214th TE Technical Meeting (TE-TM)
4 November 2024

WP16

Commissioning of the cryogenic system of the HL-LHC Inner Triplet (IT) String without magnets and next steps

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https://indico.cern.ch/event/1470595/

Outline

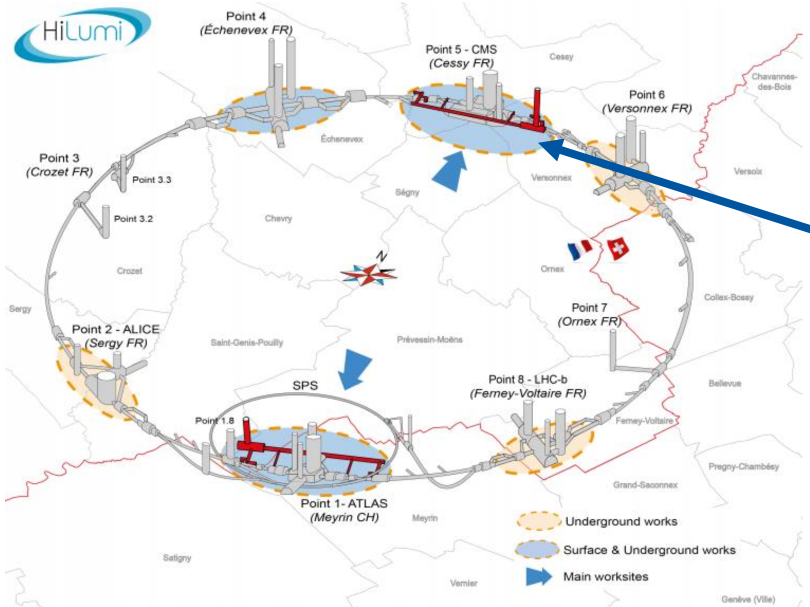
- Introduction and cryogenic infrastructure of IT String
- Overview of commissioning phases
- Main commissioning results
  - Cold compressor
  - Heat loads and pressure drop on the lines
  - Estimated cooling capacity
- Next steps and conclusions

Introduction

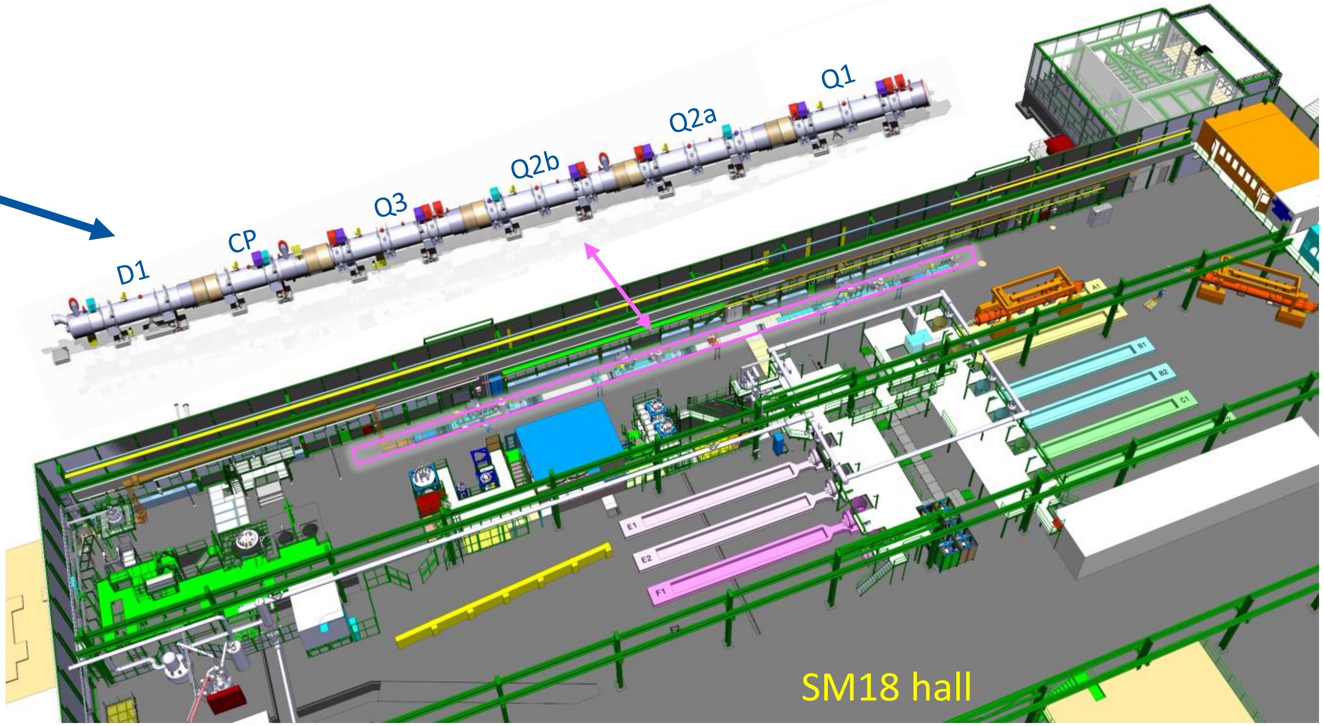
<u>IT String test facility</u>: consists of all magnet circuits from D1 to Q1 and cold powering with their respective systems (cryogenics, quench protection, …)

Key objectives

- <u>Validate collective behaviour</u> of the magnets & their systems in the <u>conditions as similar as possible to the operational</u> ones
- Obtain information about the operational behaviour <u>in advance</u> to <u>speed up the commissioning</u> in the LHC tunnel



For the High Luminosity LHC (HL-LHC) project, the final focusing Inner Triplet (IT) superconducting magnets around ATLAS and CMS will be replaced by a new 60 m-long set of higher performance Nb_3Sn magnets



Cryogenic architecture for HL-LHC IT String in SM18

Specific to the IT String

SQXL: cryogenic distribution line

PCDS: proximity cryogenic distribution system

CC: cold compressor

WQB: warm quench buffer

Gas management system of DFHX

Data acquisition & control system

Part of SM18 infrastructure

Warm quench buffer

Existing refrigerator

Warm pumping units

Main helium storage

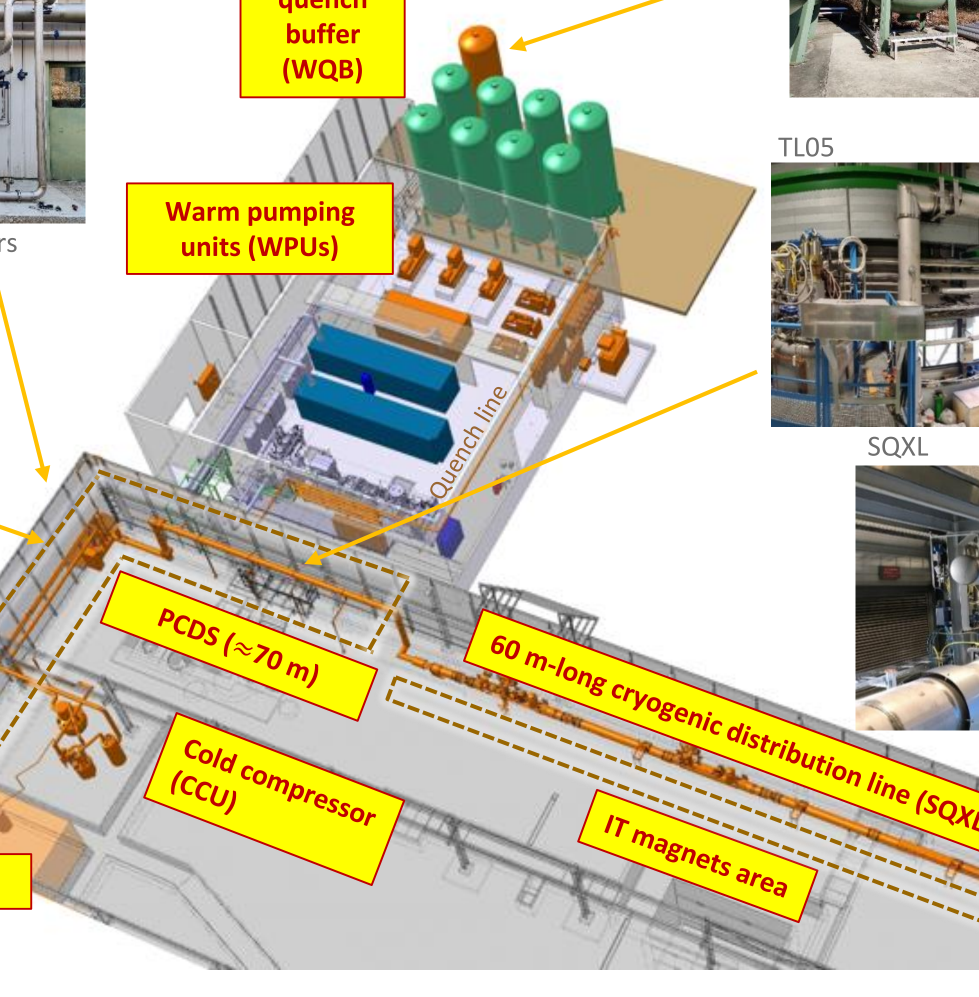
Number if items/assemblies tracked : >1000

