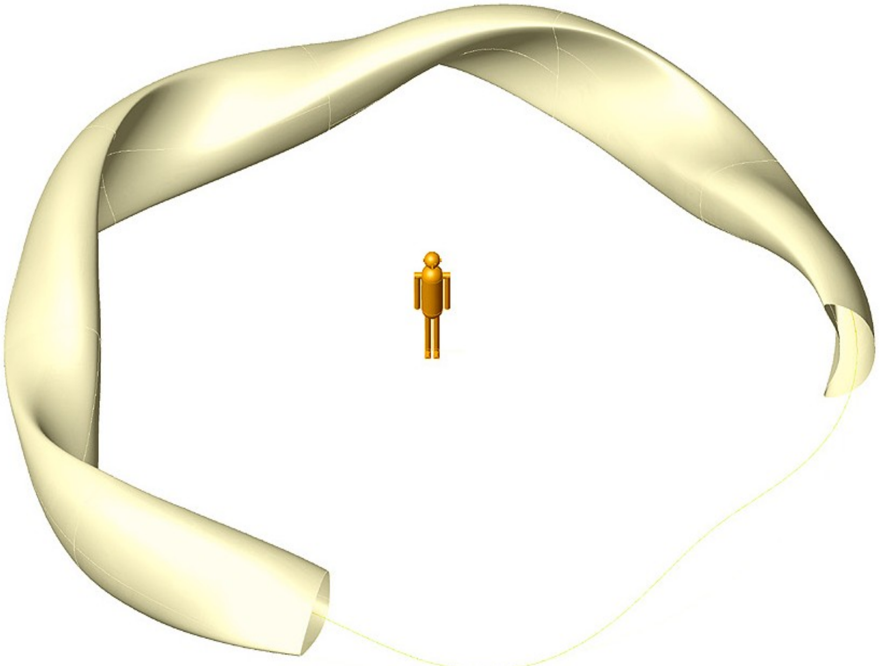






sources: IPP

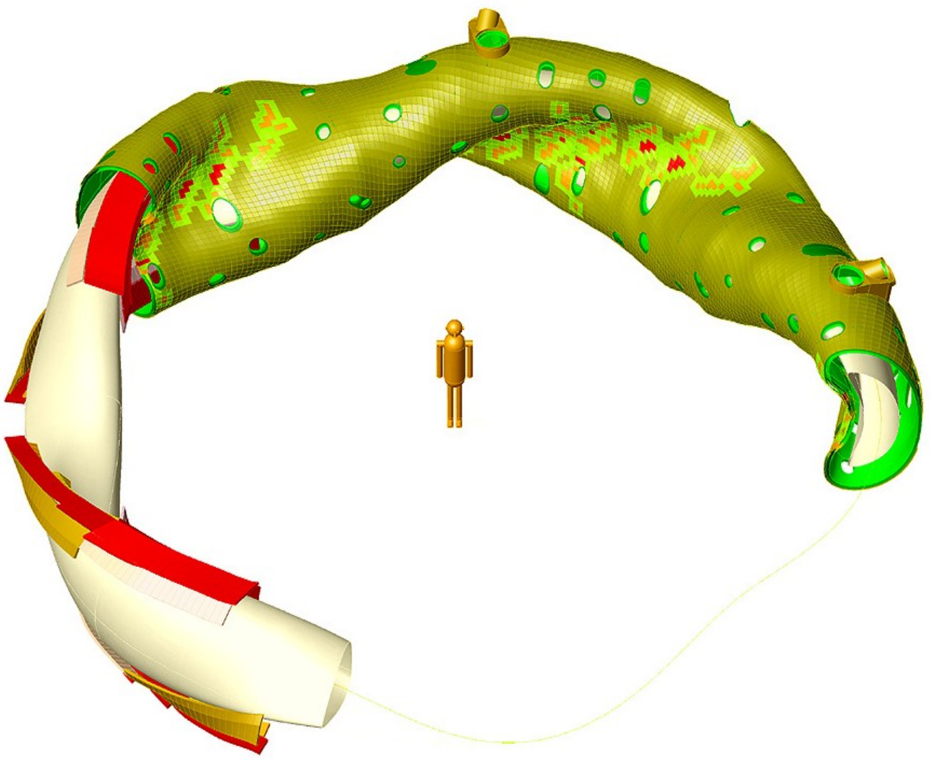
Plasma



Plasma
R: 5.5 m
<a>: 0.53 m

source: IPP

Plasma Vessel

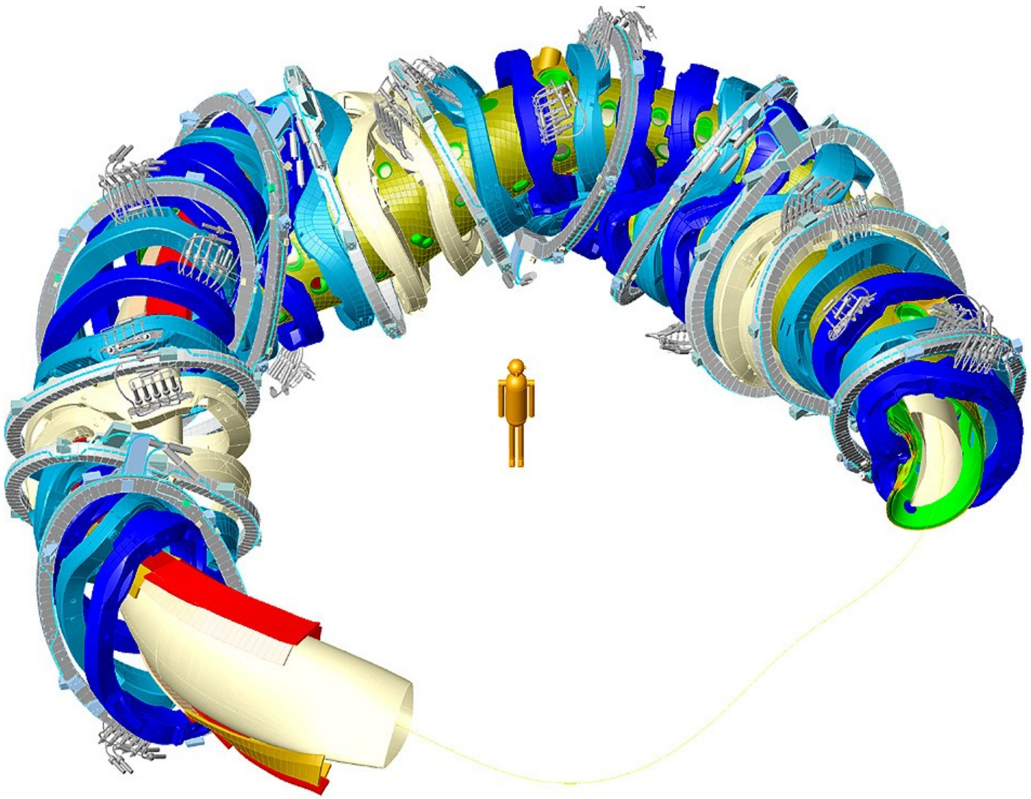


plasma
divertor

plasma vessel
volume: 110 m^3
surface: 200 m^2
vacuum: < 10^{-8} mbar
mass: 35 t
tolerances: < ± 2 mm

