Wendelstein 7-X – a concept for a steady-state fusion plasma

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Contents

- Nuclear fusion and magnetic confinement
- Wendelstein 7-X
  - Design & construction
  - Commissioning
  - Scientific programme
- Power plant concept

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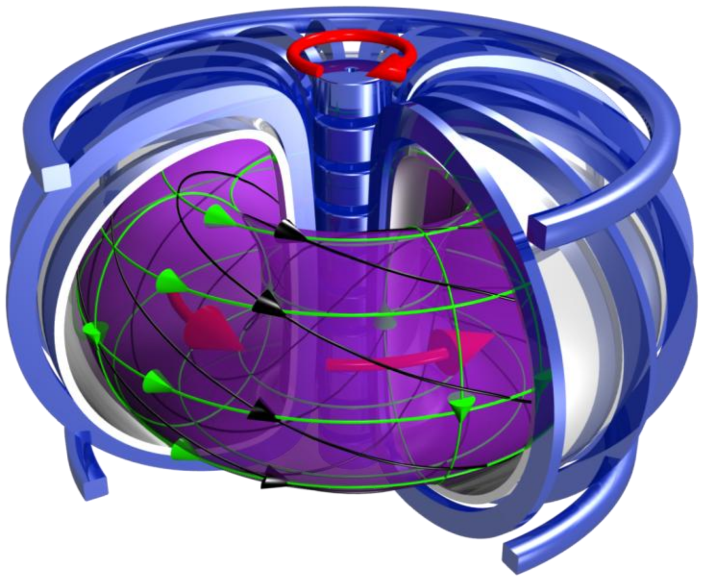
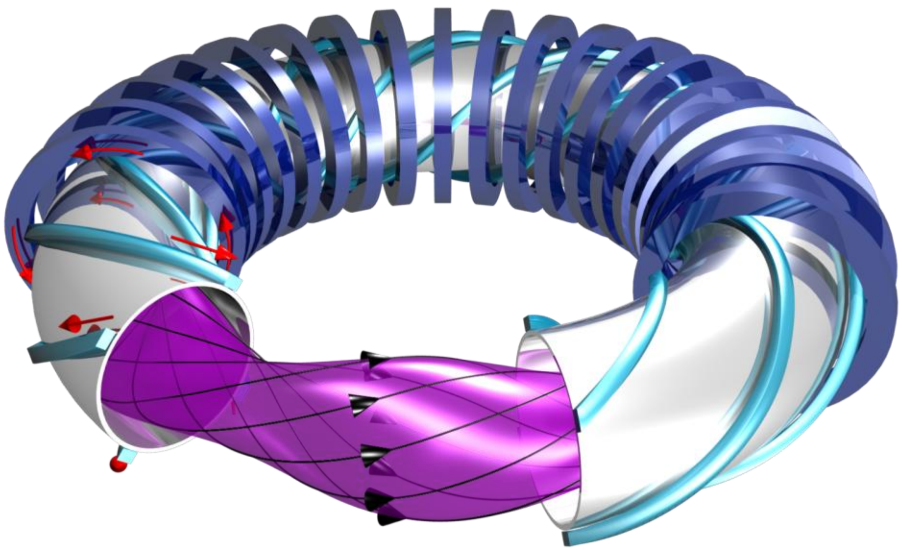
Magnetic confinement of a high-T fusion plasma

Tokamak (2D)



Large part of magnetic field by plasma current (transformer principle)

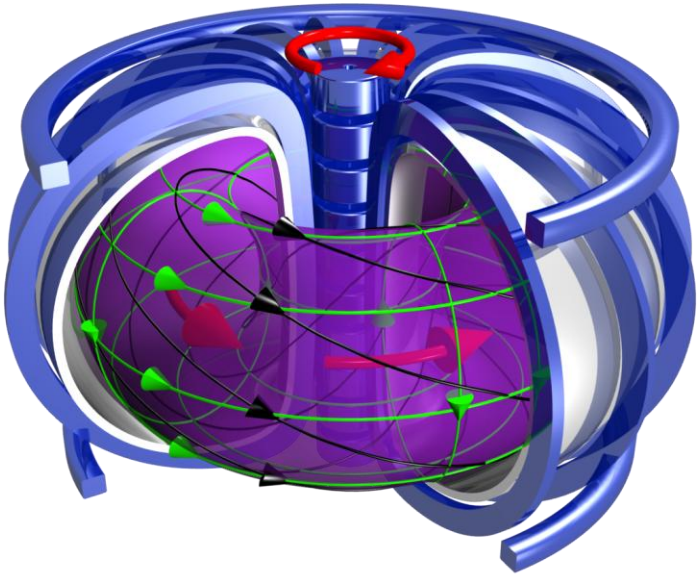
Stellarator (3D)



Magnetic field essentially by external coils

Magnetic confinement of a high-T fusion plasma

Tokamak (2D)

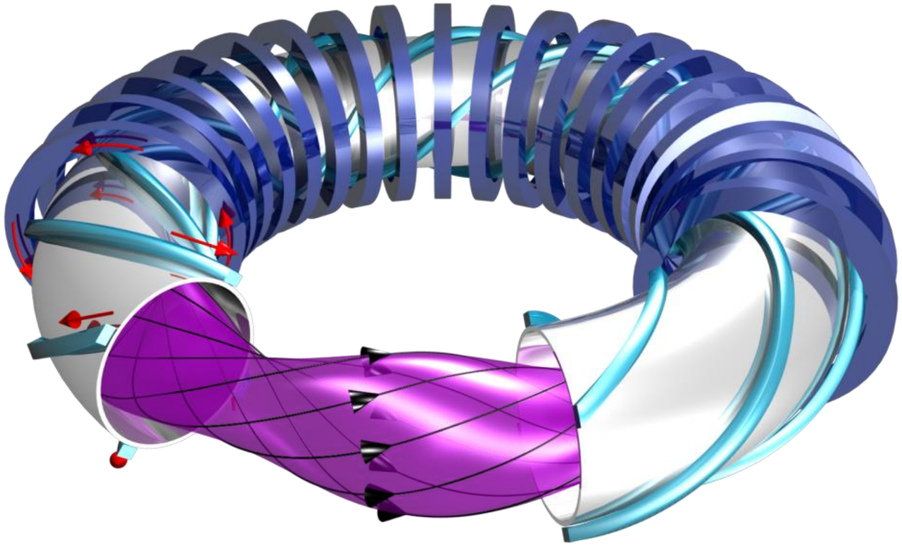


Further developed, but pulsed; steady state operation raises the question of efficiency

ITER is a tokamak

For the first time (controlled) energy production by fusion

Stellarator (3D)

