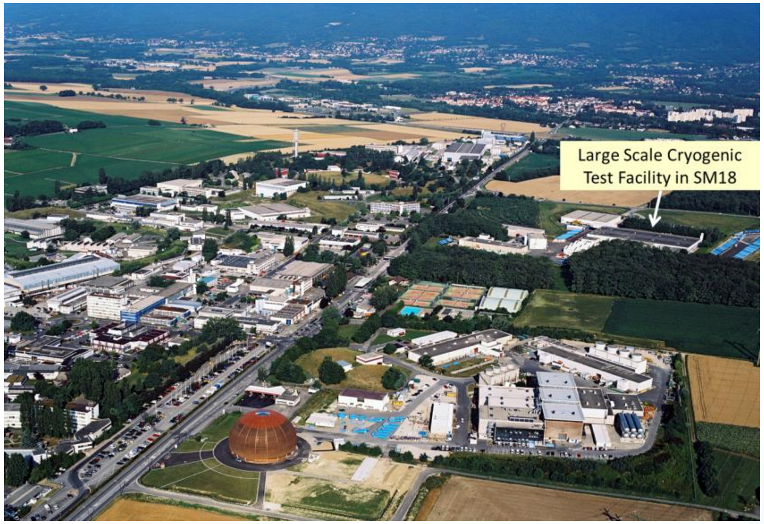



HiLumi
HL-LHC PROJECT

# Cryogenic system
## New high field magnet test facility and cryogenic feed boxes at CERN

V. Benda on behalf of cryogenic team

EuCARD²

CERN 13 June 2016

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

# New test facility required

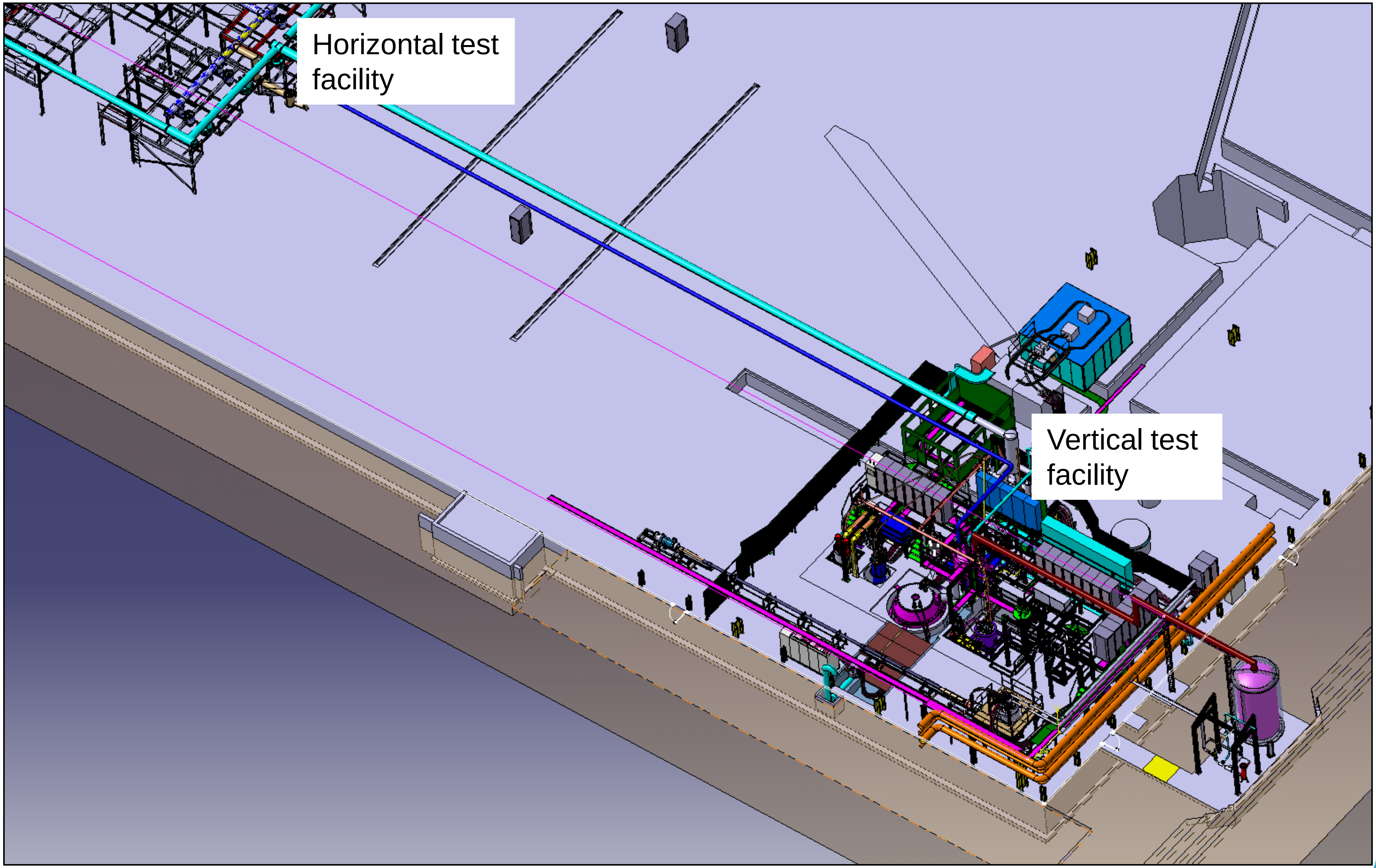
- For LHC upgrade a new generation of high field magnet is foreseen
- New High Field Magnet (HFM) test set up is required

| Parameter | Requirement |
|---|---|
| Working temperature | 1.9 ± 0.01 K (up to 4.5 K) |
| Maximum weight of the cold mass | 15 [t] |
| Maximum energy of the magnet | 10 [MJ] |
| Maximum magnet diameter and length | 1.5 / 2.5 [m] |
| Maximum number of quenches/thermal cycles | 10 000/1 000 |
| Life time | 20 [years] |
| Magnet test position | Vertical |
| Cool down and warm up speed (300 K – 80 K) | Adjustable |
| Helium management | No helium lost after a magnet quench |
| Cool down from 4.5 K down to 1.9 K | Quick and thermodynamically efficient |
| Heat in-leak of the system | Minimized |
| Process control and operation | Fully automatic and safe |

