Physics programme for initial operation of Wendelstein 7-X

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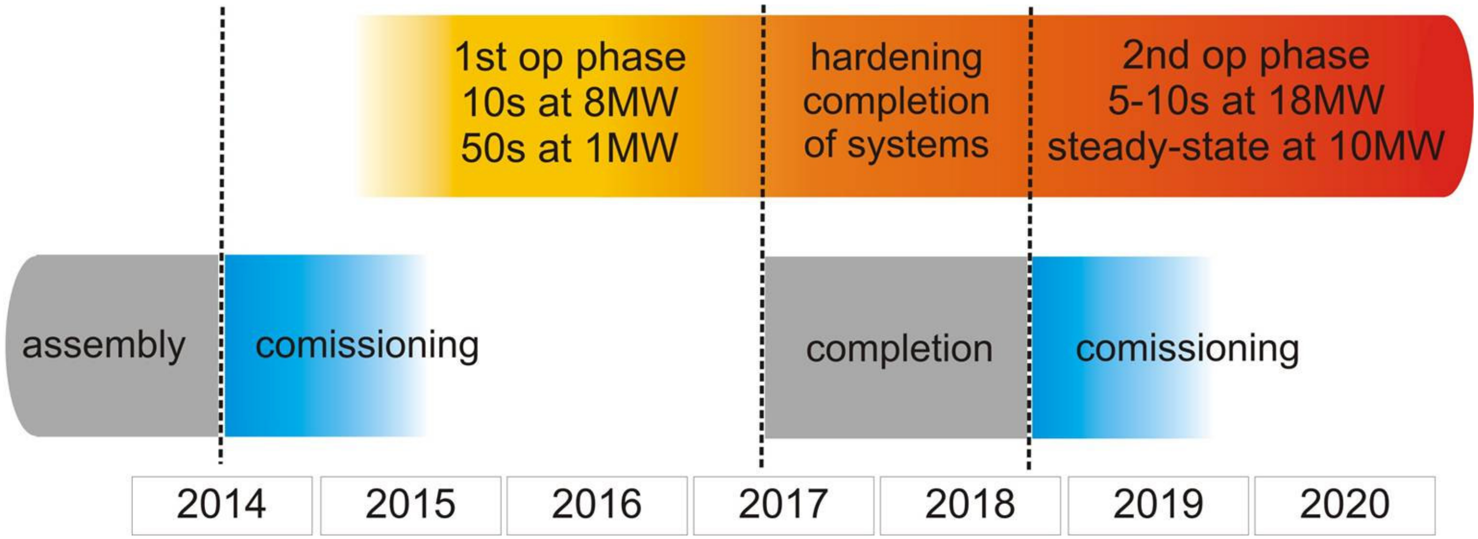
from construction to physics

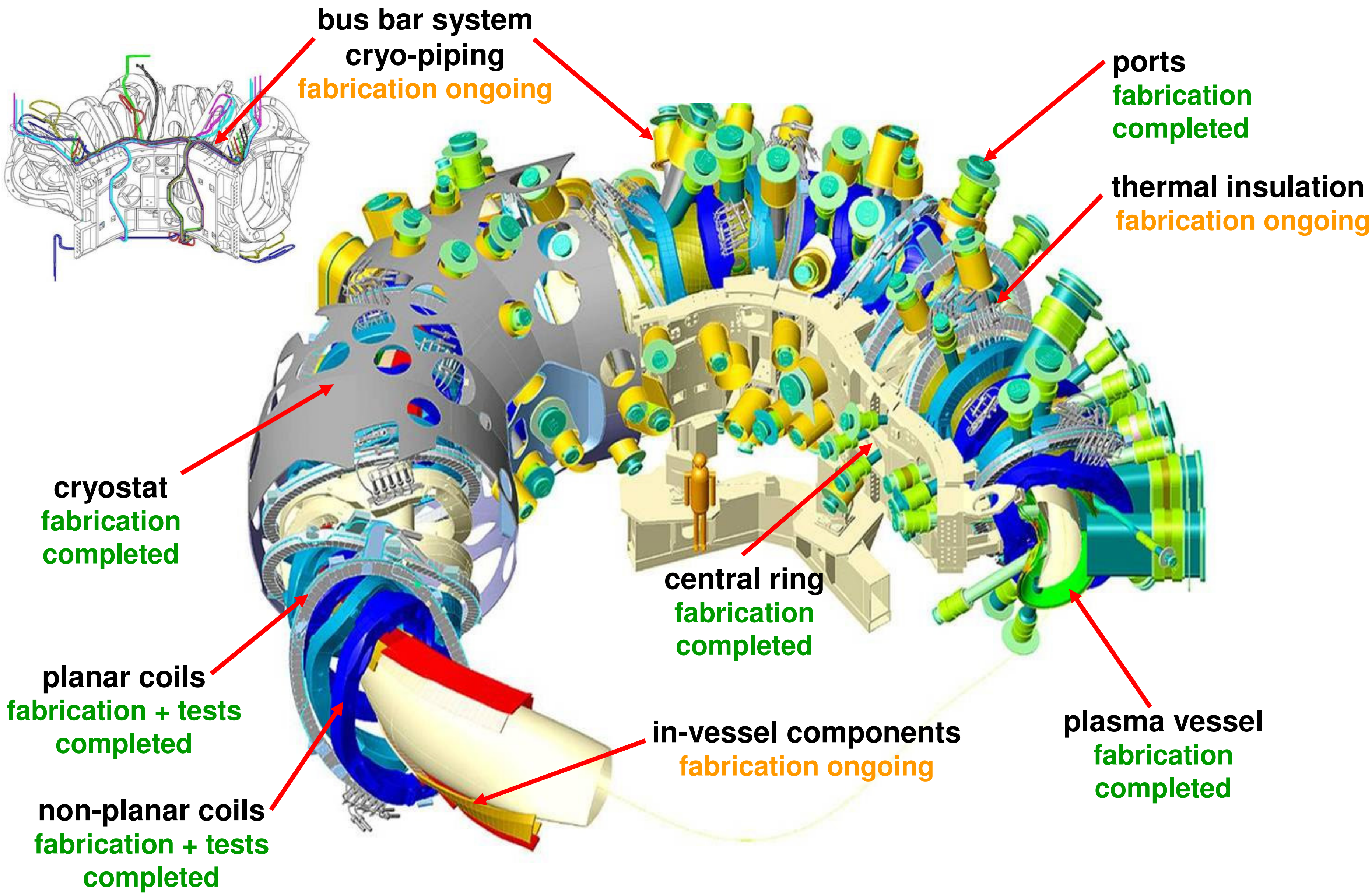


- **stepwise approach**
- **1st operation phase with 10s @ 8MW, inertially cooled divertor and only partial cooling of in-vessel components**
- **shut-down (15 months) for completion and hardening**
- **2nd operation phase to approach 30min @ 10MW**

Overview

- **Construction, status and schedule**
- **Commisioning**
- **Experimental set-up for first operation phase**
- **Initial physics programme**
- **Summary**

Wendelstein 7-X main components



Assembly

- Preparation of components is organised independently from the assembly activities
- The module assembly is carried out on different mounting stands in two halls