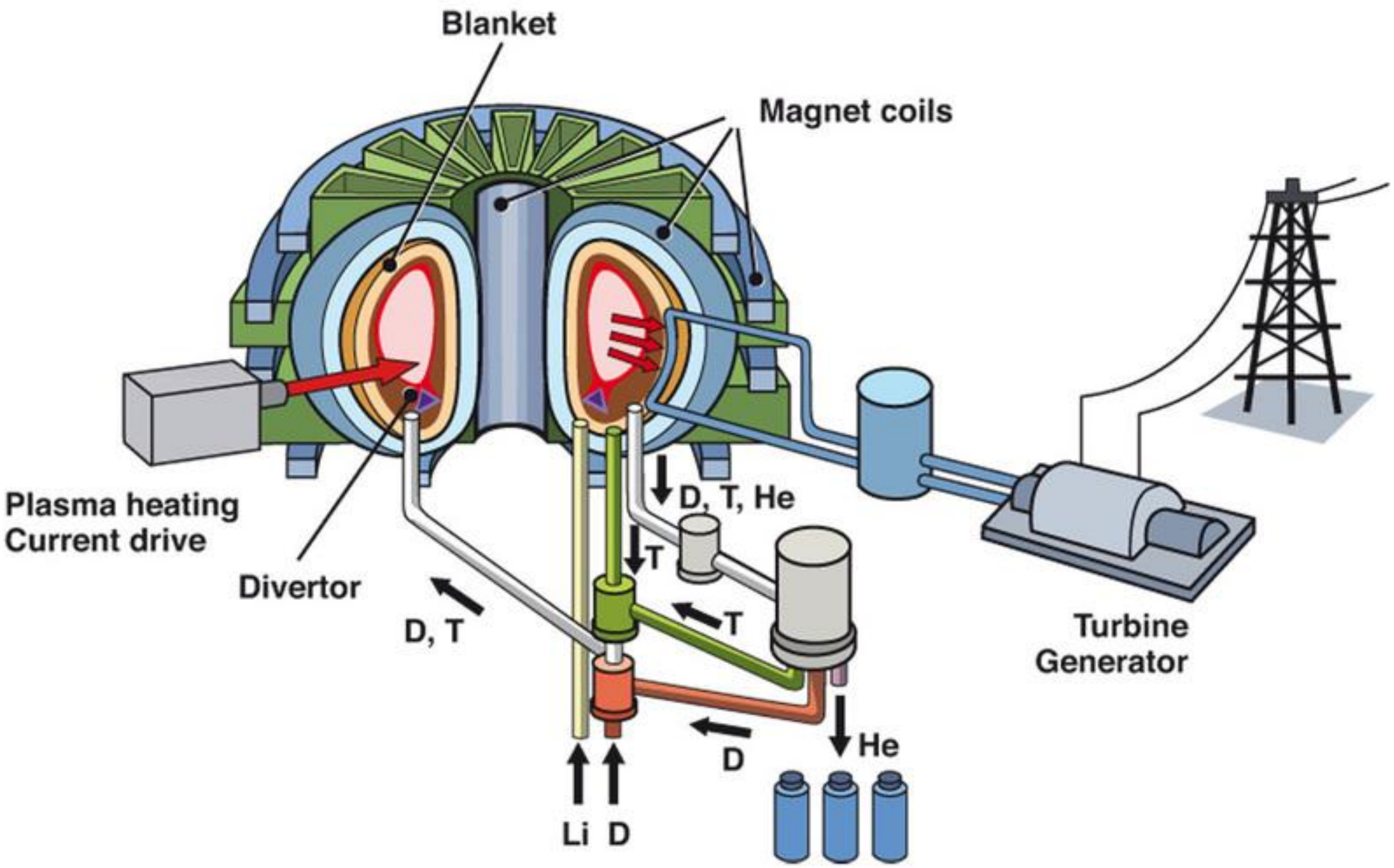


Advantageous properties for power plant (intrinsically steady state)

W7-X is a stellarator

Demonstration that plasma properties fulfil power plant requirements (tritium will not be used)

A fusion power plant



$D + T \rightarrow {}^4He$ (3.5 MeV) + n (14.1 MeV)

Optimum temperature
~ 10 keV (100 Mio. K)

Tritium breeding in a closed fuel cycle

$n + {}^6Li \rightarrow T + {}^4He$ + 4.8 MeV
($n + {}^7Li \rightarrow T + {}^4He + n'$ – 2.5 MeV)

Fusion parameters

For stability reasons $$\beta = \frac{p}{B^2/2\mu_0} \leq 5\%$$

For technical reasons $B \sim 5T$ (superconductivity, mechanical forces)

$$p \leq 5bar$$

Thus, with optimum temperature (D-T reaction) $\sim 10\ keV$

$$n \sim 10^{20} m^{-3}$$

From power balance triple product (D-T fusion)

$$nT\tau_E > 3 \cdot 10^{21} keV m^{-3} s$$

Thus (measure for heat insulation)

$$\tau_E > 3s$$

$Q = P_{fusion}/P_{heating} \sim 30$

and $\tau_E \sim 3\ s$

$P_{thermal} = P_{fusion} \sim 3\ GW$

$P_{electric} \sim 1\ GW$

Fusion parameters

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Achieved

$T > 10$ keV ✓

$n > 10^{20}$ m^{-3} ✓

$\tau_E \sim 1$ sec × 10

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IPP

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Wendelstein 7-X – objectives

The objectives of W7-X are to demonstrate the power plant capability of the stellarator concept

– Good plasma confinement up to fusion relevant temperatures (several keV) and densities (> 10^{20} m^{-3})
– Steady state plasma operation (30 minutes) and heat exhaust at 10 MW of heating power and $\langle \beta \rangle = 5\%$

→ **Requires dedicated physics optimization to overcome deficiencies of classical stellarator (no D-T operation)**

Wendelstein 7-X – physics optimization

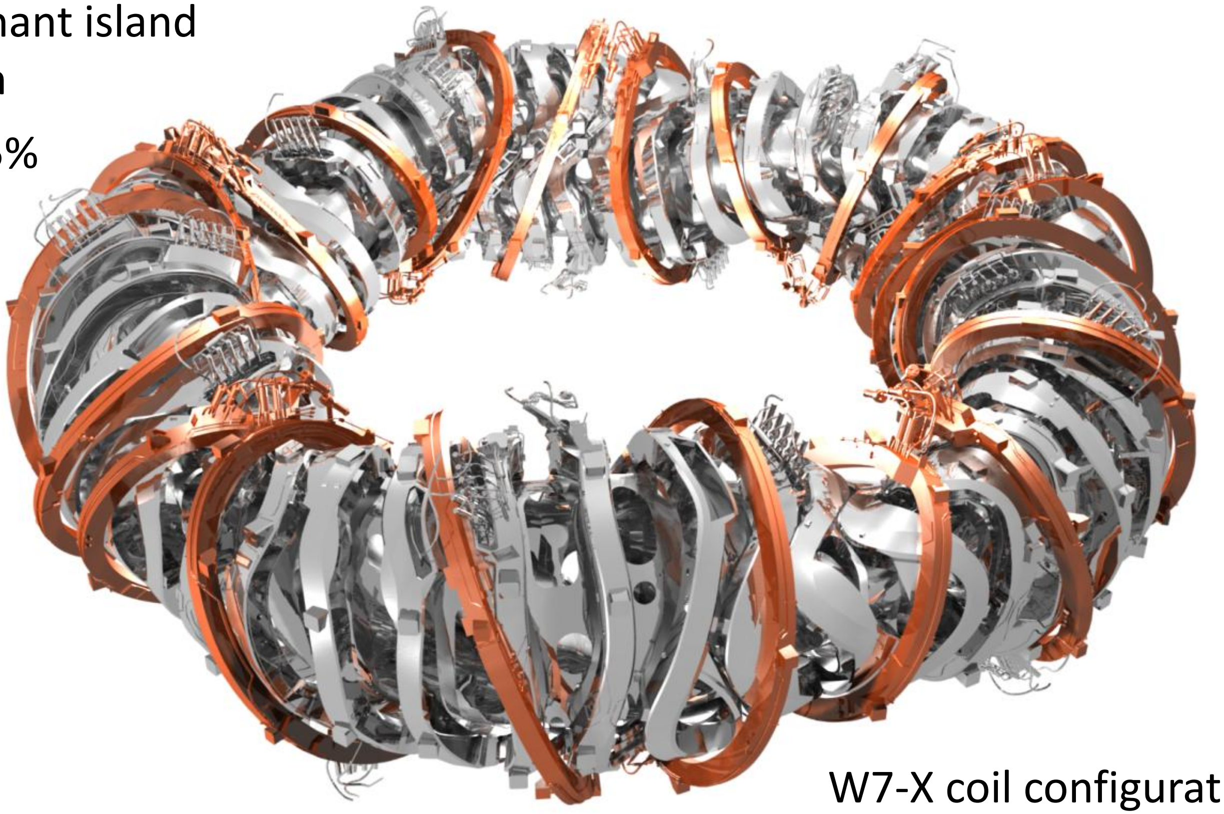
A specially tailored magnetic field to provide

– Good plasma confinement (fast ions and thermal plasma)

– Minimize plasma currents to decouple magnetic field configuration as much as possible from plasma pressure

