Wendelstein 7-X: first experience with the cryogenic system

Presented by: Chandra Prakash Dhard

Chandra Prakash Dhard, Michael Nagel, Sylvio Raatz, Holger Bau, Uwe Meyer, Konrad Riße, Thomas Rummel and W7-X team

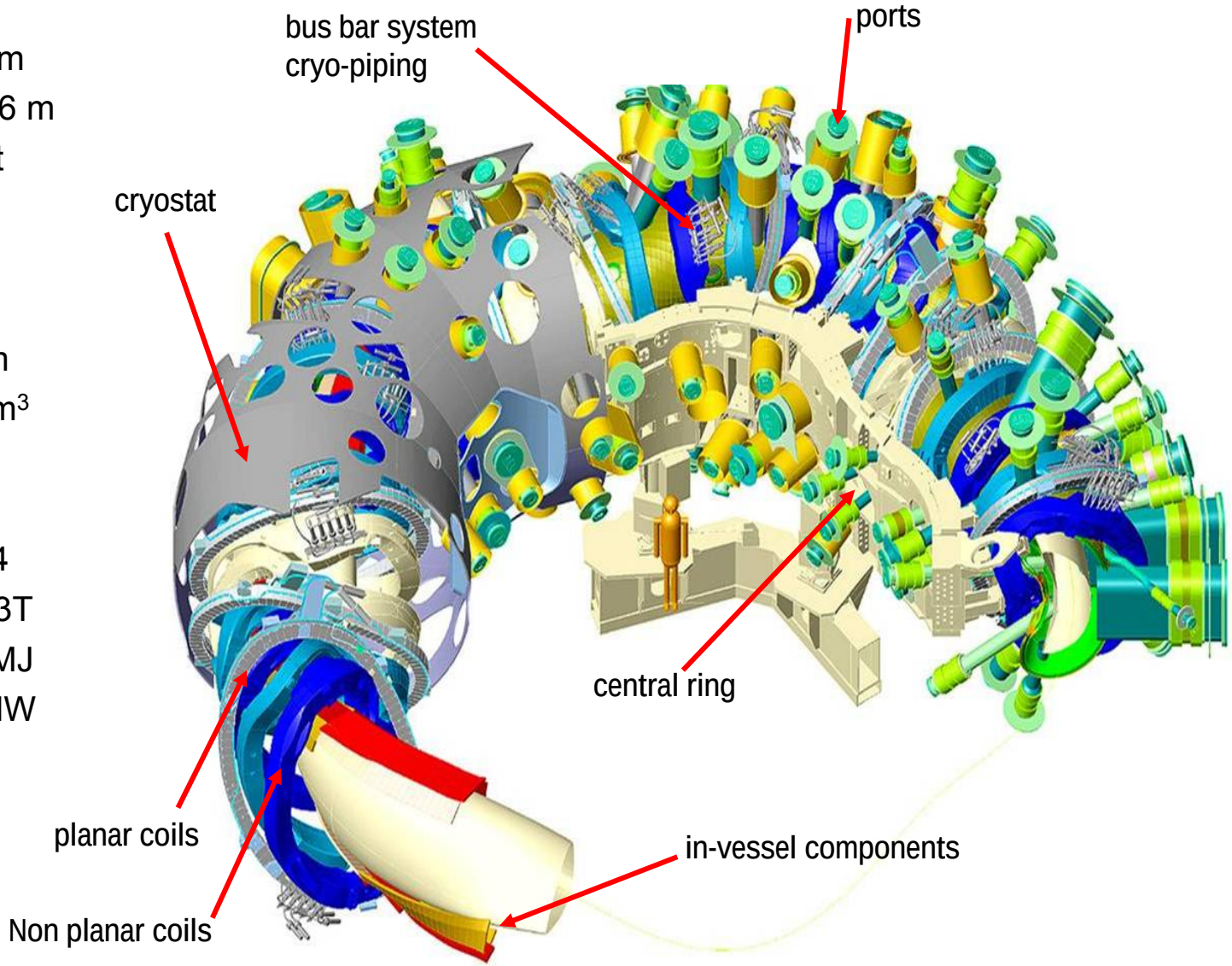
Max-Planck-Institut fuer Plasmaphysik
Wendelsteinstrasse 1, 17491 Greifswald, Germany

Contents

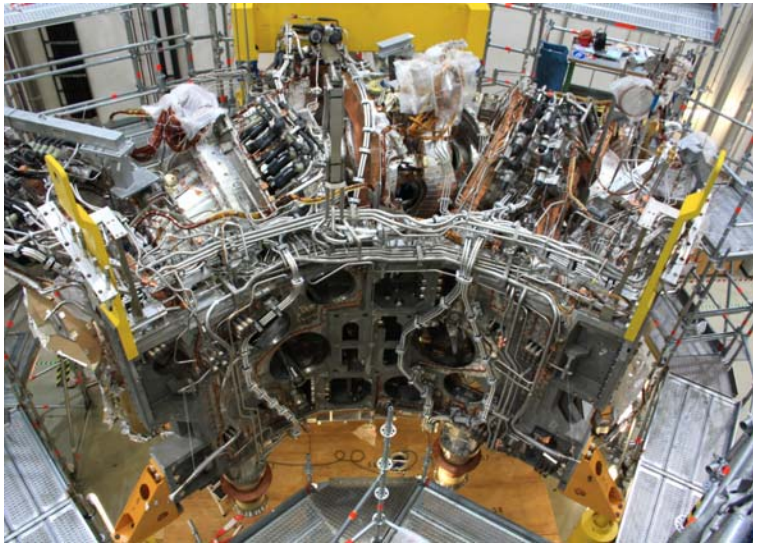
1. Introduction W7-X Stellerator overview

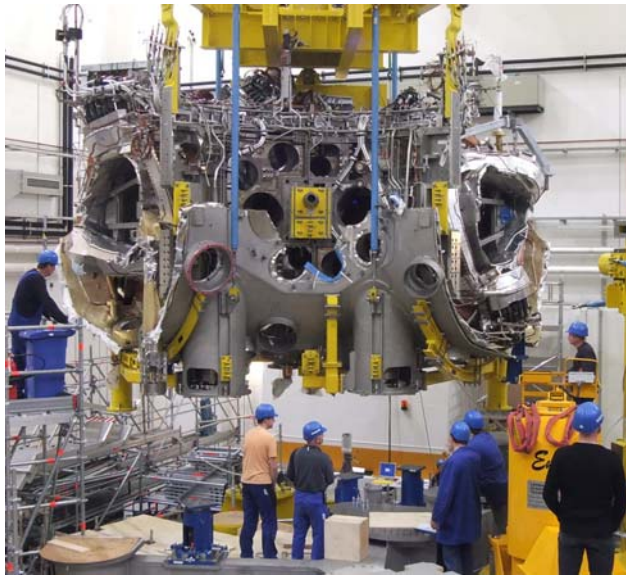
Machine height:4.5 m
Machine diameter:16 m
Machine mass:725 t
Cold mass:425 t

