The long way to steady-state fusion plasma -
the superconducting stellarator device Wendelstein 7-X

Thomas Klinger
Max-Planck-Institut für Plasmaphysik
Ernst-Moritz-Arndt University
Greifswald
Outline of the talk

I. Fusion basics
II. The device
III. Construction
IV. Research

An Institute of the Max-Planck Society

National Funding via the Helmholtz Association
Co-Funded by the European Commission

Colloquium CERN
The p-p-cycle in the sun

Credits to ESA, NASA, SOHO – EIT Consortium

Power generation in the sun

Fusion of light nuclei

\[ \text{p-p cycle } \rightarrow ^4\text{He} \]

\[ \downarrow \]

difference in binding energy

\[ \downarrow \]

energy surplus

- Plasma state \((H, \text{He}, \text{Fe})\)
- Core temperature \(~1.3\) keV
- Extremely small reaction rates
- Gravitational confinement \(m\odot\)
The p-p reactions in the sun

Weak interaction:

\[ p + p \rightarrow d + e^+ + \nu_e \]
\[ p + d \rightarrow ^{3}\text{He} + \gamma \]
\[ ^{3}\text{He} + ^{3}\text{He} \rightarrow ^{4}\text{He} + 2p \]
\[ ^{3}\text{He} + ^{4}\text{He} \rightarrow ^{7}\text{Be} + \gamma \]
\[ e^- + ^{7}\text{Be} \rightarrow ^{7}\text{Li} + \nu_e \]
\[ p + ^{7}\text{Li} \rightarrow ^{4}\text{He} + ^{4}\text{He} \]
\[ p + ^{7}\text{Be} \rightarrow ^{8}\text{B} + \gamma \]
\[ ^{8}\text{B} \rightarrow ^{8}\text{Be}^* + e^+ + \nu_e \]
\[ ^{8}\text{Be}^* \rightarrow ^{4}\text{He} + ^{4}\text{He} \]

Branch I (85%)

Branch II (15%)

Branch III (0.02%)

- Neutrinos observed on earth
p-p fusion on earth?

Conditions in the sun core

- Core plasma density $\sim 10^{31} \text{ m}^{-3}$
- Core ion temperature $\sim 1.5 \text{ keV}$
- Plasma pressure $\sim 2 \times 10^{16} \text{ Pa}$
- Total mass $m_\odot = 3.3 \times 10^5 m_\oplus$
- Reaction rate $\langle \sigma v \rangle = 10^{-43} \text{ cm}^3/\text{s}$

No!

But

Credits to ESA, NASA, SOHO – EIT Consortium
D-T nuclear fusion – binding energy

\[ _1^2 \text{D} + _1^3 \text{T} \rightarrow _2^4 \text{He} \ (3.5 \text{ MeV}) + _0^1 \text{n} \ (14.1 \text{ MeV}) \]
Fusion collision cross sections

\[ \sigma_{\text{pp}} \text{ for } p + p \text{ fusion are 20 orders of magnitude below} \]

\[ D + D \rightarrow ^3\text{He} + n + 3.27 \text{ MeV} \]
\[ D + D \rightarrow T + p + 4.03 \text{ MeV} \]
\[ D + T \rightarrow ^4\text{He} + n + 17.59 \text{ MeV} \]
\[ D + ^3\text{He} \rightarrow ^4\text{He} + p + 18.35 \text{ MeV} \]

\[ \frac{\varepsilon}{T}\cdot f(\varepsilon) \]

\[ 10 \text{ keV ion temperature} \]
Plasma confinement

- high density solar plasma
- high plasma pressure
- sun’s gravitation field
- gravitational confinement
- evacuated plasma vessel
- low density fusion plasma
- plasma pressure $O(1 \text{ bar})$
- magnetic field $\rightarrow$ Lorenz force
- magnetic confinement

\[
\beta = \frac{p_{\text{kin}}}{p_{\text{mag}}} = \frac{n k_B T}{B^2/(2 \mu_0)}
\]
Toroidal magnetic fields

radial drift \( v_R + v_{VB} = \frac{v_{\parallel}^2 + v_{\perp}^2/2}{\omega_{cj}} \frac{\vec{B} \times \nabla \vec{B}}{B^2} \) → charge separation

Poincaré section

toroidally twisted magnetic field line:
rotational transform \( u/2\pi = \langle \Delta(\theta_1, \theta_2) \rangle \)
Closed magnetic flux surfaces