– Required for 3D resonant island divertor configuration

– Stability up to <β> = 5%



W7-X coil configuration

Wendelstein 7-X – design

Magnetic field
3 T

Superconducting coils
70

Cold mass
425 t

Magnetic field energy
600 MJ

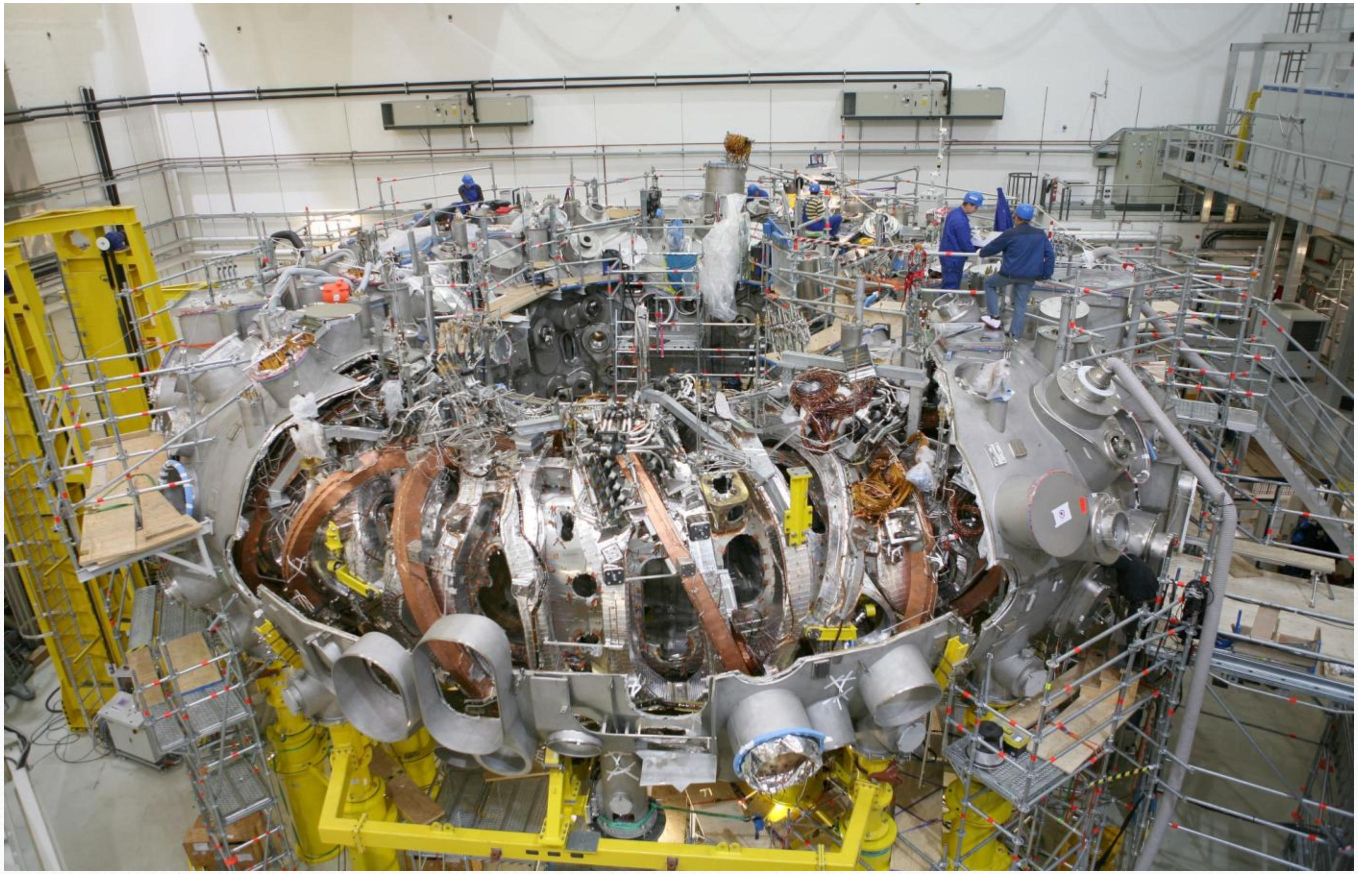
Plasma volume
30 m^3

Plasma duration
30 minutes

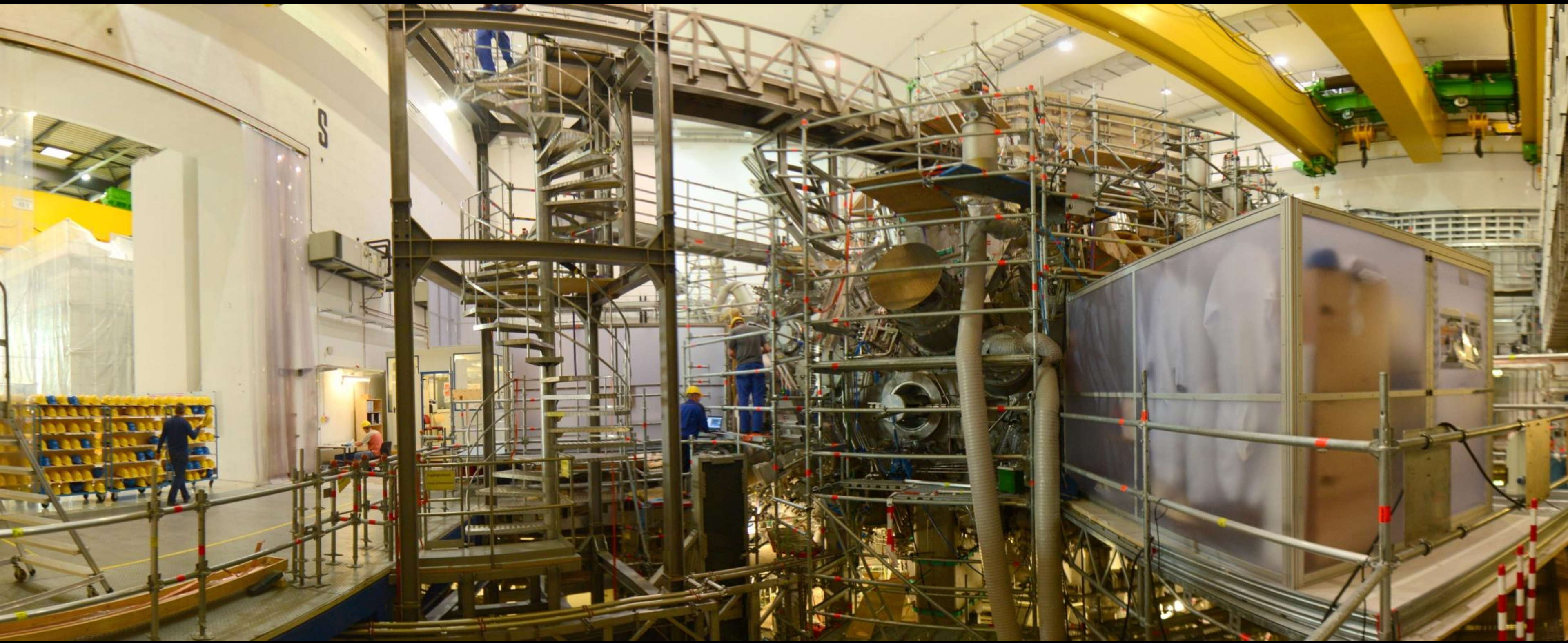
Heating power
10 MW (30 MW)

