Max-Planck-Institut
für Plasmaphysik

ITER, Wendelstein 7-X und DEMO – aktueller Stand der Fusionsforschung

Robert Wolf

Fusion – Energiequelle der Sonne

Hohe Temperaturen: °C

Extrem hoher D 10 Milliarden bar

Auf der Erde nicht möglich !

Verschmelzung von 4 Protonen (Wasserstoff) zu Helium

ABER: Wasserstofffusion ist extrem (!) ineffizient

Inhalt

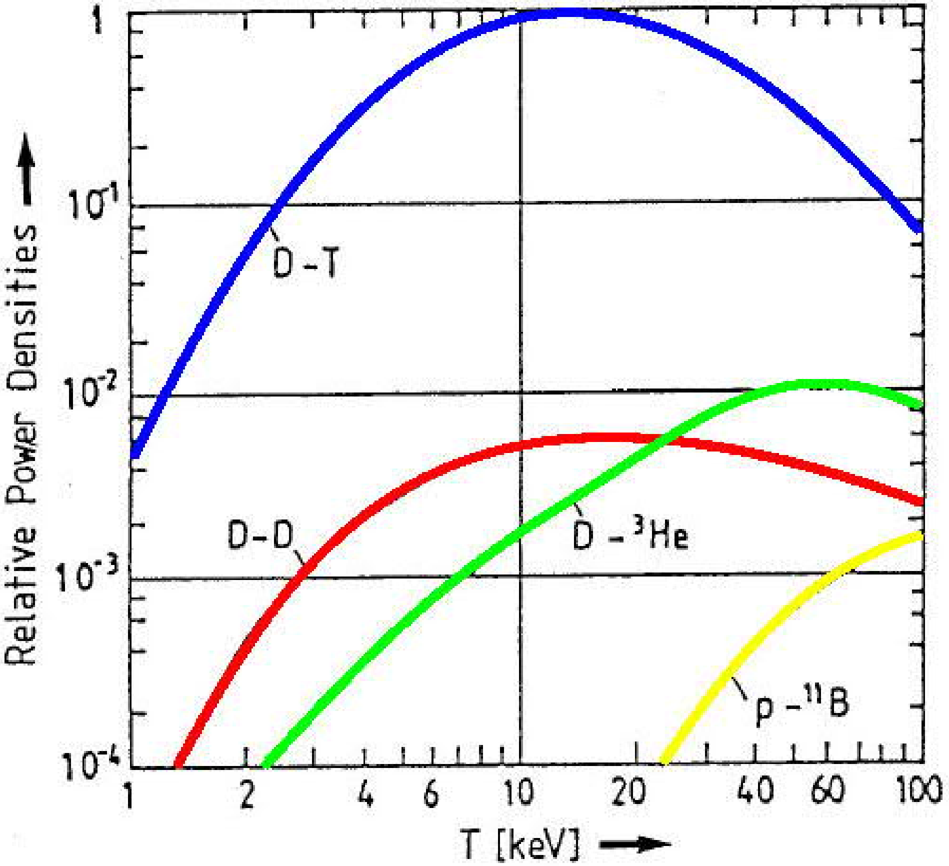
Fusionsreaktionen

$$R = n_D n_T < \sigma v >$$

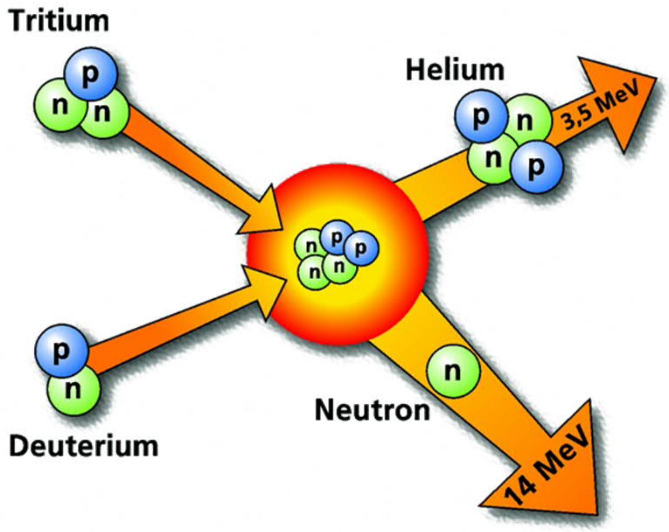
$$= p^2 \frac{< \sigma v >}{T^2}$$

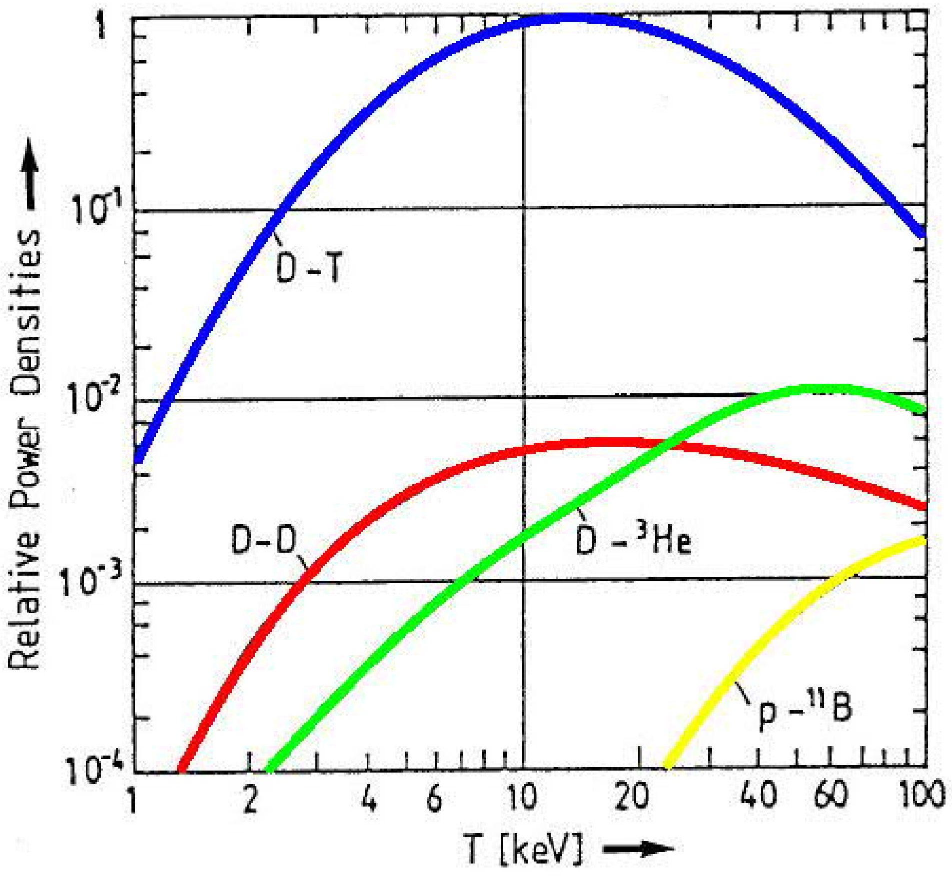
$$\propto \frac{< \sigma v >}{T^2}$$

Optimum temperature range for D-T reaction 10 – 20 keV (~150 MK)



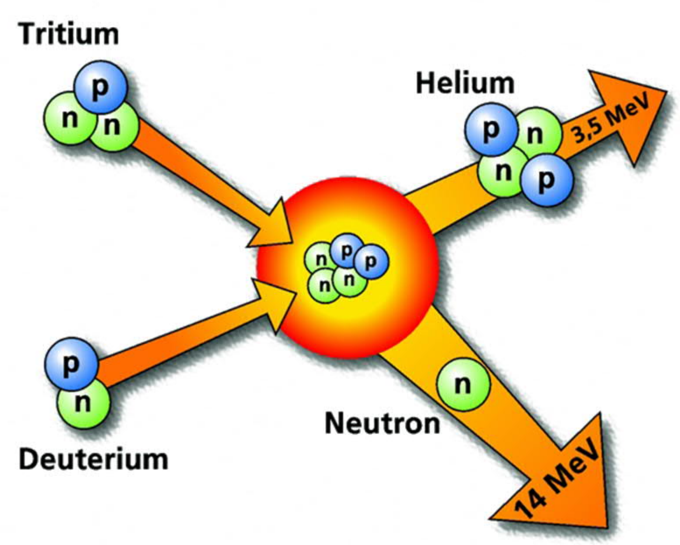
Fusionsreaktionen





Optimum temperature
range for D-T reaction
10 – 20 keV (~150 MK)

Fusionsreaktion mit höchstem Wirkungsquerschnitt

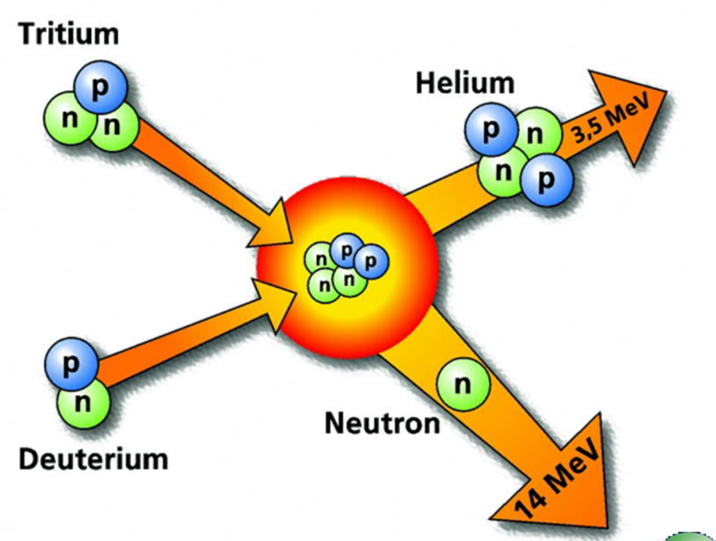


10^6-mal energy per mass
than in chemical reactions

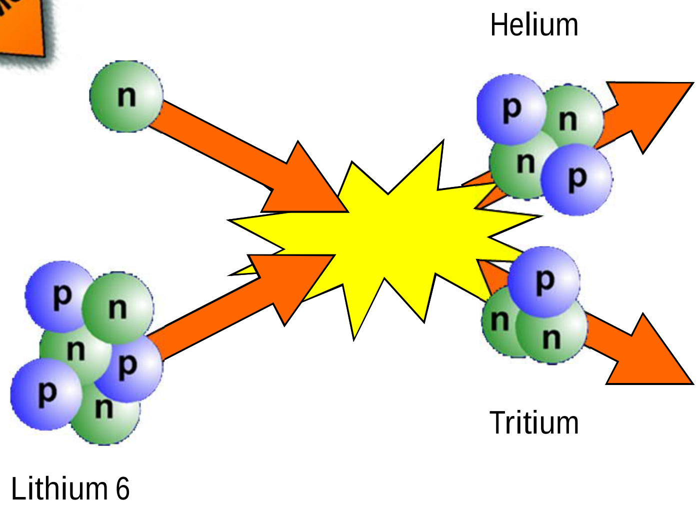
Heat

Steam
|
Steam turbine
|
Electricity generator
...

Fusionsreaktion mit höchstem Wirkungsquerschnitt

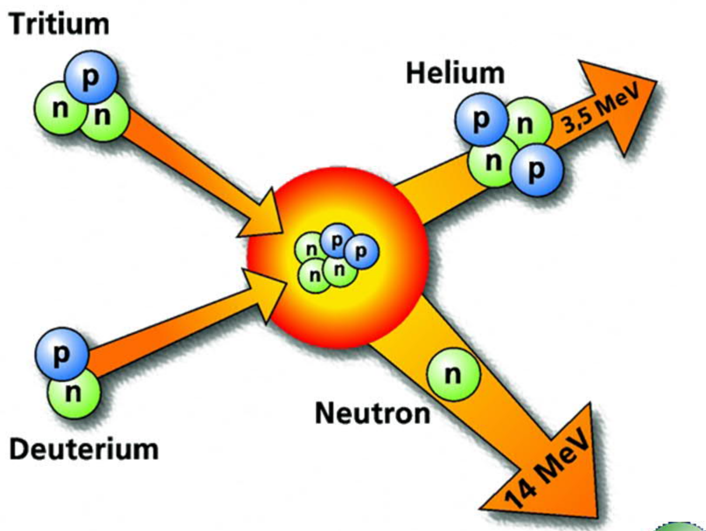


Tritium has to be bred



Closed
tritium cycle

Rohstoffe sind Deuterium und Lithium

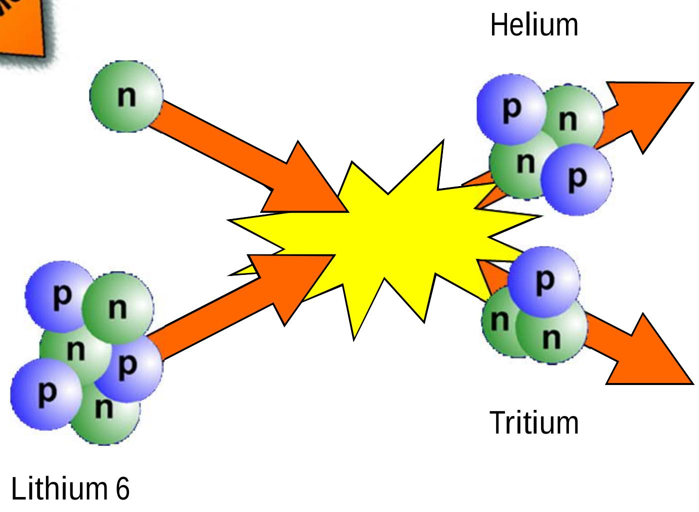


Fusion

$$\left.\begin{array}{lll} D + T & \rightarrow He + n & + 17.6\ \mathrm{MeV} \\ \underline{n + {}^{6}Li} & \underline{\rightarrow He + T} & \underline{+ \ \ 4.8\ \mathrm{MeV}} \\ D + {}^{6}Li & \rightarrow 2\ He & + 22.4\ \mathrm{MeV} \end{array}\right\} \boxed{1\ GW_{th} \leftrightarrow 0.3\ kg/Tag}$$

Kohle

$$\left.\begin{array}{ll} C + O_2 & \rightarrow CO_2 + 13.5\ \mathrm{eV} \end{array}\right\} \boxed{1\ GW_{th} \leftrightarrow 10^6\ kg/Tag}$$

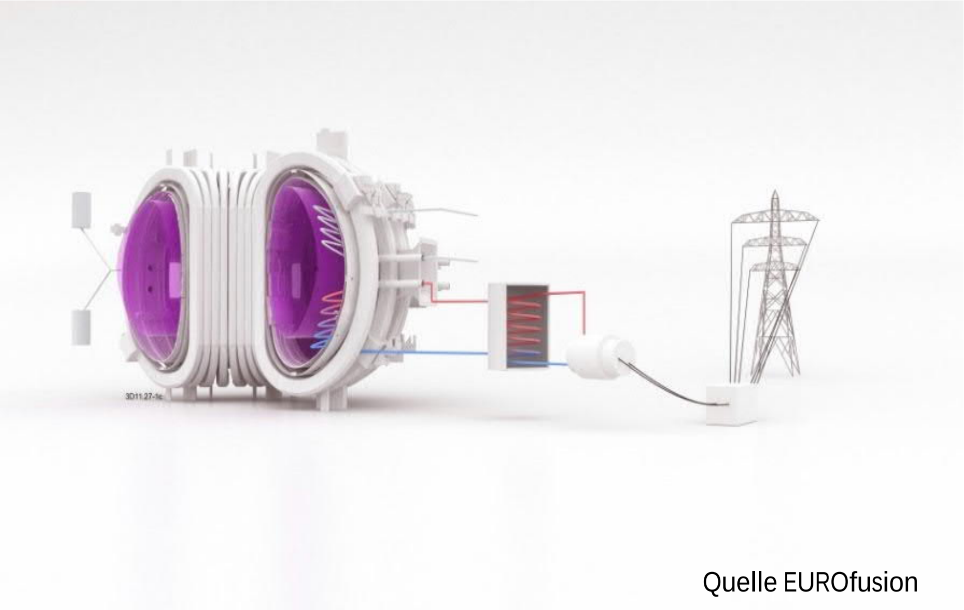


Closed
tritium cycle

Energie aus Fusion

Development of a new primary energy source on the basis of magnetically confined fusion plasmas

- Small fuel consumption
  - 3 GW_{th} correspond to ~ 1 kg (D and Li) per day
- Abundant fuel resources (D and Li)
- Advantageous environment and safety properties
  - No CO_2-production
  - No non-lived nuclear waste
- Plant size ~ 3 GW_{th} or ~ 1 GW_e
  - Size of a base load power plant
  - Suitable for large cities or energy intensive industries
  - Heat source in a renewable economy



Quelle EUROfusion

Inhalt

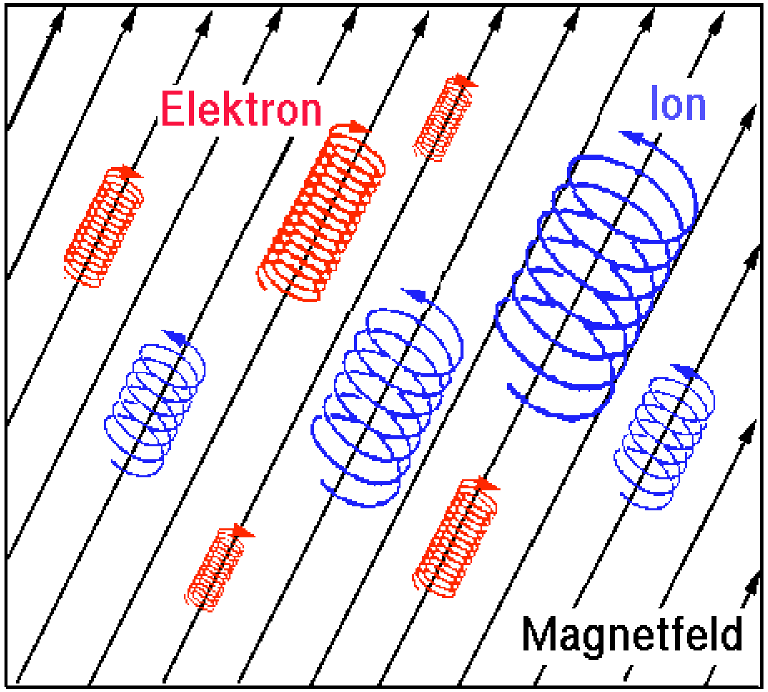
- Energie aus Fusion
- Magnetischer Einschluss
- Stand der Fusionsforschung
- Auf dem Weg zu einem Fusionskraftwerk
- Fazit und Ausblick

Magnetischer Einschluss

Ignition

Heating from fusion reactions has to compensate losses (perpendicular to the magnetic field):

- Radiations losses (impurities, bremsstrahlung, ...)
- Heat conduction and convection (binary Coulomb collisions, turbulent transport)

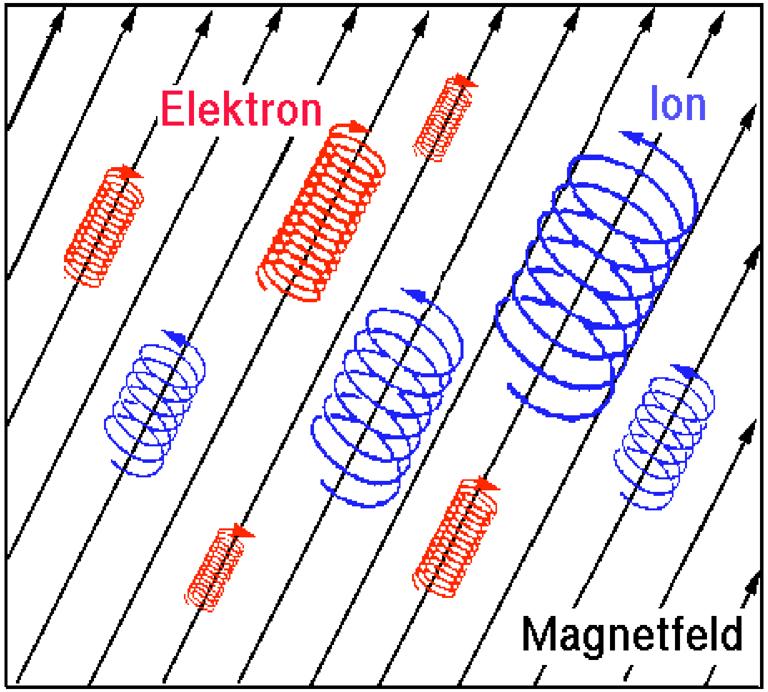


Magnetischer Einschluss

$Q = P_{fusion} / P_{heating} >> 1$

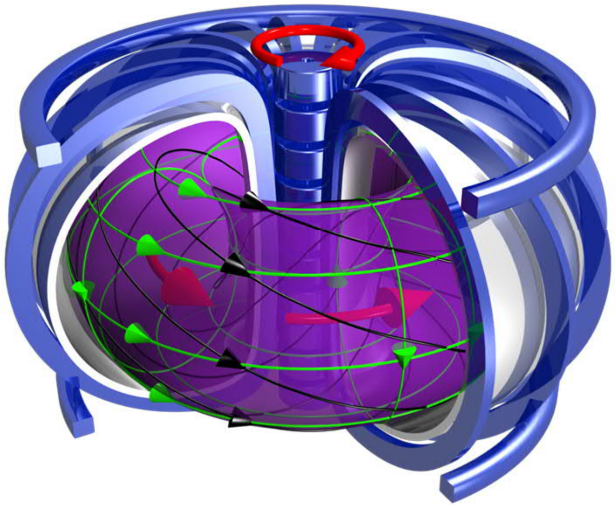
Heating from fusion reactions & external heating has to compensate losses (perpendicular to the magnetic field):

