Final integration, commissioning and start of the Wendelstein 7-X stellarator operation

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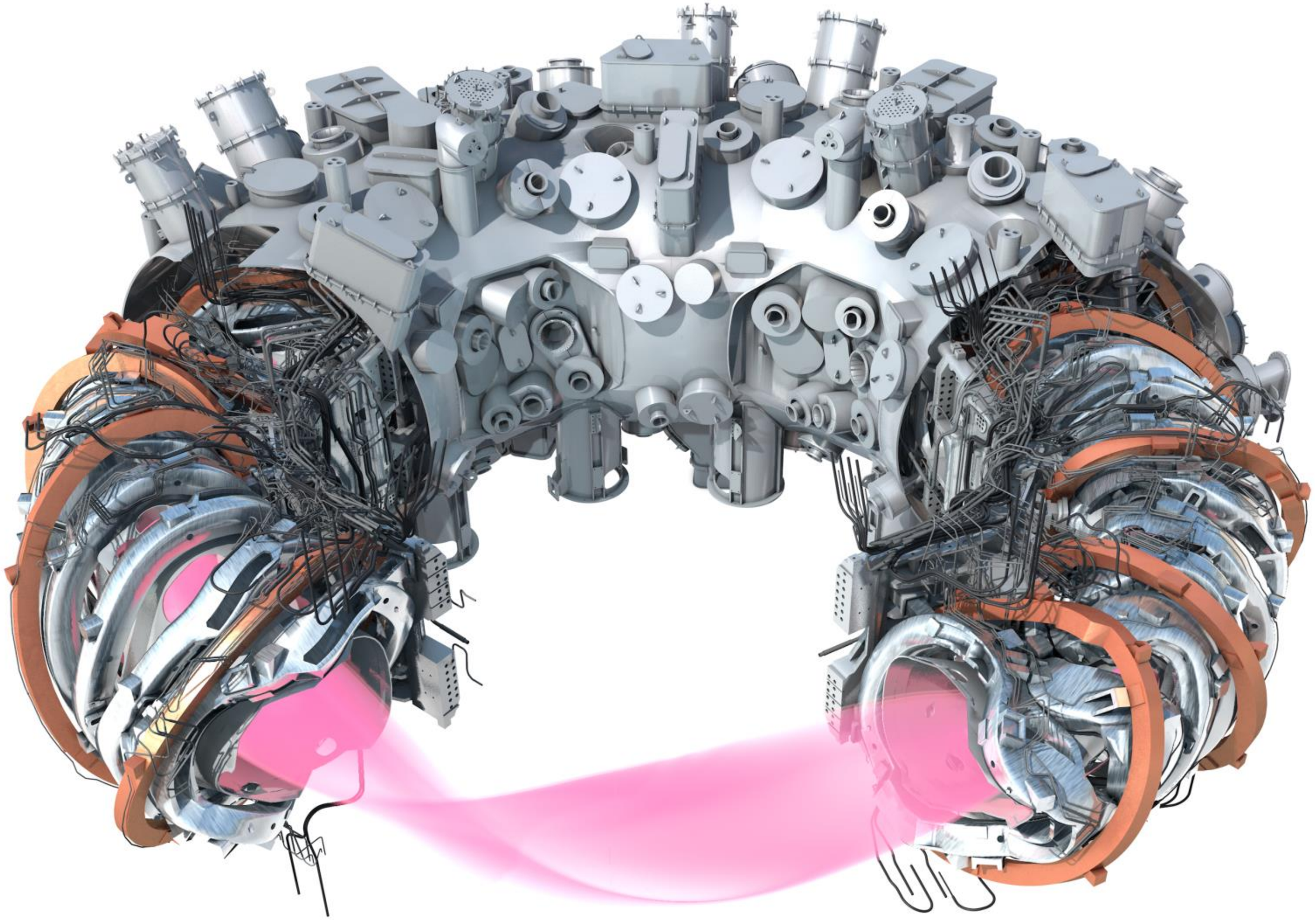
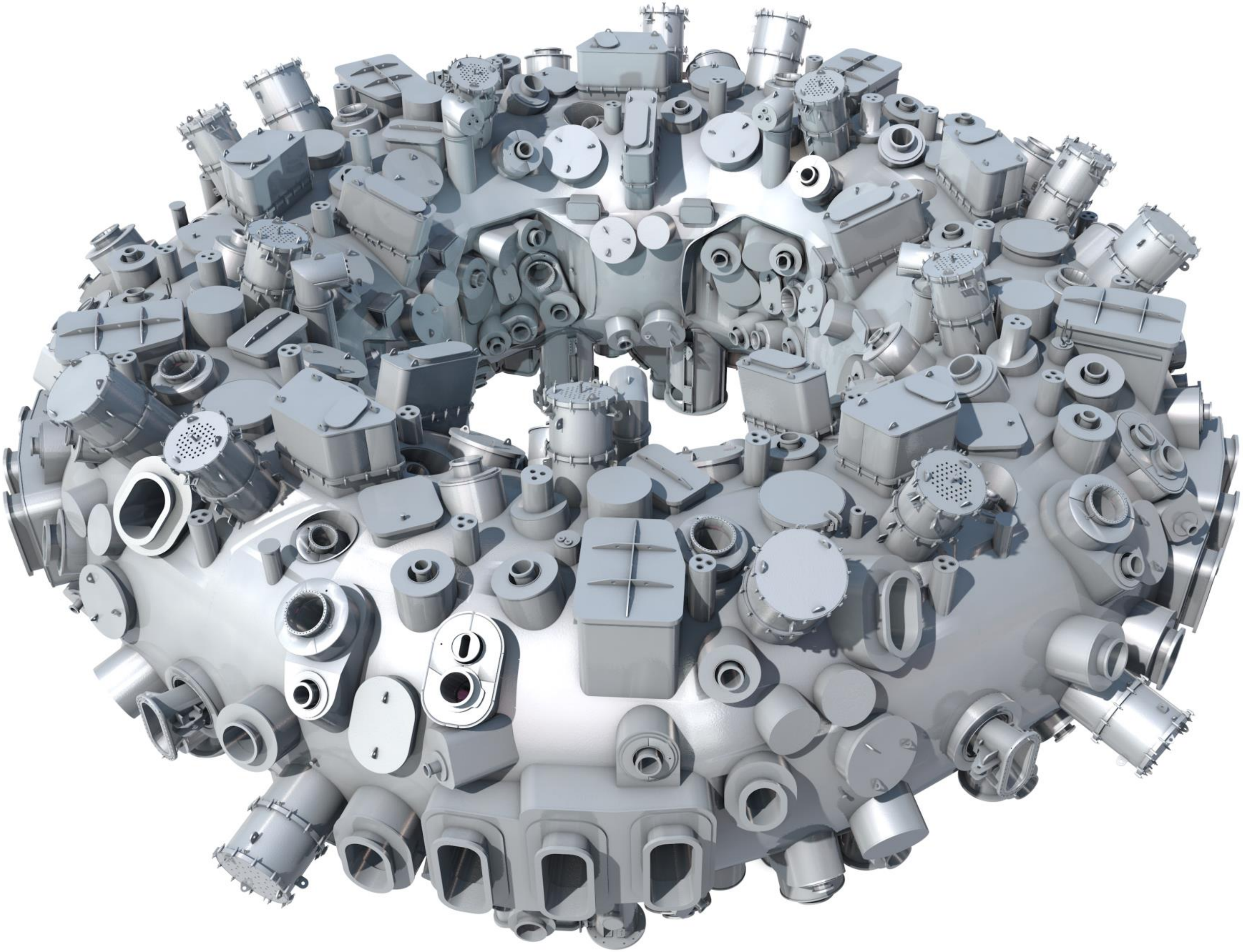
- Introduction W7-X
- Commissioning
- Operation

