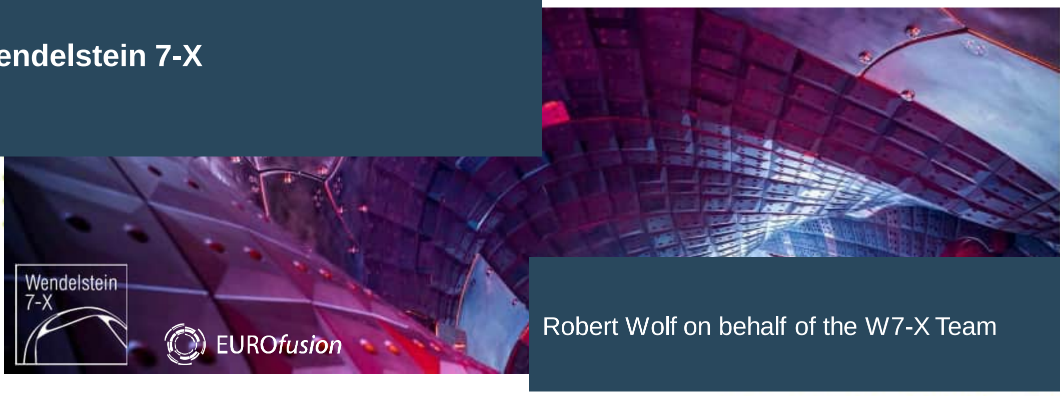
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Wendelstein 7-X



Robert Wolf on behalf of the W7-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.

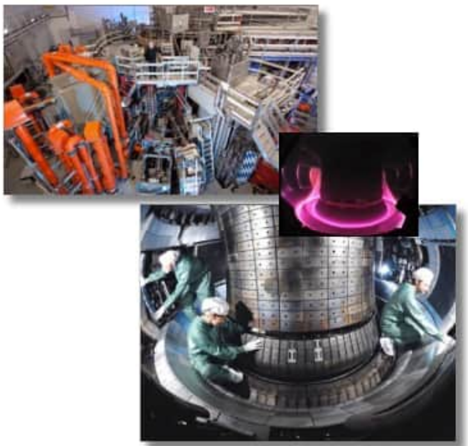
Welcome to Max-Planck-Institut für Plasmaphysik

Source: MPI für Plasmaphysik, photo: Fetzi Baur

Two sites
Garching near Munich & Greifswald
1100 employees, ~450 in Greifswald

Max-Planck-Institut für Plasmaphysik pursues both confinement concepts

Tokamak
ASDEX Upgrade



Photos: MPI für Plasmaphysik

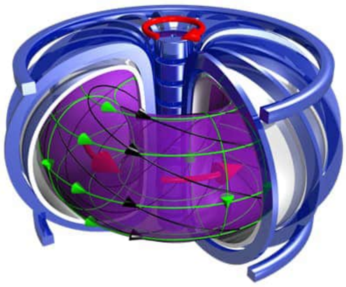
Stellarator
Wendelstein 7-X

Photos: MPI für Plasmaphysik

Why stellarators?

Magnetic confinement concepts

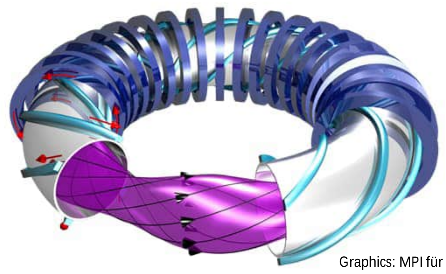
Tokamak



Historically ←

More recently →

Stellarator



Graphics: MPI für Plasmaphysik

- More advanced
- Less efficient when operated stationary / difficult behaviour near operational boundaries
- Tokamak ITER: First demonstration of a burning fusion plasma
- SPARC, the most advanced privately financed fusion project is a tokamak

- More demanding geometry
- Intrinsically steady-state, more efficient as a fusion power plant
- Stellarator Wendelstein 7-X: Demonstrate that plasma properties fulfil power plant requirements
- The two German magnetic confinement fusion start-ups pursue stellarator concept