- Radiations losses (impurities, bremsstrahlung, …)
- Heat conduction and convection (binary Coulomb collisions, turbulent transport)

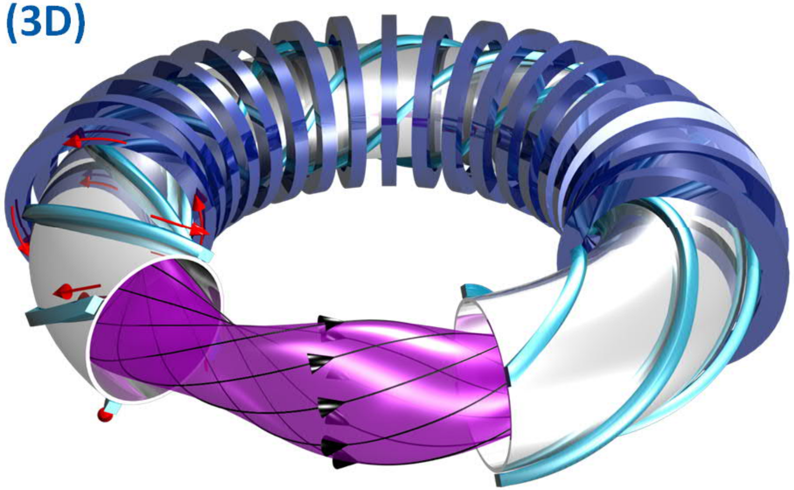


Toroidale Magnetfeldkonfigurationen

Tokamak (2D)



Stellarator (3D)



Grafiken: IPP

Großer Teil des Magnetfeld durch Plasmastrom ~MA (transformatorprinzip)

Weiter entwickelt, aber gepulst; stationärer betrieb unter Effizienzeinbußen

ITER ist ein Tokamak

Zum ersten Mal (kontrollierte) Energieproduktion mit Fusion

Magnetfeld im Wesentlichen durch externe Spulen

Vorteilhafte Eigenschaften für ein Kraftwerk (intrinsisch stationär)

Wendelstein 7-X ist ein Stellarator

Nachweis, dass Plasmaeigenschaften Kraftwerksanforderungen erfüllen (keine Verwendung von Tritium)

Fusionsbedingungen

Plasma stability

$$\beta = \frac{p}{B^2/2\mu_0} \leq 5\%$$

Because of technical reasons $B \sim 5T$
(superconductivity, mechanical forces)

$$p \leq 5bar$$

Together with optimum temperature range
(D-T-reaktion) ~10 keV it follows

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

From power balance triple product can be derived
(D-T fusion)

$$nT\tau_E > 3 \cdot 10^{21} keV m^{-3} s$$

With n and T one gets (measure for heat insulation)

$$\tau_E > 3s$$

$Q = P_{fusion}/P_{heating} \sim 30$

und $\tau_E \sim 3\ s$

$P_{thermal} = P_{fusion} \sim 3\ GW$

$P_{electric} \sim 1\ GW$

Fusionsbedingungen

Plasma stability

$$\beta = \frac{p}{B^2/2\mu_0} \leq 5\%$$

Because of technical reasons $B \sim 5T$
(superconductivity, mechanical forces)

$$p \leq 5bar$$

Together with optimum temperature range
(D-T-reaktion) $\sim 10\ keV$ it follows

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

From power balance triple product can be derived
(D-T fusion)

$$nT\tau_E > 3 \cdot 10^{21} keV m^{-3} s$$

With n and T one gets (measure for heat insulation)

$$\tau_E > 3s$$

Achieved

$T > 10$ keV ✓

$n > 10^{20}$ m^{-3} ✓

$\tau_E \sim 1$ sec × **10**

Fusionsbedingungen

Plasma stability

$$\beta = \frac{p}{B^2/2\mu_0} \leq 5\%$$

Because of technical reasons $B \sim 5T$
(superconductivity, mechanical forces)

$$p \leq 5bar$$

Together with optimum temperature range
(D-T-reaktion) $\sim 10\ keV$ it follows

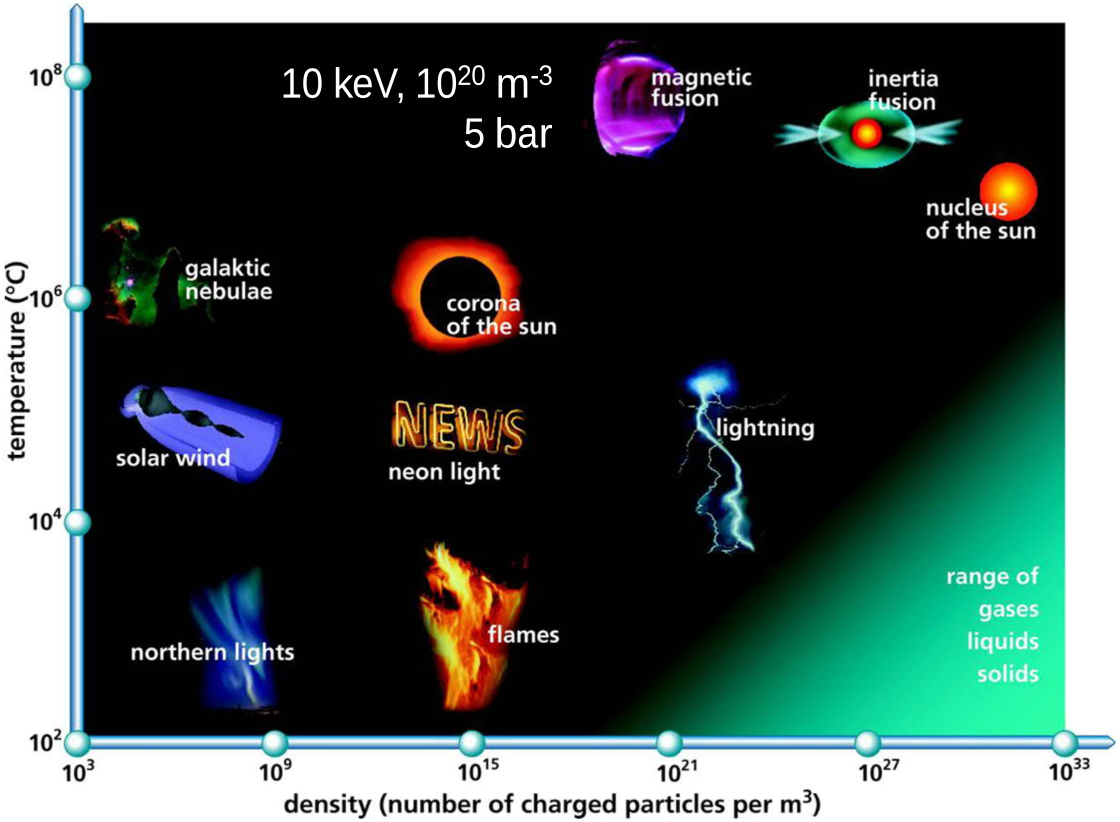
$$n \sim 10^{20} m^{-3}$$

From power balance triple product can be derived
(D-T fusion)

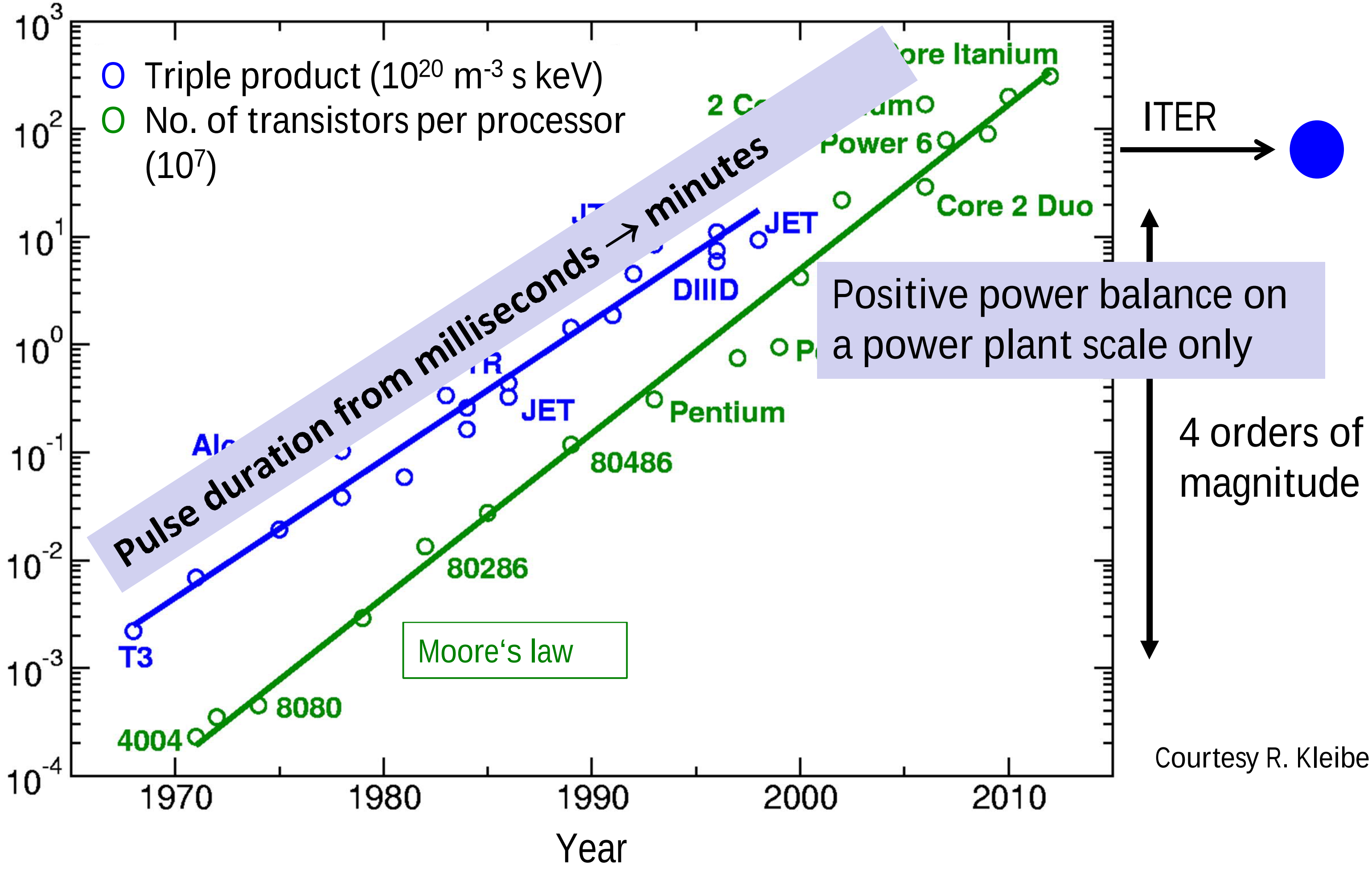
$$nT\tau_E > 3 \cdot 10^{21} keV m^{-3} s$$

With n and T one gets (measure for heat insulation)

$$\tau_E > 3s$$



Fortschritt Fusion: Tripel-Produkt



O Triple product (10^{20} m^{-3} s keV)

O No. of transistors per processor (10^7)

Pulse duration from milliseconds → minutes

Moore‘s law

Positive power balance on a power plant scale only

4 orders of magnitude

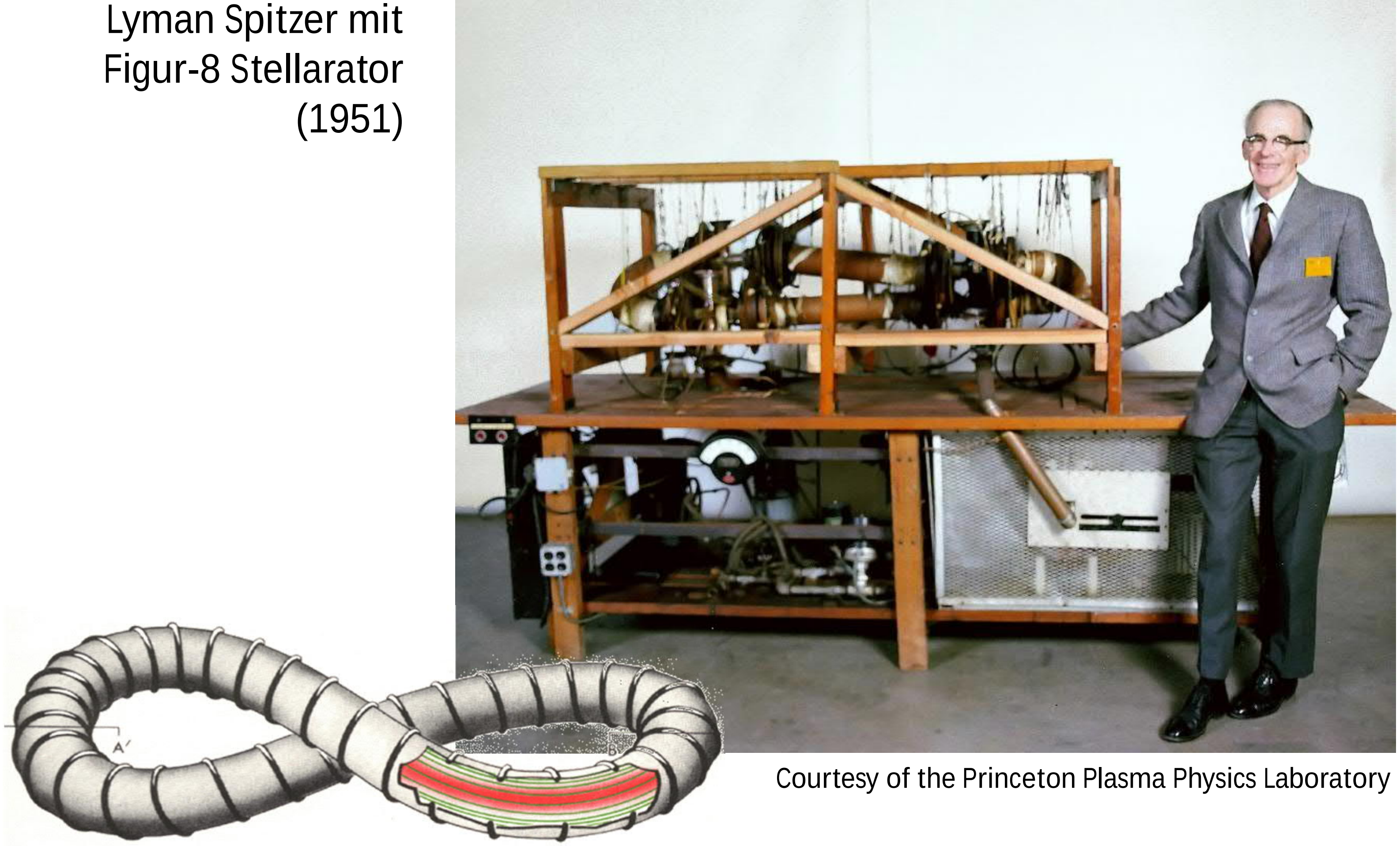
Courtesy R. Kleiber

Inhalt

- Energie aus Fusion
- Magnetischer Einschluss
- Stand der Fusionsforschung
- Auf dem Weg zu einem Fusionskraftwerk
- Fazit und Ausblick

Stellarator → Tokamak → Tokamak & Stellarator

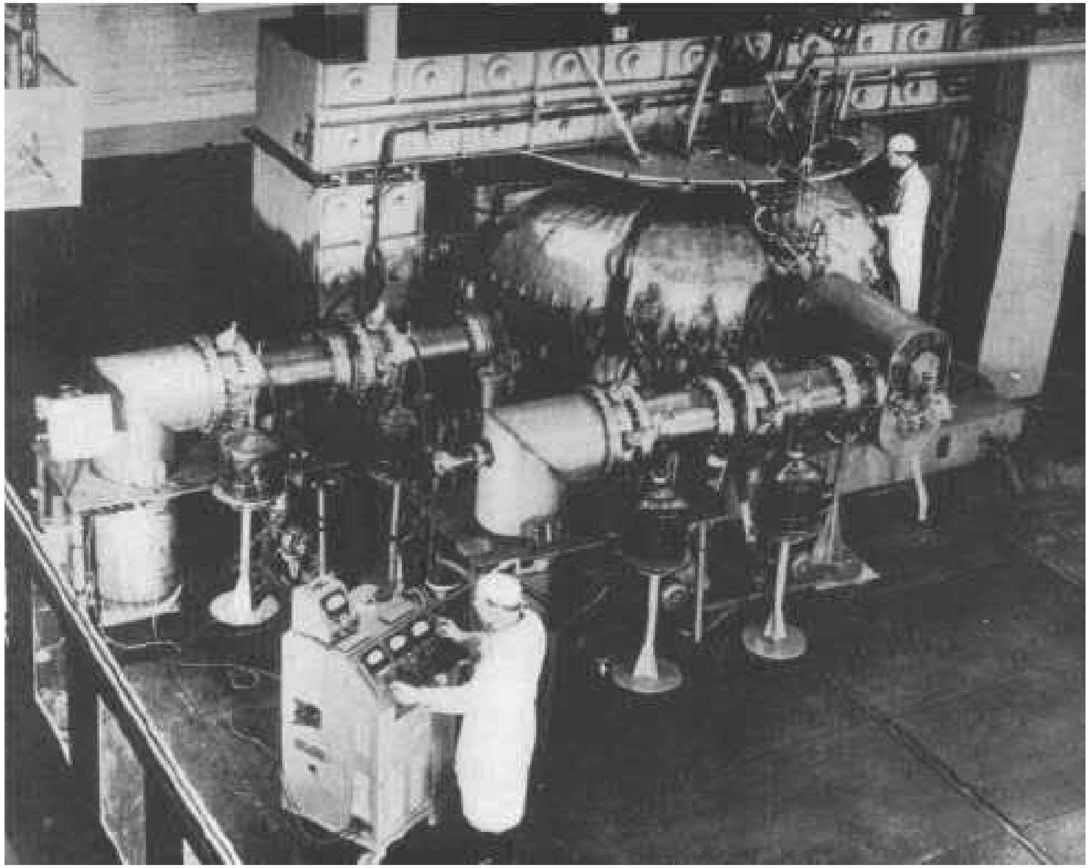
Lyman Spitzer mit
Figur-8 Stellarator
(1951)



Courtesy of the Princeton Plasma Physics Laboratory

Stellarator → Tokamak → Tokamak & Stellarator

Erreichen fusionsrelevanter Temperaturen im Tokamak T3 (1969, Kurtschatow-Institut, Moskau) führt zur schnellen Weiterentwicklung des Tokamakprinzips