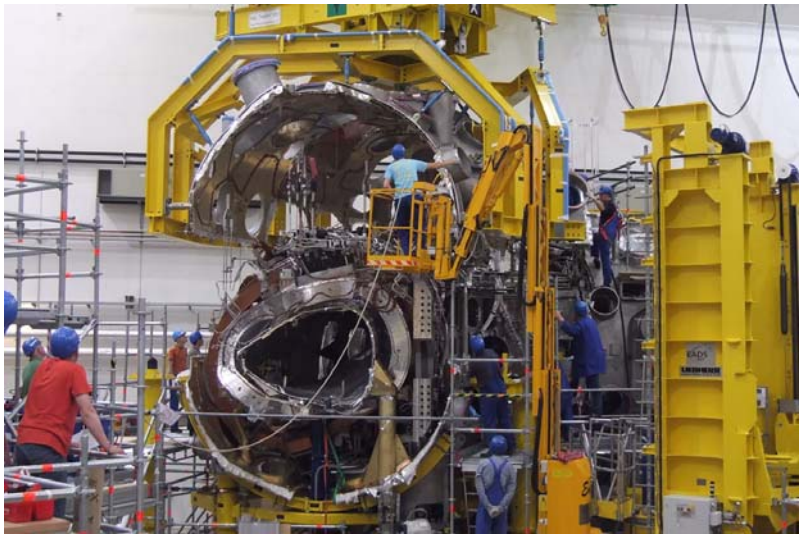
Major radius: 5.5 m
Minor radius: 0.53 m
Plasma volume:30 m^3
Non-planar coils:50
Planar coils:20
Number of ports:254
Induction on axis:< 3T
Stored energy:600 MJ
Heating power:10 MW
Duration: 30 min