Stellarators – advantages and disadvantages

- Intrinsically steady-state
  - Higher efficiency conceivable (lower re-circulating power)
- No current-driven instabilities
  - “Soft” stability boundaries
- No disruptions
  - No disruption induced forces
  - No runaway electrons
- Very high plasma density possible (no Greenwald limit)
  - Operation at optimum temperature for D-T fusion conceivable (10 – 20 keV)

- 3D magnetic field configuration
  - Generally strong neoclassical transport / poor confinement of thermal plasma
  - Generally poor confinement of fast ions
  - Complex design of in-vessel components (divertor, blanket)
  - More complex coil configuration

Stellarators require optimization to achieve necessary plasma performance

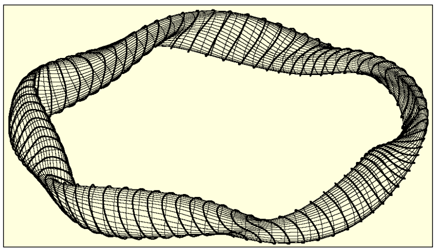
Wendelstein 7-X design & construction

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

Reduced transport losses, small electrical plasma currents, feasible exhaust concept, stable at finite pressure

Cray-1 (1976)
Deutsches Museum (Munich), https://de.m.wikipedia.org/wiki/Datei:Cray-1-deutsches-museum.jpg, Clemens Pfeiffer

Design of magnetic field geometry



Graphic: MPI für Plasmaphysik

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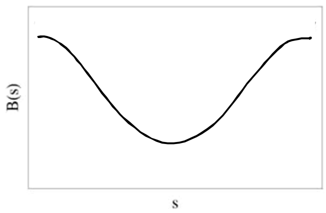
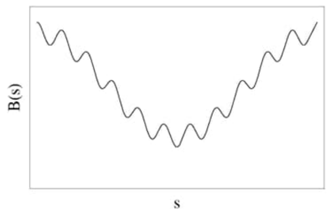
Tokamak (axisymmetric)

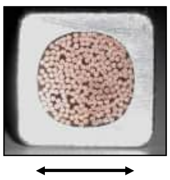


Stellarator



$$D_{1/\nu} \sim \frac{\epsilon_{eff}^{3/2} T^{7/2}}{n B^2 R^2}$$

Superconductors, modular coils



~ 11mm

W7-X superconducting cable
– up to 18 kA

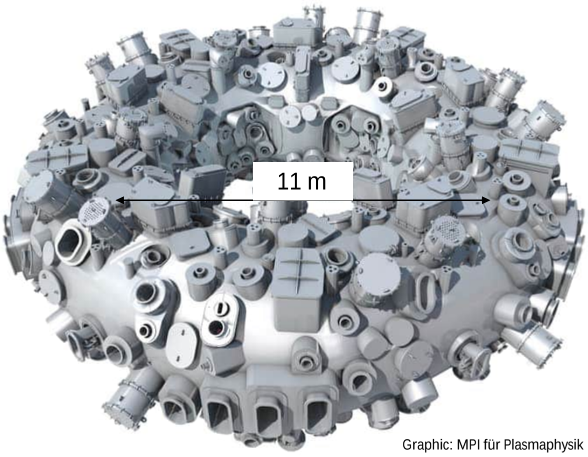
Photos: MPI für Plasmaphysik

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



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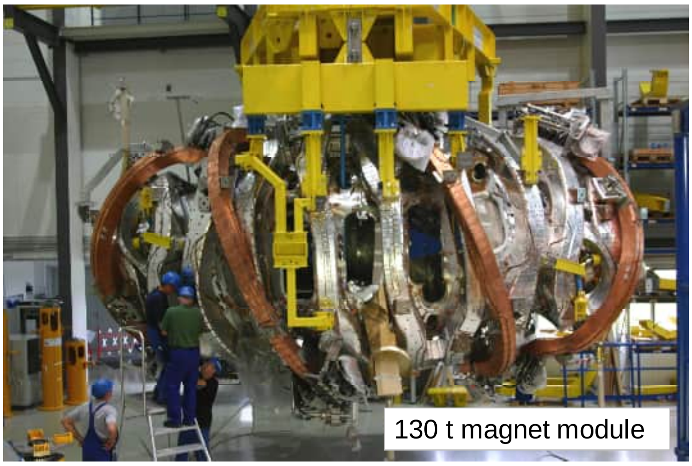