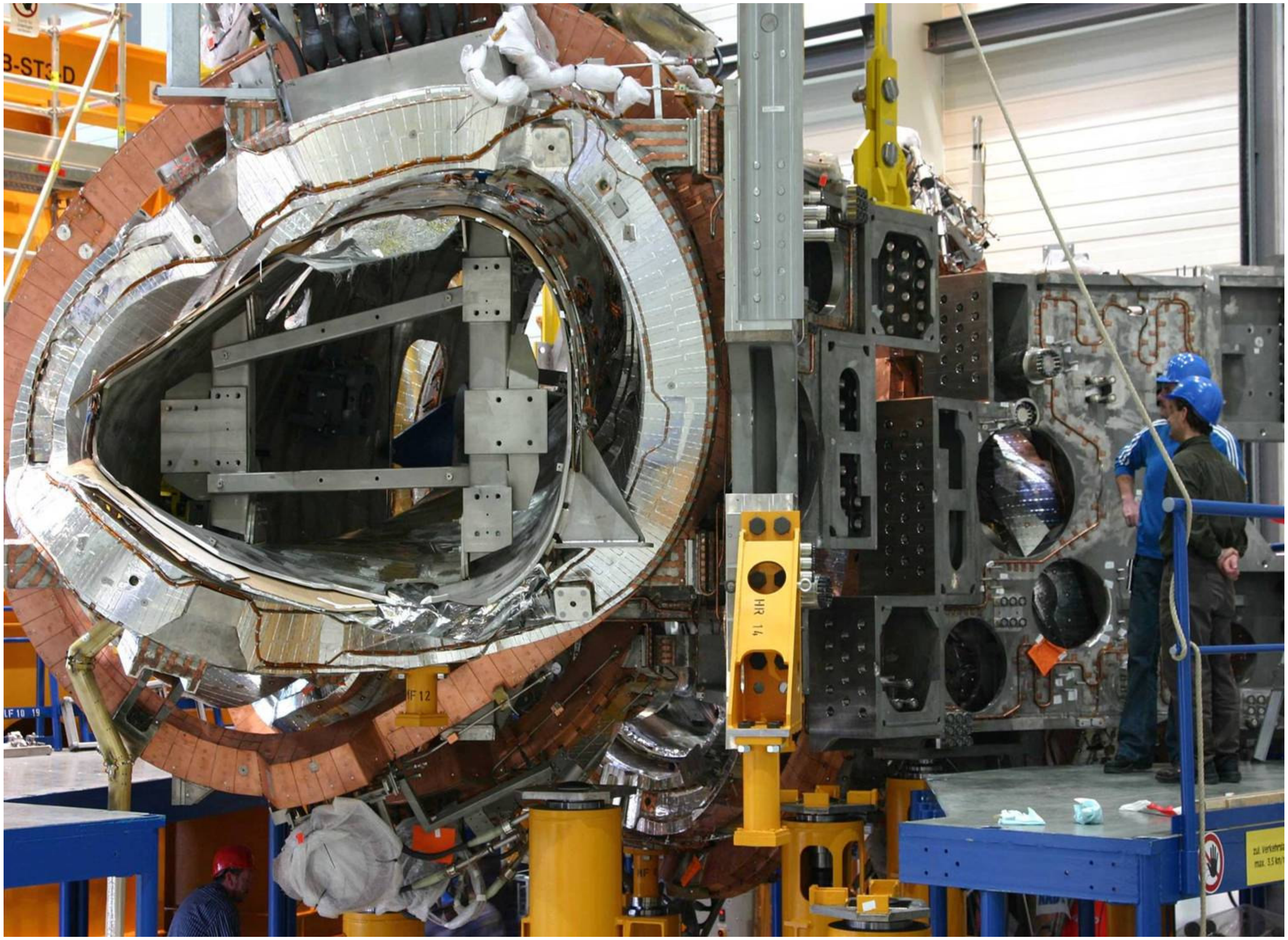
Pre-assembly, I

Coils are threaded across the plasma vessel

Thermal insulation is completed

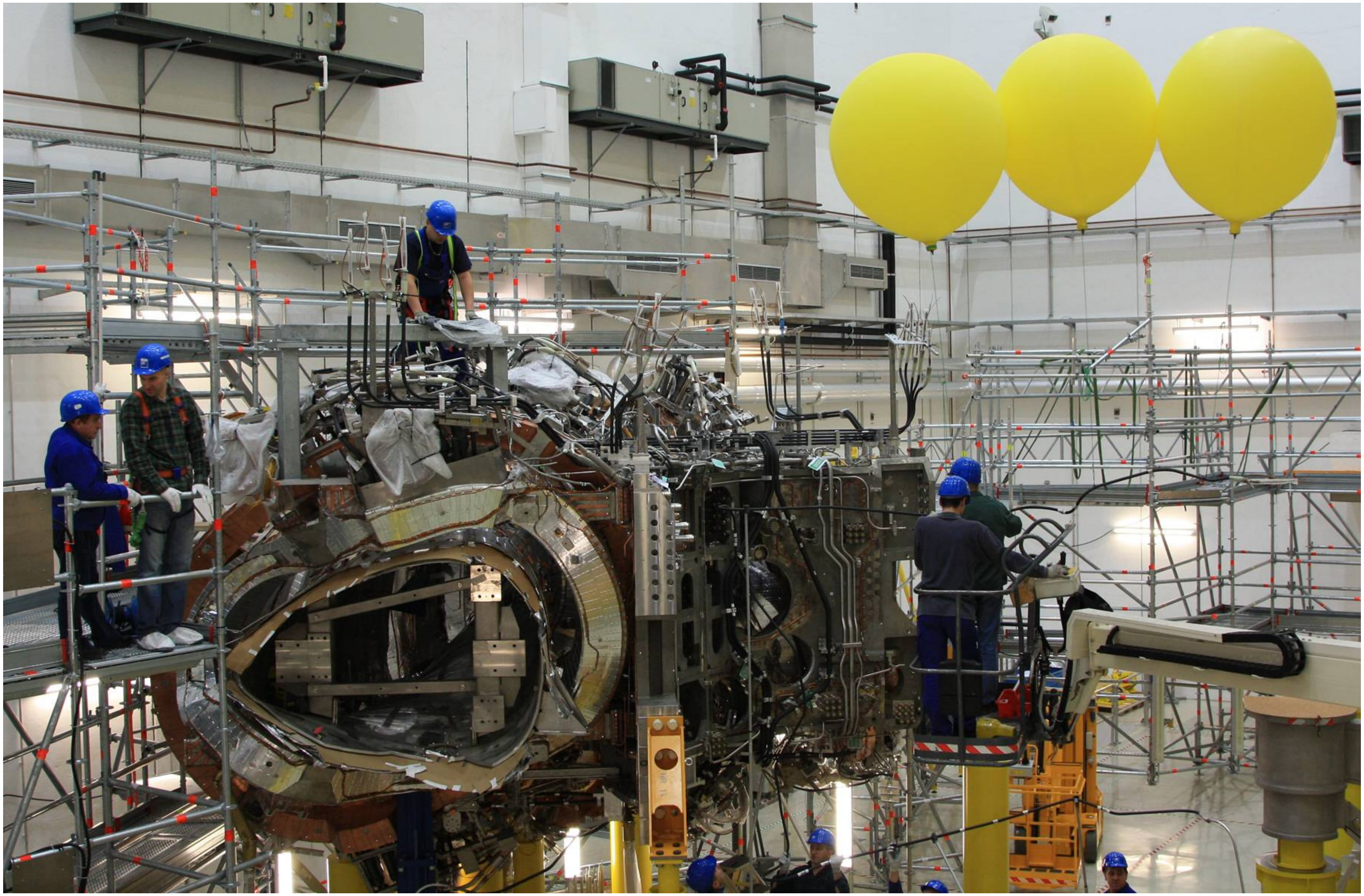
- The coil support structure is positioned in front of the 7-coil pack
- Coils are bolted to the central support ring

Pre-assembly, II



- The flip-symmetric half-modules are aligned
- The step-flange is bolted and the vessel half-modules are welded
- Thermal insulation, Inter-coil structure are completed