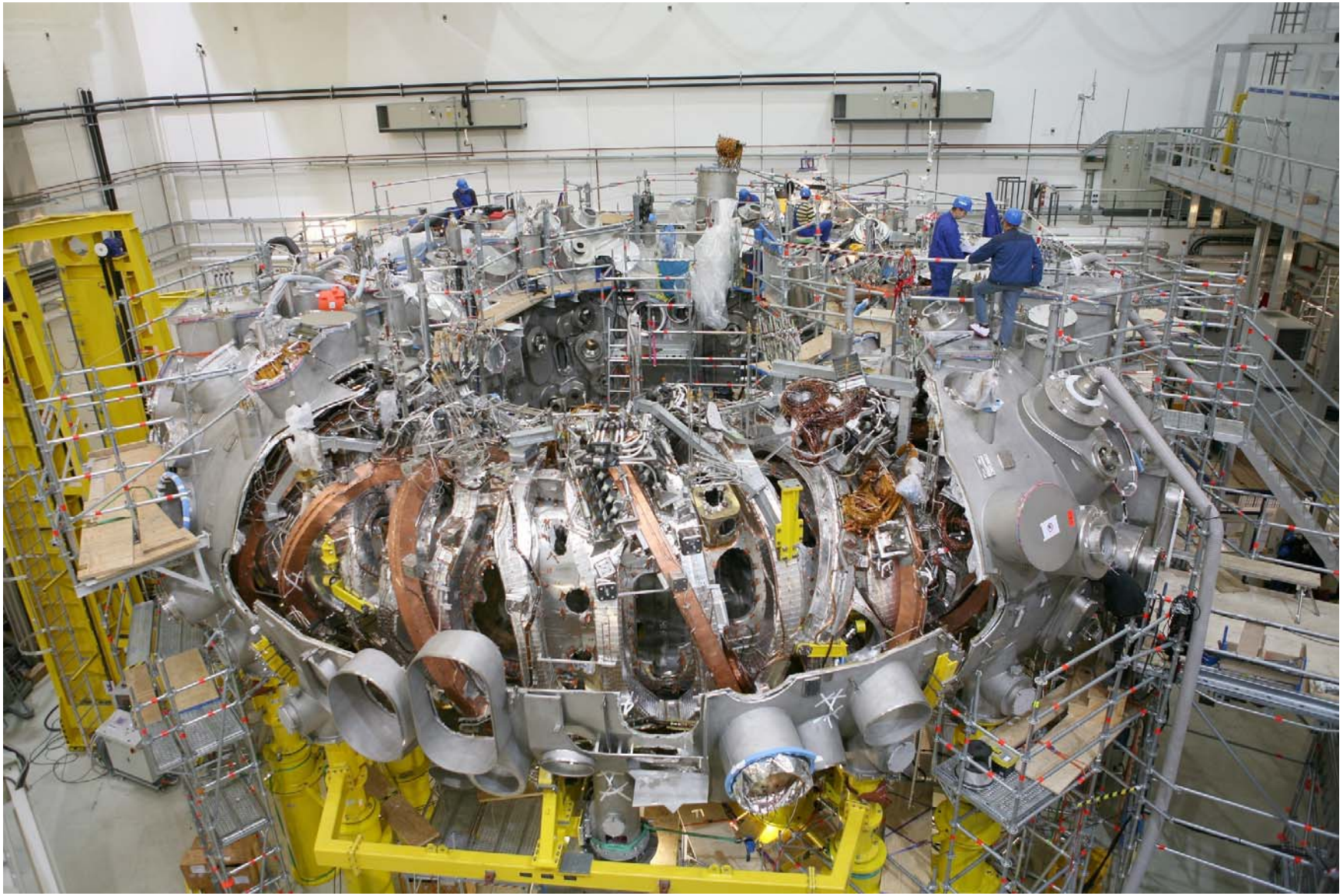
1. Torus assembly sequence



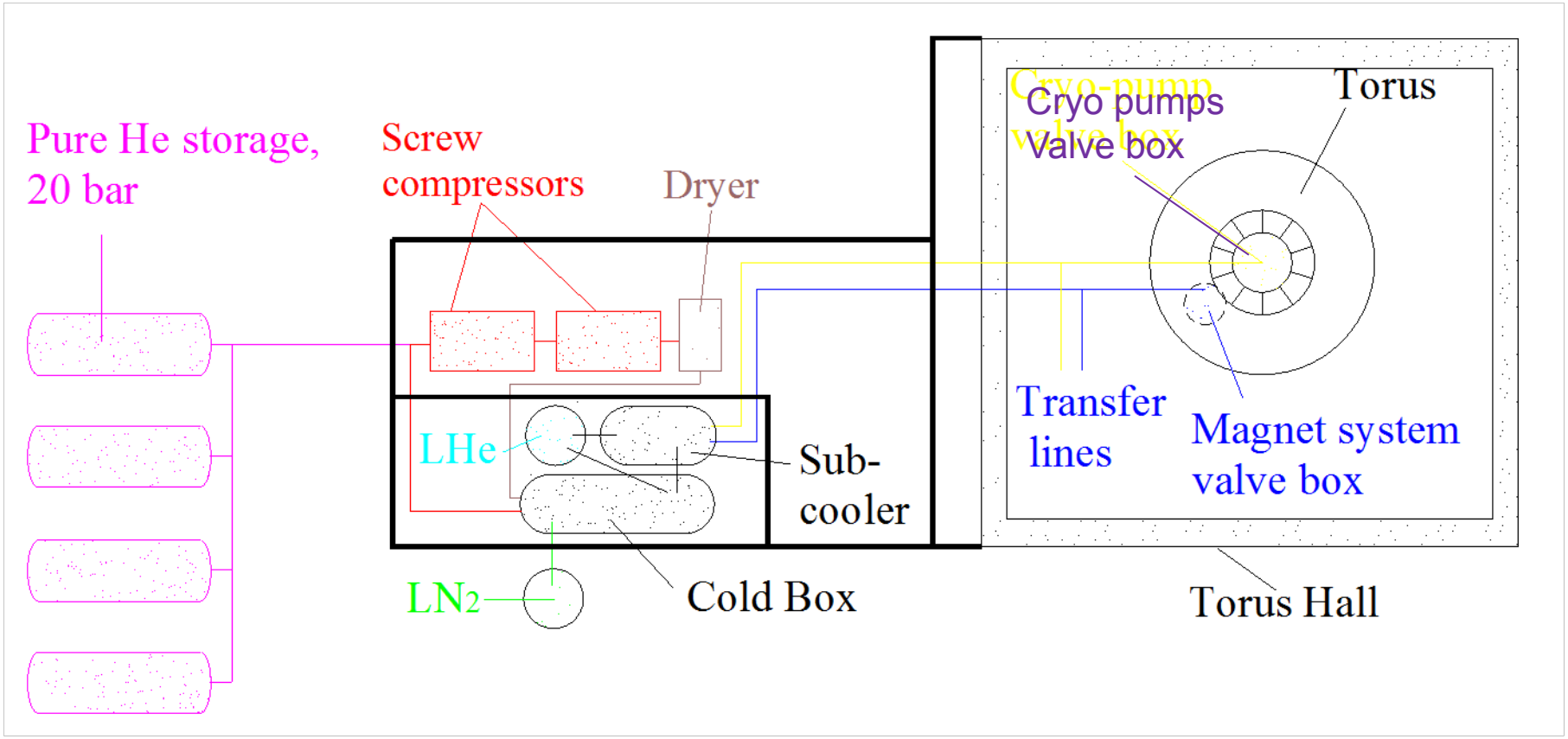




1. Torus assembled

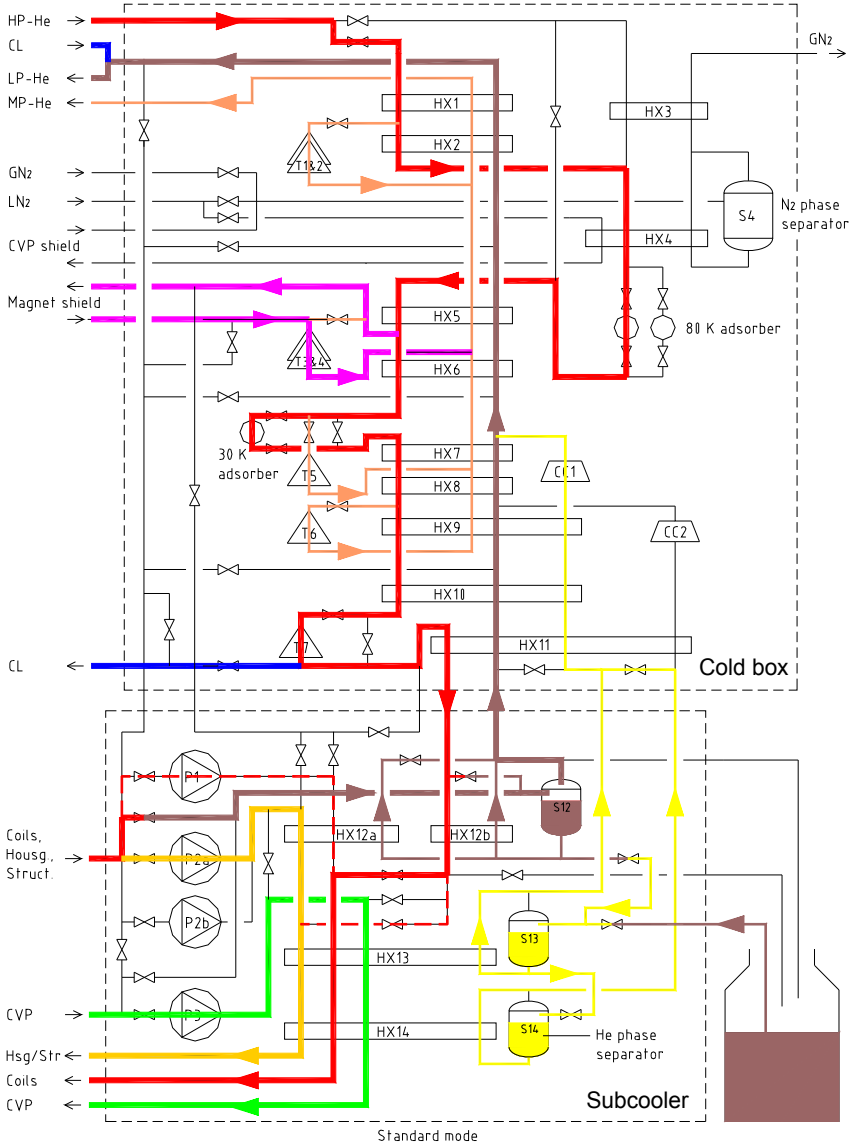


2. Helium refrigerator layout



Refrigerator supplied by Linde Kryotechnik AG

2. Refrigerator: schematics

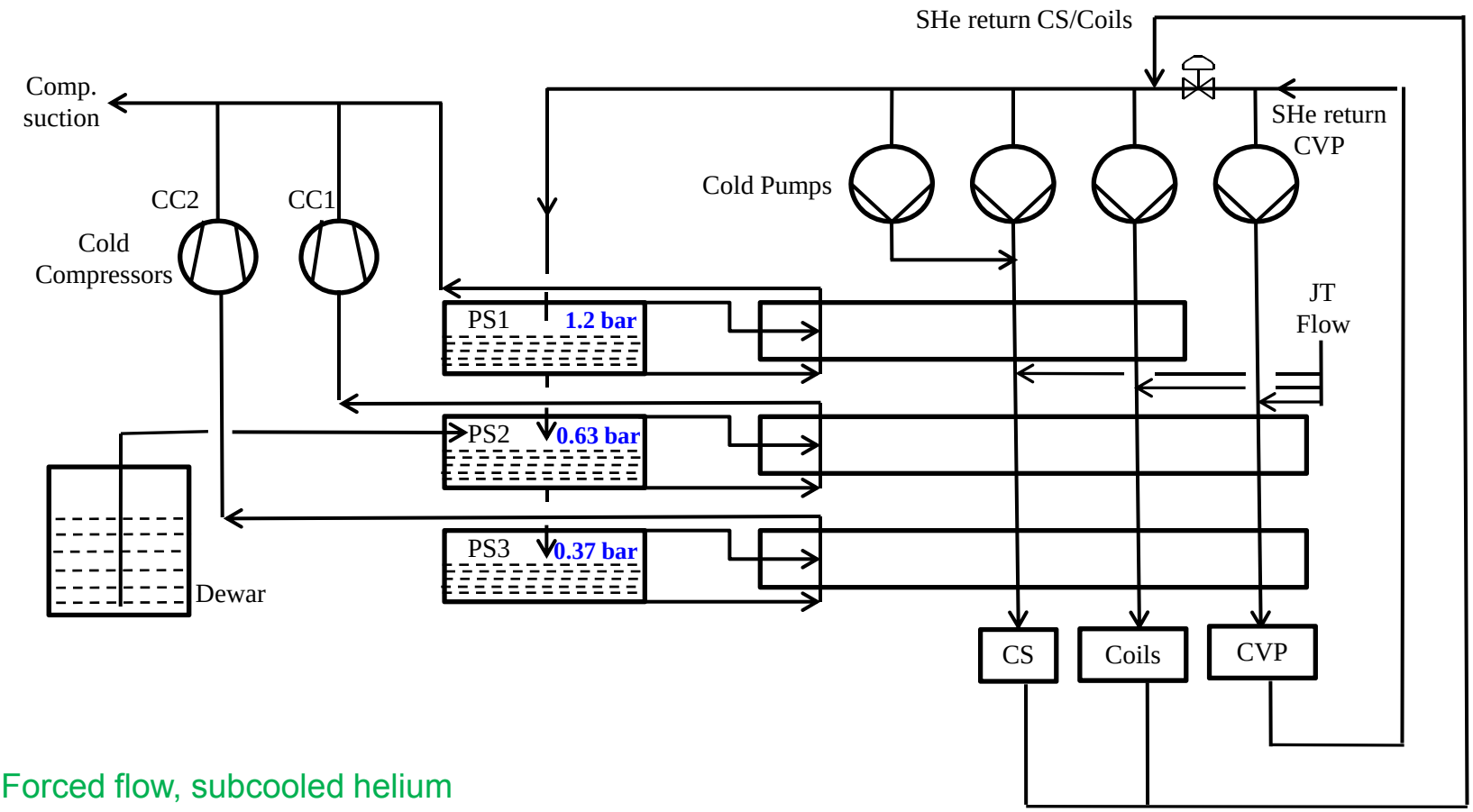


Standard mode (3.9 K, 2.5 Tesla)