Wendelstein 7-X

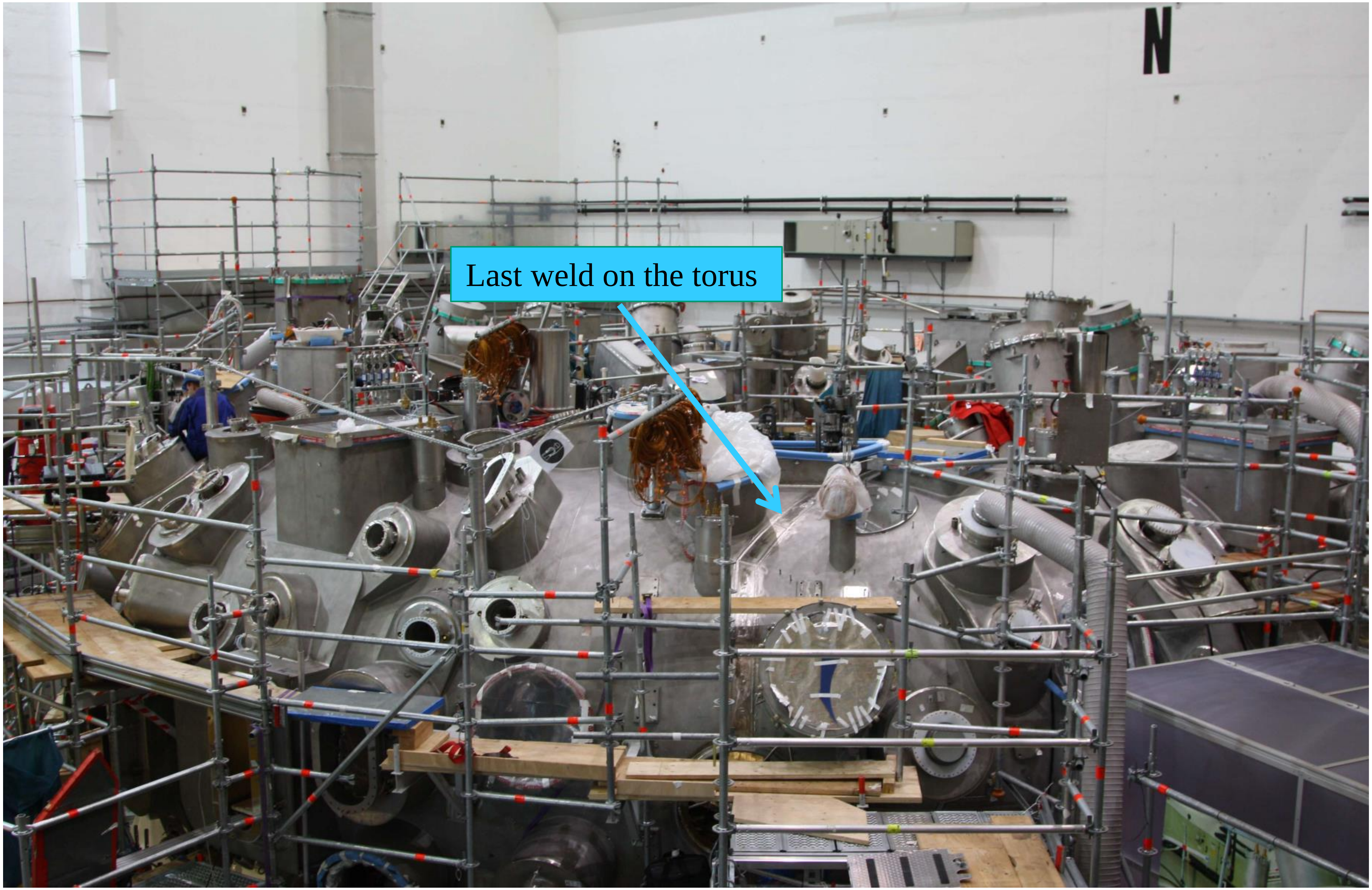


- 735 t mass with 435 t cold mass
- 70 superconducting NbTi coils
- 2.5 - 3 T magnetic induction on axis
- 30 m^3 plasma volume
- 265 m^2 plasma facing components
- 4.5 m height, 16 m diameter

Wendelstein 7-X



Closure of the torus, March 2014



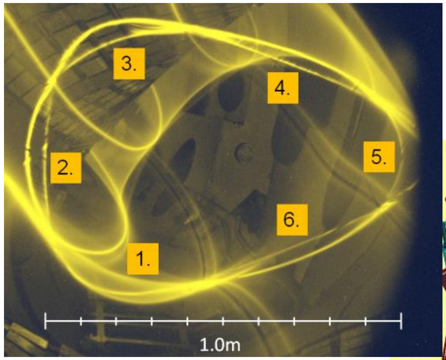
Commissioning of Wendelstein 7-X

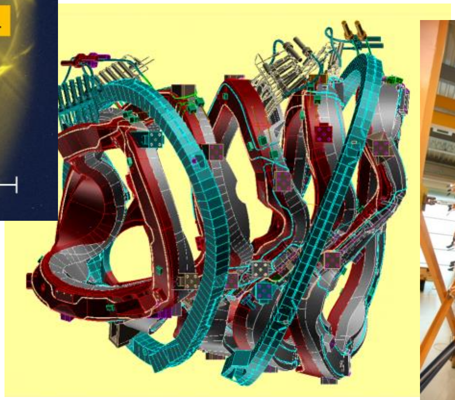
- the commissioning started after the closure of the vessel.
- assembly of in-vessel components, peripheral components and diagnostic systems was continued for another 10 months.
- simultaneous performance of assembly and commission tasks leads
  - to organisational and logistic problems, limited efficency (for both tasks)
  - to additional safety considerations to be taken into account.
- each commissioning step was prepared with
  - safety analysis
  - hazard analyis
  - Operation manual
  - commissioning assurance template (CAT, 100 in total) and WBS
- Local / Integrated commissioning
- Intensive FE-modelling of the commisioning steps was performed, in order to check the behaviour of the device.

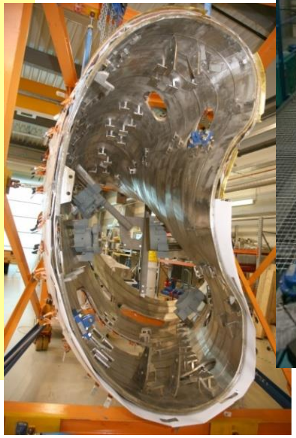
Commissioning sequence for Wendelstein 7-X

The commissioning was divided into six phases:

- i. Vacuum tests of the cryostat
- ii. Cu-coil systems tests
- iii. Cryogenic tests of the cryostat
- iv. Vacuum tests of the plasma vessel
- v. Superconducting magnet coil systems tests
- vi. Preparation for the first plasma





