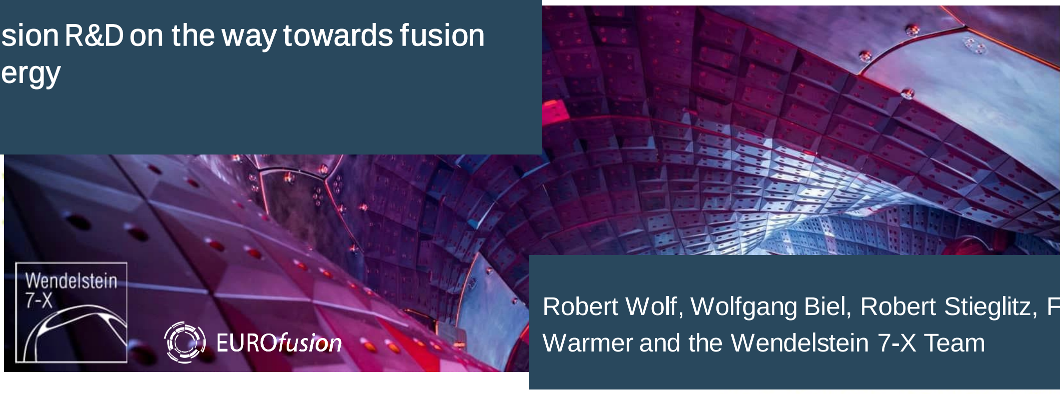
HELMHOLTZ Energy

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

KIT Karlsruhe Institute of Technology | JÜLICH Forschungszentrum | TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Fusion R&D on the way towards fusion energy



Robert Wolf, Wolfgang Biel, Robert Stieglitz, Felix Warmer and the Wendelstein 7-X Team

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

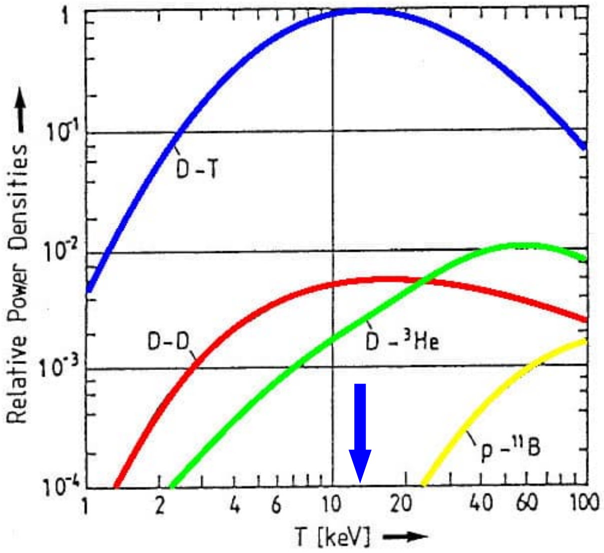
Nuclear Fusion

Fusion reactions: Why D-T fusion?

- D-T-fusion has the highest reaction rate of all fusion reactions

D + T → ^{4}He (3.5 MeV) + n (14.1 MeV)

- Optimum temperature range of D-T-fusion: 10-20 keV or ~100 M°C
- Too low temperatures: Fusion reactivity rapidly decreases with decreasing temperature
- Too high temperatures: Prohibitive synchrotron losses (in MCF systems)



Fusion reactions: Why fusion?

$$\begin{aligned} D + T &\rightarrow He + n + 17.6\ \text{MeV} \\ n + {}^6Li &\rightarrow He + T + 4.8\ \text{MeV} \\ \hline D + {}^6Li &\rightarrow 2\ He + 22.4\ \text{MeV} \end{aligned}$$

$$\boxed{1\ GW_{th} \leftrightarrow 0.3\ \text{kg/Tag}}$$

$$C + O_2 \rightarrow CO_2 + 13.5\ \text{eV}$$

$$\boxed{1\ GW_{th} \leftrightarrow 10^6\ \text{kg/Tag}}$$

Important aspects

- Neutrons used to breed tritium: Closed fuel cycle
- Fusion “ash” is helium: No CO_2 production
- Neutrons activate material surrounding the plasma
- Avoid long-term waste, recycling after < 100 years

Fusion reactions: Why fusion?

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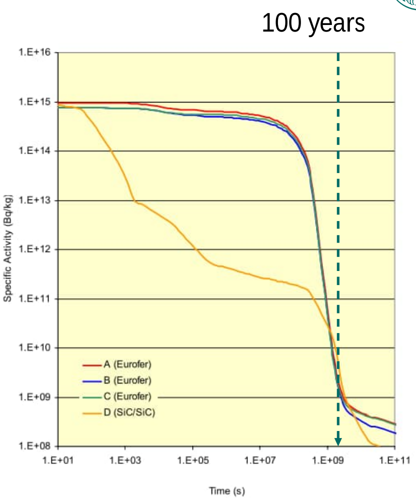
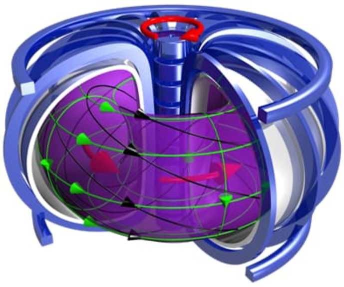