Guarantee value and (measured average value during refrigerator acceptance test)

Appln.	Heat load W	Mass flow g/s	ΔP Bar
Casing (3.87K)	1800 (1835)	300 (307)	0.1 (0.2)
Coils (3.84K)	800 (808.6)	200 (216)	0.7 (0.8)
	450 (508.5)	250 (255)	0.6 (0.53)
			T_{in} K
Shield	14000 (14553)		<70K (61K)
Leads		15 (15.43)	~4.5K (~4.5K)
LHe used (Dewar)		-22.5 (-18.65)	
LN2+ LHe used		-31.5 (-27.4) -15 (-14.35)	

2. Cold compressors / pumps



Forced flow, subcooled helium
Phase separators: PS1 (4.5K), PS2 (3.8K), PS3 (3.3K)
Peak power mode: Both cold compressors & 4 pumps in operation
Standard mode: 1 cold compressor & 2 pumps in operation

2. Cold compressor parameters

Parameters	Units	Cold compressor (CC1) (3.9K operation)		Cold compressor (CC2) (3.4K operation)	
		SM	PPM	SM (Not operating)	PPM
Mass flow	g/s	102.8	113.3	--	126.6
Suction pressure	mbar a	640	760	1250	350
Suction temperature	K	12.8	10.8	6	5.25
Discharge pressure	bar a	1.25	1.25	1.25	1.25
Discharge temperature	K	18.4	14.2	--	10.2
Efficiency Isentropic	%	≥ 70	≥ 70	--	≥ 70
Heat inleak with intercept cooling	W	≤ 50	≤ 50	≤ 50	≤ 50

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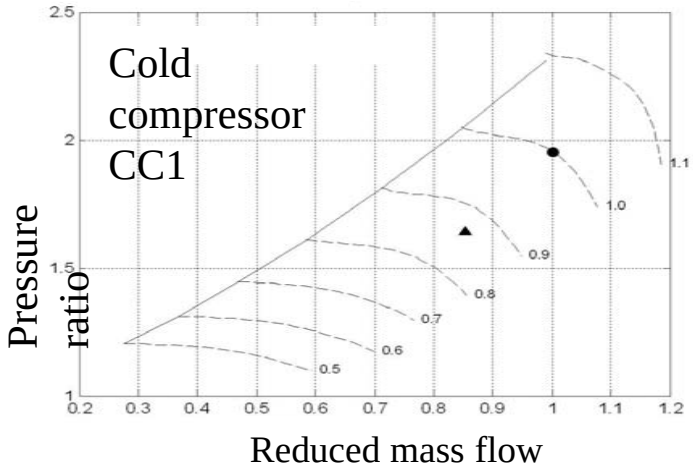
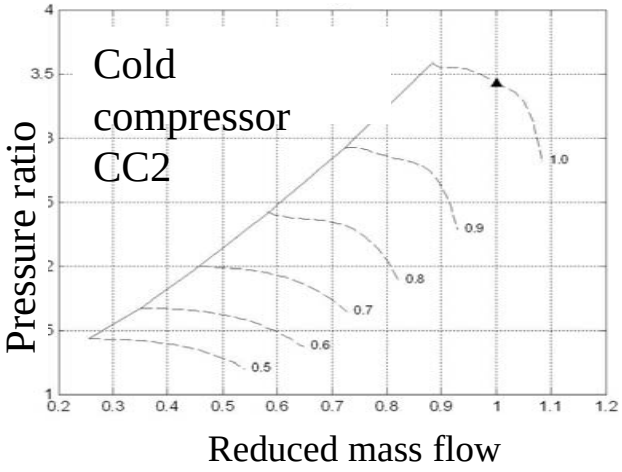
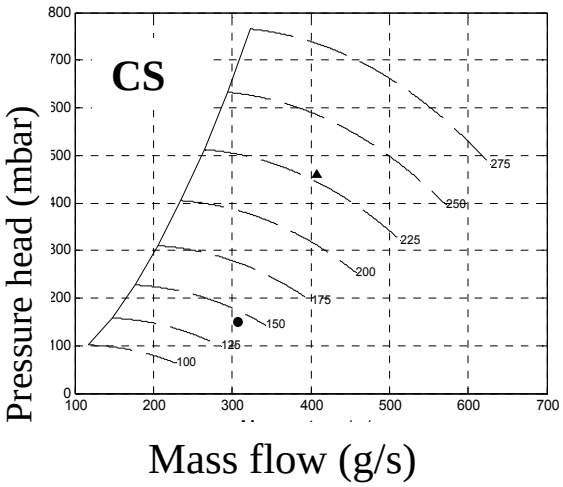




2. Cold pumps parameters

Parameters	Units	Pumps for casings & structure (CS)		Pump for coils		Pump for CVP	
		SM	PPM (2 pumps)	SM (Not operating)	PPM	SM	PPM
Mass flow	g/s	306	816	--	275	255	255
Suction pressure	bar	3	3	3	3	3	3
Suction temperature	K	5.09	4.3	5.09	4.3	4.5	4.14
Discharge pressure	bar	≥ 3.15	3.46	--	5.38	3.66	3.66
Discharge temperature	K	5.2	4.38	--	4.74	4.61	4.26
Efficiency Isentropic	%	≥ 55	≥ 55	≥ 55	≥ 55	≥ 55	≥ 55



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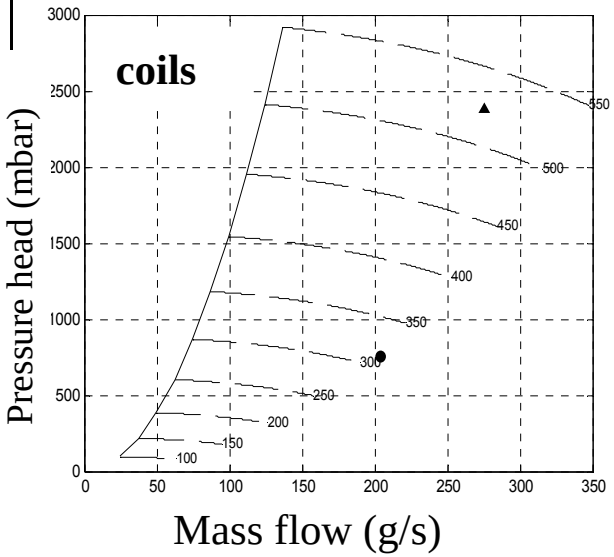
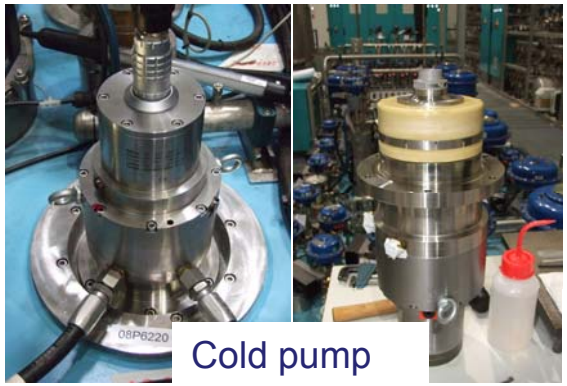