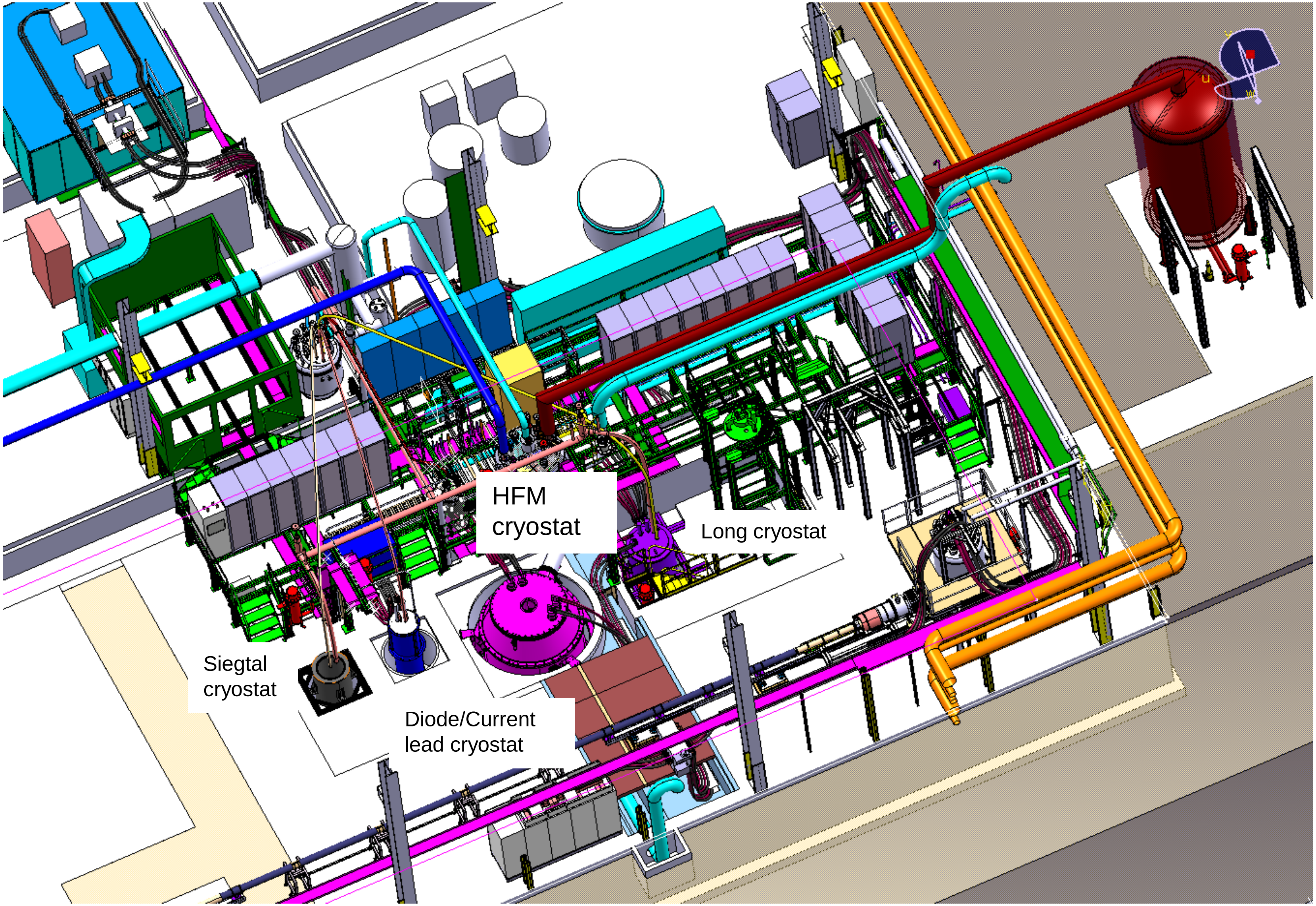
# HFM phases duration

| Phase | Duration | Note |
|---|---|---|
| Purge of the system including a leak test | $\tau = 2$ h | |
| Magnet cool down from 300 K to 80 K | $\tau = 10$ h - 200 h | If cooling speed limited |
| Magnet cool down from 80 K to 4.5 K | $\tau < 10$ h | At flow of LHe 15 g/s |
| Cryostat filling with saturated LHe at 1.3 b | $\tau < 5$ h | At flow of LHe 15 g/s |
| Magnet cool down from 4.5 K down to 1.9 K | $\tau = 24$ h | |
| Nominal condition during the magnet test at 1.9 K up to 4.5 K | One week | At least |
| Quench recovery | $\tau \sim 24$ h | Depending on quench energy |
| Evaporation of LHe from the system after magnet test | $\tau = 5$ h | |
| Magnet warm up from 5 K to 300 K | $\tau = 12$ h - 200 h | If warming speed limited |

