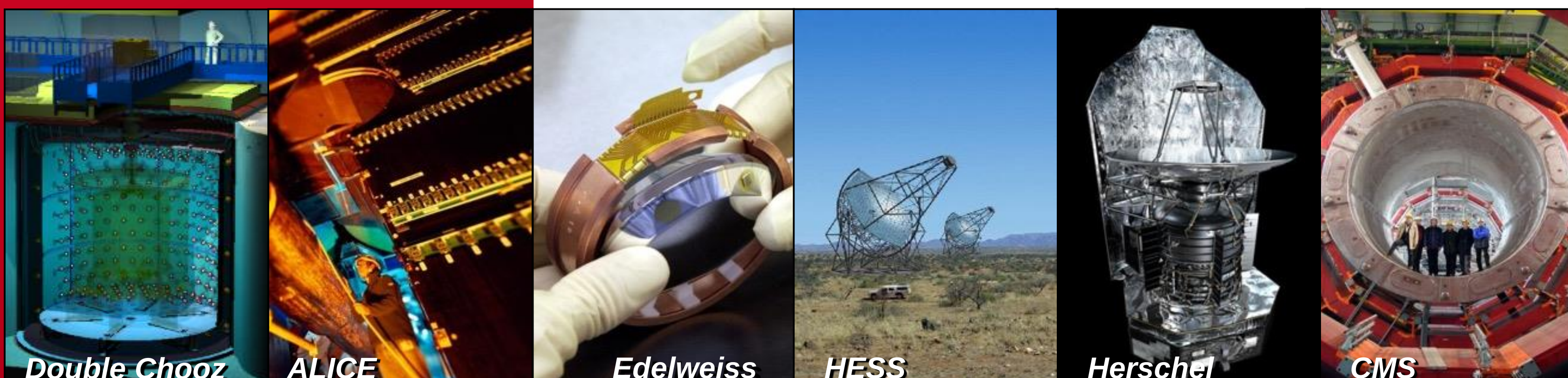
DE LA RECHERCHE À L'INDUSTRIE

# Cryogenics for high magnetic field whole body MRI :

# ISEULT 11.7 T at NEUROSPIN




*Déchiffrer les rayons de l'Univers*

**Philippe BREDY**

30th of september 2019

# SUMMARY

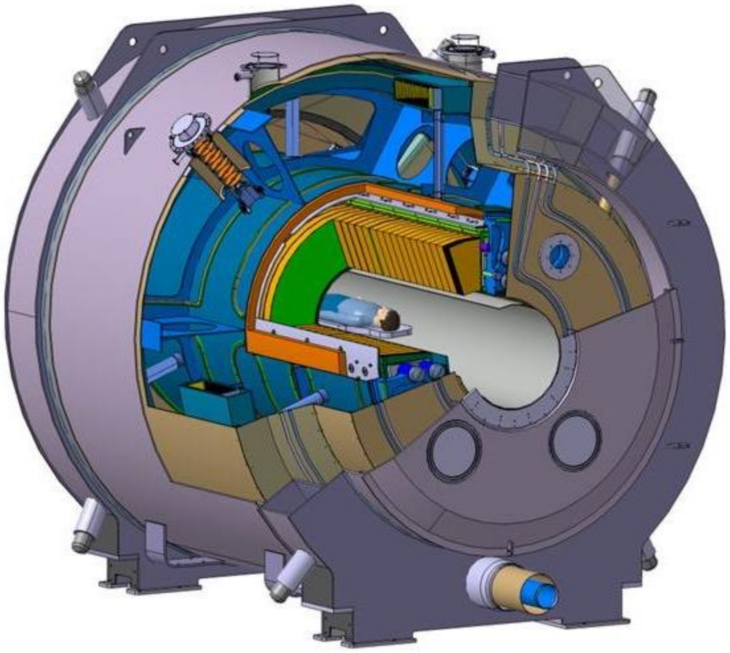
Initial parameters of the Sc magnet

Main cryogenics choices

Detailed design and cooling down

Associated cryoplant

Cool-down and first measurements with field



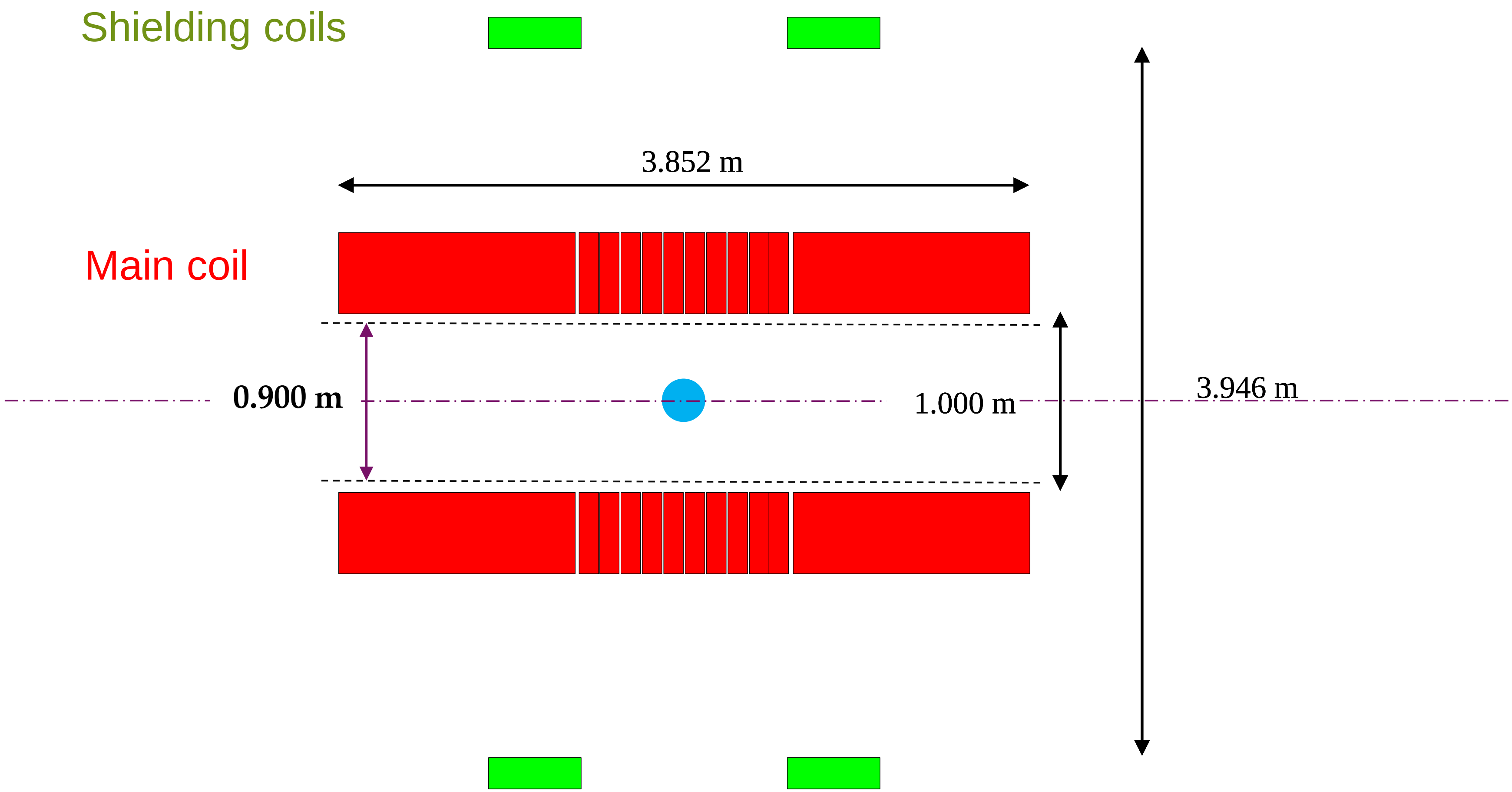
# INITIAL PARAMETERS OF THE SC MAGNET

***Magnetic Parameters***

| | | |
|---|---|---|
| Maximum Nominal Frequency | **499,8** | MHz |
| Internal diameter for whole body | **900** | mm |
| | | |
| Maximum User Field (for maximum frequency) | **11,739** | **T** |
| Homogeneity on the 22 cm diameter sphere (Peak-to-Peak) | **< 0.5** | ppm |
| Homogeneity on the 22 cm diameter sphere (RMS) | **< 0.05** | ppm |
| Long term drift | **0,05** | ppm/h |
| Short term drift (time tbd) | **0,4** | ppb |
| | | |
| 5 Gauss line position (radially) | **< 13.5** | m |
| 5 Gauss line position (axially) | **< 10.5** | m |

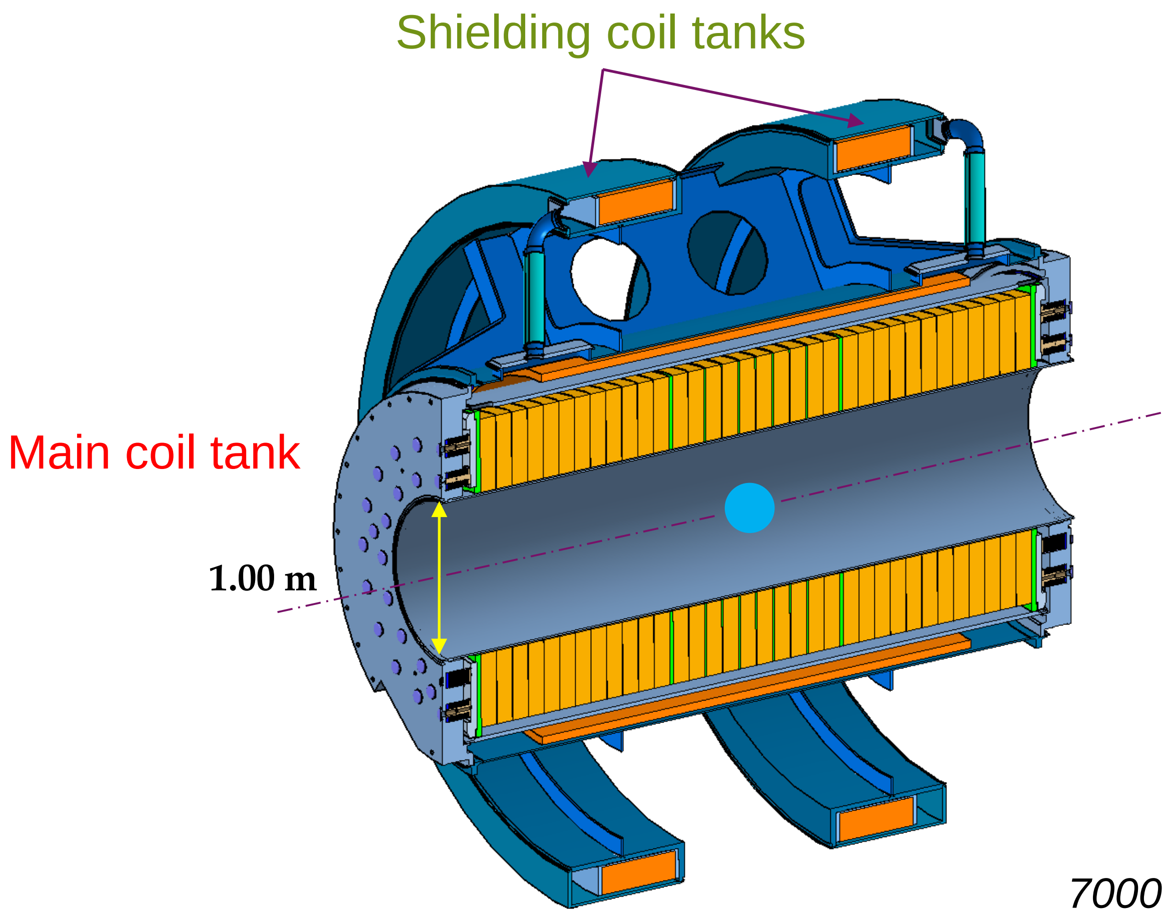
# INITIAL PARAMETERS OF THE SC MAGNET

**Design of the Sc coils to be cooled (with a fixed current density on NbTi conductor*)**




***: Nb3Sn excluded (lack of internal knowledge and high level technological risk)***

**Design of the Sc coils to be cooled into a common bath inside 3 tanks communicating together**



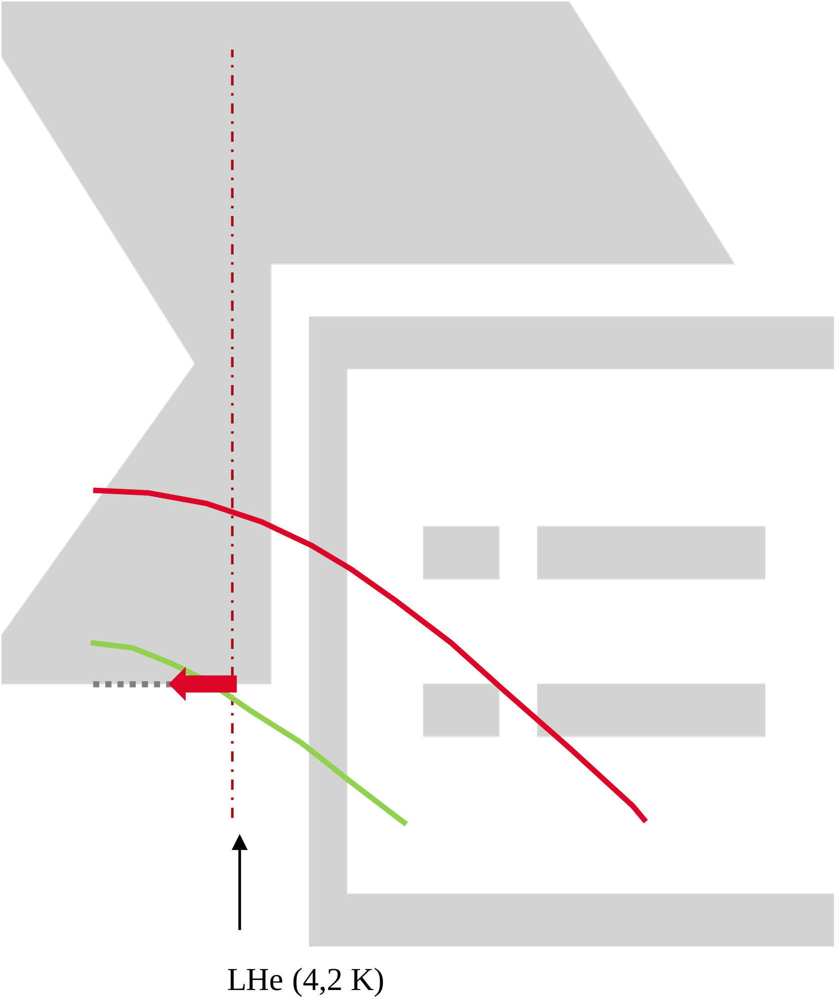

*7000 litres to be filled !*

# INITIAL PARAMETERS OF THE SC MAGNET

***Superconducting parameters and T° of bath***

- High magnetic field ( 11.7 T)
- Use of **NbTi** , very close to its Sc limits

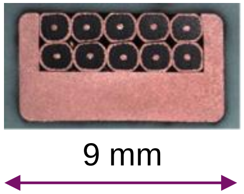
$\Rightarrow$ Operating T° below 4.2 K *(4.2 K =He I at 1 atm)*