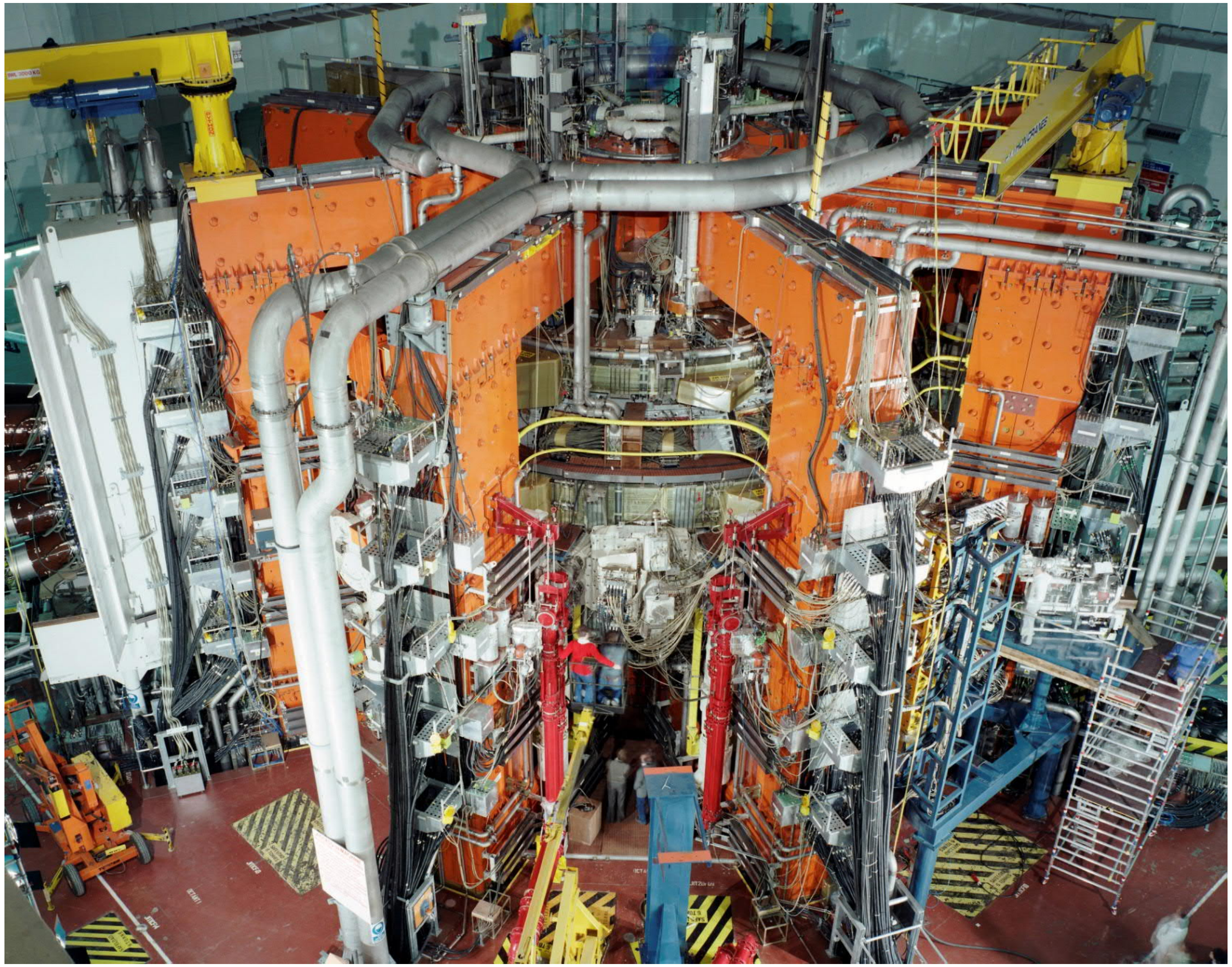


alltheworldstokamaks.wordpress.com/gallery-of-external-views/t3/

Stellarator → Tokamak → Tokamak & Stellarator

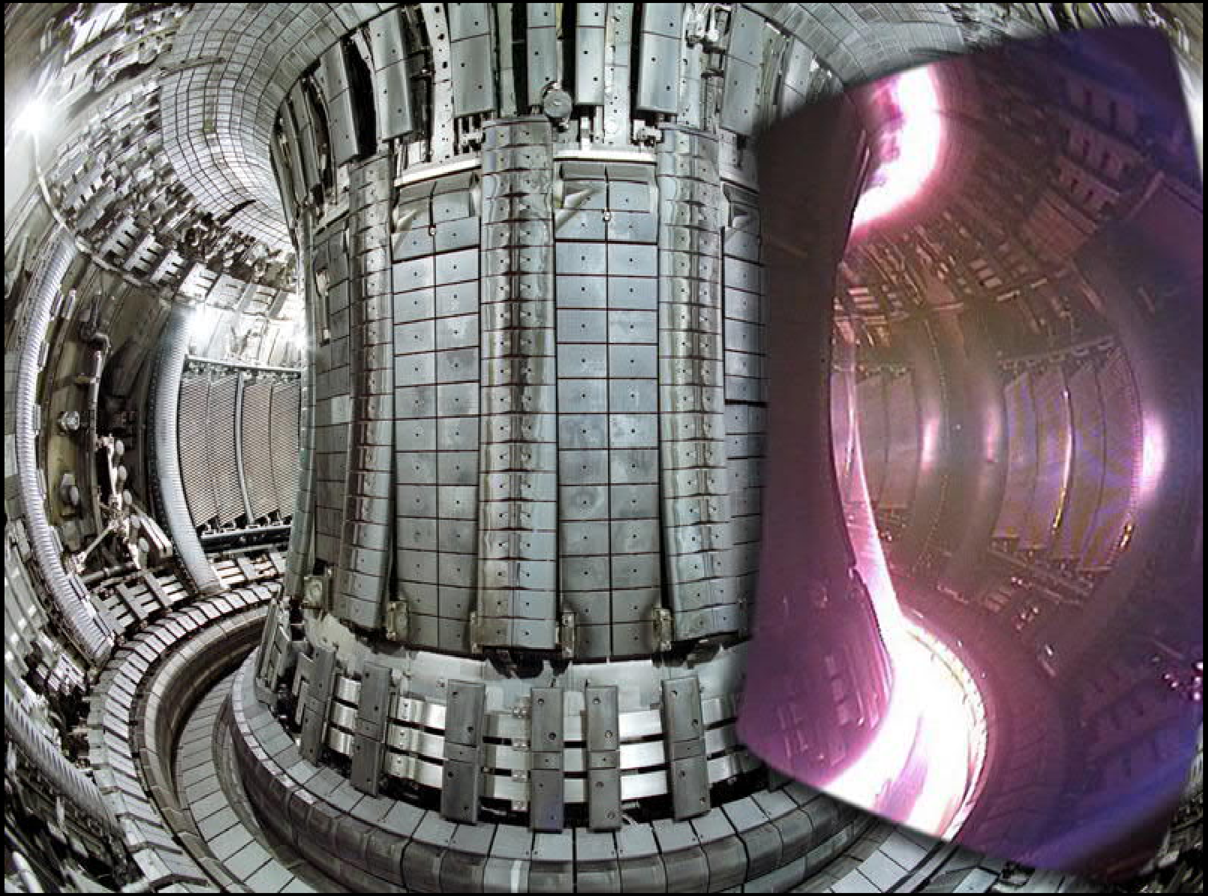
Joint European Torus (JET), größtes derzeit laufendes Fusionsexperiment

https://de.wikipedia.org/wiki/Joint_European_Torus



Plasmavolumen ~ 100 m^3
Magnetfeld ~3T (Kupferspulen)
Plasmastrom ~3 MA

JET von innen



https://de.wikipedia.org/wiki/Joint_European_Torus

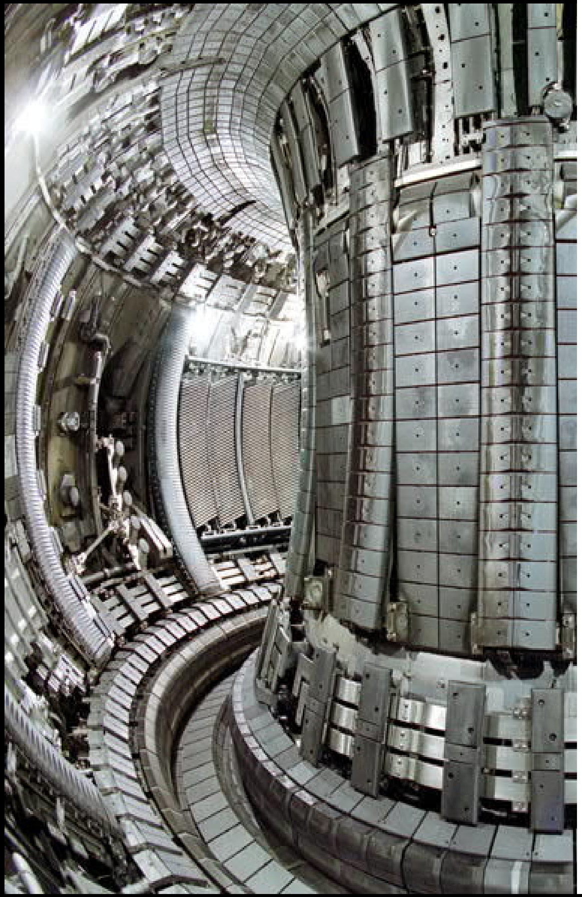
16 MW Fusionsleistung für ~ 1 Sek

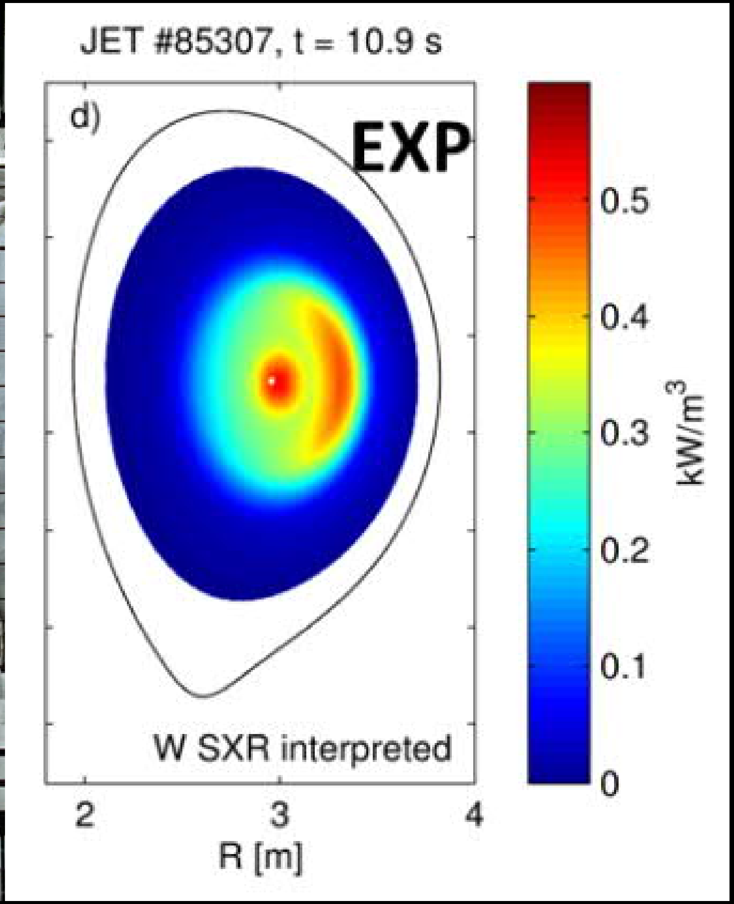
$P_{Fusion} \sim P_{Heizung}$

$P_{\alpha} \sim 0.2 \times P_{heizung}$

4 MW Fusionsleistung für ~5 Sek

JET von innen





Röntgenemission
T ~ 100 Mio °C

P. Mantica et al 2015 Proc 42nd EPS Konferenz Plasma Physik P1.101

Stellarator → Tokamak → Tokamak & Stellarator

ITER

www.iter.org/album/Media/4 - Aerial - Dezember 2018

Copyright: ITER Organization

Eines der größten F&E Projekte weltweit

ITER-Partner repräsentieren die halbe Weltbevölkerung und 80% des Welt-BIPs

Stellarator → Tokamak → Tokamak & Stellarator

www.iter.org/album/Media/4 - Aerial - Mai 2021

Copyright: ITER Organization / EJF Riche

Plasmavolumen ~ 800 m^3

Magnetfeld ~6T (supraleitende Spulen)

Plasmastrom ~15 MA

Zum ersten Mal brennendes Fusionsplasma

500 MW Fusionsleistung über ~10 Minuten

$P_{\text{Fusion}} \sim 10 \times P_{\text{Heizung}}$

$P_{\alpha} \sim 2 \times P_{\text{Heizung}}$

Inbetriebnahme ab 2025
Fusionsleistung > 2030

Stellarator → Tokamak → Tokamak & Stellarator

Wendelstein 7-X

Magnetfeldstärke
  3 T

Supraleitende Spulen
  70

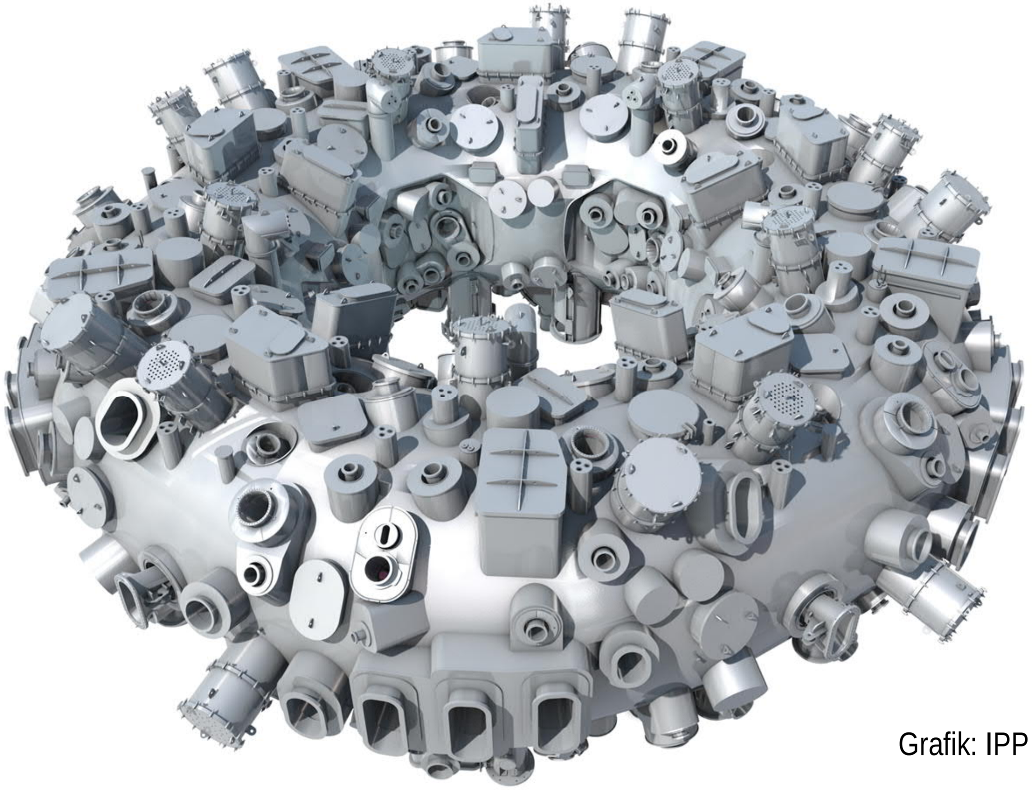
Kalte Masse / Gesamtmasse
  425 t / 700 t