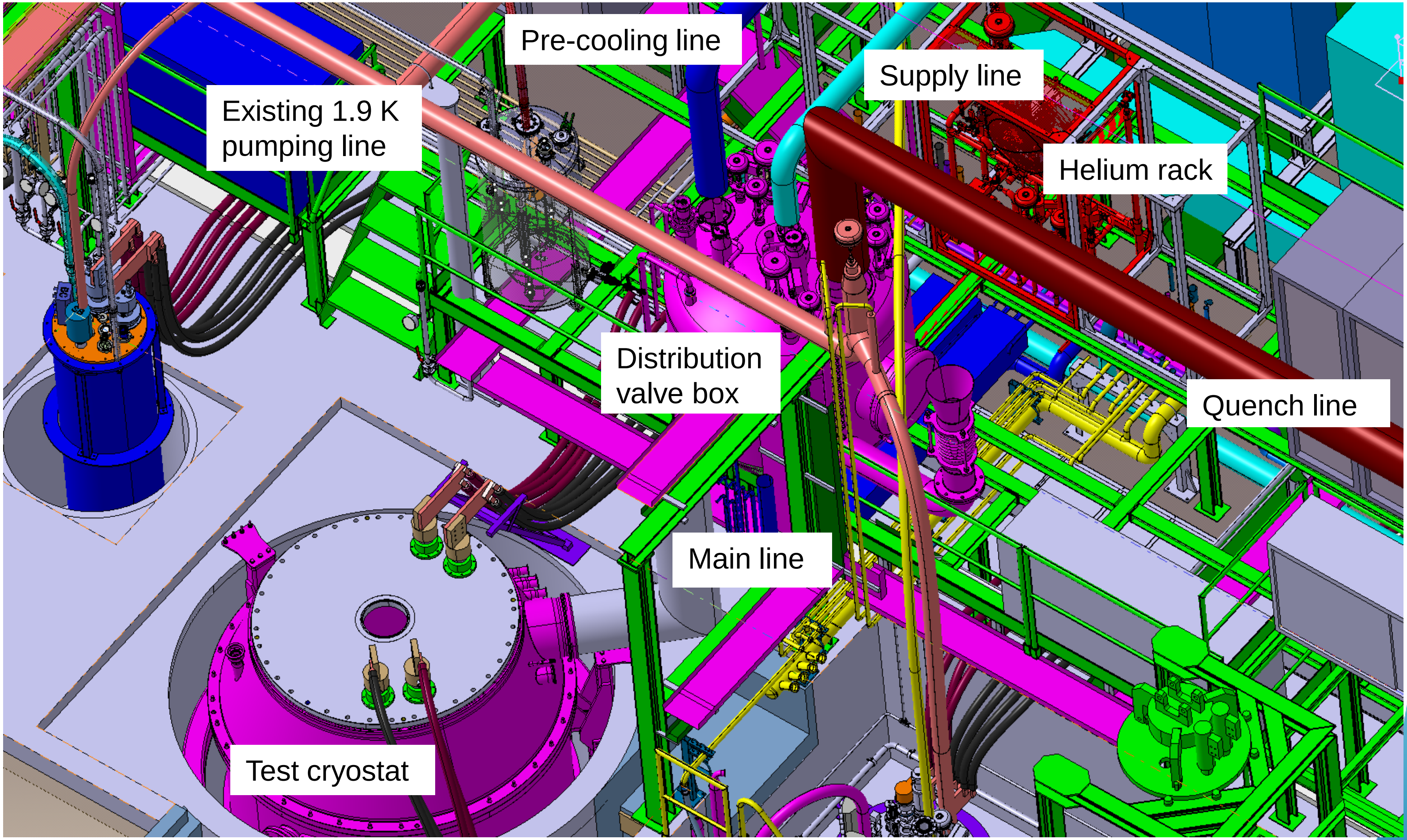
# SM18 overview



# HFM integration in the vertical test facility

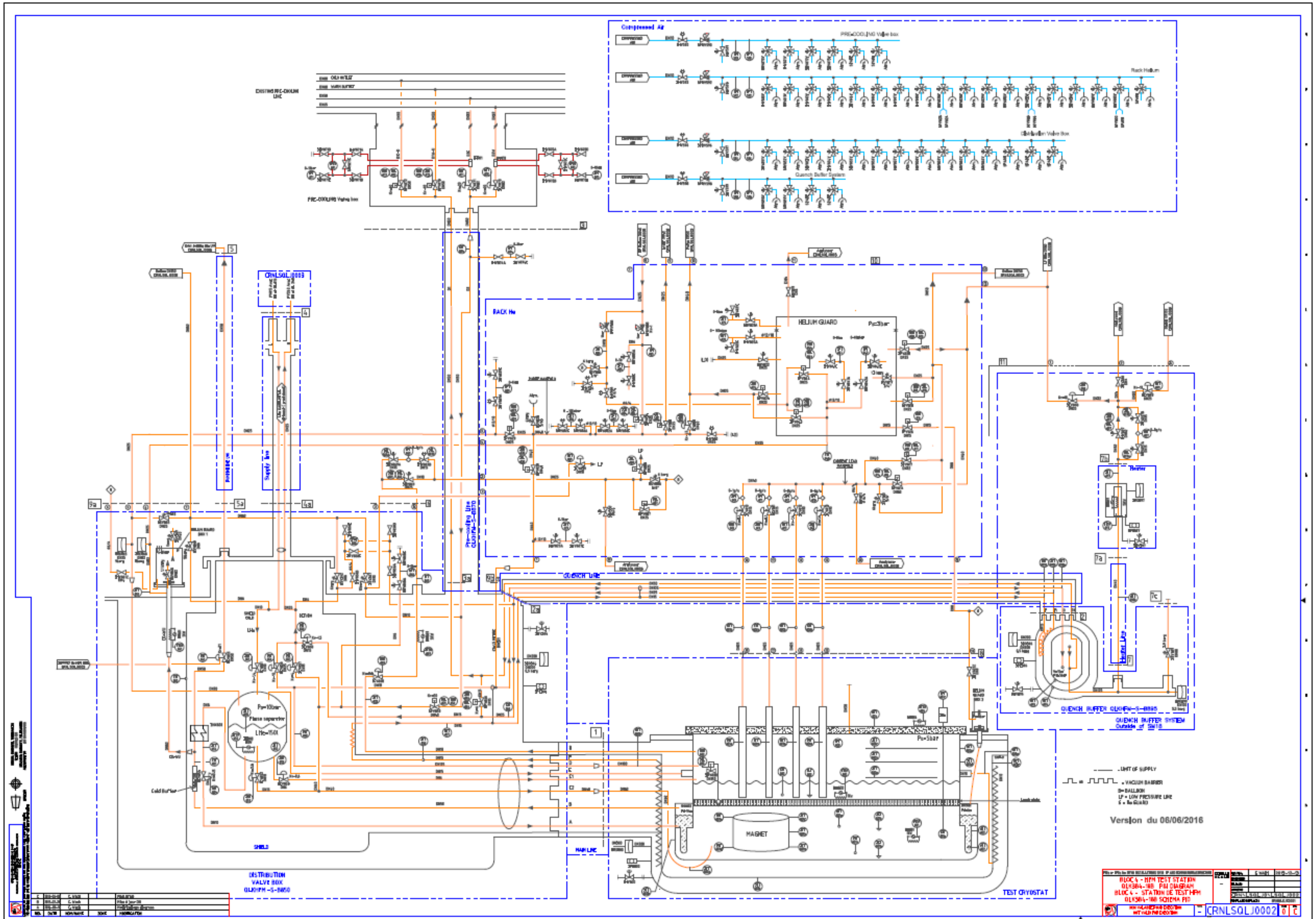


# HFM layout



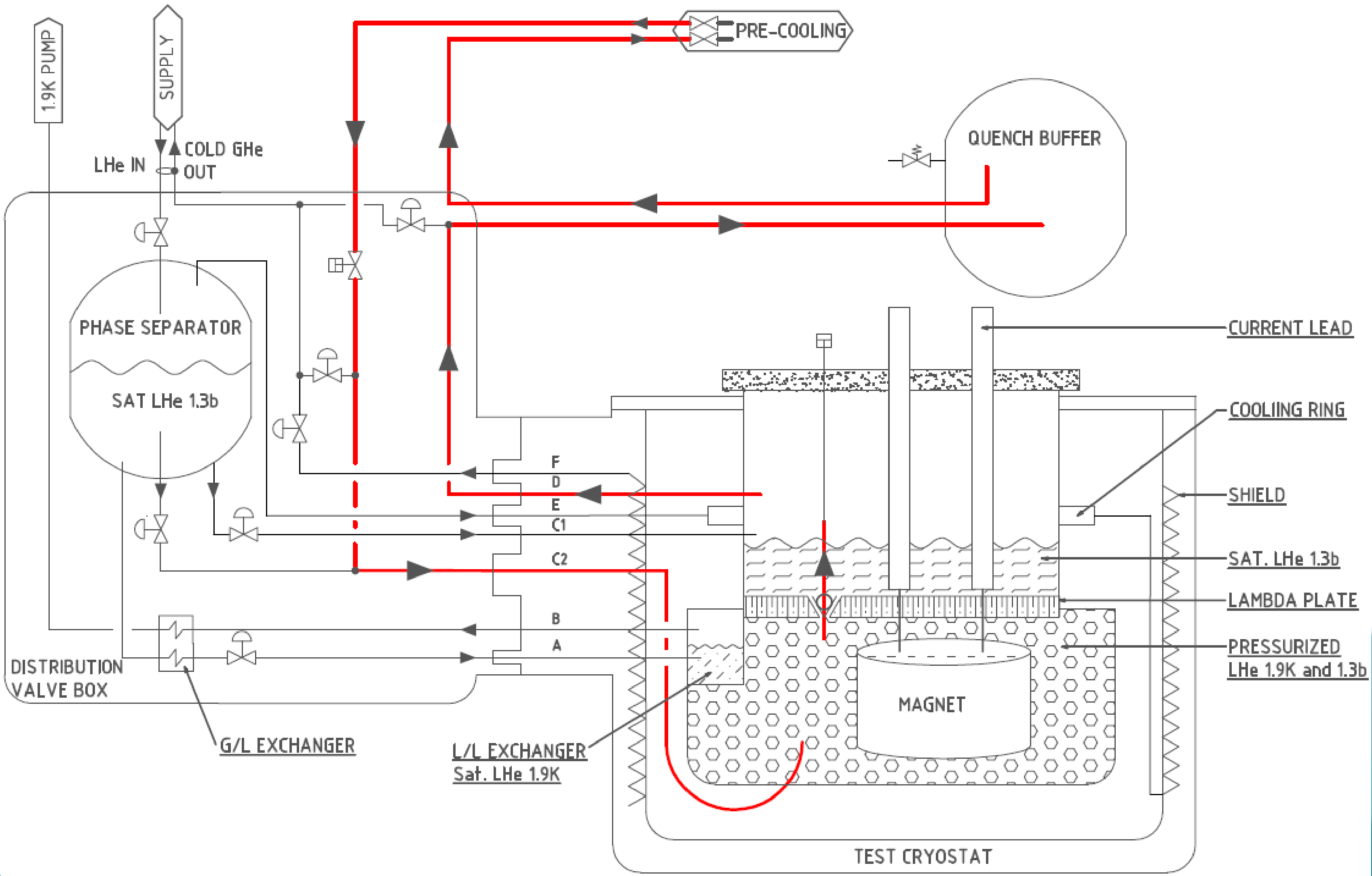
Pre-cooling line
Supply line
Existing 1.9 K
pumping line
Helium rack
Distribution
valve box
Quench line
Main line
Test cryostat

