Heat and mass transfer analysis for the design of the cryogenic system for the HL-LHC IT String

G. Rolando, O. Duran Lucas, A. Wanninger, O. Pirotte, M. Sisti and A. Perin

CERN, Technology Department, Cryogenics Group

CHMT 2019
November 5th, 2019

Outline

The HL-LHC & IT String projects

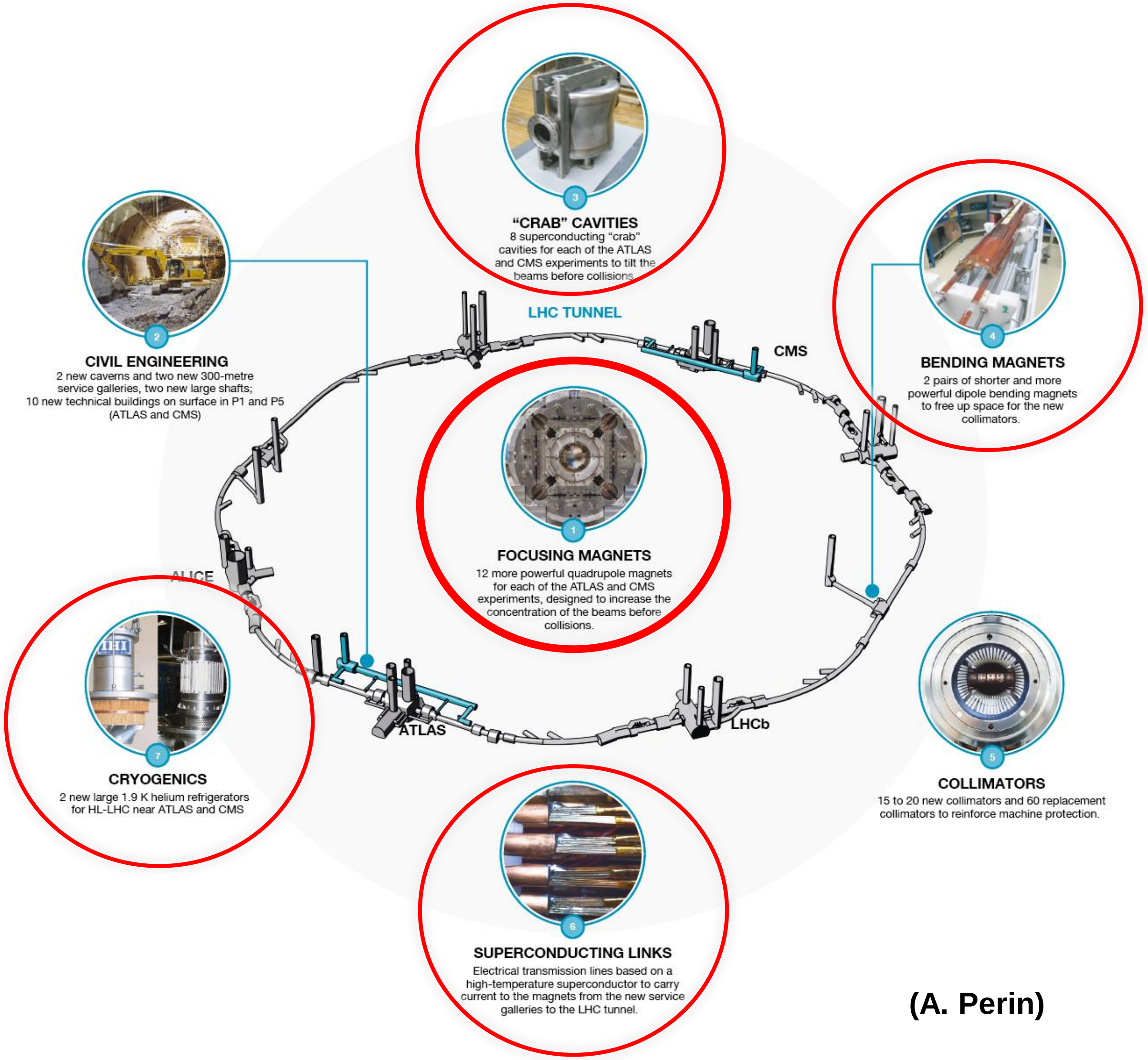
- Objectives
- Operation modes
- The cryogenic distribution system