Final Report of the European Fusion Power Plant Conceptual Study EFDA(05)-27/4.10

Magnetic confinement fusion (MCF)

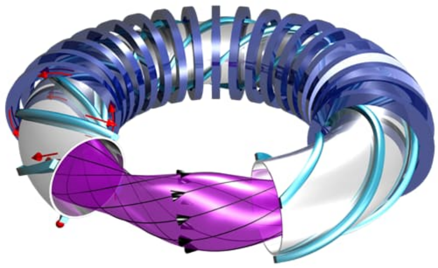
Magnetic confinement concepts

Tokamak



- Simpler geometry
- Usually pulsed operation
- Steady state using current drive
- ITER is a tokamak

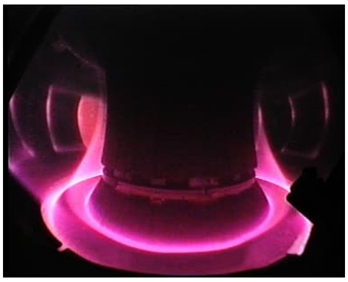
Stellarator



- More demanding geometry
- Magnetic field only from external coils
- Intrinsically steady-state
- Wendelstein 7-X is a stellarator

Magnetic confinement fusion (MCF) parameters

Deuterium-Tritium-Plasma	Luft
10^{20} m^{-3}	10^{25} m^{-3}
100 Million °C (100 MK)	20 °C (300 K)
~5 bar	1 bar



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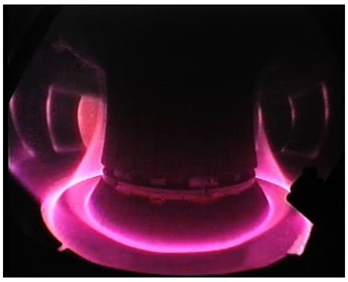
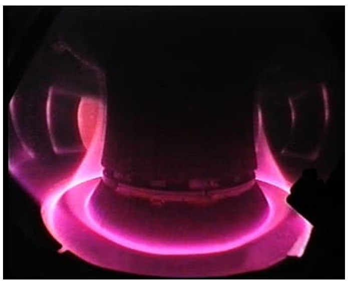


Plasma state due to high temperatures

Magnetic confinement due to Lorentz force acting on charges plasma particles

Inertial confinement fusion (ICF) parameters

Deuterium-Tritium-Plasma	Deuterium-Tritium-Plasma
10^{20} m^{-3}	10^{32} m^{-3}
100 Million °C (100 MK)	10 Million °C (10 MK)
~5 bar	~100 Gbar



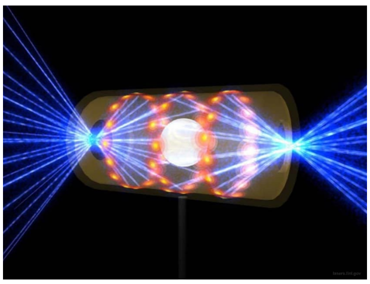


Foto: Lawrence Livermore National Laboratory

Inertial confinement fusion (ICF) parameters

Deuterium-Tritium-Plasma

10^{32} m^{-3}

10 Million °C (10 MK)

~100 Gbar

Plasma parameters and plasma behaviour fundamentally different in MCF and ICF devices

MCF: Steady-state burning plasma

ICF: Pellet ignition lasting nanoseconds at several Hertz

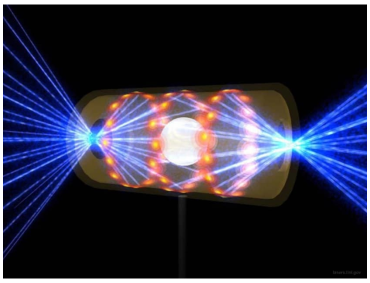
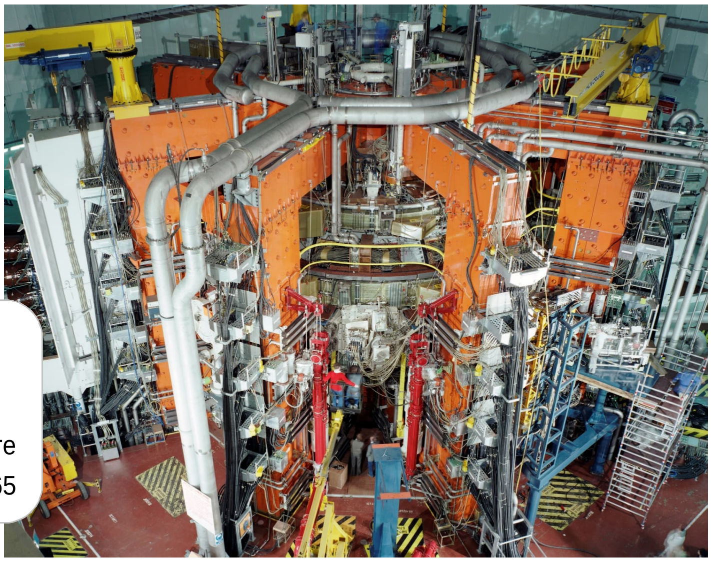


Foto: Lawrence Livermore National Laboratory

To date largest MCF device: Joint European Torus (JET)