source: IPP

Superconducting Coil System

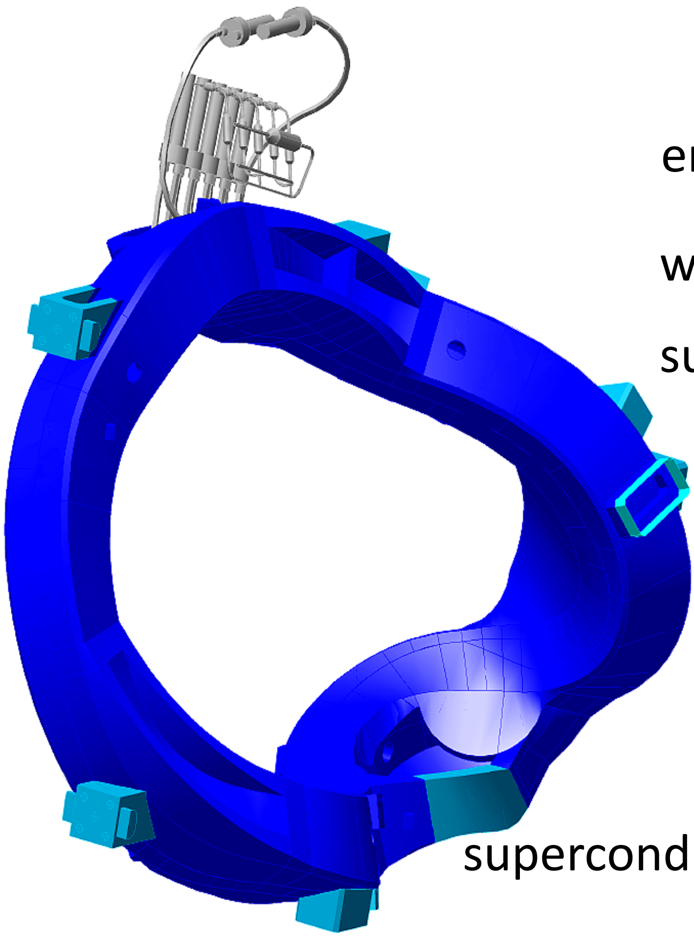


plasma
divertor
plasma vessel

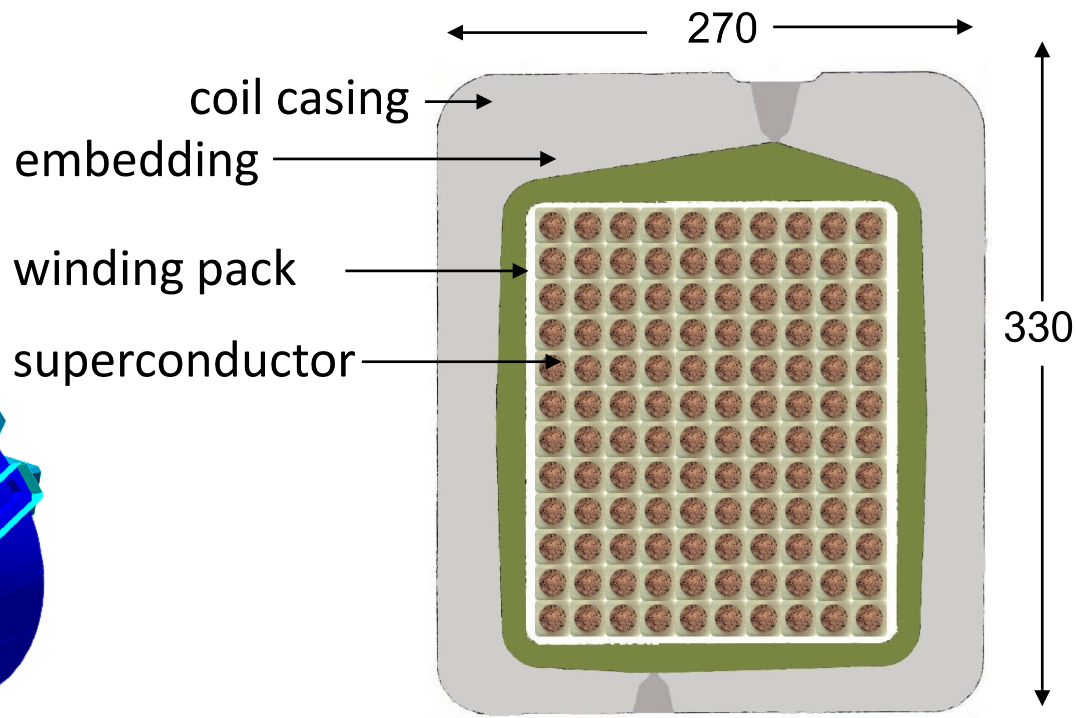
coil system
50 non-planar coils,
20 planar coils,
NbTi superconductors
(T < 3.4 K)
induction on axis:
2.5 T
induction within coil:
6.8 T at 17.8 kA

source: IPP

non-planar superconducting coil



NbTi-superconductor ($T_C \approx 4$ K)



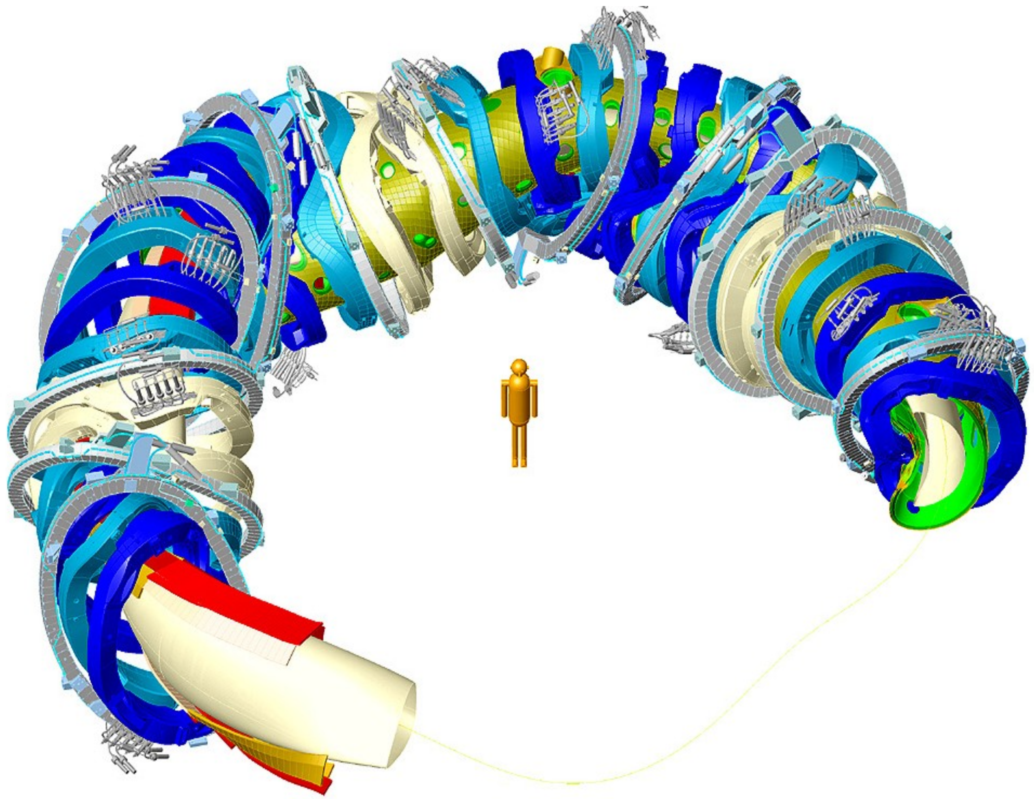
coil cross section

superconductivity: electric resistivity vanishes below a transition temperature T_C

source: IPP

5 modules with 10 non-planar and 4 planar coils each

Superconducting Coil System



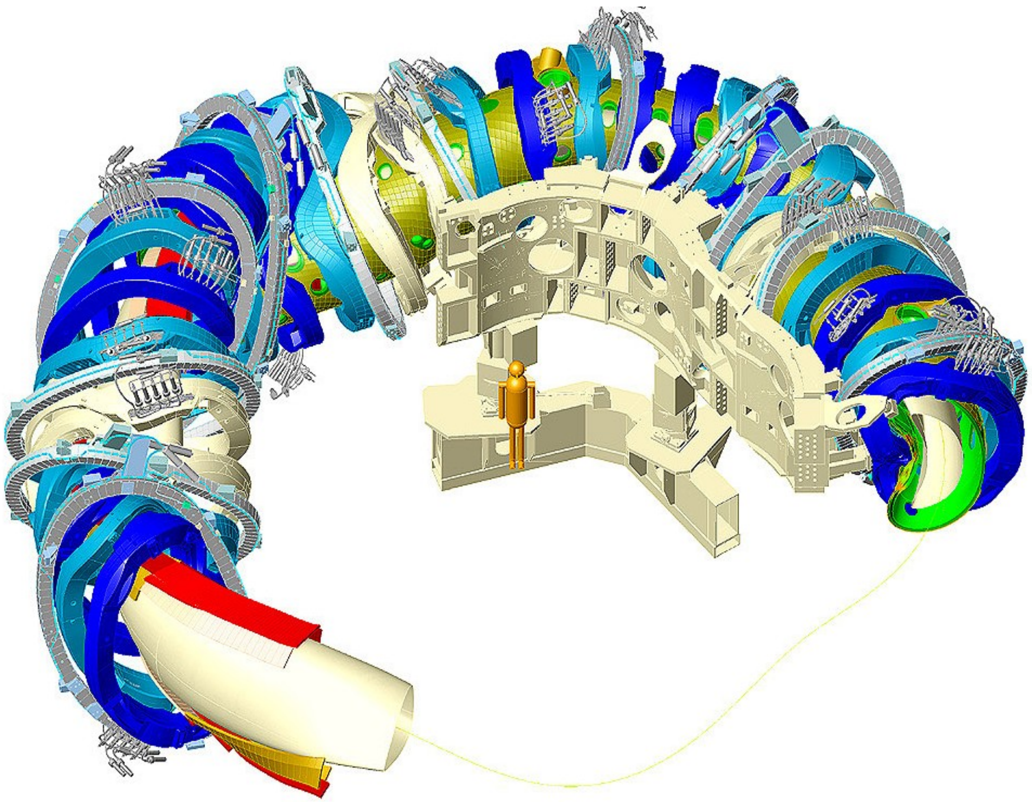
plasma
divertor
plasmavessel

coil system

50 non-planar coils,
20 planar coils,
NbTi superconductors
(T < 3.4 K)
induction on axis:
2.5 T
induction within coils:
6.8 T at 17.8 kA