Instrumentation: 376 items with 190 not in magnets & cold powering

- Thermometers : 227 with 81 not in mag. & cold powering
- Valves : 185 total, 31 cryogenic

2 x 15 kW heaters

Gas management panel



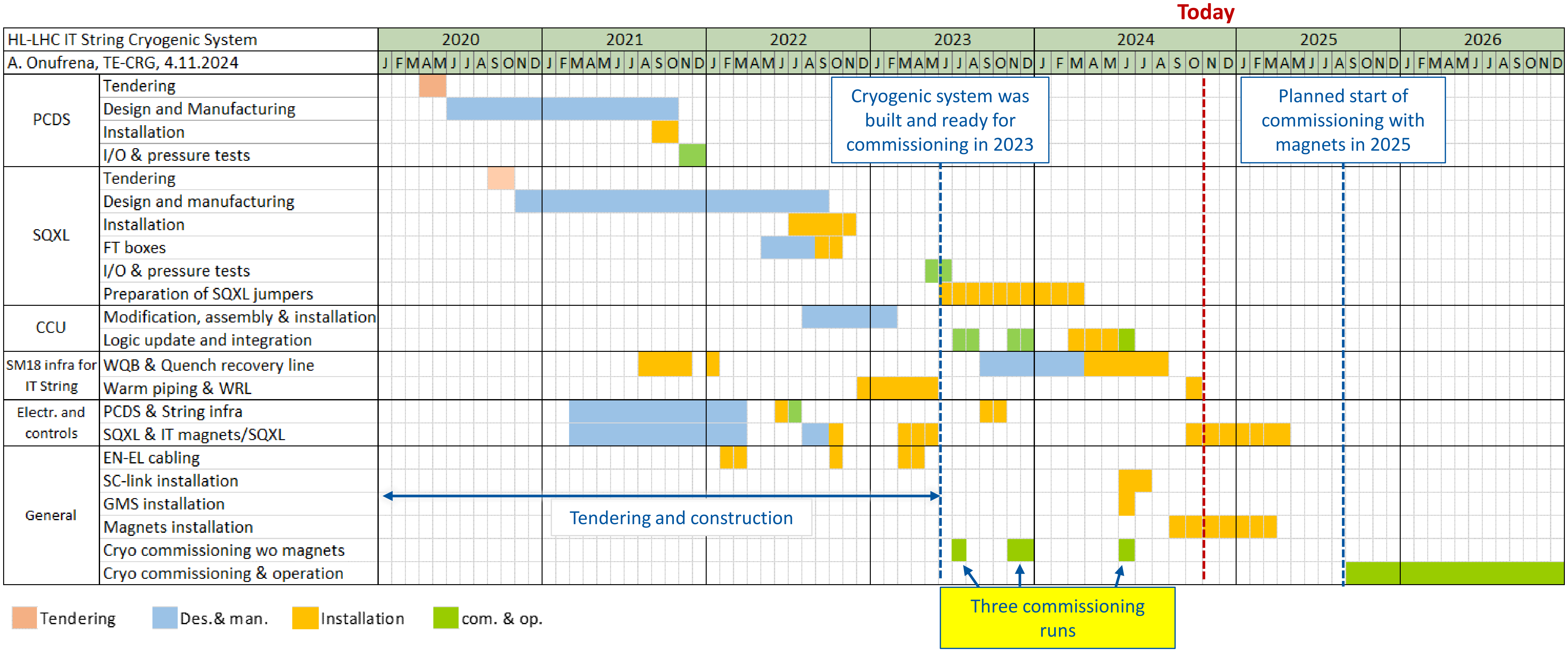
Warm Quench Buffer

TL05

SQXL

Project overview

- Cryogenic system was under design and construction from 2020 and underwent three commissioning runs in 2023-2024



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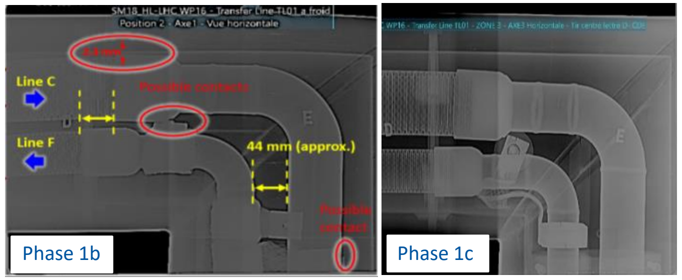
IT String commissioning phases

Strategy: commission the cryogenic system in a standalone mode before operation with magnets (allows to anticipate and resolve any potential issues)

- Phase 1: commissioning of the cryogenic system without magnets (complete!)
- Phase 2: commissioning (and then operation) of the cryogenic system with magnets (2nd half of 2025)

Heat load in TL01, contacts and repair



System ready for the cooldown

Jun 2023 (and before) → Jul-Aug 2023 → Aug-Oct 2023 → Nov 2023 → Dec 2023 → Jan-Apr 2023 → May 2023 → Jun 2023 → Jul - Oct 2024

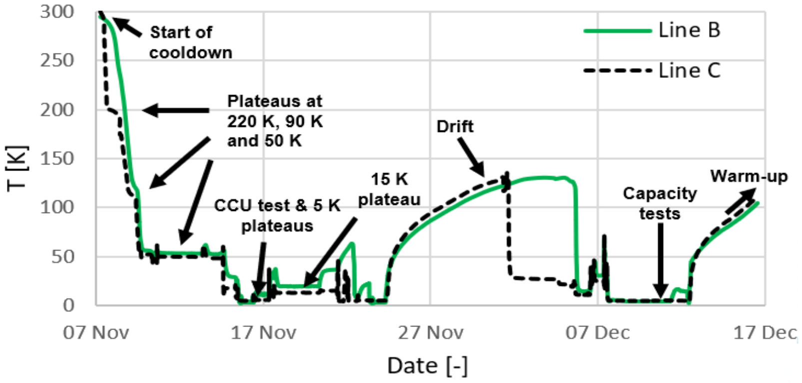
Phase 1a
- Controlled cooldown
- Mechanical integrity validation
- Heat load on some segments is higher than expected

Phase 1b (further validation and studies):
- System thermal characterization (heat loads, pressure drop)
- X-ray inspection of TL01 line at cold
- Further tuning of control loops and CCU logic test

Phase 1c (additional studies):
- CCU logic validation
- TL01 repair validation and capacity measurements

Cryogenics operating team

Repair of the cold compressor (CCU)



Requirements and operating parameters of the cryogenic system

Operating requirements for IT String (derived from HL-LHC)

Parameter	Value
Static heat load (conduction and radiation) on all cold masses at 1.9 K	135 W
Dynamic heat load (magnetisation during a nominal current ramp and splice resistance) on cold masses at 1.9 K	201 W
Magnet cold mass temperature	1.9 K
Nominal magnet current and ramp rate	16.2 kA @ 14.6 A/s
Screen temperature	50 K-75 K
Mass flow for cold powering system	6 g/s
Max. allowed ΔT along the magnets	30 K
Max. allowed ΔT within thermal radiation shields	100 K
Maximum cooldown duration	15 days