Maximum heat load
10 MW/m^2

November 2011

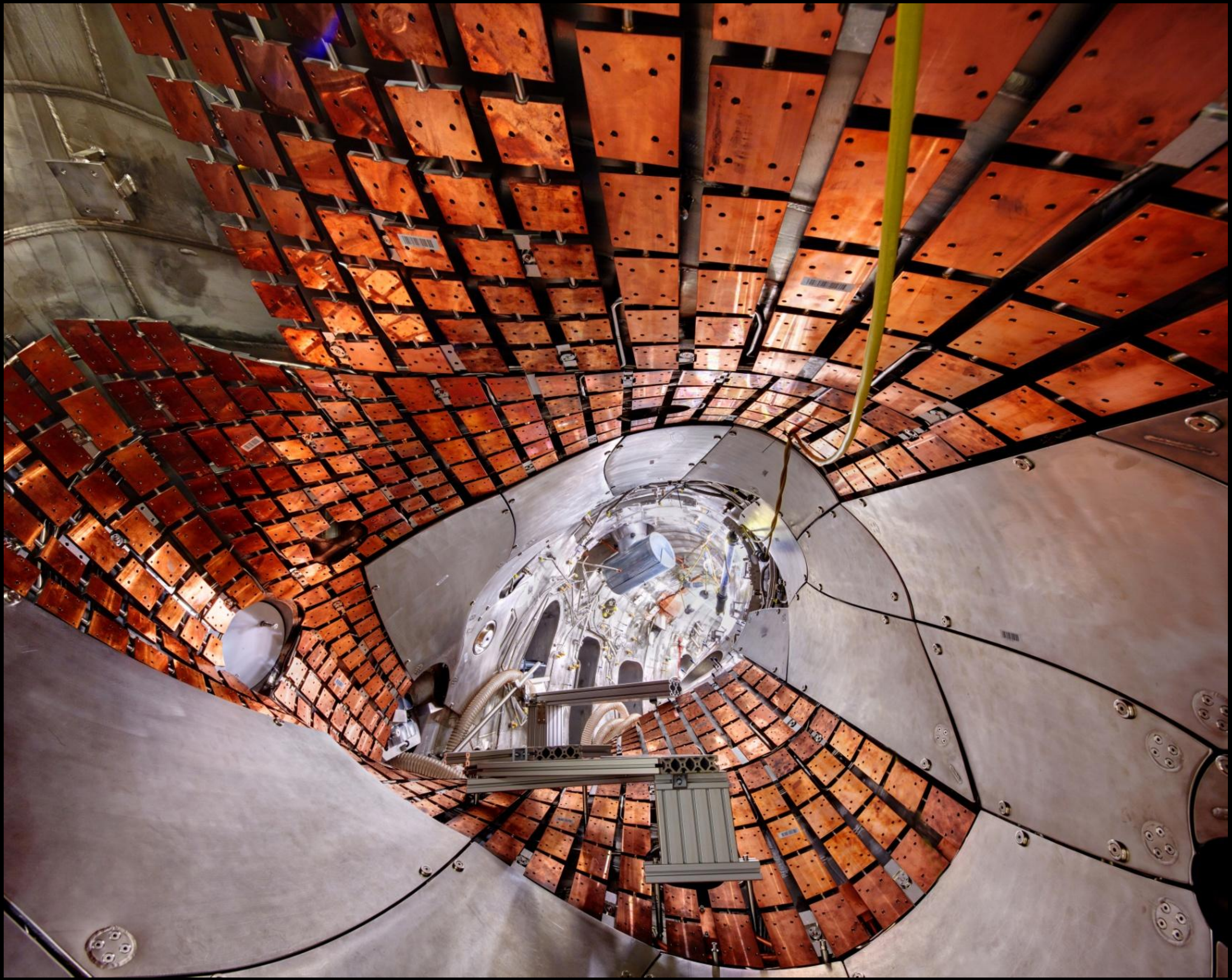


Construction of main components completed in 2014



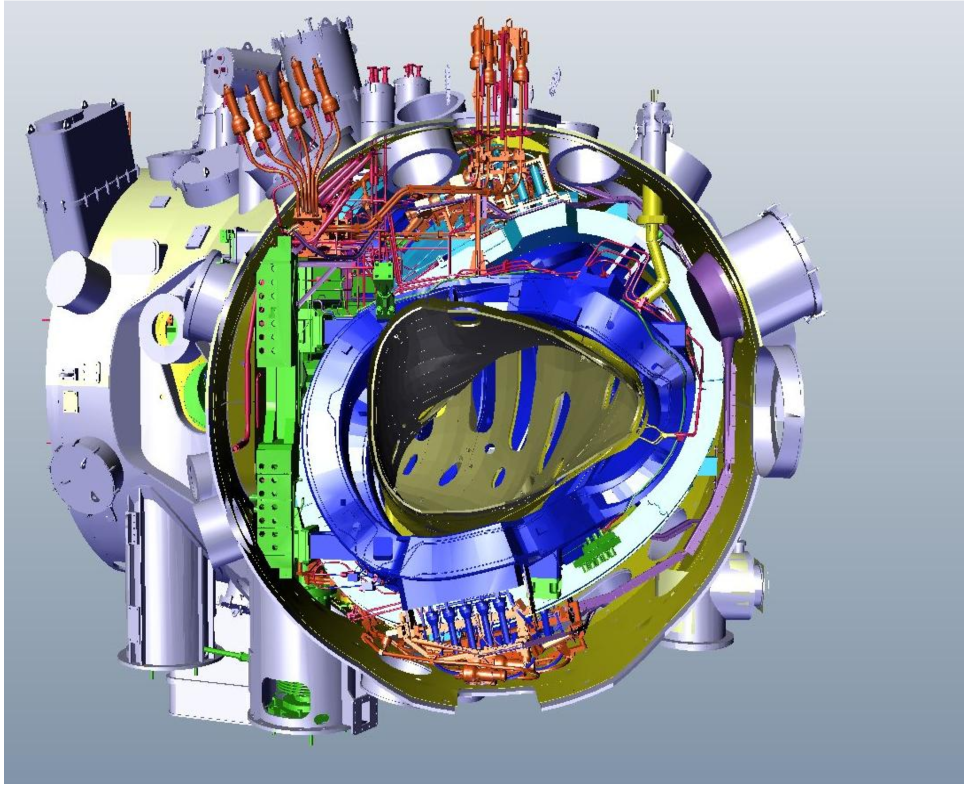
Courtesy G. Wurden, July 2014

Inside the plasma vessel (2015)

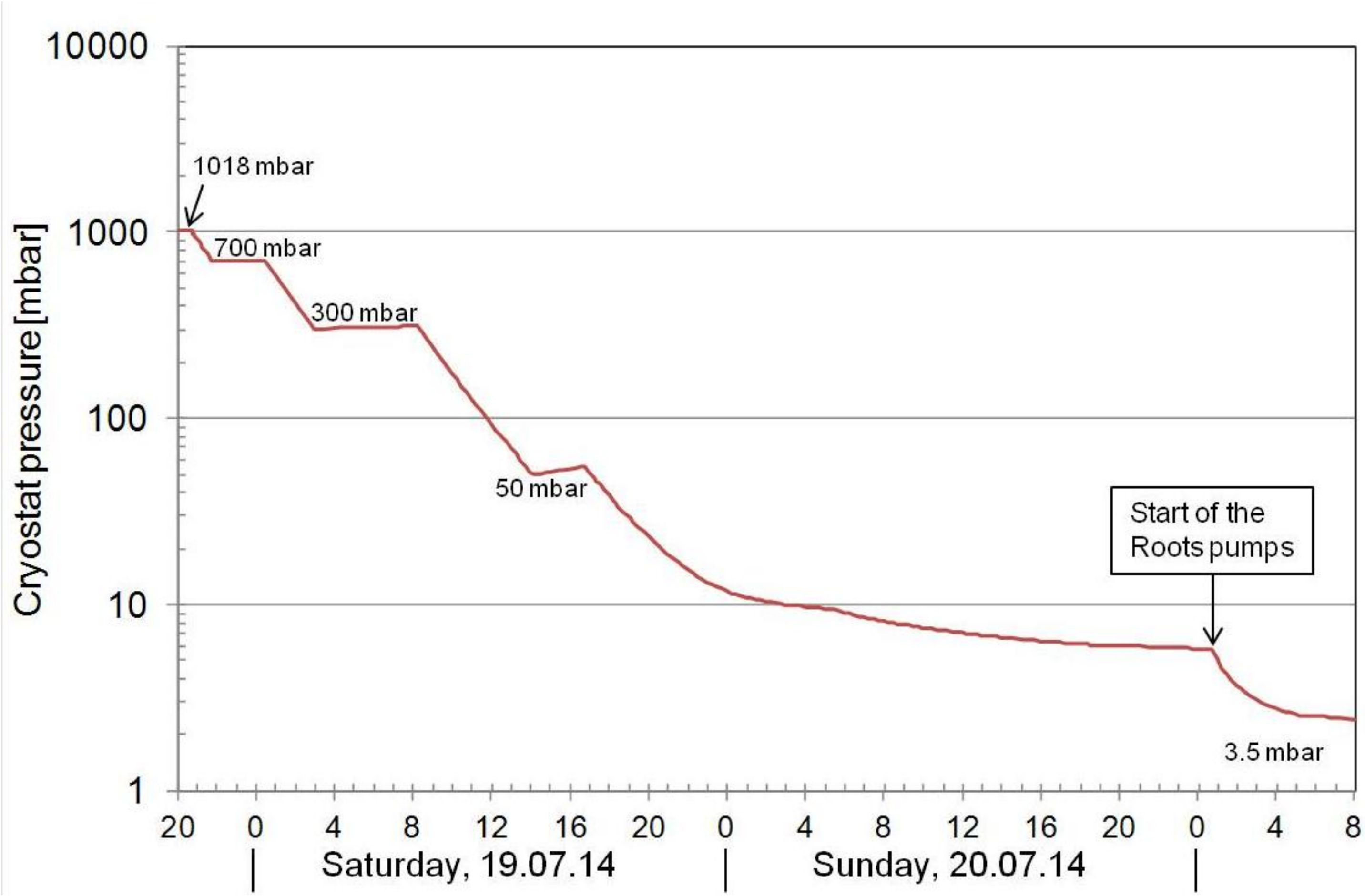


Commissioning (April 2014 – August 2015)

- Pumping of cryo-vacuum
  - Volume ~ 380 m^3
  - Surface ~ 1100 m^2 (× 100)
- Cool-down
  - Coils, coil casings, coil support structure, current-leads, cold-shields
- Pumping of plasma vessel including ports (for pumping, water-cooling, plasma heating, plasma diagnostics)
- Commissioning of superconducting coils
- Ramp-up magnetic field to 2.5 T
- Preparation of plasma operation
  - Baking of plasma vessel
  - Plasma diagnostics
  - Heating system

