The construction of the Wendelstein 7-X stellarator

Thomas Klinger
Max-Planck Institute for Plasma Physics
on behalf of the enterprise Wendelstein 7-X
Outline of the talk

I. Stellarator principles
II. Construction status
III. Research plan
IV. Lessons learned
Intro: Tokamak and Stellarator

A very schematic comparison ...

- current in coils and plasma
- current-carrying plasma
- self-organized equilibrium

- current in the coils only
- very small plasma current
- field-defined equilibrium

- good neoclassical confinement
- toroidal symmetry
- advanced scenarios and current drive
- active control of plasma instabilities

- good neoclassical confinement
- quasisymmetry
- steady state operation
- no current driven instabilities
The stellarator family

Stellarators
- Classical: C, Cleo, W7-A, L2, WEGA
- Modular: W7-AS

Torsatrons
- Advanced: W7-AS

Heliotrons
- Quasi-symmetric: ATF, CAT, URAGAN
- Modular: He-E, LHD, He-J, CHS

Heliacs
- Modular: H1, TJ-II

Additional notes:
- Shut down: W7-X
- Operating: HSX
- Under construction: NCSX
- Planned: CHS-qa
The optimized stellarator W7-X

seven optimization criteria
1. feasible modular coils
2. good, nested magnetic surfaces
3. good finite-β equilibria
4. good MHD stability
5. small neoclassical transport
6. small bootstrap current
7. good confinement of fast particles

five main development tasks
1. optimum $nT_{E}$ and high $\beta$ discharges [EX/P5-9 Weller, TH/P8-10 Beidler]
2. impurity generation and transport [EX/P4-26 Burhenn]
3. island divertor [TH/P4-4 Feng, TH/P9-9 Drevlak]
4. steady state operation [18th ITC]
5. high density ECR heating and CD [EX/P6-18 Laqua, FT/P2-24 Gantenbein]
Island divertor – the idea

- natural resonant magnetic islands
- intersection with target plates
- top/bottom divertor module per period
- toroidal location with lowest $\beta$-variation

![Diagram of island divertor](image)
### Operation with divertor – HDH

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>High pressure</td>
<td>$\beta = 3.4%$</td>
</tr>
<tr>
<td>$\beta_N \sim 9.3$</td>
<td></td>
</tr>
<tr>
<td>High density</td>
<td>$n_e = 2.5 \cdot 10^2 \text{ m}^{-3}$</td>
</tr>
<tr>
<td>$n_e / n_eGW = 2.5$</td>
<td></td>
</tr>
<tr>
<td>Confinement</td>
<td>$HISS95 = 1.4$</td>
</tr>
<tr>
<td>MHD stability</td>
<td></td>
</tr>
<tr>
<td>Absorption</td>
<td>$P_{abs} = 2.5 \text{ MW}$</td>
</tr>
<tr>
<td>Stationarity</td>
<td>$T_{flattop} \sim 100 \tau_E$</td>
</tr>
</tbody>
</table>

McCormick et al. PRL 89 (2002) 015001

Cf. also review „Major results from the stellarator Wendelstein 7-AS“, PPCF 50 (2008) 053001
X2 and O2 current drive in W7-X

- remaining bootstrap current \( O(10kA) \)
- weak current drive probably required for tuning of edge \( \iota(1) \)
- off-axis steady-state ECR-CD
- \( X2 \) up to \( 1.2 \cdot 10^{20} \text{m}^{-3} \) and \( O2 \) up to \( 2 \cdot 10^{20} \text{m}^{-3} \)

1d transport simulation code coupled to raytracing code

[Turkin et al., FST 50 (2006) 387]
[Turkin, Marushenko et al. tbp 2008]
Outline of the talk