Cryogenic operation modes

- Cool down
- Quench

Conclusions

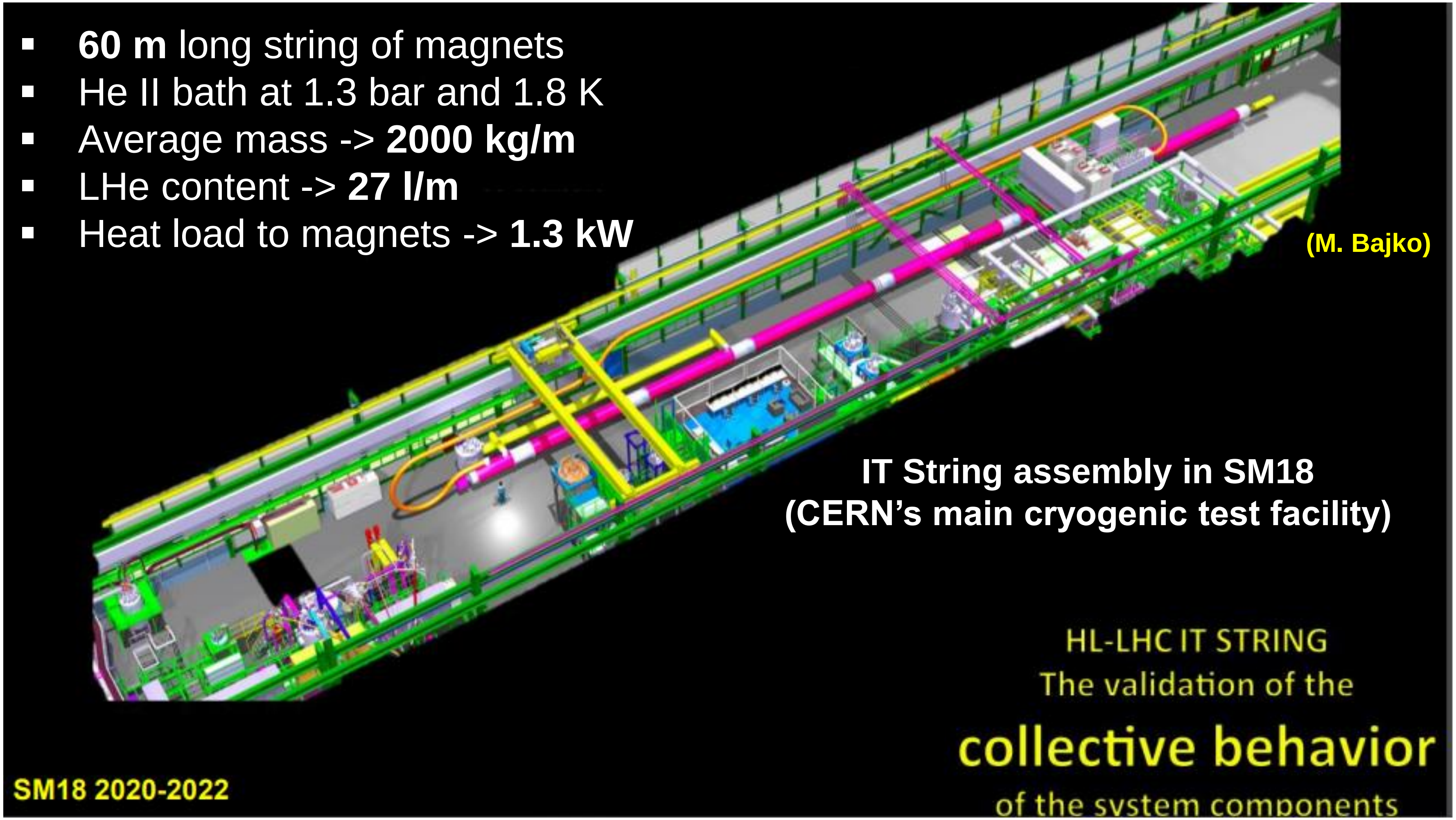
Cryogenics for the HL-LHC project



(A. Perin)

The Inner Triplet String project

- **60 m** long string of magnets
- He II bath at 1.3 bar and 1.8 K
- Average mass -> **2000 kg/m**
- LHe content -> **27 l/m**
- Heat load to magnets -> **1.3 kW**



(M. Bajko)

IT String assembly in SM18
(CERN's main cryogenic test facility)

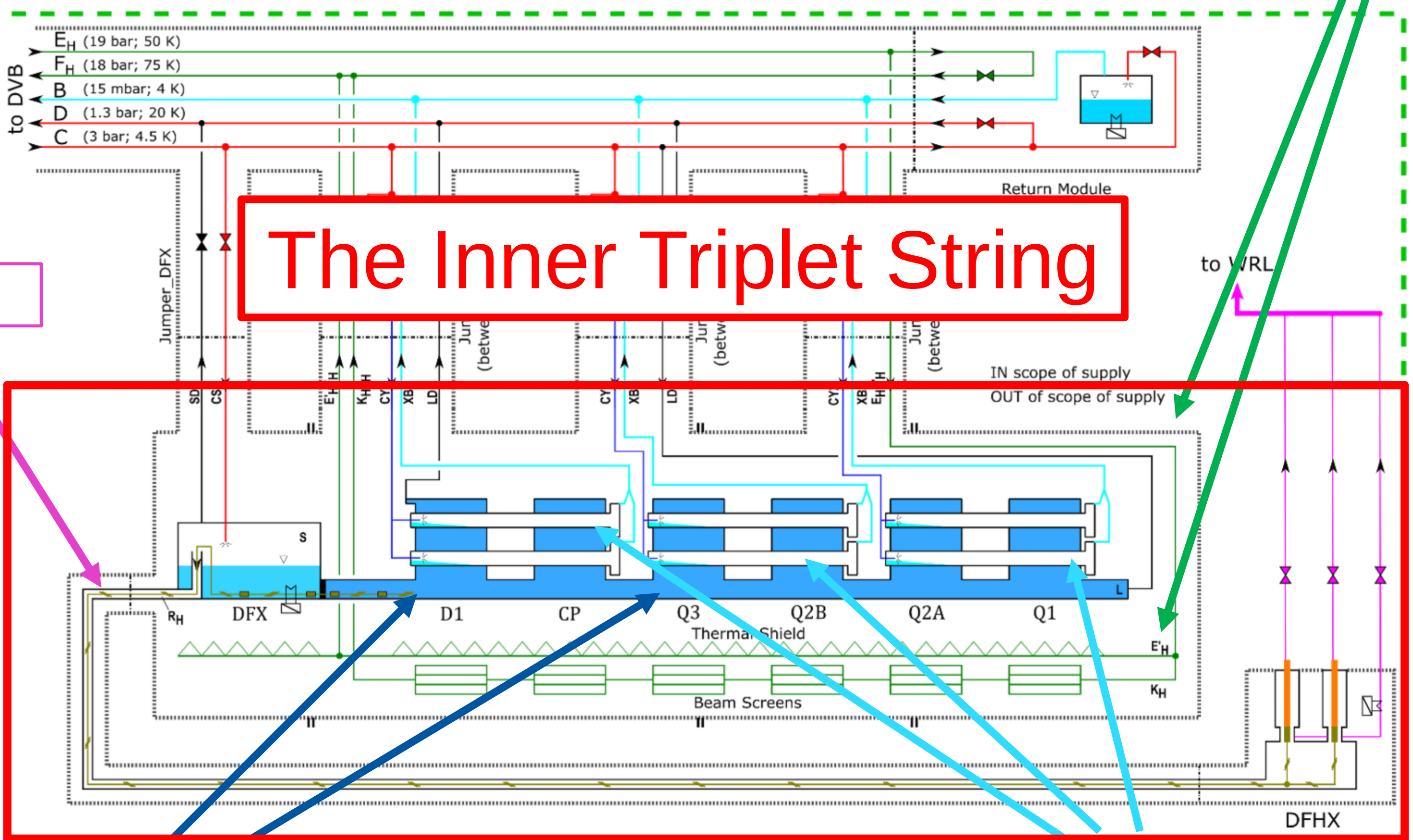
Operation modes

- **Cool down** in **max 15 days** using existing SM18 cryogenic infrastructure
  1. From 300 K to 4.5 K
  2. Magnet filling by condensation
  3. From 4.5 K to 1.8 K
- Steady state operation
- Current ramping of the magnets
- Maximum heat load test (removal of 500 W)
- **Magnet quench**
- **Quench recovery** in **max 12 hours** to limit the duration of the test program
- Warm Up
  1. Magnet empting
  2. From 5 K to 300 K