Hamiltonian form

\[
\frac{d\psi}{d\varphi} = -\frac{\partial H}{\partial \zeta} \quad \psi \quad \text{toroidal flux}
\]

\[
\frac{d\zeta}{d\varphi} = \frac{\partial H}{\partial \psi} \quad \zeta \quad \text{canonical angle}
\]
Tokamak (1951 Sacharov und Tamm)

toroidal chamber in magnets
The stellarator device

Stellarator (1951 Spitzer)
Stella = star
„bringing the star“
Stellarator now – how and why?

optimized stellarator (2015)
„Wendelstein 7-X“

seven optimisation criteria

1. high quality of vacuum magnetic surfaces
2. good finite equilibrium properties \( @ \langle \beta \rangle = 5\% \)
3. good MHD stability properties \( @ \langle \beta \rangle = 5\% \)
4. reduced diffusive (neoclassical) transport
5. small equilibrium (bootstrap) current
6. good collisionless fast particle confinement
7. good modular coil feasibility

3d numerical codes

- vacuum field and coils
- MHD equilibrium
- MHD linear stability
- neoclassical transport
- Monte Carlo test particle
- edge and divertor
Example of a code map

goodness parameters:

\( \Delta_{is} \)  relative island width
\( \beta_{eq} \)  equilibrium-\( \beta \) value
\( \beta_{stab} \)  stability-\( \beta \) value
\( \delta_e \)  equivalent ripple
\( i_{BS} \)  relative bootstrap current
\( f_\alpha \)  fraction of lost \( \alpha \)-particles
\( \Delta W \)  distance plasma-first wall
\( R_c \)  minimum coil curvature
Robust equilibria

W7-X Vacuum Field

W7-X: \( <\beta> = 4 \% \)

plasma equilibrium

\[ \nabla p = \vec{j} \times \vec{B} \]

bean shaped cross section

high plasma pressure

\[ \Downarrow \]

- equilibrium stiff
- island location
- confined volume
- plasma location

Shafarnov shift \(~10\text{cm}\)
Drift optimization 50 keV ions

Tesla

2.0 2.2 2.4 2.6 2.8 3.0
Facts and figures

- five magnetic field periods
- modular non-planar coils
- optimized plasma equilibrium
- low equilibrium current $\rightarrow O(10 \, kA)$
- high iota and low shear
- flexible magnetic field configurations

- 735 t mass with 435 t cold mass
- 70 superconducting NbTi coils
- 14 HTSC current leads
- 3 T magnetic induction on axis
- 254 ports of 120 different types
- 30 m$^3$ plasma volume
- 265 m$^2$ in-vessel components
- 4.5m height and 16 m diameter
Major elements of Wendelstein 7-X
Cryostat vessel and thermal insulation
Superconducting magnets

coil in the assembly handling unit

coil in the test bed @ CEA Saclay
Magnet manufacturing was a pain
Integration of magnets and cryostat

T. Klinger on Wendelstein 7-X
Four out of five modules

- non-planare SC coils
- SC bus bar
- He piping
- central support ring
- thermal insulation
- outer vessel
- maschine base
- planar SC coils
- plasma vessel
The device is complete
First He plasma fast video camera recording

parameters:
- microwave power: 4 MW
- microwave frequency: 140 GHz
- magnetic field on axis: 2.5 T
- He gas pressure: $5 \cdot 10^{-4}$ mbar

plasma parameters:
- plasma density: $2 \cdot 10^{19}$ m$^{-3}$
- electron temperature: 4 keV
- ion temperature: 1 keV
- pulse length: 150 ms

Radiation death due to impurities from the wall!

now standard hydrogen plasmas
- electron temperature: 10 keV
- ion temperature: 2 keV
- pulse length: 1-7 s
Impurity spectroscopy

high resolution overview spectrometer wavelength range 20 – 160 nm

before radiation collapse

during radiation collapse
The 10 weeks if the first operation phase has exceeded all our expectations. In the end 25 diagnostic systems were commissioned and delivered data.