# Initial parameters of the Sc magnet

***Sc coil operation***

- ❑ With a "customized" industrial Cu/NbTi conductor, for the required **current density**




⇒ nominal current at 1483 A

⇒ $T_{current\ sharing}$ = **2.8 K** (need to operate below this temperature)

- ❑ Required magnetic field **time stability**

⇒ permanent connection with external electrical power supply for continuous correction of current (significant difference compared to classical MRI)

⇒ Installation of a pair of 1500 A current leads, cooled between **4 K and 300 K** and electrically supplied permanently.

# INITIAL PARAMETERS OF THE SC MAGNET

***Superconductor operation***

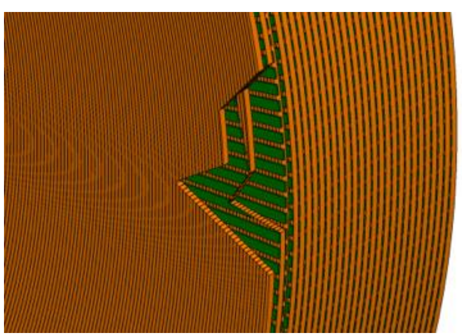
❑ Arbitrary **temperature margin of 1 K** for Sc conductor (usual margin…)

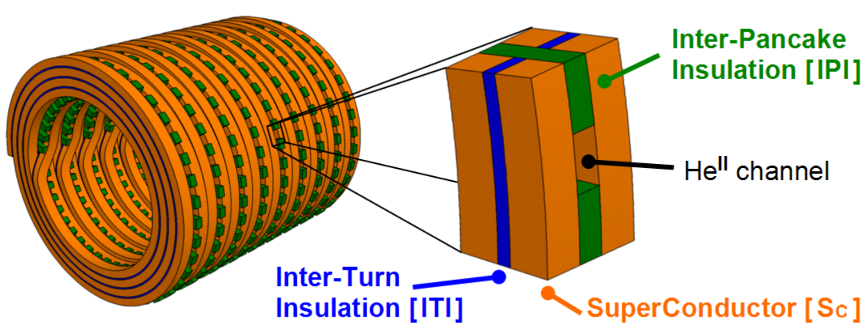
$T_{op}$ = $T_{cs}$ –margin = 2.8 - 1 = **1.8 K** as nominal operating temperature

❑ **Cryostability criteria**
(*H : one complete turn of the winding transited without reaching critical flux*)

⇒ Need internal channels inside the winding to perfectly wet the Sc conductors

⇒ Double pancake technology with radial channels and direct contact between fluid and Sc conductor

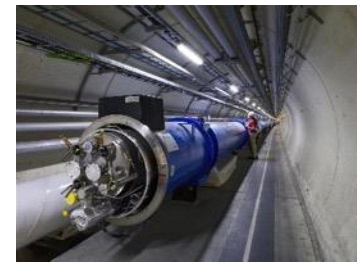




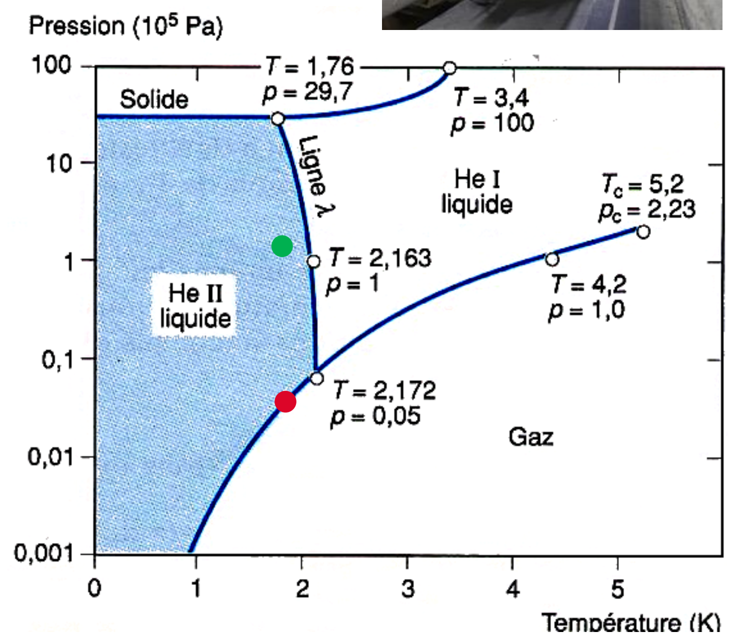
# MAIN CRYOGENIC CHOICES

***Cooling architecture***

- ❑ Based on previous successful experiments on TORE SUPRA , LCMI and LHC



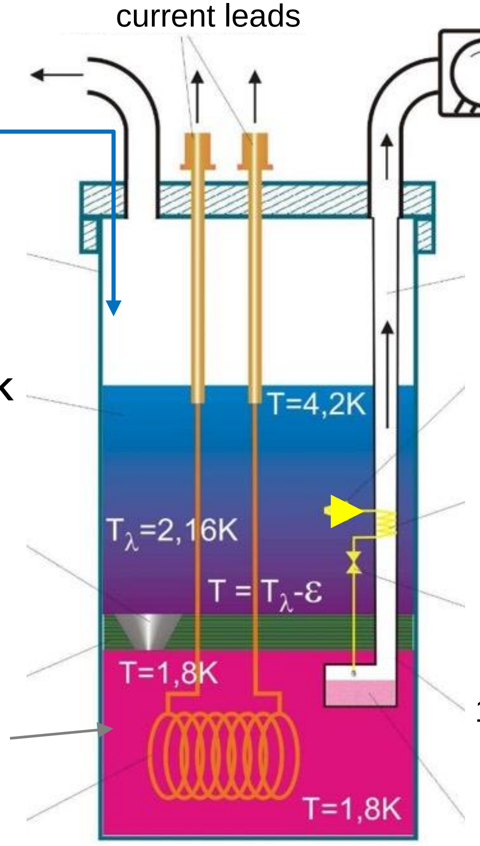
- ❑ Choice of a **static pressurized superfluid helium bath at 1.8 K and ~ 1.2 bars (pressurized He II)**
    - ○ To avoid sub-atmospheric conditions on a large cryostat (risk of air inlet on cryogenic device)
    - ○ To improve electrical insulation (higher voltage breakdown of He II at 1 atm ● compared to He II saturated at 1.8 K/16 mbars ●)
    - ○ To gain in thermal performances
        - ▪ Very high thermal conductivity of He II
            - ✓ Isothermal bath all around the winding
            - ✓ Remote the cold source outside the cryostat
        - ▪ Enthalpy margin before He I transition



# MAIN CRYOGENIC CHOICES

***General principle of a pressurized superfluid helium bath***

Double bath or “Bain Claudet”