IT String components

Thermal shield and beam screen circuits

SC link



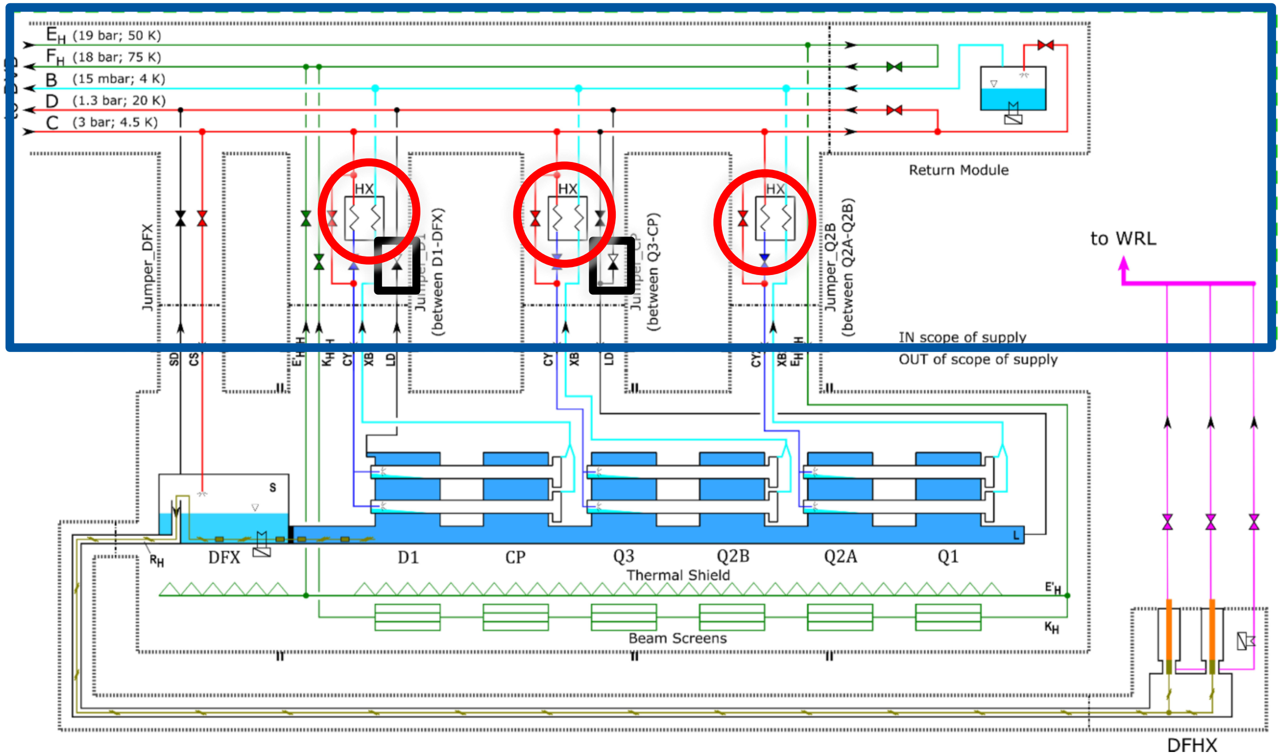
6 magnets in inter-connected cryostats

Bayonet heat exchanger for heat load removal from cold mass

Cryogenic Distribution System – Part 1

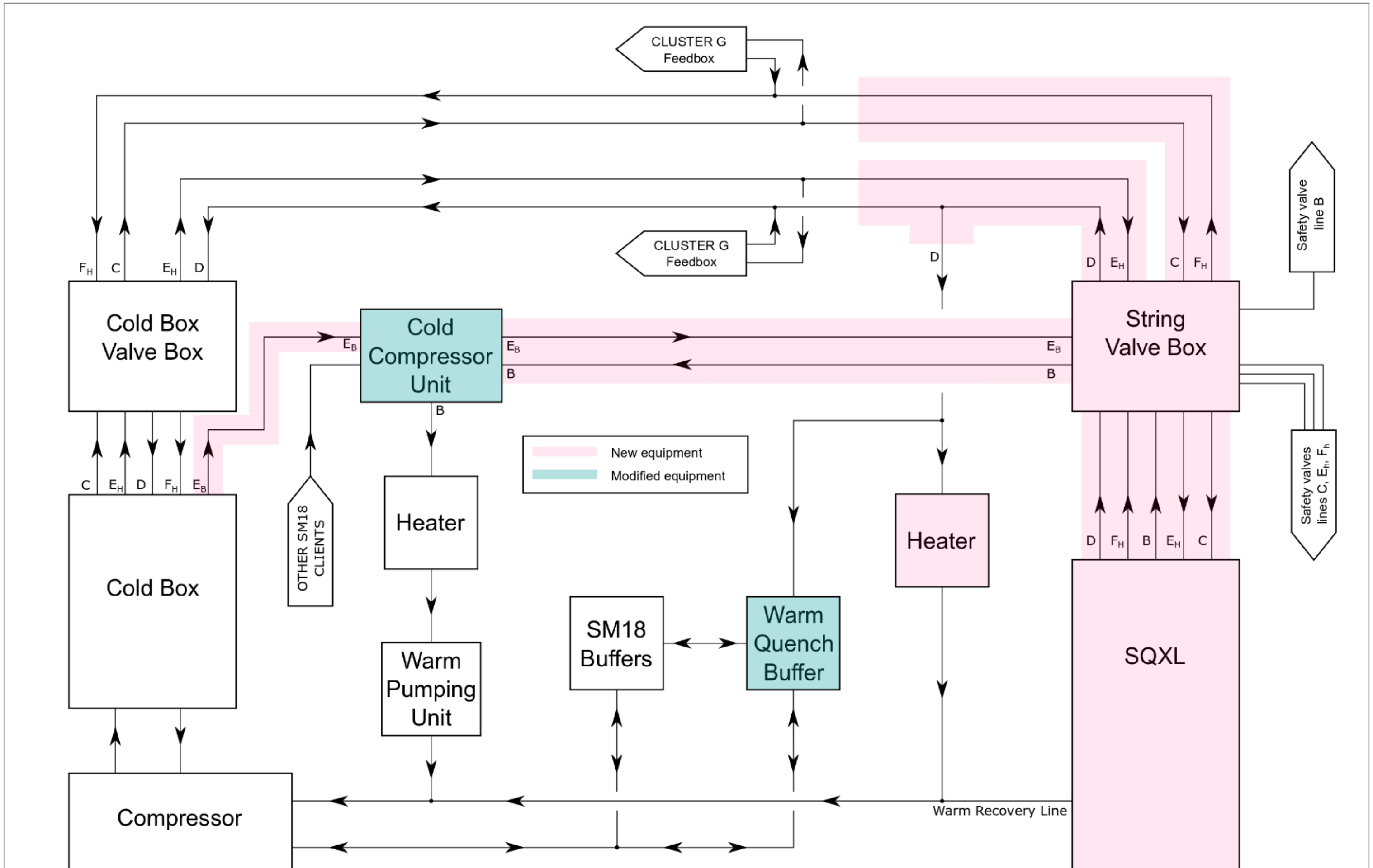
Line B – low pressure pumping
Line C – SC He supply
Line D – GHe return
Line E – thermal shield supply
Line F – thermal shield return

4.5 K LHe inlet flow sub-cooled by pumping line in counter-flow HX



Quench valves for magnet protection against over-pressure

Cryogenic Distribution System – Part 2



(O. Duran Lucas)