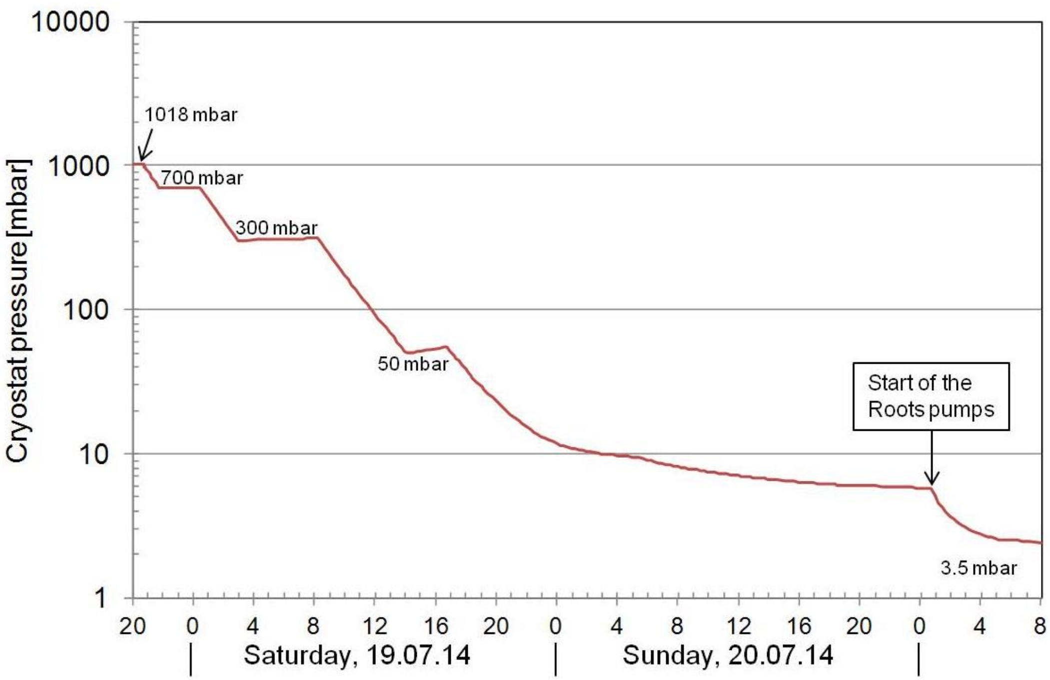


I. First pumping of the cryostat

- the cryostat is formed by the outer and inner vessel and the 254 ports
- free volume is ≈ 420 m^3 with inner metal surface ≈ 1100 m^2,
- covered by the thermal shielding
- 5 pumping stations available, for the pump-down 2 pumps were used

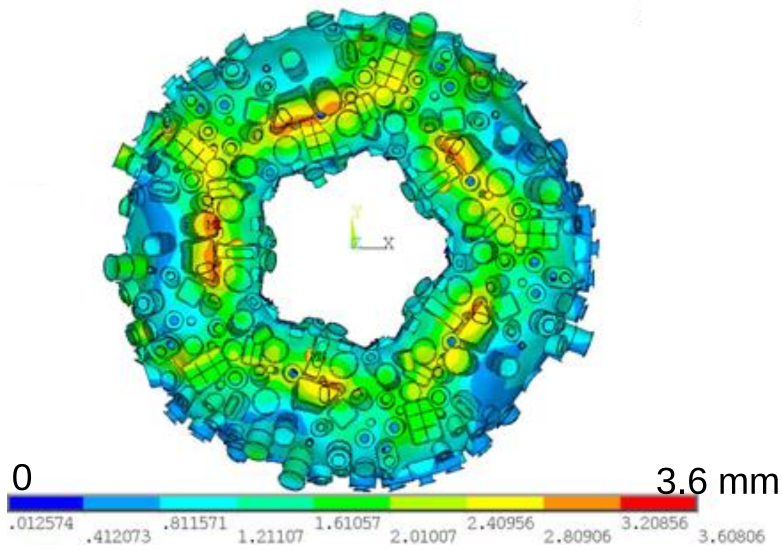
Integral commissioning of the cryostat had two goals

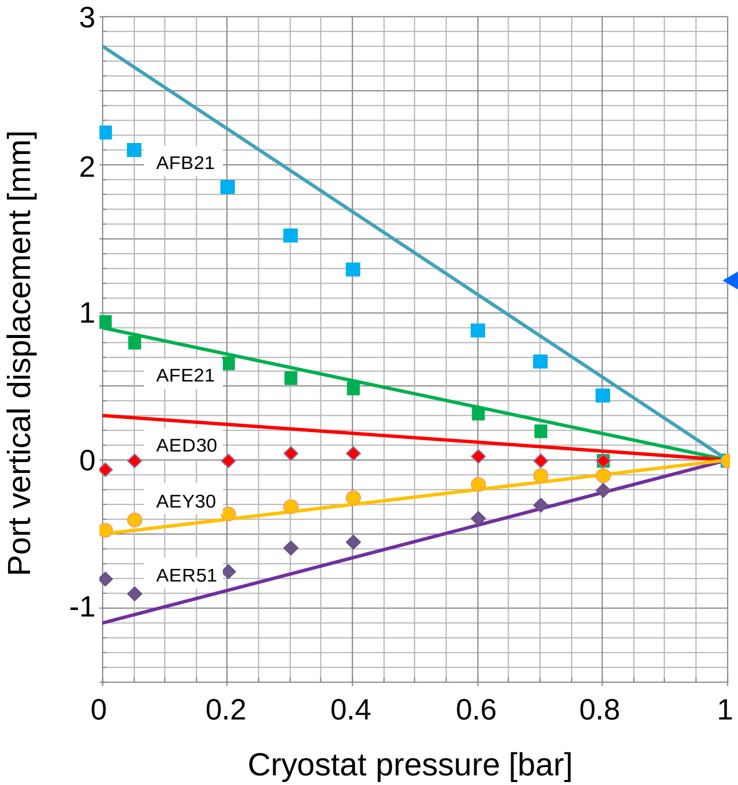
- create isolation vacuum in the cryostat for the first time
- measure the mechanical behaviour of the cryostat vessel



I. Structural integrity of the cryostat

- FE model for cryostat system
- modeling of various load cases, here of the vacuum load





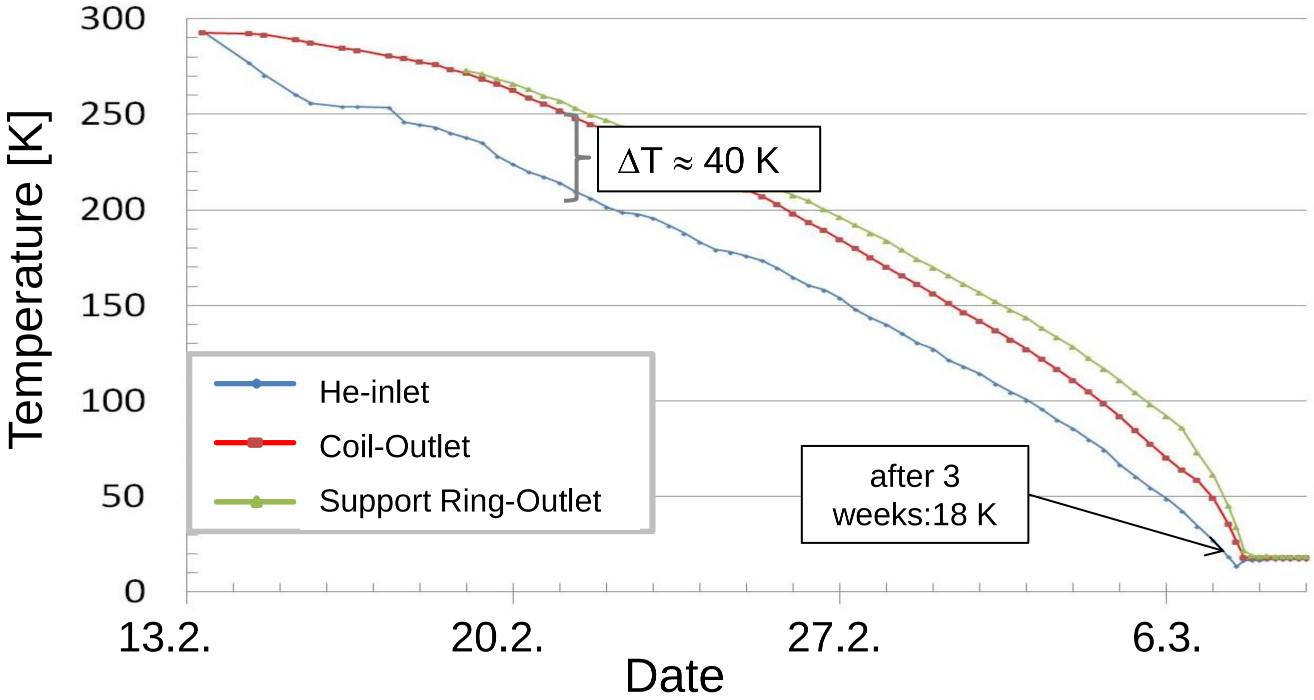
- laser tracker measurements of reference points on outer vessel and ports
- monitoring of strain gauges on the plasma vessel
- monitoring of plasma vessel supports (movements and forces)
- deformation of large rectangular and oval port bellows