336 W of heat load at 1.9 K

ΔT drives the cooldown speed

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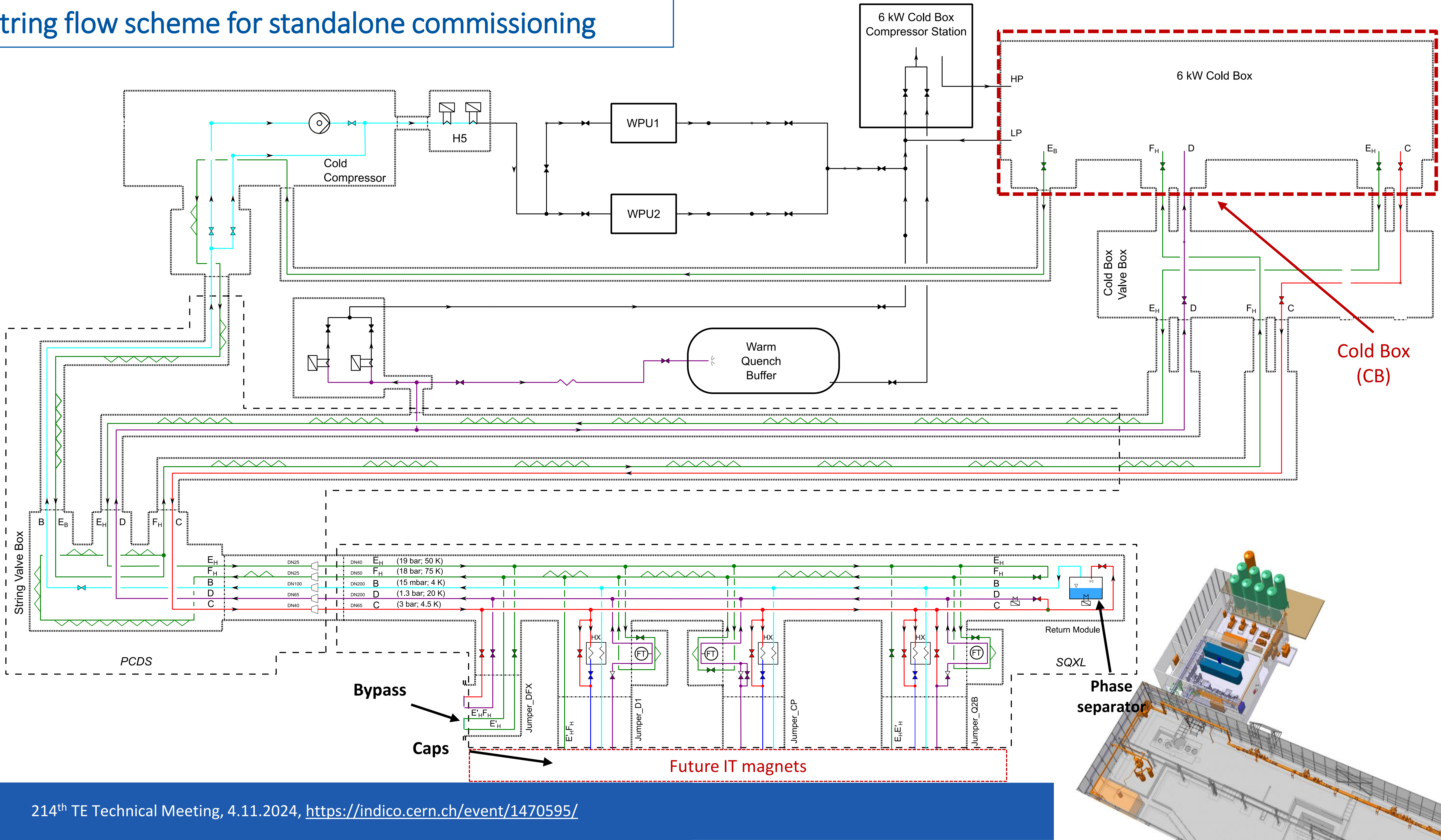
Flows, temperatures and pressures in the headers during the commissioning

			Nominal		Cooldown / warm-up	
Header	**Function**	T [K]	p [bar]	$\dot{m}$ [g/s]	p [bar]	$\dot{m}$ [g/s]
B	Line with He II at 16 mbar /1.8-1.9 K	1.9	0.016	18	< 1	1
C	He supply	4.6	3.2	26	15 → 3.2	< 100
D	LP return / quench	20	1.3	2	14 → 1.3	< 100
E	Shield lines	50	15	23	15	23
F	Shield lines	75	15	23	14	23

Goal: validate that these conditions can be achieved by the cryogenic system

IT String flow scheme for standalone commissioning



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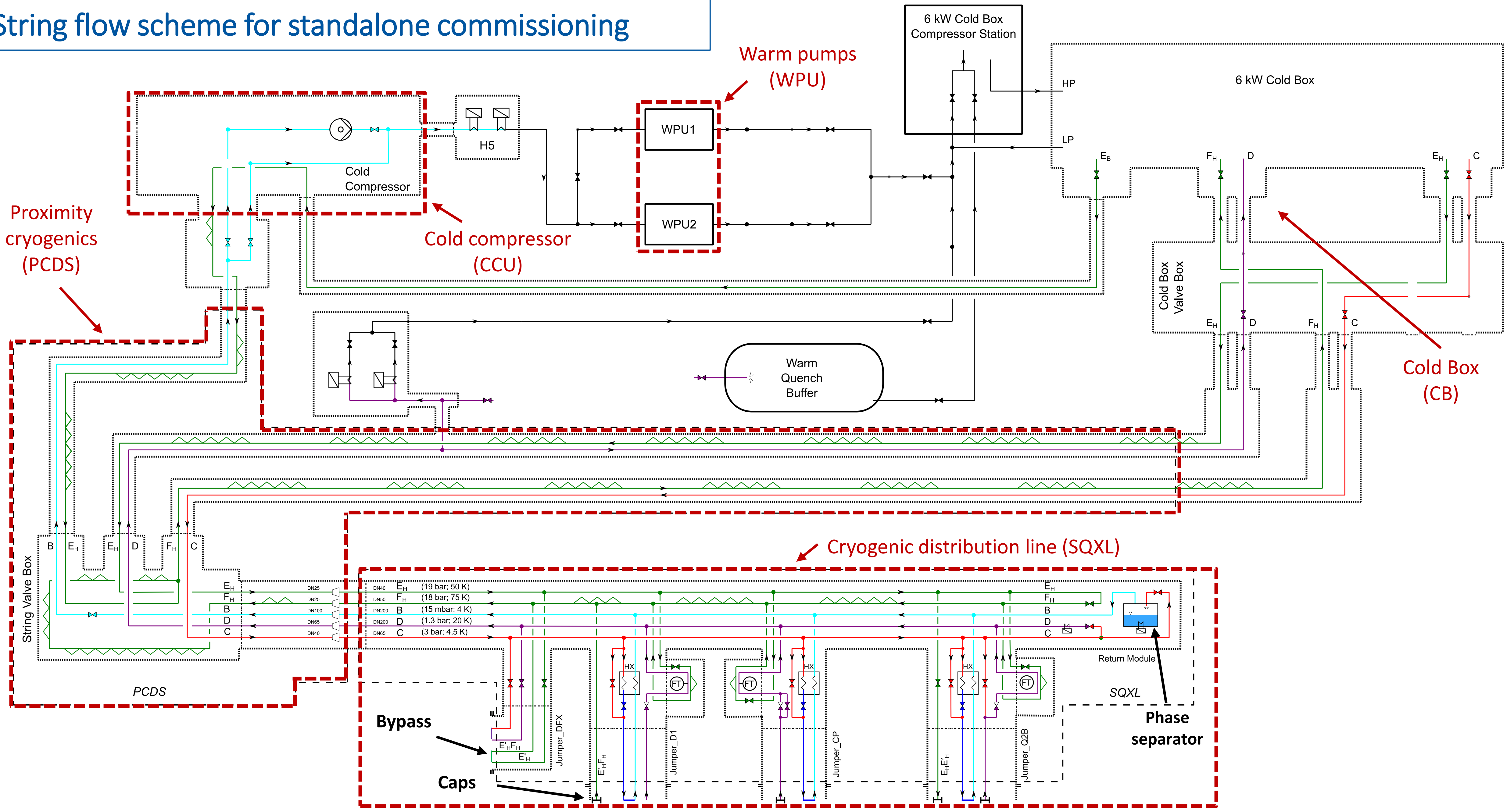
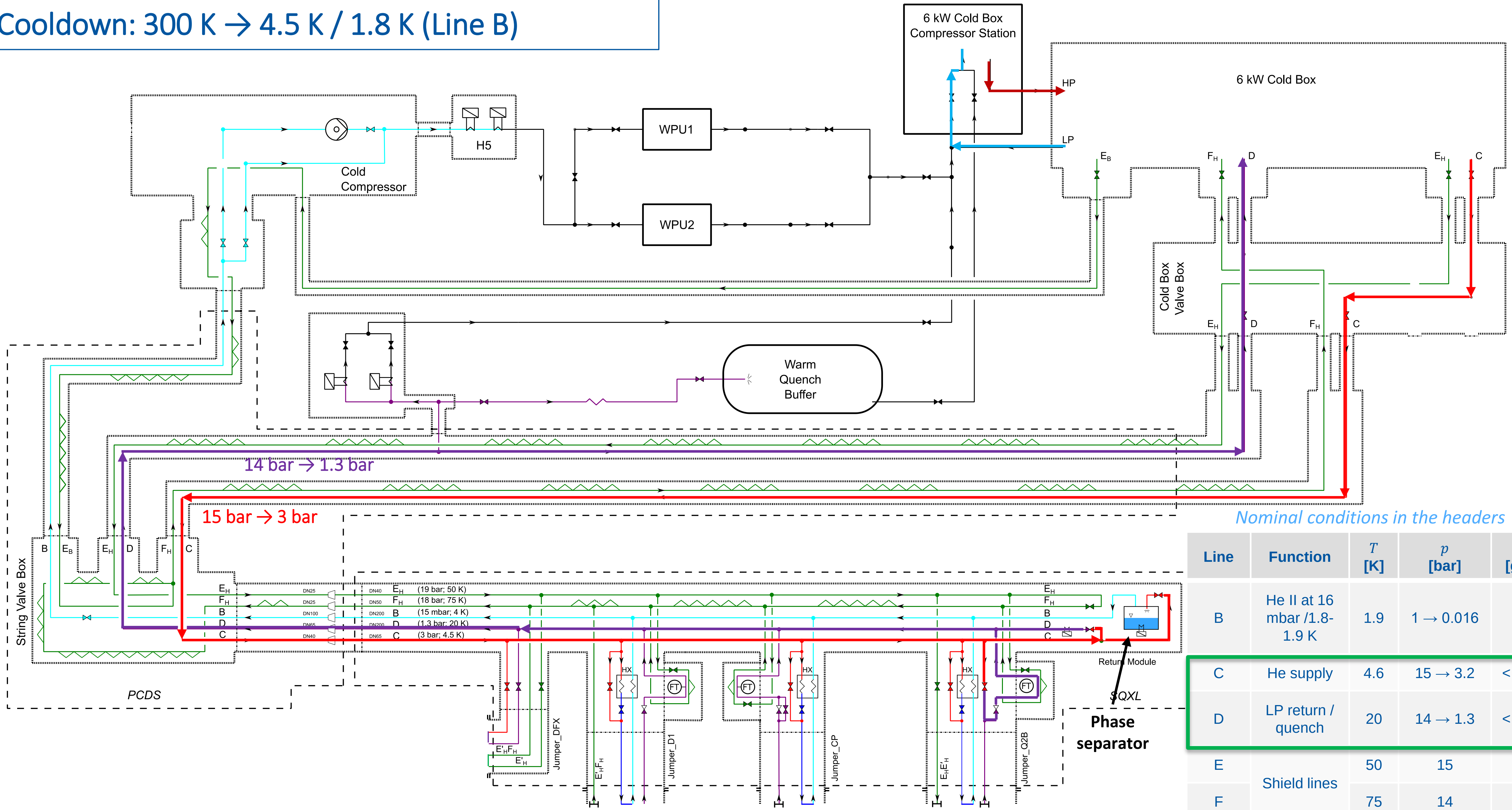