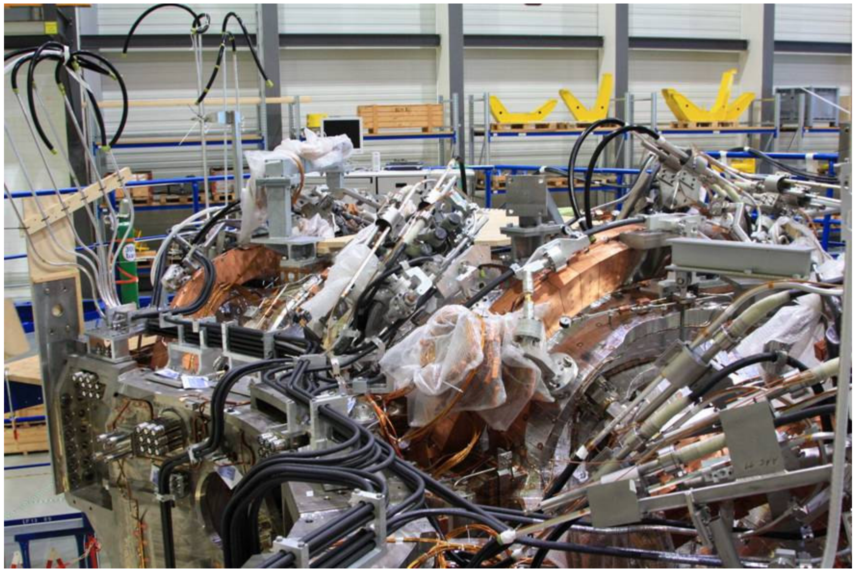
Pre-assembly, MST III



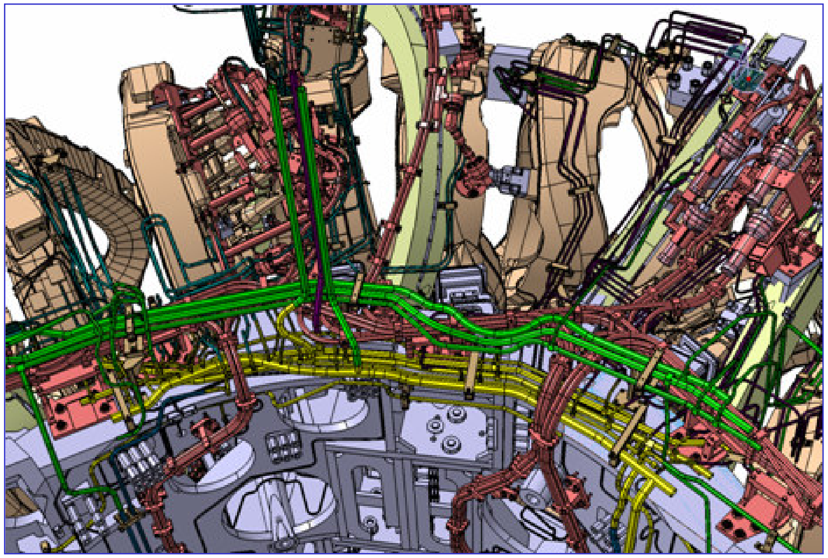
Module 5, February 2009

Pre-assembly, MST III

Cryopiping to be welded



Bus-bars to be mounted

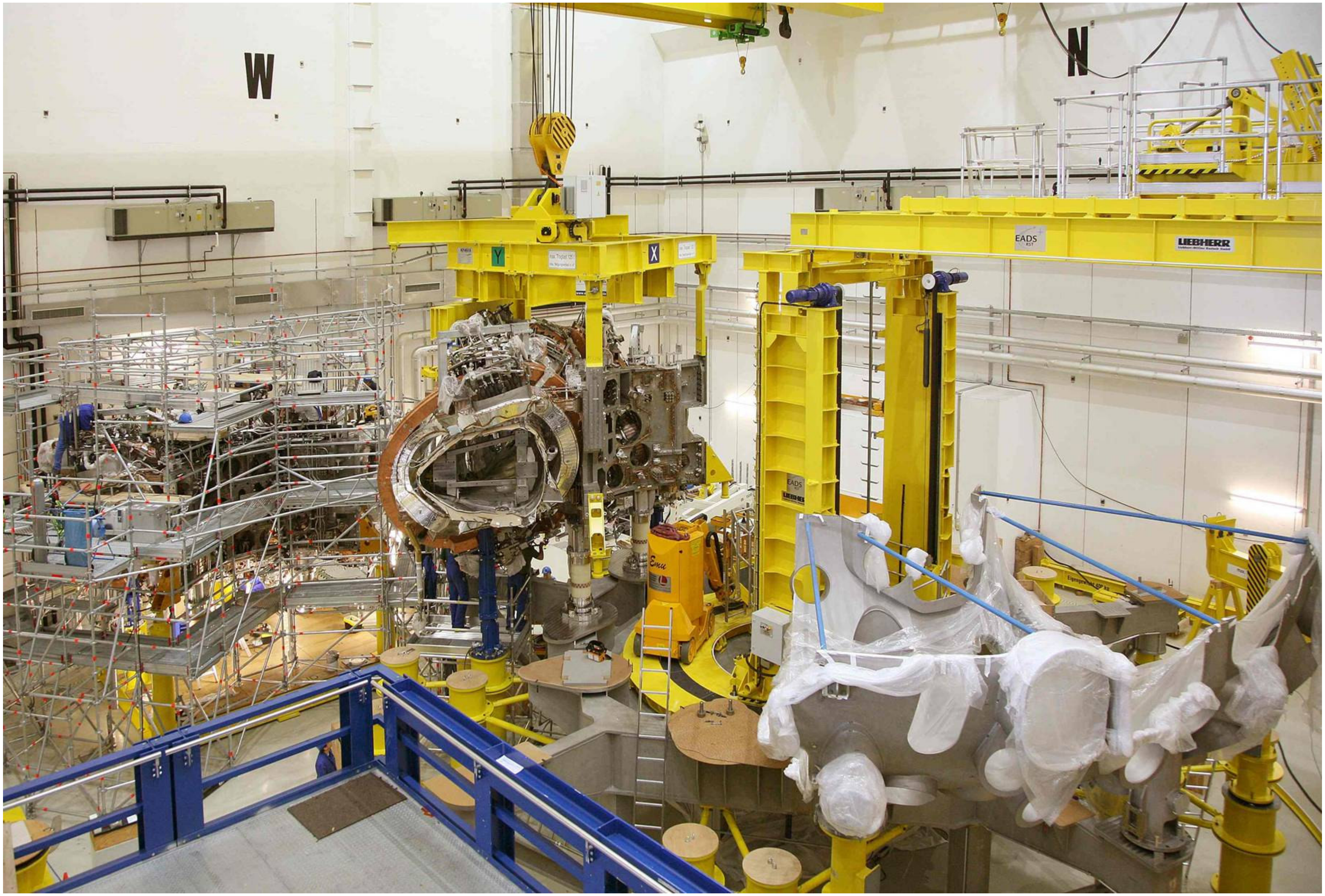


Comprehensive collision checks required during design, layout and installation of the two systems

Pre-assembly, MST III

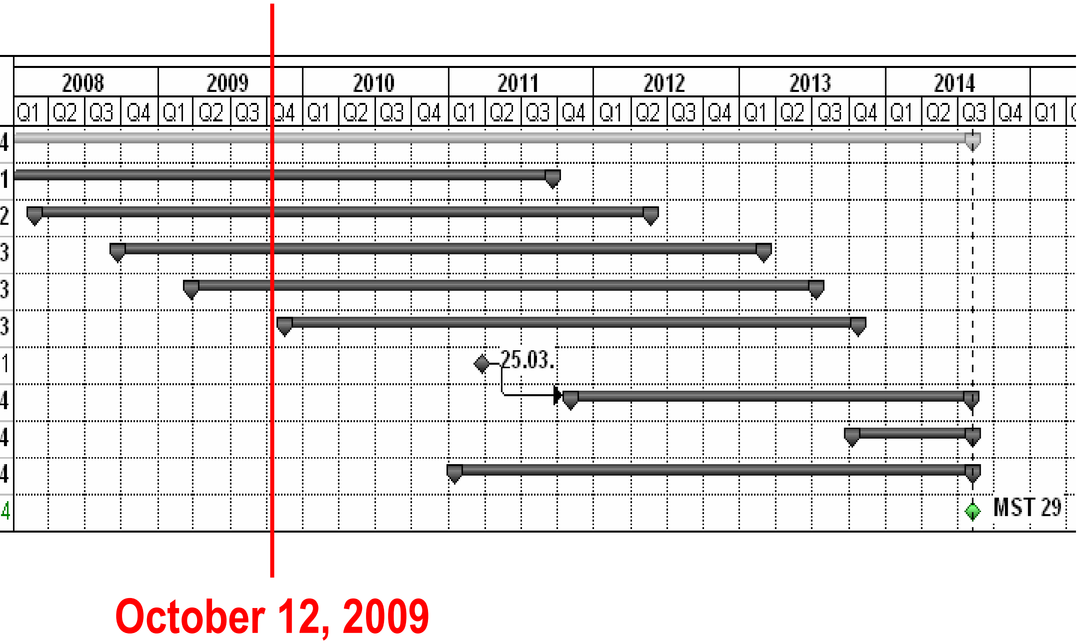
28 electrical joints between bus-bars and coil conductor are welded and insulated