III. Cryo supply

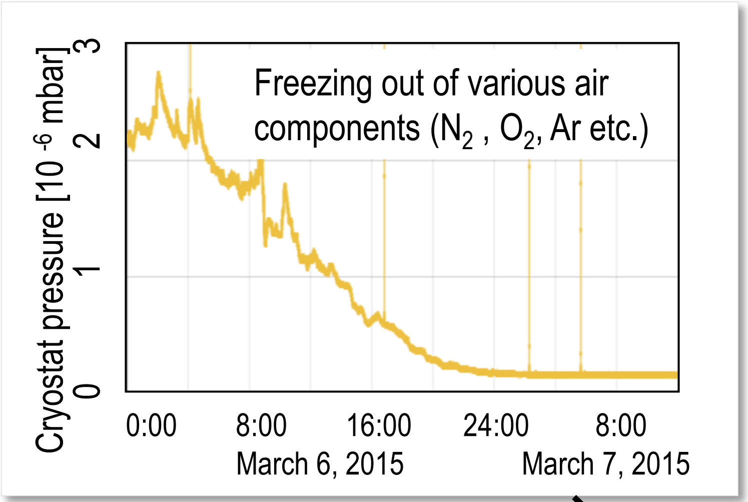
extensive preparation of the cryo supply started in fall 2014:

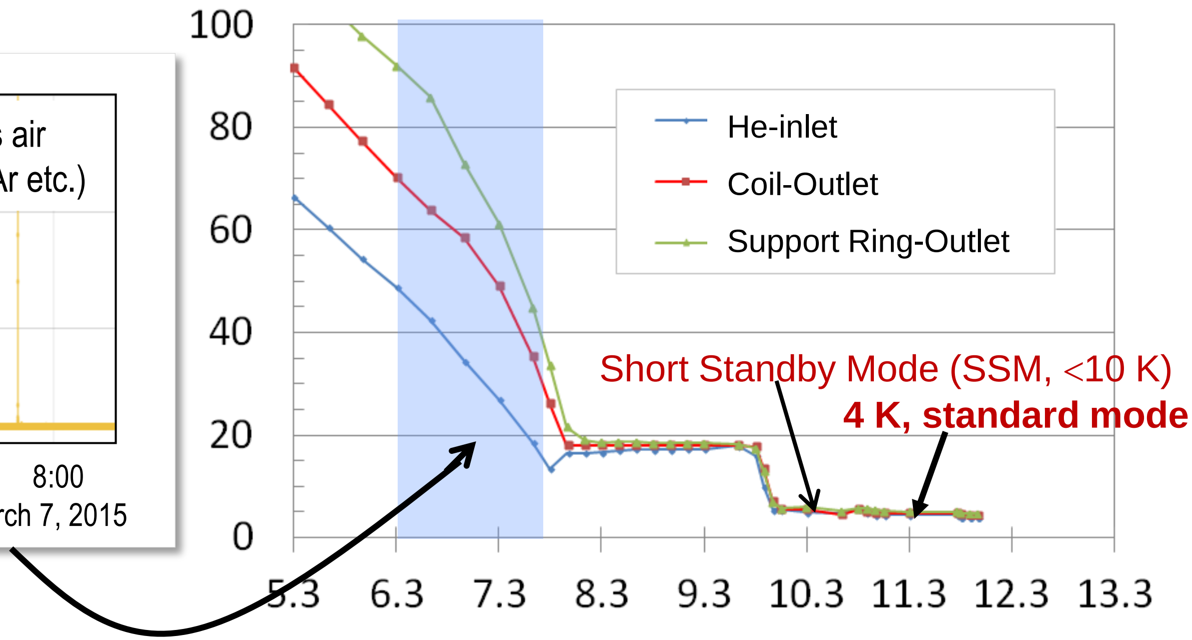
- Leak- and pressure tests of the cryo-piping
- Re-commissioning of the cryo plant
- Cleaning of the piping inside the cryostat by sudden expansion of nitrogen gas
- Purging of piping and filling with helium
- Circulation of helium gas and cleaning with the cold adsorber of cryo plant