# HFM P&I diagram

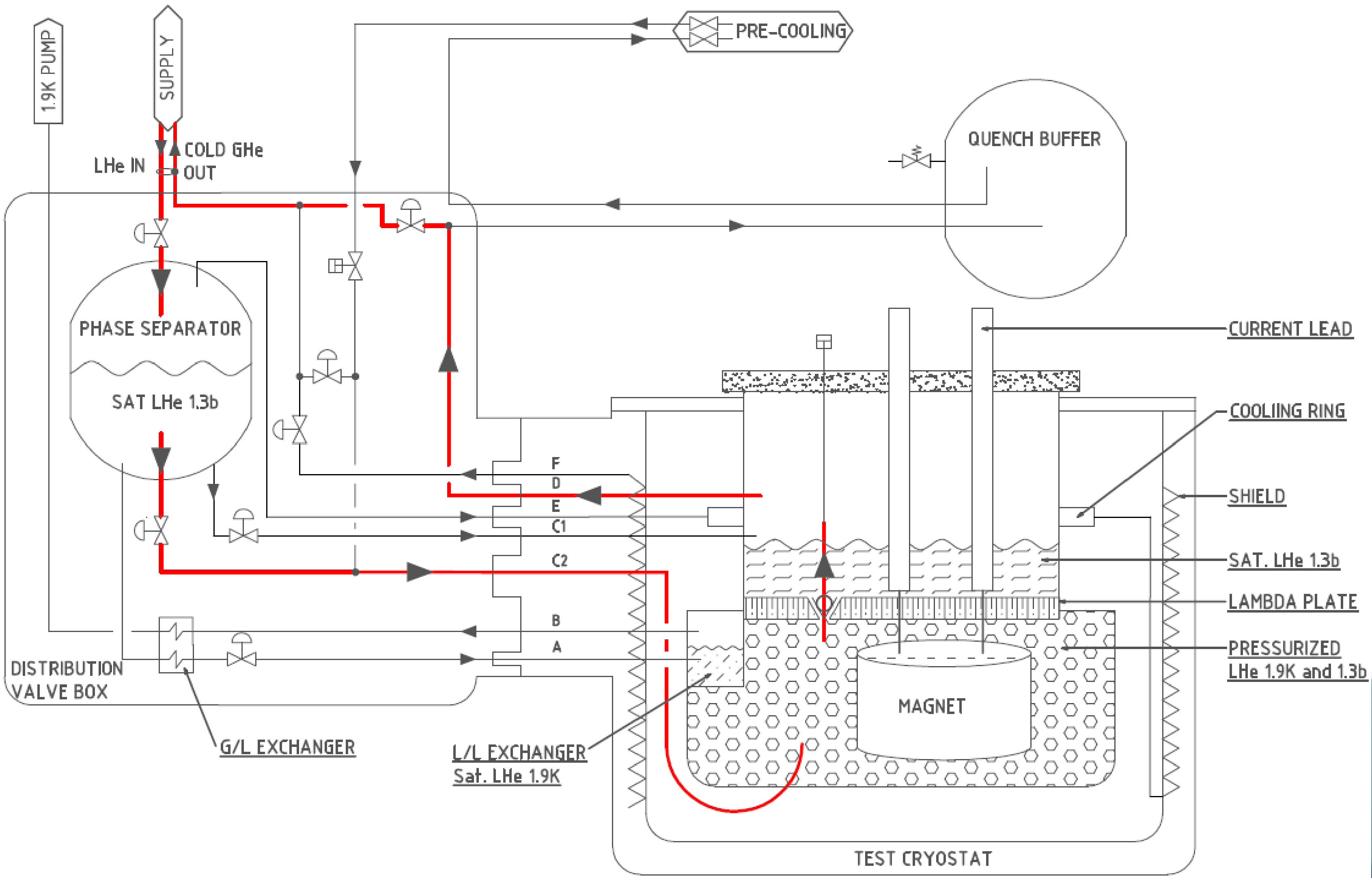


# Cool down to 80 K & warm up to 300 K

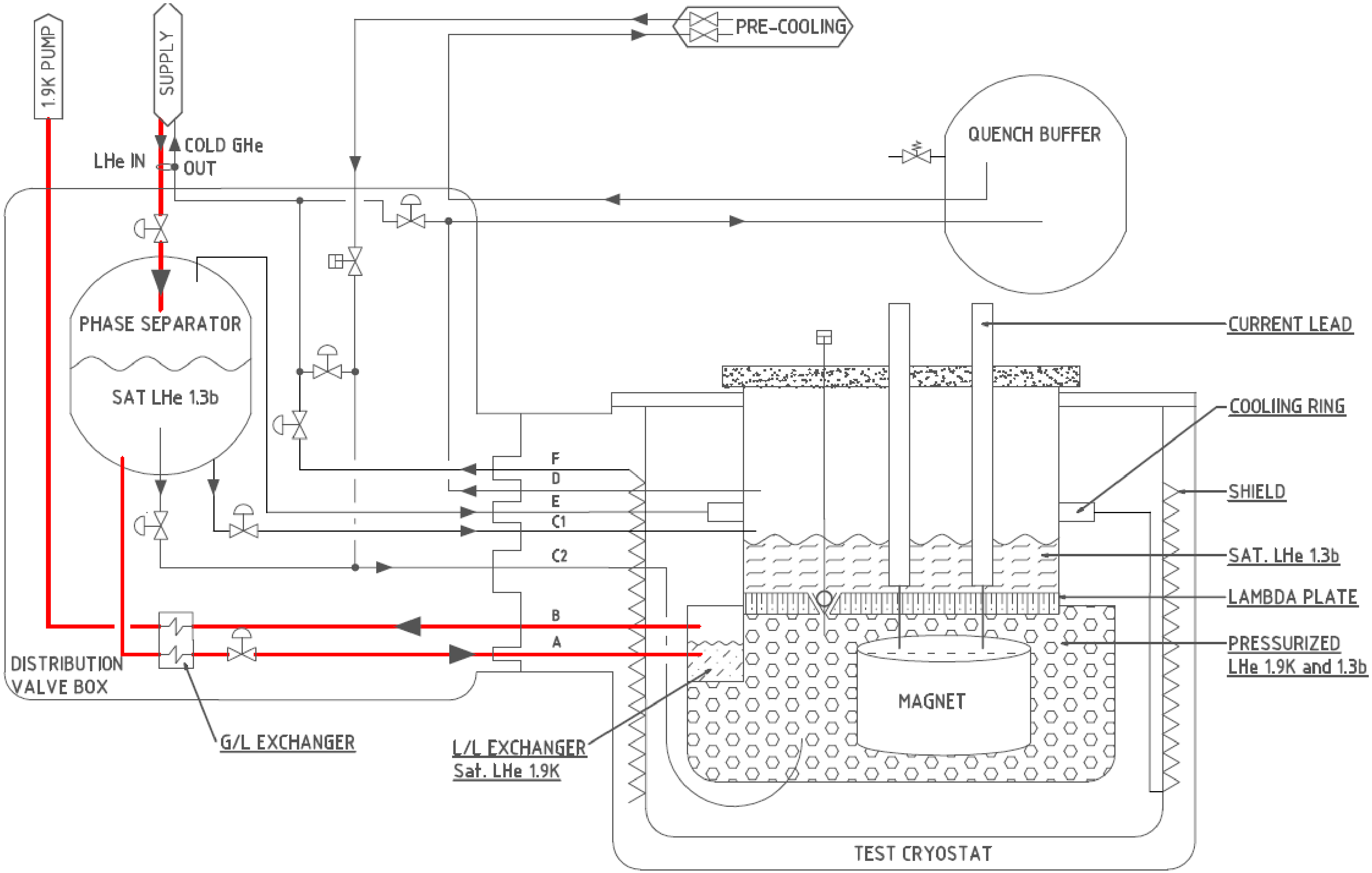
## simplified flow scheme



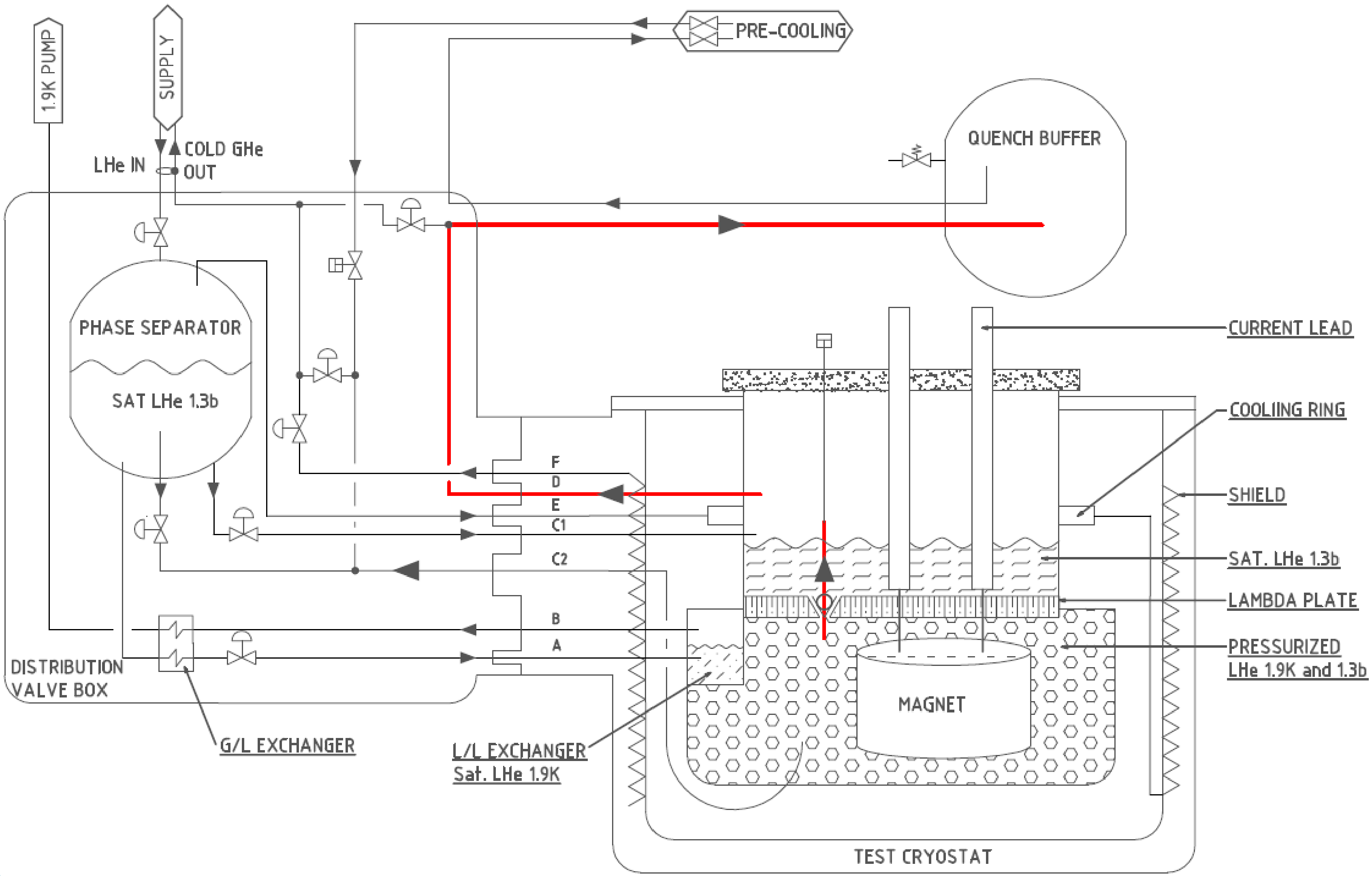
# Cool down from 80 K to 4.5 K & filling