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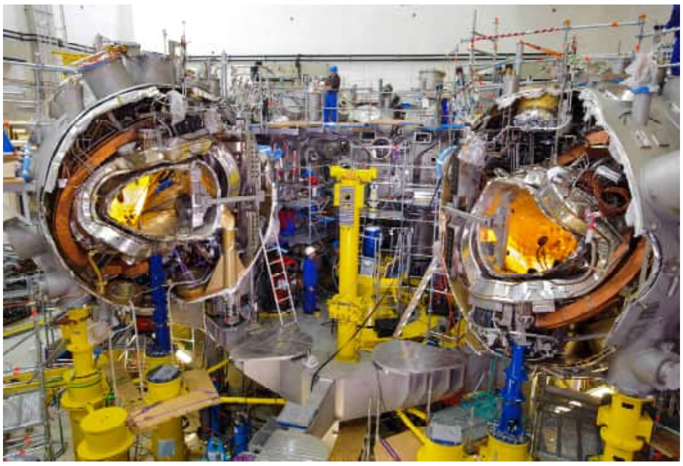

Photo: MPI für Plasmaphysik

https://www.youtube.com/watch?v=MJpSrqitSMQ

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Plasma volume
30 m^3

Plasma duration
30 minutes

Heating power
10 MW

Peak heat flux
10 MW/m^2

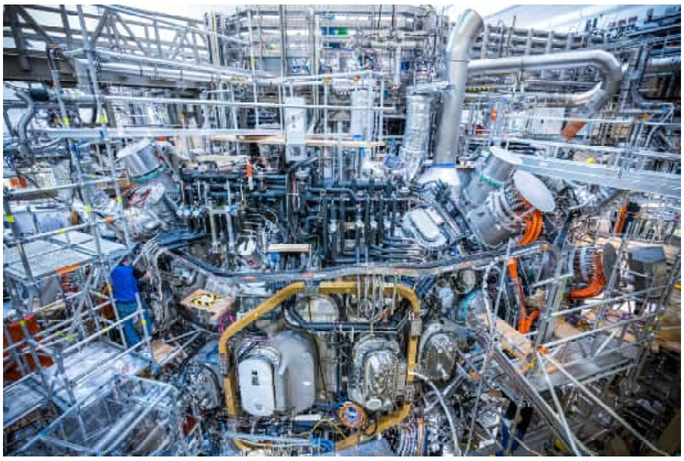

Photo: MPI für Plasmaphysik, Jan Hosan

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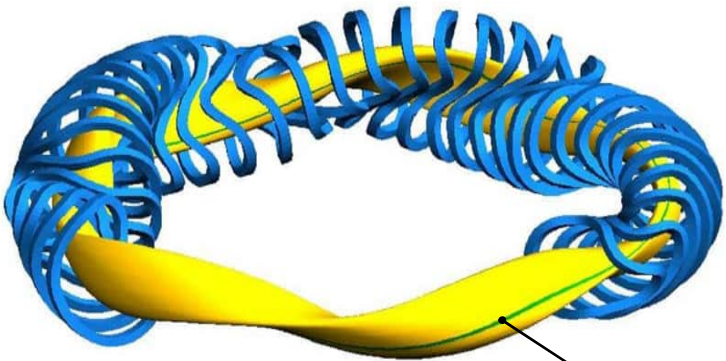
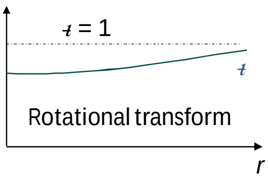
MPI für Plasmaphysik, Photo: Bernhard Ludewig

Low magnetic shear with $\iota = 1$ at the plasma boundary



Graphic: MPI für Plasmaphysik

Magnetic field line with $\iota = 1$



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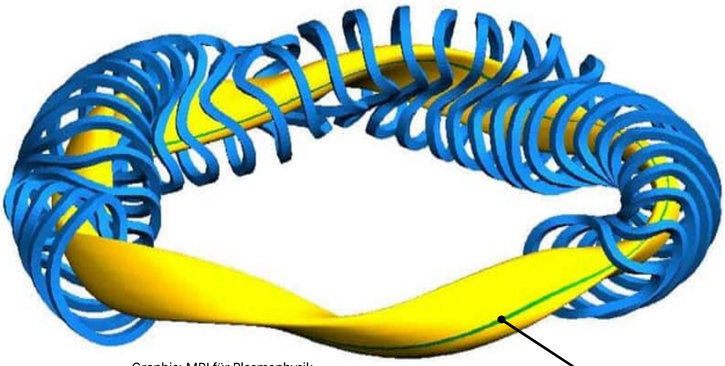