Torus hall, March 2009



Schedule

Nr.	Vorgangsname	Anfang	Ende
0	Assembly planning (technological sequence)	Mo 21.03.05	Do 07.08.14
1	1. Module (#5)	Mo 21.03.05	Mo 19.09.11
20	2. Module (#1)	Mi 27.02.08	Mo 21.05.12
42	3. Module (#4)	Mi 24.09.08	Fr 01.03.13
65	4. Module (#2)	Do 26.03.09	Fr 12.07.13
88	5. Module (#3)	Di 17.11.09	Mi 23.10.13
110	Final adjustment of modules	Fr 25.03.11	Fr 25.03.11
111	Module connections (parallel work)	Fr 04.11.11	Di 05.08.14
134	Completion of torus	Mi 09.10.13	Do 07.08.14
142	Periphery installation in torus hall	Di 18.01.11	Do 07.08.14
151	MST 29: Start Commissioning	Do 07.08.14	Do 07.08.14



- The module assembly is organised in parallel
- 4 out of 5 modules are in the works
- The assembly schedule still contains half a year buffer times
- Assembly will be finished in summer 2014

Overview

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Commissioning

Commissioning of W7-X has three steps with increasing levels of system integration.

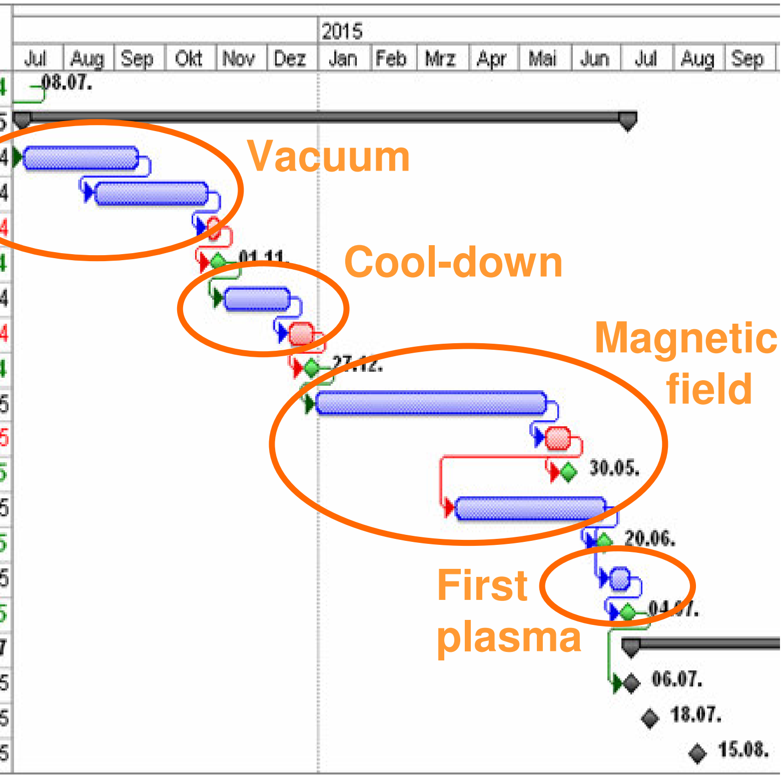
1. **Local commissioning** of the technical components. This includes instrumentation and local control and will be done before the end of W7-X assembly.
2. **Integrated commissioning**: Stepwise integration of these components into the overall system, the central device control and the central data acquisition system.

   This process is centred around four major work packages

   - Vacuum operation
   - Cryogenic operation
   - Magnetic field operation
   - First plasma
3. **Transition into plasma operation**: Demonstration that the overall system meets the basic technical requirements and enables scientific use of the device. This includes plasma start-up and control.

Commissioning schedule

Nr.	Vorgangsname	Dauer	Anfang	Ende
3	Start 1. Commissioning	0 Wochen	Di 08.07.14	Di 08.07.14
4	Commissioning phase	51,72 Wochen	Di 08.07.14	Sa 04.07.15
5	Pumping, leak testing cryo vacuum	9,8 Wochen	Di 08.07.14	Sa 13.09.14
6	Pumping, leak testing plasma vessel	9,8 Wochen	Di 19.08.14	Sa 25.10.14
7	Contingency	1 Woche	Sa 25.10.14	Sa 01.11.14
8	Vacuum in plasma vessel and cryo vacuum	0 Wochen	Sa 01.11.14	Sa 01.11.14
9	Cooling-down the magnet system	5,6 Wochen	Di 04.11.14	Sa 13.12.14
10	Contingency	2 Wochen	Sa 13.12.14	Sa 27.12.14
11	Magnet system cold (superconducting)	0 Wochen	Sa 27.12.14	Sa 27.12.14
12	Ramp-up of magnetic field	19,7 Wochen	Di 30.12.14	Sa 16.05.15
13	Contingency	2 Wochen	Sa 16.05.15	Sa 30.05.15
14	Magnetic field of 2,5 T	0 Wochen	Sa 30.05.15	Sa 30.05.15
15	Measuring the magnetic surface	12,9 Wochen	Mo 23.03.15	Sa 20.06.15
16	Magnet field structure measured	0 Wochen	Sa 20.06.15	Sa 20.06.15
17	Creation of first plasma	1,6 Wochen	Di 23.06.15	Sa 04.07.15
18	First plasma	0 Wochen	Sa 04.07.15	Sa 04.07.15
19	First operation phase	43,33 Wochen	Mo 06.07.15	Sa 01.07.17
20	start of plasma operation	0 Wochen	Mo 06.07.15	Mo 06.07.15
21	long pulse plasma	0 Tage	Sa 18.07.15	Sa 18.07.15
22	symmetry verification	0 Tage	Sa 15.08.15	Sa 15.08.15



- first planning of the four work packages available
- milestones have been identified
- detailed planning has to be worked out (optimization of work steps)

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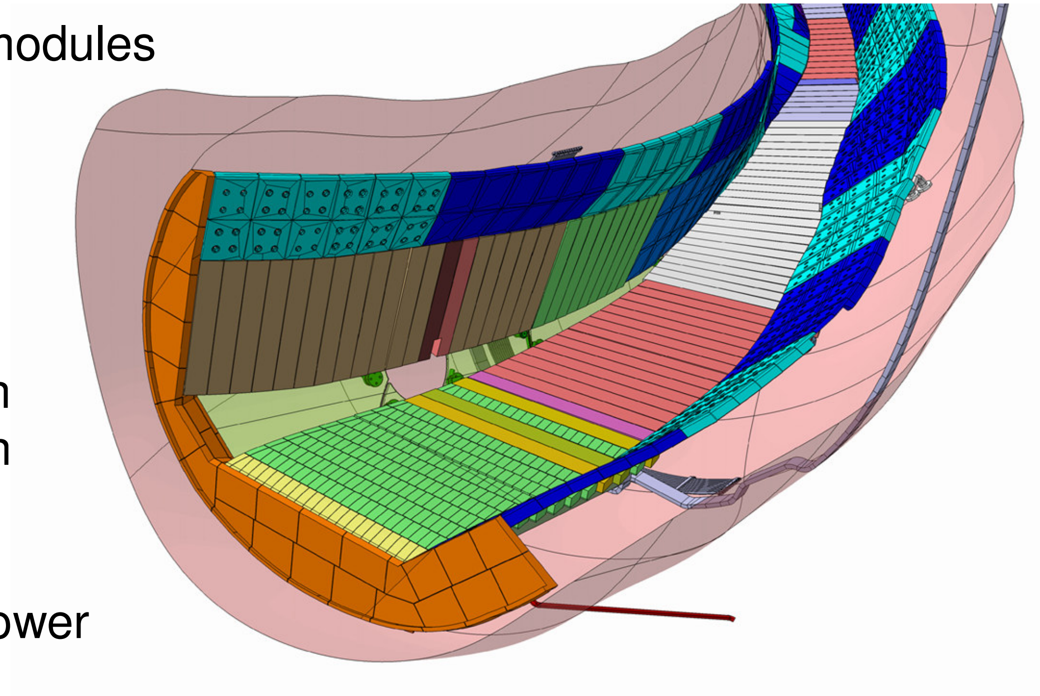
In-vessel components