source: IPP

Central Support

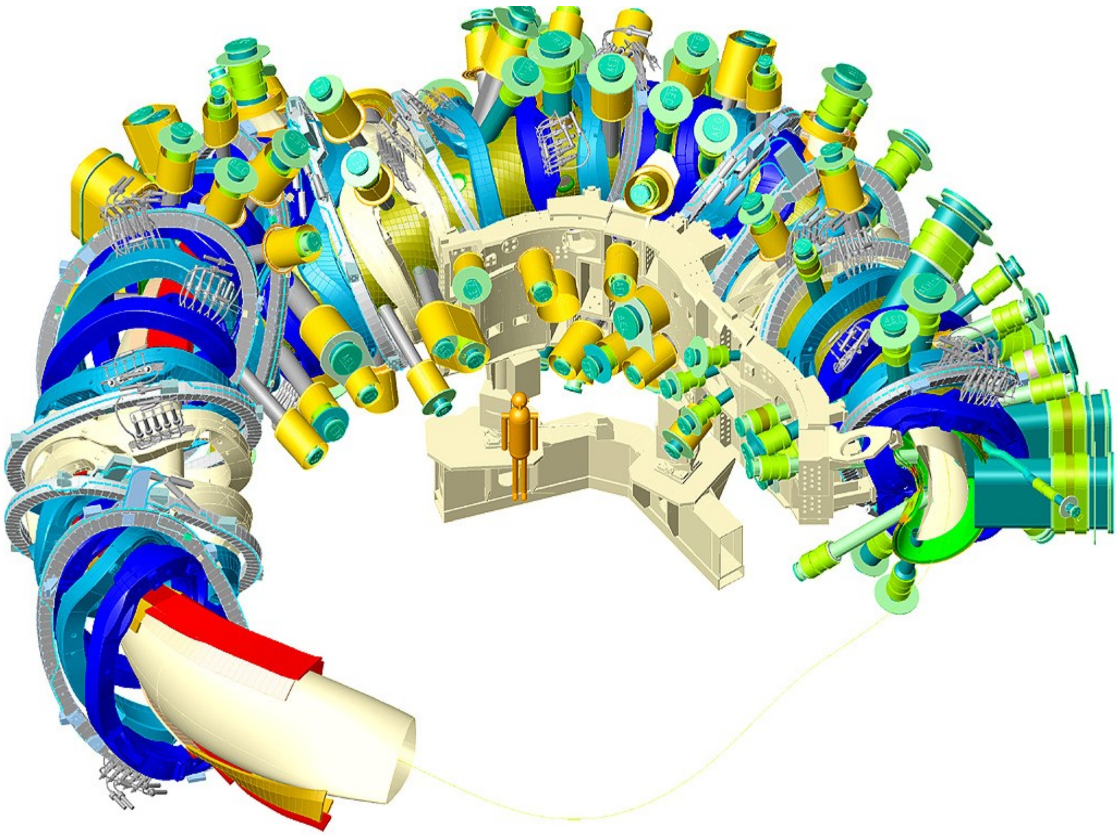


plasma
divertor
plasma vessel
coil system

support structure
max. force/coil: 3.6 MN

Quelle: IPP

Diagnostic Ports

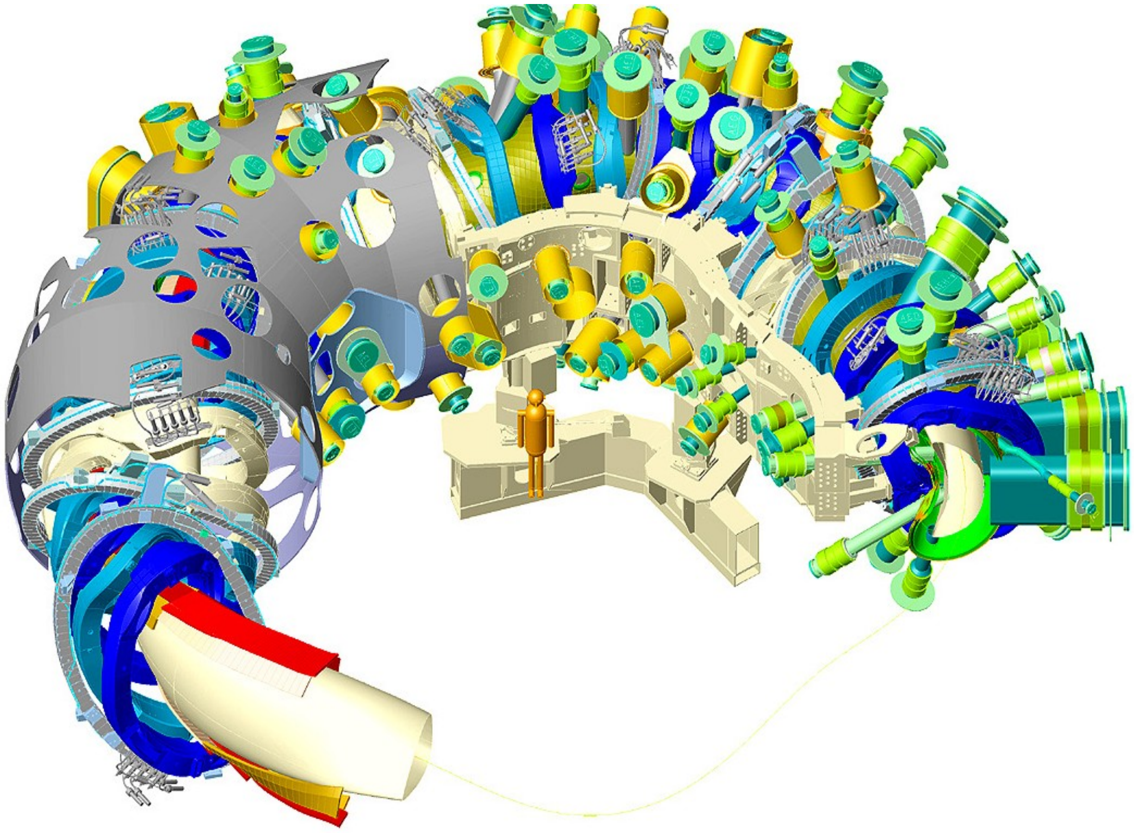


plasma
divertor
plasma vessel
coil system
support structure

ports
254 ports
32 types

source: IPP

Outer Vacuum Vessel (Cryostat)