⇒ common cool-down of cryo-plant and W7-X started mid of February 2015



III. Cooling down



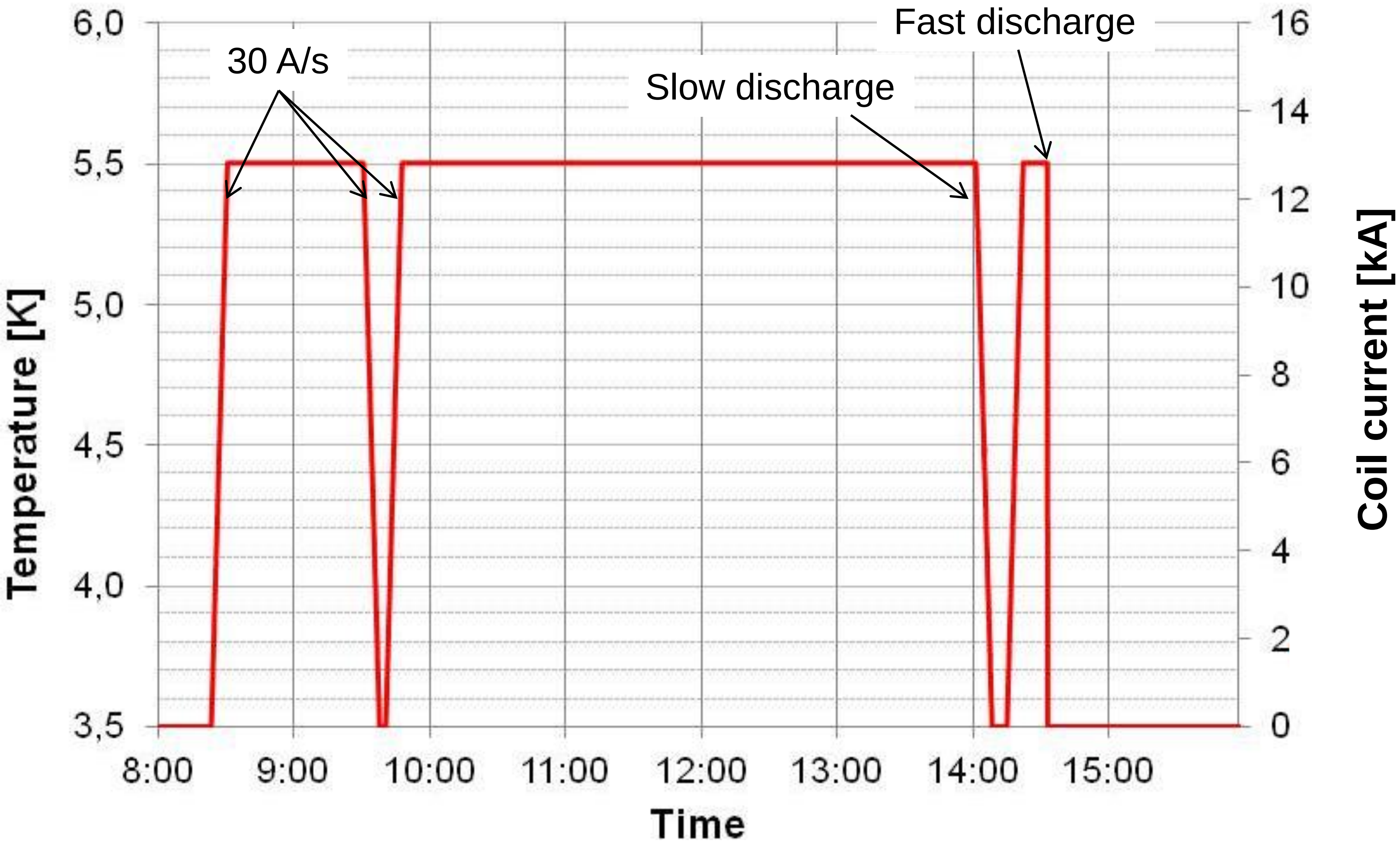


- both operation modi were successfully tested (adjustement of circuits, energy balances, automation, liquefaction, …)
- no problems encountered during the cooling down
- thermal insulation turned out to be better than expected

V. Superconducting coil system

- HV and Paschen test of the full coil system in December 2014
- HV test of the cold magnet system in March 2015
- within the commissioning process different tasks were performed
    - balancing the quench-detectors
    - checking the safety system of the coils
    - measuring the mechanical behavior of the coil system (stresses, deformations, contact sensors, …)
    - Adjusting the He-cooling during magnet operation
- current tests started with single coil-circuits, for each of the 7 types of coils (non-planar coils: 12.8 kA, planar coils: 5.0 kA)

V. Superconducting coil system



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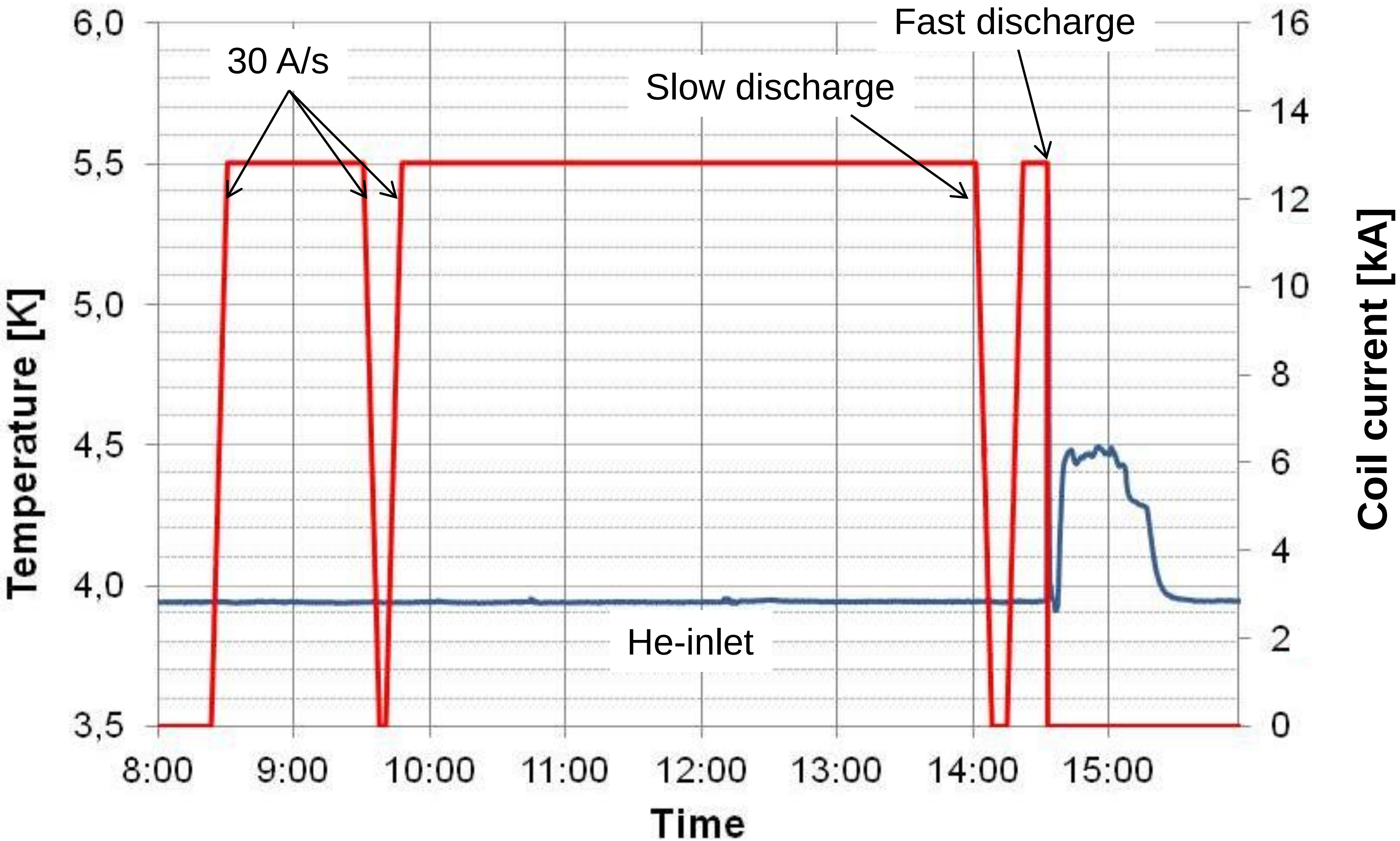

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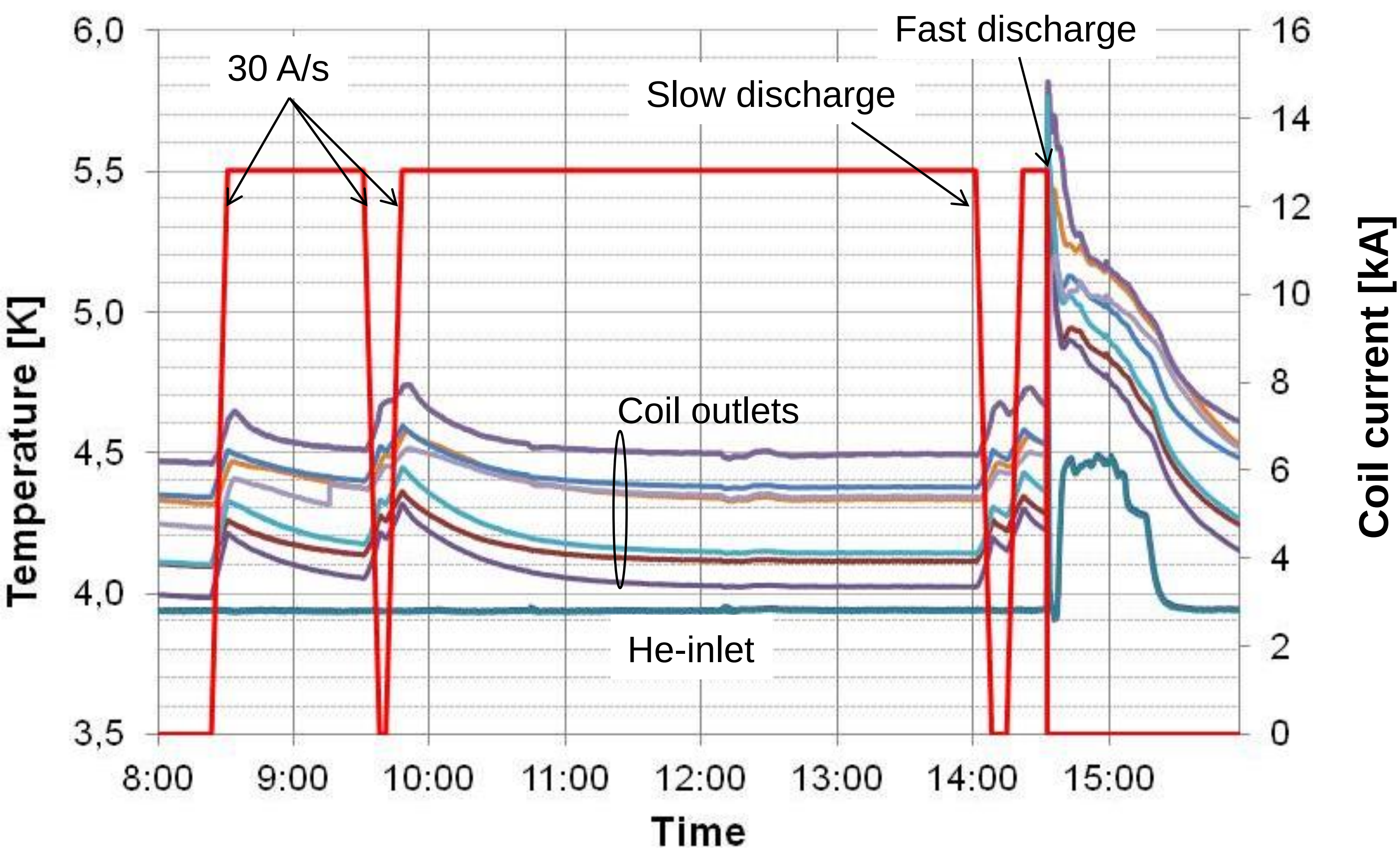