Cooldown: 300 K → 4.5 K / 1.8 K (Line B)



Nominal conditions in the headers

Line	Function	T [K]	p [bar]	$\dot{m}$ [g/s]
B	He II at 16 mbar /1.8-1.9 K	1.9	1 → 0.016	1
C	He supply	4.6	15 → 3.2	< 100
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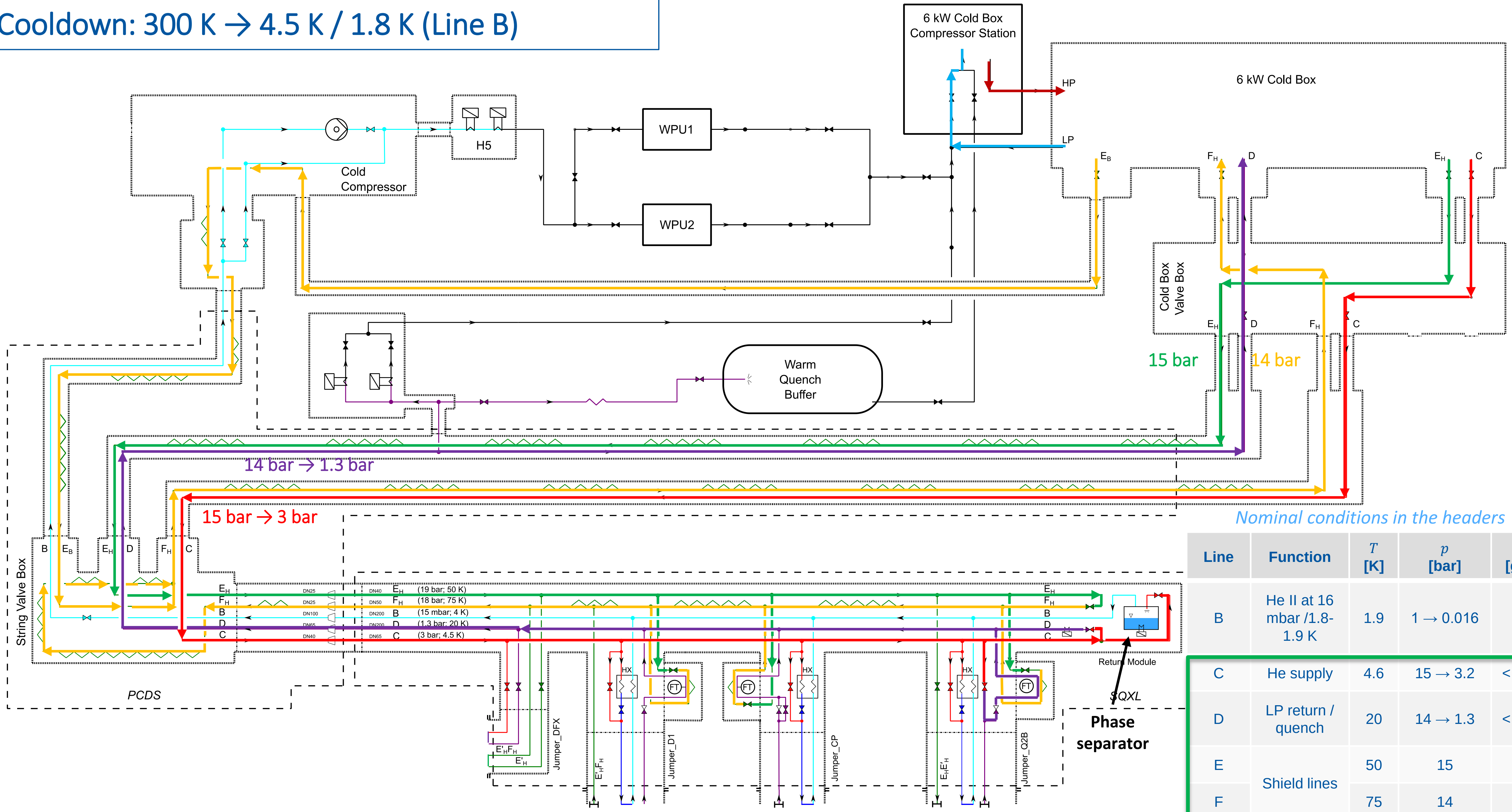