# Cool down from 4.5 K to 1.9 K - nominal

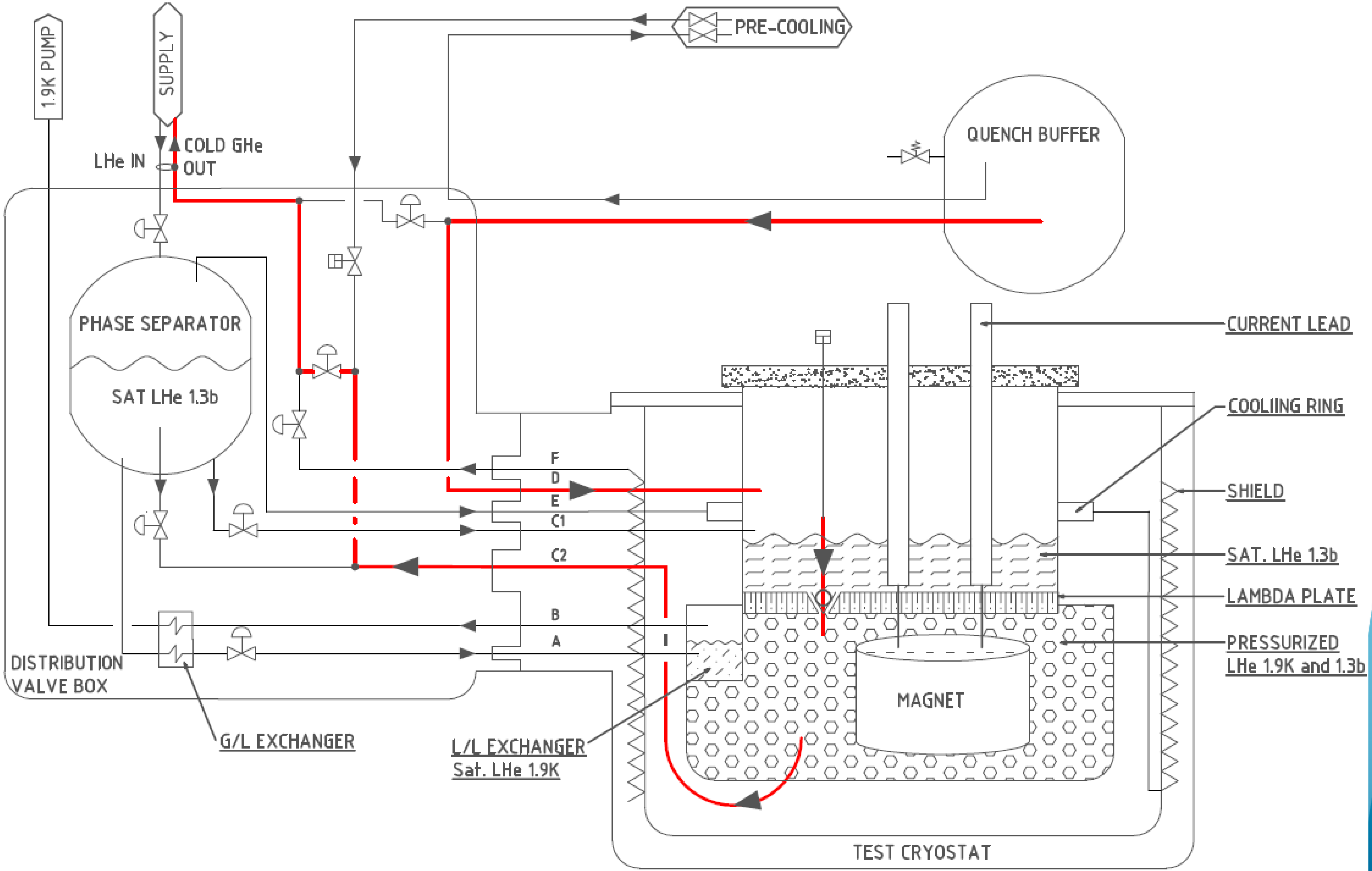


# Quench



1.9K PUMP
SUPPLY
PRE-COOLING
QUENCH BUFFER
LHe IN
COLD GHe
OUT
PHASE SEPARATOR
SAT LHe 1.3b
F
D
E
C1
C2
B
A
CURRENT LEAD
COOLING RING
SHIELD
SAT. LHe 1.3b
LAMBDA PLATE
PRESSURIZED
LHe 1.9K and 1.3b
MAGNET
DISTRIBUTION
VALVE BOX
G/L EXCHANGER
L/L EXCHANGER
Sat. LHe 1.9K
TEST CRYOSTAT

# Quench recovery

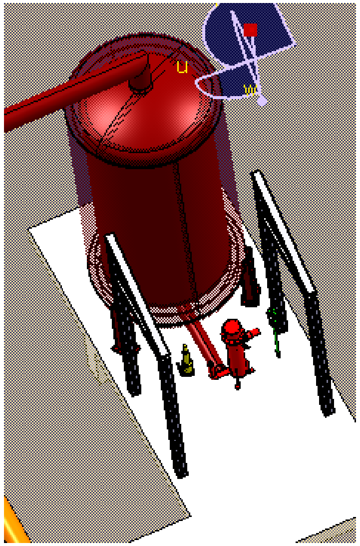


# Design challenge

- Quench buffer
- Liquid/liquid heat exchanger 1.9 K
- Cryostat heat in-leak minimization
- Pre-cooling system
  - Magnet precooling by circulating HP GHe cool down by LN
    - Mass flow 90  g/s, Pressure up to 4 bar, Temperature to be adjustable
    - Maximum dT on the magnet 50 K
    - Existing pre-cooling system in SM 18 to be used
- Safety
  - Correct analysis, dimensioning of safety organs
    - Main safety valve & rupture disk (loss of vacuum)
    - Safety valve in the lambda plate
    - Rupture disks of vacuum vessels

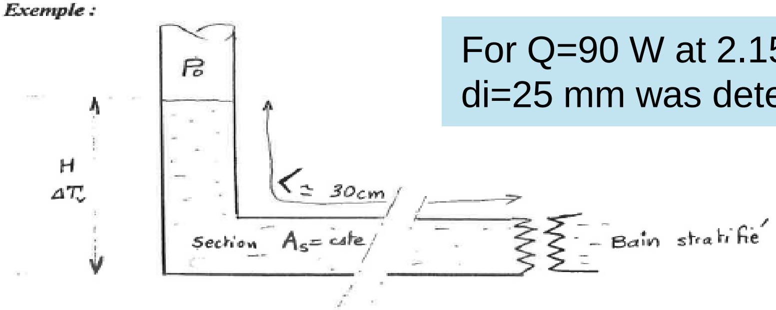
# Quench buffer
## justification and volume determination

- Design parameters
  - Design pressure of the cryostat — 5 bar
  - Magnet energy — 10 MJ
  - Volume of LHe below lambda plate — 2 $m^3$
  - Volume of LHe above lambda plate — 0.5 $m^3$
  - Volume of GHe in the cryostat — 1.6 $m^3$
- Calculation strategy: Internal energy and adiabatic expansion
  1. The magnet and surrounding LHe is in closed vessel
     - $dq = du - p\,dv$, for V=const. dV=0, thus dQ=dU
     - $dU = Q_q/M$ and $U = U_0 + dU$; for given U and v, the $p_1$ and $T_1$ can be found
  2. Quench buffer volume is connected to the cryostat
     - $p_2 = p_1(\rho_2/\rho_1)^{\varkappa}$
  3. $p_2$ shall be corrected as $pv/rT \neq 1$
- Without quench buffer
  - Pressure in the cryostat after quench would be — 25 bar
  - Loss of He via safety valve to atmosphere — 240 kg = 12 kCHF/quench
  - For 100 quenches it represents — 1200 kCHF
- With quench buffer
  - Pressure after quench — 3 bar
  - No loss of helium
- Required volume is 15 $m^3$ in order to be safely below 4 b