Plasmavolumen
  30 m^3

Plasmadauer bis
  30 Minuten

Heizleistung
  10 MW

Maximale Wärmeflüsse
  10 MW/m^2



Grafik: IPP

Stellarator → Tokamak → Tokamak & Stellarator

Wendelstein 7-X

Magnetfeldstärke
3 T

Supraleitende Spulen
70

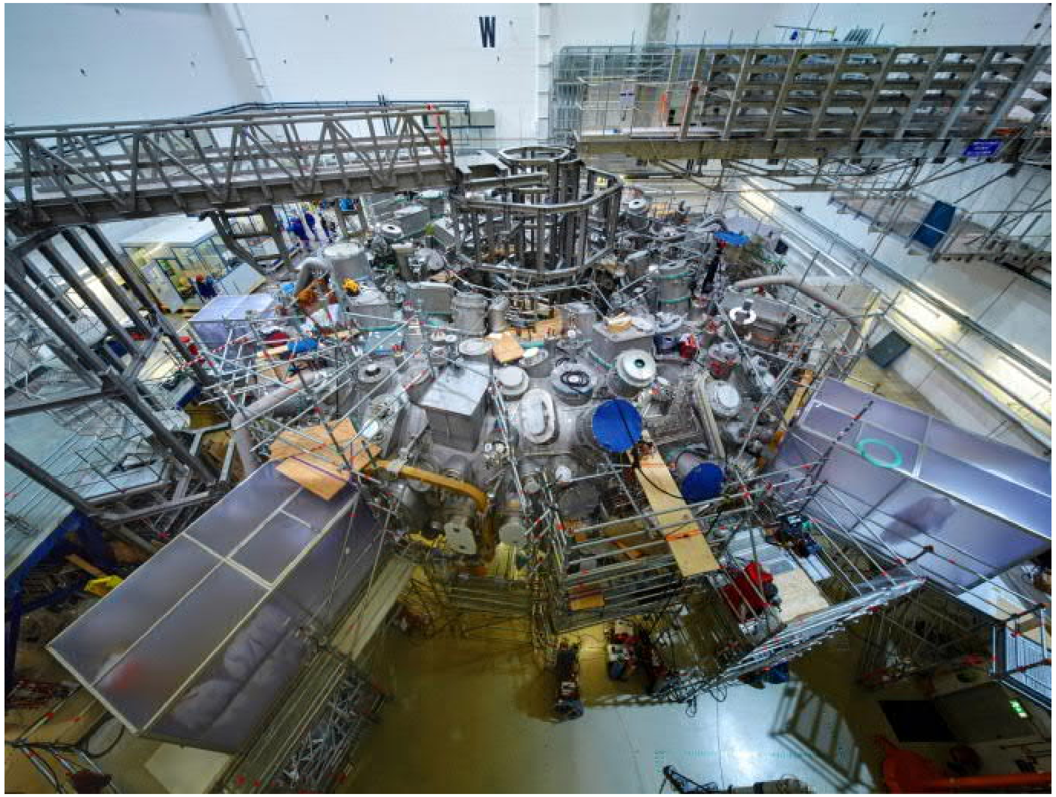
Kalte Masse / Gesamtmasse
425 t / 700 t

Plasmavolumen
30 m^3

Plasmadauer bis
30 Minuten

Heizleistung
10 MW

Maximale Wärmeflüsse
10 MW/m^2



IPP, Foto: Bernhard Ludewig

Stellarator → Tokamak → Tokamak & Stellarator

Wendelstein 7-X

Magnetfeldstärke
  3 T

Supraleitende Spulen
  70

Kalte Masse / Gesamtmasse
  425 t / 700 t

Plasmavolumen
  30 m^3

Plasmadauer bis
  30 Minuten

Heizleistung
  10 MW

Maximale Wärmeflüsse
  10 MW/m^2

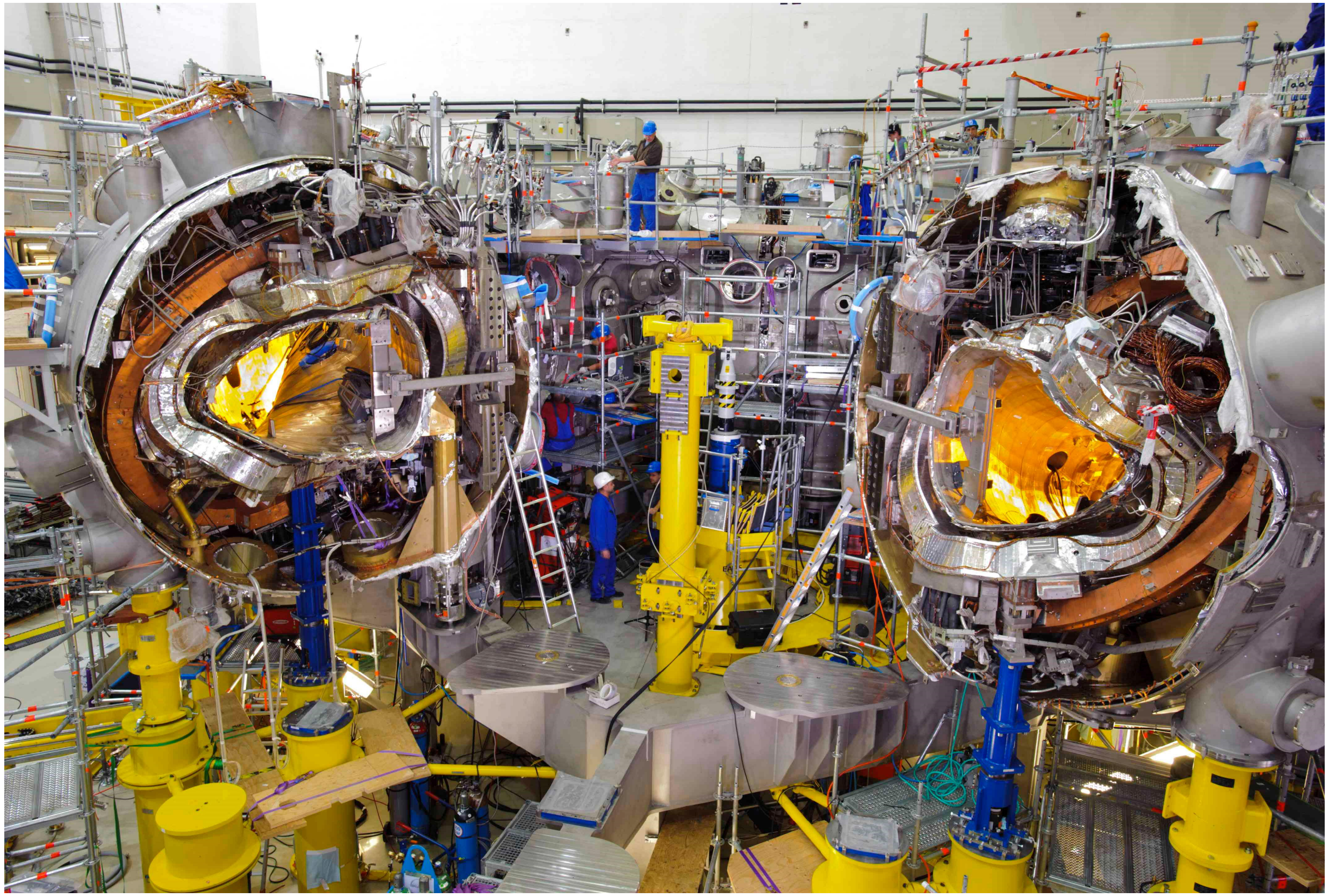
IPP, Foto: Bernhard Ludewig

Stellarator → Tokamak → Tokamak & Stellarator

Wendelstein 7-X

Bereits der Bau einer solchen Anlage ist ein Forschungs- und Entwicklungsprojekt

10 Jahre Montagedauer (2005 – 2014)
www.youtube.com/watch?v=MJpSrqitSMQ



IPP, Foto: Wolfgang Filser

Stellarator → Tokamak → Tokamak & Stellarator

Wendelstein 7-X Plasma 30 sec → 30 min

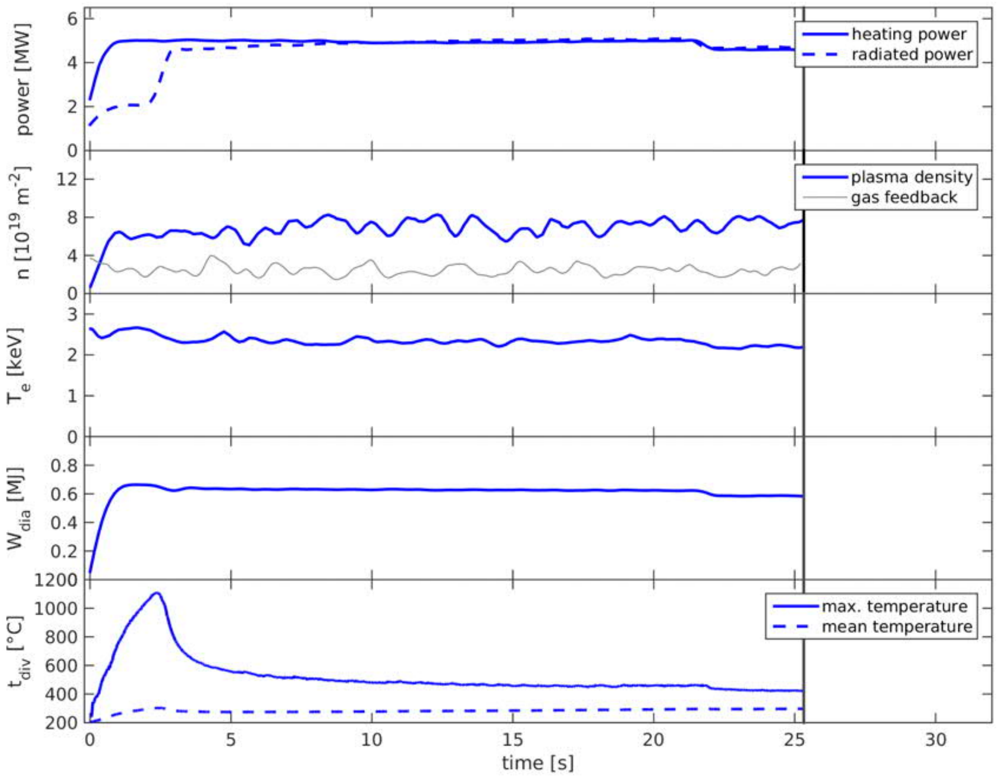
Heizleistung
Abgestrahlte Leistung

Plasmadichte

Temperatur
(Elektronen)

Plasmaenergie

Wandtemperatur
(hochbelastete Teile)



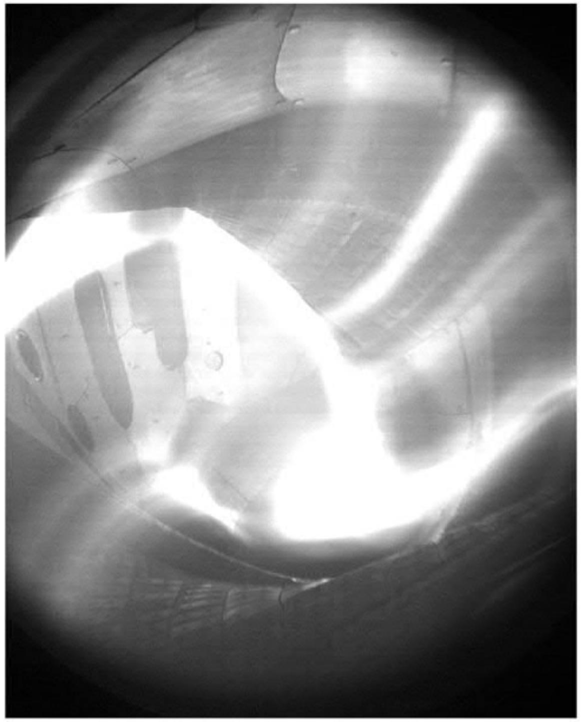
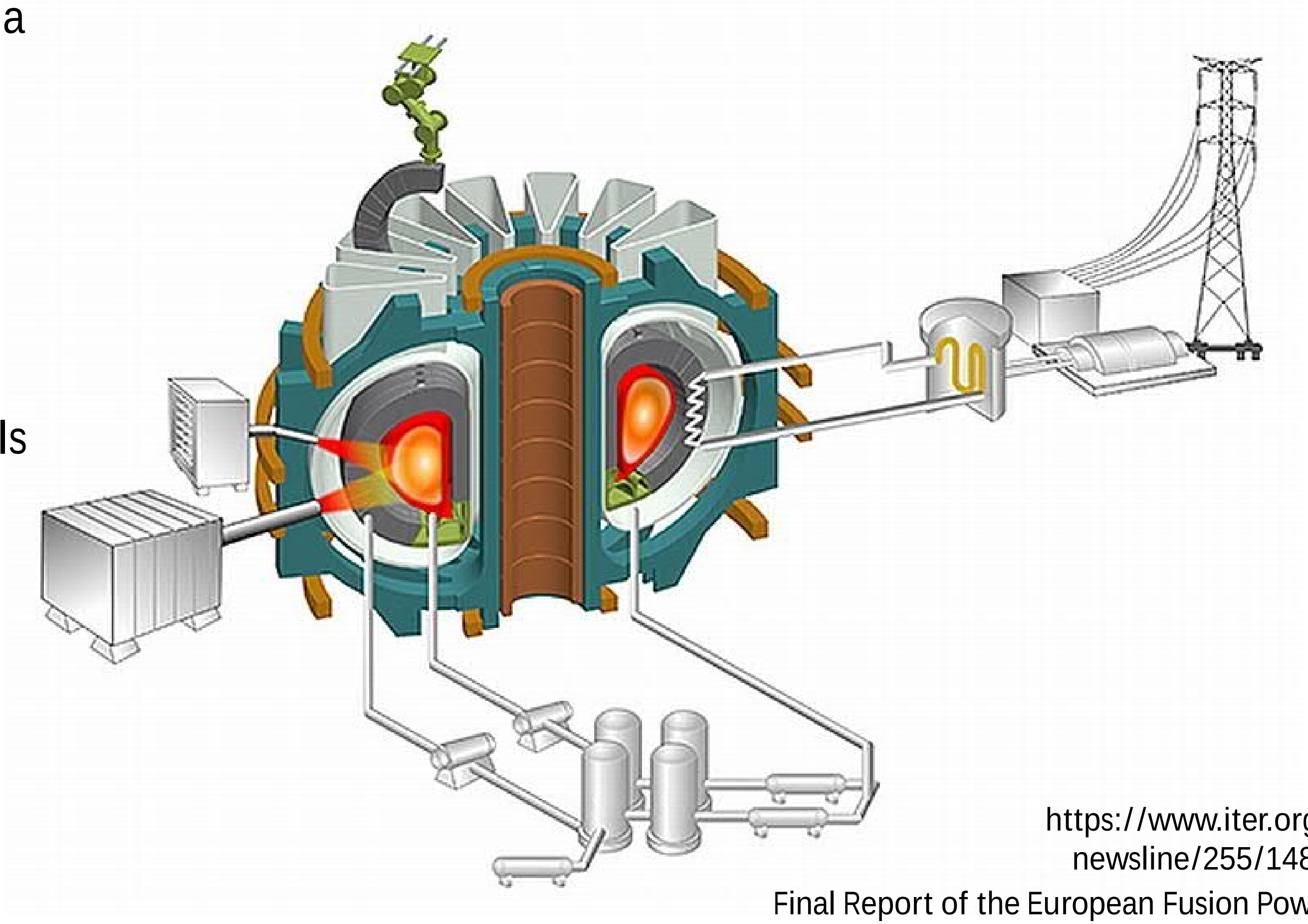


Foto: IPP

Aufbau einer Fusionsanlage

- Magnetically confined fusion plasma
- Plasma facing materials
- Heat and particle exhaust
- Breeding blanket
- Plasma / vacuum vessel
- Remote maintenance
- Superconducting magnetic field coils
- Cryostat vessel
- Auxiliary systems & diagnostics
  - Plasma start-up
  - Plasma heating
  - Current drive
- Fuel cycle
  - Plasma fuelling
  - Gas exhaust
  - Isotope separation



https://www.iter.org/newsline/255/1481

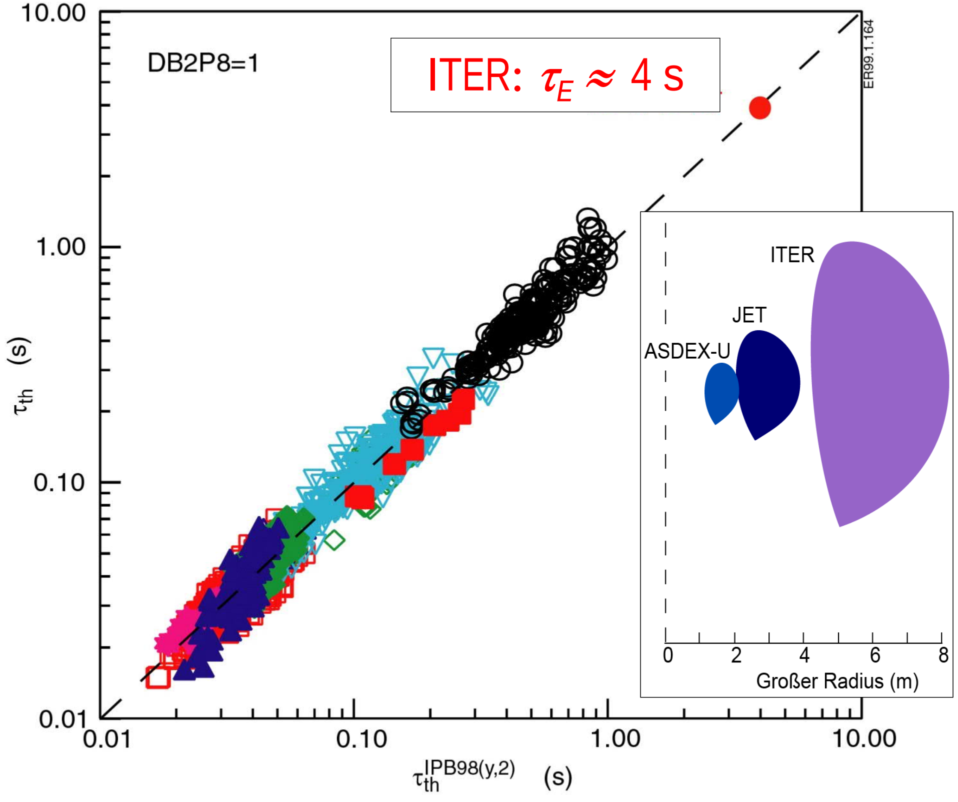
Final Report of the European Fusion Power Plant Conceptual Study EFDA(05)-27/4.10

Magnetischer Einschluss

Energy confinement / transport

- Confinement scaling (engineering approach)
- Discovery of H-mode
- Internal transport barriers
- Confinement optimization of stellarators

$$\tau_E \propto A^{0.40}\,\underline{I^{0.90}}\,\underline{P^{-0.65}}\,\underline{R^{1.90}}\,a^{0.20}\,\kappa^{0.80}\,B^{0.05}\,n^{0.30}$$

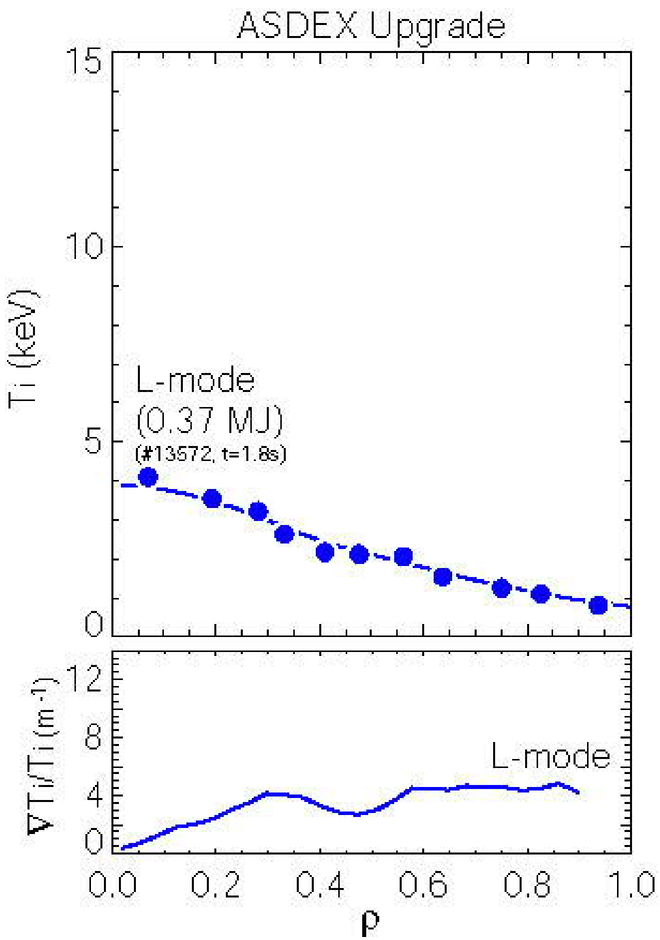


Magnetischer Einschluss

Energy confinement / transport

- Confinement scaling (engineering approach)
- Discovery of H-mode
- Internal transport barriers
- Confinement optimization of stellarators

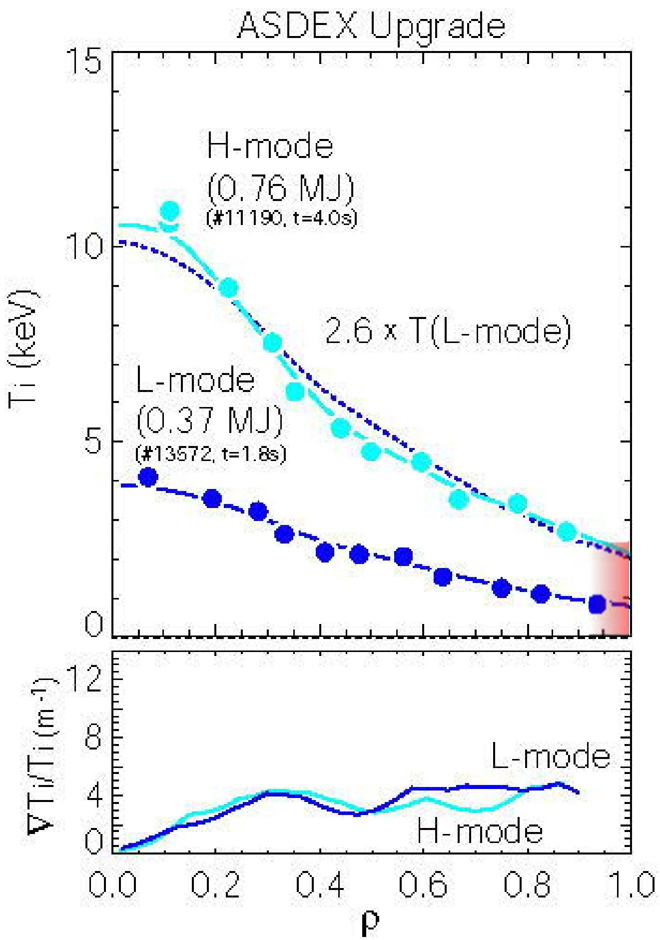
Ion temperature in ASDEX Upgrade
L-mode plasma
@ 5 MW heating power



Magnetischer Einschluss

Energy confinement / transport

- Confinement scaling (engineering approach)
- Discovery of H-mode
- Internal transport barriers
- Confinement optimization of stellarators



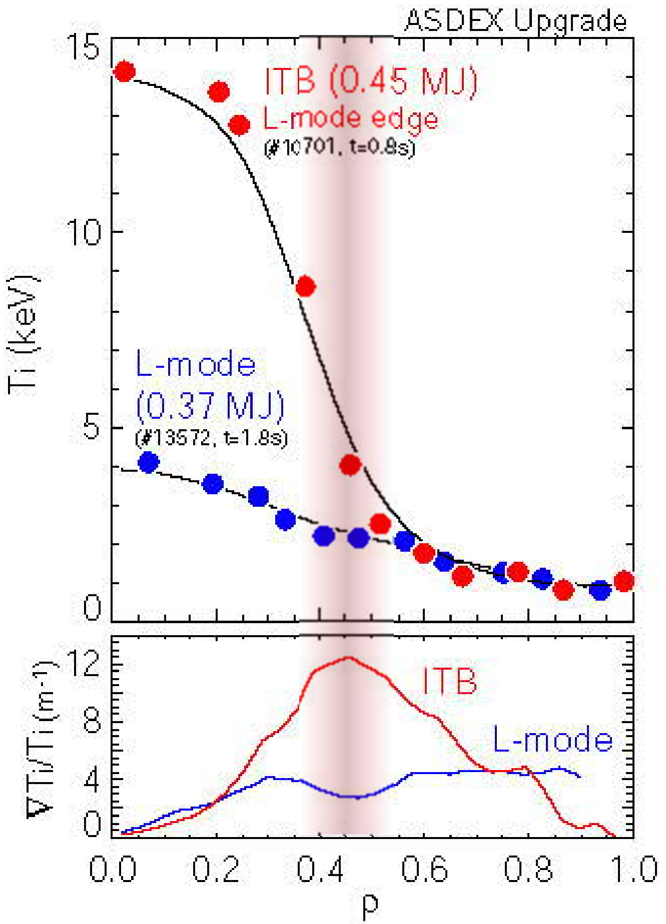
Ion temperature in ASDEX Upgrade H-mode plasma
@ 5 MW heating power
Confinement improvement by factor of 2

F Wagner et al 1982 Phys. Rev, Lett. 49 1408
F Wagner 2007 Plasma Phys. Control. Fusion 49 B1

Magnetischer Einschluss

Energy confinement / transport

- Confinement scaling (engineering approach)
- Discovery of H-mode
- Internal transport barriers
- Confinement optimization of stellarators



Ion temperature in ASDEX Upgrade
Internal transport barriers
@ 5 MW heating power

R Wolf 2003 Plasma Phys. Control. Fusion 45 R1

Magnetischer Einschluss

Energy confinement / transport

- Confinement scaling (engineering approach)
- Discovery of H-mode
- Internal transport barriers
- Confinement optimization of stellarators

Turbulence and turbulence suppression (by sheared flows) plays a major role in plasma transport