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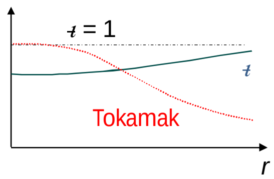

Resonant magnetic island divertor for heat and particle exhaust

Graphic: MPI für Plasmaphysik

Resonant magnetic island divertor for heat and particle exhaust

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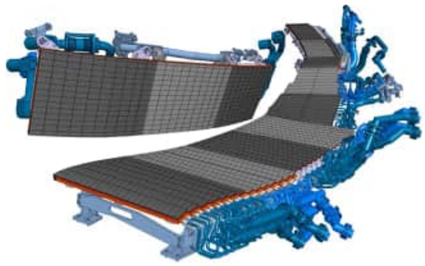
Resonant magnetic island divertor for heat and particle exhaust

Graphic: MPI für Plasmaphysik

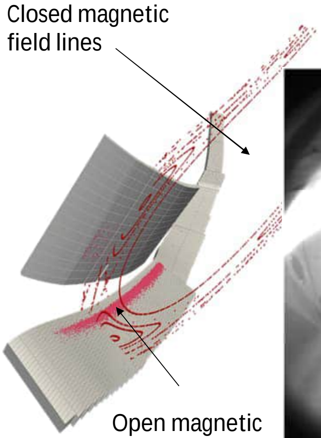
Heat exhaust in Wendelstein 7-X

Actively (water) cooled high heat flux targets

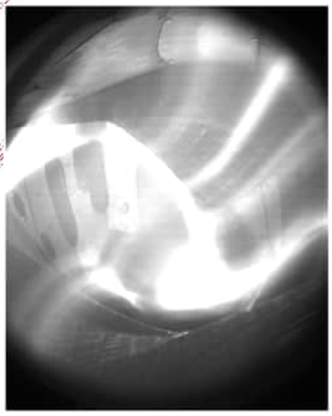


Graphic: MPI für Plasmaphysik

Closed magnetic field lines



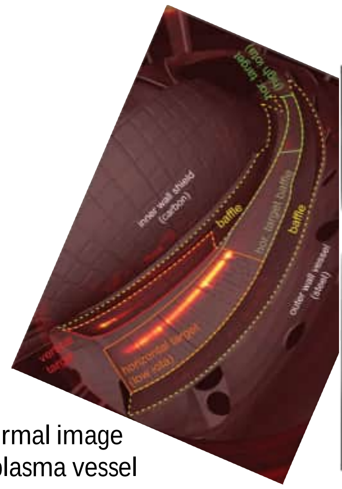
Open magnetic field lines



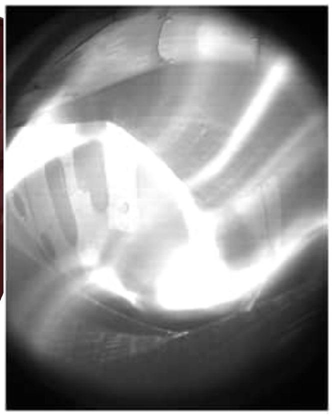
Seconds → minutes requires specially cooled targets and active cooling of all in-vessel components

Heat exhaust in Wendelstein 7-X

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



Thermal image of plasma vessel



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Heat exhaust in Wendelstein 7-X