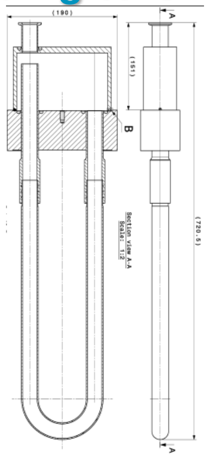


# Limit of heat flux in 1.9 K L/L heat exchanger according to G. Bon Mardion

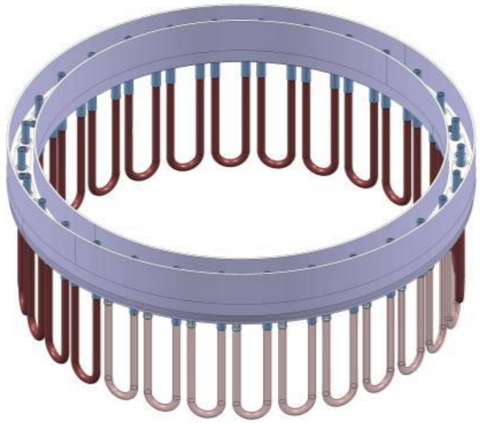
***Exemple :***




For Q=90 W at 2.15 K, di=25 mm was determined



Sample



Complete heat exchanger

*Soit :* $T_0 = 1,70\ K \rightarrow P_0 = 11,45\ mb$

$H = 10\ cm \rightarrow \Delta p = \rho g H = 1,427\ mb$

*avec :* $\rho_{He}(1,70) = 0,145\ g/cm^3$

$P_v = P_0 + \Delta P = 12,88\ mb \rightarrow T_v = 1,7305$

*soit :* $\Delta T_v = 30,5\ mK$

*De la référence [3], on a :*

$$W_v(T_0) = \left[ y(T_0) \cdot \frac{dT}{dx} \right]^{0,294}$$

Heat flux limit when bubbles start to appear

$$\frac{dT}{dx} = \frac{\Delta T_v}{L} = \frac{30,5.10^{-3}}{30} = 1,017.10^{-3}\ K.cm^{-1}$$

$$T_{moyen} = T_0 + \frac{\Delta T_v}{2} = 1,715\ K$$

$y(1,715\ K) = 740$ (cf.[3]) Heat conductivity

$$W_v(1,70) = \left[ 740 \times 1,017.10^{-3} \right]^{0,294} = 0,92\ W.cm^{-2}$$

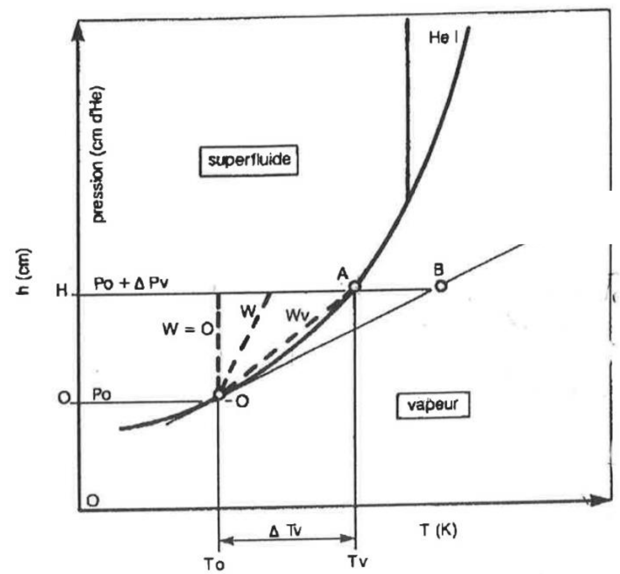
*d'où :* $$A_S\ cm^2 \geq \frac{Puissance\ de\ réfrigération\ à\ 1,70\ K}{0,92\ W.cm^{-2}},\ en\ W$$

No bubbles to be created in saturated LHeII

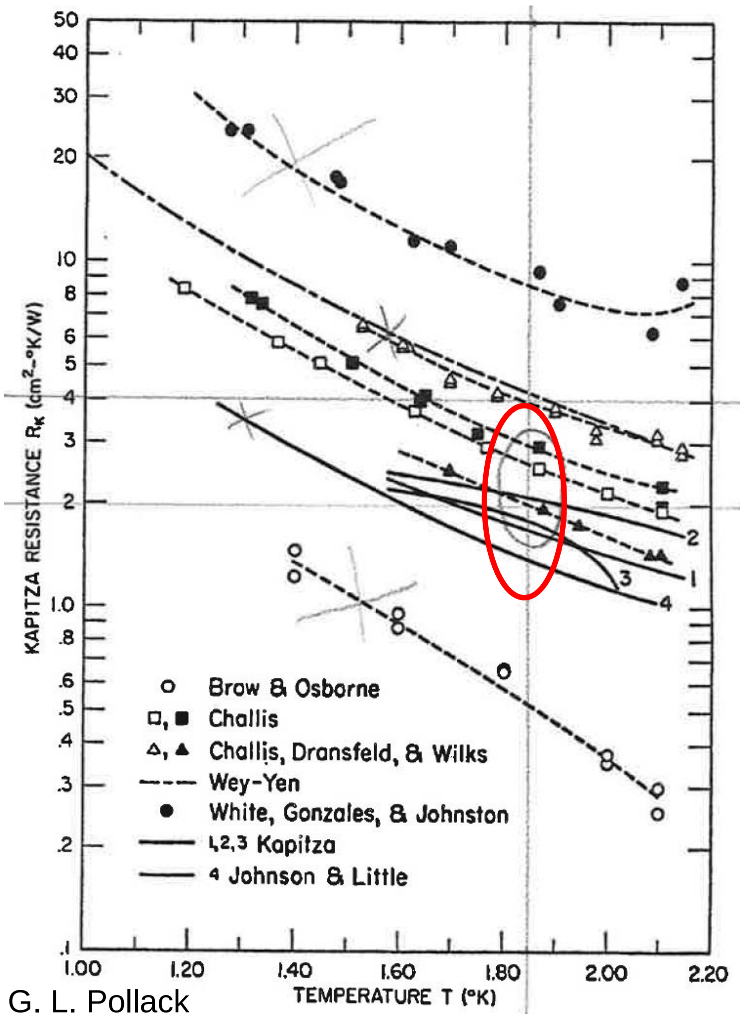
As the $T_\lambda$ is dimensioning the required cross section can be calculated as follows