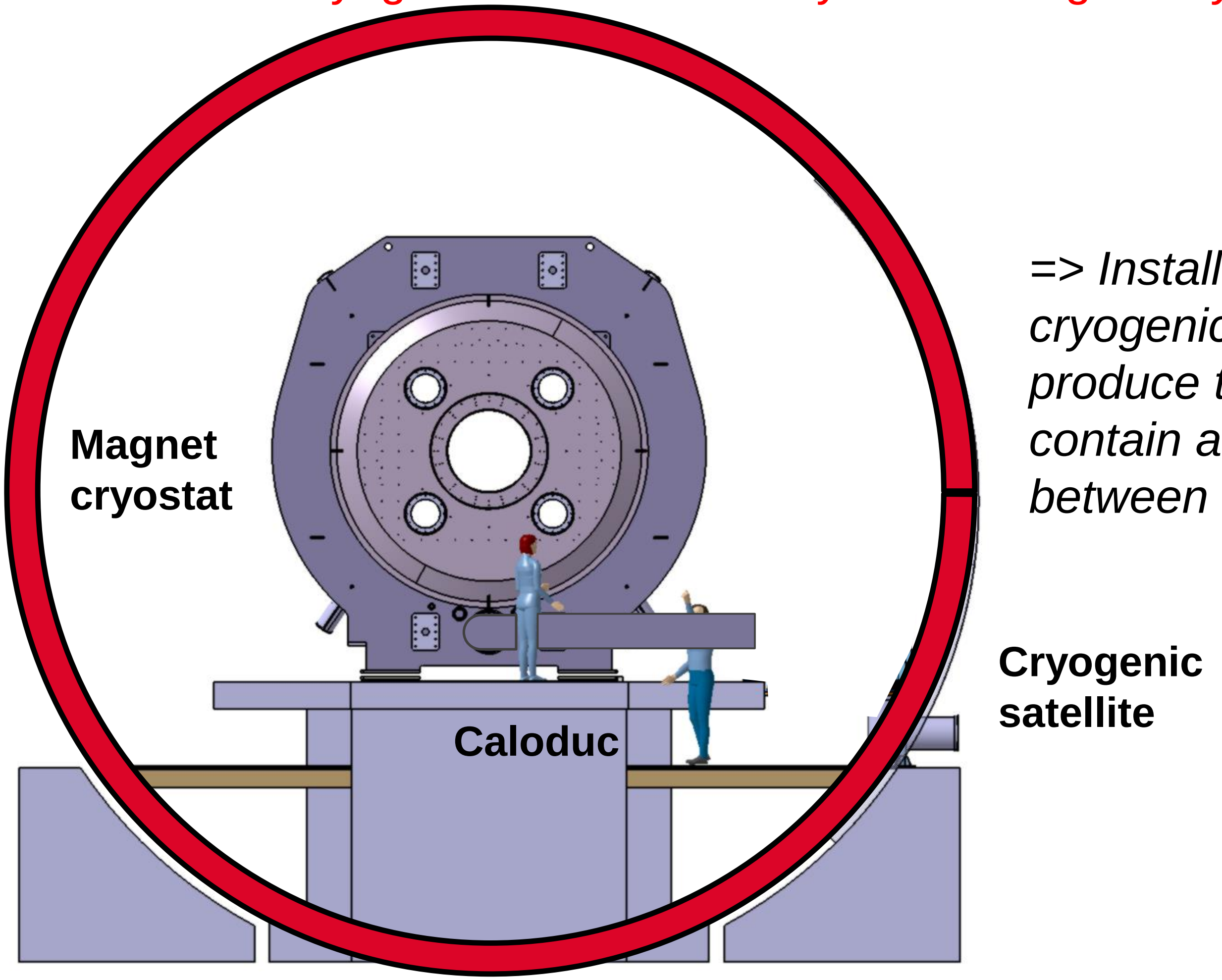


# MAIN CRYOGENIC CHOICES

***Applying the pressurized superfluid helium bath for Iseult magnet***

No enough space inside the cryostat and above the cryostat in the magnet room

\+ Choice for no active cryogenic element directly on the magnet cryostat

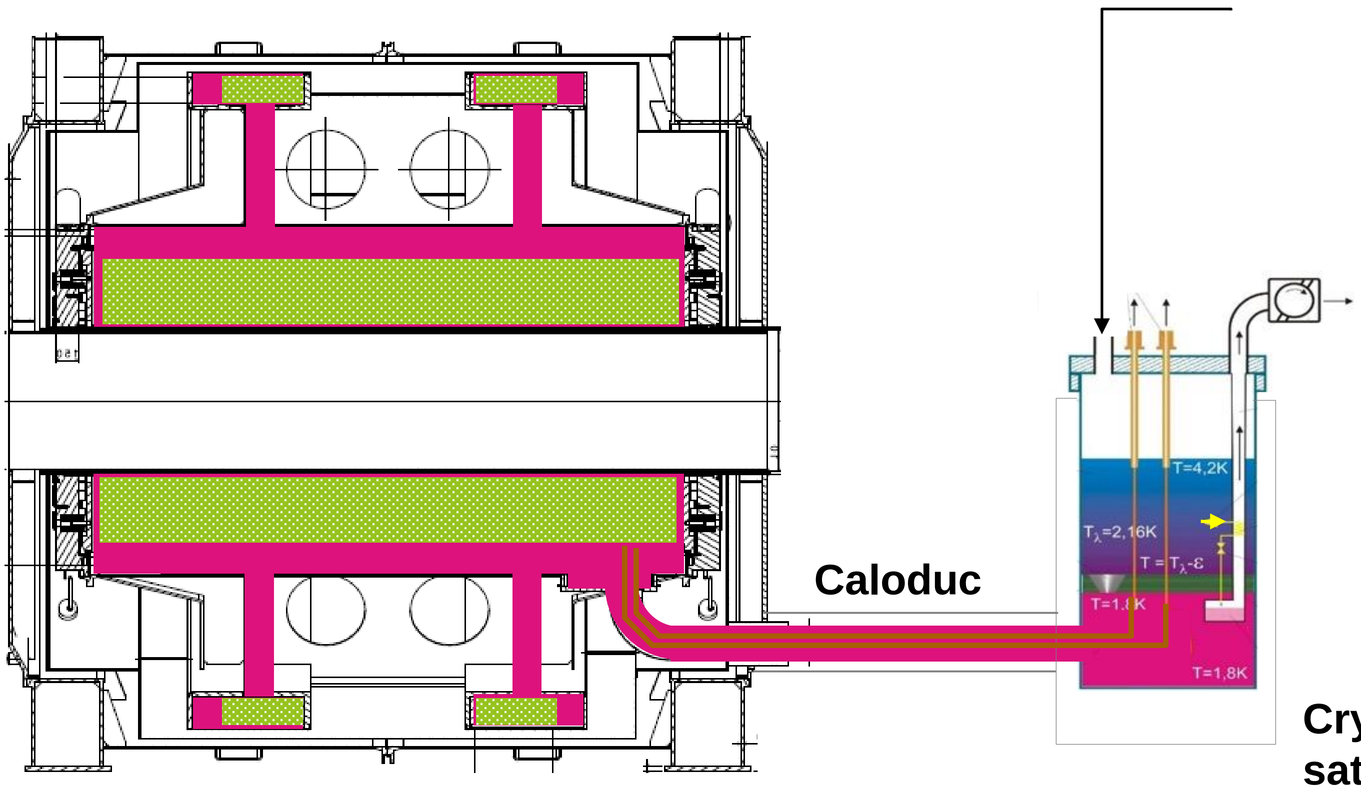



*=> Installation of a remote cryogenic satellite able to produce the double bath and contain all the interfaces between Sc coil and utilities*

***Applying the pressurized superfluid helium bath for Iseult magnet***

Remote the cold source and consider the He tank around the coils as « *cul de sac* » :

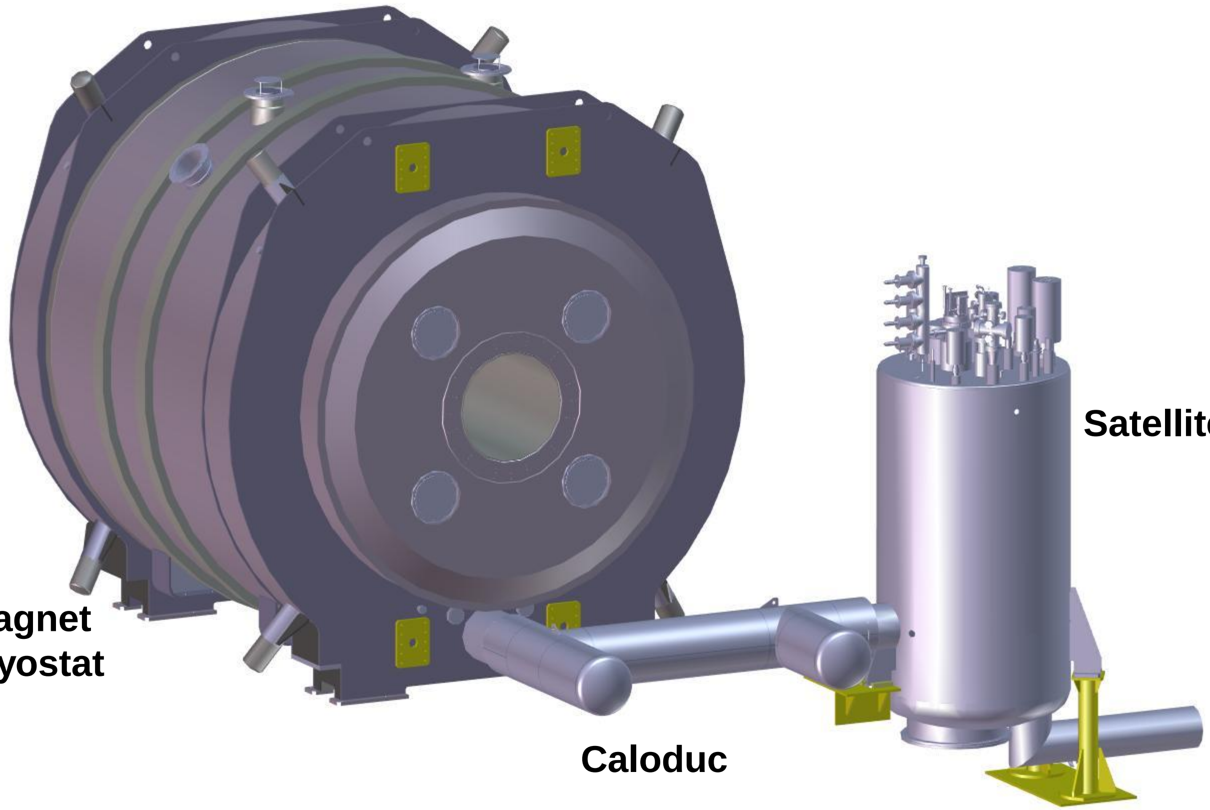
⇒ Cryogenic satellite and He II pipe as thermal link (caloduc)



# MAIN CRYOGENIC CHOICES

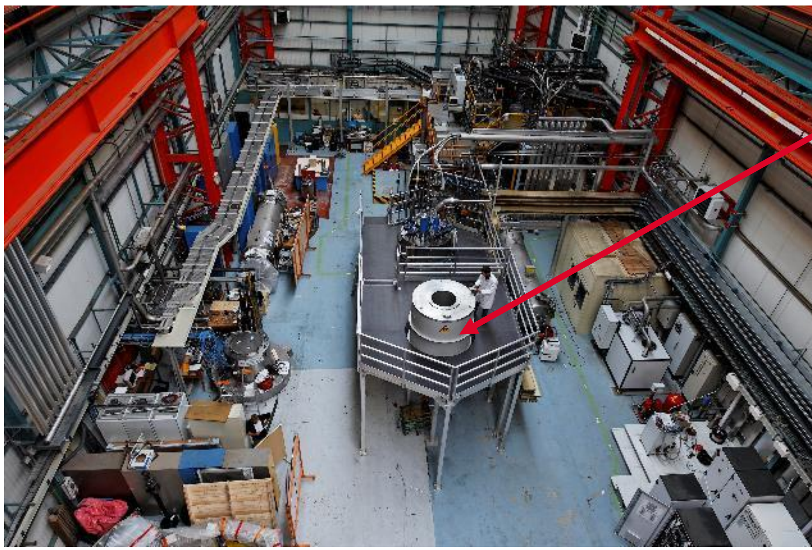
***Applying the pressurized superfluid helium bath on Iseult***

Final configuration in the magnet room



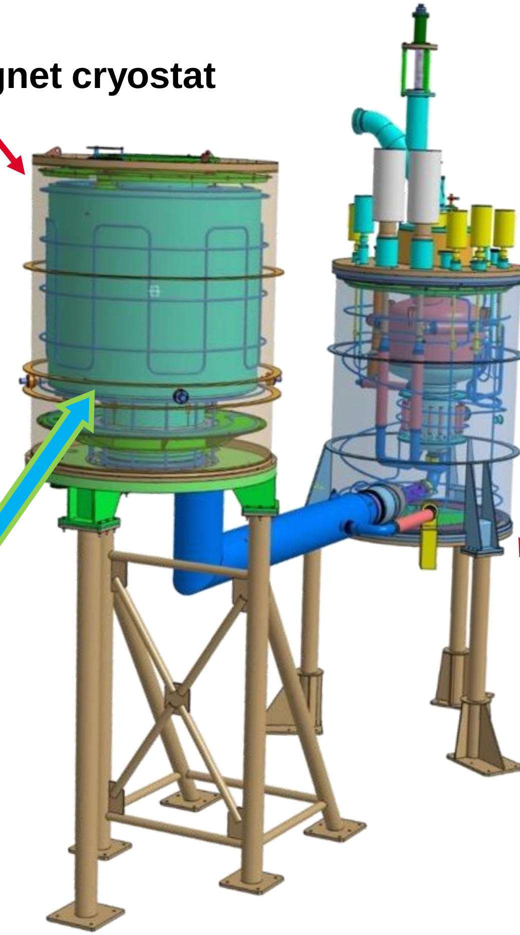
***SEHT test facility :***

*Preliminary test to validate the operation of a similar Sc double pancake winding with a superfluid pressurized helium bath (including quench behaviour)*



**Overview of SEHT facility**

**Magnet cryostat**



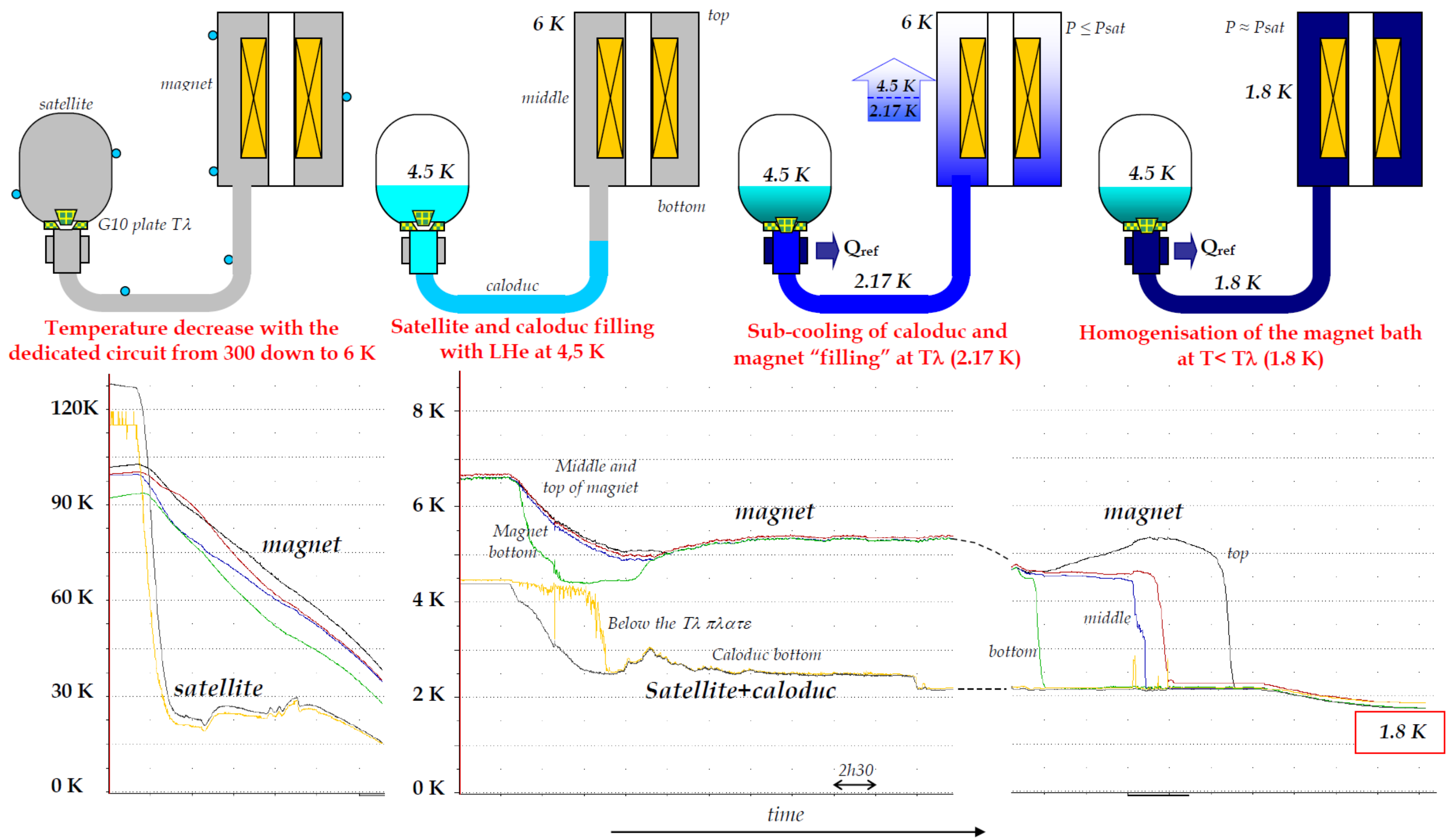
**Cryogenic satellite**

**Sc coil (ex LCMI 8 T NbTi coil in vertical axis)**

## *SEHT test facility :*

## Cooling down process

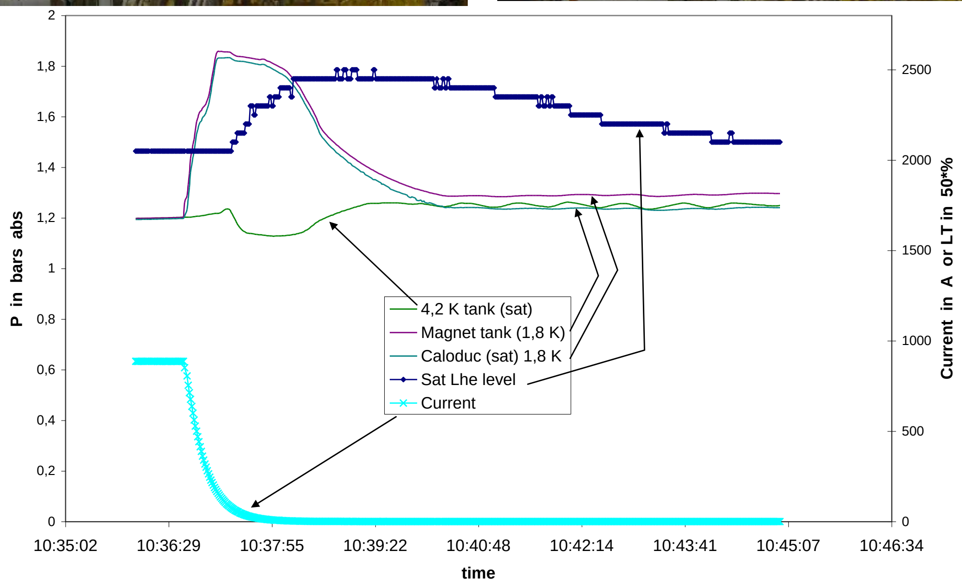
### Different steps in the SEHT cooling down (through its temperatures)