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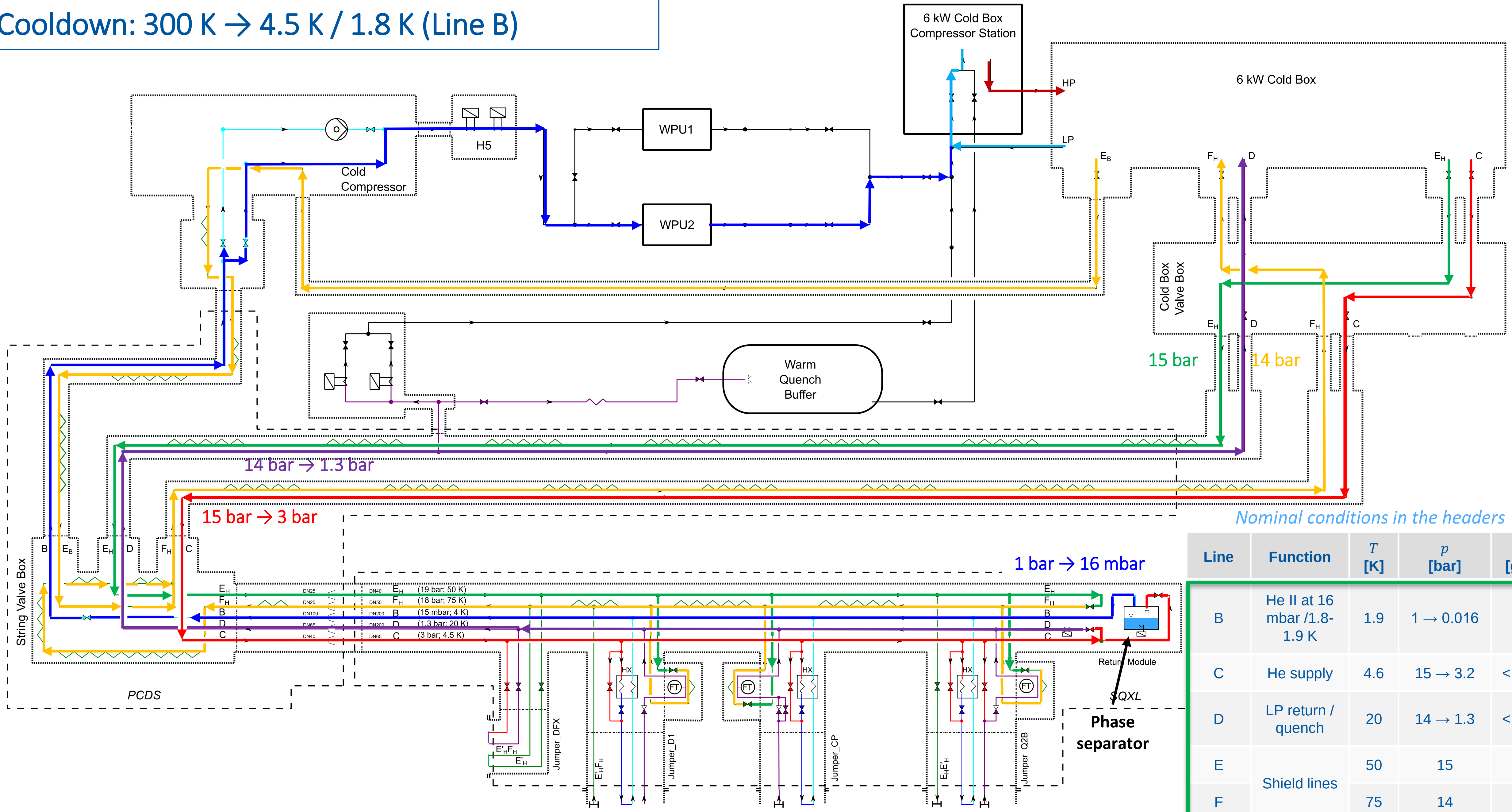

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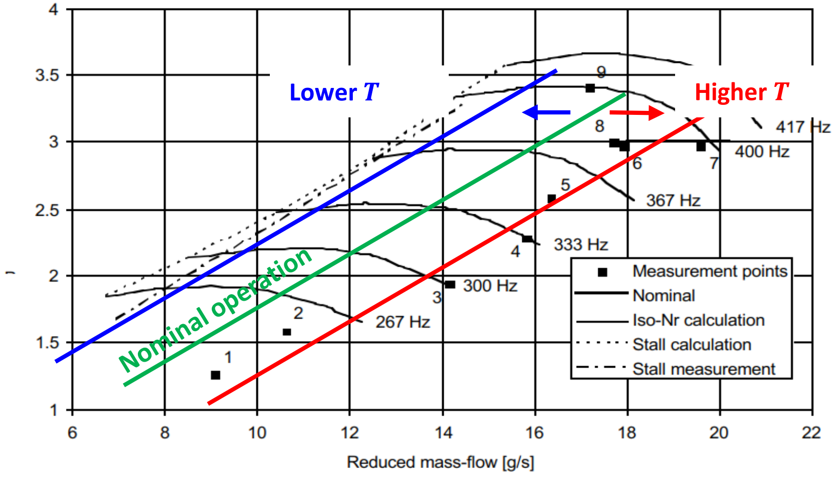
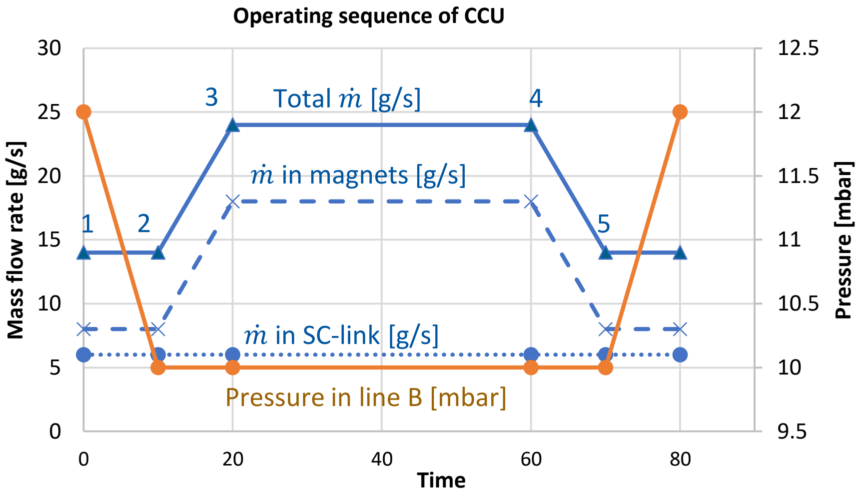
Cold compressor logic validation

- System is equipped with a cold compressor unit (CCU) to allow for a lower pressure (and T) in line B
- CCU is a centrifugal compression machine, may be subject to stall-surge during operation (especially in transient modes)
- Special control sequence was developed and CCU was tested in transient and nominal regimes