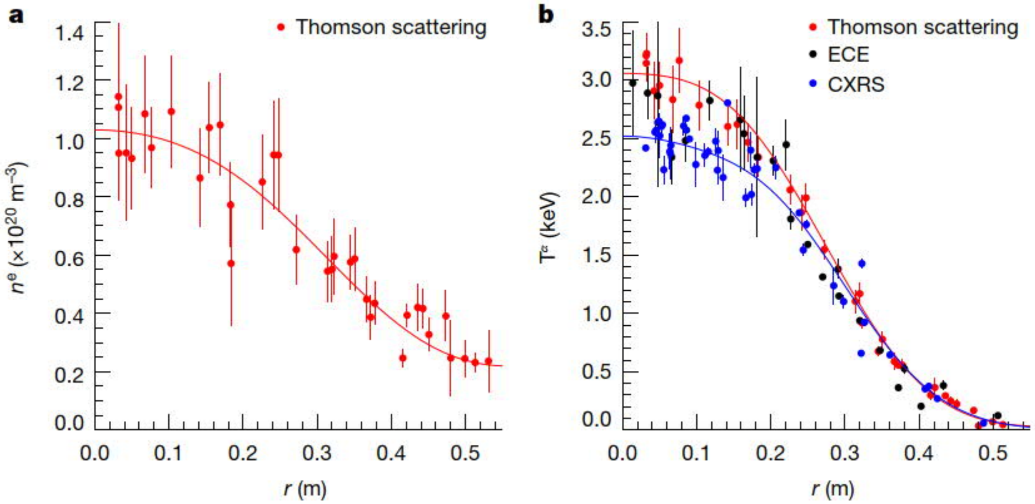
www.genecode.org

Prediction of turbulent transport (based on gyrokinetic theory) requires supercomputer

Magnetischer Einschluss

Energy confinement / transport

- Confinement scaling (engineering approach)
- Discovery of H-mode
- Internal transport barriers
- Confinement optimization of stellarators



Article

Demonstration of reduced neoclassical energy transport in Wendelstein 7-X

https://doi.org/10.1038/s41586-021-03687-w

Received: 30 April 2020

Accepted: 2 June 2021

C. D. Beidler[1✉], H. M. Smith[1], A. Alonso[2], T. Andreeva[1], J. Baldzuhn[1], M. N. A. Beurskens[1], M. Borchardt[1], S. A. Bozhenkov[1], K. J. Brunner[1], H. Damm[1], M. Drevlak[1], O. P. Ford[1], G. Fuchert[1], J. Geiger[1], P. Helander[1], U. Hergenhahn[1,5], M. Hirsch[1], U. Höfel[1], Ye. O. Kazakov[3], R. Kleiber[1], M. Krychowiak[1], S. Kwak[1], A. Langenberg[1], H. P. Laqua[1], U. Neuner[1], N. A. Pablant[4], E. Pasch[1], A. Pavone[1], T. S. Pedersen[1], K. Rahbarnia[1], J. Schilling[1], E. R. Scott[1], T. Stange[1], J. Svensson[1], H. Thomsen[1], Y. Turkin[1], F. Warmer[1], R. C. Wolf[1], D. Zhang[1] & the W7-X Team*

Research on magnetic confinement of high-temperature plasmas has the ultimate goal of harnessing nuclear fusion for the production of electricity. Although the tokamak[1] is the leading toroidal magnetic-confinement concept, it is not without shortcomings and the fusion community has therefore also pursued alternative concepts such as the stellarator. Unlike axisymmetric tokamaks, stellarators possess a three-dimensional (3D) magnetic field geometry. The availability of this additional dimension opens up an extensive configuration space for computational optimization of both the field geometry itself and the current-carrying coils that produce it. Such an optimization was undertaken in designing Wendelstein 7-X (W7-X)[2], a large helical-axis advanced stellarator (HELIAS), which began operation in 2015 at Greifswald, Germany. A major drawback of 3D magnetic field geometry, however, is that it introduces a strong temperature dependence into the stellarator's non-turbulent 'neoclassical' energy transport. Indeed, such energy losses will become prohibitive in high-temperature reactor plasmas unless a strong reduction of the geometrical factor associated with this transport can be achieved; such a reduction was therefore a principal goal of the design of W7-X. In spite of the modest heating power currently available, W7-X has already been able to achieve high-temperature plasma conditions during its 2017 and 2018 experimental campaigns, producing record values of the fusion triple product for such stellarator plasmas[3,4]. The triple product of plasma density, ion temperature and energy confinement time is used in fusion research as a figure of merit, as it must attain a certain threshold value before net-energy-producing operation of a reactor becomes possible[1,5]. Here we demonstrate that such record values provide evidence for reduced neoclassical energy transport in W7-X, as the plasma profiles that produced these results could not have been obtained in stellarators lacking a comparably high level of neoclassical optimization.

In the quest for a viable fusion reactor, consideration of the plasma energy balance shows that—regardless of the confinement concept—a minimum value of the fusion triple product, $nT\tau_E$, must be attained before net-energy-producing operation becomes possible[1,5]. Here, n is the fuel density, T is its temperature and τ_E is the energy confinement time, defined by the ratio W/P, where W is the stored plasma energy and P is the heating power provided by fusion reactions. The temperature dependence of the fuel's fusion reactivity provides an additional constraint; for deuterium–tritium fusion, this reactivity falls rapidly below a temperature of 10 keV ($\approx1.2\times10^8$ K). High temperatures are thus mandatory in fusion plasmas but must be simultaneously consistent with a tolerable level of energy transport if the required τ_E is to be achieved.

Toroidal magnetic confinement of fully ionized fusion plasmas requires that field lines spiral around the minor axis of the torus poloidally as they encircle the major axis toroidally, tracing out magnetic flux surfaces in the course of numerous transits about the device. For a tokamak these toroidal and poloidal components of $\mathbf{B}$ are provided, respectively, by planar current-carrying coils situated outside the plasma and by a toroidal plasma current induced with a central

---

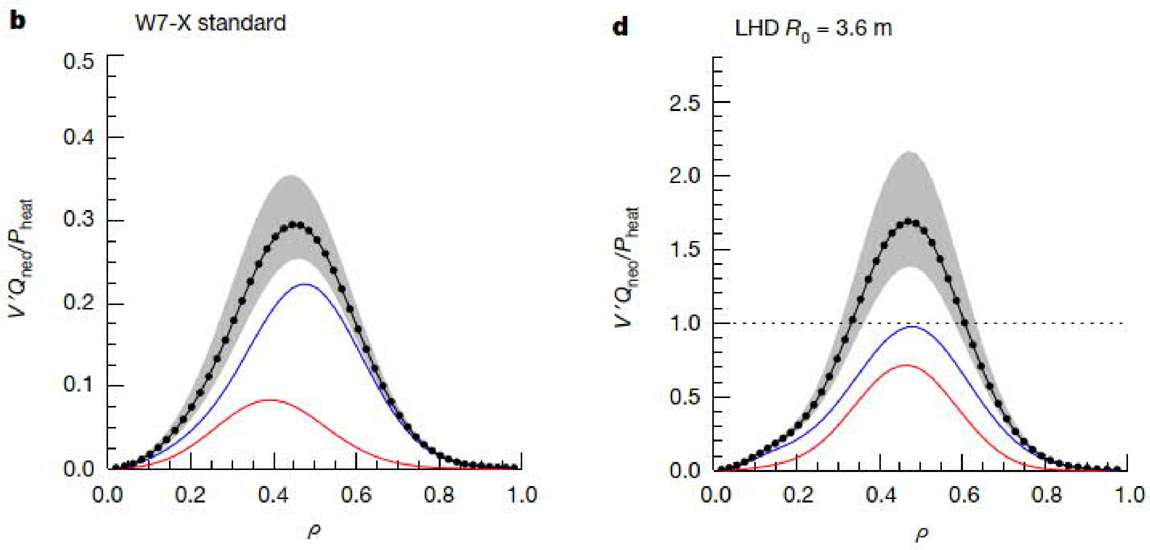
[1] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany. [2] Laboratorio Nacional de Fusion, CIEMAT, Madrid, Spain. [3] Laboratory for Plasma Physics (LPP), École royale militaire/Koninklijke Militaire School (ERM/KMS), Brussels, Belgium. [4] Princeton Plasma Physics Laboratory, Princeton, NJ, USA. [5] Present address: Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany. *A list of authors and their affiliations appears at the end of the paper. ✉e-mail: Craig.Beidler@ipp.mpg.de

C. Beidler et al 2021 Nature 596 221

Magnetischer Einschluss

Energy confinement / transport

- Confinement scaling (engineering approach)
- Discovery of H-mode
- Internal transport barriers
- Confinement optimization of stellarators



Article

Demonstration of reduced neoclassical energy transport in Wendelstein 7-X

https://doi.org/10.1038/s41586-021-03687-w
Received: 30 April 2020
Accepted: 2 June 2021

C. D. Beidler[1,5], H. M. Smith[1], A. Alonso[2], T. Andreeva[1], J. Baldzuhn[1], M. N. A. Beurskens[1], M. Borchardt[1], S. A. Bozhenkov[1], K. J. Brunner[1], H. Damm[1], M. Drevlak[1], O. P. Ford[1], G. Fuchert[1], J. Geiger[1], P. Helander[1], U. Hergenhahn[1,5], M. Hirsch[1], U. Höfel[1], Ye. O. Kazakov[3], R. Kleiber[1], M. Krychowiak[1], S. Kwak[1], A. Langenberg[1], H. P. Laqua[1], U. Neuner[1], N. A. Pablant[4], E. Pasch[1], A. Pavone[1], T. S. Pedersen[1], K. Rahbarnia[1], J. Schilling[1], E. R. Scott[1], T. Stange[1], J. Svensson[1], H. Thomsen[1], Y. Turkin[1], F. Warmer[1], R. C. Wolf[1], D. Zhang[1] & the W7-X Team*

Research on magnetic confinement of high-temperature plasmas has the ultimate goal of harnessing nuclear fusion for the production of electricity. Although the tokamak[1] is the leading toroidal magnetic-confinement concept, it is not without shortcomings and the fusion community has therefore also pursued alternative concepts such as the stellarator. Unlike axisymmetric tokamaks, stellarators possess a three-dimensional (3D) magnetic field geometry. The availability of this additional dimension opens up an extensive configuration space for computational optimization of both the field geometry itself and the current-carrying coils that produce it. Such an optimization was undertaken in designing Wendelstein 7-X (W7-X)[2], a large helical-axis advanced stellarator (HELIAS), which began operation in 2015 at Greifswald, Germany. A major drawback of 3D magnetic field geometry, however, is that it introduces a strong temperature dependence into the stellarator's non-turbulent 'neoclassical' energy transport. Indeed, such energy losses will become prohibitive in high-temperature reactor plasmas unless a strong reduction of the geometrical factor associated with this transport can be achieved; such a reduction was therefore a principal goal of the design of W7-X. In spite of the modest heating power currently available, W7-X has already been able to achieve high-temperature plasma conditions during its 2017 and 2018 experimental campaigns, producing record values of the fusion triple product for such stellarator plasmas[3,4]. The triple product of plasma density, ion temperature and energy confinement time is used in fusion research as a figure of merit, as it must attain a certain threshold value before net-energy-producing operation of a reactor becomes possible[1,5]. Here we demonstrate that such record values provide evidence for reduced neoclassical energy transport in W7-X, as the plasma profiles that produced these results could not have been obtained in stellarators lacking a comparably high level of neoclassical optimization.

In the quest for a viable fusion reactor, consideration of the plasma energy balance shows that—regardless of the confinement concept—a minimum value of the fusion triple product, $nT\tau_E$, must be attained before net-energy-producing operation becomes possible[1,5]. Here, n is the fuel density, T is its temperature and τ_E is the energy confinement time, defined by the ratio W/P, where W is the stored plasma energy and P is the heating power provided by fusion reactions. The temperature dependence of the fuel's fusion reactivity provides an additional constraint; for deuterium–tritium fusion, this reactivity falls rapidly below a temperature of 10 keV ($\approx 1.2 \times 10^8$ K). High temperatures are thus mandatory in fusion plasmas but must be simultaneously consistent with a tolerable level of energy transport if the required τ_E is to be achieved.

Toroidal magnetic confinement of fully ionized fusion plasmas requires that field lines spiral around the minor axis of the torus poloidally as they encircle the major axis toroidally, tracing out magnetic flux surfaces in the course of numerous transits about the device. For a tokamak these toroidal and poloidal components of **B** are provided, respectively, by planar current-carrying coils situated outside the plasma and by a toroidal plasma current induced with a central

---

[1] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany. [2] Laboratorio Nacional de Fusion, CIEMAT, Madrid, Spain. [3] Laboratory for Plasma Physics (LPP), École royale militaire/Koninklijke Militaire School (ERM/KMS), Brussels, Belgium. [4] Princeton Plasma Physics Laboratory, Princeton, NJ, USA. [5] Present address: Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany. *A list of authors and their affiliations appears at the end of the paper. e-mail: Craig.Beidler@ipp.mpg.de

C. Beidler et al 2021 Nature 596 221

Magnetischer Einschluss

Particle confinement

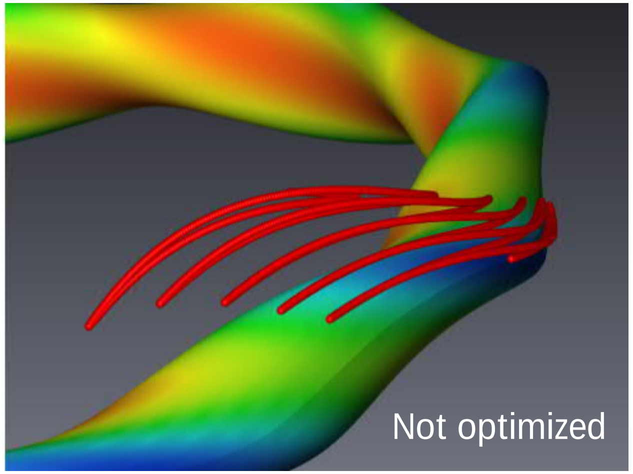
- Plasma fuel (D, T)
- Helium exhaust
- Impurity confinement

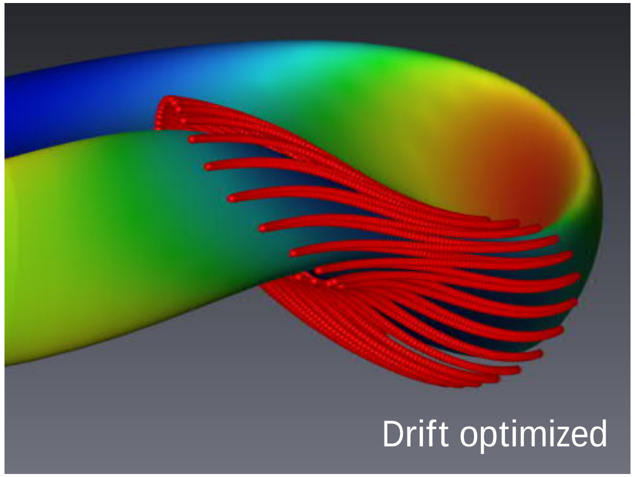
Fast ion confinement (3.5 MeV α-particles)

- Essential for self-heating of the plasma
- Essential not to damage plasma facing components
- Difficult to achieve in stellarators

Stability

- Limits plasma $\beta = B^2/2\mu_0$
- Biggest issue in tokamaks are current disruptions occurring when reaching operational limits





Courtesy J. Proll

Magnetischer Einschluss

Particle confinement

- Plasma fuel (D, T)
- Helium exhaust
- Impurity confinement

Fast ion confinement (3.5 MeV α-particles)

- Essential for self-heating of the plasma
- Essential not to damage plasma facing components
- Difficult to achieve in stellarators

Stability

- Limits plasma $\beta = B^2/2\mu_0$
- Biggest issue in tokamaks are current disruptions occurring when reaching operational limits

$$P_{fusion} = \frac{1}{4}\int n^2 \langle \sigma v \rangle E_{fusion} dV \quad \sim n^2 \langle \sigma v \rangle R^3$$

$$\sim n^2 T^2 R^3$$

$$\boxed{\sim \beta^2 B^4 R^3}$$

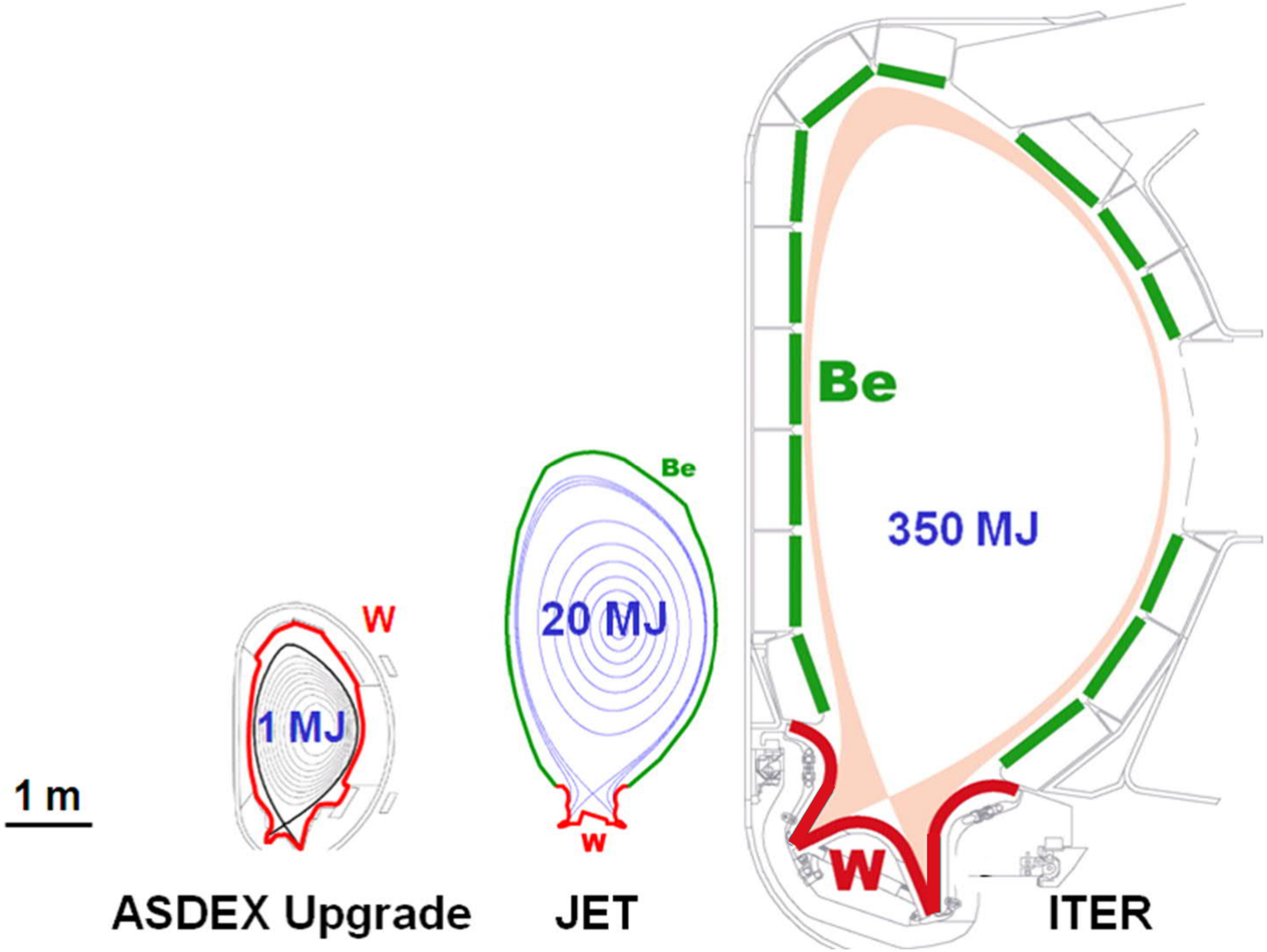
Dem Plasma ausgesetzte Materialien

Avoid plasma contamination

- Fuel dilution (low-Z)
- Radiation losses (high-Z)