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



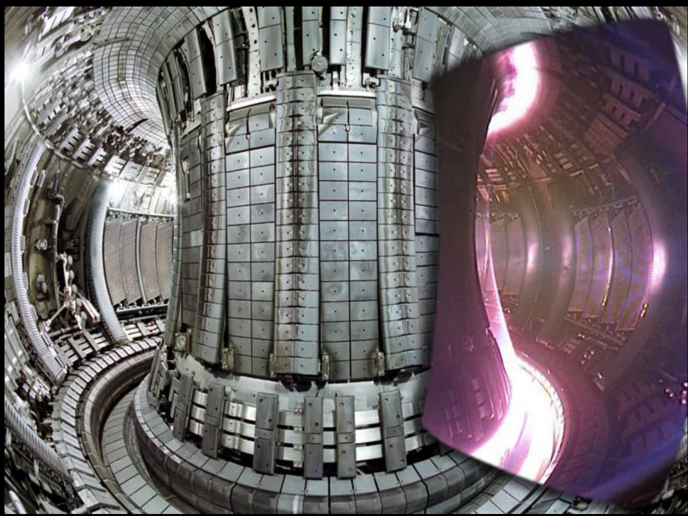
Plasma volume ~ 100 m^3

Magnetic field ~3T (copper coils)

One of two MCF experiments worldwide which used D-T-mixture

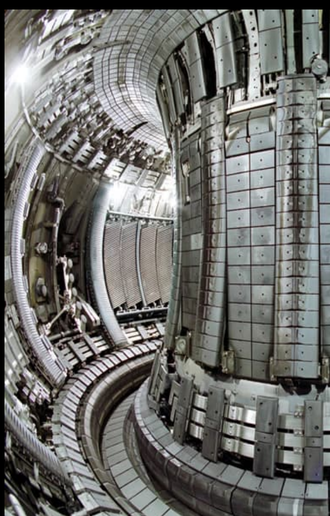
16 MW of fusion power at Q = 0.65

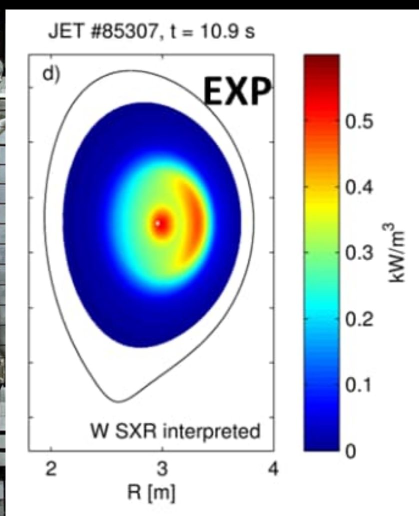
Joint European Torus (JET)



Visible emission
T ~ 100 Mio °C

Joint European Torus (JET)





X-ray emission
T ~ 100 Mio °C

P. Mantica et al 2015 Proc 42nd EPS Conferenz on Plasma Physics P1.101

ITER

Plasma volume ~ 800 m^3

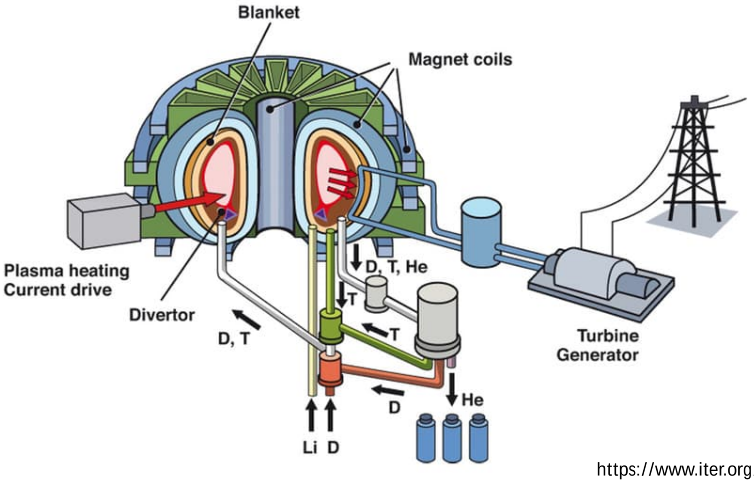
Magnetic field ~6T (superconducting coils)

Burning fusion plasma for the first time

500 MW fusion power for ~10 minutes from 50 MW of heating power (Q = 10)

Layout of a fusion power plant: Integration of physics and technology solutions

- Fusion plasma
- Heat and particle exhaust
- Breeding blanket
- Superconducting magnetic field coils
- Heating & current drive systems
- Fuel cycle