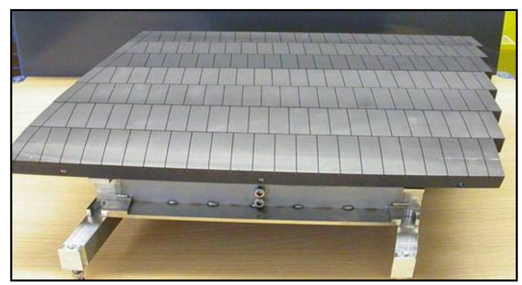
- inertially cooled „test divertor" – 10 modules
- conventional graphite tiles
- same geometry as HHF-divertor
- adjustable frame

⇒ Allows much more robust operation and check of magnetic geometry, in preparation of HHF-divertor

- operation limited to 5-10s at 8MW power
- no cryo pumps
- limited water-cooling inside plasma vessel

- design review in March 2009
- manufacturing has started

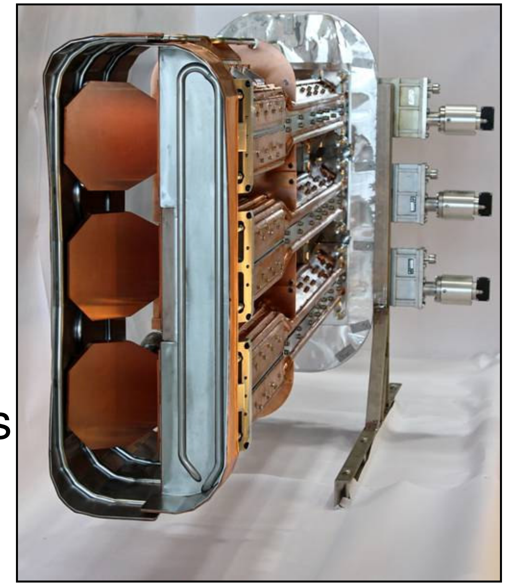
prototype graphite module



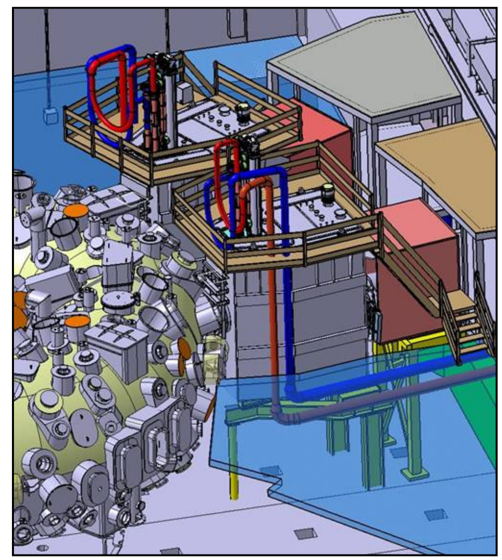
The test divertor will be replaced by the HHF-divertor after the first operation phase.

Heating

- 8 x 1 MW ECRH @ 140 GHz available (30min)
- tuning to 105 GHz at 50% output power possible
- switch between X and O polarisation
- 4 ECRH beam launchers with 3 individual front steering mirrors
- steering range $-15° < \Phi_{tor} < +35°$ and $-25° < \theta_{pol} < +25°$ with 25°/s
- cooled reflector tiles on the high field side



- two NBI boxes with two beams each
- 7 MW for H (55 keV) and 10 MW for D (60 keV) operation
- copies of the AUG system with RF PINIS
- rather radial injection ± 7.44°
- about 50% Polish contribution (decision pending)



Diagnostics

I: plasma core spectrocopy	concept	design	manufacturing	cooperation
diagnostic beam	●	●	◑	FZJ/Budker (Rus)
CXRS	◕	○	○	
soft x-ray tomography	●	◕	◔	
pulse height analysis	●	◔	○	IPPLM (PL)
bolometry	●	◑	○	
C/O-monitor	●	◔	○	U-Opole (PL)
HEXOS VUV spectroscopy	●	●	●	FZJ
neutron counters	●	◔	○	PTB
II: microwaves and laser diagnostics				
thomson scattering	●	◑	◔	IPP-AUG
interferometry	◕	◑	◔	FZJ
electron cyclotron emission	●	●	◑	

III: divertor diagnostics and magnetics	concept	design	manufacturing	cooperation
neutral gas gauges	●	●	◔	
divertor thermography	●	○	○	
divertor thermo couples (TDU)	◕	◑	○	
video diagnostics	●	●	◑	KFKI (Hun)
magnetic diagnostics	●	◕	◑	
langmuir probes (TDU)	●	●	○	
Hα diagnostics	●	○	○	
visible spectroscopy	◕	○	○	
thermal Helium beam	●	●	○	FZJ
laser-induced flourescence	●	◕	◔	FZJ

- about 20 different diagnostic systems will be available for the first operation phase
- development structured in three topical groups
- progress presently hampered by bottlenecks in design capacity
- steady state CoDaC system

Overview

- Construction, status and schedule
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- **Initial physics programme**
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Research programme

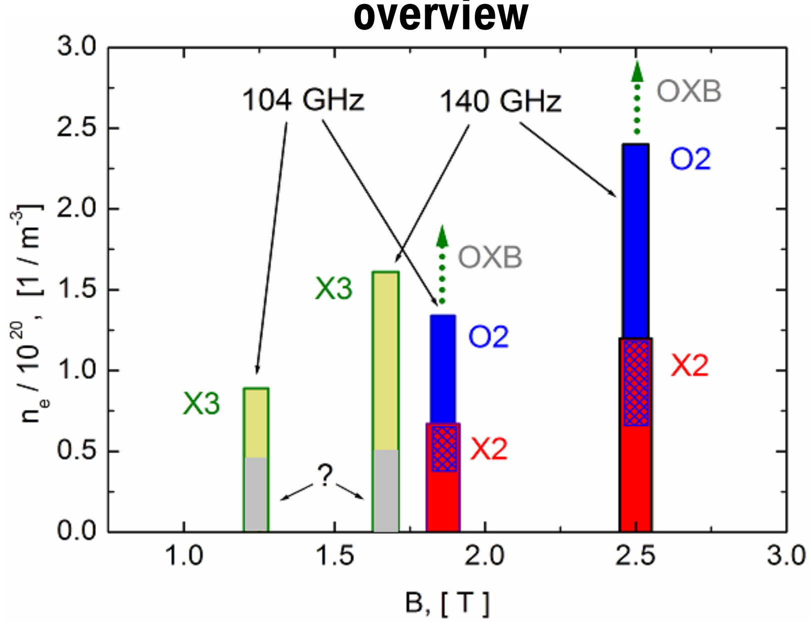
- Development of the programme has started with a dedicated seminar series, involving all senior scientists and covering all physics aspects.
- The final goal of the first operation phase is to develop an integrated high-density scenario with configuration control and edge conditions suitable for divertor operation.
- This scenario forms the basis for high-power steady-state operation to be explored during the second operation phase.
- The first operation phase of Wendelstein 7-X can be broken down in a number of (technical) milestones and intermediate scientific aims.