2. Various components / parameters

Screw compressor

Cold box


Coalescer + adsorber


Cold pump


Dryer

No.	Device
7 kW	Refrigerator power at 4.5 K
2	Screw compressors 1.6 MW electrical power
1 2	Oil removal system Dryers
3	Pressure levels 1.1; 3-4;11-17 bar
7	Turbines in cold box
1	Phase separator
2	Sub coolers with cold compressors
4	Cold circulators
1	LHe - dewar
5	Different consumers

2. Preperation of cryogenic system

<u>Cryogenic system:</u> refrigerator, supply lines to cryostat, piping inside the cryostat, current leads, quench gas exhaust system

- Verification that assembly and tests had been done successfully

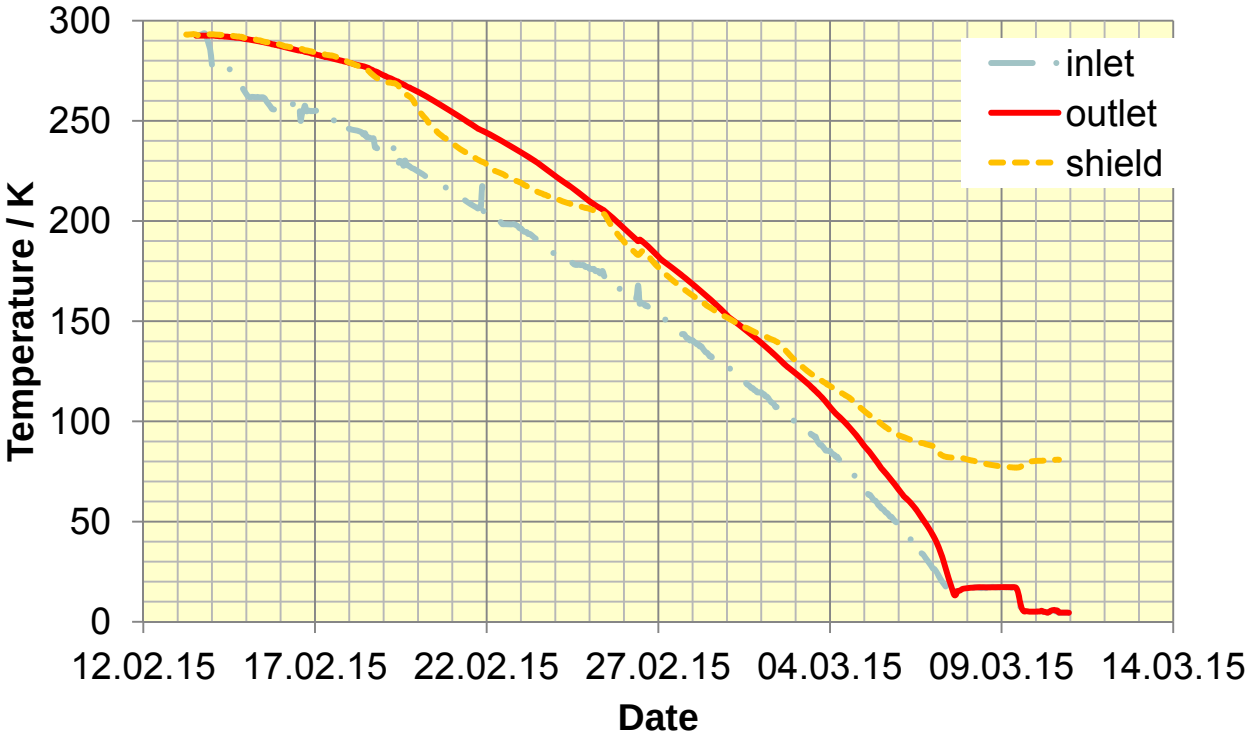
- Flushing procedure:
  - filling to 3 bars, rapid expansion, gas was filtered
  - at least three times
  - inside cryostat pressure increased from 3 to 12 bars

- Pumping and filling of the single cooling circuits (three times):
  - evacuated to 30 mbar
  - filled to 1 bar with helium

- Cleaning using the dryer and cold adsorber of refrigerator
  - first cleaning of single circuits, than all circuits together
  - impurity less than 10 vpm for nitrogen
  - 4 weeks cleaning time

- Inside the cryostat:
  - helium leak rate better than $3*10^{-5}$ mbar *l/s (warm condition)
  - vacuum $2*10^{-4}$ mbar before cool down

2. W7-X first cool-down



- cold mass 456 tons
- max(ΔT) = 40 K
- cool down rate 1 K/h
- cryostat pressure
  10^{-4} mbar (warm)
  10^{-7} mbar (cold)
- helium leak rate at 4 K
  ≈ $5*10^{-5}$ mbar*l/s

- Parallel cool down of cryostat and refrigerator
- Visual checks, no ice formation or water condensation on cryostat or components
- No vibrations or fluctuations
- Check of flow distribution in circuits
- Check of displacement sensors at coils, at GFK-supports at magnet structure and at CL
  ➔ Displacements within predicted range!
- Smooth cool down in 4 weeks

2. Heat load & flow conditions

Mode	SM (3.9 K)			SSM (<10 K)
	Coil housing and structure	Conductor cooling	Shield cooling	Coil conductor, housing and structure
Feed temperature [K]	3.9	3.9	50	5.2
Flow rate [g/s]	300	200	110	160
Heat Load [W]	426	256	5600	566
Design value for heat load [W]	1800	800*	9000	1800
Pressure drop [mbar]	140	360	1180	140-290