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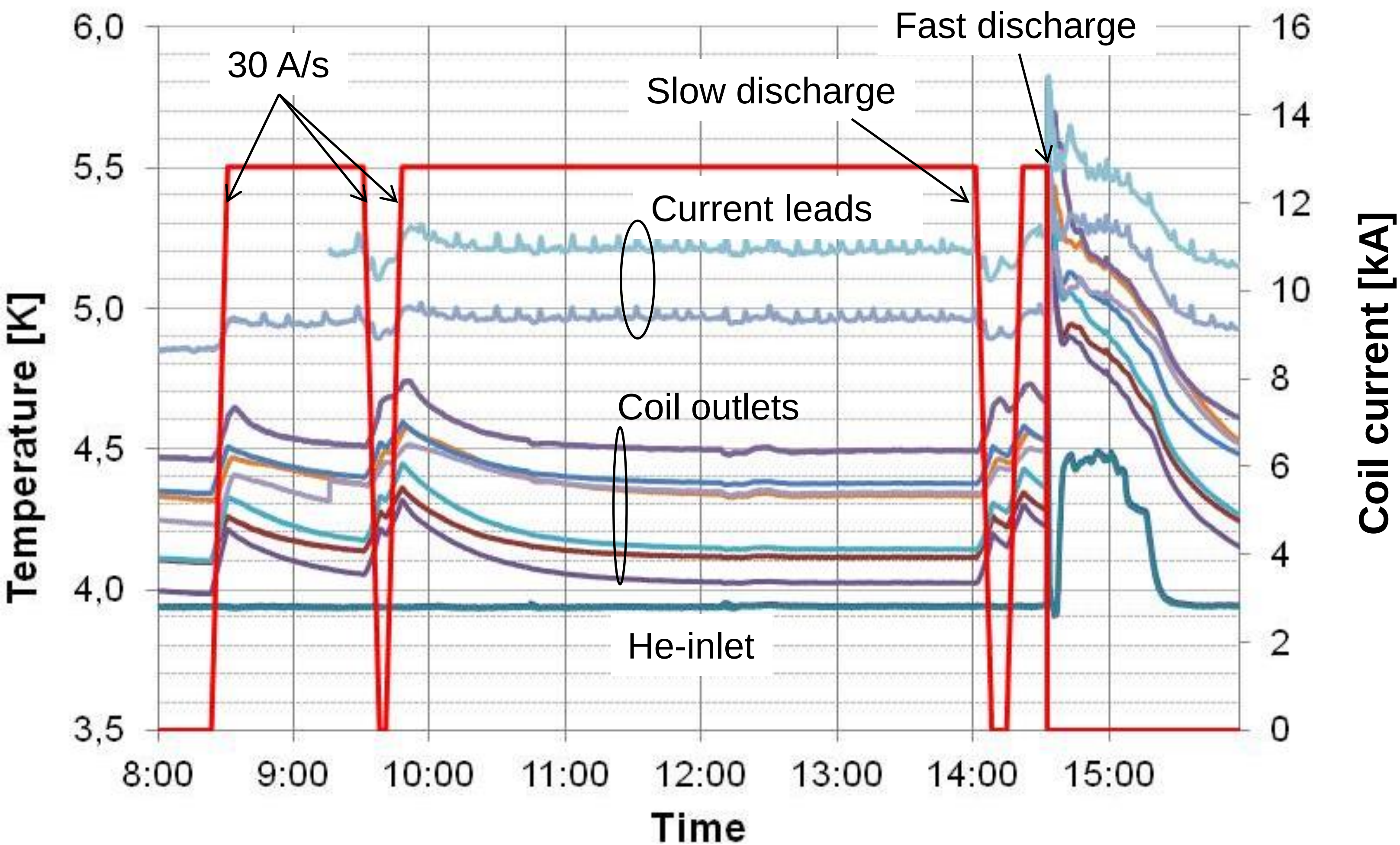
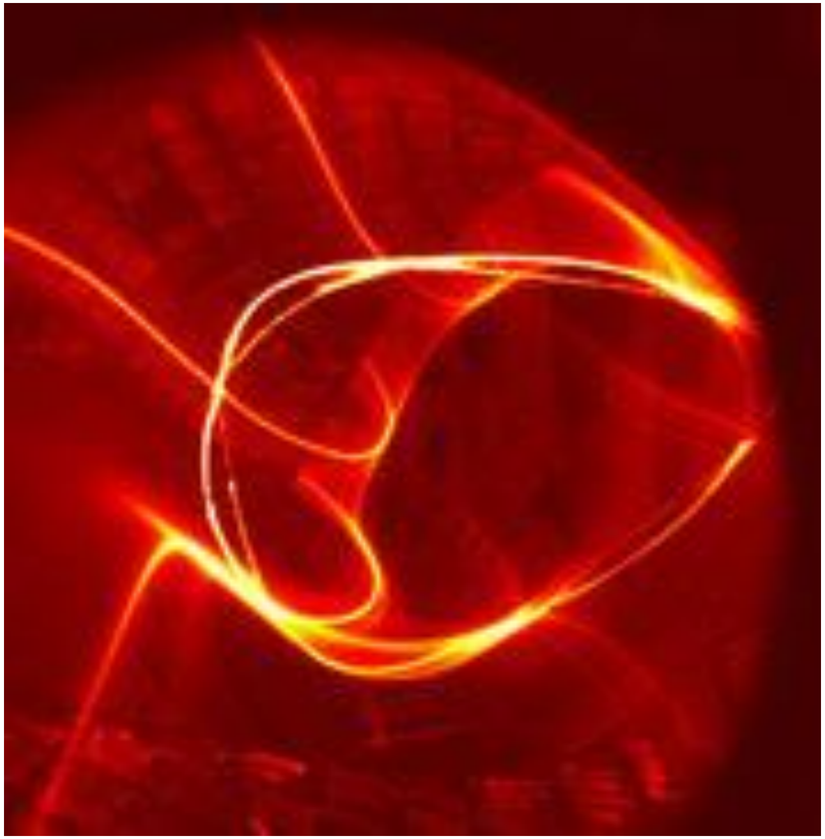
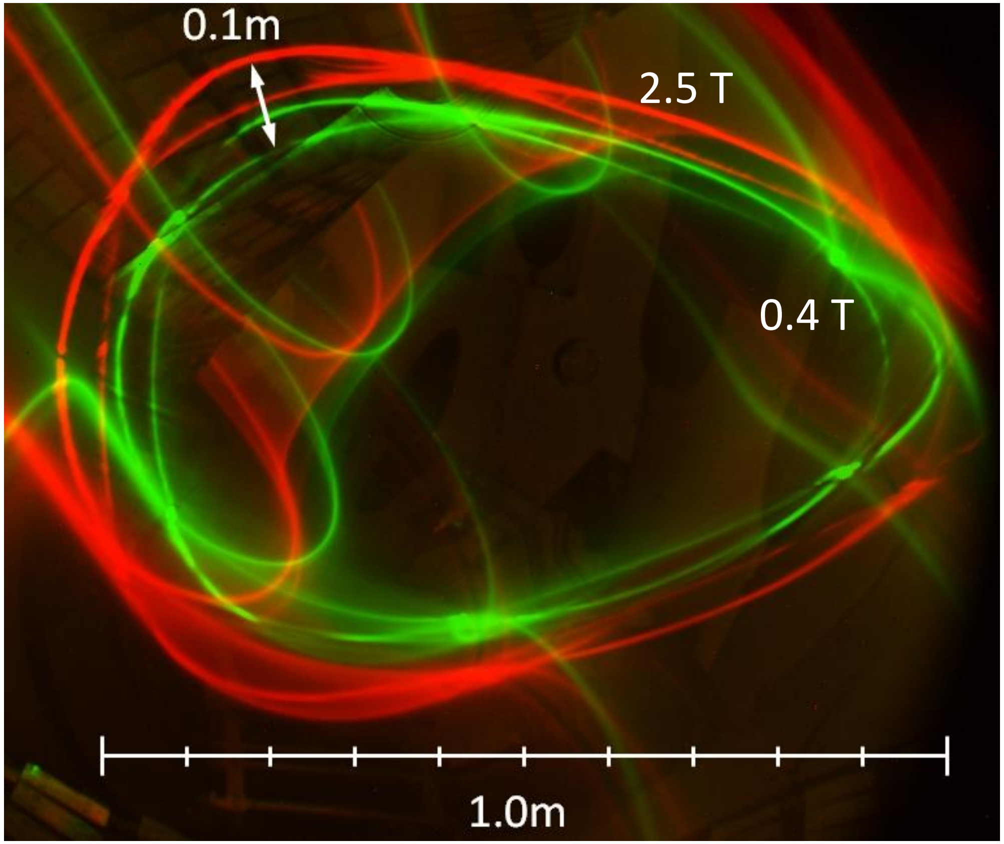