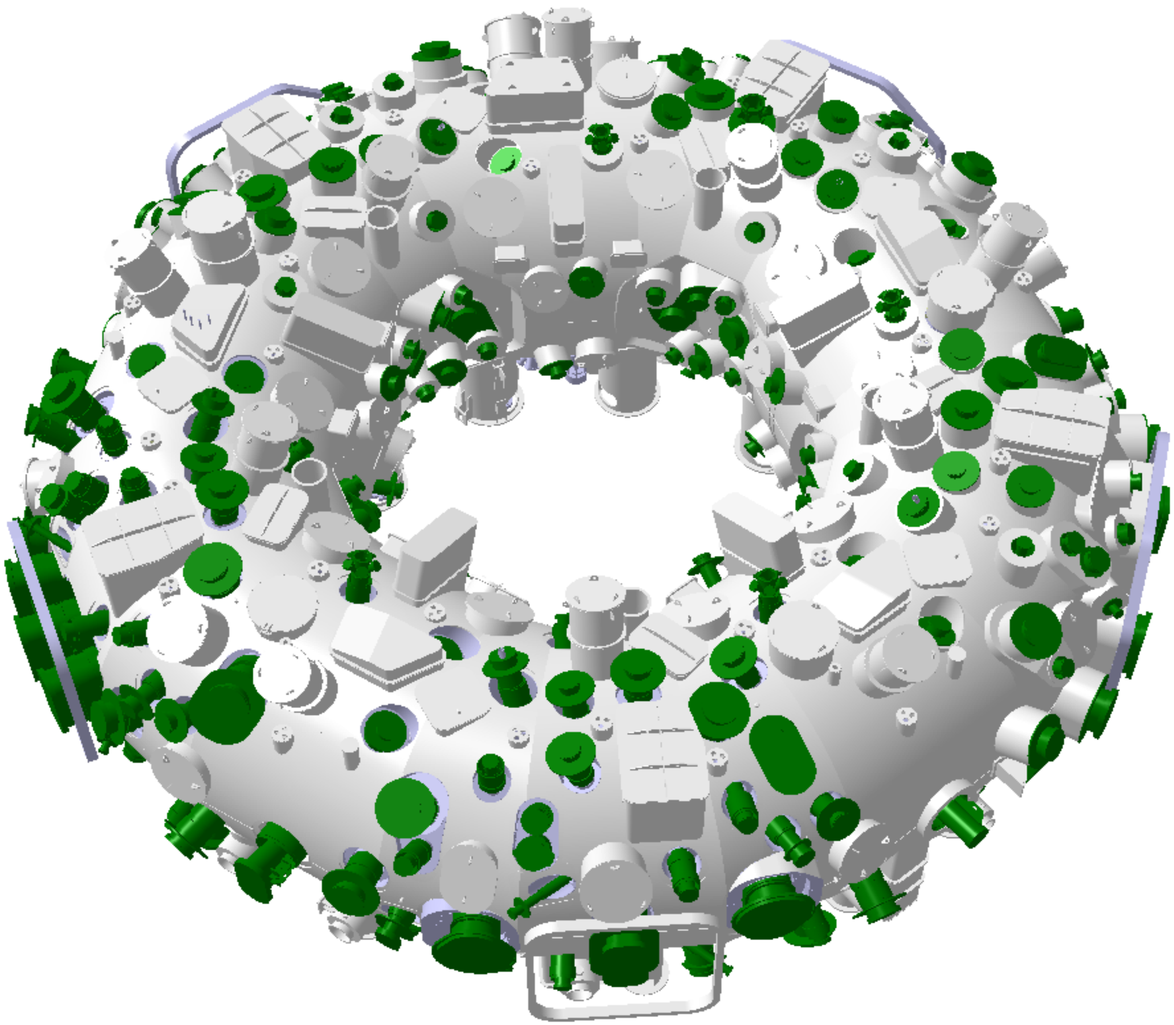


plasma
divertor
plasma vessel
coil system
support structure
ports

cryostat
volume: 525 m^3
surface: 480 m^2
vacuum: < 10^{-5} mbar
mass: 150 t

source: IPP

Simplified View of W7-X

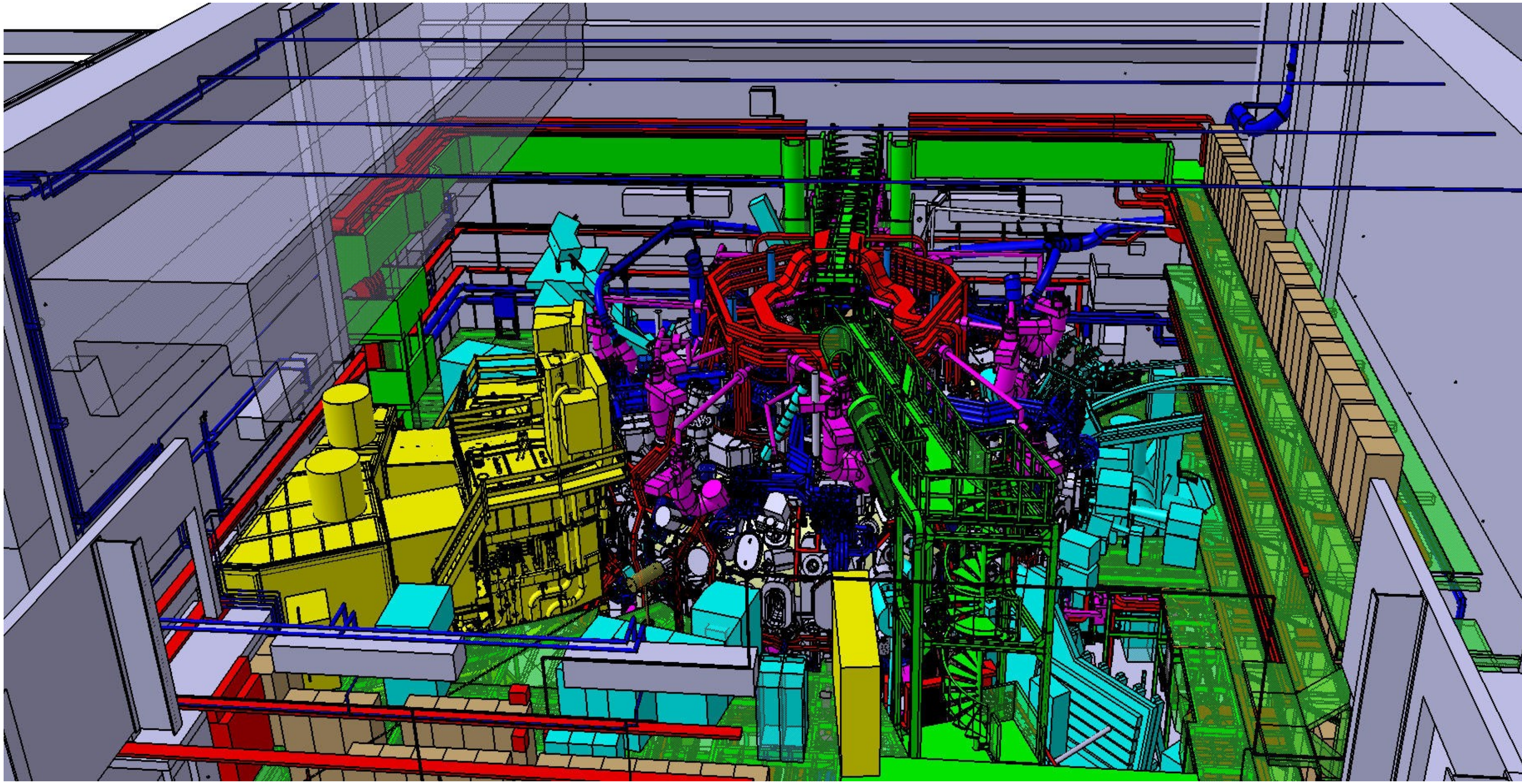


plasma
divertor
plasma vessel
coil system
support structure
ports
cryostat

W7-X
height: 4.5 m
diameter: 16 m
mass: 725 t
cold mass: 425 t
heating power: 15-30 MW
pulse duration: 30 min

source: C. Klug 2008

Periphery of Wendelstein 7-X

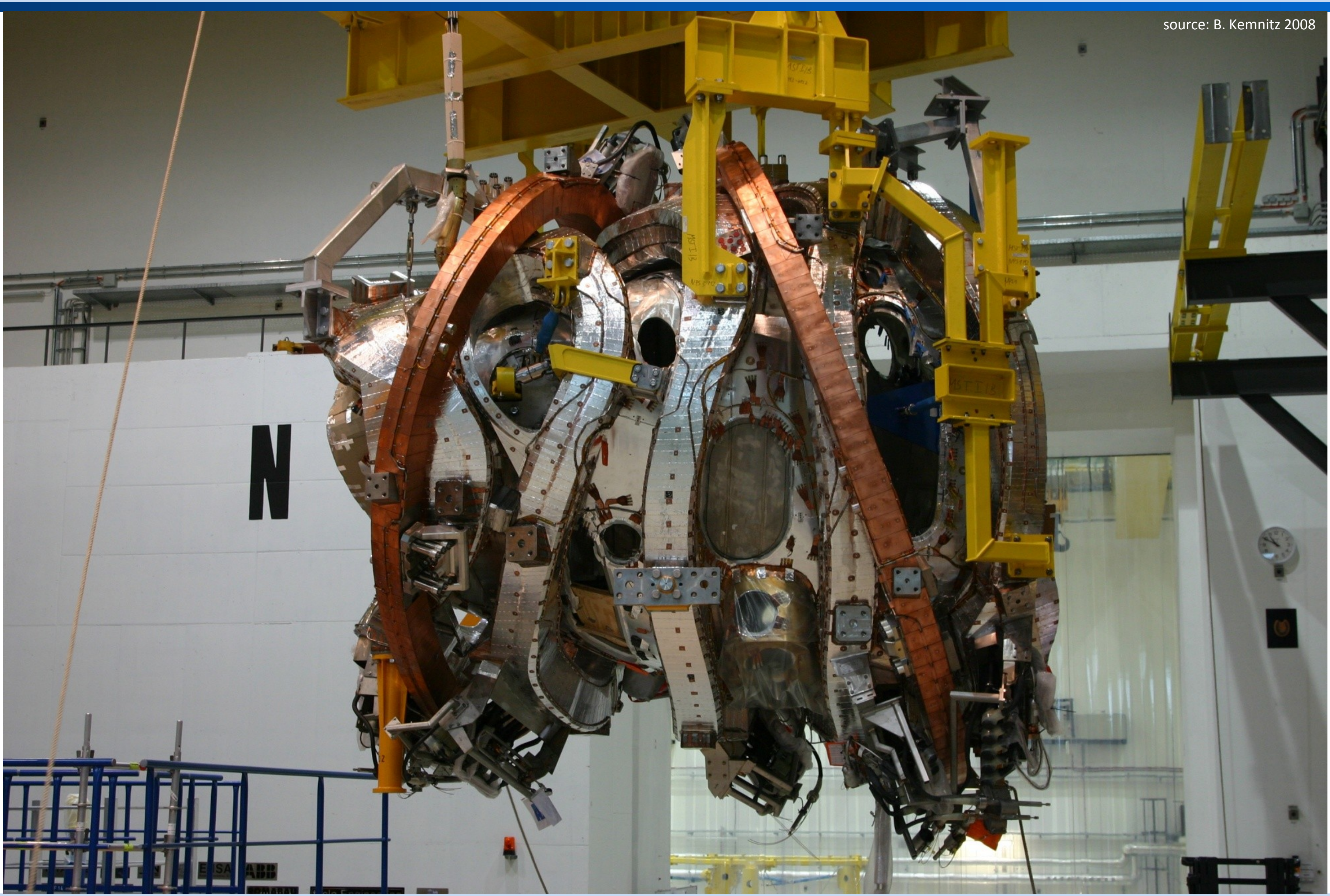


source: IPP

- torus hall with cryostat
- piping (cooling, extinguishing system, gas exhaust)
- cable lines
- Thomson bridge, heavy weight structure etc.
- vacuum systems
- elektronic racks
- heating systems (without ECRH)
- several diagnostic modules