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

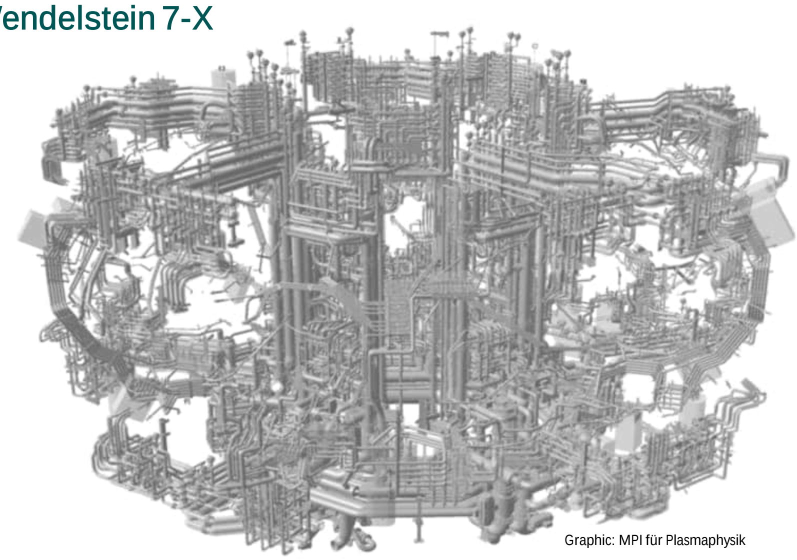
Work inside plasma-vessel during COVID

Photo: MPI für Plasmaphysik

Seconds → minutes requires specially cooled targets and active cooling of all in-vessel components

Heat exhaust in Wendelstein 7-X

Water manifold

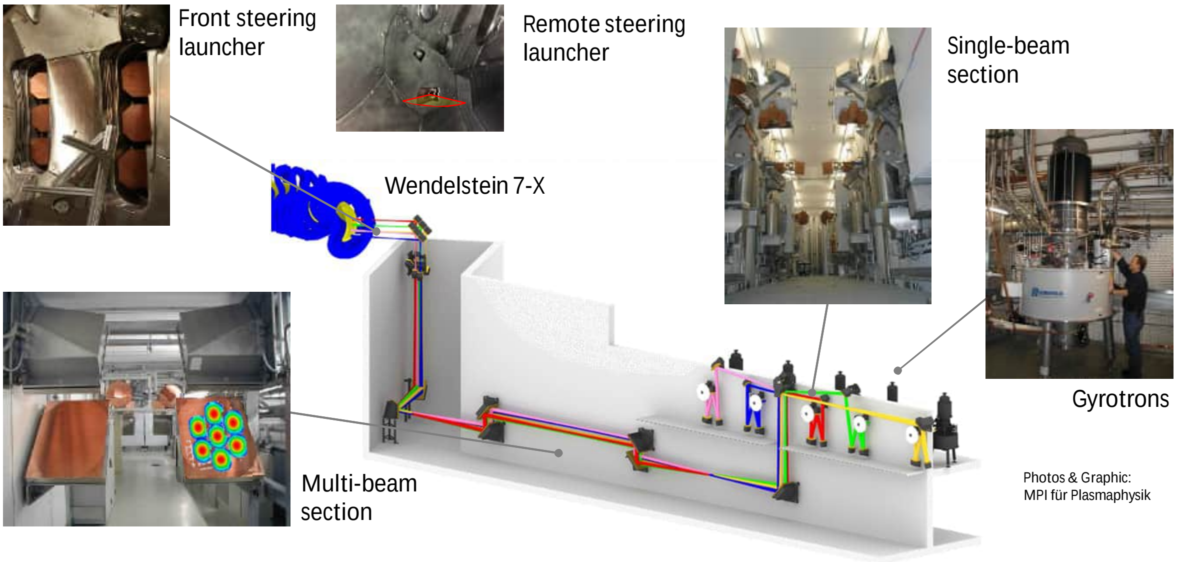


Graphic: MPI für Plasmaphysik

Seconds → minutes requires specially cooled targets and active cooling of all in-vessel components