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

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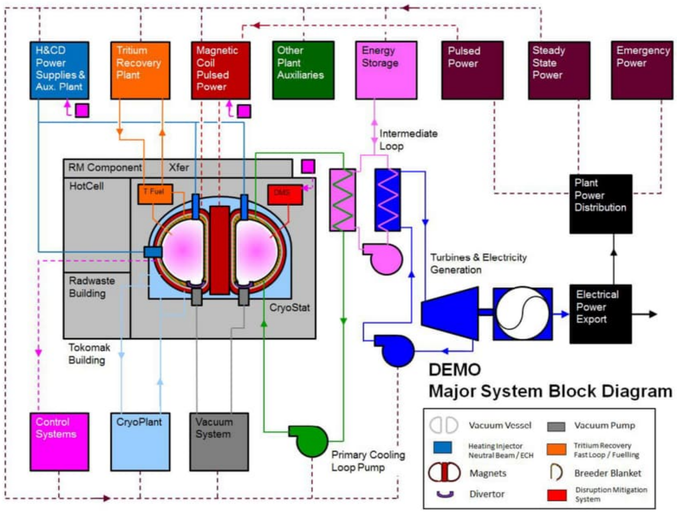
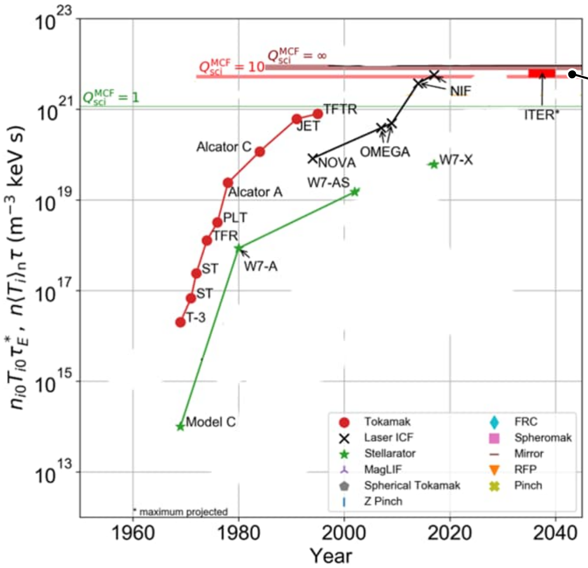


Source ???

Achievements – where are we?

Triple product describes the distance to burning fusion plasma or ignition



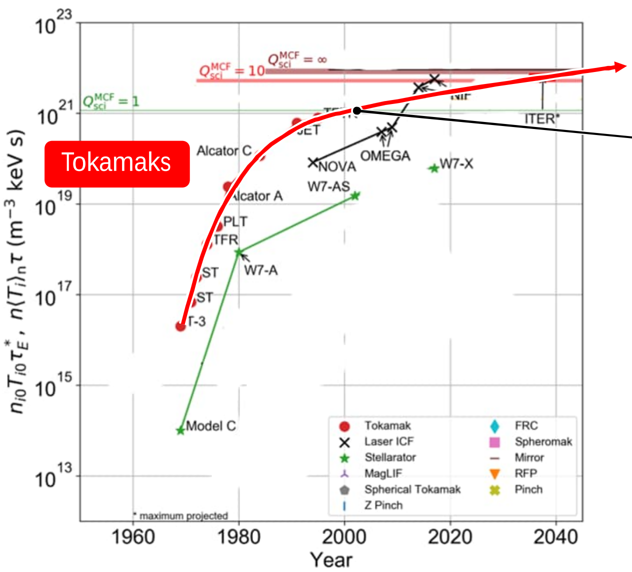
Burning fusion plasma

$$Q = \frac{P_{fusion}}{P_{heating}} = \frac{5P_\alpha}{P_{heating}} >> 1$$

Demonstration of burning fusion plasma only possible at power plant level

S.E.Wurzel, S.C.Hsu, Phys. Plasmas 29 (2022) 062103
doi: 10.1063/5.0083990

Triple product describes the distance to burning fusion plasma or ignition



Improvement of confinement (heat insulation)
Increase of magnetic field
Increase of size (volume to surface ratio)

Plasma duration from milliseconds to minutes and hours
Transition from copper to superconducting magnetic field coils
Heat exhaust becomes increasingly important

Overall, increasing level of scientific and technical integration and complexity

S.E.Wurzel, S.C.Hsu, Phys. Plasmas 29 (2022) 062103
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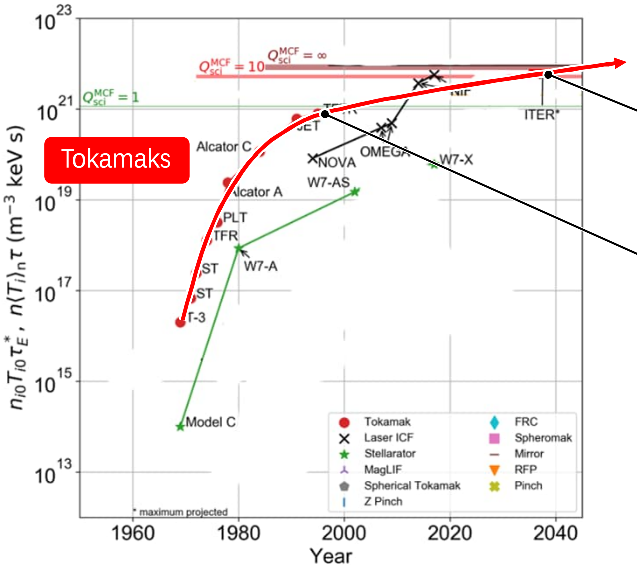