Overview of the first operation phase

- $T_e = 1 \text{ keV}$
- $T_i < 1 \text{ keV}$
- $n_{e0} \sim 2 \cdot 10^{19} \text{ m}^{-3}$
- $t_d = 50 \text{ ms}$

- $T_e = 7 \text{ keV}$
- $T_i = 1.2 \text{ keV}$
- $n_{e0} = 3 \cdot 10^{19} \text{ m}^{-3}$
- $t_d = 250 \text{ ms}$

- $T_e = 8 \text{ keV}$
- $T_i = 1 \text{ keV}$
- $n_{e0} = 2 \cdot 10^{19} \text{ m}^{-3}$
- $t_d = 6 \text{ s}$

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<td>$T_e = 8 \text{ keV}$</td>
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<td>$T_i = 2 \text{ keV}$</td>
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On the 10th of March 2016 the operation was suspended as planned.
**Typical radial temperature profiles**

![Graph showing radial temperature profiles]

**X-ray imaging crystal spectrometer**

\[ 500 \, \text{eV} < T_e < 10 \, \text{keV} \]

\[ 500 \, \text{eV} < T_i < 4 \, \text{keV} \]

**Ar impurity seeding**

**Plasma densities**

\[ n_e < 4 \cdot 5 \cdot 10^{19} \, \text{m}^{-3} \]

**Thomson scattering system**

\[ 20 \, \text{eV} < T_e < 10 \, \text{keV}, \ 5 \cdot 10^{18} \, \text{m}^{-3} < n_e < 5 \cdot 10^{20} \, \text{m}^{-3}, \ \Delta r_{\text{eff}} \approx 2-3 \, \text{cm} \]

Two Nd-YAG lasers 2J/pulse @ f=20 Hz, laser beam \( \varnothing=5-7 \, \text{mm} \)

[by courtesy of S. Bozhenkov]
Numerous research topics addressed:

- Radial electric field and plasma rotation
- Magnetic configuration influence on particle transport
- Heat wave experiments for confinement studies
- Electron cyclotron current drive
- Identification of impurities and radiation collapse
- Advanced heating schemes
- Filamentation in the plasma edge
- Limiter heat loads and influence of trim coils
Unresolved: Turbulence in 3d magnetic field

T. Klinger on Wendelstein 7-X

Xanthopoulos et al. PRL, 113, 155001 (2014)

Wendelstein 7-X „by chance“ turbulence optimized?
Global Gyrokinetic Simulation of Turbulence in ASDEX Upgrade

gene.rzg.mpg.de
The mid term plan for Wendelstein 7-X

- Inertially cooled divertor
- Water cooled graphite wall tiles
- Pulse energy ≤ 80 MJ @ 10 MW
- Many more diagnostic systems
- More heating power 15 MW

- Actively cooled divertor
- Pulse energy ≤ 18 GJ @ 10 MW
- More heating power 20 MW
The stellarator reactor T. Klinger on Wendelstein 7-X design study stellarator power station
- 3 GW$_{th}$
- 44 m
- 1500 m$^3$
- 30,000 t

- thermal power
- diameter
- plasma volume
- total weight

- outer vessel (OV)
- coils of type 1 2 3 4 5
- weight support
- ports
- structure panels
- plasma vessel (PV)
The reactor scheme

D concentration in water 0.015%

in situ T generation

\[ ^{7}\text{Li} + n \rightarrow ^{4}\text{He} + ^{3}\text{T} + n \]

\[ ^{6}\text{Li} + n \rightarrow ^{4}\text{He} + ^{3}\text{T} \]

coolant

to heat exchanger

a fully ionized D-T-plasma at 10 keV ion temperature with an average particle density \( n_d \sim n_T \sim 10^{20}\text{m}^{-3} \) yields a fusion power density \( P/V \sim 2 \text{ MW/m}^3 \)
The blanket – a critical component

Tritium breeder
\( \text{Li}_2\text{TiO}_3, \text{Li}_2\text{O} \)

neutron multiplier \( \text{Be}, \text{Be}_{12}\text{Ti} \)

critical is the T self-sufficiency

A comprehensive research program is needed and must be intensified – first test blanket modules will be investigated in the ITER tokamak (under construction)

https://www.iter.org/mach/Blanket
https://www.fusion.kit.edu
Wendelstein 7-X is an optimized SC stellarator
completed after 15 years of construction
the machine works perfectly fine
the first plasma operation with He and H has started
physics program based on a staged approach to steady-state

Why fusion at all and why stellarators?

a new primary energy source — probably needed in future
backbone power stations of the GW class
basic research on magnetized high-temperature plasmas needed
the stellarator promises stable steady-state operation
Wendelstein 7-X is the key experiment for reactor extrapolation