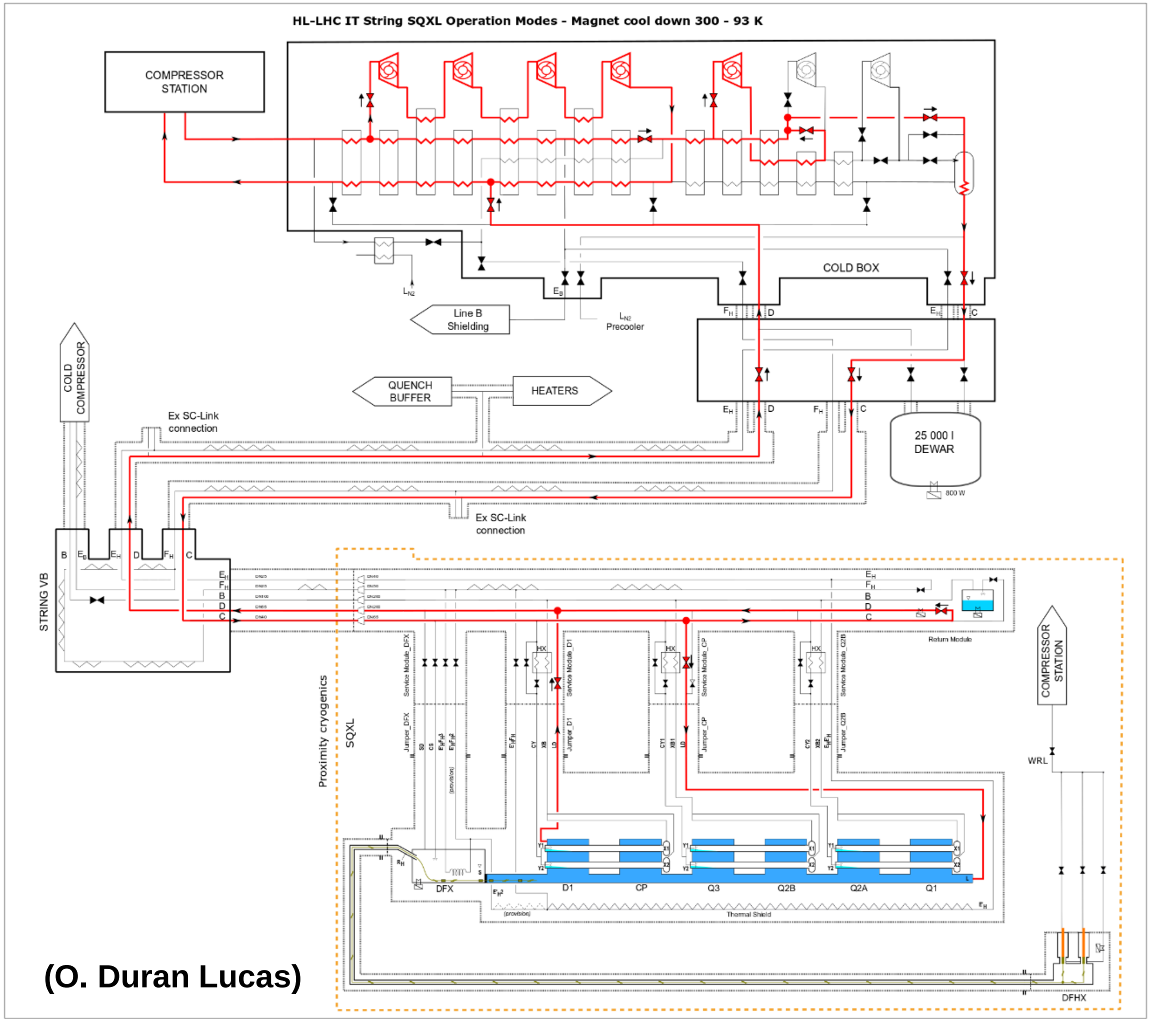
Cool down from 300 K to 1.8 K

LN_2 pre-cooling is used for the cool down of the LHC.
Is LN2 pre-cooling required to meet the IT String target cool down time of 15 days?

Cool down from 300 K to 4.5 K

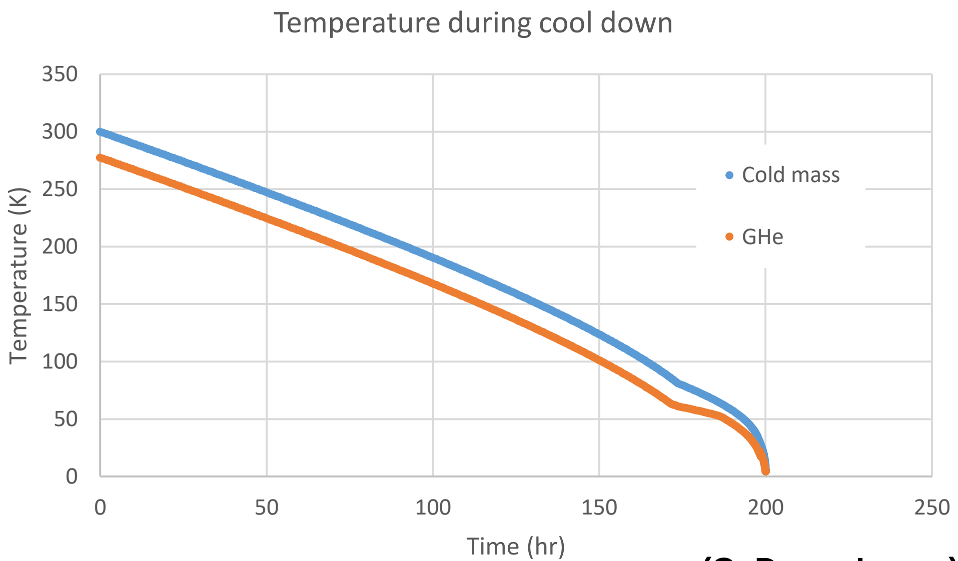
Cold box refrigeration power between 300 K and 4.5 K without LN_2 pre-cooling
(U. Wagner)

Helium supply temperature [K]	Cold box power [kW]
300	16.6
285	12.2
70	11.7
20	6
4.5	4



(O. Duran Lucas)

Cool down from 300 K to 4.5 K



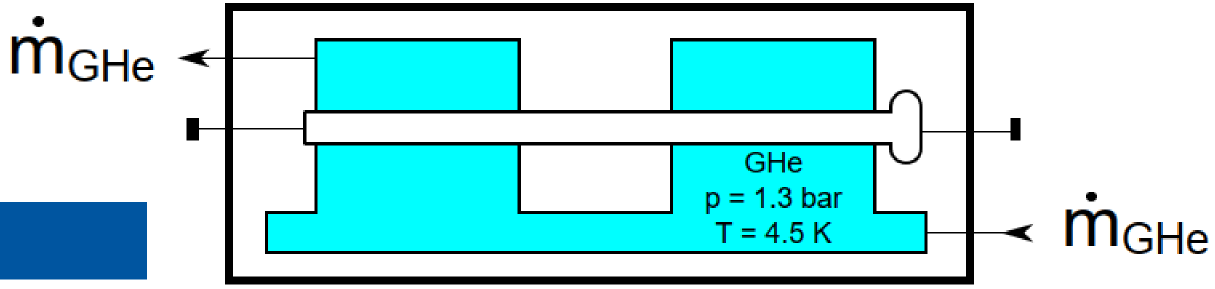
(O. Duran Lucas)