Energy confinement time has to be increased by an order of magnitude

Essential parameters achieved

- Density ~ 10^{20} m^{-3}
- Ion temperature ~10 keV

S.E.Wurzel, S.C.Hsu, Phys. Plasmas 29 (2022) 062103
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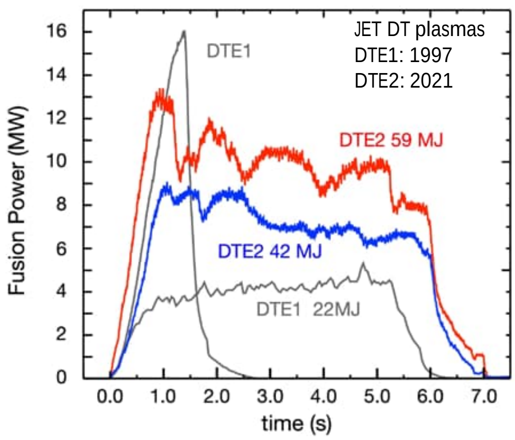
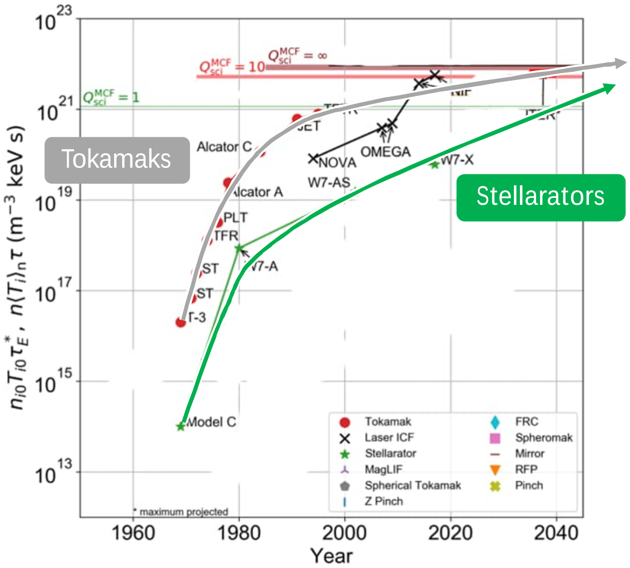
D-T-fusion energy record in JET

- JET is one of two MCF devices which used tritium
- Physics and technology platform to contribute to the ITER physics and technology base
- DTE1: α-heating with Q = 0.65 confirmed (Q= 1 corresponds to ~20% of α-heating power)
- DTE2: Extended phase of ~10 MW of fusion power by optimizing confinement and stability properties and significantly higher heating power



Record fusion energy $\int P_{fusion} dt$ (from 2021)

Triple product describes the distance to burning fusion plasma or ignition



Intrinsically steady steady-state

Soft operational boundaries, much reduced plasma control effort

Overall, optimized stellarator promises more economic power plant

However, requires elaborate physics and technology design optimization to achieve required confinement quality

The design of Wendelstein 7-X was only possible with the advent of super computers

S.E.Wurzel, S.C.Hsu, Phys. Plasmas 29 (2022) 062103
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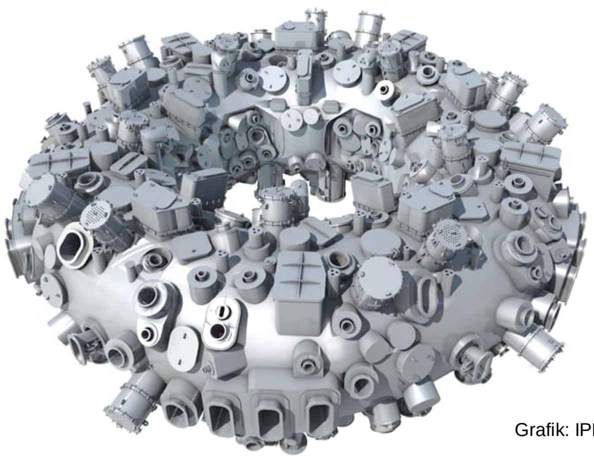
Wendelstein 7-X is the first fusion devices the design of which is based on a comprehensive optimization procedure

- Magnetic field
  - 3 T
- Superconducting coils
  - 70
- Plasma volume
  - 30 m^3
- Plasma duration
  - 30 minutes
- Heating power
  - 10 MW
- Peak heat flux
  - 10 MW/m^2



Grafik: IPP

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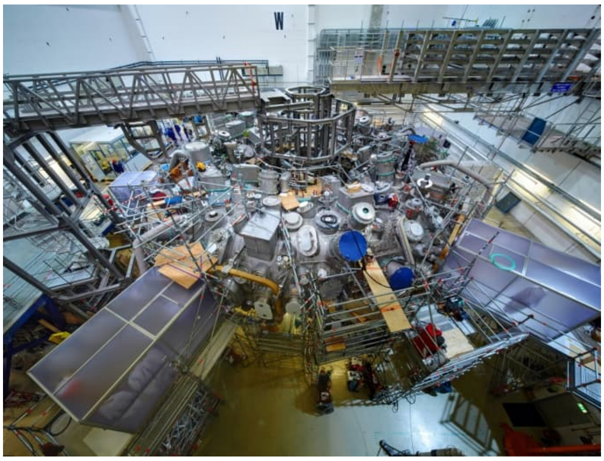

IPP, Foto: Bernhard Ludewig

Wendelstein 7-X is the first fusion devices the design of which is based on a comprehensive optimization procedure