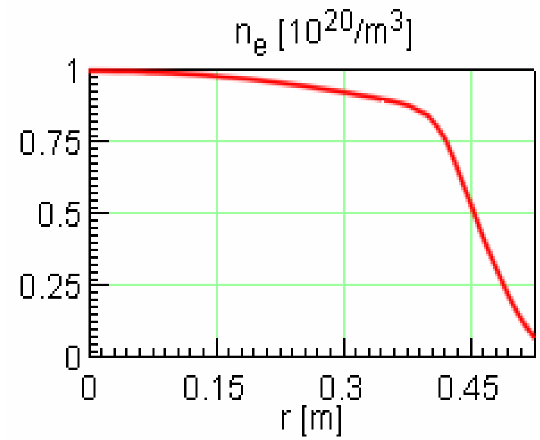
Research programme

Nr.	milestone/work package	4 Q2 Q3 Q4 / 2015 Q1 Q2 Q3 Q4 / 2016 Q1 Q2 Q3 Q4 / 2017 Q1 Q2 Q3 Q4
1	vacuum conditions achieved	12.09.
2	magnet system cold	07.11.
3	2.5T magnetic field achieved	10.04.
4	magnetic field structure confirmed	01.05.
5	diagnostic systems ready	01.05.
6	heating systems ready	01.05.
7	first plasma	15.05.
8	long pulse plasma	29.05.
9	symmetry verification	26.06.
10	density control investigations	
11	X2-heating up to cutoff	
12	confinement properties	
13	impurity control investigations	
14	tolerable divertor load scarios	
15	X2-current drive for edge iota tuning	
16	dense NBI driven plasmas	
17	divertor high-recycling regime	
18	O2-heating and cutoff	
19	shut down for completion	15.05.

X2-Heating up to the cut-off limit

overview

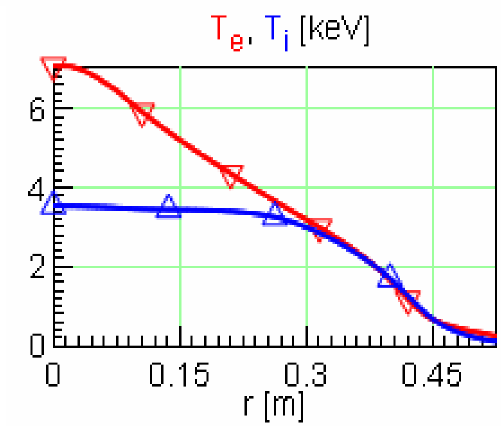




combined ray tracing and 1D transport calculations

5 ECRH-beams

P_{ECRH} **= 5 MW**



standard configuration

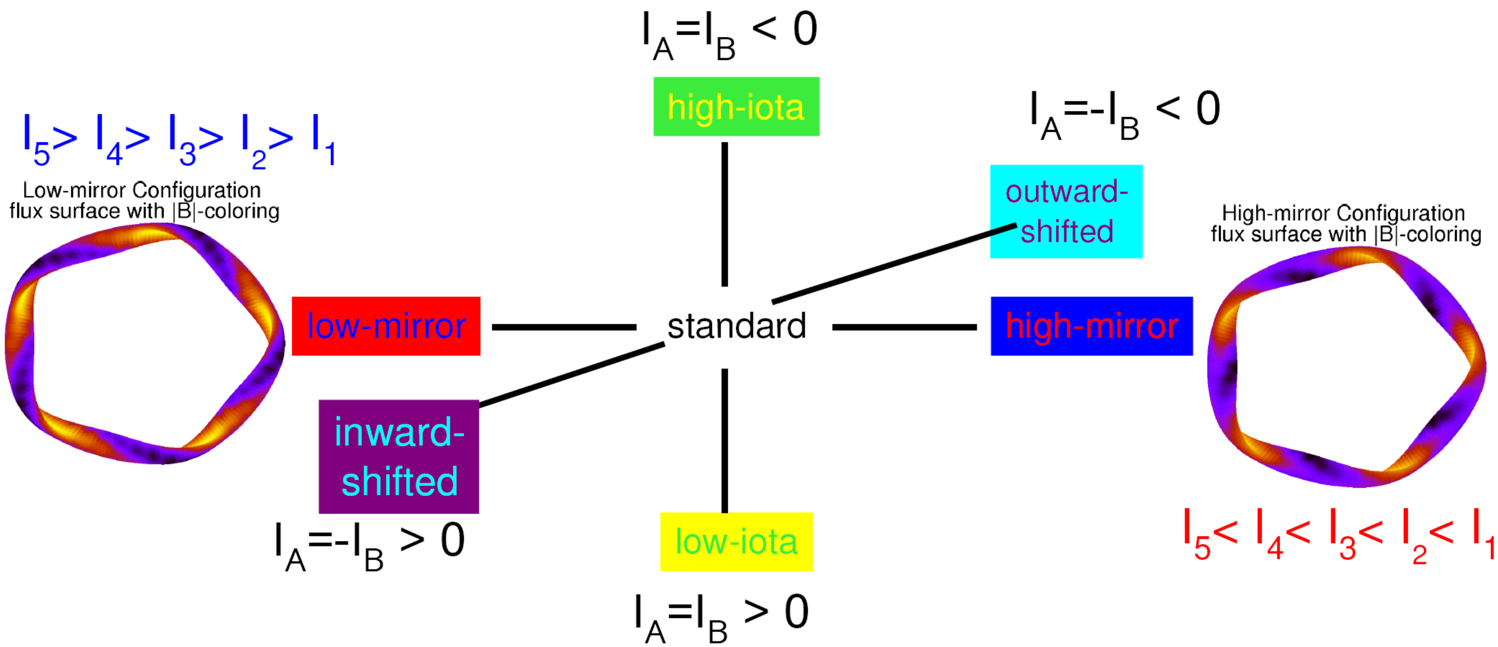
$B_{max}(0)$ **= 2.56 T (vac)**

$<\beta>$ **= 2%**

- **plasma startup 0.7MW X2 at 140 or 104 GHz**
- **low density plasma <= $1.2 \cdot 10^{19}$ m^{-3}**
- **high electron temperature >4 keV**

Confinement studies

magnetic flexibility of the device

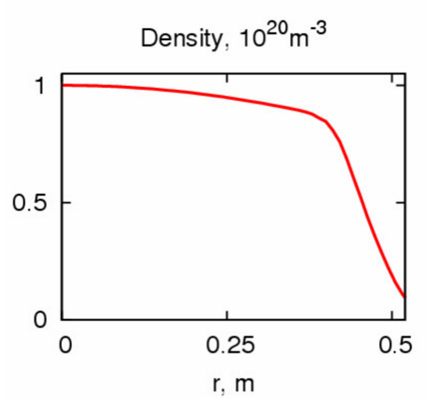


- variation of the toroidal mirror component varies ε_{eff} ~ 0.0 … 0.1 varies χ_e
- verification of reduced $1/\nu$ transport in the X2 4MW discharge scenario
- confinement scaling and comparison to ISS04
- configurational effect on $\langle j_{||}\rangle/\langle j_{\perp}\rangle$ (Shafranov shift, ι-profile)
- MHD stability limits? $\leftarrow \langle\beta\rangle$ too low
- fast particle confinement? $\leftarrow \langle\beta\rangle$ too low