I. Stellarator principles
II. Construction status
III. Research plan
IV. Lessons learned
Wendelstein 7-X main components

- **Bus bar system**
- **Thermal insulation**
- **Ports**
- **Cryostat**
  - 10 half shells
  - 10 half modules
  - Central ring
    - 10 segments
- **Components in plasma vessel**
  - 20 planar coils
  - 50 non-planar coils
- **Components in cryostat**
- **Major radius**: 5.5 m
- **Minor radius**: 0.53 m
- **Plasma volume**: 30 m$^3$
- **Stored energy**: 600 MJ
- **Machine mass**: 725 t
Steady-state ECRH heating

- power gyrotrons
- $10 \times 1\text{MW} 140\text{GHz}$
- pulse length 1800s
- quasi-optical duct

[Poster FT/P2-24 Gantenbein]

- integrated cw design
- world record „shot“
- achieved in 10/05
- series production …

$30\text{min}$
$\sim 1\text{MW}$
Design of In-vessel components

divertor module

- target elements CFC sealed on cooled CuCrZr
- baffle elements graphite clamped on CuCrZr
- cryopumps and sweep coils
- about 250,000 parts w 130,000 being non-standard
- about 4km in-vessel water pipe lines
- start of operation with inertially cooled test divertor

wall panel cooling

test divertor

• target elements CFC sealed on cooled CuCrZr
• baffle elements graphite clamped on CuCrZr
• cryopumps and sweep coils
• about 250,000 parts w 130,000 being non-standard
• about 4km in-vessel water pipe lines
• start of operation with inertially cooled test divertor
Manufacturing in-vessel comp‘s

Target modules (Plansee)

Heat shield (IPP)

Wall pannels (MAN DWE)

Cooling pipes (IPP and n.n.)

Cryo pumps (IPP)
Superconducting coils

CAD drawing non-planar coil

Status coil delivery
20 planar coils
50 non-planar coils
100M€ contract → consortium
100% manufactured
70% successfully cold tested
The outer vessel

more than 1000 openings ~ thermal insulation laborious
Coil assembly

the 20 coils of first two modules completely assembled
the five assembly stands are ready and fill step-wise (now 3/5)
The completed first magnet module went into the next assembly stand.
Schedule

- completion date 2014 fixed
- ~ 1y buffer time on critical path
- 30 assembly milestones (3 passed)
- no schedule slippage since ~2y
- immediate counter measures
I. Stellarator principles
II. Construction status
III. Research plan
IV. Lessons learned
• 1st operation phase with 10s @ 8MW and 50s @ 1MW
• inertially cooled divertor and only partial cooling of in-vessel comp‘s
• shut-down (15 months) for completion and hardening
• 2nd operation phase to approach 30min @ 10MW
• 3rd operation phase with 10MW ECRH, 20MW NBI and 10MW ICRH
Key elements of initial research

Start of operation

• basic divertor operation and density control
• approach X2-density limit
• prove good confinement/neoclassical optimisation/MHD-stability
• achieve impurity transport control
• tolerable divertor load at full heating power
• X2 off-axis current drive for bootstrap current compensation
• approach O2-density limit
• divertor high-recycling regime
• first O2 off-axis current drive experiments

Shut down (15 months): replacement of divertor modules and hardening

• operation of actively cooled divertor
• step-wise approach towards 10MW 30min shots
• long-pulse discharge scenario optimisation
Outline of the talk

I. Stellarator principles
II. Construction status
III. Research plan
IV. Lessons learned
Lessons learned

• proper project structure with clear interfaces/responsibilities
• quick decision making on all levels
• strong home team with experience an know-how (~400 now on W7-X)
• formal but sufficiently pragmatic procedures, in particular …
  ○ documentation (e.g. PLM) and central design office
  ○ strong quality management also on-site with the manufacturers
  ○ configuration management with fast track option
  ○ permanent risk identification/mitigation on management level
• close collaboration with industrial suppliers in solving problems
• experienced and well-trained inspectors must be in site – change!
• transfer of technical risks into industry is generally expensive
• sufficient buffer times and contingencies always required

Don‘t be afraid of stellarators: right 3d-tools/experience ✡