Magnetic field
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Superconducting coils
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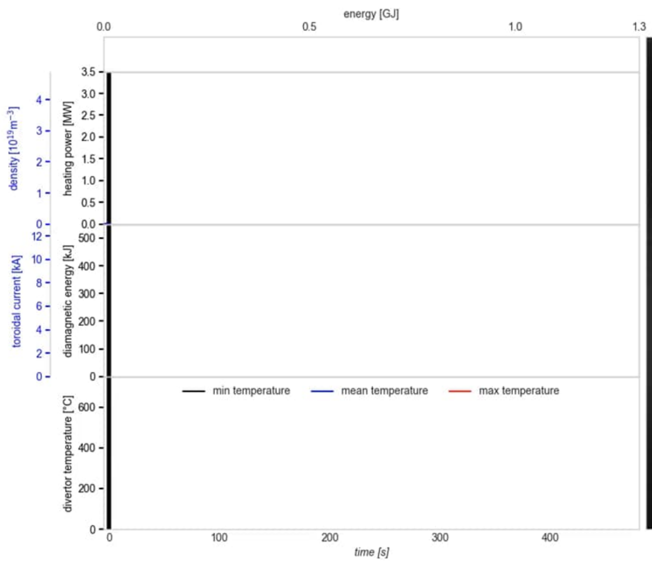
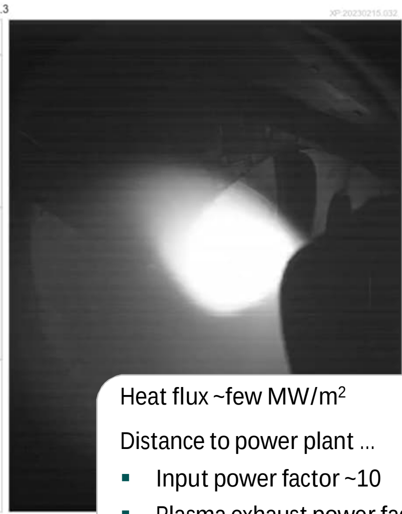
Plasma volume
30 m^3
Plasma duration
30 minutes
Heating power
10 MW
Peak heat flux
10 MW/m^2

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/m^2)

IPP, Foto: Bernhard Ludewig

On the way to a high-power steady-state fusion plasma



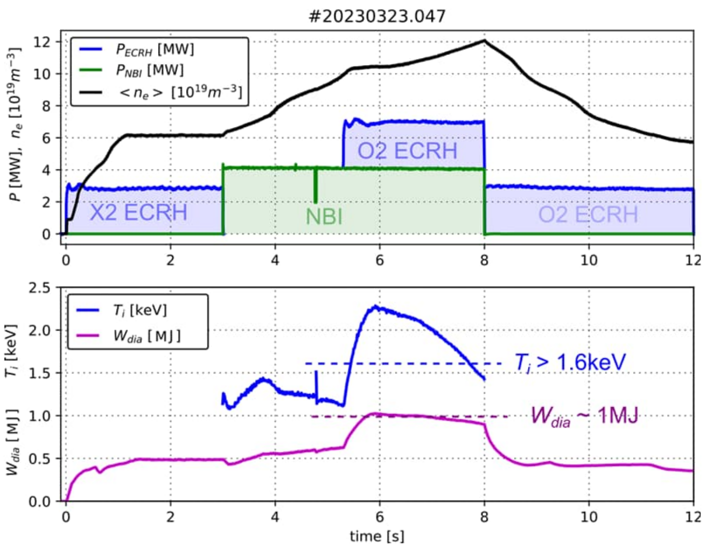


Heat flux ~few MW/m^2

Distance to power plant …

- Input power factor ~10
- Plasma exhaust power factor ~100

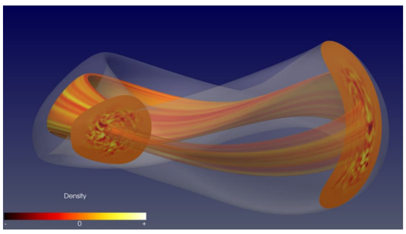
On the way to a high performance plasma



Major optimization criteria verified

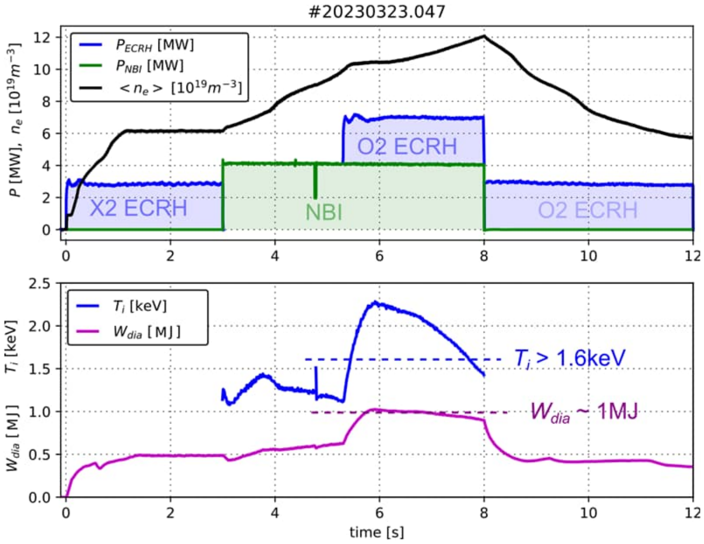
- Low plasma currents
- Low collisional transport