- **Cool down** time from 300 K to 4.5 K is **8.5 days**, without LN2 pre-cooling
- **Max temperature difference** between GHe flow and cold mass is **23 K**
  - ➢ **important for Nb_3Sn magnets!**

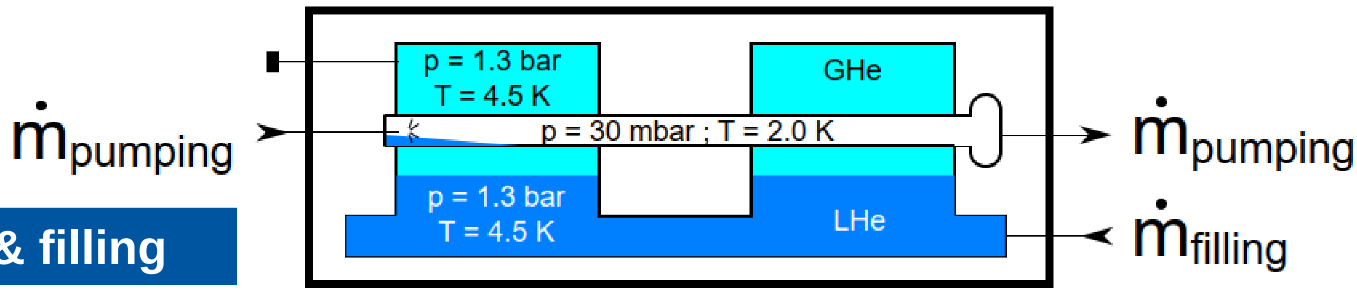
Magnet filling by condensation

- GHe in cryostat is liquefied by pumping, while the cryostat is filled
- **Cryostat** volume is **1.5 m^3**
- Available **LHe** mass flow is **25 g/s**
- Available pumping capacity is **18 g/s at 30 mbar**

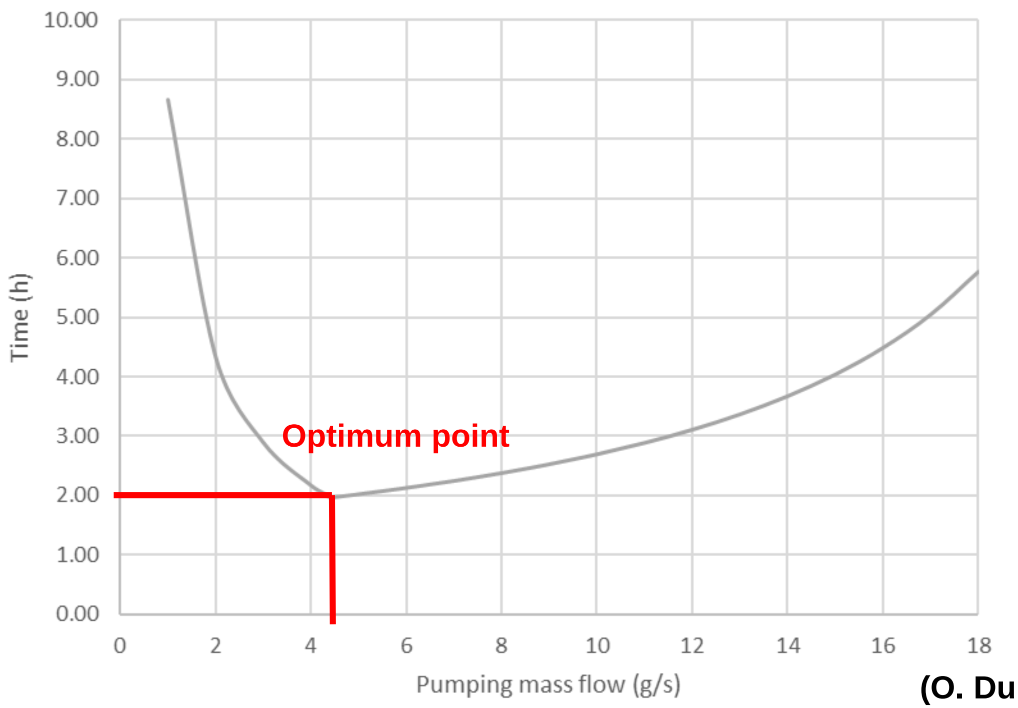
1. Initial state



2. Condensing & filling



Optimization of magnet filling

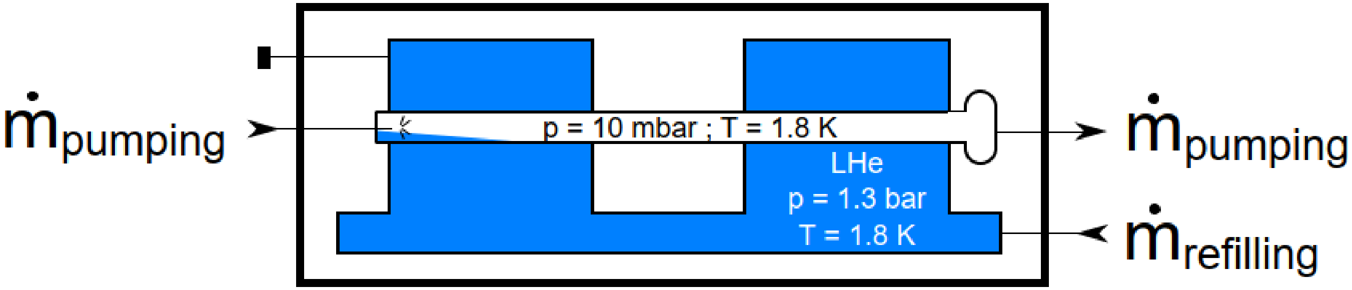


(O. Duran Lucas)

- Magnet **filling** requires **2 h**
- Optimal flow repartition is **5 g/s** for **pumping** and **20 g/s** for **filling**
- Optimal mass flow repartition is independent from initial LHe level in cryostat

Cool down from 4.5 K to 1.8 K

Available pumping speed reduces from 18 g/s at 30 mbar in bayonet HX to 6 g/s at 10 mbar



- **Cool down** time from 4.5 K to 1.8 K is **2.1 hours**
- **Filling** LHe mass flow required during cool down to 1.8 K is **6.6 g/s**
- **Overall LHe mass flow** during cool down from 4.5 K to 1.8 K is **lower than** cold box liquefaction capacity of **25 g/s**

Overall cool down time of HL-LHC IT String from 300 K to 1.8 K is well below 15 days

Quench

How much helium will be expelled from the cryostat?
What is the temperature of the helium?
Will there be any liquid to boost the quench recovery?

The HL-LHC IT String quench program

A **magnet quench** is the transition from the superconducting to the normal conducting state.
The energy stored in the magnetic field is dissipated into the cables and released into the cold mass.