# PROTOTYPING AND PRELIMINARY TESTS

***SEHT test facility :***

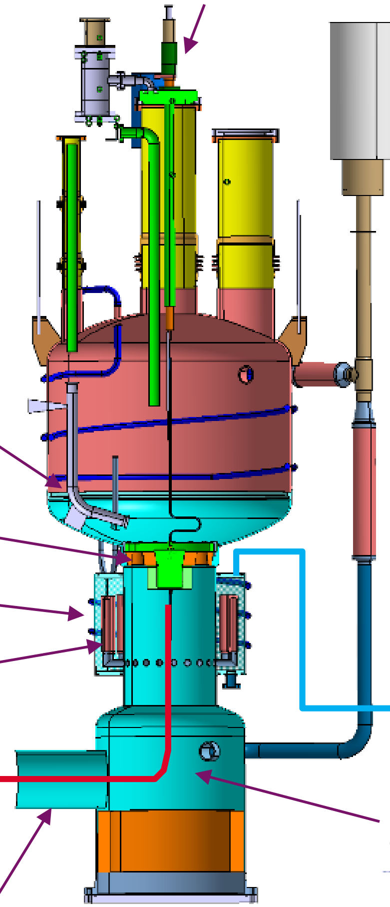
Quench (triggered) and thermohydraulic studies (He overpressure)



# DETAILED DESIGN

## Internal tanks of satellite

Vapor cooled current leads
(1500 A Brass VCCL)



LHe bath 4.2 K
*(with enough free volume for recovering the He stored inside the channels*)

Verepox Tλ plate

1.8 K evaporator (cold source)

1.8 K saturated (16 mbars)
/1.8 K pressurized (1.2 bars)
heat exchanger

Electrical NbTi busbars to superconducting coil

Beginning of the He II caloduc

Quench safety valve

*Not represented :*
*Vacuum vessel, thermal shield, instrumentation, wires, cryogenic valves, safety elements…*

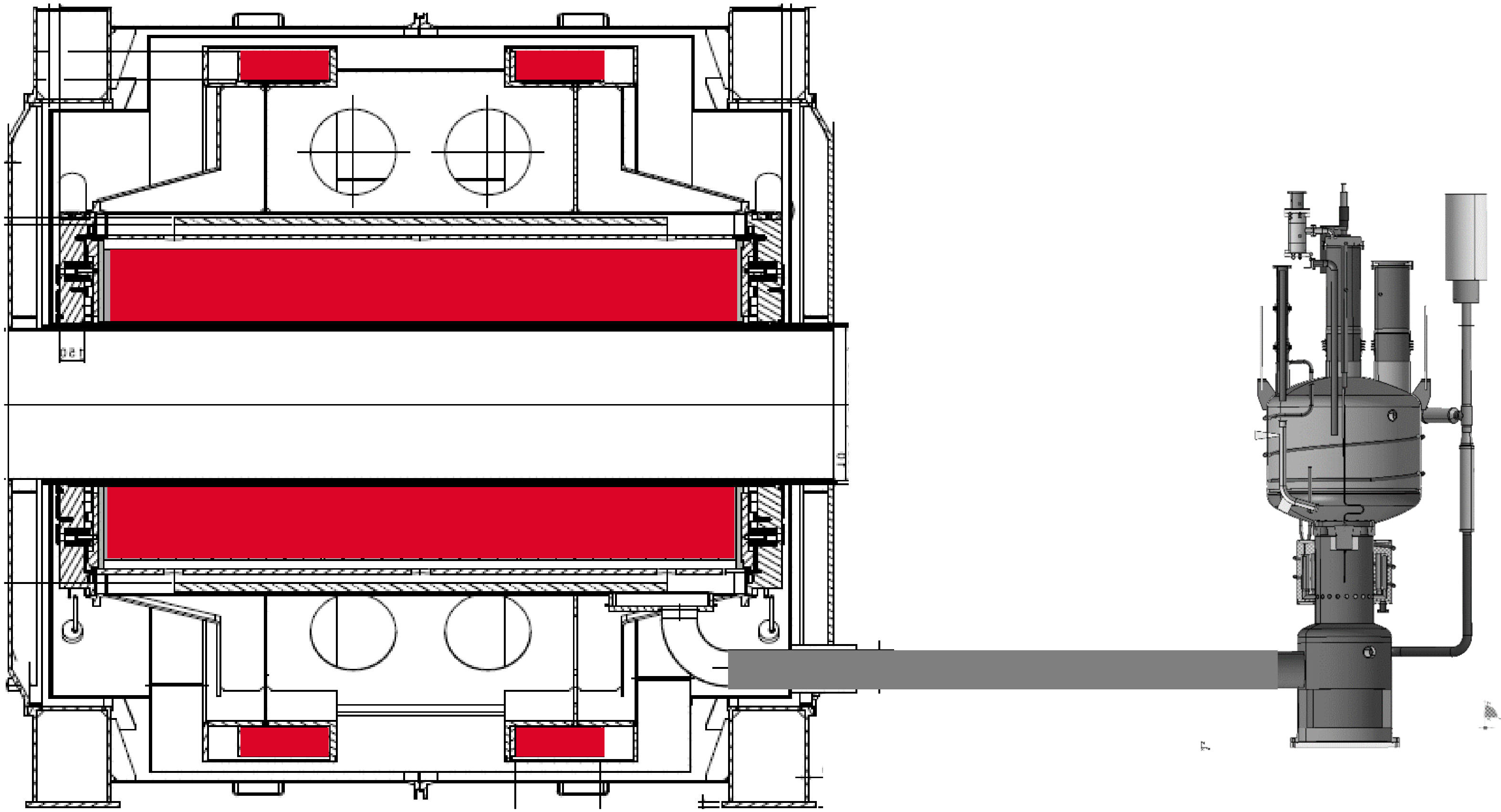
To sub-atmospheric He pumping unit

1.8 K pressurized bath

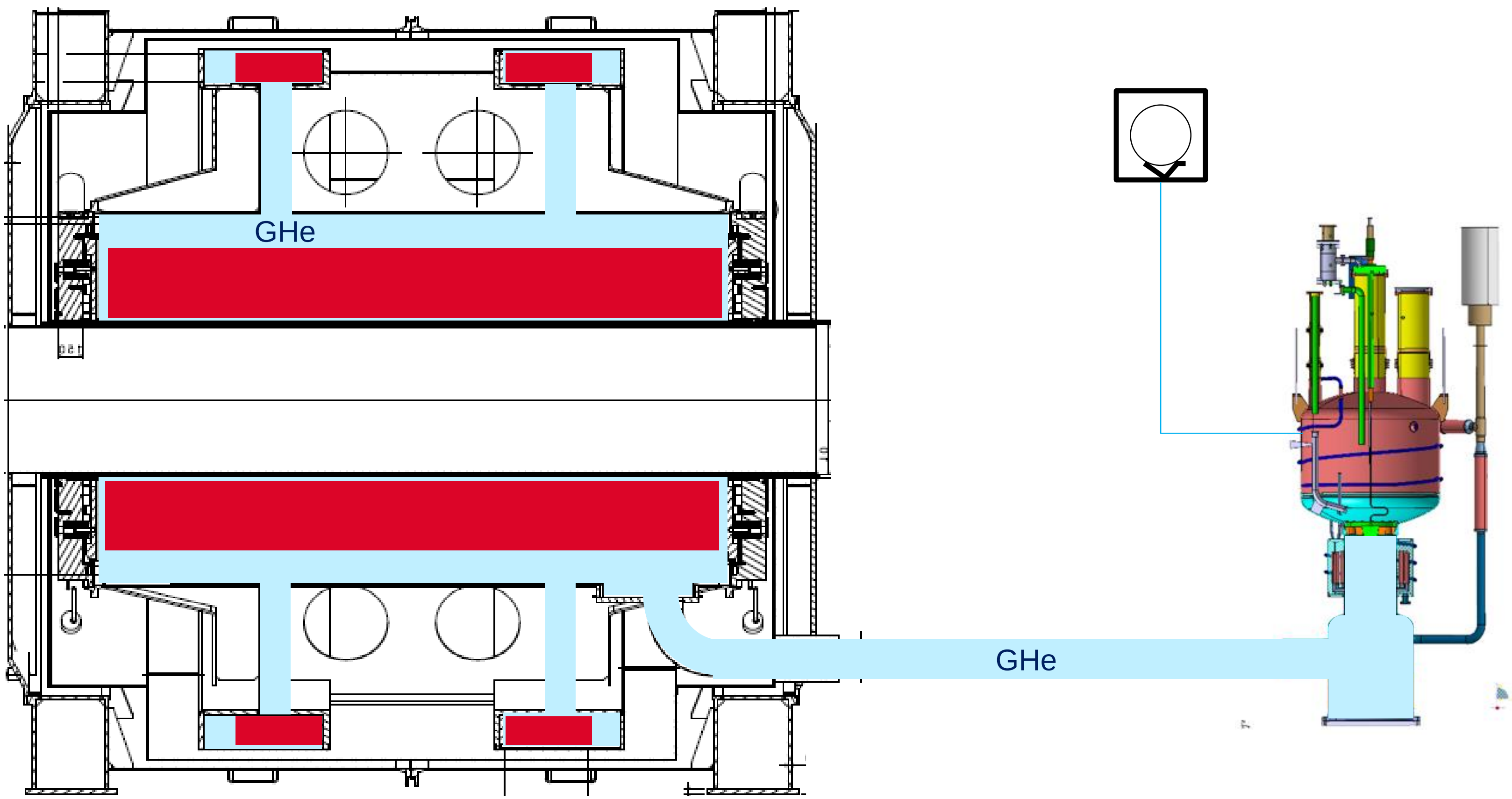
# COOLING DOWN

7400 l to be filled

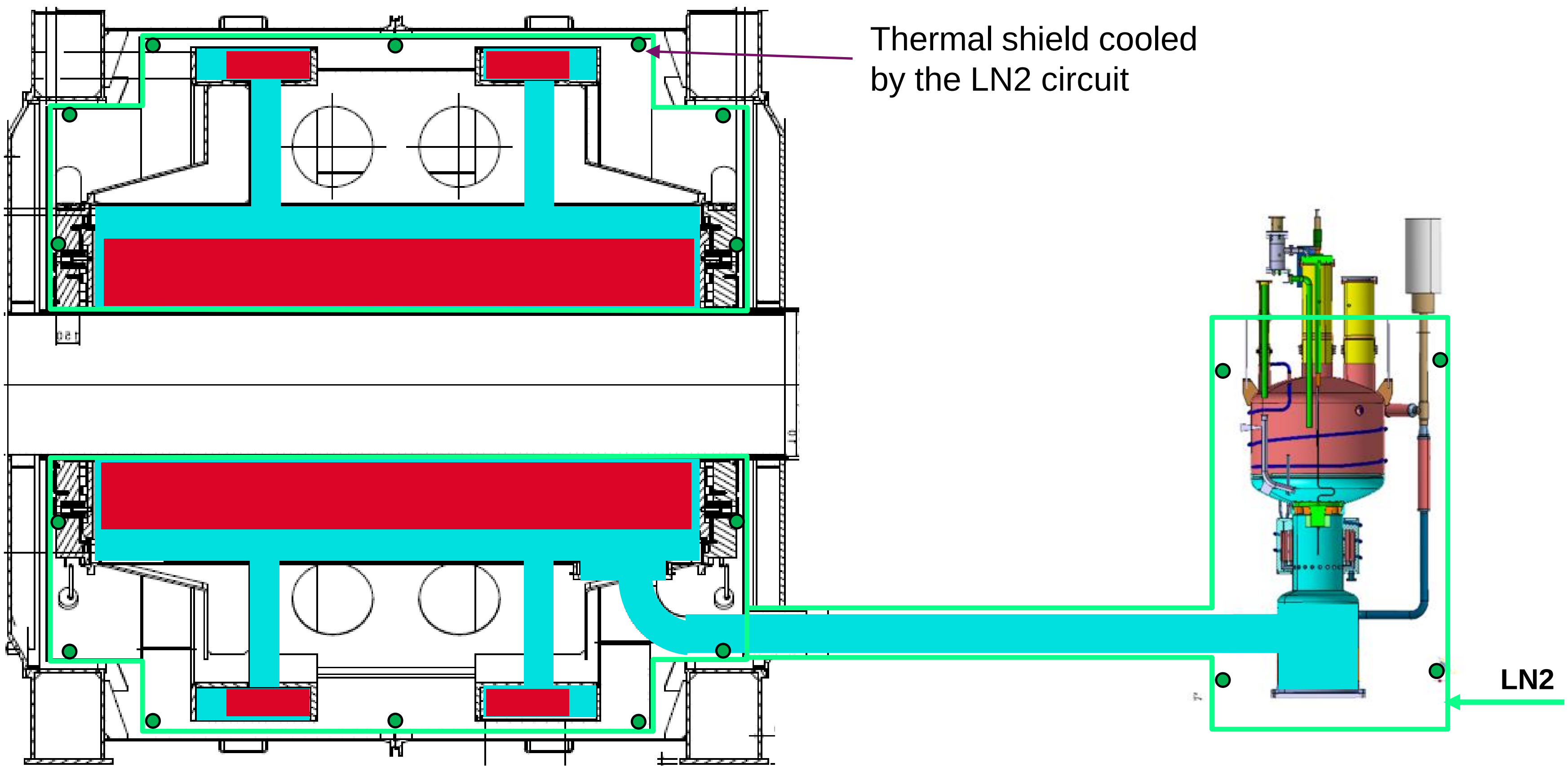
110 tons to cool down from 300 K to 1.8 K