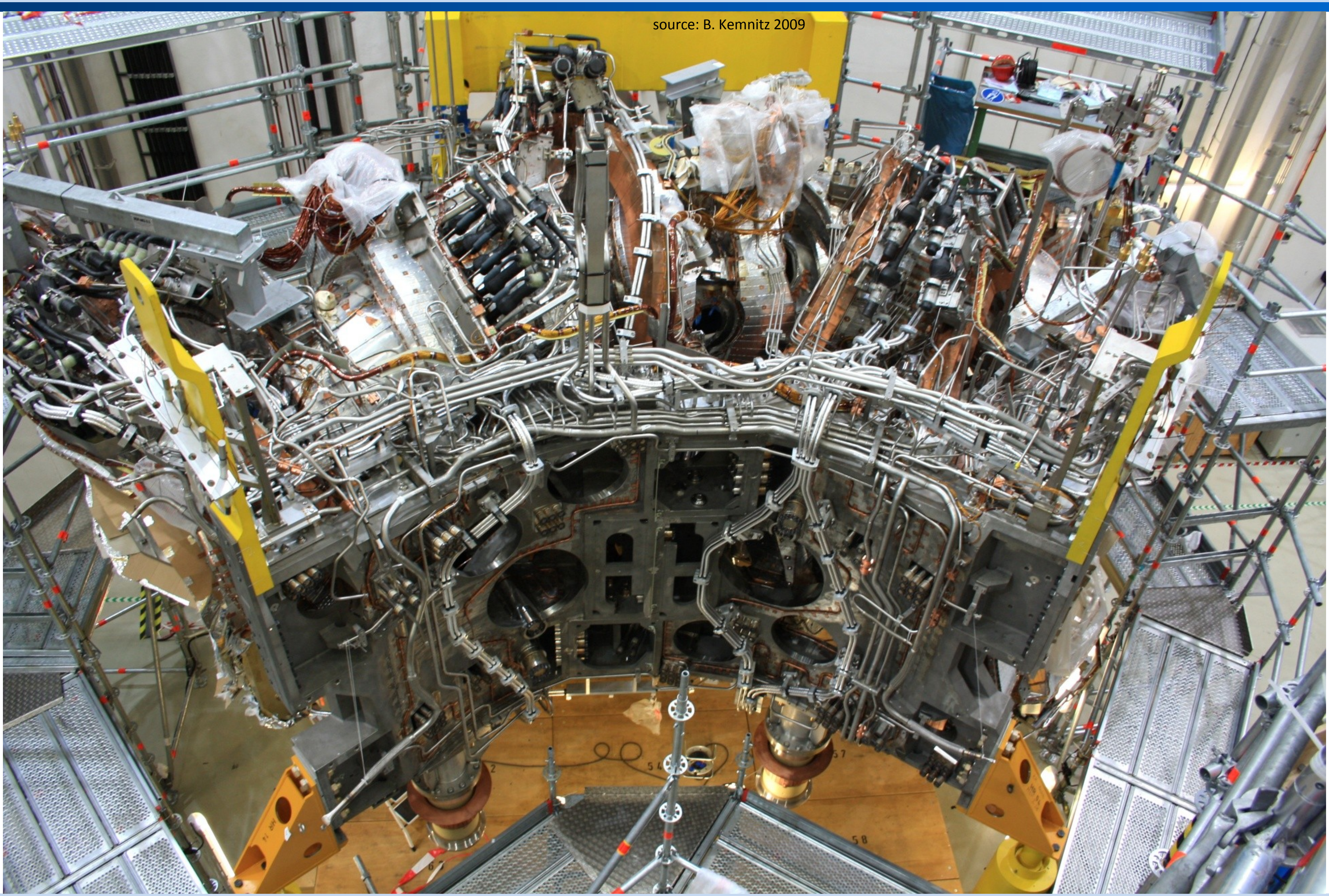
Coil Assembly

Half Module



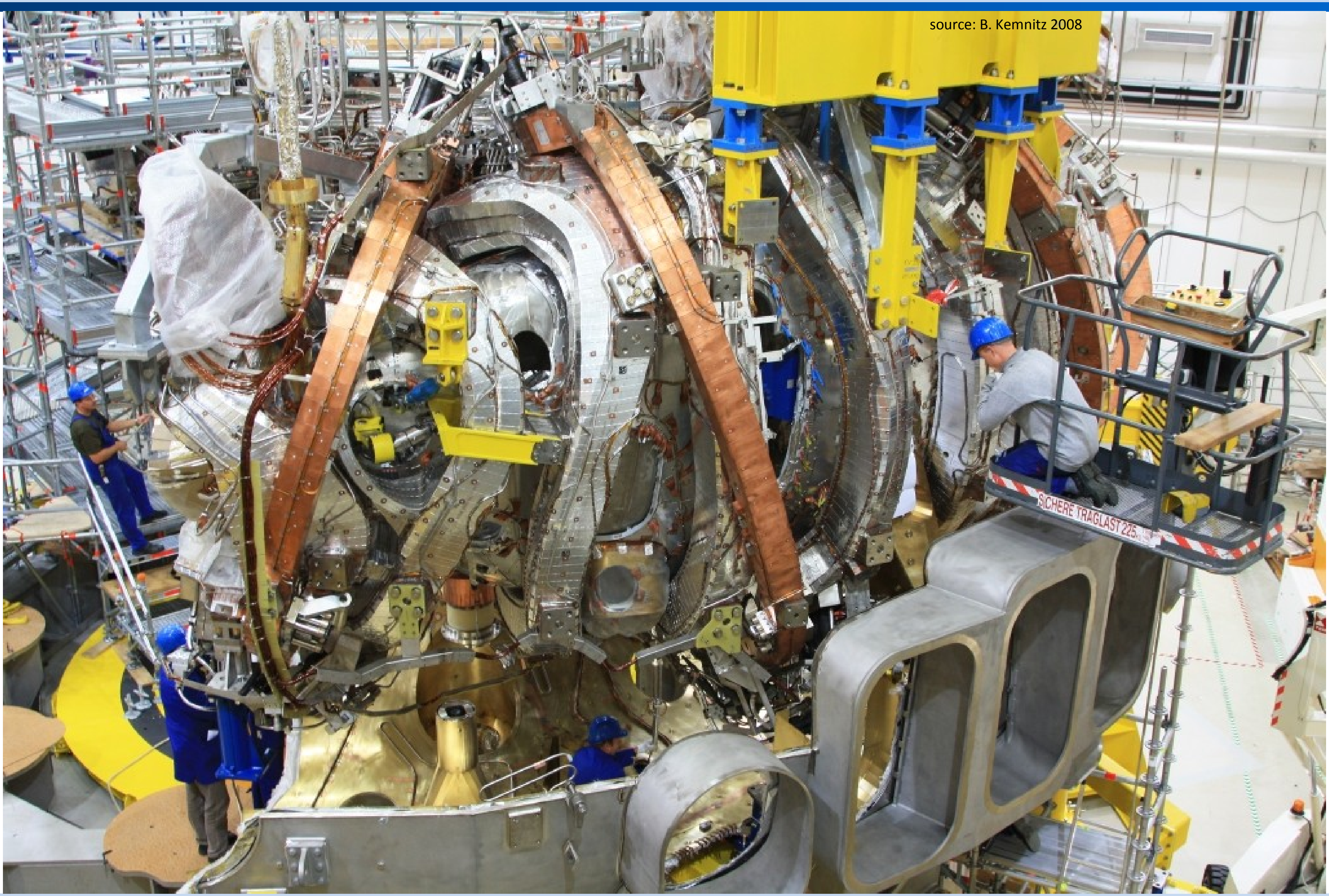
source: B. Kemnitz 2008

Magnetic Module

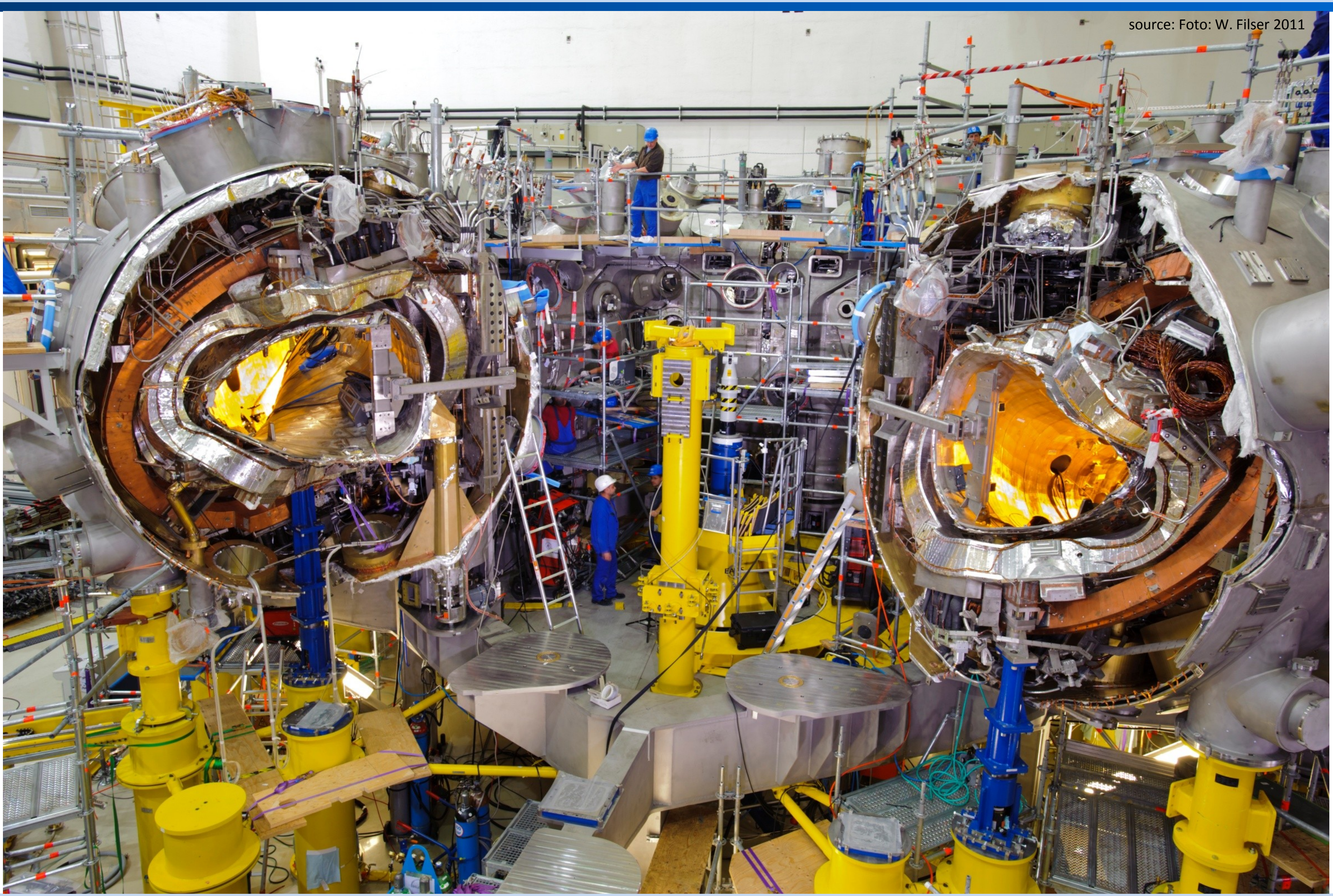


Magnetic Module with Lower Half of Cryostat

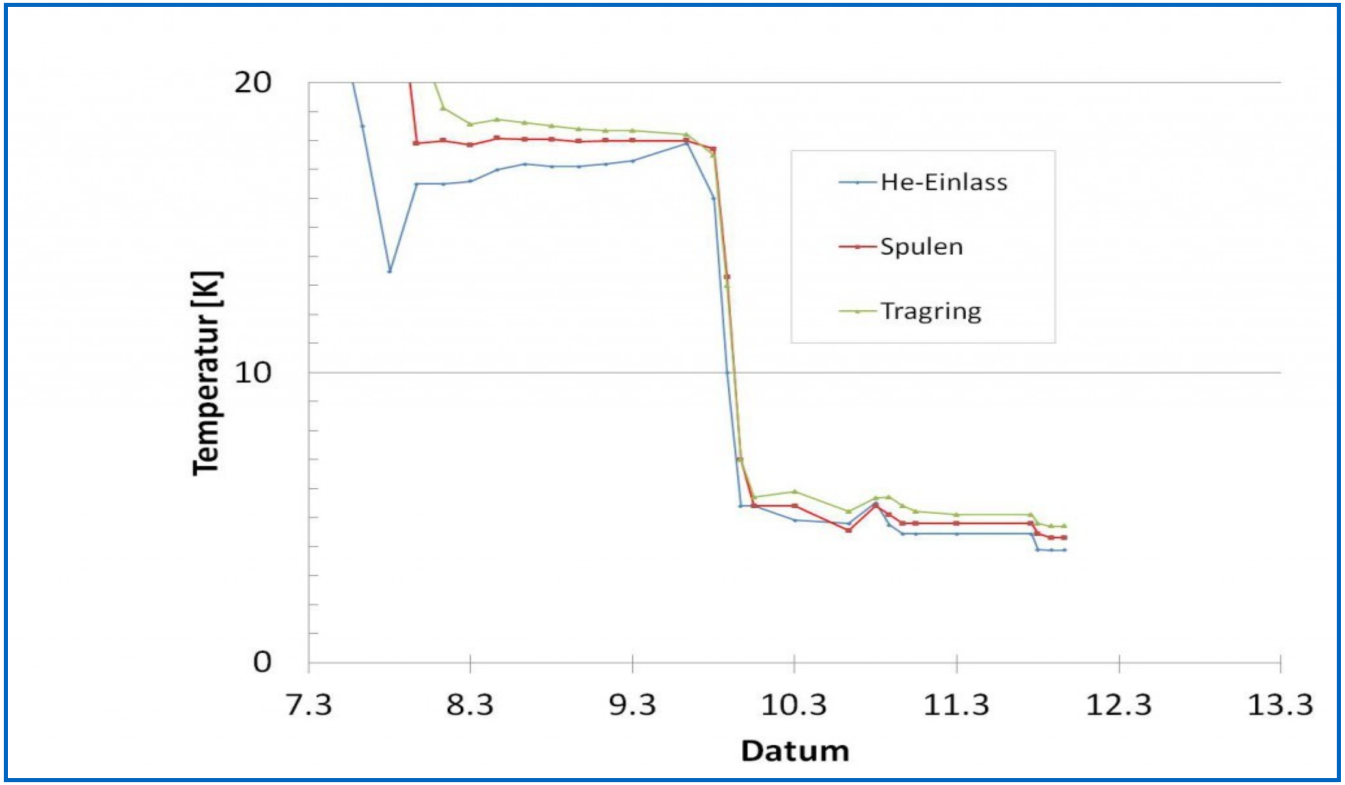
source: B. Kemnitz 2008



View into Torus Hall



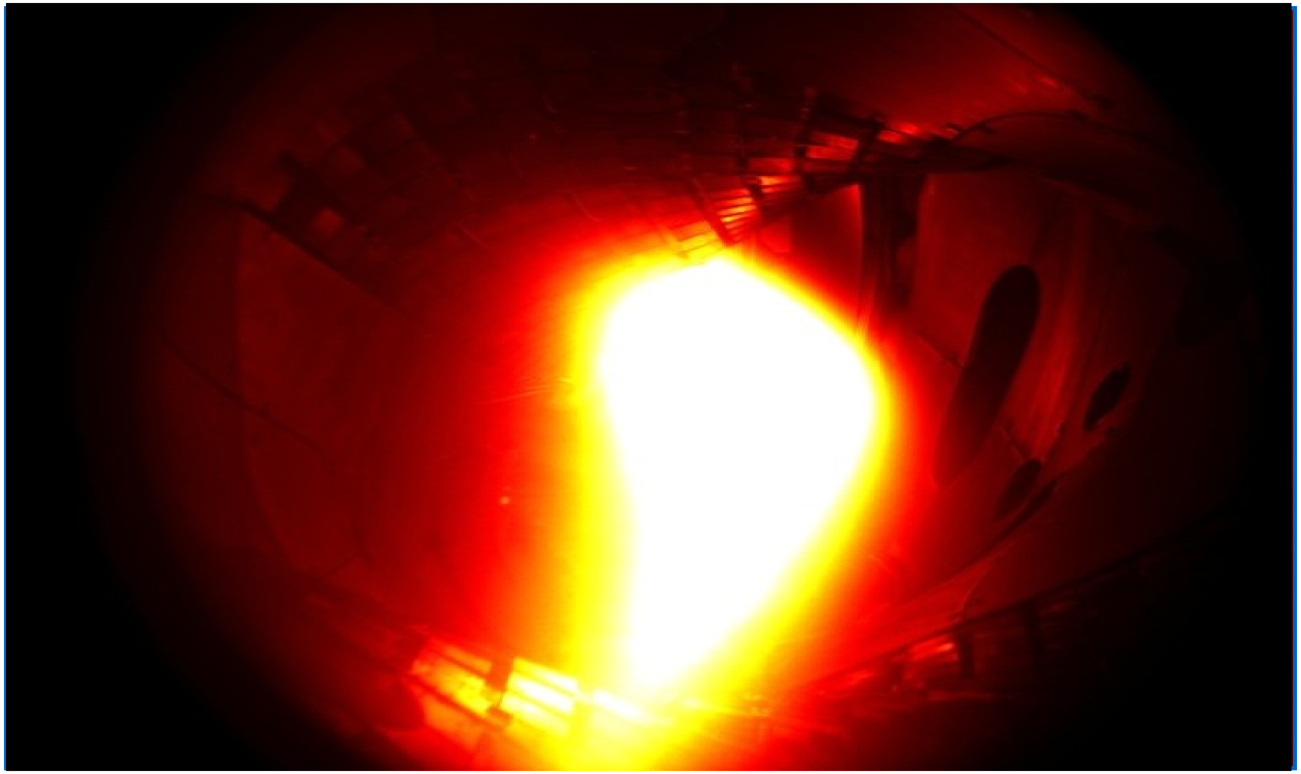
Milestones 2015 (I)



- source: H.S. Bosch (w7x-blog)

- successful cool-down of cryostat (III/2015)
- successful test of magnetic system (VI/2015)
- successful evacuation of plasma vessel (VI/2015)

Milestones 2015 (II)



- source M. Otte (IPP)

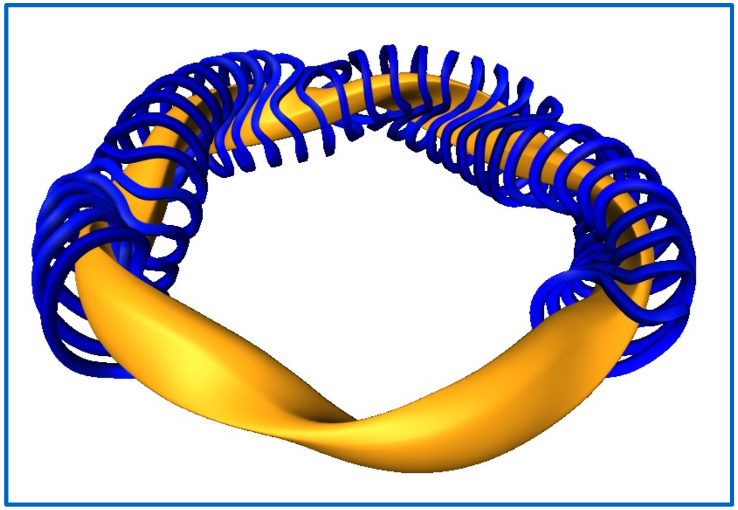
- first flux surface measurements (VII/2015)