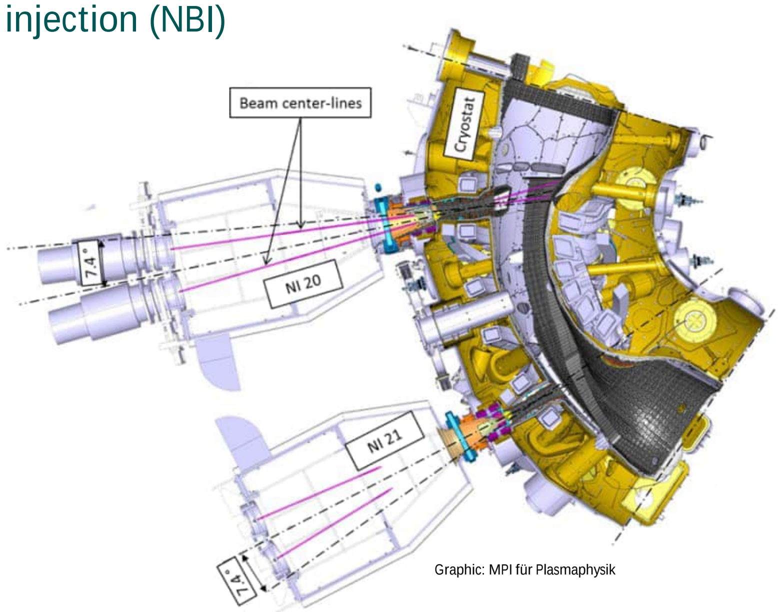
World's largest ECRH facility in operation

Universität Stuttgart



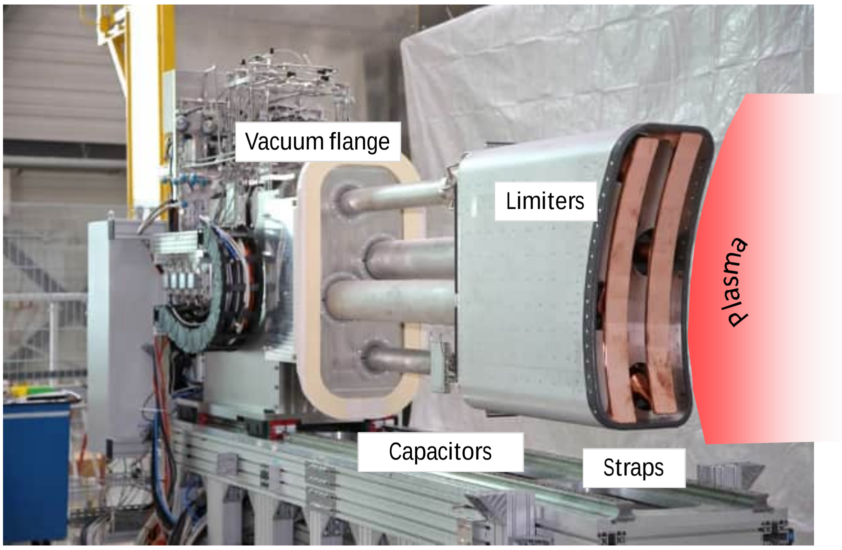
Photos & Graphic:
MPI für Plasmaphysik

Neutral beam injection (NBI)



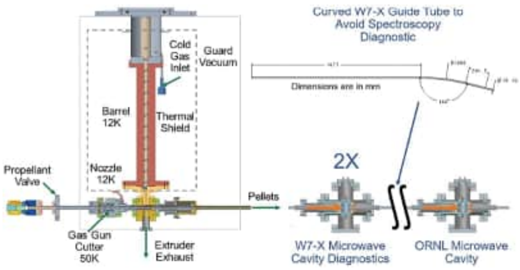
Graphic: MPI für Plasmaphysik

Ion cyclotron resonance heating (ICRH)



J. Ongena at al, Fusion Eng. Design 192 (2023) 113627

Steady-state pellet injection



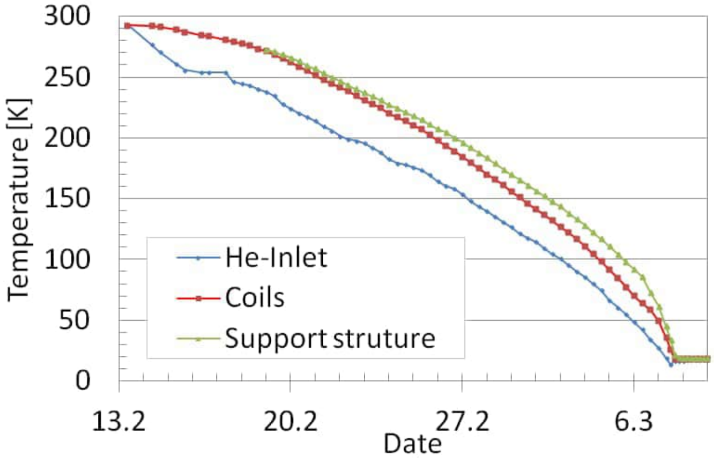
S. J. Meitner, L. R. Baylor, Fusion Science and Technology 79 (2023) 1065