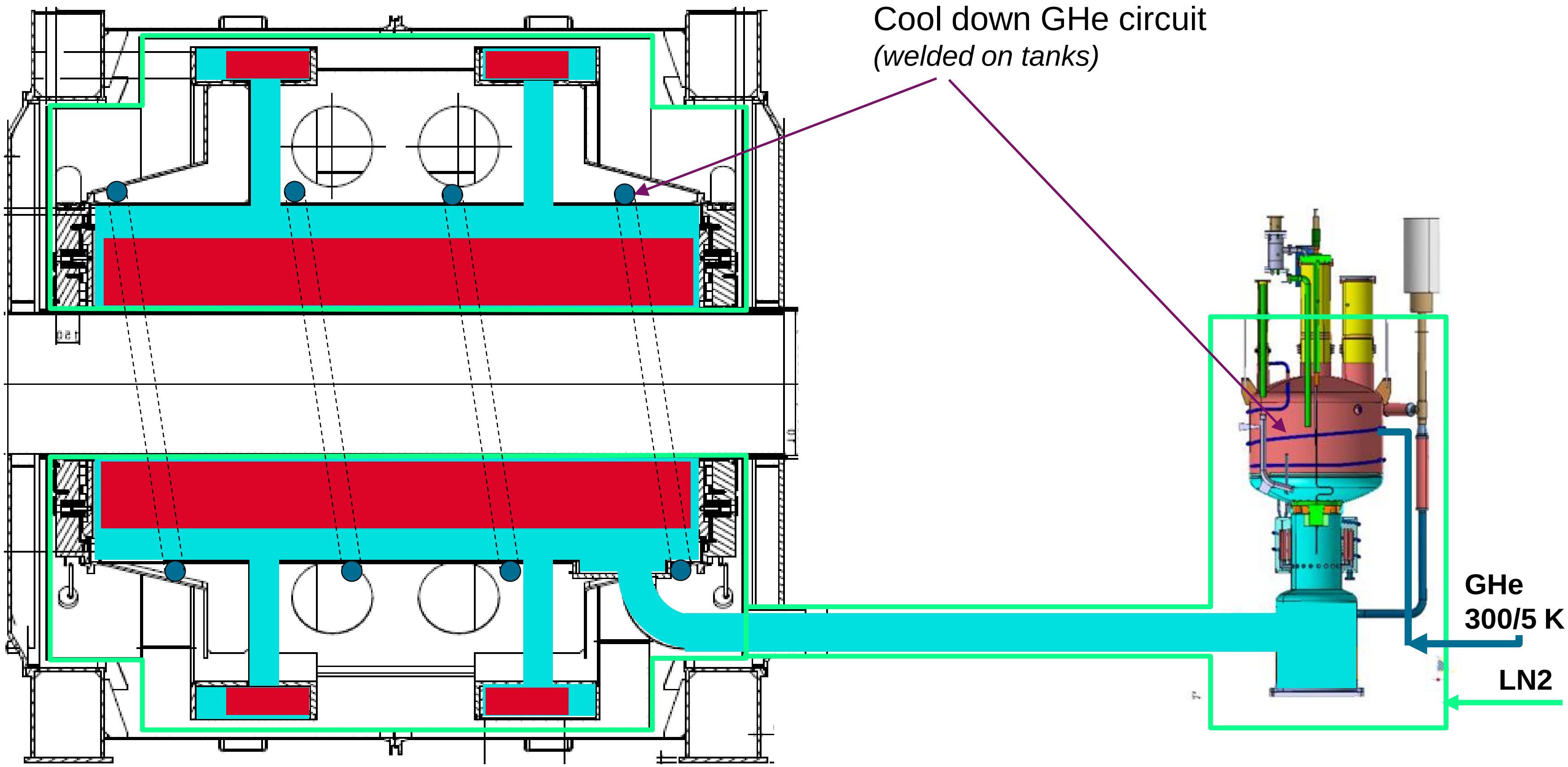
## Rinsing and purging with pure He



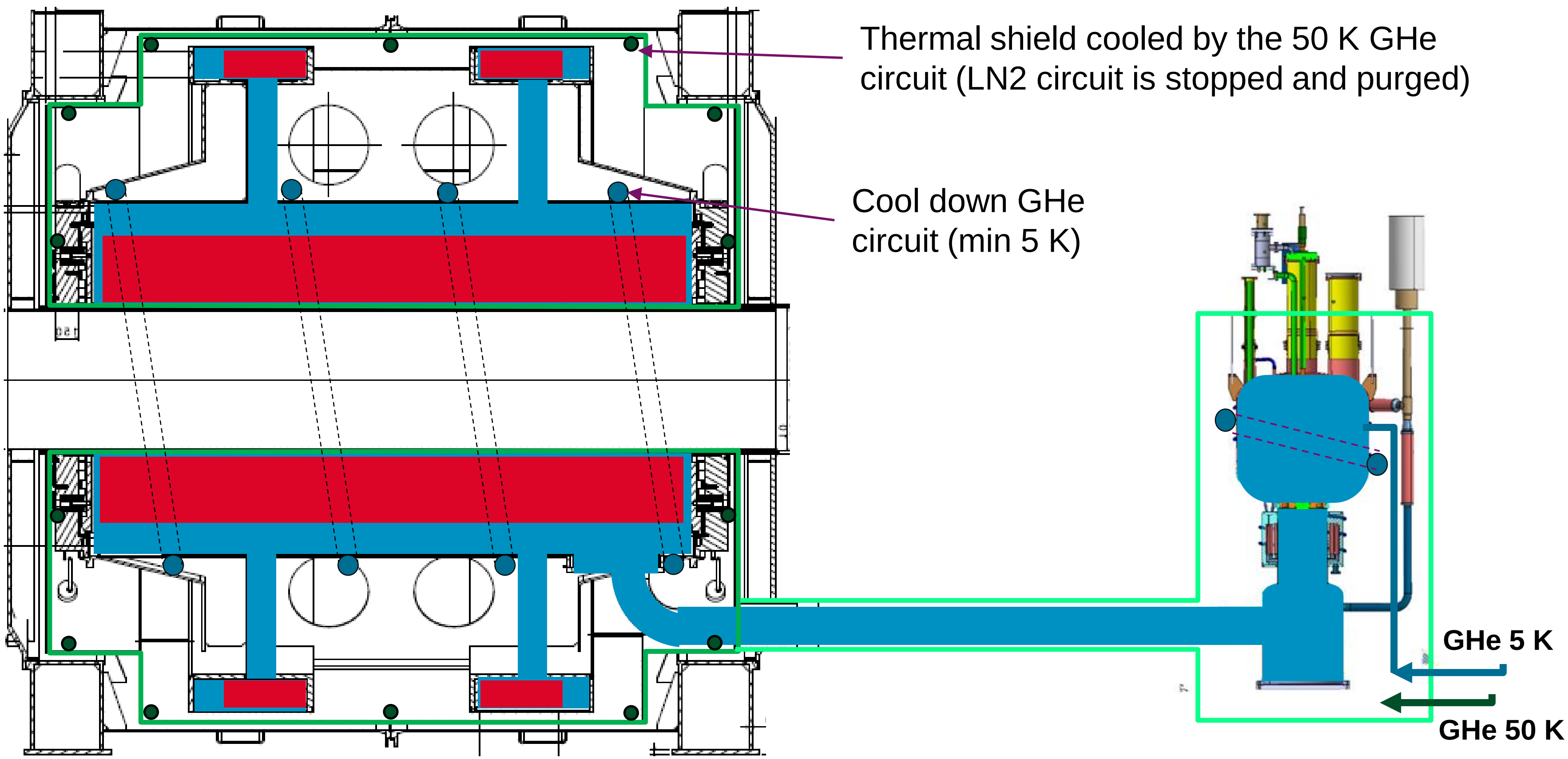
## Cooling of the unique thermal shield down to 80 K (LN2 flow)