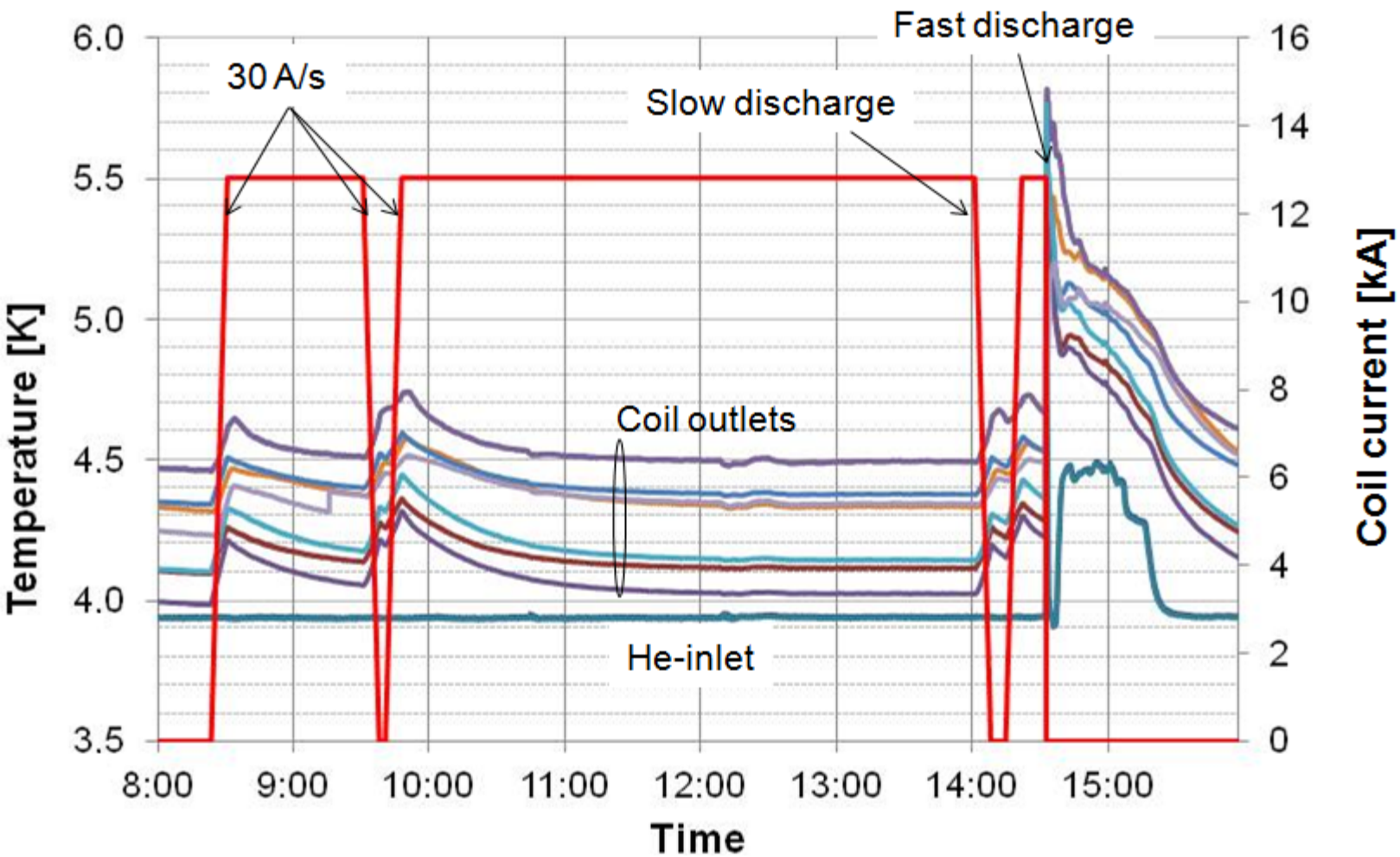
* design value for refrigerator performance

SSM = short stand by mode
SM = standard mode

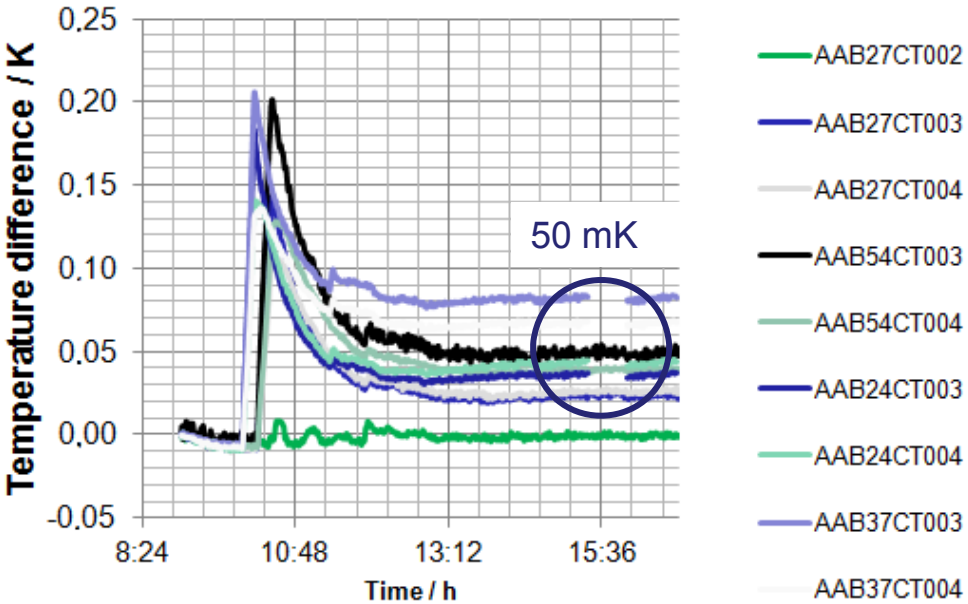
- ✓ Specified mass flow rates achieved
- ✓ Pressure drop within limits
- ✓ Average thermal loads on shield 4 W/m²
- ✓ Average thermal loads on cold structure 0.55 W/m²
- ✓ Conductor outlet temperatures between 4.0 to 4.7 K

2. Helium cooling during current load steps

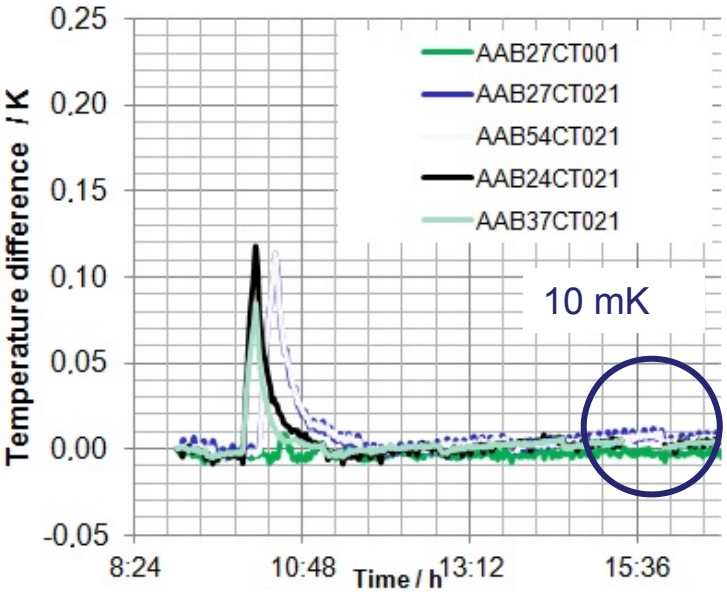
- Non-planar coils: 12.8 kA, planar coils: 5.0 kA
- Cooling with helium flow (3.7 bar, 3.9 K)