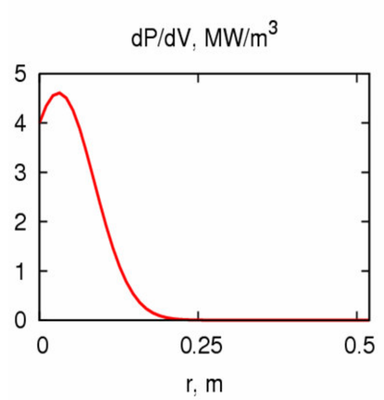
Confinement and configuration

Predictive transport simulations for a variation of the mirror ratio

$n_e = 10^{20}\ m^{-3}$

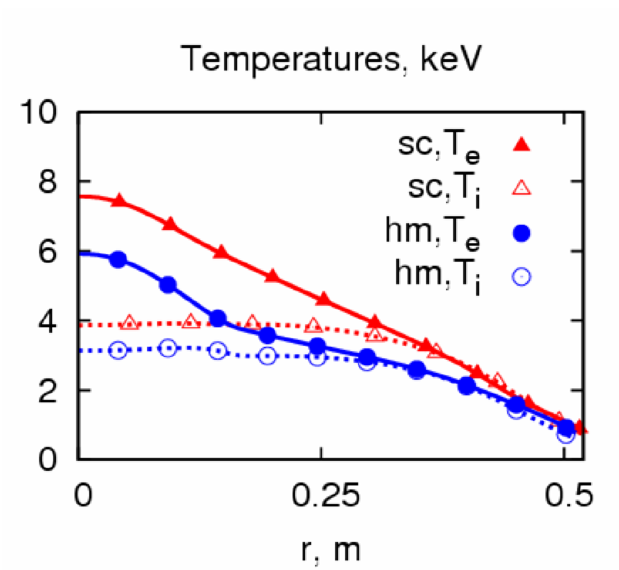


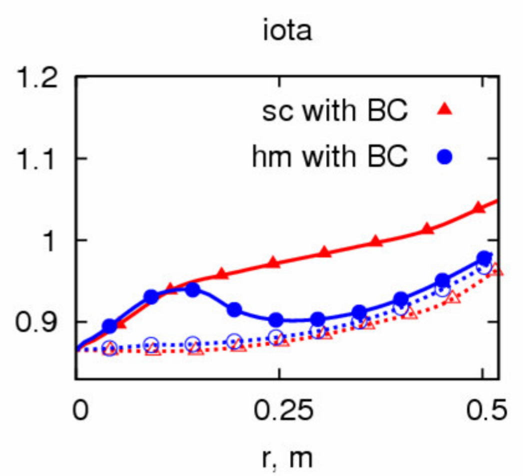
6 MW ECR heating



sc: **S**tandard **C**onfiguration **W=3.5 MJ**

hm: **H**igh **M**irror conf. **W=2.6 MJ**





Temperatures and plasma energy are higher for standard configuration.

However, bootstrap current increases edge iota and must be compensated in this case.

Impurity studies

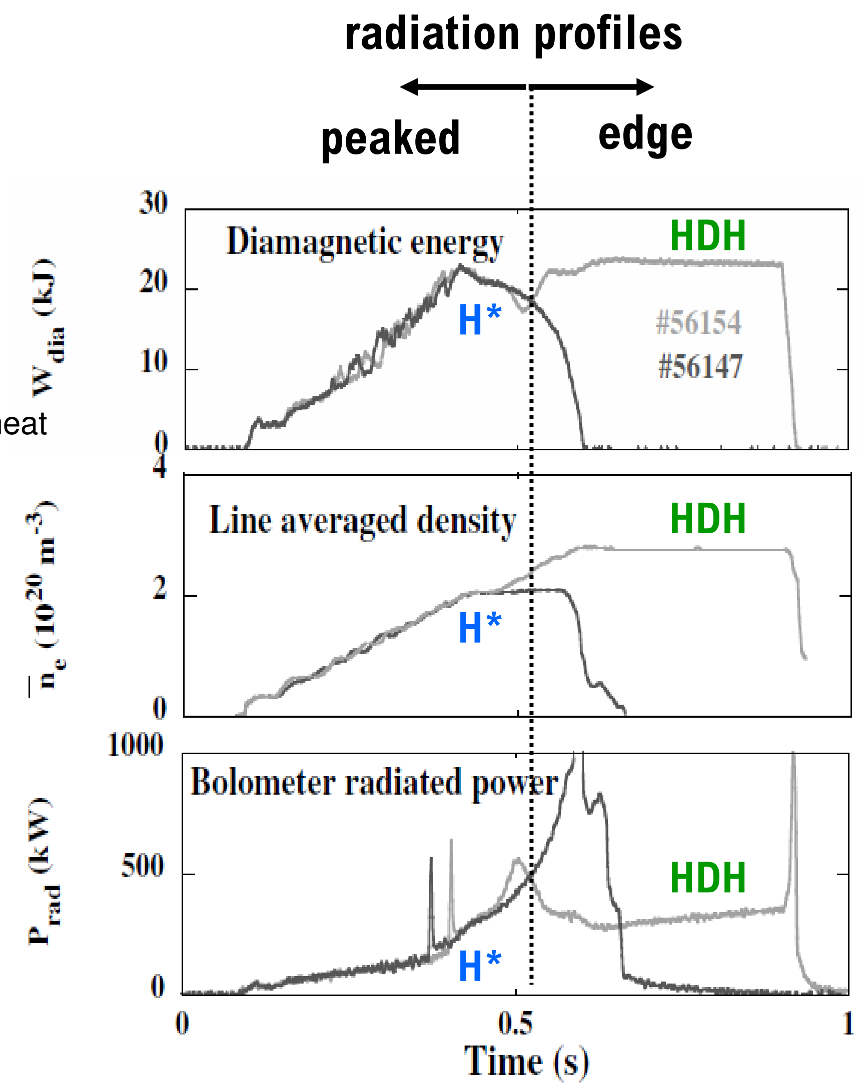
Stellarators have a soft density limit with the scaling $n_{DL} = 1.46\ (P/V)^{0.48}\ B^{0.54} \leftarrow$ verify

impurity accumulation at higher densities

the aim is stationary plasma with $P_{rad} < 50\%\ P_{heat}$

- reduction of impurity confinement
- reduction of impurity influx
    - drag forces at the plasma edge?
    - role and control of ELMs?
    - role of turbulence?

Note:
temperature screening does not occur in stellarators, even for positive radial electric field (e-root)



experience with W7-AS

Divertor load studies

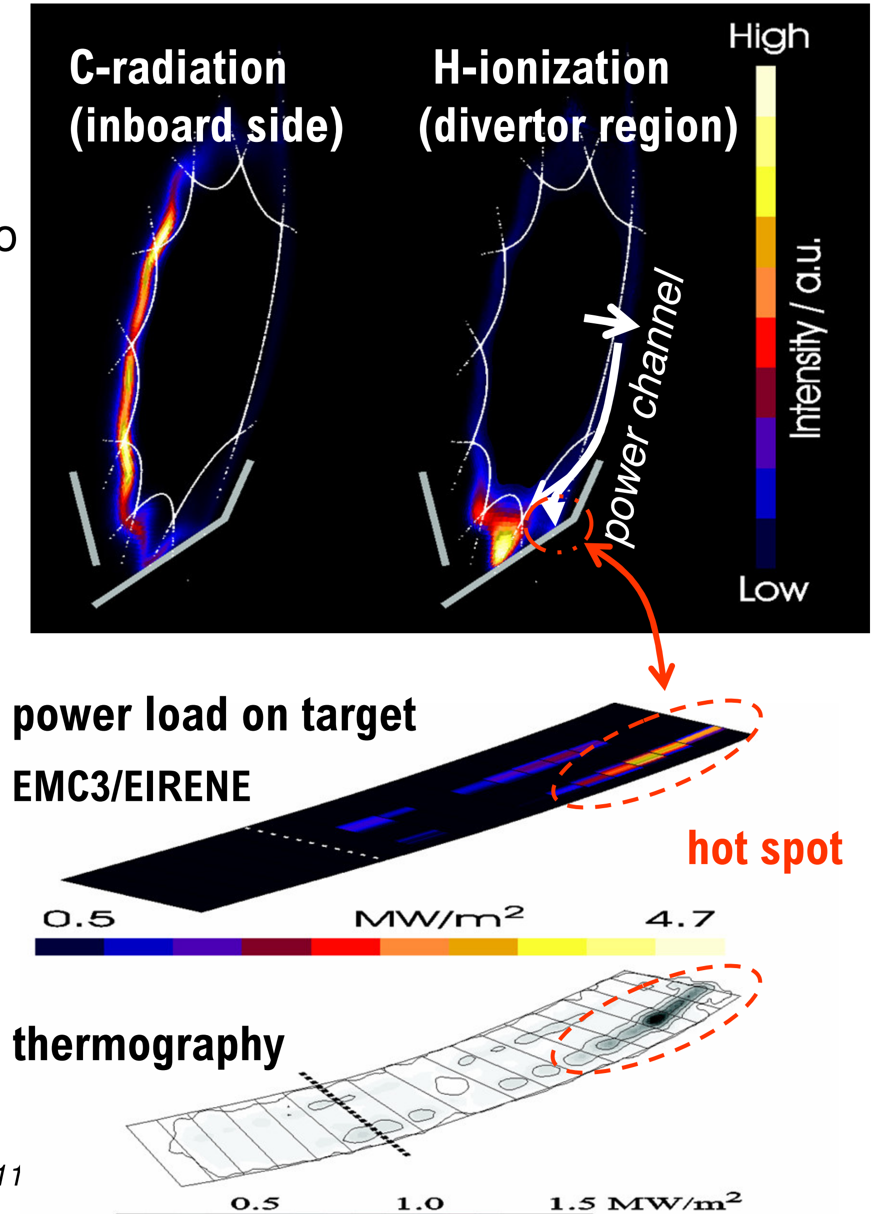
- experience with W7-AS island divertor
- good modelling capabilities with EMC3/EIRENE
- divertor target overload at ι=1 by factor ~2 due to
    - coil alignment → field errors B_{11}/B_0=1-5·10^{-4}
    - divertor misalignment 1-2cm
    - additional impact of $E \times B$ drift