CCU head during re-integration



Examples of CCU operation curves on its performance map

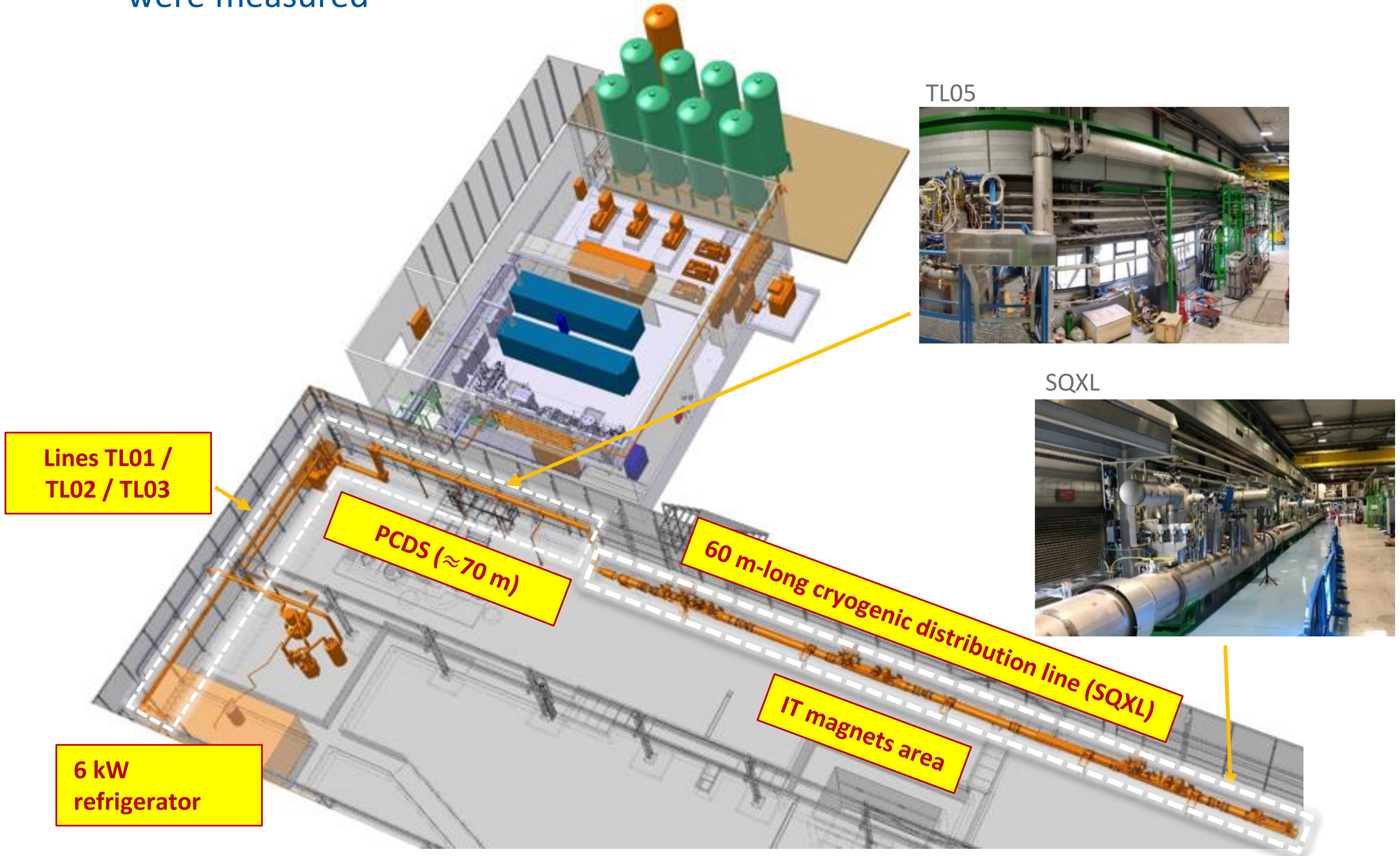


1 → Start ($\dot{m}$ corresponds to static $\dot{Q}$ of the magnets + SC-link) & thermalisation
1-2 → **Start the CCU** which controls the pressure in line B
2-3 → Transient: **pre-loading of the magnets**
3-4 → **Ramp** / **nominal operation**
4-5 → Deceleration and controlled stop

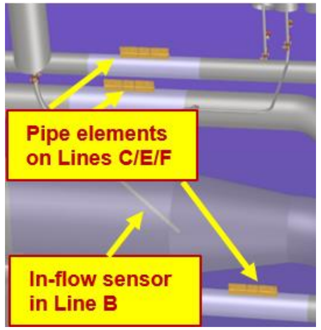
Results: sequence was validated, developed logic was able to ensure operation in the stable (1h) and transient regimes (temperature and heat load variation, quench-like pressure rises) within stall-surge limits

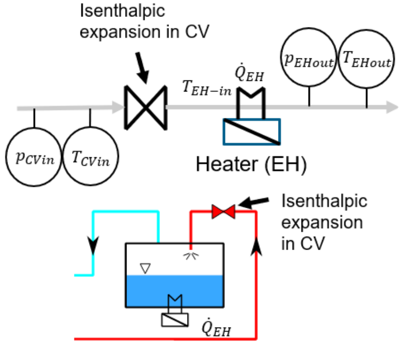
Pressure drop and heat loads

- Pressure drops and heat loads of distribution system consisting of proximity cryogenics (PCDS) and cryo distribution line (SQXL) were measured



- Δp was measured using absolute pressure sensors with prior x-calibration
- T and $\dot{m}$ measurement methods:





Pressure drop

- Challenge: large system with low Δp & absolute pressure sensors (offset-calibration before each measurement)

Critical lines

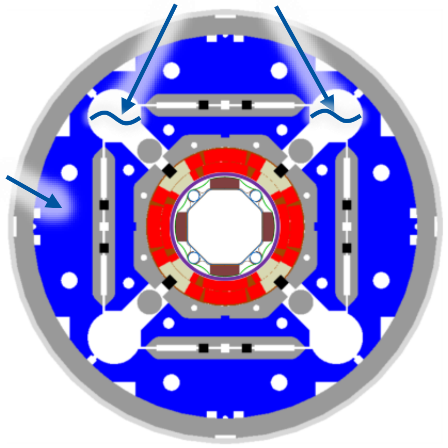
- Line D (Δp affects helium release after quench): pressure drop in line with predictions, no abnormality observed
- Line B (pumping, Δp defines the lowest p for saturated helium → magnet T):

	$\dot{m}$ [g/s]	T_{LineB} [K]	p_{ps} [mbar]	Total Δp [mbar]	
				Predicted	*Test*
Line B	18	2.4	13.6	4.1	5.0±0.2

Warm Quench Buffer

Magnet bath at 1.3 bar (Line D to quench buffer)

Bayonet HX (Line B to pumps)



Cross-section of IT magnet

Magnet temperature analysis:

- Worst case scenario: test results transfer into 17.5 mbar and 1.82 K inside the bayonet HX during nominal operation → margin for operation (0.3 K below λ-point)

Result: measured pressure drop is in line with predicted values and compatible with operations

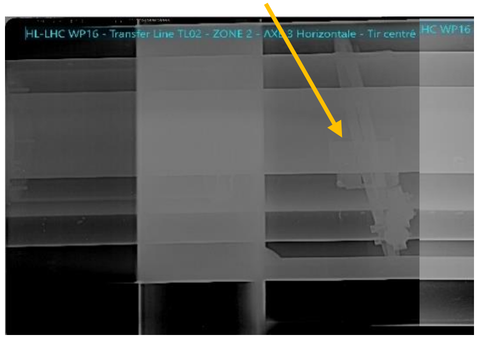
Heat loads

	Proximity cryogenics (PCDS), length ≈ 70 m				Cryo distribution line (SQXL), length ≈ 60 m			Total (PCDS+SQXL), length ≈ 130 m		
	TL01 Line C	TL02 Line D	TL03 Line B	TL05 Lines C/D/B	Line C	Line D	Line B	Line C	Line D	Line B
Predicted [W]	7	13	9	10/10/10	9	33	15	26	56	34
Measured [W]	6	83	< 9	15/5/7	29	60	12	50	148	28
Error [%]	20	15	34	22/22/29	23	16	24	18	14	22

$\dot{Q}$ on Line D inside TL02 is higher than expected

- Measured $\dot{Q}$ on Lines B / C(PCDS) / TL05 are in line with predictions
- TL01 repair reduced the heat load by 6-16 W

Ice on TL02 (Line D)

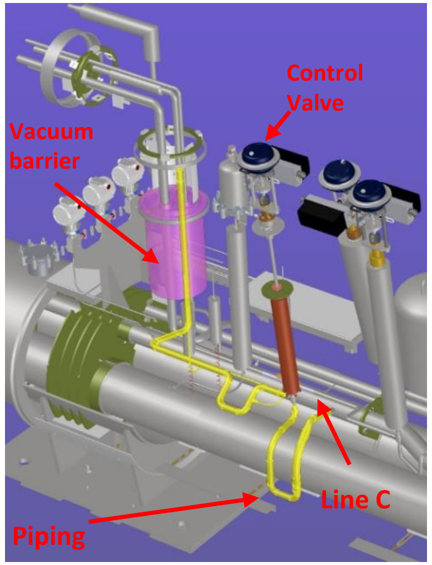


Bent spacer inside TL02

Potential reasons for observed $\dot{Q}$:

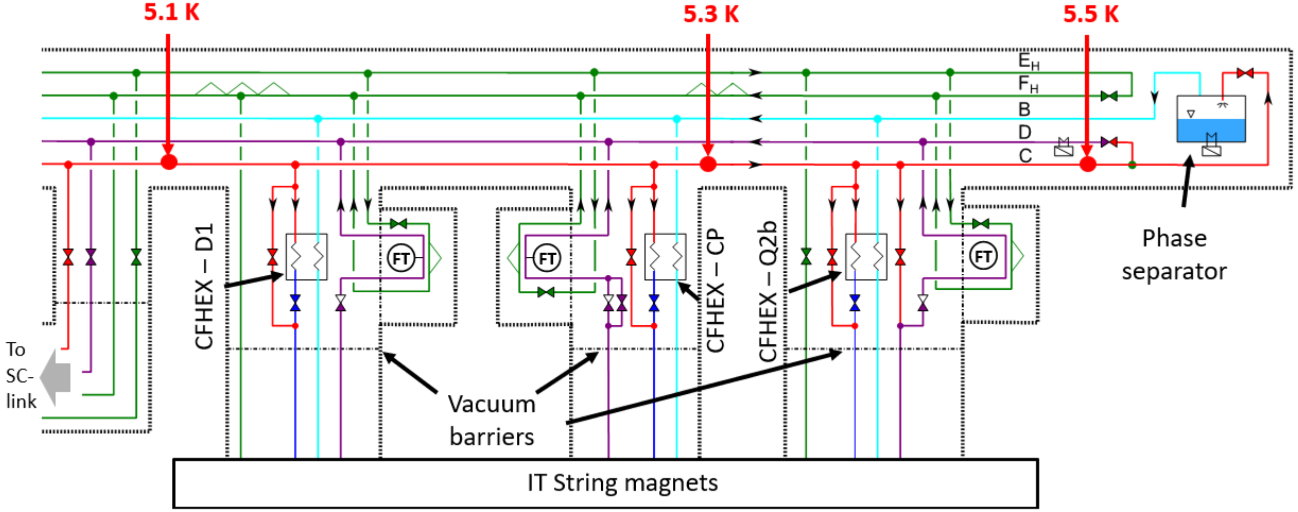
- Conduction / radiation from warm vacuum barriers (not the case during operation with magnets)
- Other sources: improperly mounted MLI & design issues (under investigation)