Quench test program

Name	Current	Energy [MJ]	Number
Low	0.1 x $I_{nominal}$	0.4	69
Medium	0.4 x $I_{nominal}$	6.3	51
High	0.75 x $I_{nominal}$	22.0	51
Nominal	$I_{nominal}$	39.1	20

The **quench relief system** includes all the components necessary to accommodate the quench energy in the cryogenic system without exceeding the design parameters of the system.

Buffer volumes are integrated into the cryogenic system to accommodate the quench energy:

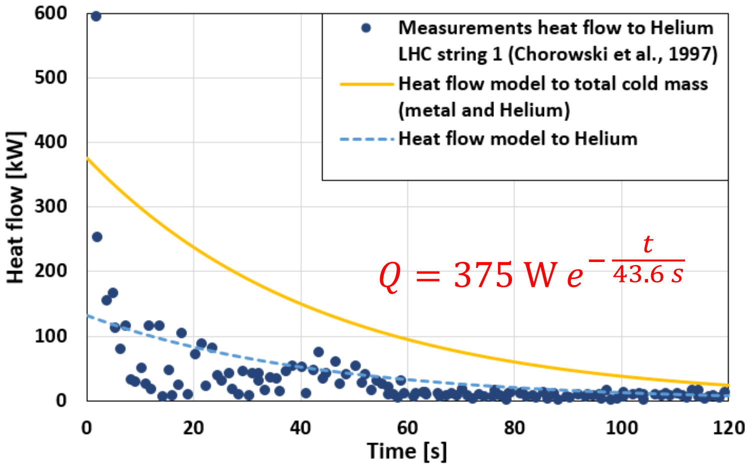
- **cold buffers** maintained at cryogenic temperatures during operation;
- **warm buffers** at ambient temperature.

The **cold quench buffer** is used to recuperate cold He during a quench to **speed up quench recovery** by boosting the cold box.

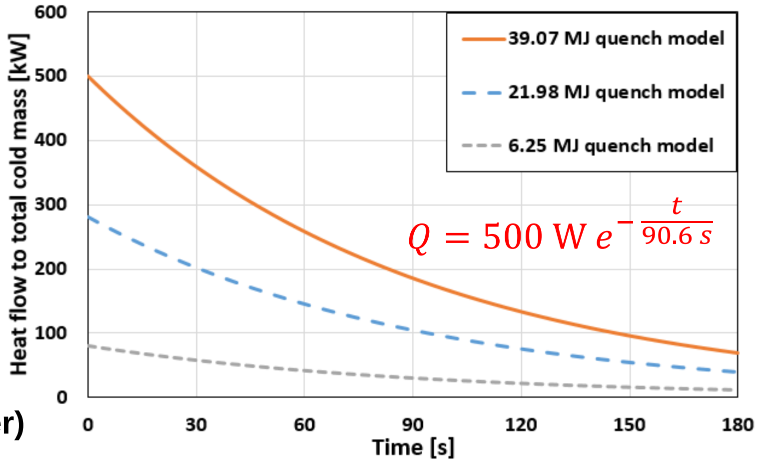
Heat flow during a quench

- **Input** for quench analysis is the **heat deposited into the cold mass and helium**
- No data available for HL-LHC magnets. Deposited **heat load obtained by re-scaling LHC data**
- Nb_3Sn HL-LHC inner triplet magnets
  - "Dry magnets" -> no He entering through pores into the SC cable and in contact with the strands
  - Coils impregnated with insulating epoxy resin -> lower heat transfer area and higher (x10) thermal resistance
  - Higher (x1.33) temperature increase in SC cable following a quench

LHC heat load following a quench



HL-LHC heat load following a quench

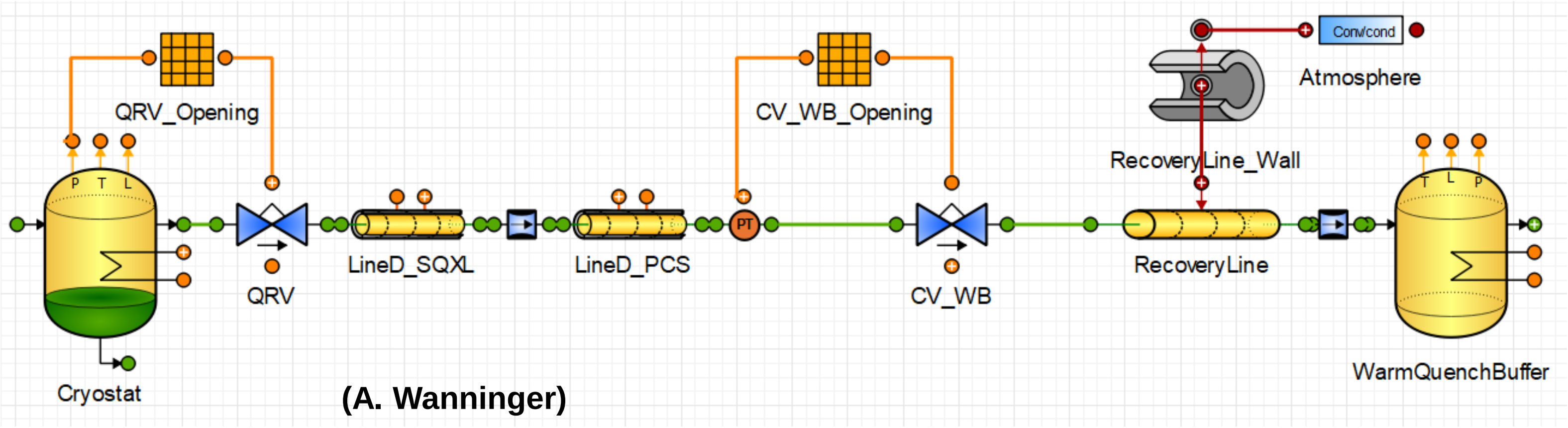


(A. Wanninger)

1D-thermohydraulic dynamic model - EcosimPro

CRYOLIB is a EcosimPro library developed at CERN of cryogenic components for thermodydraulic network systems.