However, turbulent losses become important



M.Maurer, PhD thesis (2020) TUM
https://mediatum.ub.tum.de/doc/1539628/1539628.pdf

On the way to a high performance plasma



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- Low plasma currents
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However, turbulent losses become important

Distance to power plant ...
- Density achieved
- Temperature factor ~ 5
- Energy confinement ~10

Inertial confinement fusion (ICF)

National ignition facility (laser driven fusion)

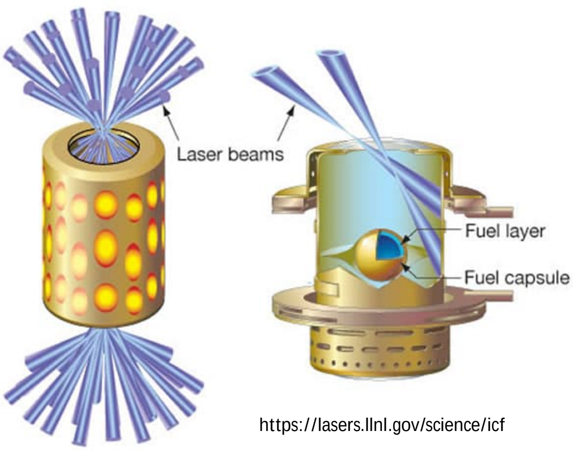
Target chamber

- Commissioning 2009
- Primary objectives are defence applications

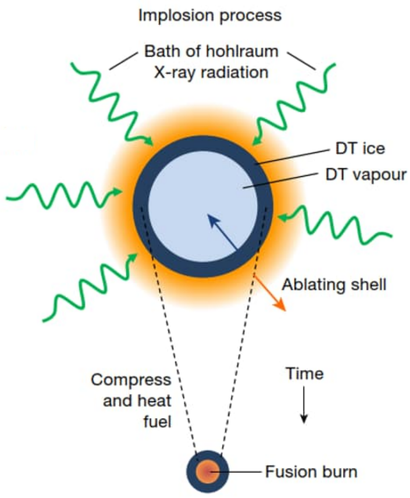
Laser installation

Source:
lasers.llnl.gov/multimedia/photo_gallery/

Inertial confinement fusion (ICF) principle – indirect drive



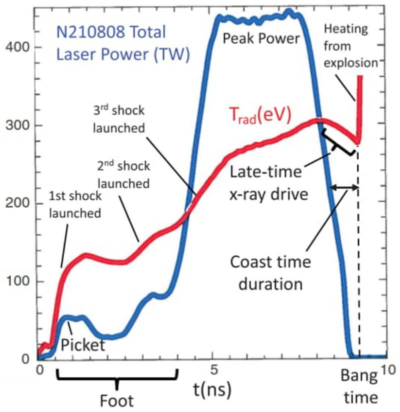
https://lasers.llnl.gov/science/icf



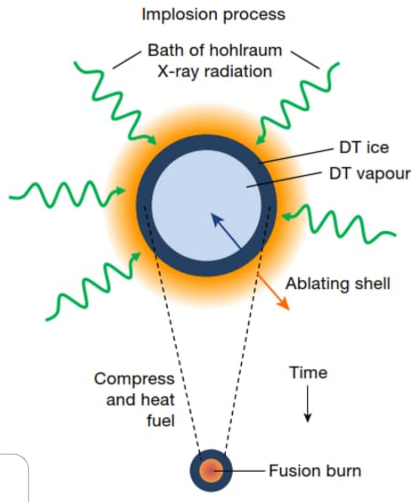
A. B. Zylstra et al. Nature 601 (2022) 542

Inertial confinement fusion (ICF) principle – indirect drive

H. Abu-Shawareb et al. Phys. Rev. Lett. 129 (2022) 075001



Ignition Dec ‘23: 400 MJ input to lasers → 2 MJ laser energy to target → conversion o X-rays 0.2 MJ → 3,1 MJ fusion energy



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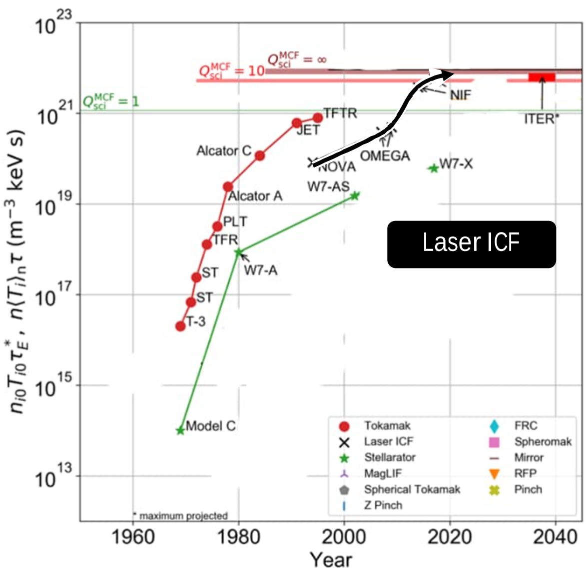