- bake-out of plasma vessel (IX/2015)
- first plasma (XII/2015)

Nine Years in Three Minutes

Time-lapse movie of assembly

Goals of the Wendelstein 7-X Project

- confirm:
  - feasibility (coil system)
  - successful optimisation
  - long-pulse operation (suitability for power plant)
- extensive research programme:
  - transport of plasma and impurities
  - efficiency of non-ohmic heating (ECRH, ICRH, NBI)
  - control of boundary layer plasmas (divertor)
  - verification of numerical models

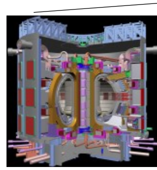


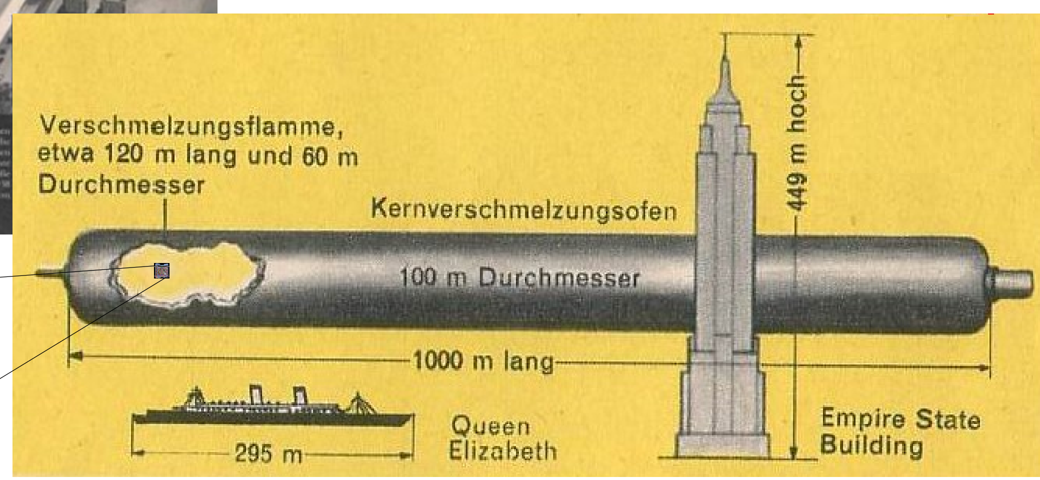
Quelle: M. Borchardt 2012

W7-X is an experiment and will not produce any energy
(HH and HD plasmas only)

Do stellarators play a role for future power plants?