Low plasma erosion

- Heat fluxes up to 10 MW/m^2



Dem Plasma ausgesetzte Materialien

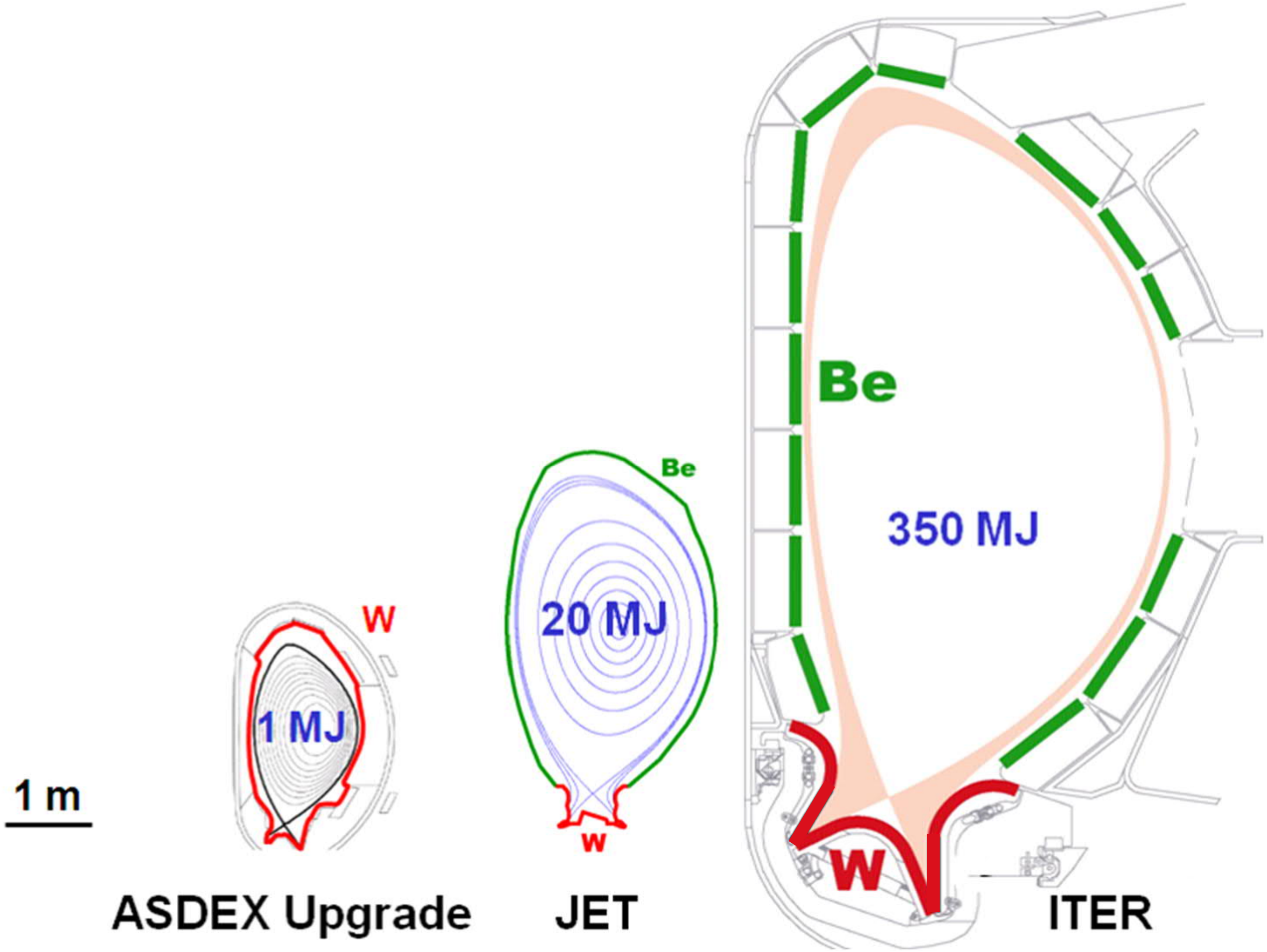
Carbon

- Sublimation at high temperatures
- Low Z
- But high (chemical) erosion
- And tritium co-deposition
- Neutron flux cause reduction of heat conductivity

Tungsten

- High Z
- Tungsten as plasma facing material was pioneered by ASDEX Upgrade
- Candidate material for a fusion power plant is tungsten

R. Neu et al 2007 J. Nucl. Mat. 367–370, 1497

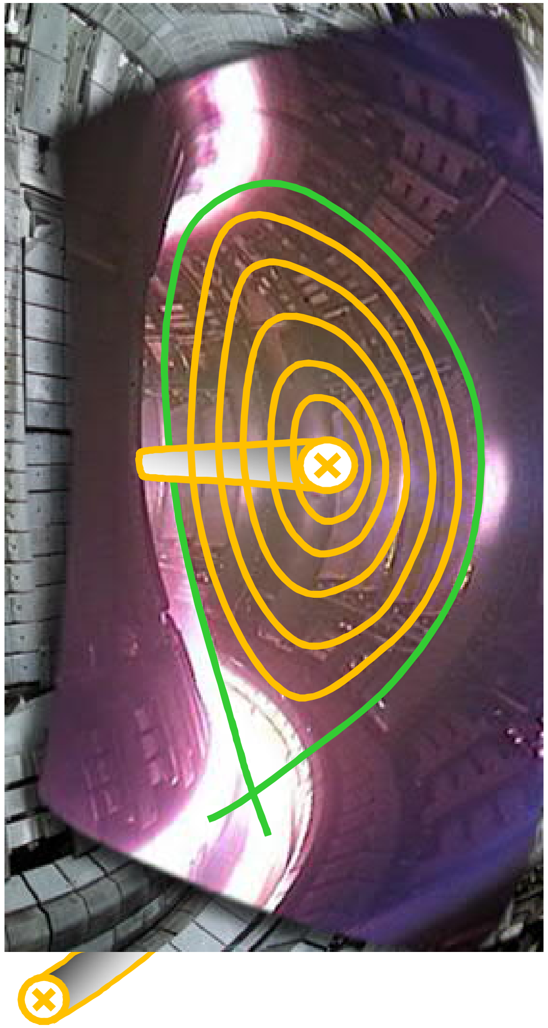


Wärme- und Teilchenabfuhr

Neutrons deposit 4/5 of the energy in the blanket volume

The rest has to be dissipated by plasma facing components

- About 10% to the divertor
- High heat flux targets ~ 10 MW/m^2 connected to the plasma boundary by the open magnetic field lines
- About 90% isotropic radiation
- Particles are exhausted formation of neutral gas by recombination of cold plasma (only neutral gas can be pumped)



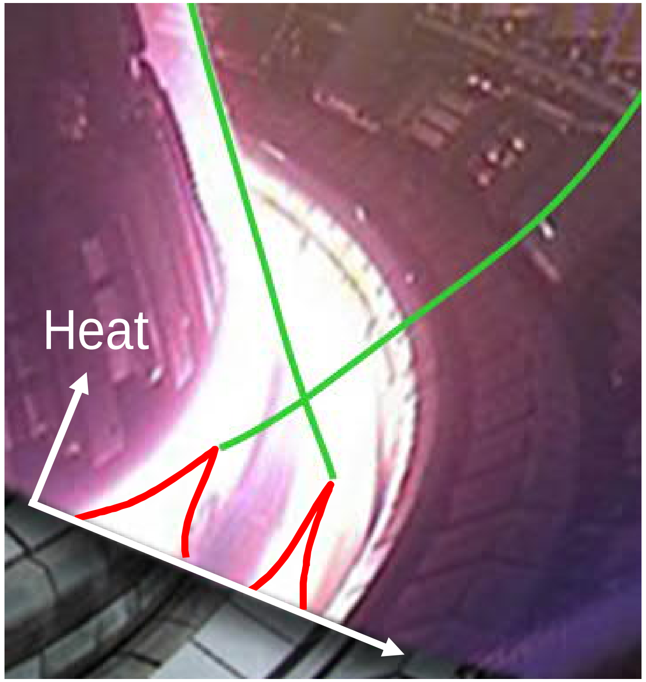
Wärme- und Teilchenabfuhr

Typical heat fluxes

- Fusion ~ 1.000 – 10.000 kW/m^2
- Fossil, fission ~ 500 kW/m^2
- Solar < 1.4 kW/m^2 (average in Germany 0.1 kW/m2)

Limitation of local heat fluxes by increasing the radiated power

- Homogeneous distribution over the surface of the plasma vessel
- Dedicated seeding of impurities



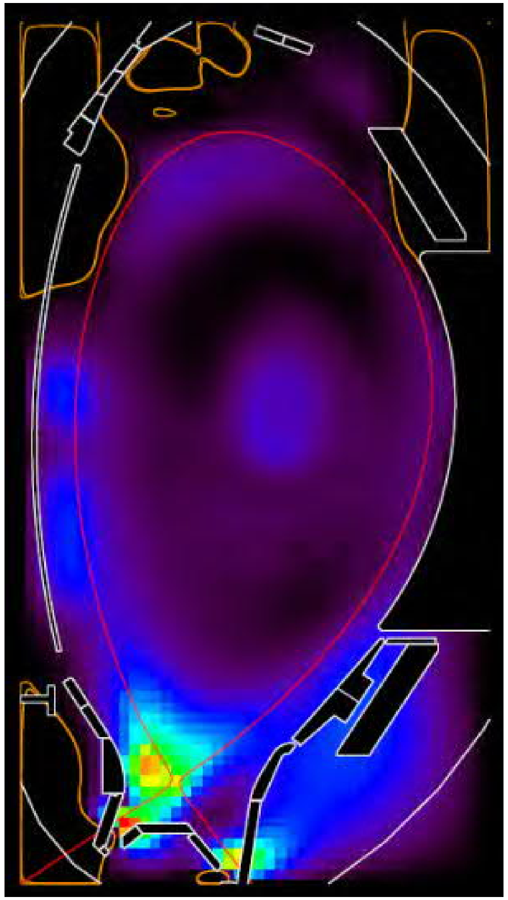
Wärme- und Teilchenabfuhr

Typical heat fluxes

- Fusion ~ 1.000 – 10.000 kW/m^2
- Fossil, fission ~ 500 kW/m^2
- Solar < 1.4 kW/m^2 (average in Germany 0.1 kW/m2)

Limitation of local heat fluxes by increasing the radiated power

- Homogeneous distribution over the surface of the plasma vessel
- Dedicated seeding of impurities



Tomographic reconstruction of radiated power for a 23 MW ASDEX Upgrade plasma limiting the heat flux to 5 MW/m^2 by using argon

A. Kallenbach et al 2012 Nucl. Fusion 52 122003

Wärmeabfuhr in Wendelstein 7-X

Targets (Plansee) for stationary heat fluxes up to 10 MW/m^2

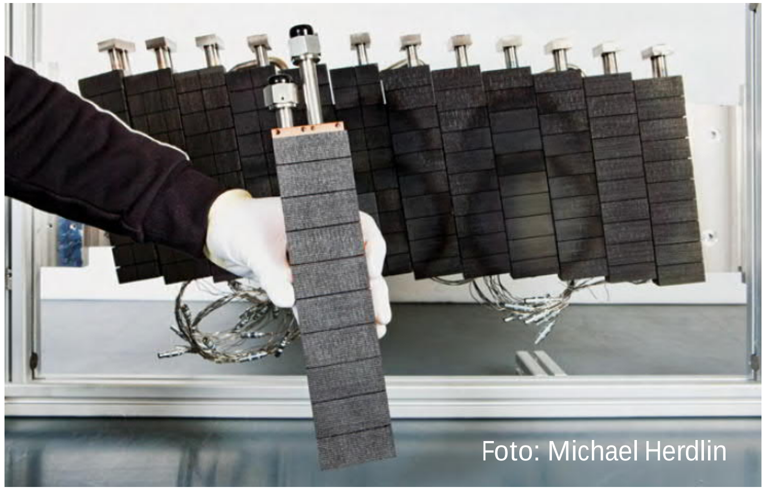
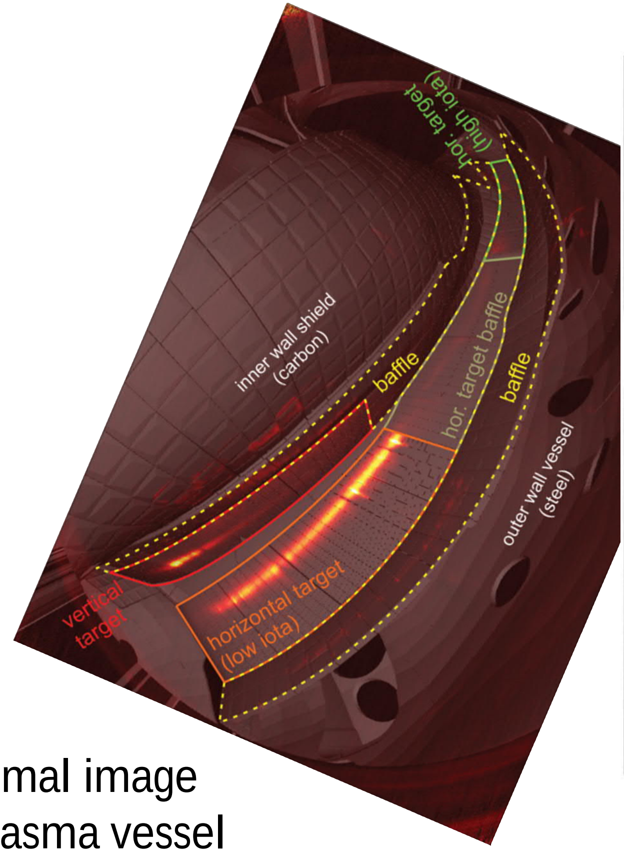
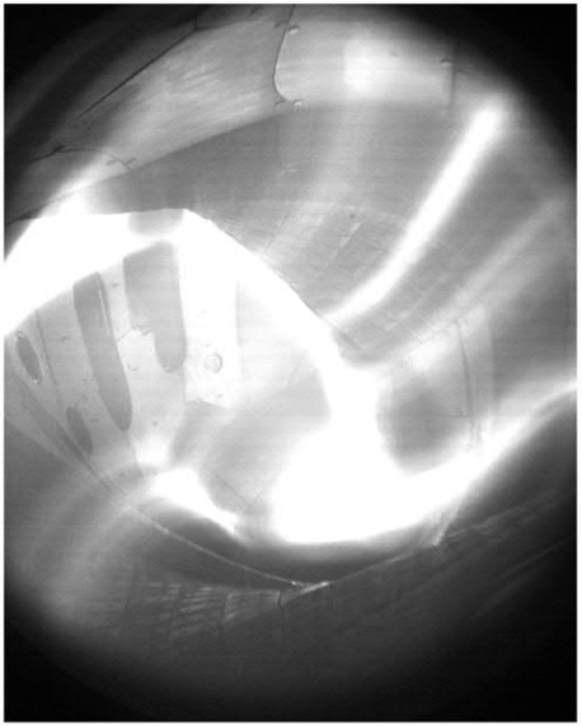


Foto: Michael Herdlin



Thermal image
of plasma vessel



30 seconds → 30 minutes requires specially cooled targets

Breedingblanket und Plasma-/Vakuumgefäß

Neutron fluences correspond to

- ~1 dpa in ITER
- ~100 dpa in a fusion power plant

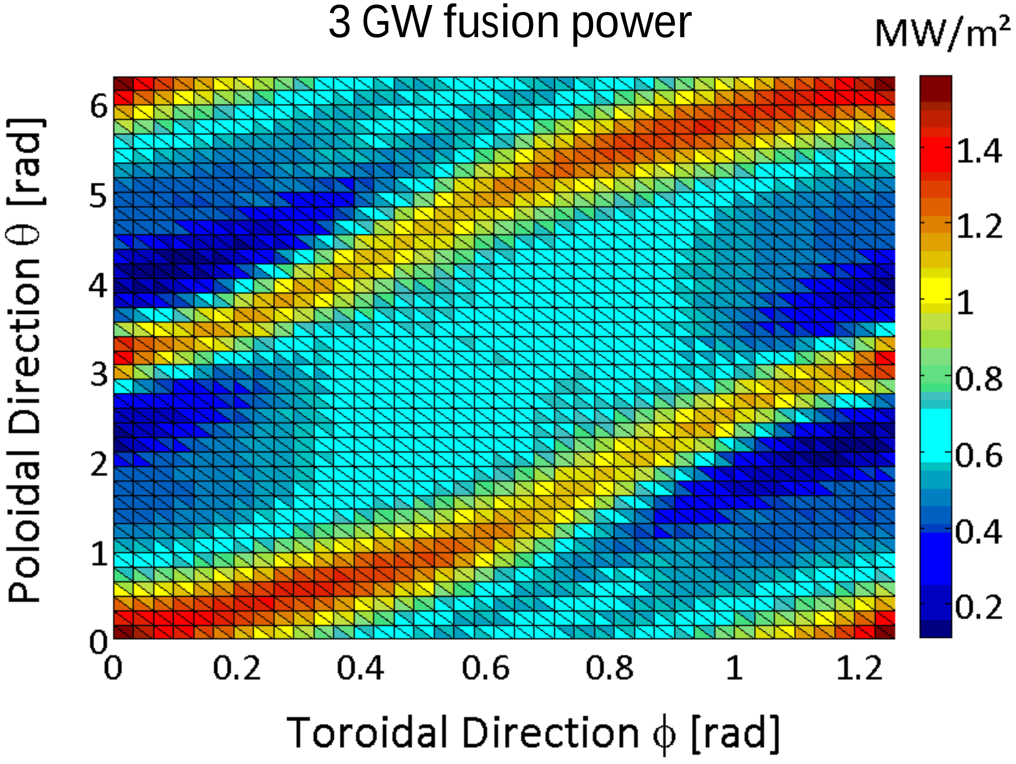
Blanket

- Breeding of tritium
- Heat exchange
- Screening of neutrons
- First test blankets in ITER

Vacuum vessel

- Further screening of neutrons
- Overall screening requirement ~10^{-6}

Neutron flux for stellarator fusion power plant extrapolated from Wendelstein 7-X
3 GW fusion power



A Häußler et al 2018 Fusion Eng. Design 136 345

Breedingblanket und Plasma-/Vakuumgefäß

Neutron fluences correspond to

- ~1 dpa in ITER
- ~100 dpa in a fusion power plant

Blanket

- Breeding of tritium
- Heat exchange
- Screening of neutrons
- First test blankets in ITER

Vacuum vessel

- Further screening of neutrons
- Overall screening requirement ~10^{-6}

ITER vacuum vessel

www.iter.org/news/galleries

Copyright: ITER Organization

Breedingblanket und Plasma-/Vakuumgefäß

Neutron fluences correspond to

- ~1 dpa in ITER
- ~100 dpa in a fusion power plant

Blanket

- Breeding of tritium
- Heat exchange
- Screening of neutrons
- First test blankets in ITER

Vacuum vessel

- Further screening of neutrons
- Overall screening requirement ~10^{-6}

ITER vacuum vessel

www.iter.org/news/galleries

Breedingblanket und Plasma-/Vakuumgefäß

Neutron fluences correspond to

- ~1 dpa in ITER
- ~100 dpa in a fusion power plant

Blanket

- Breeding of tritium
- Heat exchange
- Screening of neutrons
- First test blankets in ITER

Vacuum vessel

- Further screening of neutrons
- Overall screening requirement ~10^{-6}

A Häußler et al 2018 Fusion Eng. Design 136 345

ITER vacuum vessel

www.iter.org/news/galleries
Copyright: ITER Organization

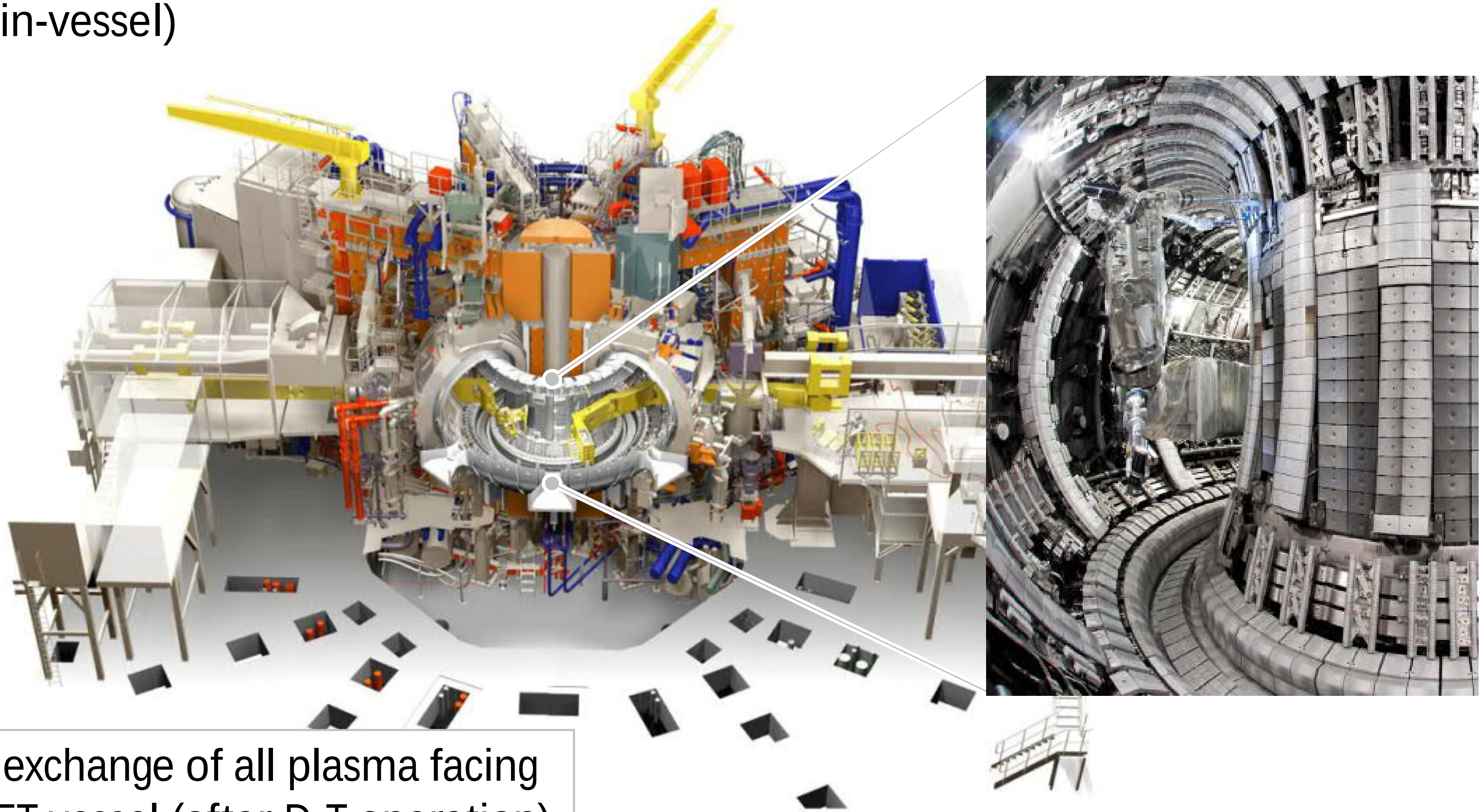
Remote Maintenance

Remote maintenance required for repair and exchange of activated (in-vessel) components