- Frozen hydrogen pellets are an efficient way to fuel a fusion plasma
- W7-X: Pellet speeds up to 1000 m/s
- Goal: Steady state fuelling over 30 min

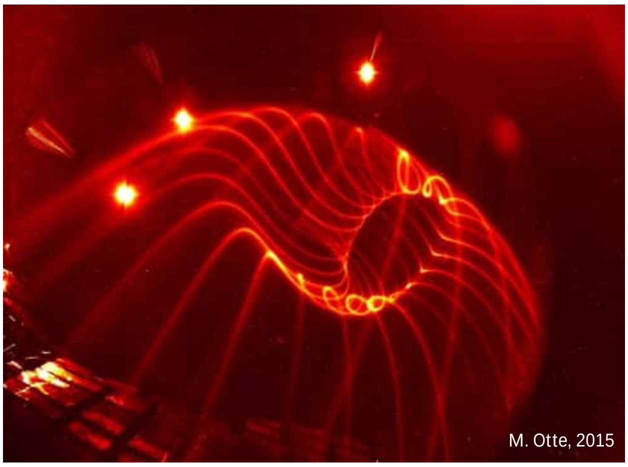
Wendelstein 7-X scientific operation and design validation

Wendelstein 7-X commissioning

Cool down of 425 tonnes cold mass



On the way to a high performance plasma



Major optimization criteria verified

- Magnetic field accuracy
  T. Sunn Pedersen et al, Nature Communications 7 (2016) 13493
  https://doi.org/10.1038/ncomms13493
- Low plasma currents
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However, turbulent losses become important

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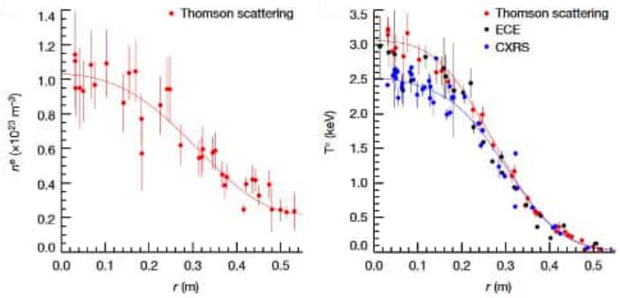

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  - $T_i \approx T_e$
- Demonstration of neoclassical optimization
  - For optimized config. neoclassical energy fluxes < 1
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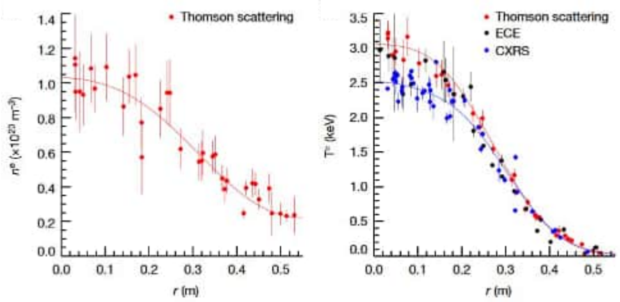
However, turbulent losses become important