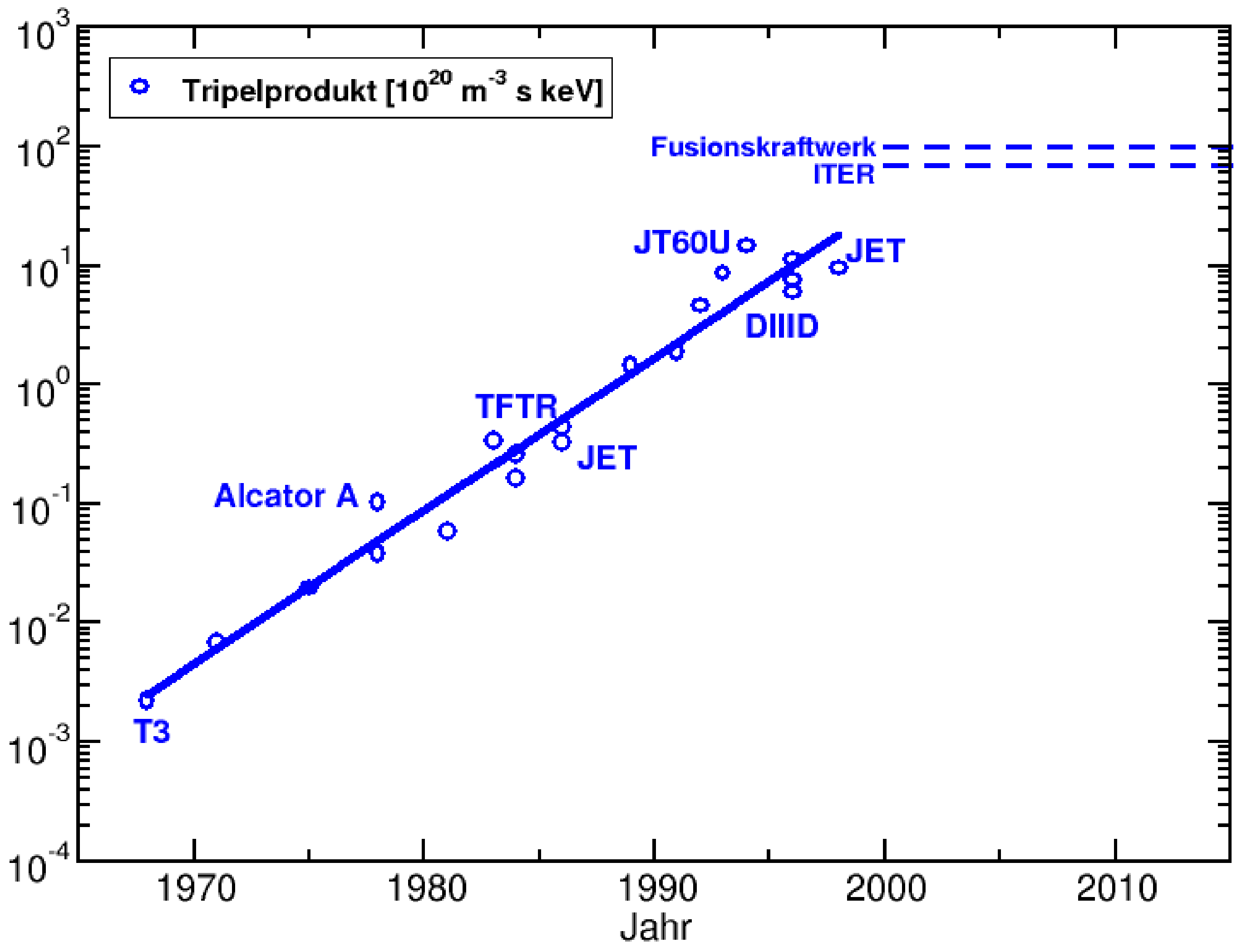
SUMMARY & OUTLOOK





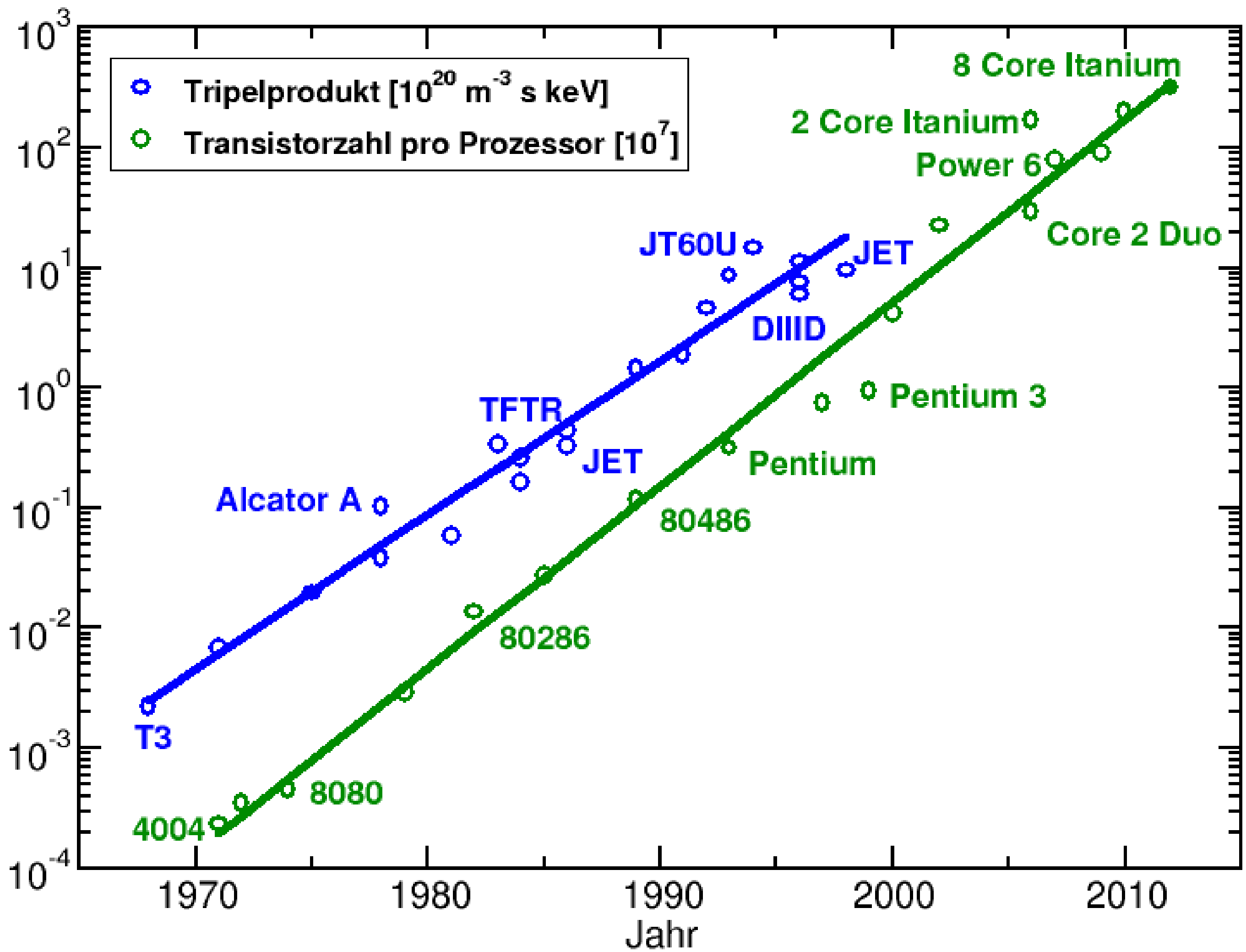
source: article in "Hobby", 1957, Nr. 8, S. 68

Progress in Fusion Research



Quelle: R. Kleiber 2012

Progress in Fusion Research



Quelle: R. Kleiber 2012

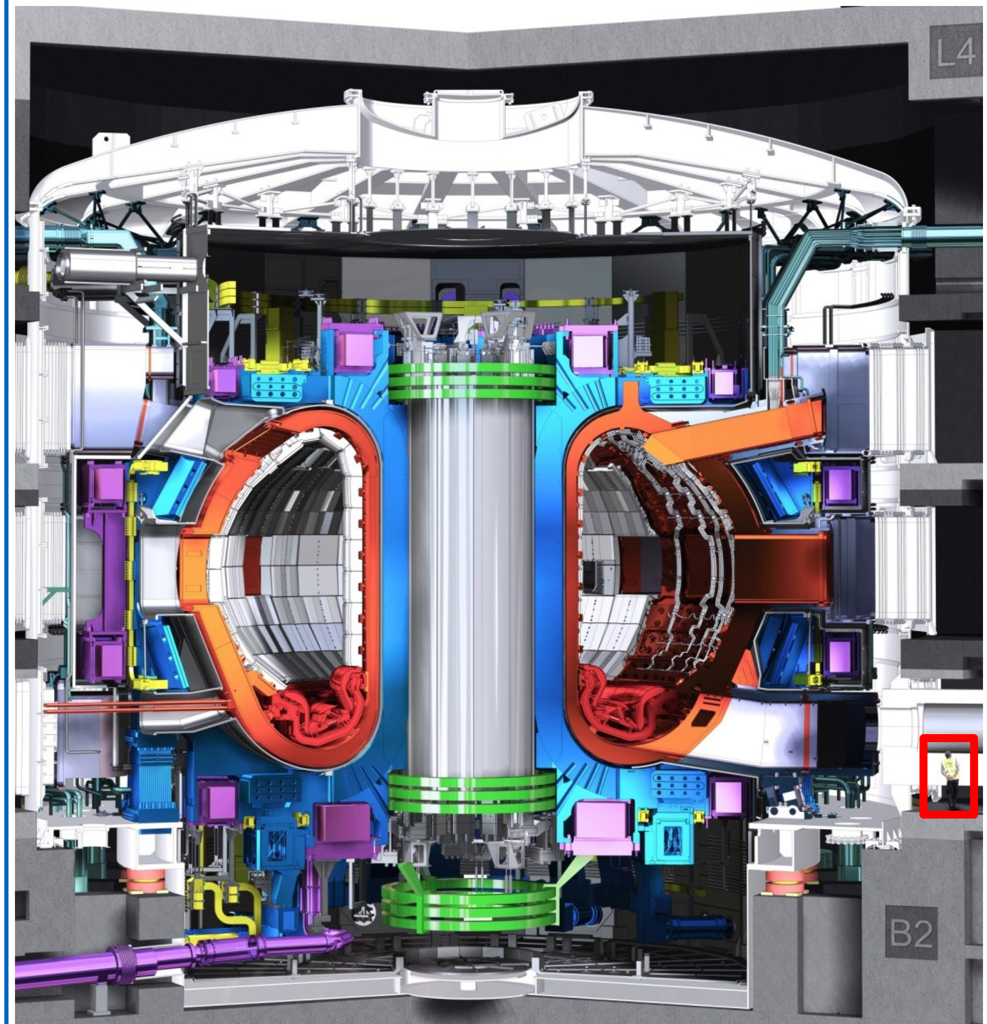
ITER

- final report: 2001
- site: CEA Cadarache
- start of construction: 2009
- first plasma: 2025

The purpose of ITER is to show the scientific and technological feasibility of fusion power.