**Cooling of the He tanks and coils from 300 K down to 5K (cold GHe flow from He liquefier)**

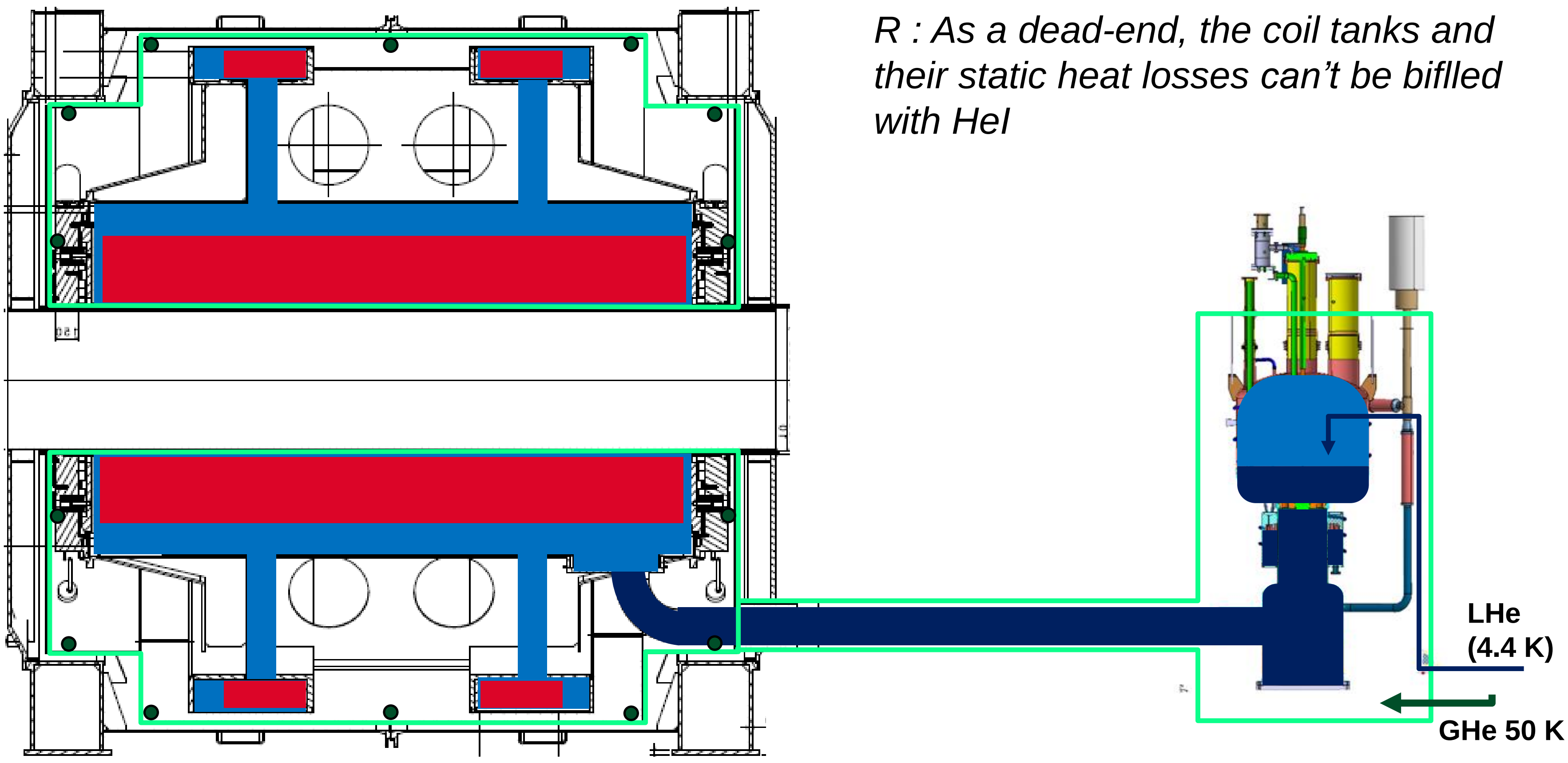


**He tanks and coils near 5 K and thermal shield cooled by « 50 K » GHe flow from He liquefier**



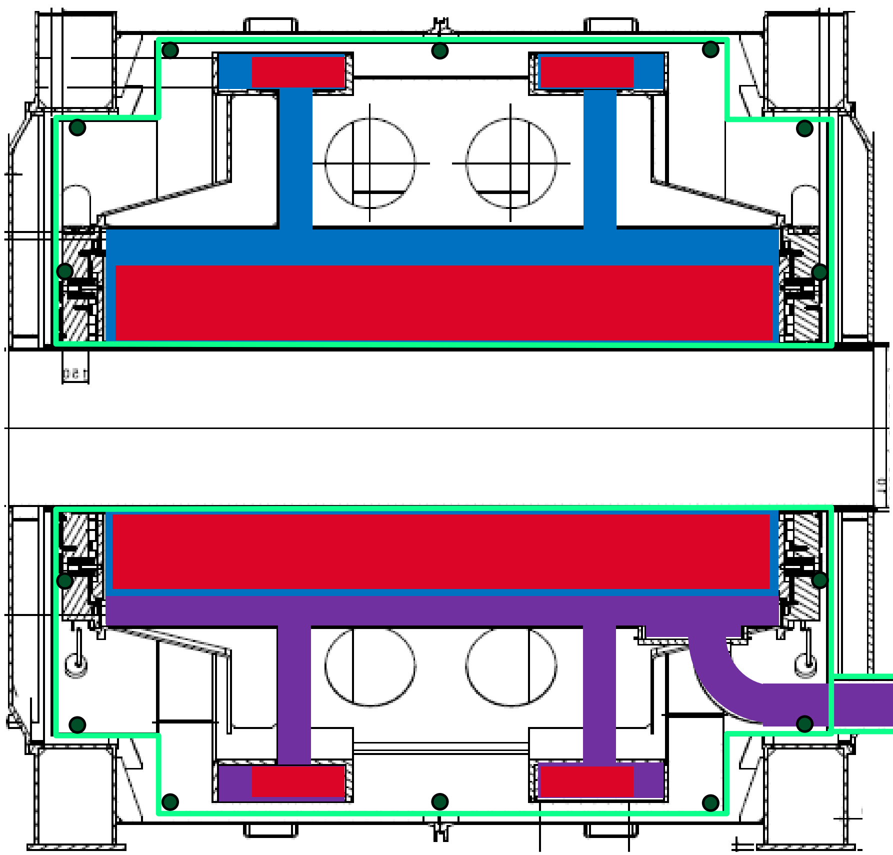
**Filling of satellite with LHe produced by He liquefier (thermal shield still cooled by « 50 K » GHe)**

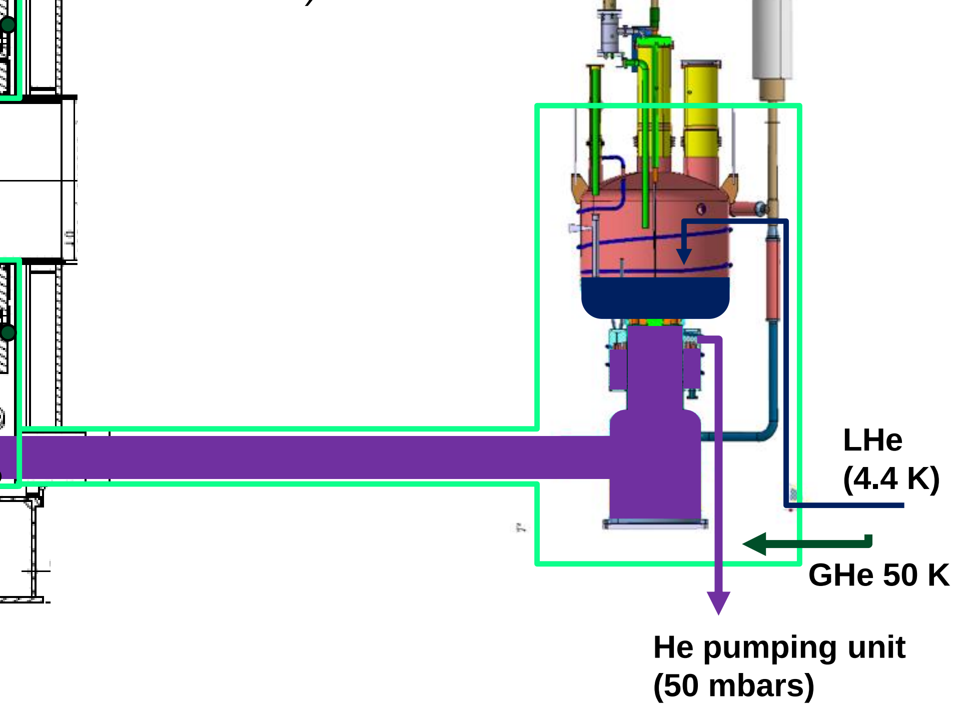
*R : As a dead-end, the coil tanks and their static heat losses can't be biflled with HeI*



**Starting up of the cold source below 4 K by pumping unit (tank filling by condensation of GHe down to He II at $T_{\lambda}$= 2.17 K)**

*R : With our slow cooling down, the small hydraulic leaks on the Lambda plate are sufficient to maintain 1.2 bars during condensation phase (without extra heat leaks…)*

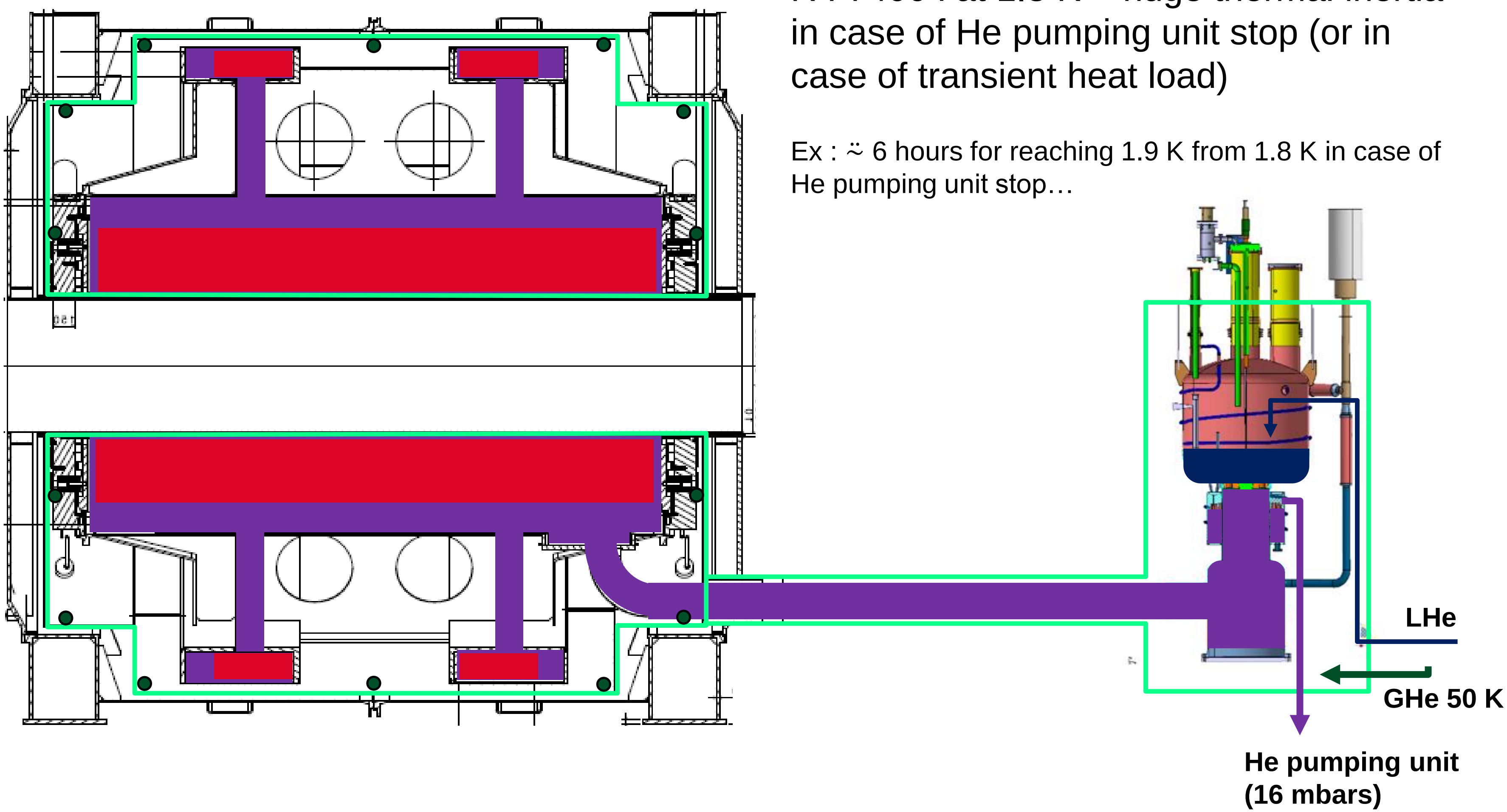




**Coil tank entirely filled with subcooled superfluid He (He II at 1.8 K and 1.2 bar)**

R : 7400 l at 1.8 K = huge thermal inertia in case of He pumping unit stop (or in case of transient heat load)

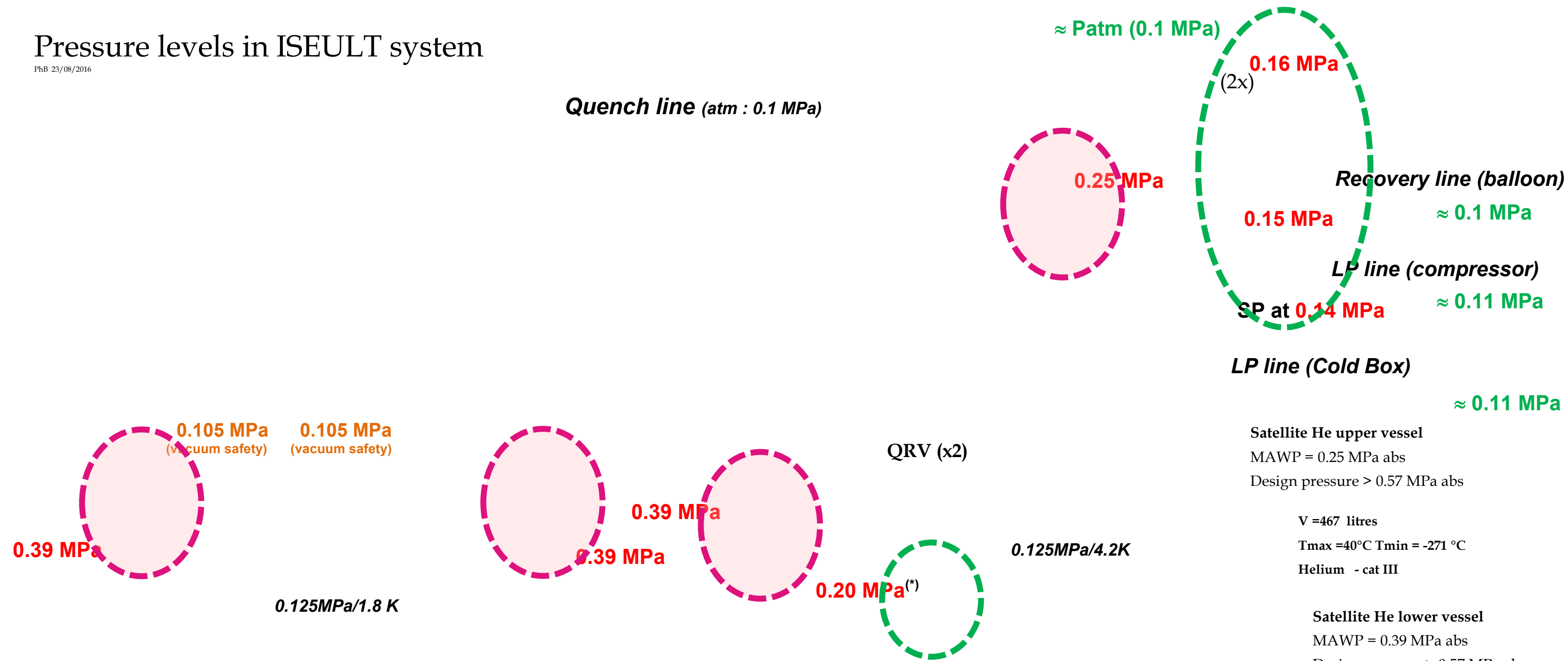
Ex : ≈ 6 hours for reaching 1.9 K from 1.8 K in case of He pumping unit stop…