To be investigated:

1. flux surface structure (islands if possible)
2. strike line locations
3. strike line extensions (length & width)
4. power load distribution within strike lines

Resulting actions:

divertor re-alignment, sweep coils B_{33}, trim coils B_{11}



Summary

- Fabrication of components well under way/finished
- Assembly on 4 out of 5 modules in progress
- Commissioning will start in summer 2014

- Test divertor unit to study operation limits and develop divertor scenarios
- 8MW ECRH and 7 MW NBI
- Diagnostics sufficient to conduct the initial program is being prepared

- Scientific program has been developed by the W7-X team – first steps:

1. Low density ECRH heating scenarios
2. Confinement studies at moderate β
3. Density limits and impurity transport
4. Tolerable divertor loads

Thank you !

Commissioning

Commissioning of W7-X has three steps with increasing levels of system integration.

1. Local commissioning of the technical components. This includes instrumentation and local control and can mostly be done before the end of W7-X assembly.
    - device control, safety control, data acquisition
    - vacuum systems
    - water cooling/baking system
    - wall conditioning systems (glow discharge, HF-conditioning)
    - cryo plant and He distribution system
    - coil power supplies including QD system
    - gas injection system
    - start-up diagnostics
    - Heating systems (ECRH, NBI)
2. Stepwise integration of these components into the overall system, the central device control and the central data acquisition system.
3. Demonstration that the overall system meets the basic technical requirements of the W7-X system specification and enables scientific use of the device. This includes plasma start-up and control.

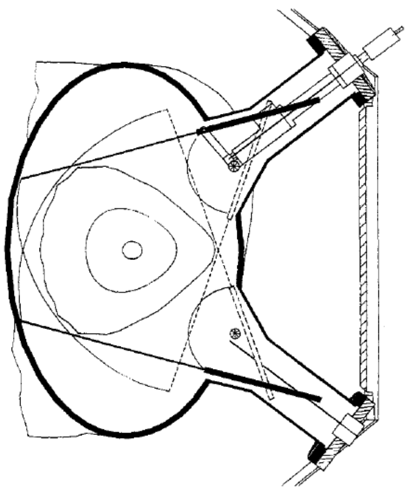
Commissioning

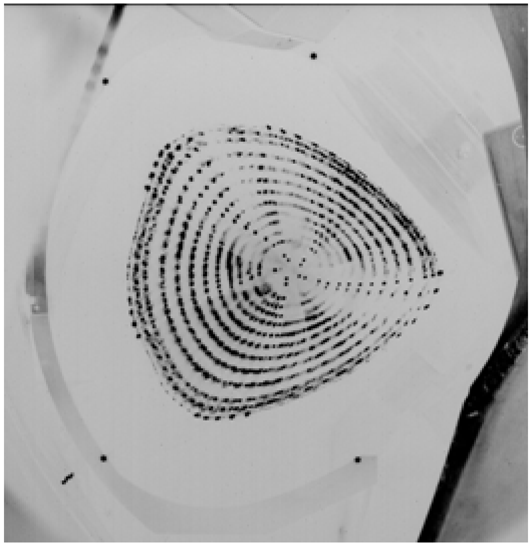
1. **Vacuum (Vacuum systems, control, instrumentation, conditioning systems)**
   - leak tightness of plasma vessel and outer vessel, evacuation
   - leak tightness of water and He cooling pipes, cooling water flow adjustments
   - cleaning of vacuum vessel, wall conditioning, baking
2. **Cooling (cryo plant, instrumentation, control system)**
   - leak tightness of *cold* cooling pipes
   - cryogenic He-flow adjustments
   - cool down of magnet system
     - » insulation (heat balance, heat leaks)
     - » movements during cool-down (check for collisions)
3. **Magnetic field (power supplies, QD-system, control system, flux surface measurement)**
   - initial operation of magnet system and magnet safety system
   - superconductivity (especially in joints)
   - forces and movements under load
     - » monitoring by strain gauges, distance sensors and contact sensors
     - » Comparison with predictions from finite element codes
   - magnetic surfaces (at low field and at higher field)

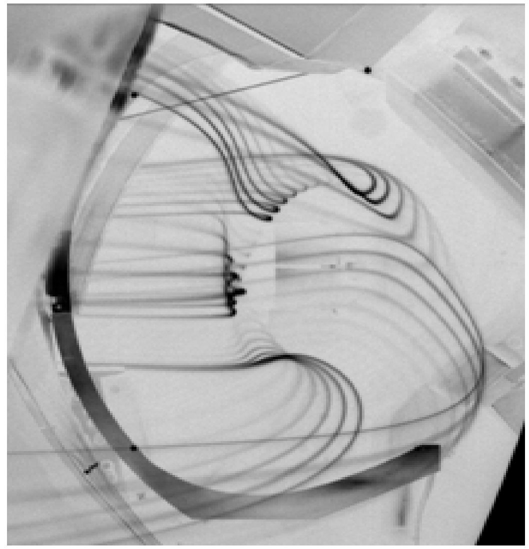
Flux surface measurements

fluorescent method:
interaction of e-beam with fluorescent detector in a fixed plane → 2D Poincaré plot

field line tracing in background gas:
excitation in background gas by e-beam → 3D trace in torus







- **rod with ~ 2mm diameter**
- **highly transparent ~ few 10 transits**
- **small details visible (e.g. magn. axis, island)**
- **duration: ~10s/flux surface (manipulator)**
  ~0.5h/magnetic configuration

W7-AS: 35 transits ≈ 450m
W7-X: 10-15 transits expected

- **magnetic axis, X-points, separatrix**
- **possible calibration source for diagnostics**

Key elements of inital 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 bootstap 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

Scenario 3

Bundle of measures to stabilise the completion date mid 2014 (BMBF workshop Sept 2007)

- **Reduction of complexity**
- **Reduction of project risks**
- **Acceleration measures (by 2 years)**

	acceleration	assembly risks	delivery risks	budget risks	operation
assembly based on 96h/week = 2 shifts on 6 days/week	×				
additional assembly equipment for parallel works	×				
parallelisation of port assembly	×				
shift of work packages into component preparation	×				
omission of 45 ports		×		×	
introduction of 68 weeks buffer time on the critical path		×			
only partial installation of cooling circuits		×		×	×
start with 8MW ECRH and 10MW NBI				×	
Start with inertial test divertor – staged aproach to steady-state		×	×	×	×

Cf. Annex 1-B and Report Bosch