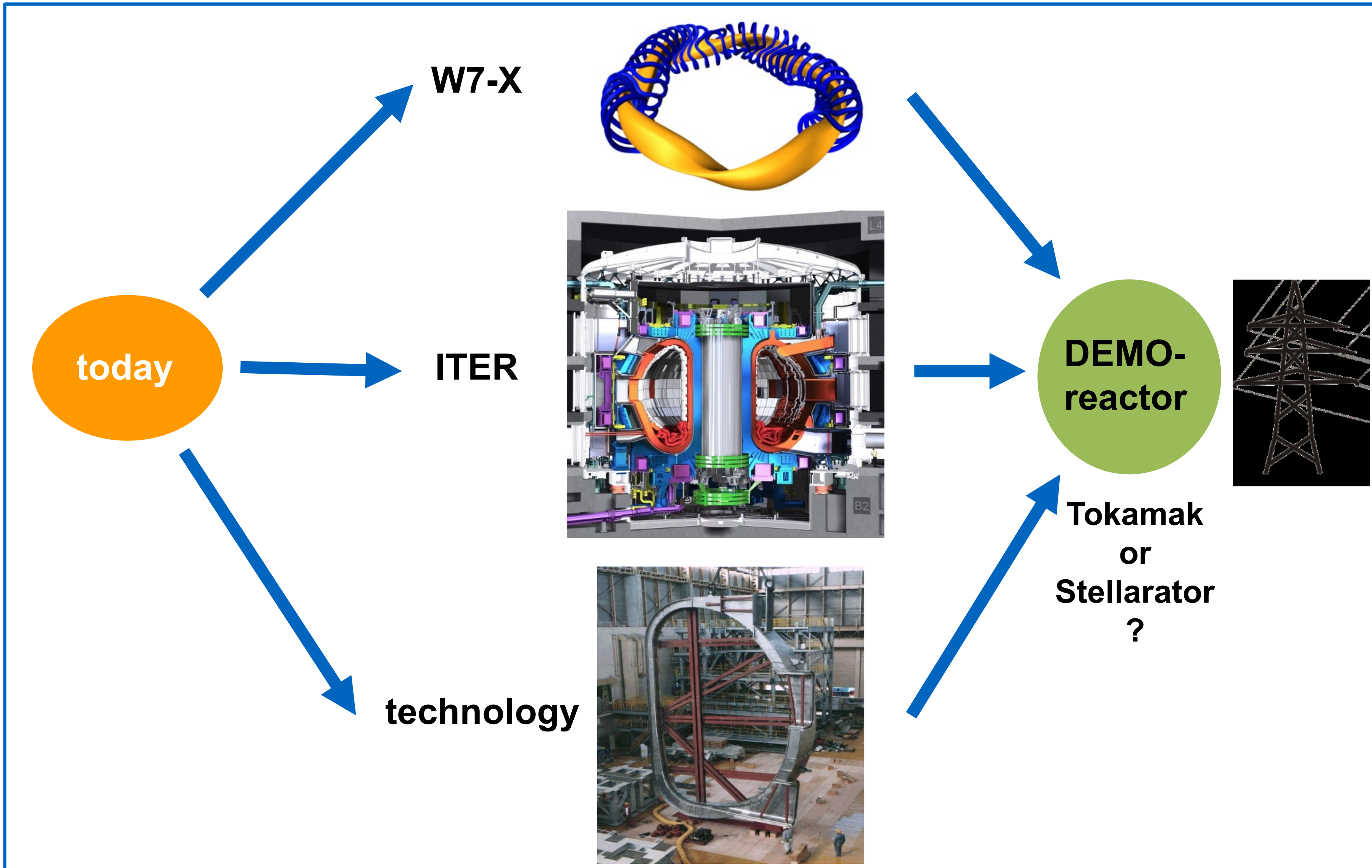
basic specifications

R [m]	6.2
a [m]	2.0
T_{Puls} [s]	300
P_{Fusion} [MW]	500
power gain (Q)	10
cost [G€]	15



Quelle: ITER 2013

The Path towards a Power Plant



Quelle: R. Kleiber 2013

Open Problems

Tokamaks

- advanced operational scenarios, i.e. current drive
- suppression of disruptions
- control of edge localised plasma bursts (ELMs): 10 GW/m^2 for ITER

Stellarators

- suitability of the stellarator for power generation
- impurity transport and confinement of α-particles

Materials and Technology

- divertor materials: high heat fluxes (10 MW/m^2)
- wall materials: fatigue caused by strong neutron flux
- robotic maintenance technology (remote handling)

Fuel Cycle

- development of blanket technology
- breeding ratio of 1.1 -1.15 required
- implementation of Tritium cycle
- exhaust of helium ash

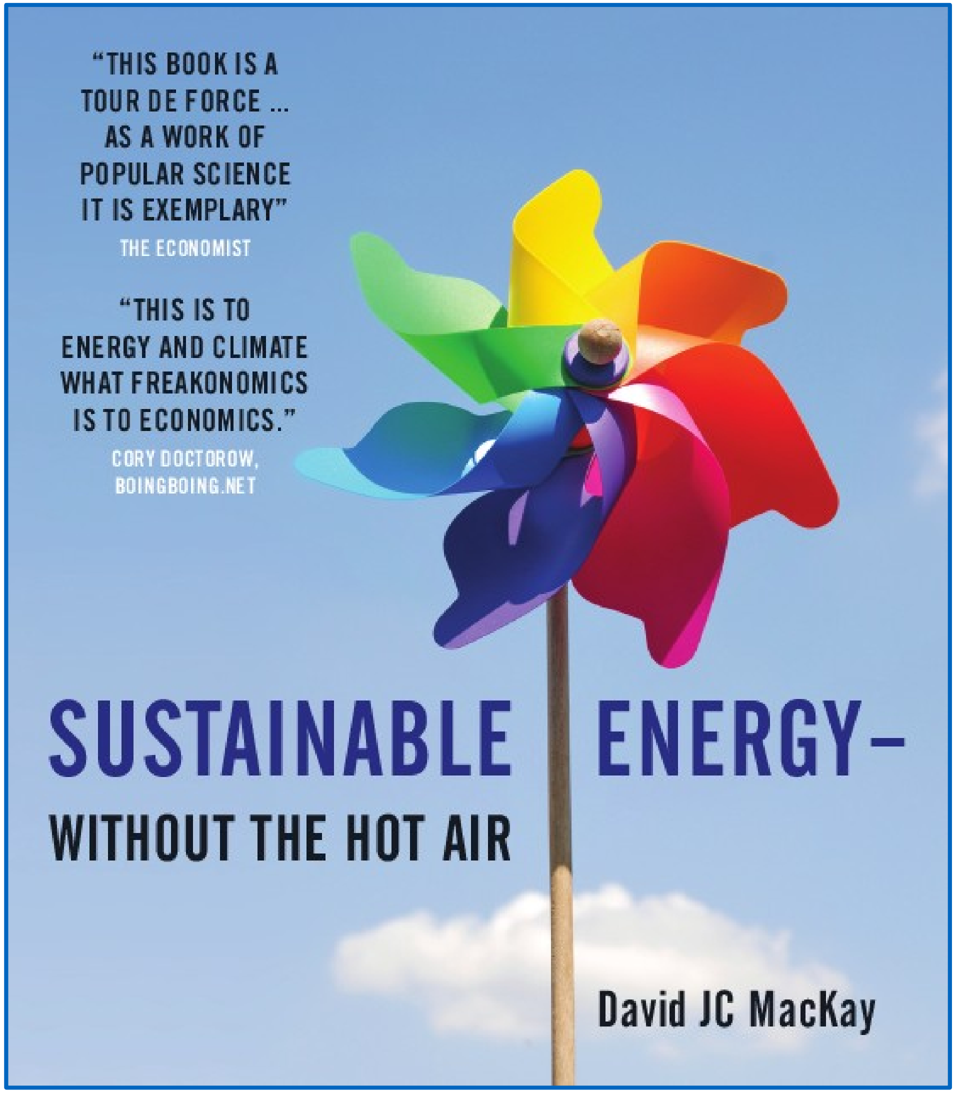
Summary

- Nuclear fusion is a virtually inexhaustible source of energy.
- Fusion power offers an enhanced level of safety that is due to its fundamental physical properties.
- Nuclear fusion is achieved in sufficiently hot and dense plasmas.
- Magnetic confinement is an approach to utilise fusion energy.
- Experiments explore the potential of both tokamaks and stellarators.
- W7-X is an optimised stellarator designed for operation with long pulses.
- ITER is expected to be the first machine generating excess power.
- DEMO will be the first fusion power plant.

Further Reading

David J.C. MacKay,
UIT Cambridge (2009)
www.withouthotair.com

free download
(in many languages)



source: http://www.withouthotair.com/ 2009

Events and Guided Tours

- advanced training for teachers on „Generation and Consumption of Energy“
- guided tours at the Max-Planck-Institut für Plasmaphysik in Greifswald and Garching

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