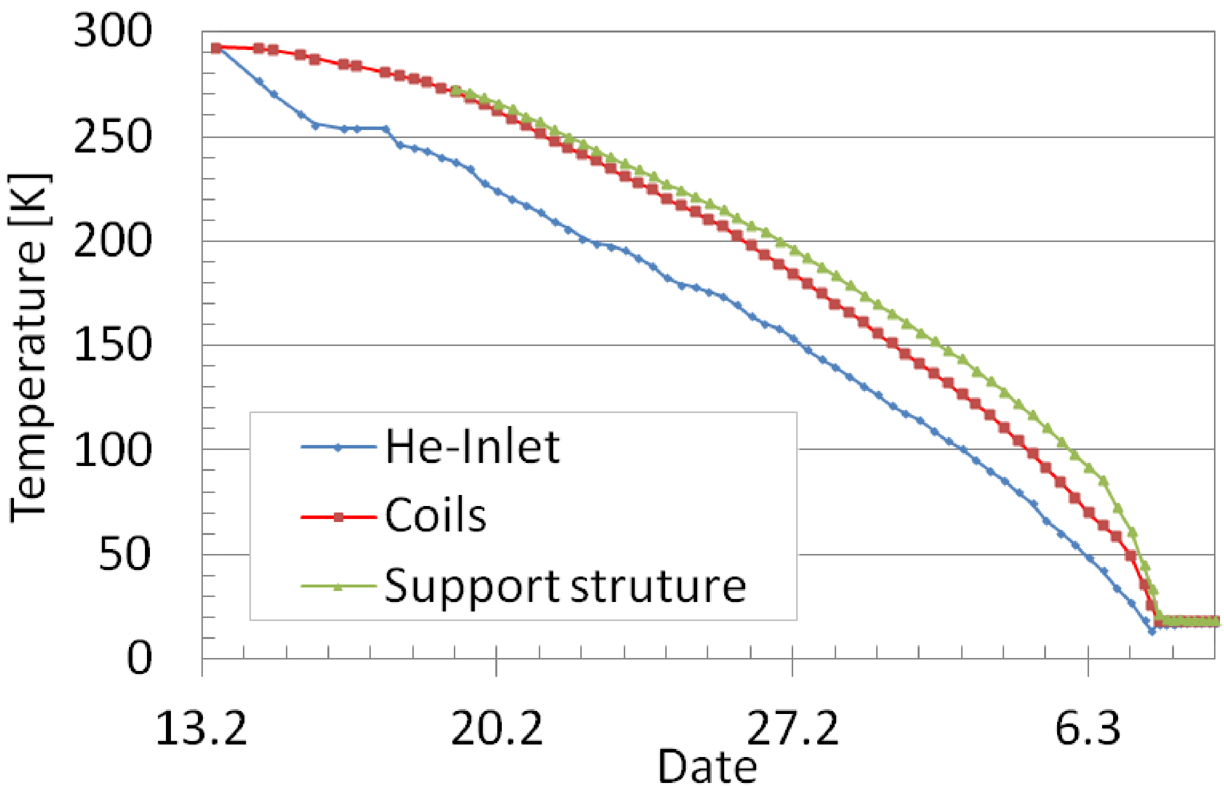


Pumping of cryo-vacuum



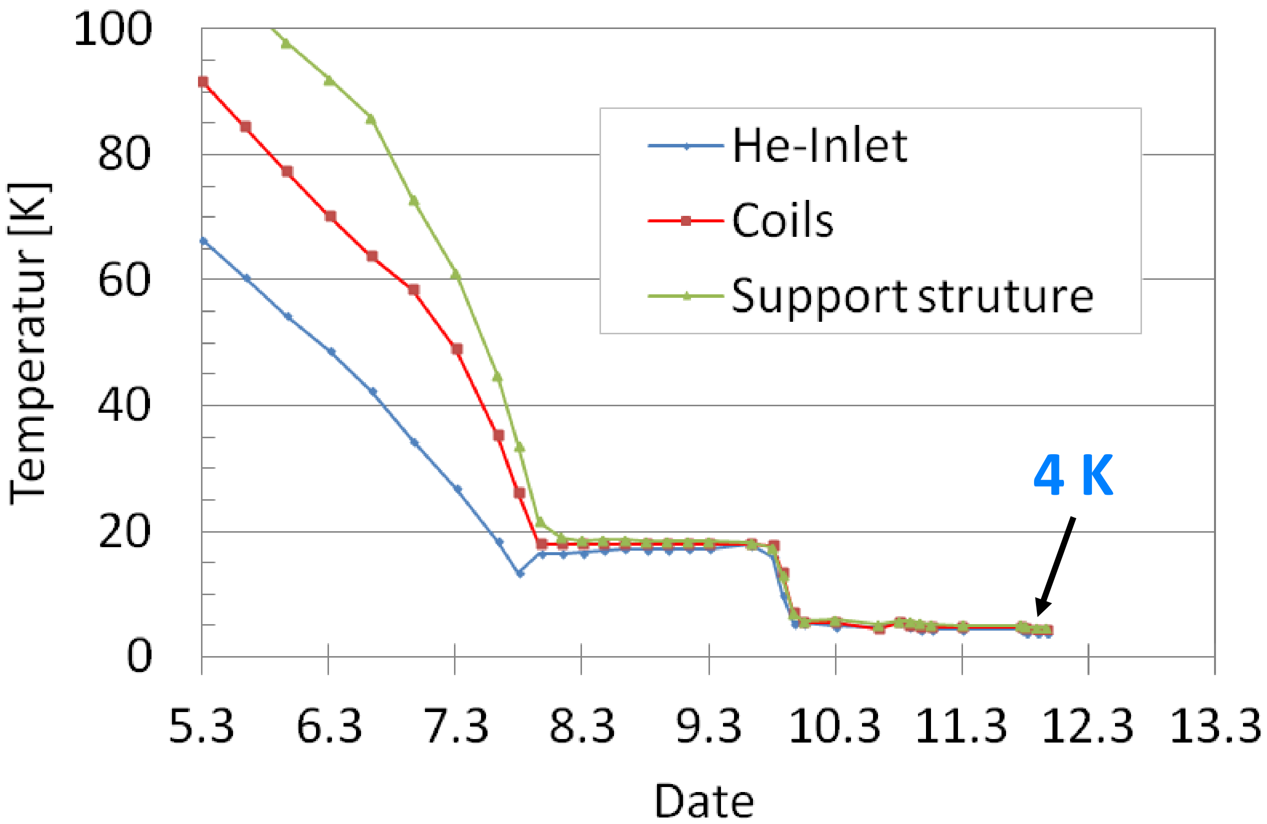
- Extensive leak search, 30 leaks identified and repaired
- Pressure steps correspond to measurements of vessel deformation

Cool-down

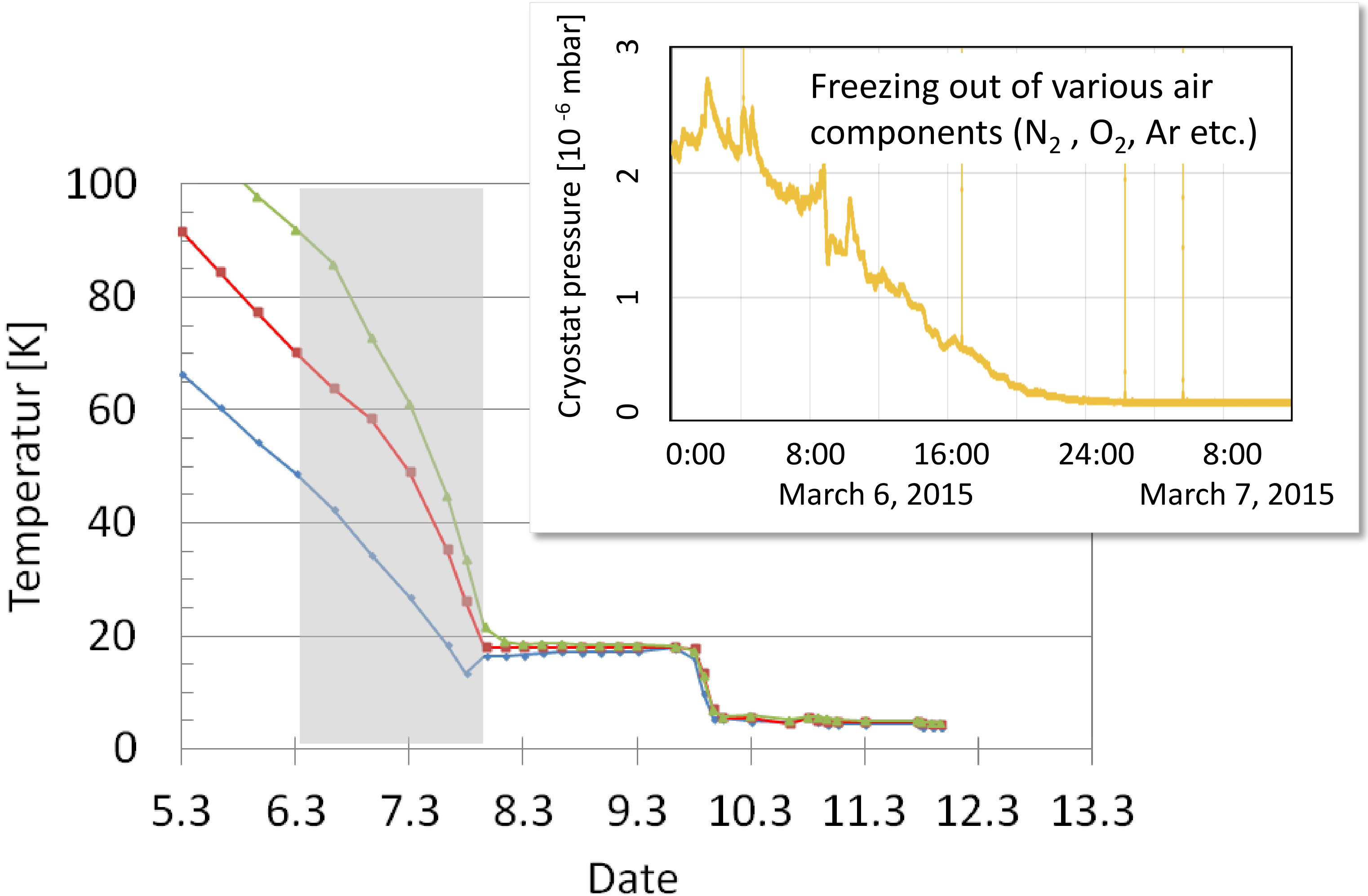


Thermal shrinking of coil structure results in inward movement of cryo-feet by several cm

Cool-down


100
80
60
40
20
0
Temperatur [K]
5.3
6.3
7.3
8.3
9.3
10.3
11.3
12.3
13.3
Date
He-Inlet
Coils
Support struture
4 K