2. Coil temperatures during magnets operation



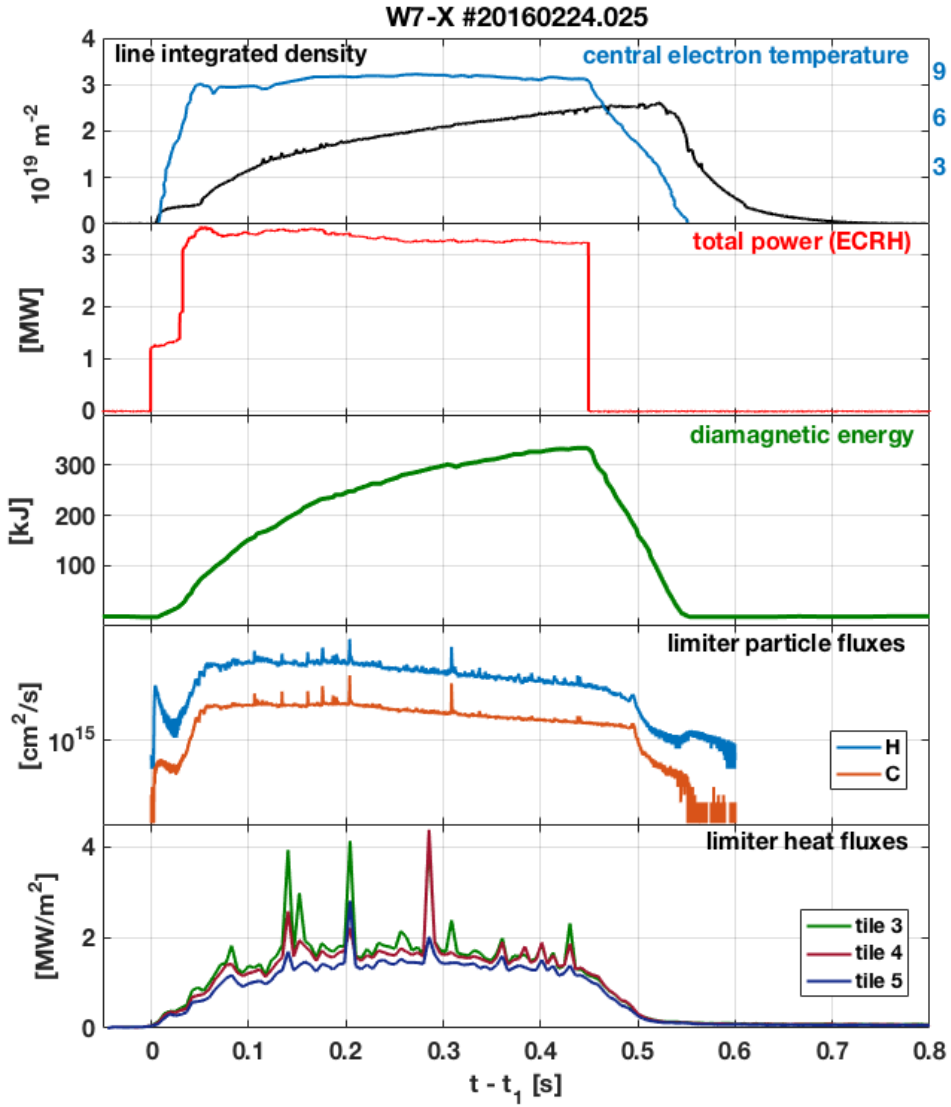
Helium outlet temperature of the coil conductor cooling



Helium outlet temperature of coil housing cooling

- Current ramp 15 A/s from 0 to 12.8 kA in the NPC
  - ➔ Maximum 200 mK temperature increase due to eddy currents
- Stable current operation with 12.8 kA
  - ➔ in the average ΔT = 50 mK for conductor cooling
  - ➔ ΔT = 10 mK for coil housing cooling
  - ➔ low ohmic heating, good quality of joints

2. First plasma operations



3.2.2016, 15:21:25.822 (local time)

- Plasma campaign 10.12.2015 – 10.03.2016
- 1st Helium plasma: 10.12.2015
- 1st Hydrogen plasma: 03.02.2016
- Plasma parameters achieved:
  - ✓Pulse time upto 6s
  - ✓ECRH energy upto 4MW
  - ✓Temp_electron upto 9 keV
  - ✓Temp_ion upto 2 keV
  - ✓Density ~ 2…3x10^{19}/m^3

3. W7-X warm-up

Temp diff. ($T_{max} - T_{min}$) ≤ 40 K

Took about 6 Weeks

Temp. on hold during Easter vacations

2. Operation personnel / duties

- 3 shift operation: Cool-down & warm-up

- 2 shift operation: Standby modes (SSM, LSM), standard mode
  - On call duty for the night shift (1 colleague from Cryo)
  - On call duty for the night shift (W7-X main operation team & other systems)
  - Refrigerator sends the alarm by itself in case of problems

- 2 colleagues / shift: 1 electrical/controls + 1 mechanical

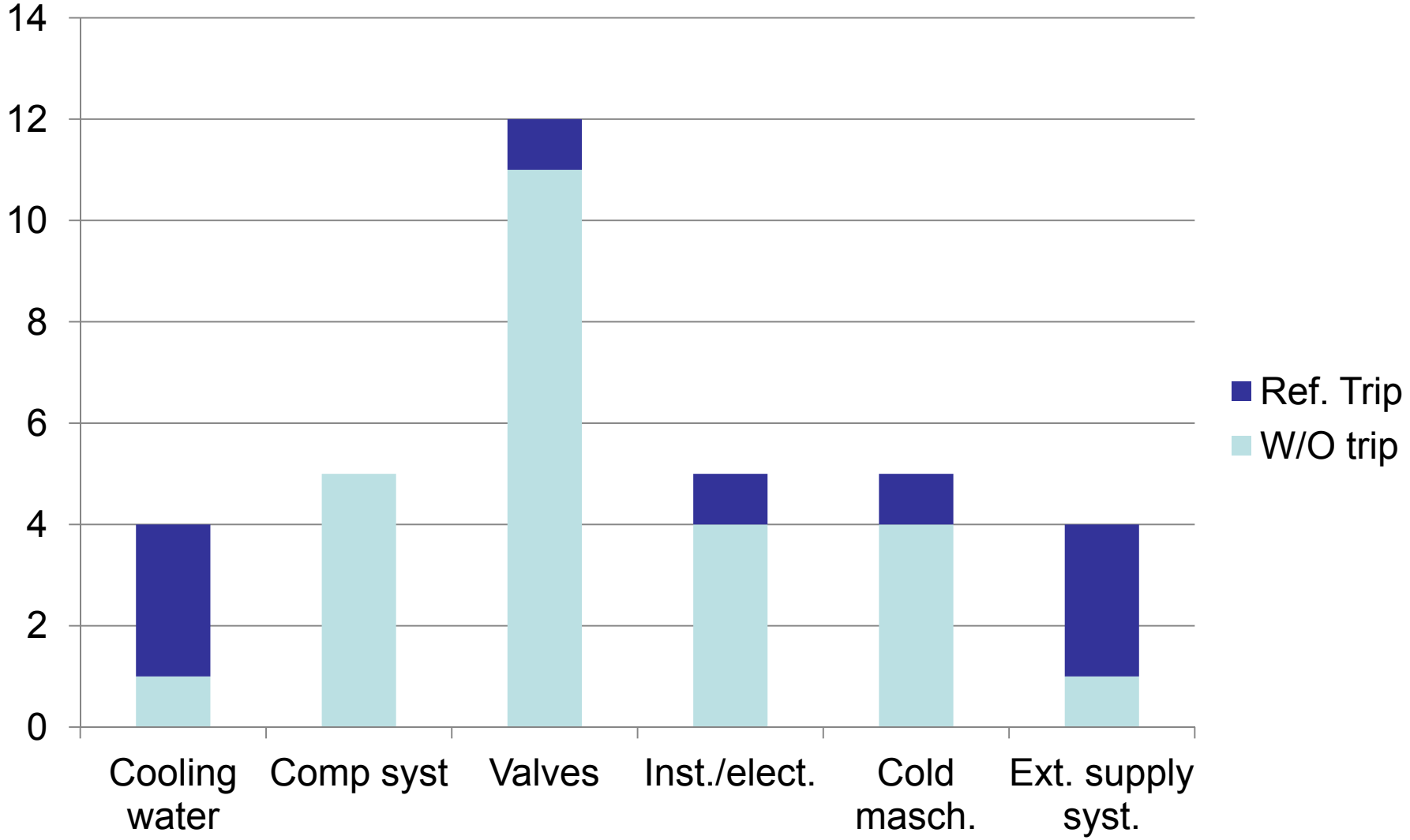
- The responsible officers (refrigerator operation), available in normal working hours and on call duty (under rotation)