Recipe
5 MW of ECRH + pellet injection

Triple product world record for stellarators

On the way to a high performance plasma



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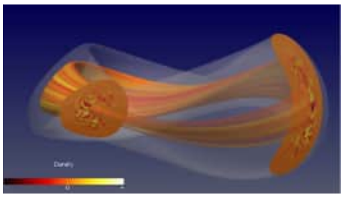
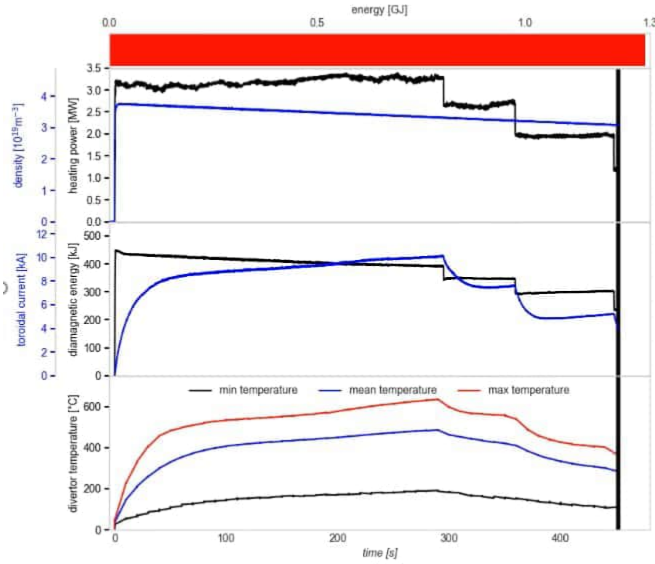
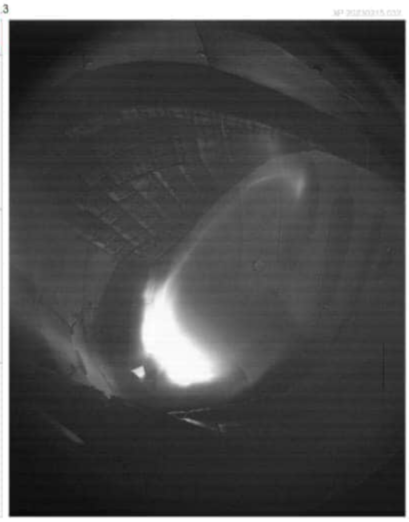


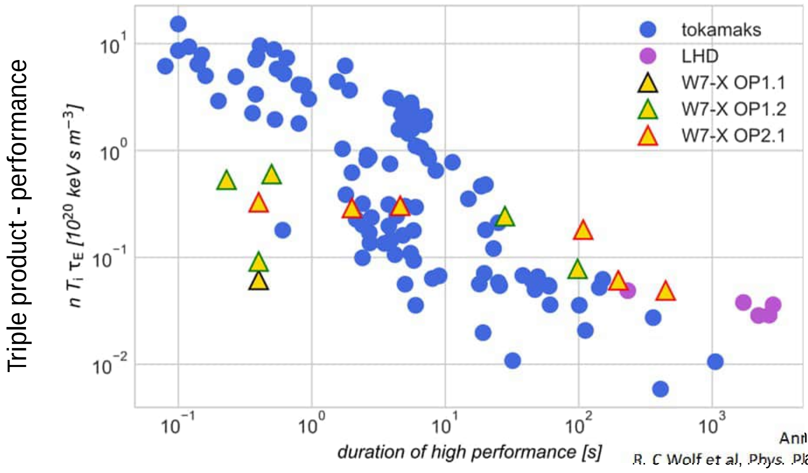
M. Maurer, PhD thesis (2020) TUM
https://mediatum.ub.tum.de/doc/1539628/1539628.pdf

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





On the way to high performance steady-state operation

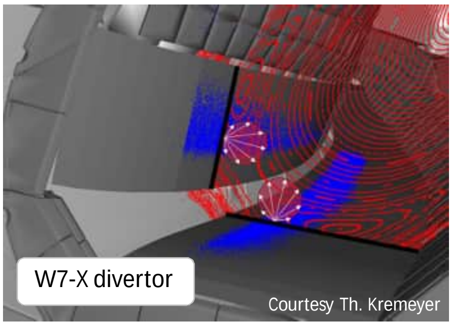


Annual report CICLOP group
R. C Wolf et al, Phys. Plasmas 26 (2019) 082504
O. Grulke, IAEA Fusion Energy Conference 2023

Conclusions & outlook

Conclusions & outlook

- Wendelstein 7-X is an experimental device for validating the underlying physics and technology design concepts
  - Minimized plasma currents ✓
  - Reduced neoclassical transport losses ✓
  - Fast ion confinement which improves with increasing (normalized) plasma pressure !
  - Sufficiently good plasma equilibria at high (normalized) plasma pressure !
  - Plasma stability at high (normalized) plasma pressure !
  - Reasonable balance between reduced turbulence transport losses and avoidance of impurity accumulation
  - Heat and particle exhaust solutions
  - Long pulse (near steady-state) operation: 10 MW (in the plasma) for up to 30 minutes
- Outlook: Objectives require
  - Magnetic field scaling
  - More heating power and flexible heating mix
  - Advanced plasma control (e.g. density profile control)
  - Development of modified divertor concept



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