Effect of warm vacuum barriers



Capacity tests

- Goal: validate that the cryogenic system can provide sufficient cooling for the magnets
- Highest heat dissipation during 19-minute nominal magnet ramp (14.6 A/s): 135 W (static) + 201 W (dynamic) → **336 W**
- Capacity tests: nominal fluid conditions during the ramp → cooling power can be calculated from temperatures in Line C



Results

- Cooling capacity (after TL01 repair): 6 g/s (cold powering) + **310 W** (magnets) at 1.8 K
- With the measured $\boldsymbol{\Delta p}$ **in Line B,** the current ramp will start at 1.8 K → magnets will drift in T by less than 0.1 K during the ramp and remain at around 1.9 K during ramp & nominal operation

Conclusion: cryogenic system has a sufficient cooling capacity to keep the magnets at 1.9 K during nominal operation

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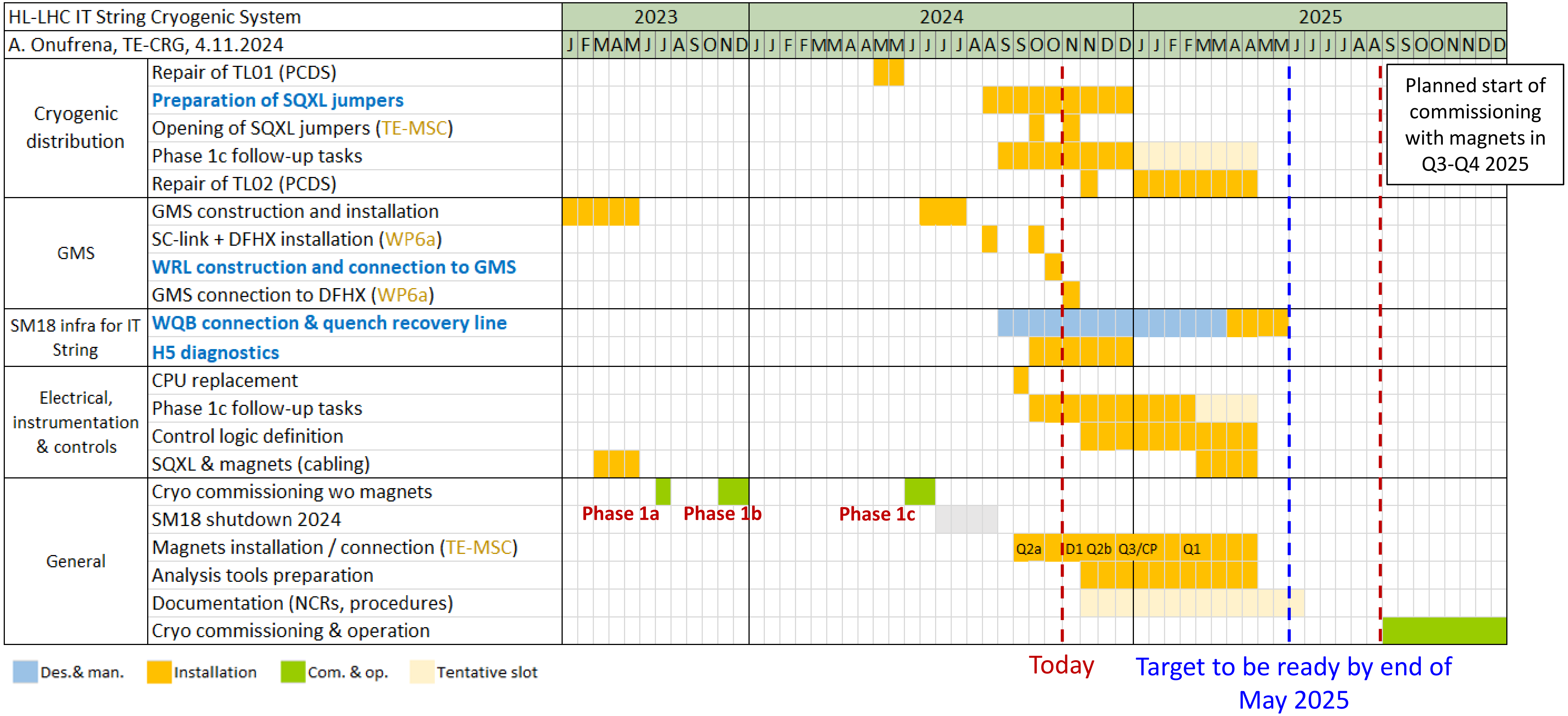
Next steps: planning for 2025

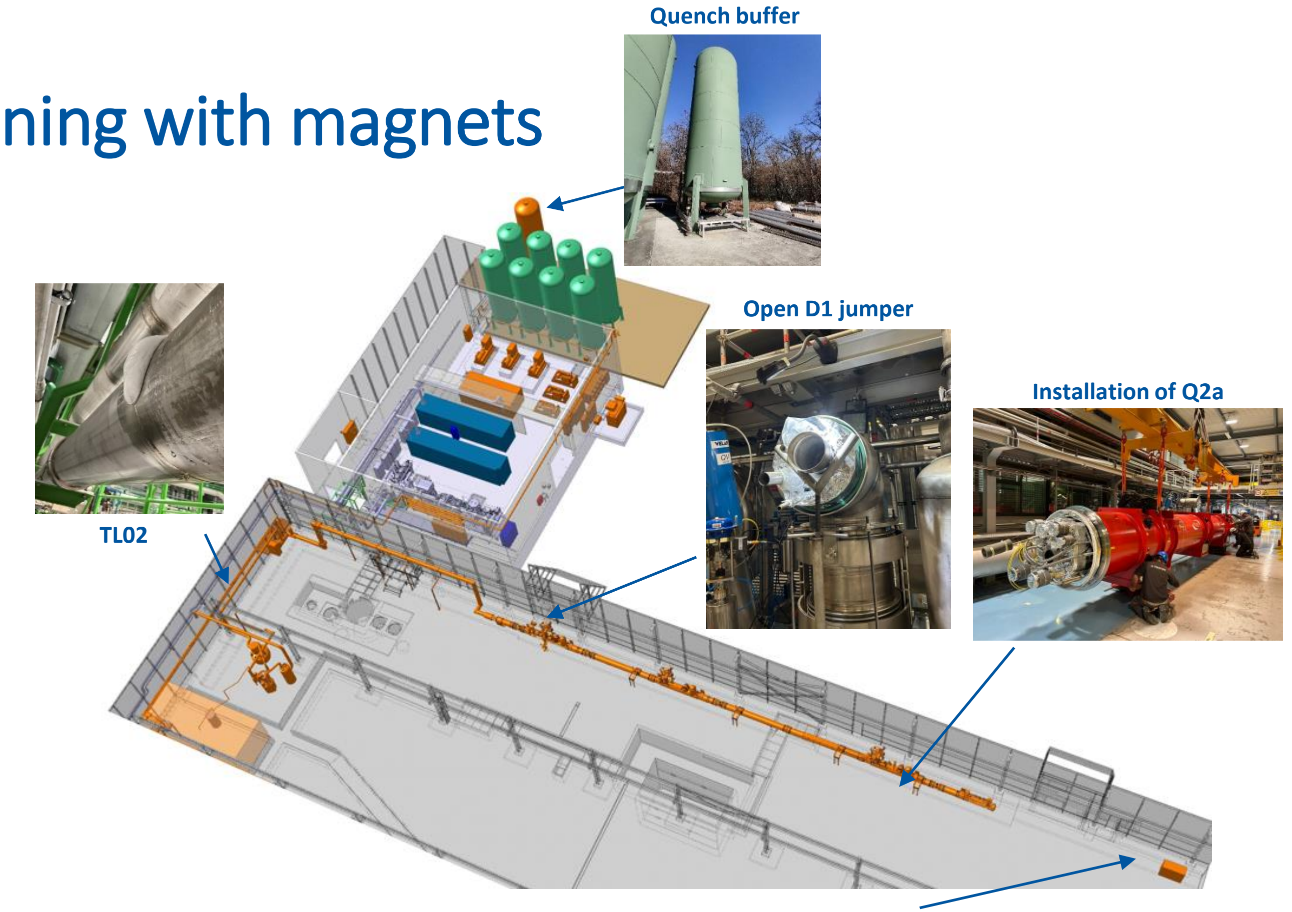
- Magnets planned to be in place by Mar 2025 and commissioning with magnets is planned for Q3-Q4 of 2025 → aim to have the cryogenic system ready by May 2025