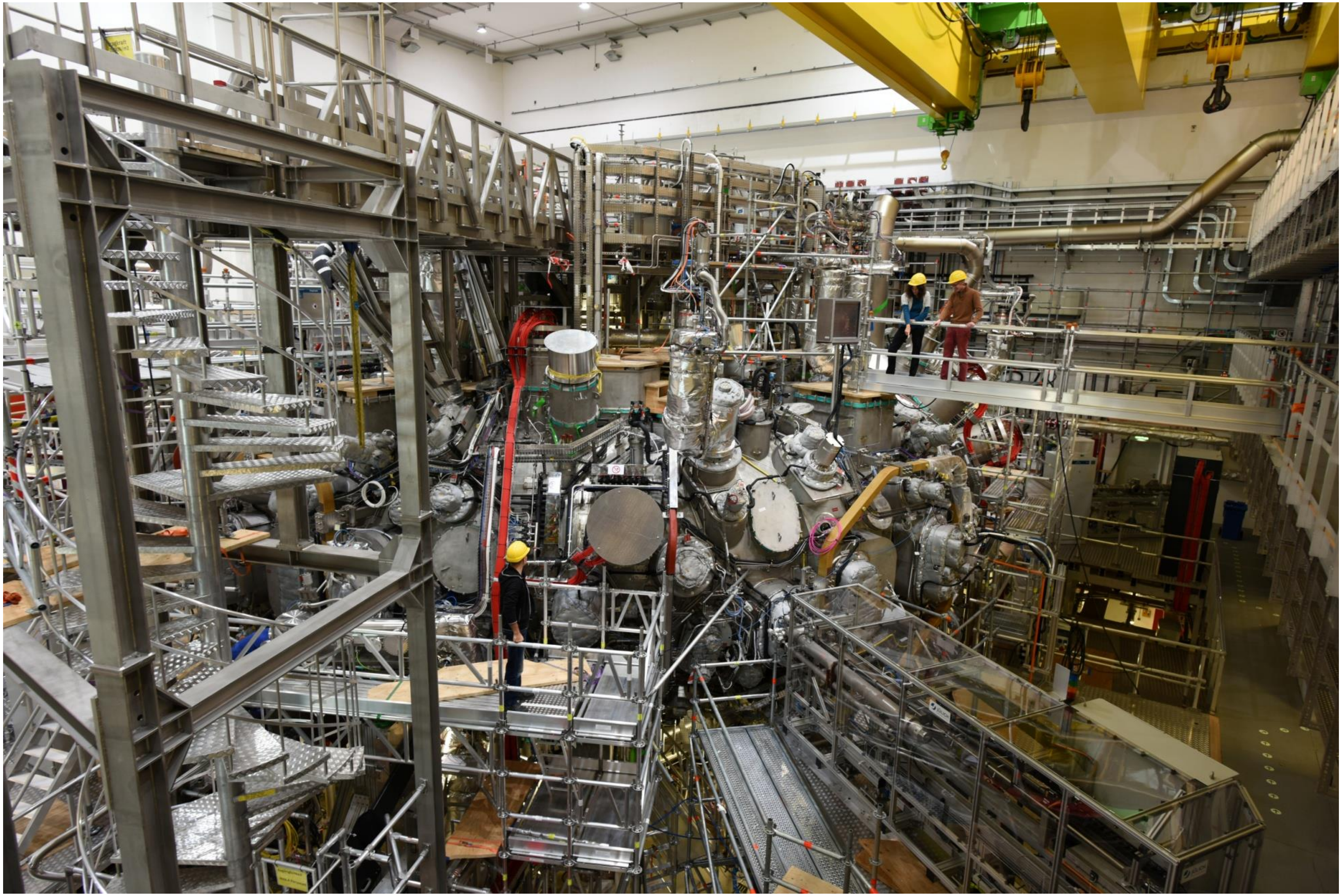
VI. Confirmation of magnetix flux surfaces





Deformation of the sc coils from the coils current
$\Rightarrow$ modification of the iota-profile (extending the plasma volume)
this effect was predicted by FE modelling of the coils