- **Cryostat**: single volume (1.5 m³ Helium and 84.2 tons metal) with heat source
- **Quench relief valve (QRV)**: Kv 30, opens at 17 bar, fully open at 20 bar
- **Line D**: two pipe components with a total volume of about 2 m³ and total length of 90 m
- **Cold buffer:** different volumes (optional)
- **Control valve to warm buffer (CV_WB):** opening at 13 bar
- **Recovery line**: > 100 m non-insulated pipe (atmospheric heating)
- **Warm buffer**: 80 m³ single volume



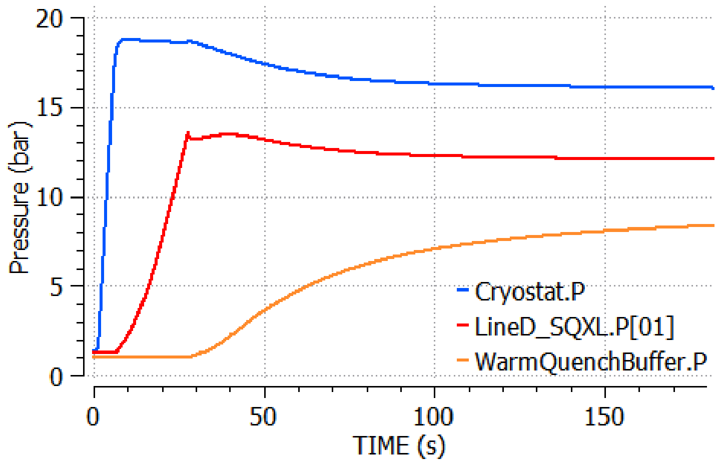
(A. Wanninger)

Dynamic quench simulation results

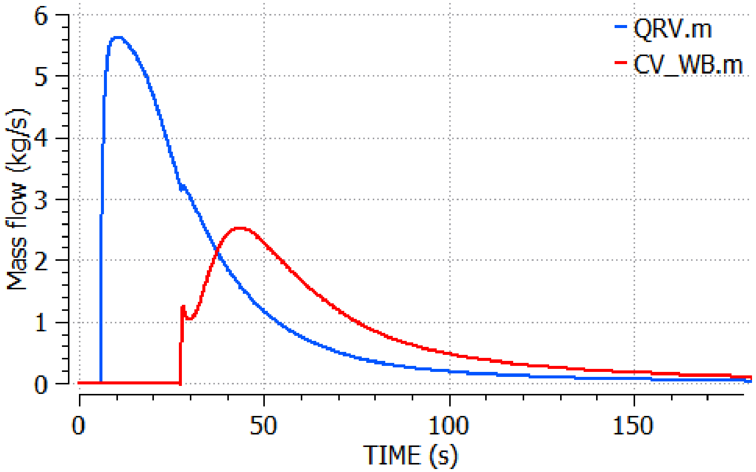
The cryogenic system following a 39.1 MJ quench:

- Heat is transferred from the magnet coils to the magnet cold mass after the quench at t = 0 s
- At 17 bar in the cryostat, the quench valve opens and helium is relieved into line D
- At 13 bar in line D, helium is relieved into the warm buffer

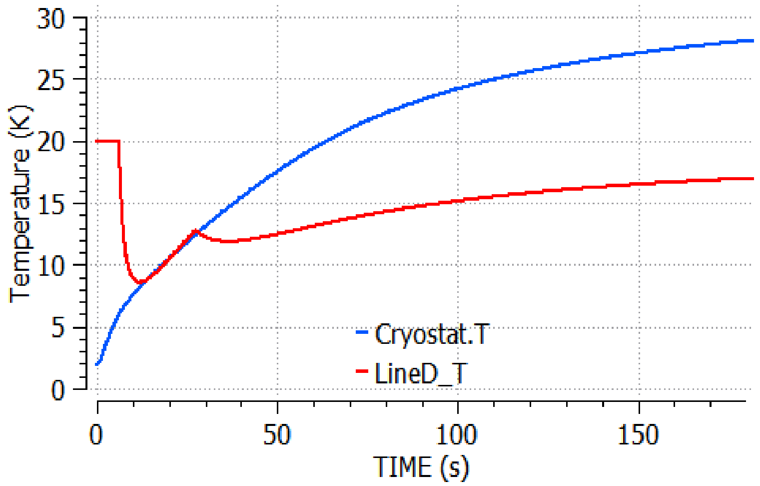
Pressure in cryostat and buffers



Mass flow through valves



Temperature in cryostat and line D



(A. Wanninger)

Conclusions

Heat and mass transfer analysis for the design of the Proximity Cryogenics for the IT String:

- Cool down
- Quench analyses
- Quench recovery strategy
- Warm quench buffer minimum temperature following a quench
- Warm-up time and heater power

Cryogenic parameters

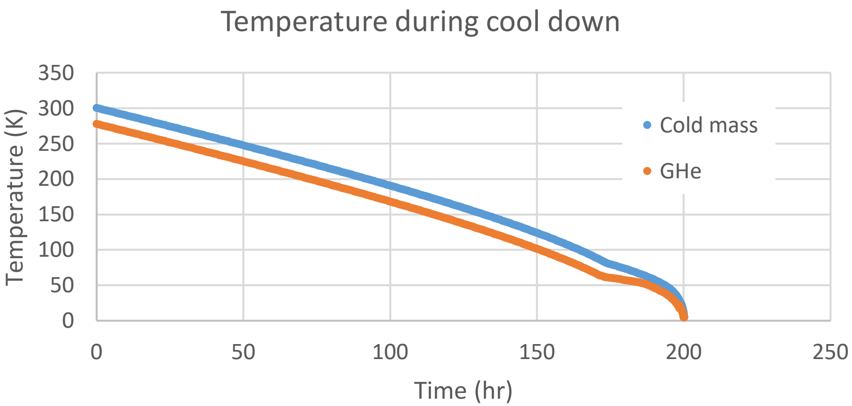
Line	Pipe Size	Nominal Pressure [bar]	Operational Temperature [K]	Maximum Flow Rate [g/s]
B	DN100	0.010 – 0.016	4.5	24
C	DN40	4	4.6	25
D	DN65	1.3	20	5800
E_{th}	DN25	19	50	23
E_{th}	DN25	19	50	23
F_{h}	DN25	18	75	23

Cool down from 300 K to 4.5 K

$$P_{CB} = \dot{m}_{He} \cdot \left(h_{T_m} - h_{T_{He}}\right) = m_m \cdot Cp_m \cdot CD_{Rate}$$

- P_{CB}: Cold box power
- $\dot{m}_{He}$: He mass flow rate
- $h_{T_m} - h_{T_{He}}$: He flow – cold mass enthalpy difference
- m_m: Cold mass
- Cp_m: Cold mass specific heat
- CD_{Rate}: Cold mass cool down rate

Cool down time from 300 K to 4.5 K

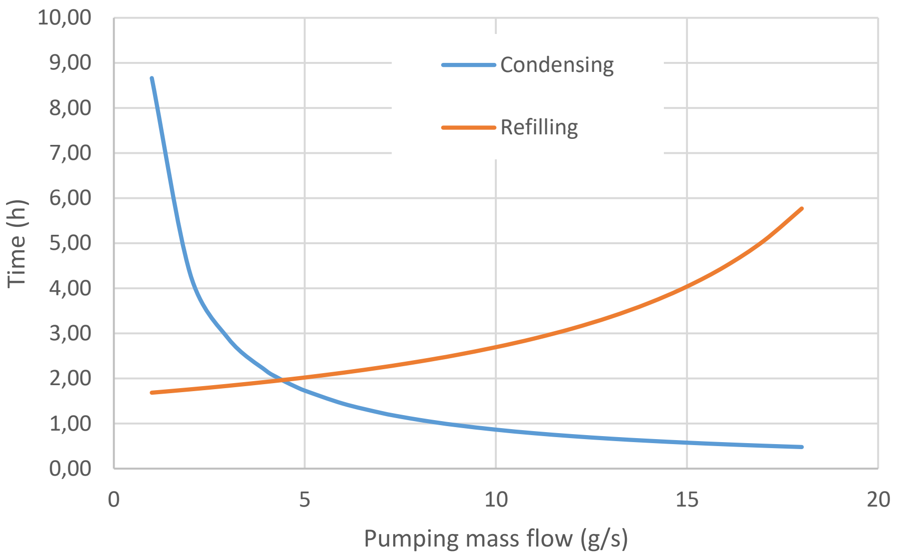


Conclusions:

- **Cool down** time from 300 K to 4.5 K is **8.5 days**
- **Max temperature difference** between GHe flow and cold mass is **23 K** – important for Nb_3Sn magnets!
- **No need of LN_2 pre-cooling**

Magnet filling

- GHe in cryostat is liquefied by pumping, while the cryostat is filled
- Cryostat volume is 1.5 m^3
- Available LHe mass flow is 25 g/s
- Available pumping capacity is 18 g/s at 30 mbar



$$t_{liquefaction} = \frac{V_{cryostat} \cdot \rho_{sat\ GHe\ @\ 1.3\ bar} \cdot L_{@\ 1.3\ bar} \cdot \left(1 - \%_{cryostat\ initial\ filling}\right)}{\dot{m}_{pumping} \cdot L_{@\ 30\ mbar} \cdot (1 - \%_{flash})}$$

$$t_{filling} = \frac{V_{cryostat} \cdot \rho_{sat\ LHe\ @\ 1.3\ bar} \cdot L_{@\ 1.3\ bar} - m_{initial\ LHe\ in\ cryostat} - m_{initial\ GHe\ in\ cryostat}}{\dot{m}_{filling}}$$

Conclusions:

- Magnet **filling** requires **2 h**
- Optimal flow repartition is **5 g/s** for **pumping** and **20 g/s** for **filling**
- Optimal mass flow repartition is independent from initial LHe level in cryostat

Cool down from 4.5 K to 1.8 K

Available pumping speed reduces from 18 g/s at 30 mbar in bayonet HX to 6 g/s at 10 mbar

$$\boldsymbol{t_{cool\ down}} = \frac{m_{He} \cdot \Delta H_{He\ 4.5\ K\ -1.9\ K} + m_{cold\ mass} \cdot \Delta H_{SS\ 4.5\ K\ -1.9\ K}}{\dot{m}_{pumping} \cdot L_{@\ pressure\ bayonet\ HX} \cdot (1\ - \%_{flash})}$$

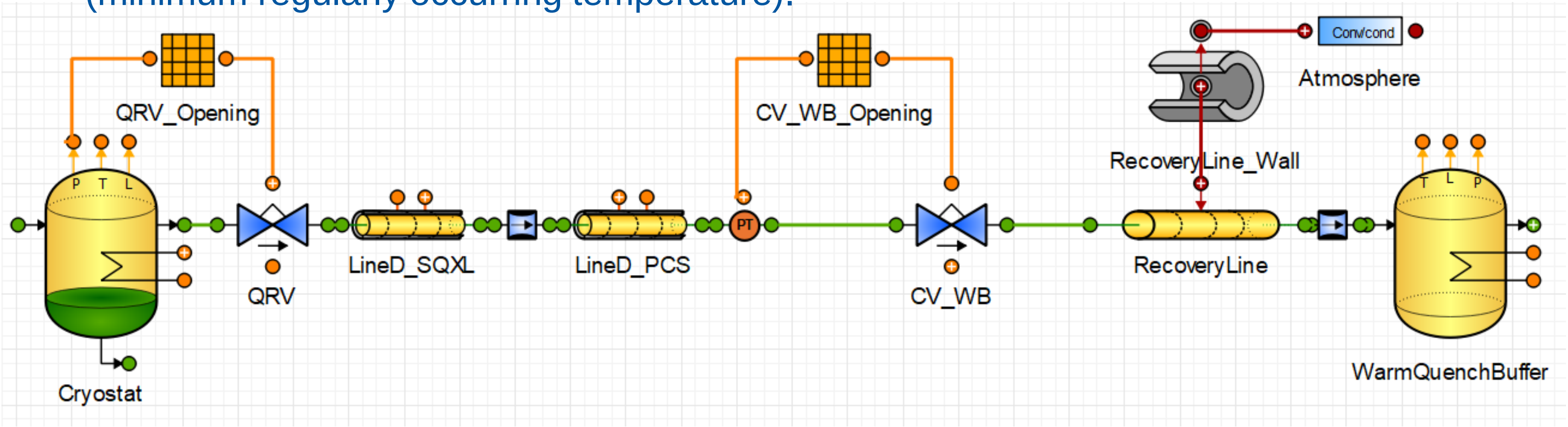
Conclusions:

- **Cool down** time from 4.5 K to 1.8 K is **2.1 hours**
- **Filling** LHe mass flow required during cool down to 1.8 K is **6.6 g/s**
- **Overall LHe mass flow** during cool down from 4.5 K to 1.8 K is **lower than** cold box liquefaction capacity of **25 g/s**

Overall cool down time of HL-LHC IT String from 300 K to 1.9 K is well below 15 days

Thermohydraulic dynamic model – Initial conditions and component details

- **System components:**
  - **Cryostat**: single volume with heat source and thick stainless-steel wall to represent heat capacity of metal cold mass, initially at 1.3 bar and 1.9 K.
  - **Quench relief valve**: Kv30, opens at 17 bar, fully open at 20 bar.
  - **Header D**: two pipe components (SQXL (string cryogenic transfer line): 50 m, DN 200; PCS (Proximity cryogenic system): 40 m, DN65), initially at 1.3 bar and 20 K.
  - **Cold buffer:** different volumes (only if required), initially at 1.3 bar and 20 K.
  - **Control valve to warm buffer (CV_WB):** opening at 13 bar.
  - **Recovery line**: > 100 m DN 150 non-insulated pipe exposed to natural convection and condensation of ambient air (atmospheric heating).
  - **Warm buffer**: 80 m³ single volume with carbon-steel wall, initially at 1 bar and -10 °C (minimum regularly occurring temperature).



Cold vs warm quench buffer

- Quench recovery by pumping on bayonet heat exchangers is not possible in 12 hours
  - ➢ Cryostat and line D must be depressurised after quench
- All inner triplet magnets quench simultaneously (as opposed to LHC dipole magnets)
  - ➢ Only small amounts of liquid expelled from cryostat, which is mostly evaporated within line D
  - ➢ Large cold buffer to retrieve cold Helium not useful

- 2 m³ of line D act as cold buffer volume

No interest in a cold quench buffer
Existing 80 m³ carbon-steel warm buffer is sufficient