- Cryo group has 17 colleagues, 12 from these are under regular shift duty, others substitute in case of need and remain available for on call duty

3. Problems, concerns, learnings …

- Operational: training while operating
- Controls: Optimize the logic program (& online reload), input table values, controller parameters, old computers → being updated
- Instrumentation:
  - Temperature sensor malfunctioning (often) leading to operational problems → online chage if possible, removing from logic, keep enough spares, within W7-X cryostat not possible to access → rely on redundant ones
- Valves:
  - Seat leakage →plug seals changed
  - Oscillations (pressure/level) →building intercepts on the stem
  - End position switches: leading to trips (component/refrigerator) → logic rethinking
  - Abrupt opening, blocking at a level → controller changed
- Cold machinary:
  - Cold compressors: limited operating range
  - Cold pumps: Spindel bearings
- Cooling water system: auto switchover (redundant), motor change
- External supply systems: Cooling tower (freezing in winter, supl. temp. limit in summer), electricity
- Lessons: prepare for online changes/replacement, keep enough spares

3. Number of failures during OP1.1



3. Helium gas management

Helium gas before start of operation:	13 600 Nm^3
Helium gas purchased during operation:	6 500 Nm^3
Helium gas available at the end of operation:	16 000 Nm^3

Helium gas loss during the operation:	4 100 Nm^3
	~ 20% (of 20100 Nm3)
	(All volums at STP)

Reasons for loss:

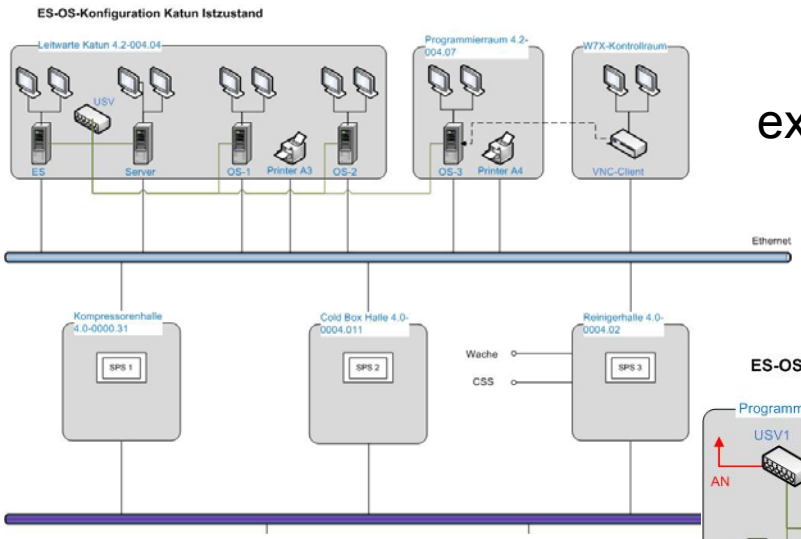
- Used during the initial purging of whole volume in W7-X and refrigerator
- Refrigerator trip in standard mode with W7-X connected: Safety valves opened, leakage at isolation valves
- During initial cleaning of whole system, several regeneration of Dryer and cold adsorber beds.

3. Further improvements: Helium gas tank

- Existing: 4 tanks, Carbon steel, with quench gas damper
- 1 tank as dedicated quench tank (once empty), p<1.5 bara
- 10 kL LHe Dewar contains He for about 2 full tanks
- During peak power mode, Dewar could be empty in couple of hours
- No He recovery system available
- Planned to buy 1 more tank

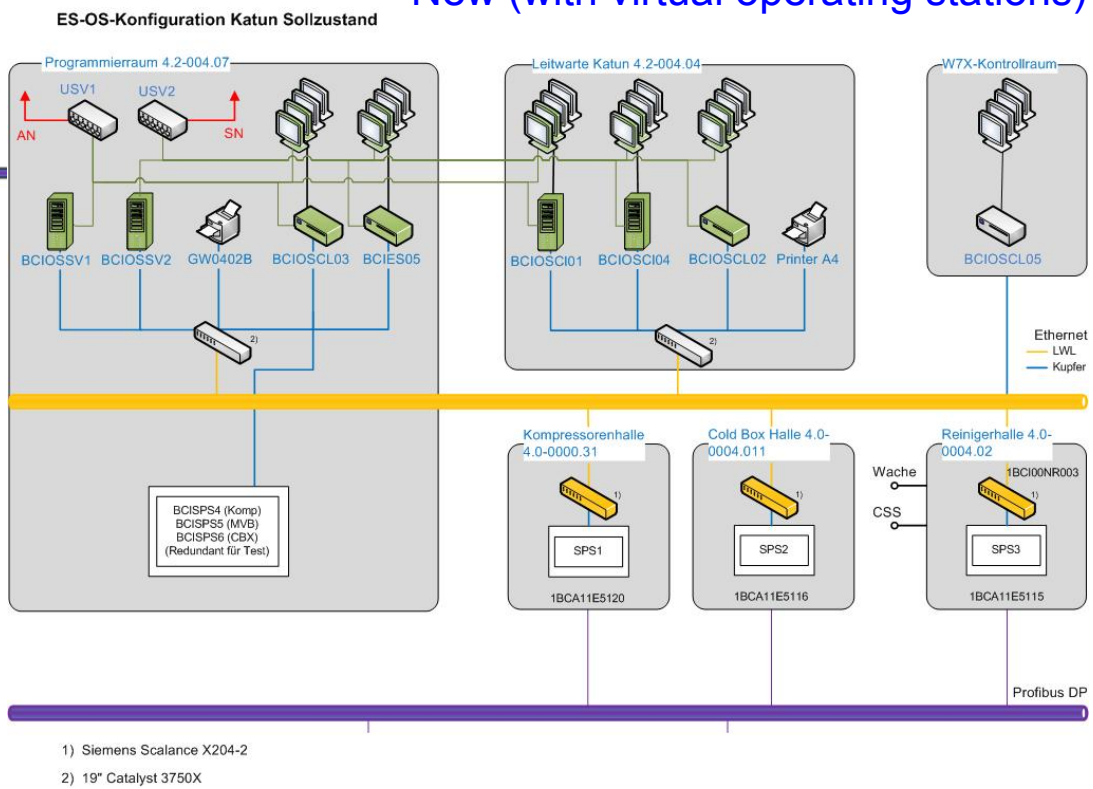
4 pure Helium gas tanks
- each 250 m^3
- working pressure 19 barg

3. Further improvements: Controls



existing

New (with virtual operating stations)



3. Maintenance: preventive, regular

Preventive:

- Physical inspection by each shift: refrigerator and W7-X cryo system
- Oil leakage checks through compressor & oil pump bearings
- Operating hours (before oil drainage) for each coalescers

Regular:

- After certain opeating hours or durations as prescribed by the manufacturer: For rotating equipments i.e. compressors, motors, oil pumps, cooling water pumps/motors, vacuum pumps etc.
- Cold machine bearing check/change
- Isolation vacuum checks of transfer lines, Dewar
- Check of valves

4. Summary and future operations

Summary:

- Cryogenic system operated continuousely (Feb 2015 – Apr 2016)
  (except few breaks due to trips etc. ☺)
- Measured heat loads well within the design values
- Designed flow, pressure and temperatures achieved
- In house training of operation team
- Adjustment of controls: logic, parameters
- Presently in progress: Maintenance and problem sorting

Future operations:

Mid 2017: Cool-down for W7-X operation phase 1.2