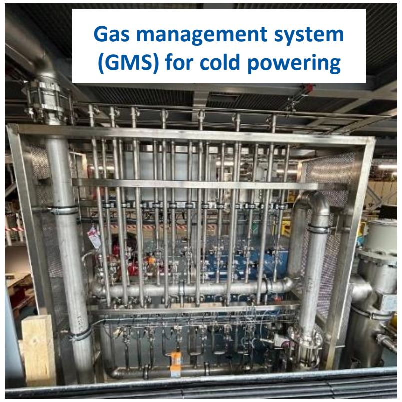


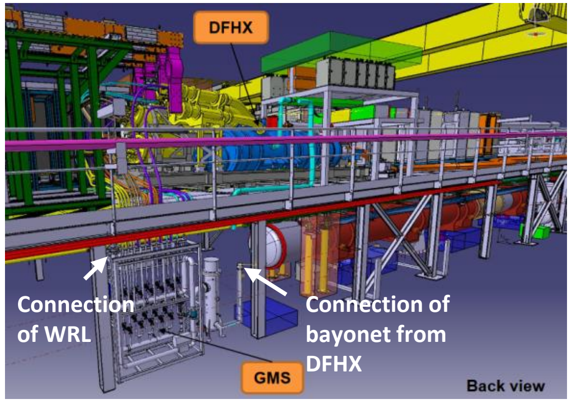
Next steps: preparation of commissioning with magnets

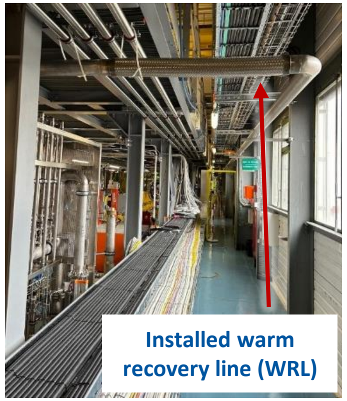
Mechanical activities

- SQXL jumper preparation for magnet connection is on-going
    - Q2a arrived and D1 jumper open (TE-MSC)
    - D1 installation planned this week
- Connection of cold powering:
    - Gas management system (GMS) installed
    - Warm recovery line (WRL) constructed and connected to GMS
    - GMS to be connected to DFHX (WP6a)
- Warm quench buffer connection
    - Design / preparation for fabrication of connection are on-going
    - Connection is planned for Mar-Apr 2025
- Mechanical consolidations following commissioning without magnets (TL02, valve checks) are on-going









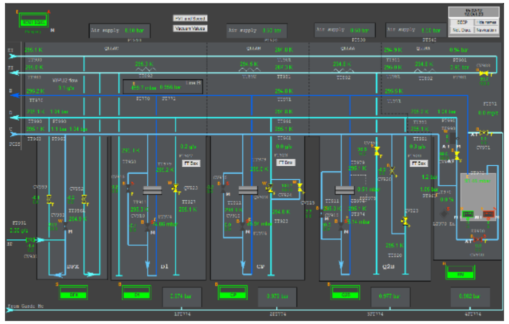
Next steps: preparation of commissioning with magnets

Electrical activities

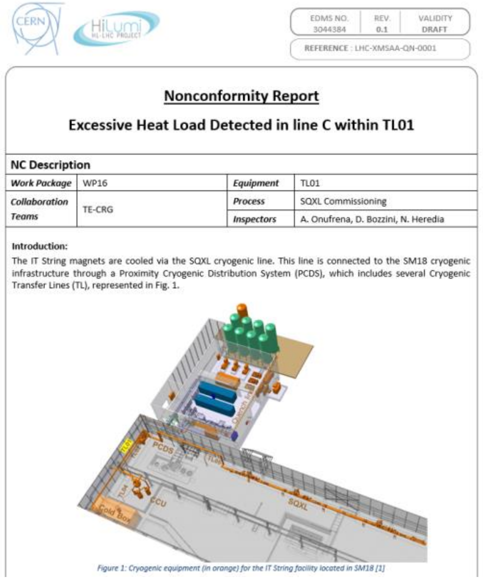
- Cabling of the magnet & cold powering instrumentation
  - Rack side: GMS and DFHX connection is in progress
  - IT String side (magnet and DFHX): connections are in preparation
- H5 diagnostics and installation of HL-LHC-like CPU (on-going)
- Fast acquisition and data acquisition validation
- Instrumentation consolidations following commissioning

Preparation for commissioning with magnets

- Preparation of test procedures and documentation
  - IT String commissioning document (sequences, functional specification)
  - NCRs (TL01 completed, TL02 in preparation)
- Control logic and analysis tools (to be defined and programmed)
- Review of interfaces with other systems (vacuum, quench protection)



Control logic to be defined



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3044384	0.1	DRAFT

REFERENCE : LHC-XMSAA-QN-0001

Nonconformity Report

Excessive Heat Load Detected in line C within TL01

NC Description

Work Package	WP16	*Equipment*	TL01
Collaboration Teams	TE-CRG	*Process*	SQXL Commissioning
		Inspectors	A. Onufrena, D. Bozzini, N. Heredia

Introduction:

The IT String magnets are cooled via the SQXL cryogenic line. This line is connected to the SM18 cryogenic infrastructure through a Proximity Cryogenic Distribution System (PCDS), which includes several Cryogenic Transfer Lines (TL), represented in Fig. 1.

Figure 1: Cryogenic equipment (in orange) for the IT String facility located in SM18 [1]

Conclusions

- Cryogenic system for IT String has been built and commissioned in a standalone mode (without magnets and cold powering)
- Mechanical integrity and functionality of instrumentation were validated
- IT String cooldown procedure was validated, and nominal conditions were achieved in all lines
- Heat loads and pressure drop measured (system characterization) → higher heat loads than expected on Lines C/D
- The cryogenic system has a sufficient cooling capacity to keep the magnets at 1.9 K → system has been validated for the IT String operation
- Activities in preparation for commissioning with magnets (Phase 2) are on-going

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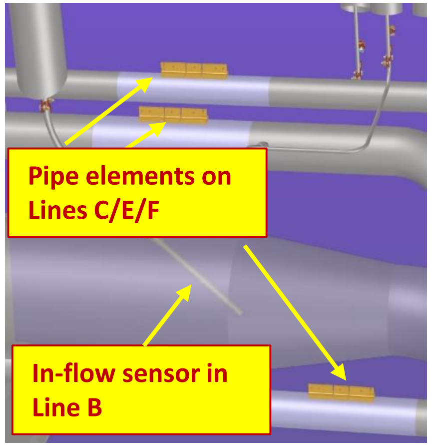
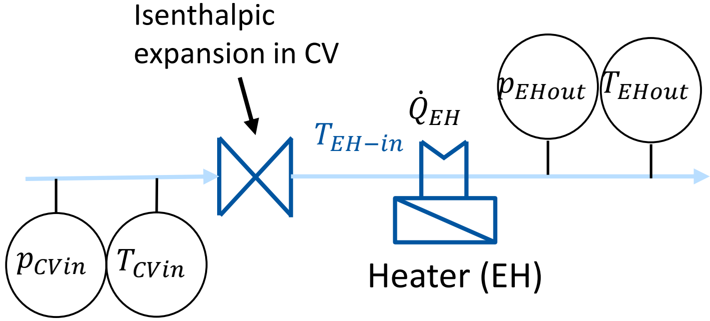
Heat loads: measurement methods and challenges



- Challenges: high uncertainties at low $\dot{m}$, low ΔT near c_p peak for Line C, stratification of supercritical fluid at low $\dot{m}$, radiation shield T drift during tests at low $\dot{m}$

$$\dot{Q} = \dot{m} \cdot (h_{in}(p_{in}, T_{in}) - h_{out}(p_{out}, T_{out}))$$

- Temperature: sensors (pipe elements and in-flow sensors) located along the lines were used for T evaluation



- Mass flows rate:
  - Mass flow meters (e.g. Coriolis) installed on some lines
  - Four additional methods to determine $\dot{m}$:
    1. Using the position and flow coefficient K_v of a control valve ($K_v \propto \frac{\dot{m}}{\sqrt{\rho \Delta p}}$)
    2. Using an in-flow heater and ΔT across it
    3. Using a heater immersed in liquid helium and the latent heat of evaporation
    4. Using the inlet pressure of the volumetric WPU