- Blanket
- Divertor

Relevant devices

- Important developments at JET
- Integral part of ITER design



For the 1st time complete exchange of all plasma facing components in activated JET vessel (after D-T operation)

G. F. Matthews et al 2011 Phys. Scr. T145 014001

Supraleitende Spulen

$n\,T\,\tau_E \sim B^2,\ P_{fusion} \sim B^4$

Magnetic field limited by

- Critical field / current of superconductor
- Mechanical forces of coil configuration

Superconductor

- NbTi (W7-X, ITER vertical field coils) up to 7 T
- Nb_3Sn (ITER central solenoid, toroidal field) up to 12 T
- Development of HT superconductors

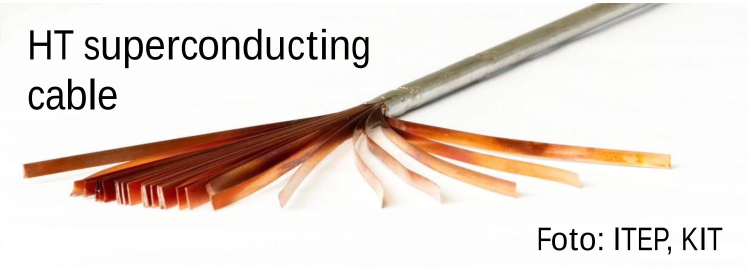
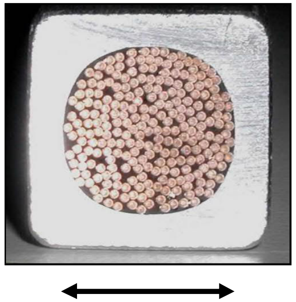
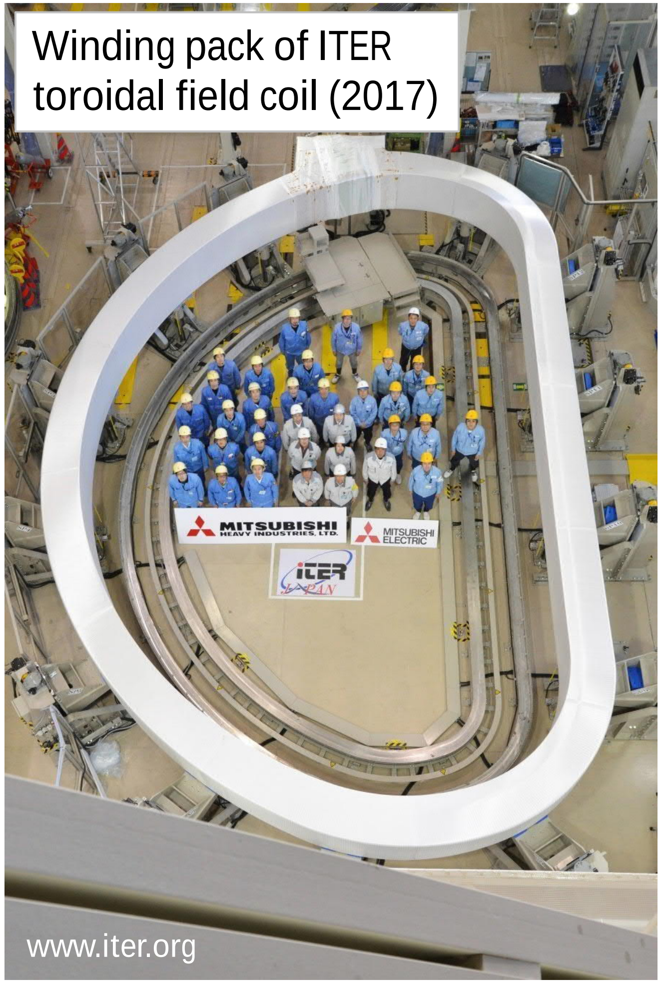

HT superconducting cable

Foto: ITEP, KIT



W7-X superconductor: up to 18 kA

Winding pack of ITER toroidal field coil (2017)



www.iter.org

Supraleitende Spulen

$n\,T\,\tau_E \sim B^2,\ P_{fusion} \sim B^4$

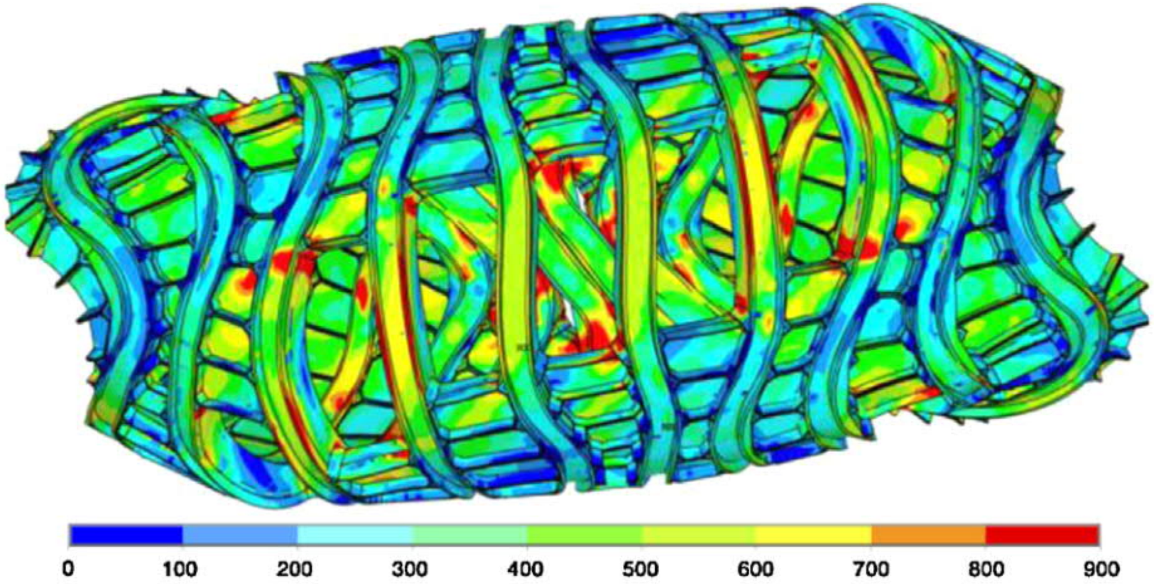
Magnetic field limited by

- Critical field / current of superconductor
- Mechanical forces of coil configuration

Superconductor

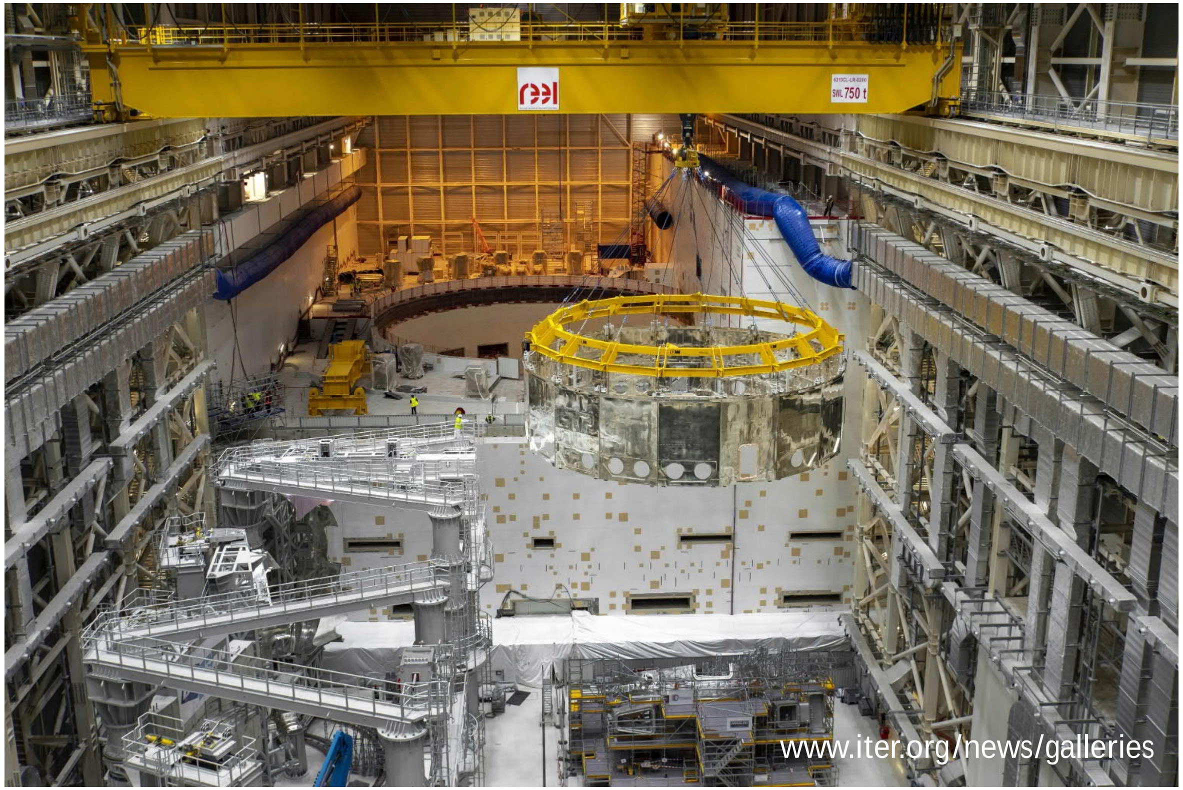
- NbTi (W7-X, ITER vertical field coils) up to 7 T
- Nb_3Sn (ITER central solenoid, toroidal field) up to 12 T
- Development of HT superconductors

Van Mises stress distribution (in MPa) of a possible coil support structure for a stellarator power plant (W7-X extrapolation)



F. Schauer et al 2013 Fusion Eng. Design 88 1619

Kryostatgefäß und thermischer Schild



Installation of first part of ITER thermal shield (January 2021)

Copyright: ITER Organization

Sections of the Wendelstein 7-X cryostat vessel

IPP, Foto: Anja Richter Ullmann

Plasmaerzeugung, -heizung und Stromtrieb

Tokamak needs current drive for becoming stationary

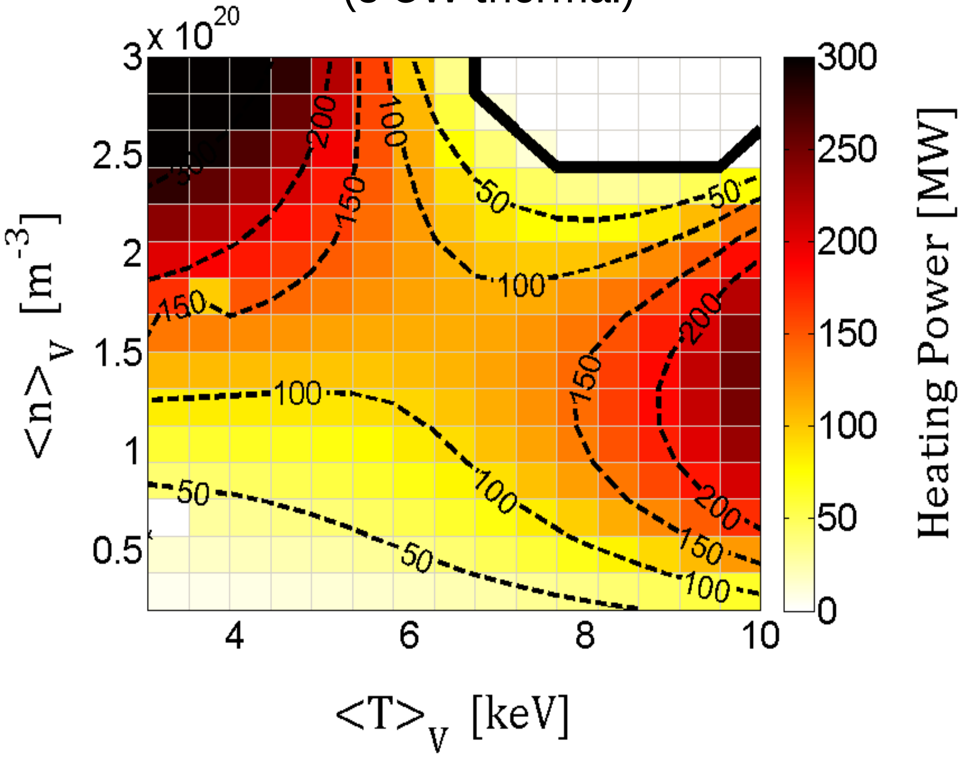
- Issue of efficiency

Stellarator is intrinsically steady state

Heating and current drive systems

- Injection of fast neutrals (NBI)
- Resonant heating of ions (ICRH)
- Resonant heating of electrons (ECRH)

Path to ignition for a stellarator power plant (3 GW thermal)

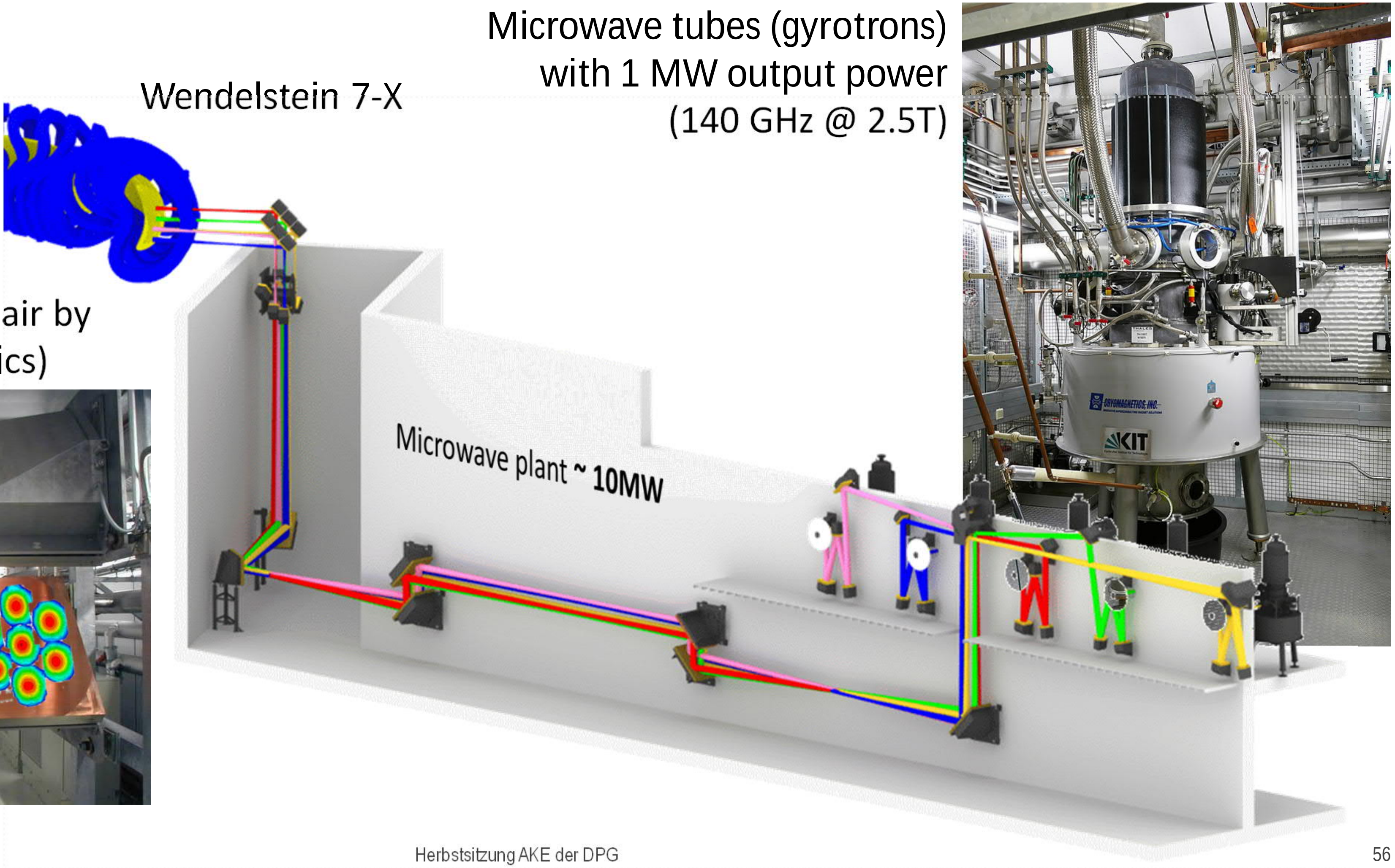


F. Warmer et al 2016, IEEE Transactions Plasma Science 44 1576

Plasmaerzeugung, -heizung und Stromtrieb

ECRH at 2nd harmonic electron cyclotron frequency

Microwave tubes (gyrotrons) with 1 MW output power (140 GHz @ 2.5T)

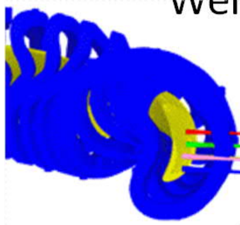


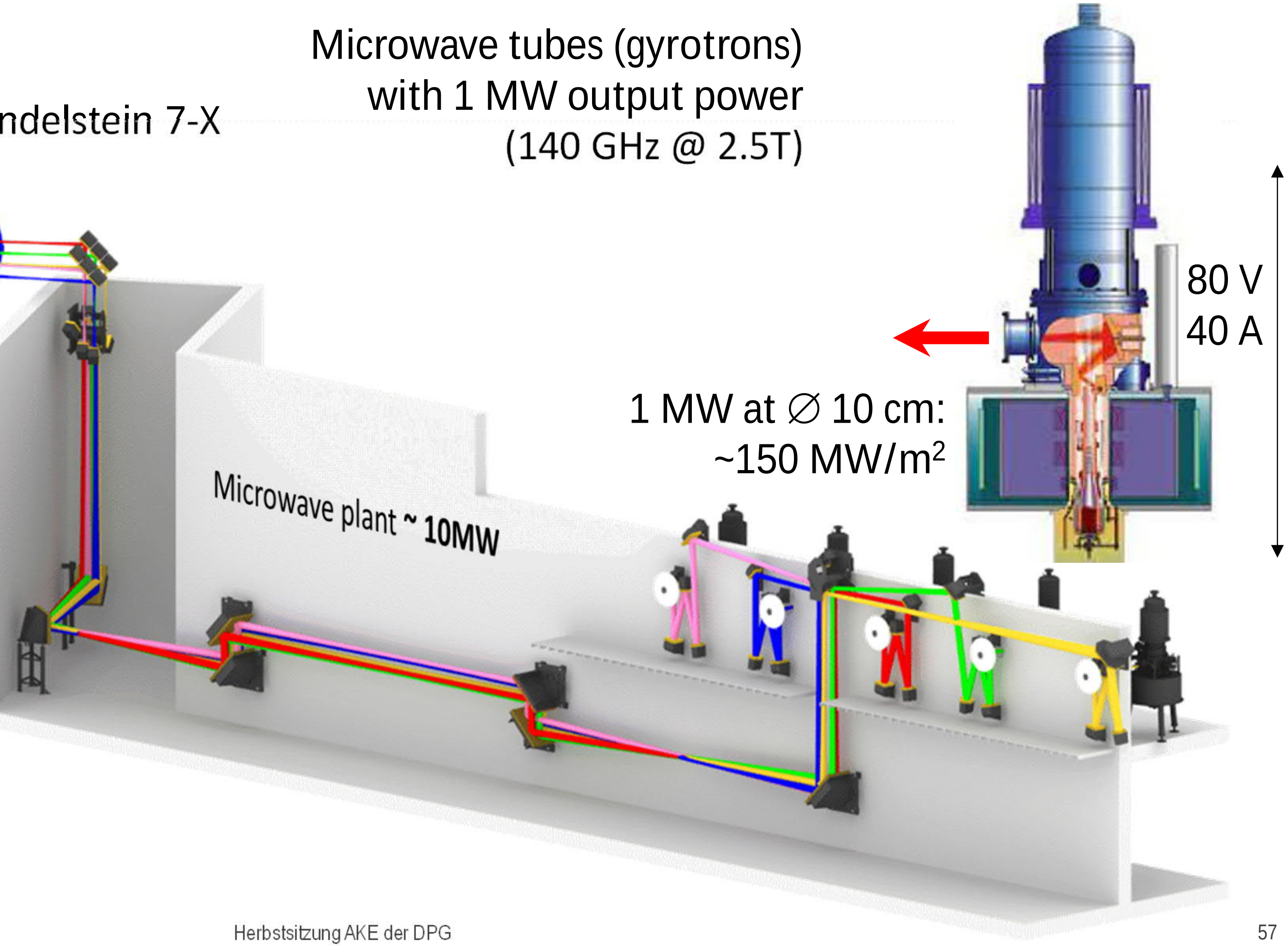
Transmission through air by mirrors (Gaussian optics)