December 2015



First plasma (Helium) on December 10, 2015

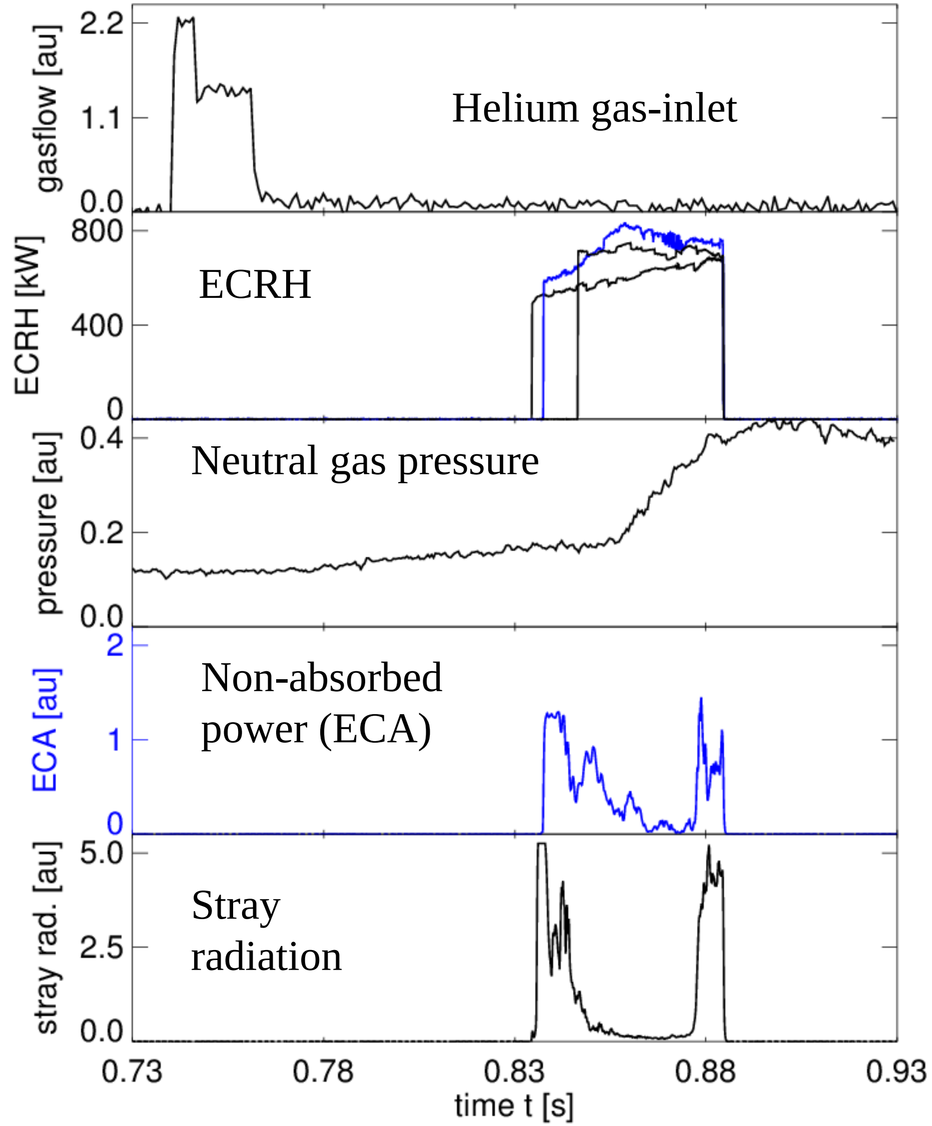
First plasmas rather short

- 500 kW – 1 MW
- limited to 100 kJ (non-absorbed microwave energy)
- 50 – 100 ms plasma duration

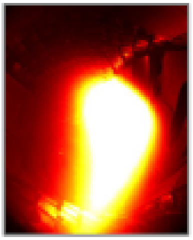
Plasma properties

- 10 ms good ECRH-coupling (X2)
- limited by impurity-radiation
- T_e ~ 1 keV
- n_e ~ 10^{19} m^{-3}

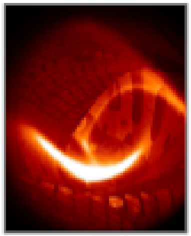
⇒ **further cleaning of the plasma vessel walls**



Operation phase 1.1



$T_e = 1\,\mathrm{keV}$
$T_i < 1\,\mathrm{keV}$
$t_d = 50\,\mathrm{ms}$



$T_e = 7\,\mathrm{keV}$
$T_i = 1.2\,\mathrm{keV}$
$t_d = 250\,\mathrm{ms}$

$T_e = 10\,\mathrm{keV}$
$T_i = 1\,\mathrm{keV}$
$t_d = 6\,\mathrm{s}$

10.12.2015
1. He Plasma

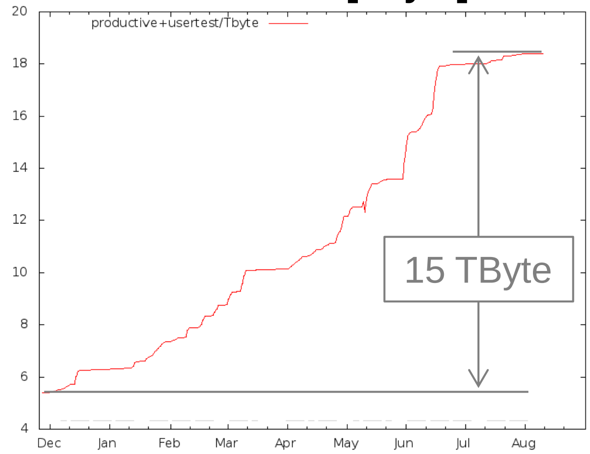
2 MJ

3.2.2016
1. H Plasma

4 MJ

10.03.2016
end of OP 1.1

Datavolume [Tbyte]



Statistics of OP 1.1

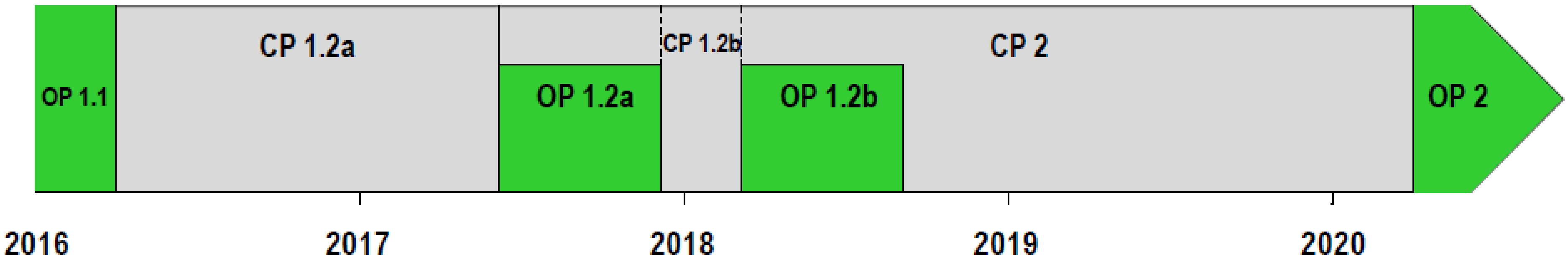
experiment type	experiment	pulses
plasma discharges	631	640
Cleaning pulses with ECRH	145	1282
test pulses	148	148
fault pulses	24	24
	948	2094

Summary

- construction of W7-X was laborious,
- but commissioning was very successful.
- the extensive QM and the FE-Modelling and have proven their value.
- the precision of assembly was important and all tolerances were kept.
- the magnetic flux surfaces have been proven to fulfill the expectations.
- the experimental operation started in December 2015 with He-plasmas.
- plasmas were dominated by impurities from the walls; slow but continuous improvement of the plasmas, measured by the length of ECRH-absorption.
- with H-plasmas duration of up to 6 s were achieved, $T_e \approx 10$ keV.
- OP 1.1 was successful with 770 experiments, no technical problems.

Thank you for your attention!

Outlook



In-vessel components for OP 1.2a

- Test Divertor Units (TDU)
- Divertor closures
- Baffle elements
- Graphite tiles
- In-vessel diagnostics

In-vessel components for OP 1.2b

- TDU scaper elements
- Diagnostics

In-vessel components for OP 2

- High-Heat-Flux divertor
- Cryo pumps
- In-vessel diagnostics
- Port protection liners