$$A_S = \frac{P^W_{réfrigération}\ à\ 2,15\ K}{0,3}\ cm^2$$

With an error smaller that 20% considering H<0.5 m



# Kapitza resistance, data & temperature difference

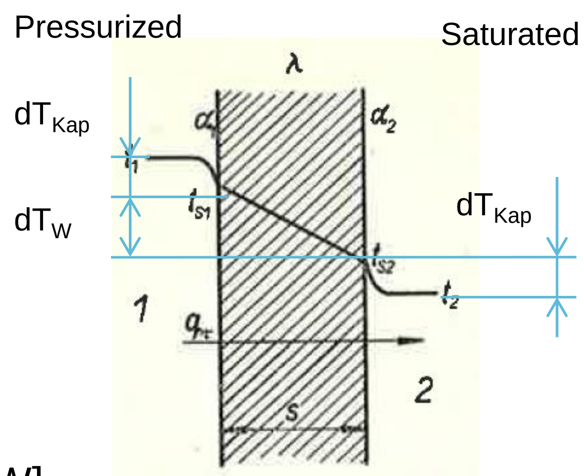



G. L. Pollack

$$r_{Kap} \approx \frac{1}{T^3}$$

$r_{Kap} = 2 * 10^{-4}$ [m$^2$K/W]
for cooper at 1.85 K

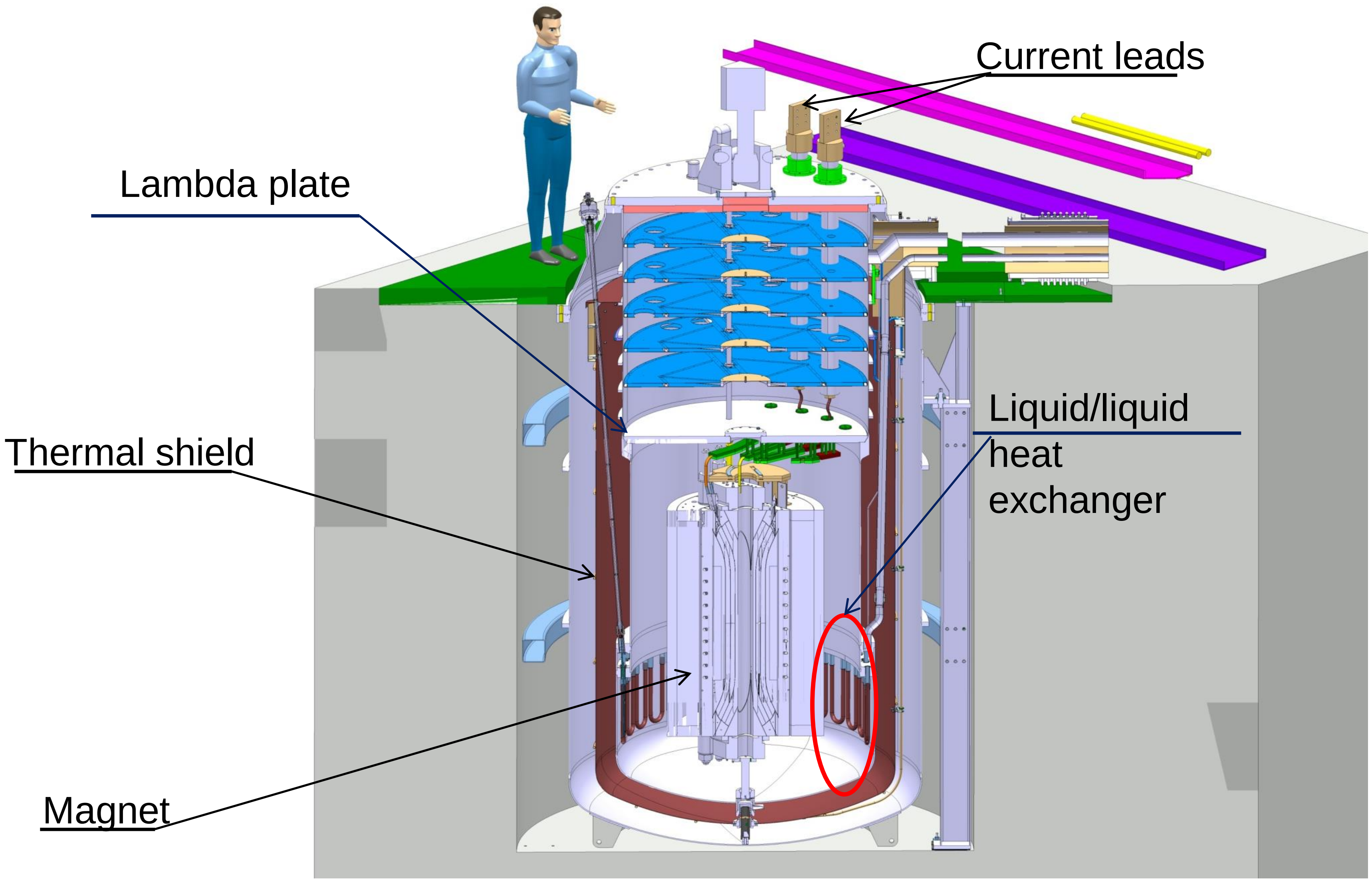
LHe at 1.9 K




$dT_{Tot} = 2 * dT_{Kap} + dT_{Wall}$
$dT_{Kap} = r_{Kap} * Q/A$

dT<0.01 K at 25W (nominal), for S=2.1 m$^2$
dT<0.03 K at 90 W for cool down

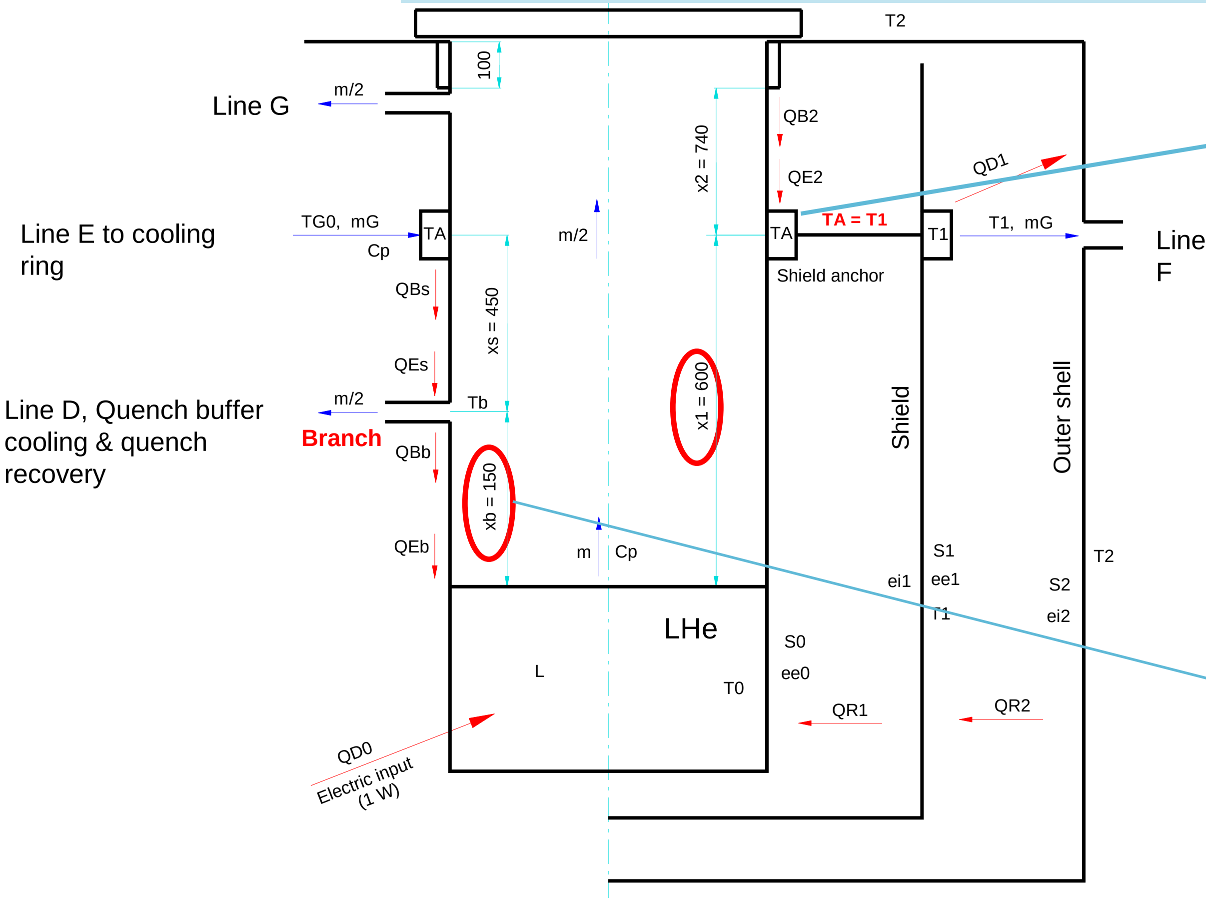
# HFM test cryostat



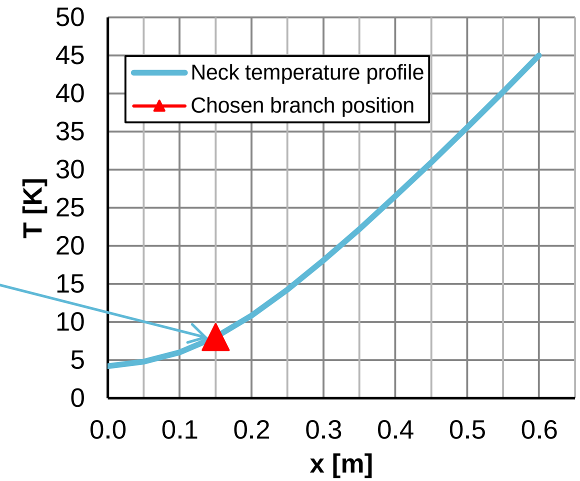
# Cryostat heat in-leak at 4.5 K

## optimized position of the cooling ring and the quench buffer cooling tap for upper part of the cryostat

Estimated minimized heat in-leak is about 3 W
Current leads are not considered

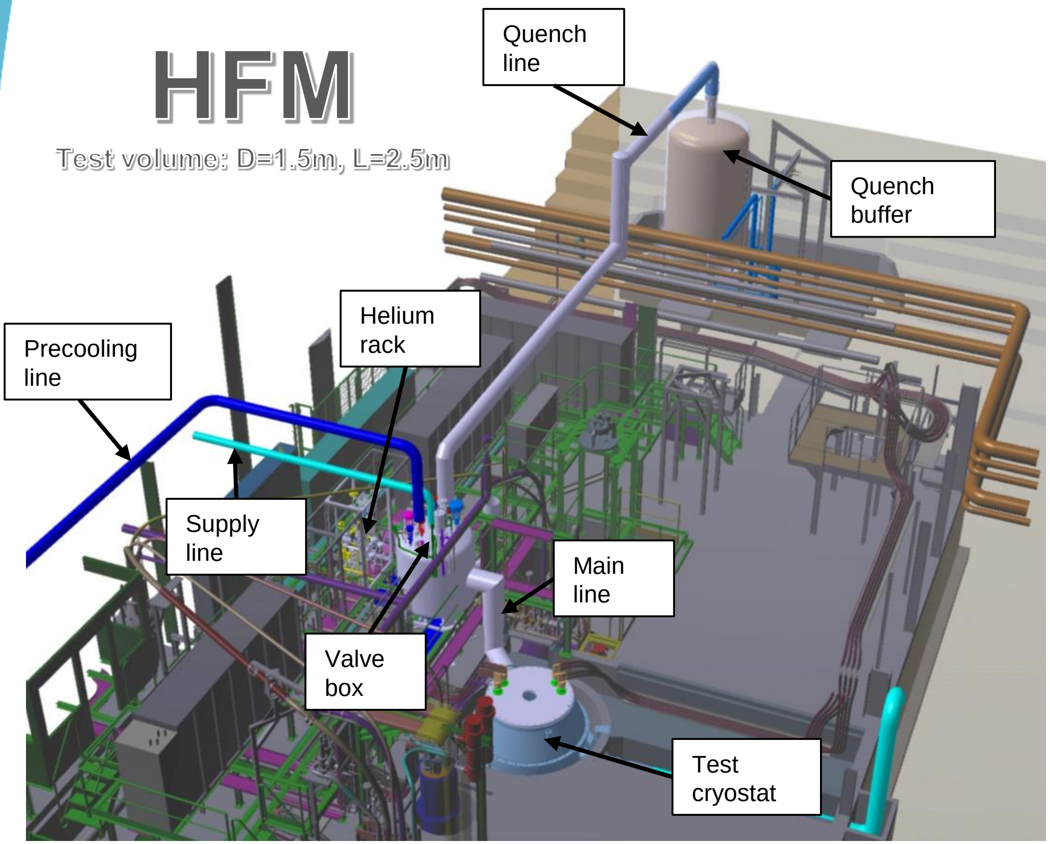


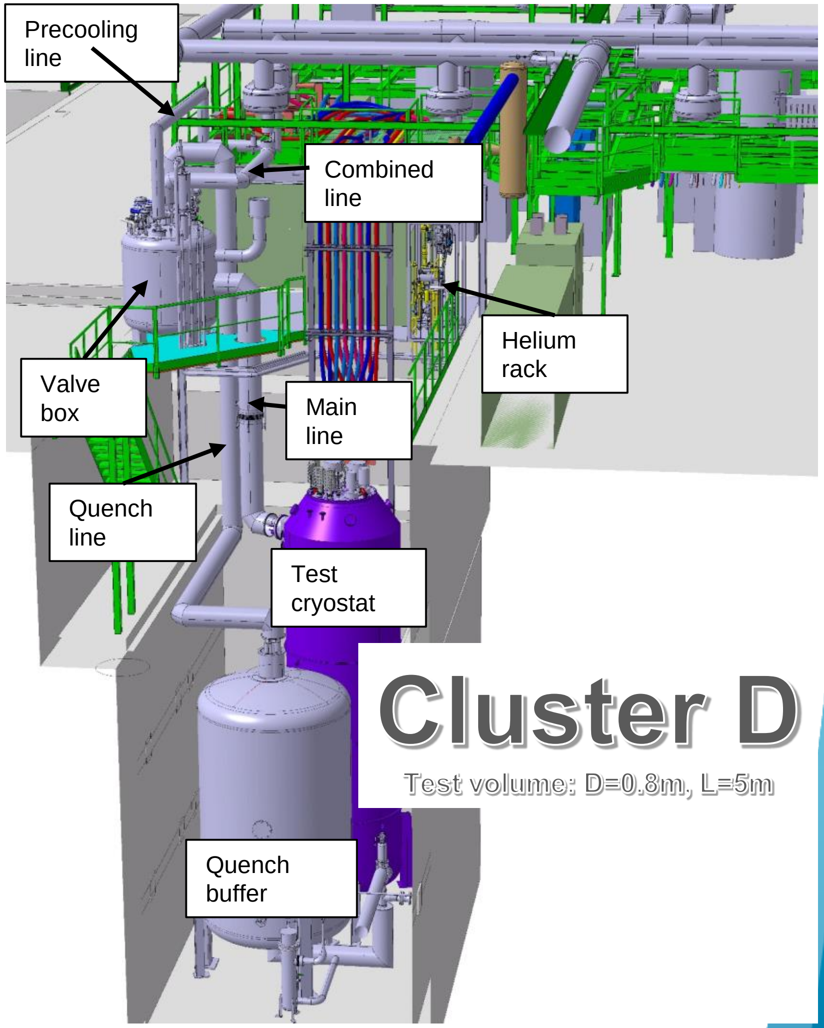

Cooling ring



# HFM - Cluster D, twin test set up

## for different magnet dimensions



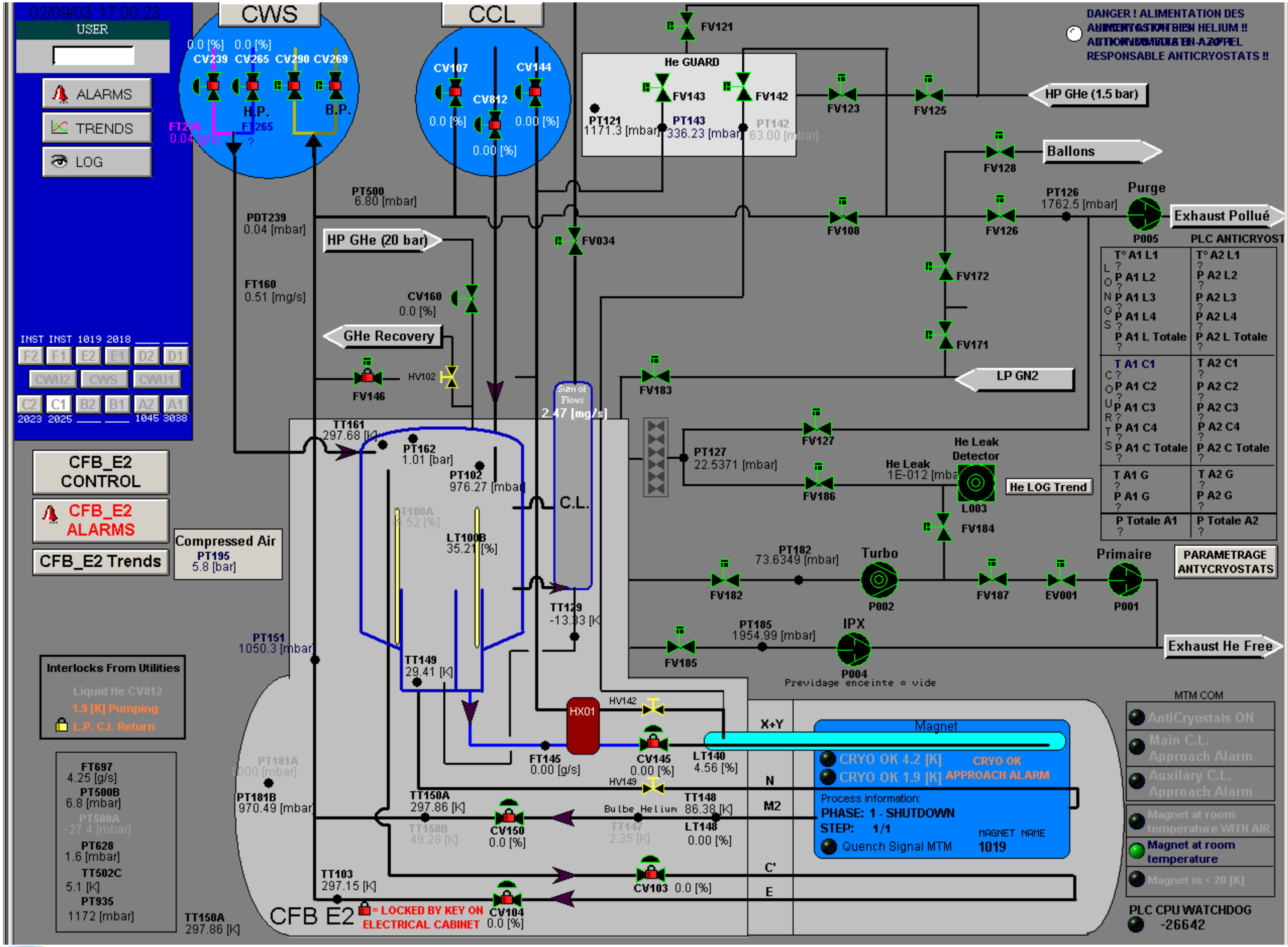
# Horizontal Cryogenic Feeder Box CFB

## The same principle as for HFM

- Precooling system from 300K down to 80 K and warm up from 5K to 300K
  - Pressurized GHe is cool down by LN at 90 g/s
- Operating temperature 1.9 K
  - G/L heat exchanger in CFB
  - L/L heat exchanger in the magnet
- Recuperation of helium after quench – quench buffer
  - Design pressure of the system is 20 bar
  - Volume of LHe in the magnet about 220 l
  - Volume of the quench buffer is around 1 $m^3$
    - As the quench buffer is small it is integrated directly in the CFB
- All LHC magnets were tested on these 12 CFBs
- Time schedule of the magnet test

| | |
|---|---|
| He circuits purge | 1d |
| Pumping of vacuum insulation & leak test | 1d |
| Cool down from 300 K down to 80 K | 11h |
| Cool down from 80 K down to 4.5 K and filling by LHe | 5+1h |
| Pumping down to 1.9 K | 4h |
| Magnetic test | |
| Quench recuperation | 4h/quench |
| Warm up | 14 h |

# CFB synoptic



***Thank you for your attention…***