# SAFETY DEVICES: HELIUM OVERPRESSURE

Pressure levels in ISEULT system

PhB 23/08/2016




**Satellite He upper vessel**
MAWP = 0.25 MPa abs
Design pressure > 0.57 MPa abs

**V =467 litres**
**Tmax =40°C Tmin = -271 °C**
**Helium - cat III**

**Satellite He lower vessel**
MAWP = 0.39 MPa abs
Design pressure > 0.57 MPa abs

**V =190 litres**
**Tmax =40°C Tmin = -271 °C**
**Helium - cat III**

**Caloduc He pipe**
MAWP = 0.39 MPa abs
Design pressure > 0.57 MPa abs

**V =184 litres**
**Tmax =40°C Tmin = -271 °C**
**Helium - cat II**

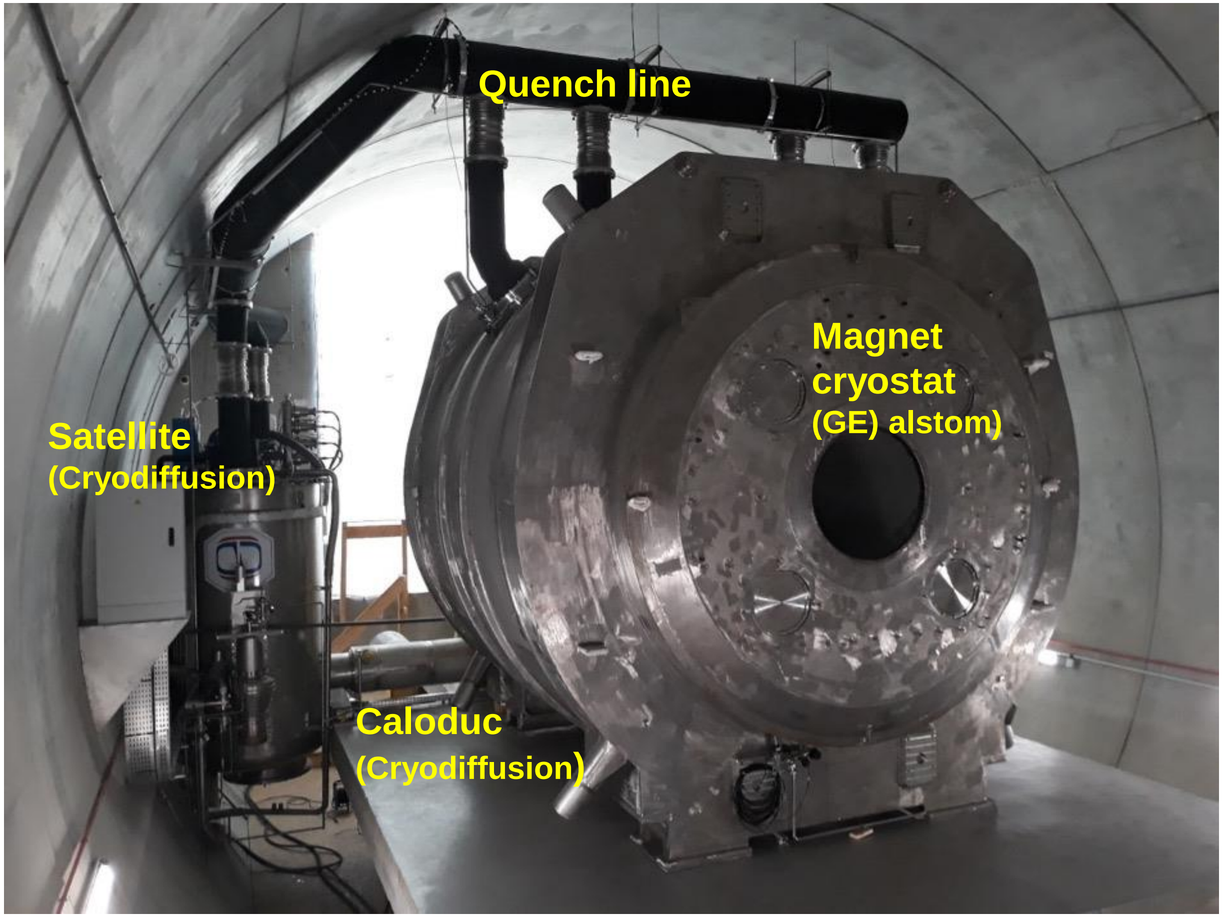
**Cryostat He vessel**
MAWP = 0.39 MPa abs
Design pressure > 0.57 MPa abs

**V =7450 litres**
**Tmax =40°C Tmin = -271 °C**
**Helium - cat IV**

Remarks: Values in **abs pressure**

QRV : (*) Opening (0%) at 0.2 MPa – Fully opened (100%) at 0.3 MPa
Not represented : PSV on thermal shield circuits, located in satellite, set at 2 MPa
Not representec: PSV on cooling-down circuits, located in satellite, set at 2 MPa (before expanding valve)

# THE CRYOPLANT FOR THE MAGNET OPERATION




And all the other equipment needed for reaching the CRYO OK…

# MAIN GOALS TO BE FULLFILLED FOR THE CRYOPLANT

110 tons of cold mass to be cooled down from 300 to 1.8 K

2.4 tons of thermal shield to be cooled from 300 to 50 K

7400 liters of He II to be filled and to maintain at 1.8 K (*1.95 K max with current*)

Estimated heat loads :

He liquefier requirements

- **20 W at 1.8 K** (magnet + satellite) (tech :1 W à 1.8 K ⇔ 2.4 l/h)
- **9 l/h** LHe for current leads cooling

**70 l/h**

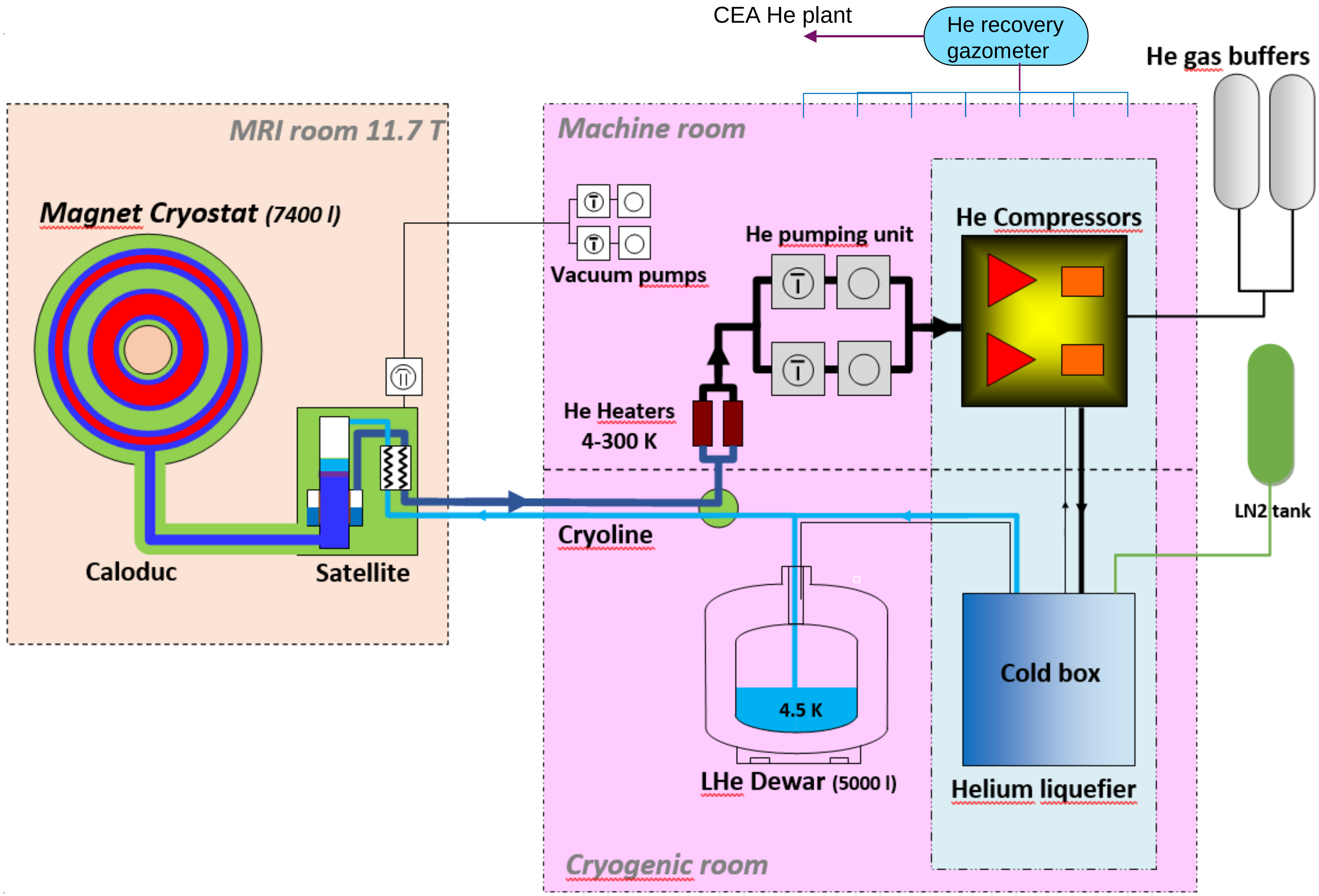
- **600 W at 50 K** (magnet + satellite) — **900 W at 50 K**
- **27 W at 4.4 K** (transfer lines and satellite) — **40 W at 4.4 K**

# Others points to be fullfilled

- Magnet continous operation : 24 h/day and 365 days/year
- Absorb losses induced by:
  - the pulsed gradient coils
  - slow discharge
  - fast discharge
- Secure the equipment in case of quench or vacuum failure
- Withstand any utility failure (electrical, water, compressed air)
- In case of a big cryoplant failure, maintain the magnet at 80 K maximum (LN2)
- Allow the maintenance actions without magnet desenergising
- Minimize manual actions on the process

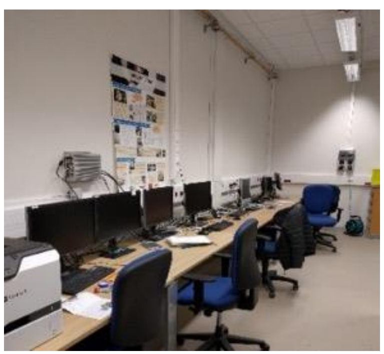
**Redundancy !**

# THE CRYOPLANT FOR THE MAGNET OPERATION



# The cryoplant for the magnet operation

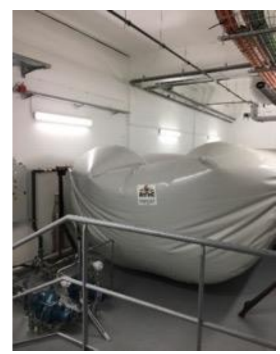

Cryoplant underground view



Control room

PLC

Power supply



He recovery

He gas buffers and LN2 tank

Cryogenic stallite

# AIR LIQUIDE HELIUM LIQUEFIER


**« HELIAL » Cold box**

**Measured capacities:**

**120 l/h**

**or**

**200 W @ 4.4 K**

**or**

**40 W + 81 l/h (nominal mode)**

**Thermal shield circuit I/O**
**900 W @ 50/55 K**

**Cool down circuit 300-5 K**

# AIR LIQUIDE LIQUEFIER


**He compressor unit**

**2 compressor + 2 ORS for <u>redundancy</u>**

**2 x 132 kW**

**40 g/s at 14.5 abars each**

**Air cooling**
**(2 x 25000 m3/h)**

# AIR LIQUIDE LIQUEFIER

**LHe dewar**

**5000 liters**

**0.35% static losses**

**Atmospheric heat exchangers**

for by-passing cold box during 300 K-100 K cooling down

R: *view before installation of the Cold Box*

# HELIUM PUMPING UNIT

He compressor unit (Oerlikon)

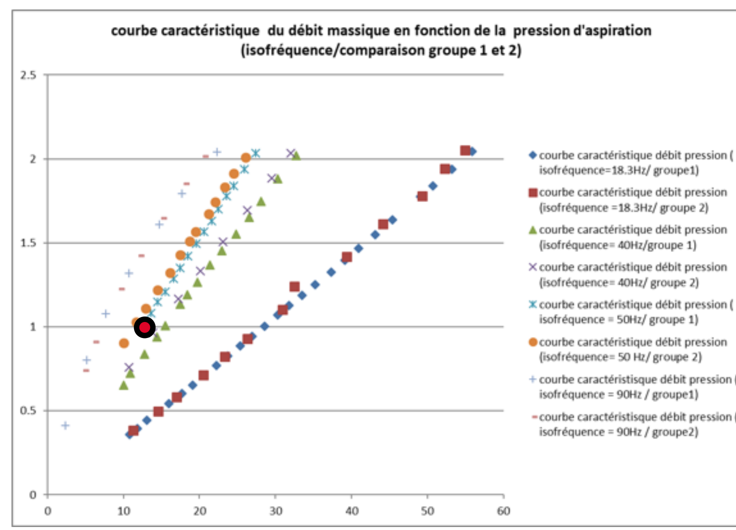
Roots (2000 m3/h with VFD 20-100 Hz) + vane pumps (750 m3/h)

2 Units for redundancy

1 g/s at 13 mbars each (50 Hz)

Air + water cooling

**Mass flow vs suction pressure for various roots speed**



# HE PUMPING UNIT : 4-300 K HEATERS

**Vacuum insulated electrical heaters installed on low pressure circuit between satellite and He pumping units (Cryodiffusion)**