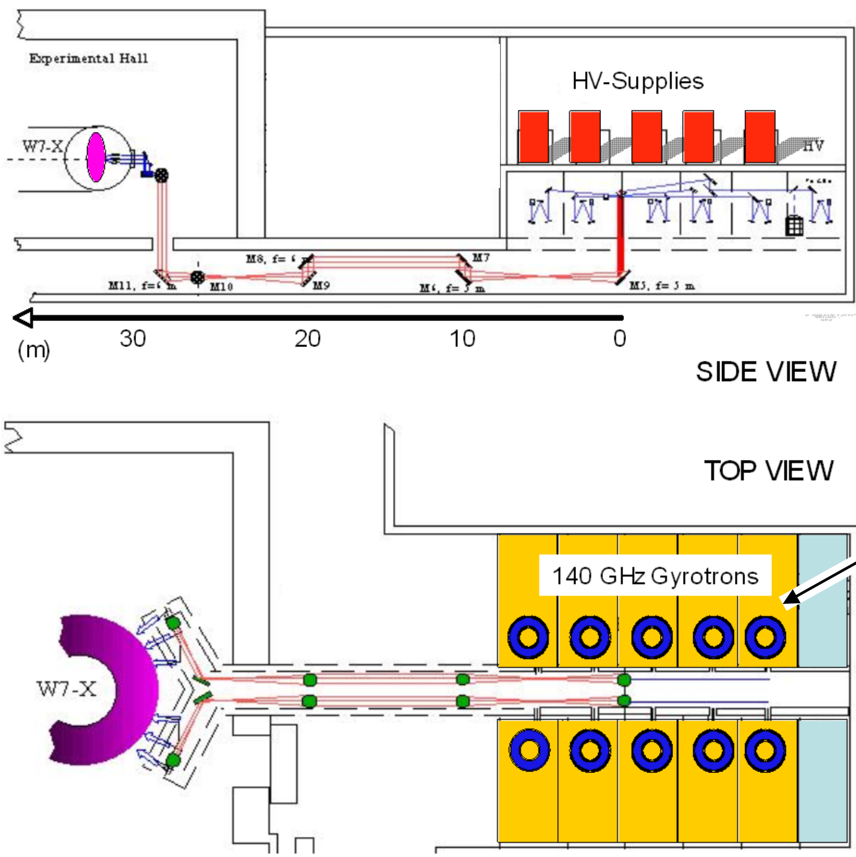
Cool-down

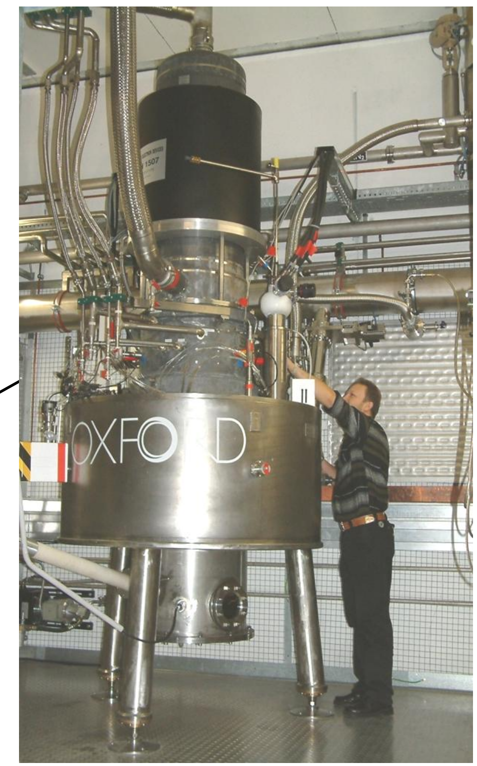


Cryostat pressure [10⁻⁶ mbar]
3
2
1
0
Freezing out of various air components (N2 , O2, Ar etc.)
0:00
8:00
16:00
24:00
8:00
March 6, 2015
March 7, 2015
100
80
60
40
20
0
Temperatur [K]
5.3
6.3
7.3
8.3
9.3
10.3
11.3
12.3
13.3
Date

Test and alignment of heating system

- Resonant heating of plasma electrons with micro-waves at 140 GHz / 2.5 T
- 6 micro-wave tubes (gyrotrons) commissioned and aligned, corresponding to 5 MW
- 10 cw-gyrotrons and up to 10 MW will be available in 2016
- Power transmission by optical system: overall loss ~ 7%





1 MW / 140 GHz cw-gyrotron

Test and alignment of heating system

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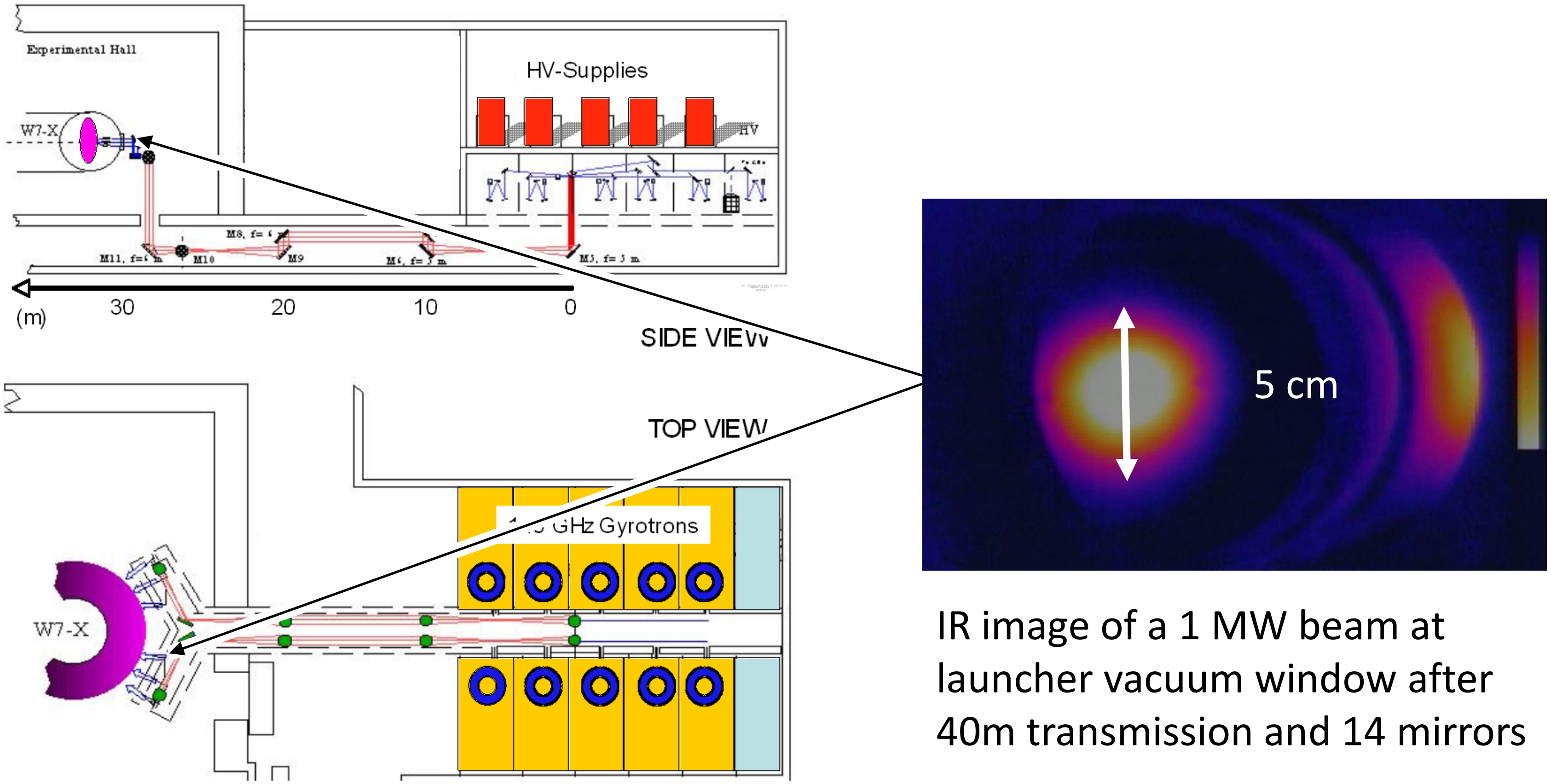


IR image of a 1 MW beam at launcher vacuum window after 40m transmission and 14 mirrors