Important milestone: Demonstration of ignition of DT pellet

Laser ICF: Only conceptual ideas for the realisation of a power plant

- Direct drive
- High frequency (several Hertz)
- Heat exhaust

MCF: Relevant technologies were from the beginning part of the development

S.E.Wurzel, S.C.Hsu, Phys. Plasmas 29 (2022) 062103
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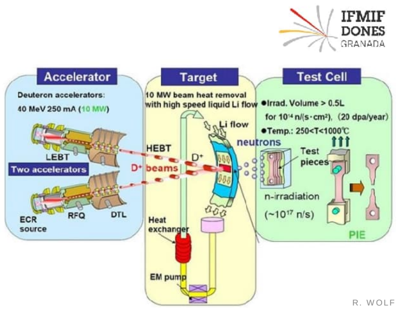
Prospects – the way forward

Key elements for the realization of fusion energy

- ITER: First demonstration of a burning fusion plasma & first time breeding tritium from fusion neutrons and lithium
- Wendelstein 7-X: Validation of an alternative confinement concept with favourable power pant properties
- Development of the first integrated design of a demonstration power plant (DEMO)
- 14 MeV neutron source (IFMIF-DONES) for the material qualification for DEMO

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



New developments

- Emerging technologies
  - High-temperature superconductors
  - Composite materials
  - Additive manufacturing
- Discussion about regulatory framework
- 4.7 b$ worldwide in fusion start-ups

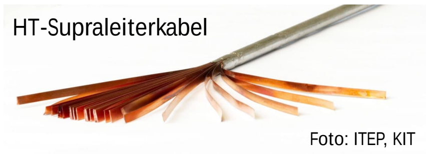
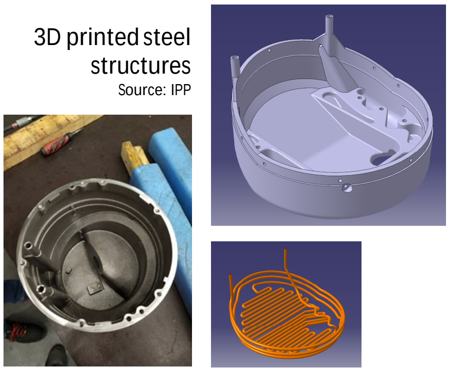
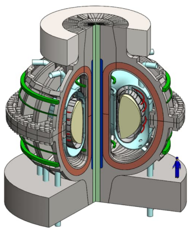


Foto: ITEP, KIT

3D printed steel structures
Source: IPP





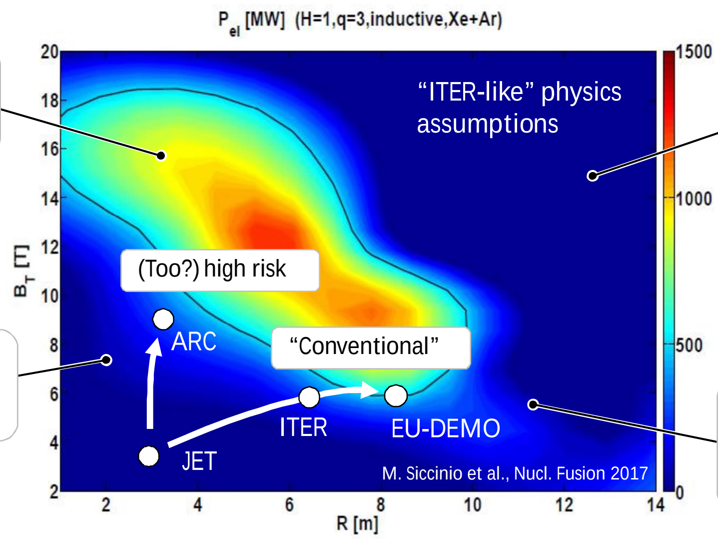
Affordable, robust, compact (ARC) reactor

B.N. Sorbom et al
Fusion Engineering and Design 100 (2015) 378

Design space boundaries

Technology not (yet) available to reach high B

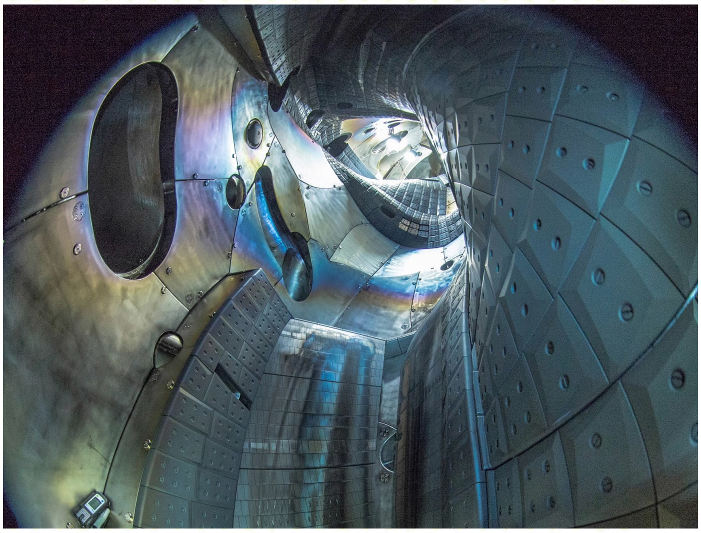
Confinement too low to achieve necessary Q



Synchrotron radiation losses too high

Excessive plasma radiation required to limit convective heat flux to divertor target

Thank you for your attention



View into the plasma vessel of Wendelstein 7-X
Courtesy C. Biedermann, G. Wurden