Plasmaerzeugung, -heizung und Stromtrieb

ECRH at 2nd harmonic electron cyclotron frequency

Transmission through air by mirrors (Gaussian optics)





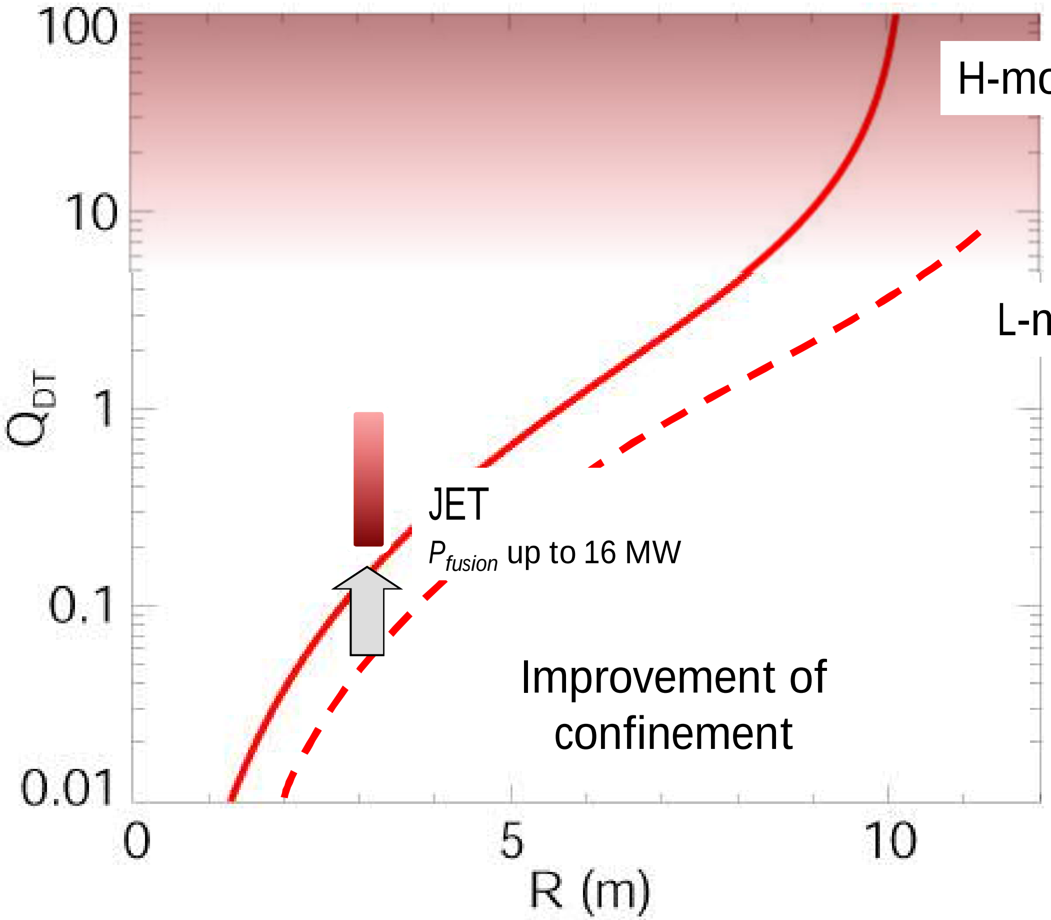
Microwave tubes (gyrotrons) with 1 MW output power (140 GHz @ 2.5T)

1 MW at ∅ 10 cm: ~150 MW/m^2

Inhalt

- Energie aus Fusion
- Magnetischer Einschluss
- Stand der Fusionsforschung
- Auf dem Weg zu einem Fusionskraftwerk
- Fazit und Ausblick

Extrapolation zu einem Fusionskraftwerk



H-mode confinement

L-mode confinement

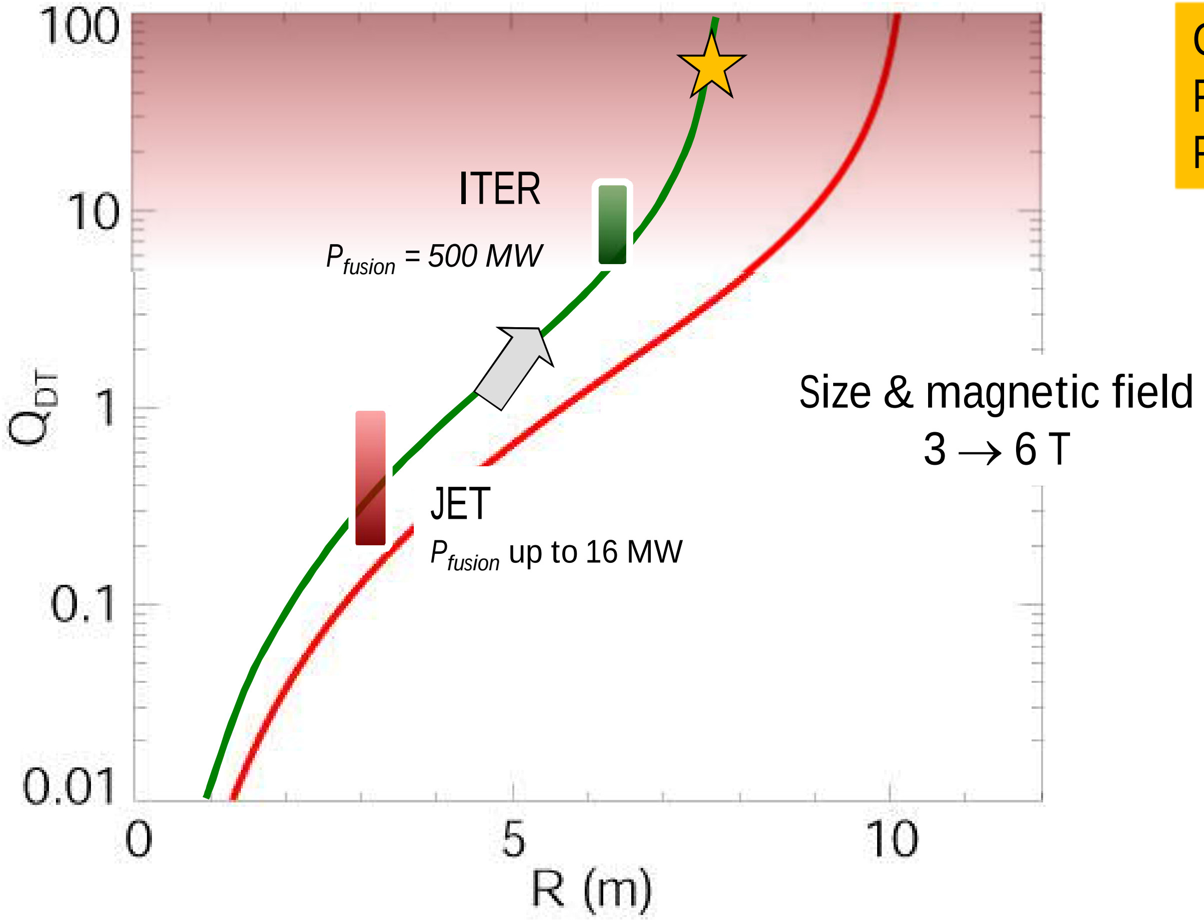
JET

P_{fusion} up to 16 MW

Improvement of confinement

R Wolf 2003 Plasma Phys. Control. Fusion 45 R1

Extrapolation zu einem Fusionskraftwerk

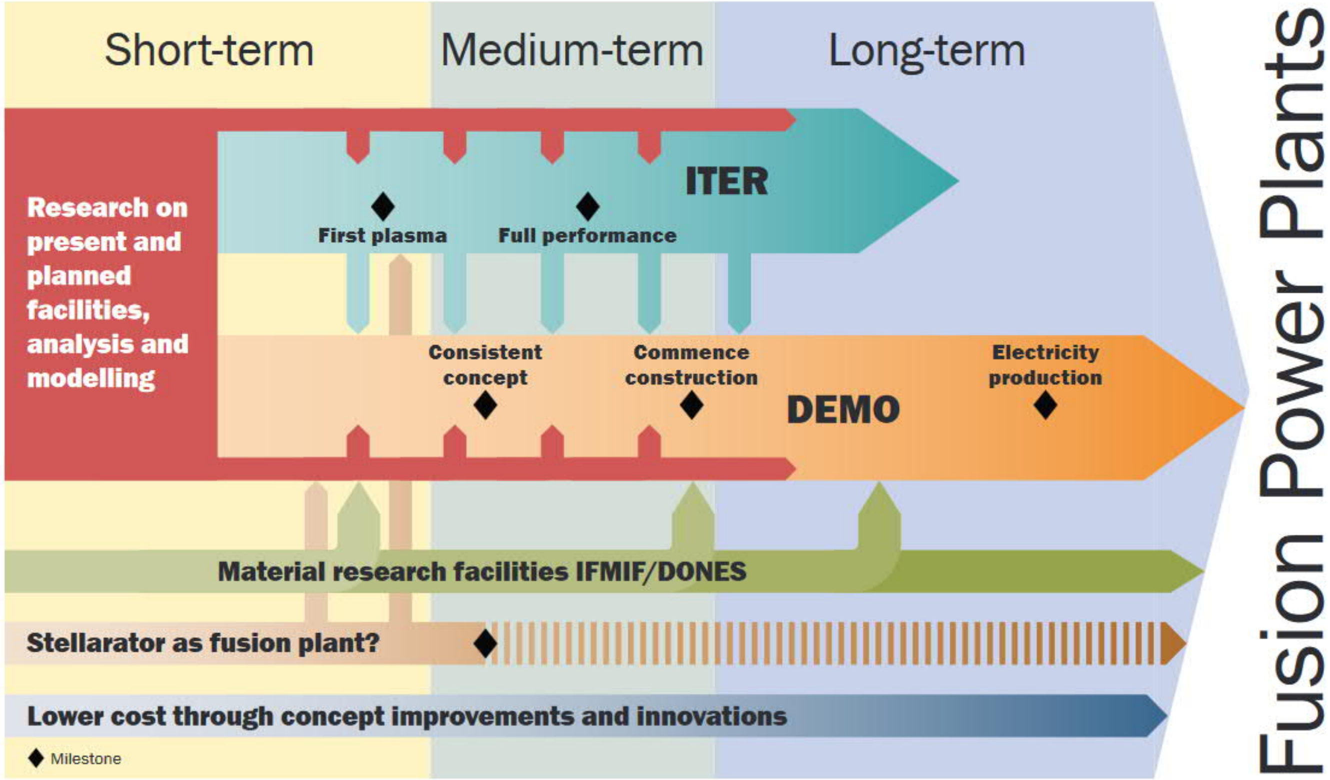


Size & magnetic field
3 → 6 T

Q ~ 50
P_{Fusion} ~ 3 GW
P_{elektr} ~ 1 GW

R Wolf 2003 Plasma Phys. Control. Fusion 45 R1

Roadmap zu einem Demonstrationskraftwerk



Short-term

Medium-term

Long-term

Research on present and planned facilities, analysis and modelling

ITER

◆ **First plasma**

◆ **Full performance**

DEMO

Consistent concept ◆

Commence construction ◆

Electricity production ◆

Material research facilities IFMIF/DONES

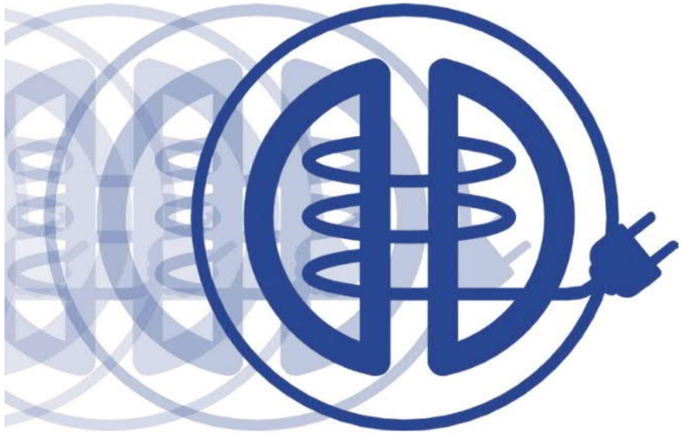
Stellarator as fusion plant? ◆

Lower cost through concept improvements and innovations

◆ Milestone

Fusion Power Plants

European Research Roadmap
to the Realisation of Fusion Energy



www.euro-fusion.org/eurofusion/roadmap/

Entscheidende Elemente für die weitere Entwicklung

Improved concepts

- Wendelstein 7-X

First burning fusion plasma, first tritium breeding

- ITER

Fundamental physics understanding

- Extrapolation

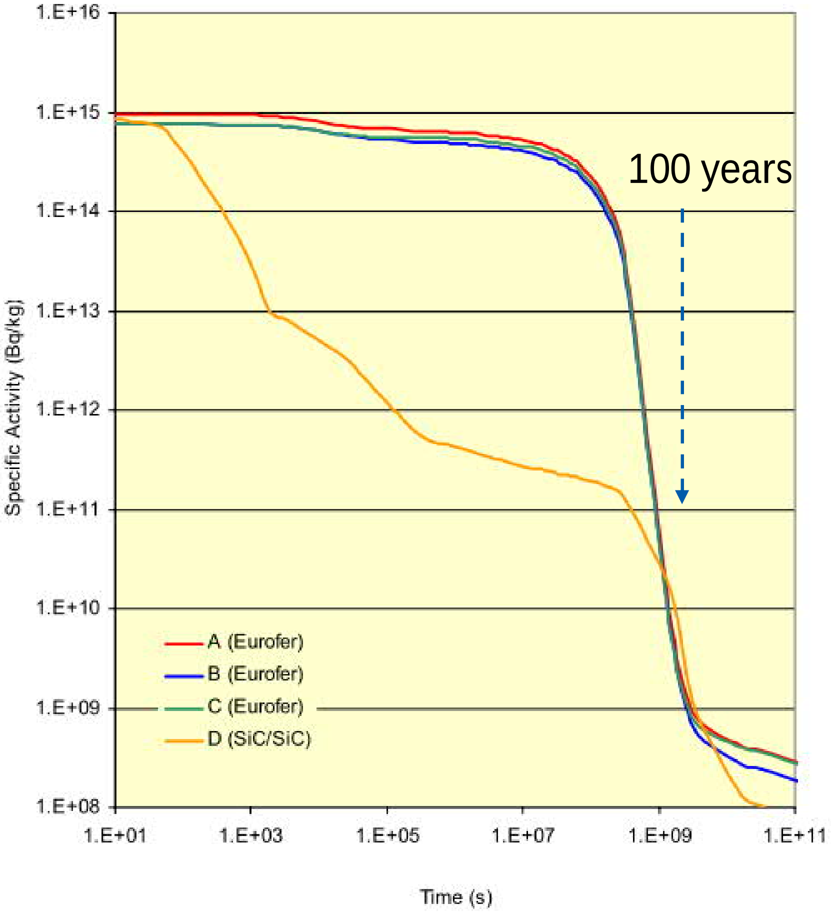
Technology development

- E.g. HT superconductors
- Higher B-field

Low activation materials, high heat flux materials

- Neutron source

First integrated design of a demonstration power plant (DEMO)



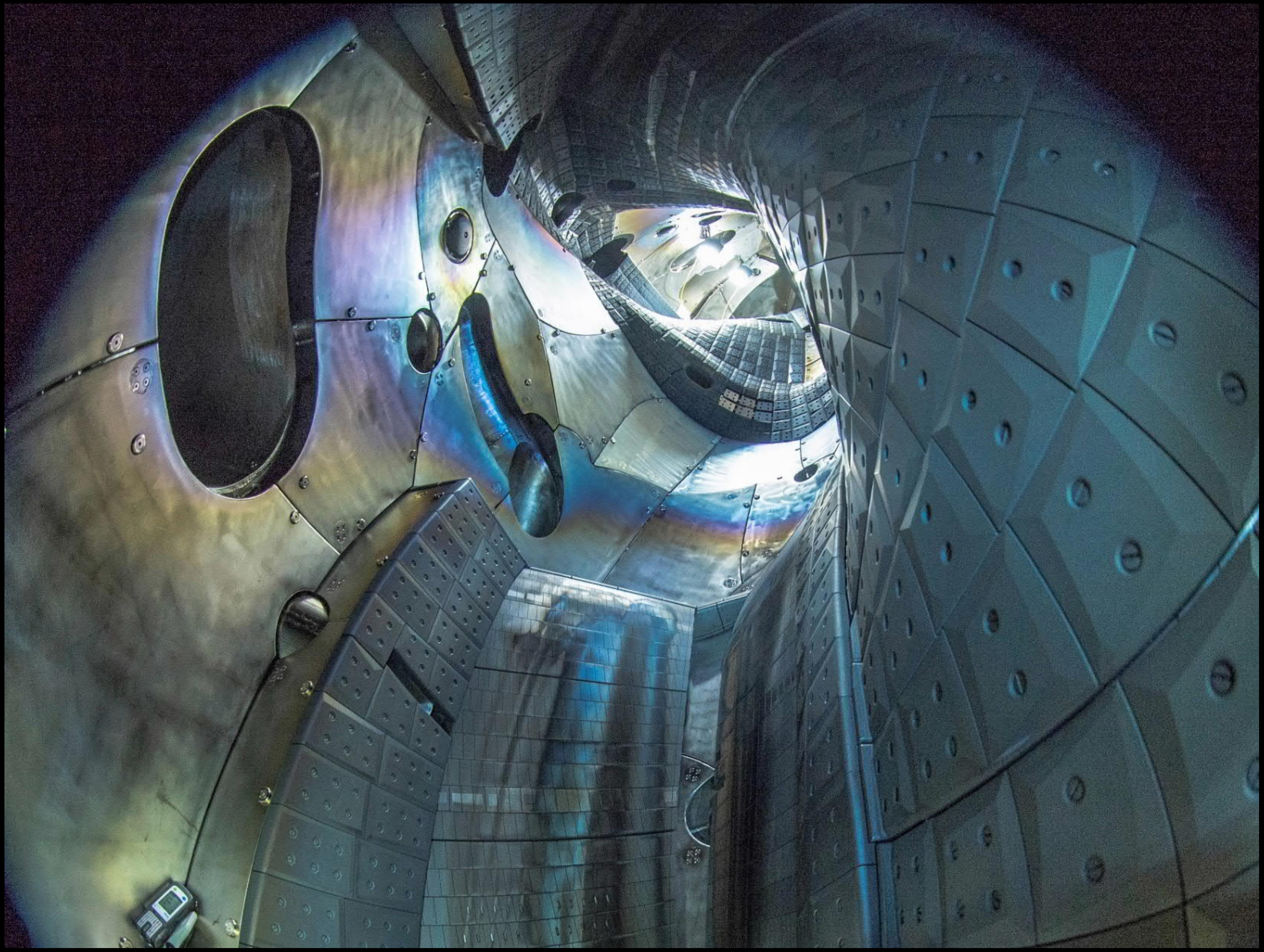
Final Report of the European Fusion Power Plant Conceptual Study EFDA(05)-27/4.10

Fazit und Ausblick

- The realization of fusion energy is scientifically and technologically one of the larges enterprises worldwide
- Leading fusion projects are
  - ITER: First demonstration of a burning fusion plasma & first time breeding tritium from fusion neutrons and lithium (on a technical scale)
  - Wendelstein 7-X: Validation of an alternative confinement concept with advantageous power pant properties
- Important key technologies are: Low activation materials, high heat flux materials, superconductors, heating methods, remote handling, high performance computing, …
- Close alignment of physics and technology is essential
- Also, close collaboration between research and industry is essential

http://www2.ipp.mpg.de/ippcms/de/externe_daten/emag/IPPundIndustrie/index.html

Danke für Ihre Aufmerksamkeit



Innenansicht Wendelstein 7-X nach erster Betriebsphase

Mit freundlicher Genehmigung von
C. Biedermann, G. Wurden (2018)