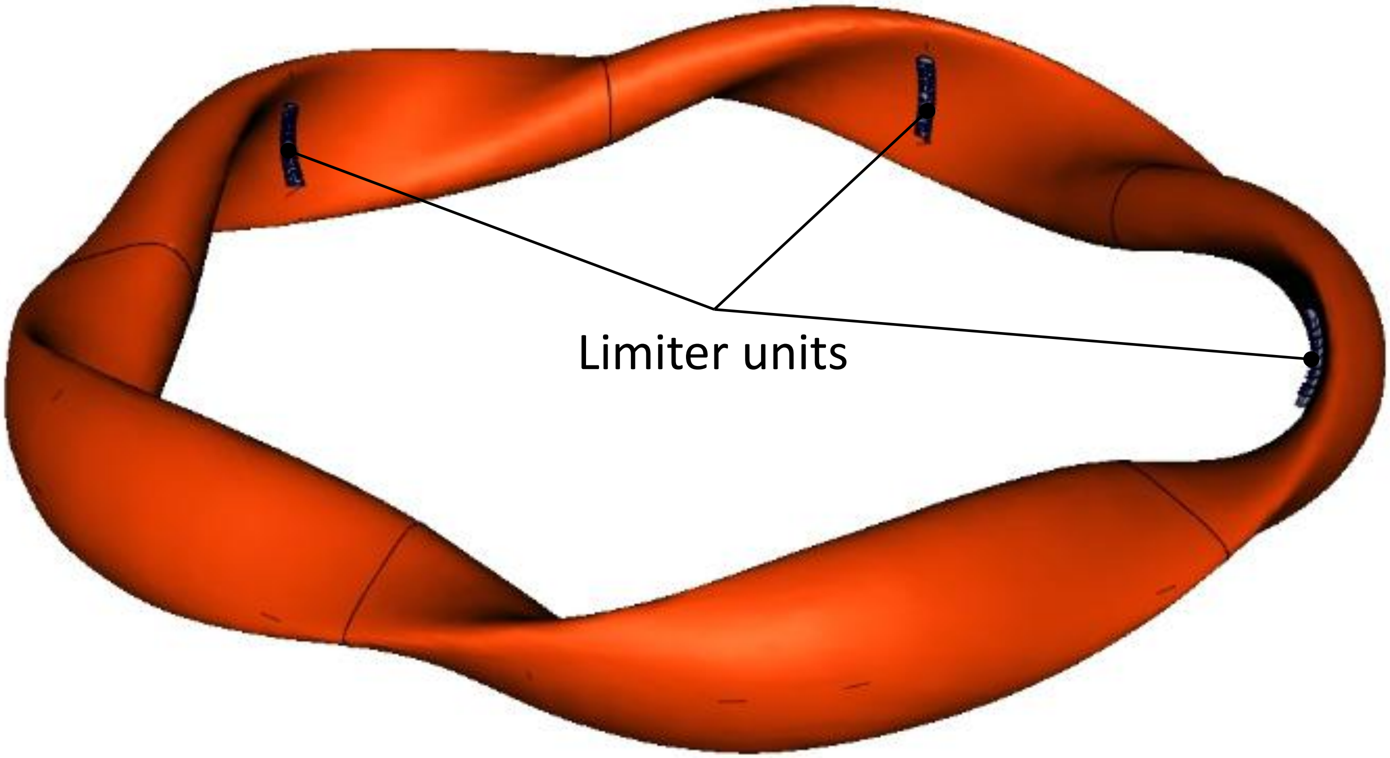
Scientific programme towards steady-state operation

2015	**Limiter configuration**	P < 5 MW
	Pulse limit	T_e (T_i) < 3 keV (1 keV)
	$\int P\,dt \leq 2$ MJ	n < 0.2 x 10^{20} m^{-3}
	τ_{pulse} **~ 1 s**	β < 1.6 %

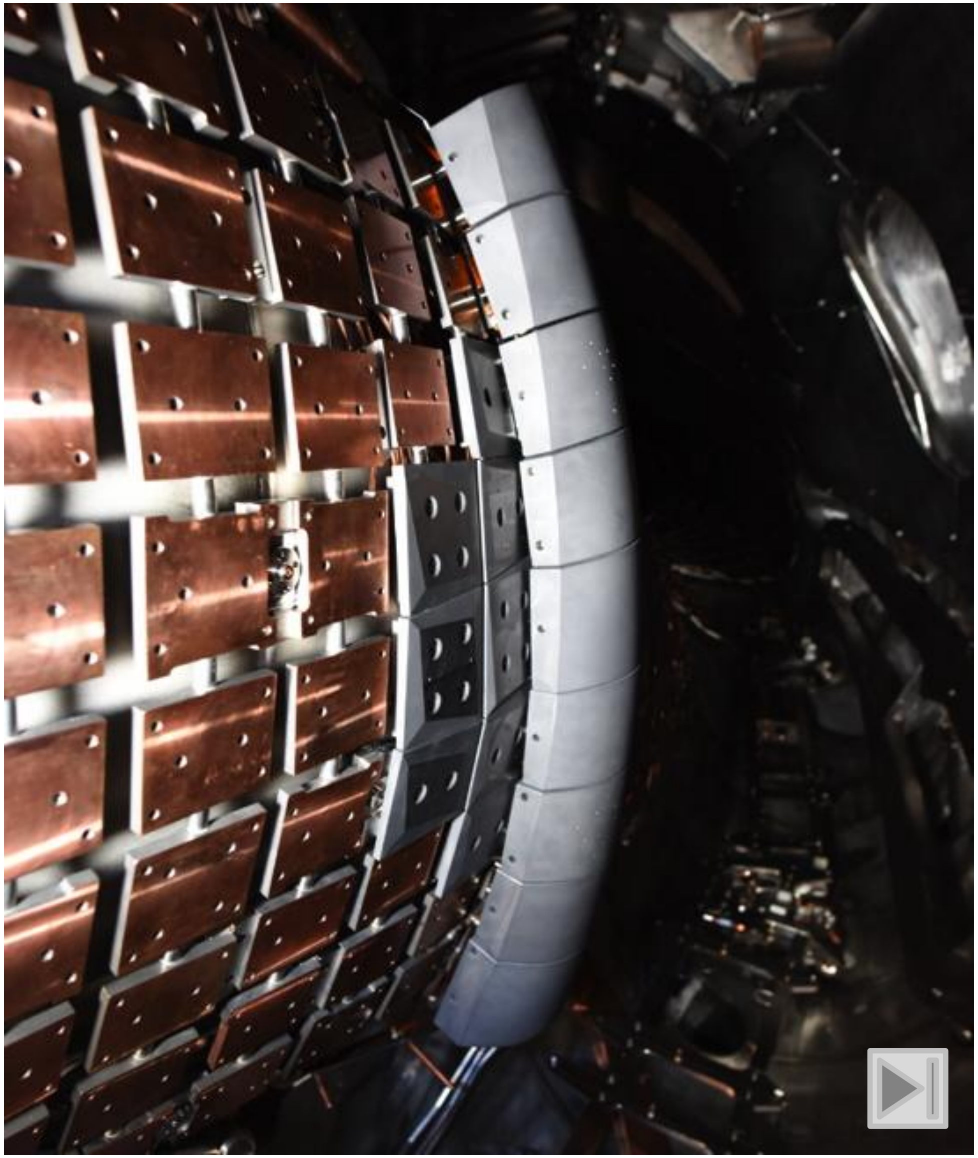
2016 / 2017	**Uncooled divertor configuration**	P ≤ 10 MW
	Pulse limit	T_e, T_i < 3 keV
	$\int P\,dt \leq 80$ MJ	n < 1.6 x 10^{20} m^{-3}
	τ_{pulse} **~ 10 s** (... 60 s @ reduced power)	β < 3 %

> 2019	**Steady-state operation**	P_{cw} ~ 10 MW
	Actively cooled divertor configuration	P_{pulse} ~ 20 MW (10 s)
	P/A ≤ 10 MW/m^2	T_e, T_i < 5 keV
	Technical limit **30 minutes** @ 10 MW	n < 2.4 x 10^{20} m^{-3}
		β < 5 %

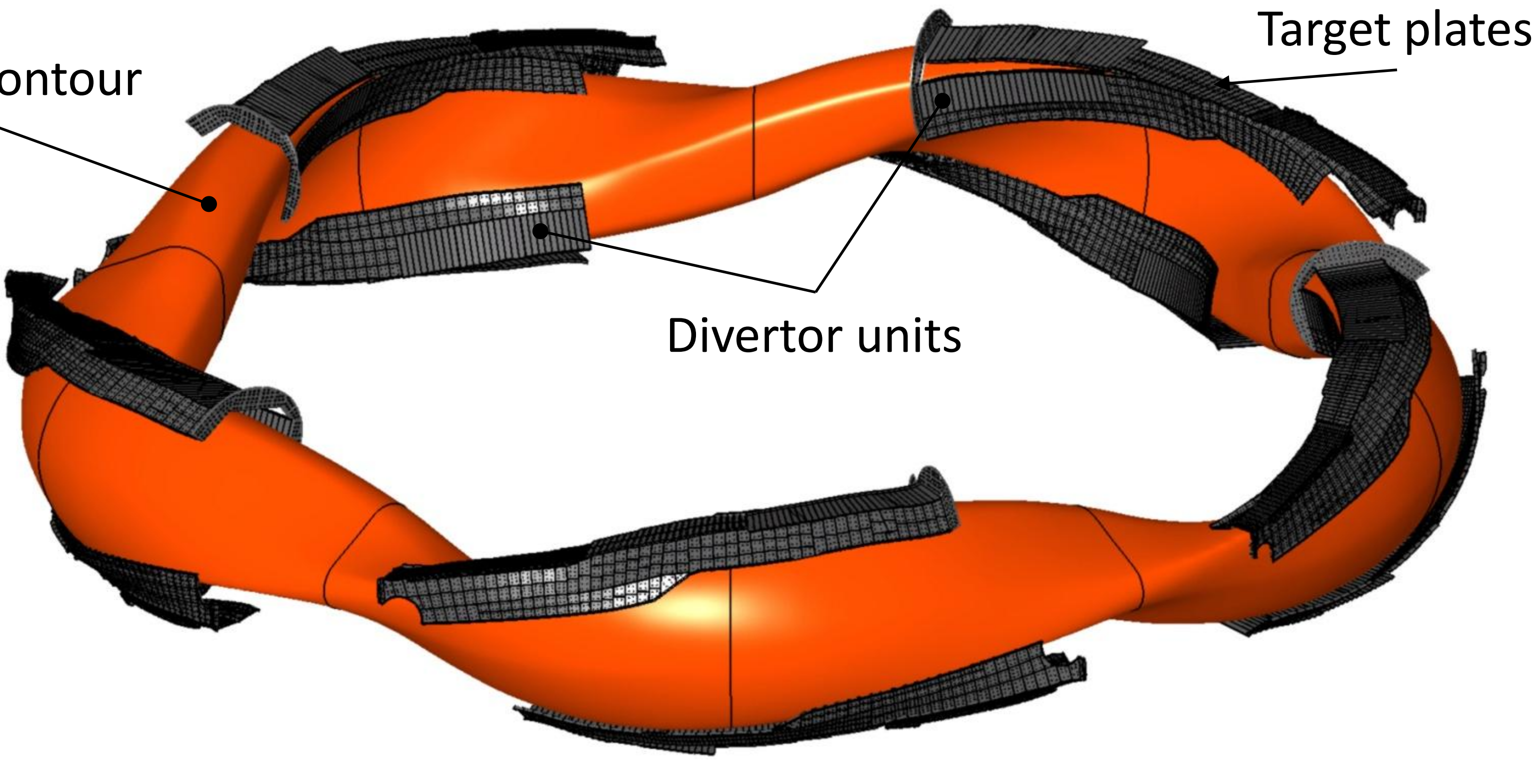
Limiter configuration



Limiter units



Divertor configuration



Target plates intersect magnetic islands at plasma boundary

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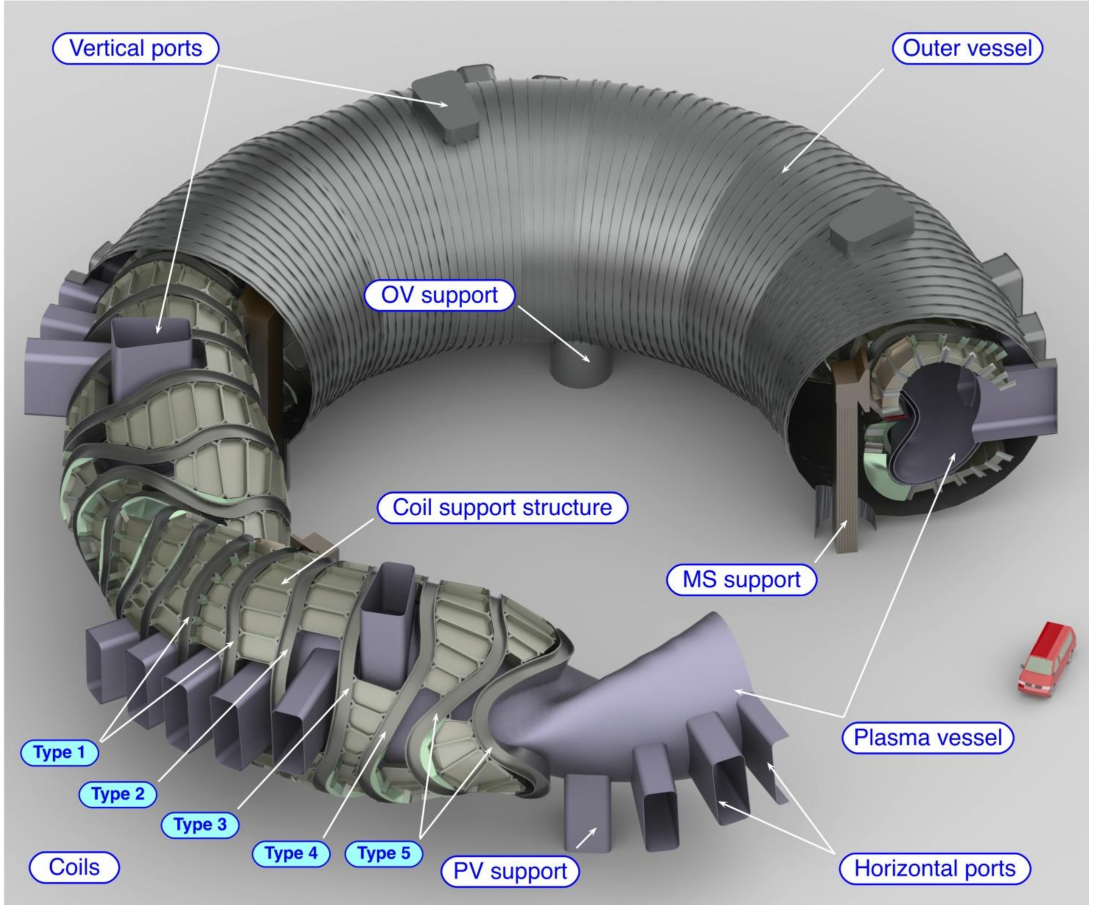
Extrapolation from Wendelstein 7-X to a power plant

Requirements / parameters

- Average magnetic field on axis 5 – 6 T (max. at coils 10 – 12 T)
- Size of coils and magnetic field similar to ITER (use of ITER coil technology)
- Sufficient space for blanket (~1.3 m between plasma and coils)
- <β> = 4 – 5 % (W7-X value!)
- Fusion power ~ 3GW
- Advantage of large aspect ratio: reduced neutron flux to the wall (average 1 MW/m^2, peak 1.6 MW/m^2)



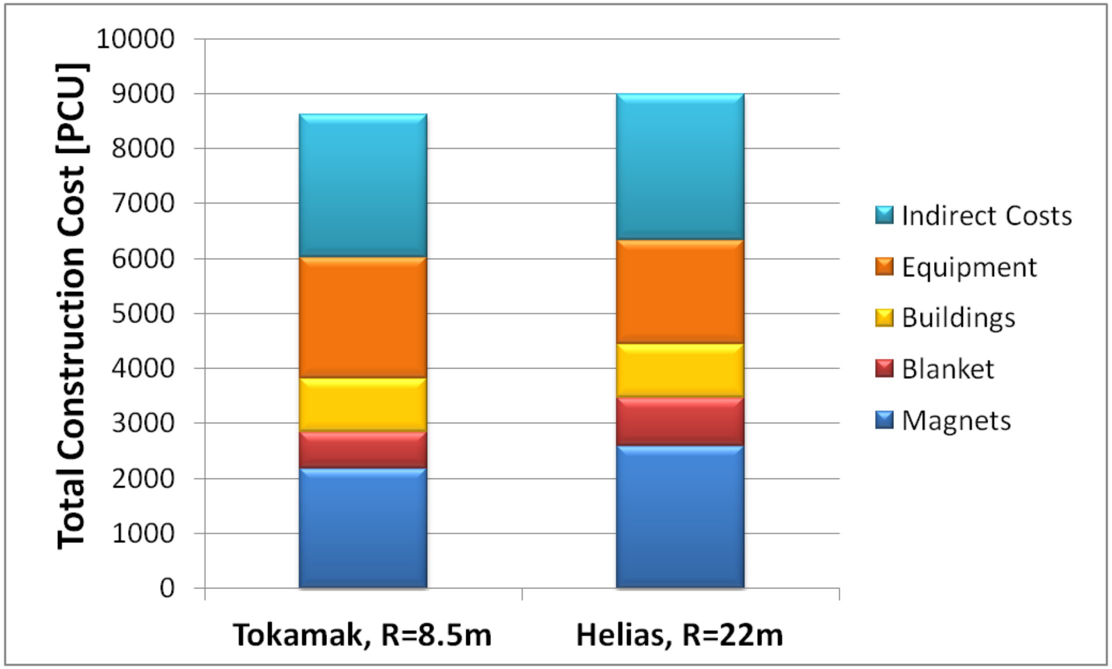
System code (PROCESS) adapted to stellarator

IPP

Adaptation includes: Plasma geometry, magnetic field coils, heat exhaust (divertor), plasma transport

Cost breakdown (share of total construction cost, from F. Warmer et al.)

Device	Tokamak	Helias
Equipment	26%	21%
Buildings	11%	11%
Magnets	25%	29%
Blanket	8%	10%
Indirect	30%	30%
Cold Mass	40kt	44kt
SC Mass	1.8kt	~2.9kt



→ Stored magnetic energy higher in tokamak than in stellarator (Helias)

→ Re-circulating power expected to be lower, because of steady-state magnetic field

Conclusions

- Wendelstein 7-X commissioning is progressing
- First plasma is expected in the second half of 2015
- Scientific programme is aligned to completion of plasma facing components
- Full steady-state capability will be achieved by 2019 / 2020
- The objective of Wendelstein 7-X is to demonstrate the power plant capability of the stellarator concept
  - ➢ Relevant plasma performance
  - ➢ High power steady state operation
  - ➢ Development of fully integrated plasma scenarios for extrapolation to a fusion power plant