**4-300 K / 8 kW**

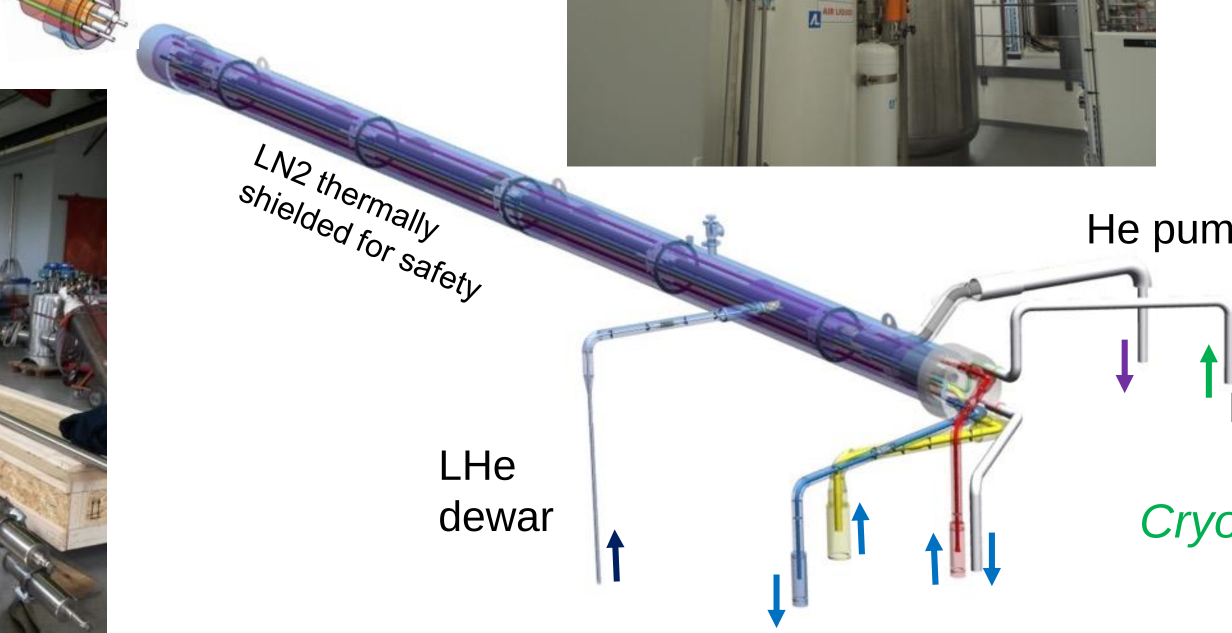
**Low pressure drop (< 1 mbars @ 1 g/s))**

**2 heaters in parallel for redundancy**

# CRYOLINE : VACUUM INSULATED CRYOGENIC MULTI-LINE

*Magnet room*

Satellite connection (vacuum barrier on satellite)




*Cryogenic room*

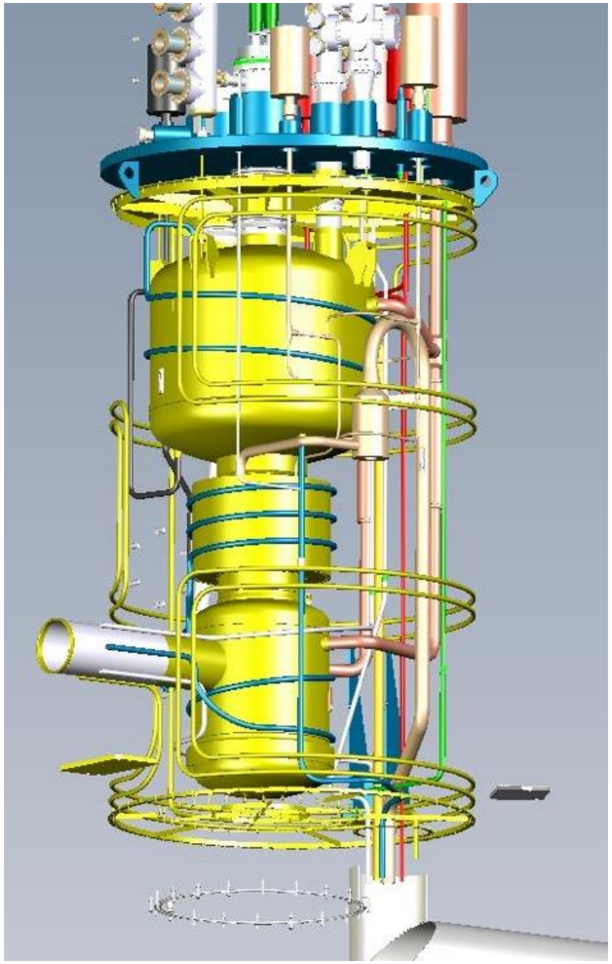
Cold Box:

- Cool down circuit outlet
- Thermal shield I/O (50/55 K)
- GHe return from 4.4 K tank of satellite

During tests at workshop

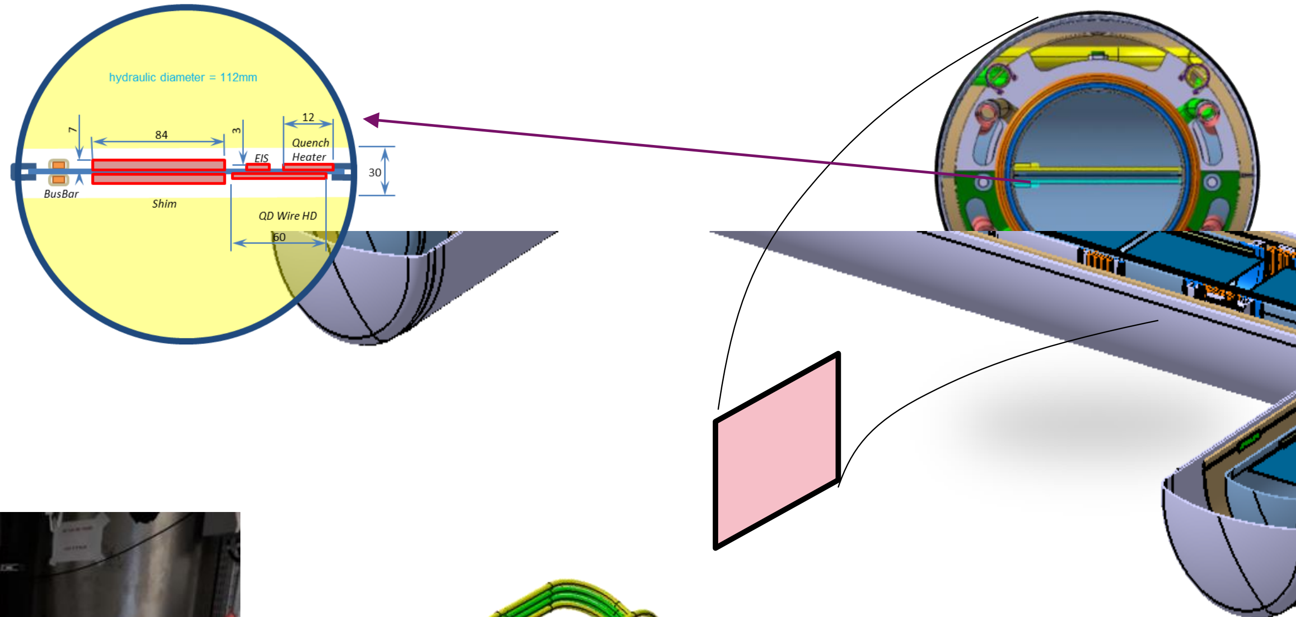
(Cryodiffusion)

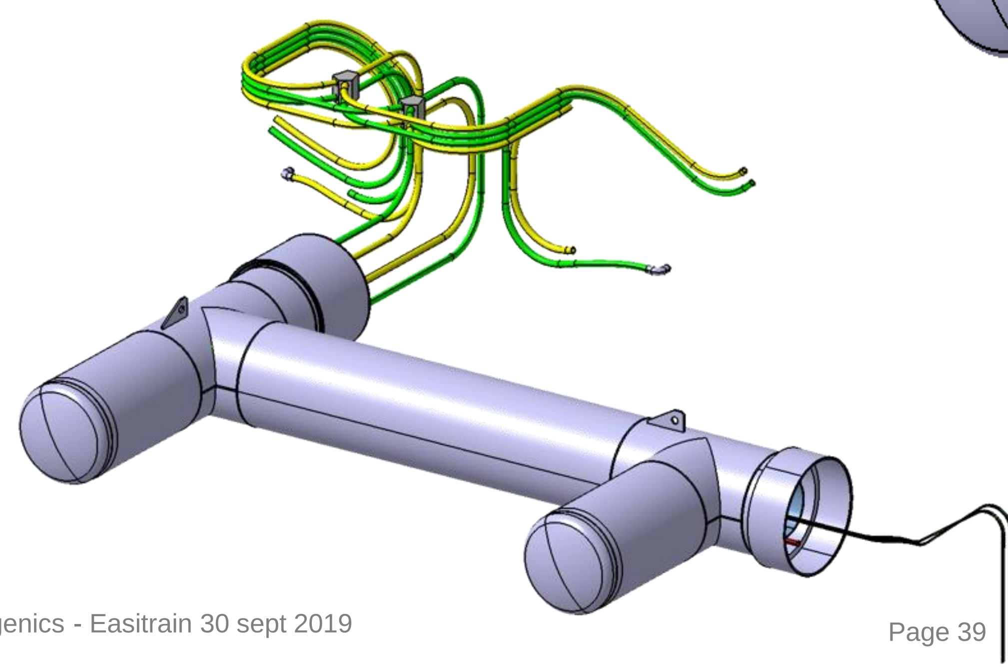
Interface for :
- Fluids
  - HeI
  - HeII saturated
  - HeII pressurized
  - LN2 and GHe
- Instrumentation
  - Magnet
  - Cryo
  - Safety
- Safety
- Electrical
  - 1500 A
  - Cryoshim
  - EIS
- Vacuum



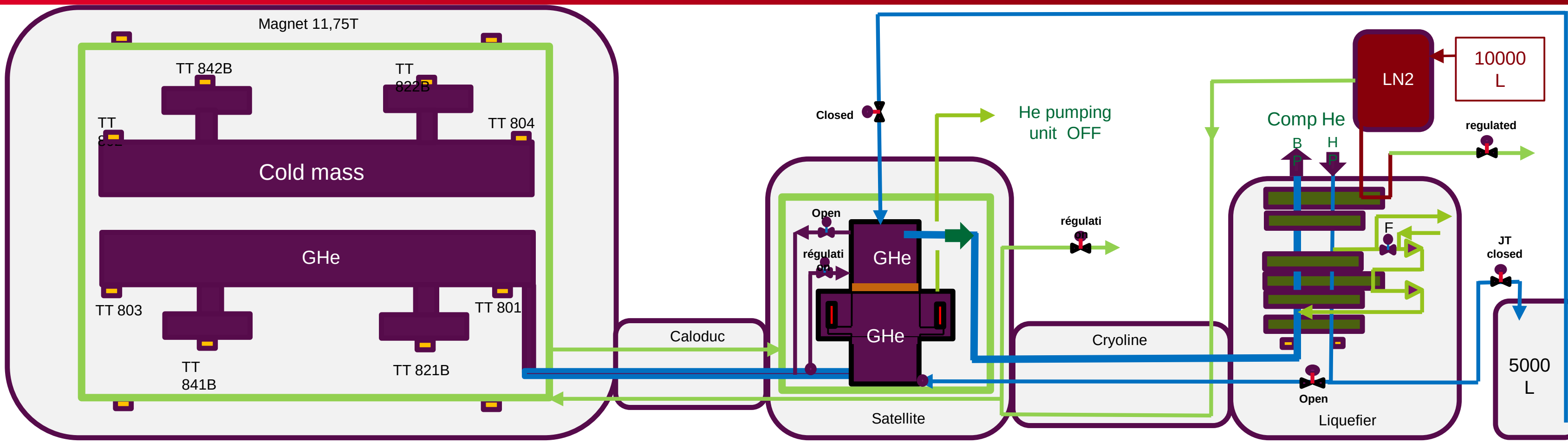
# He II caloduc

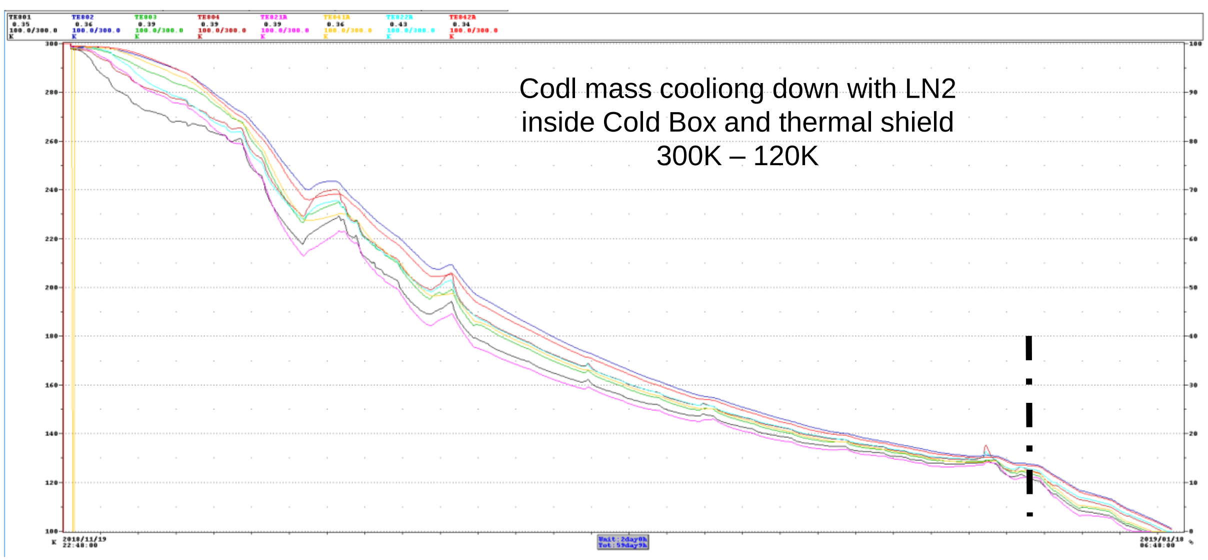
He II pipe
He andc LN2 circuits
(shields, cool down)
1500 A busbars
Cryoshim circuits
EIS heaters



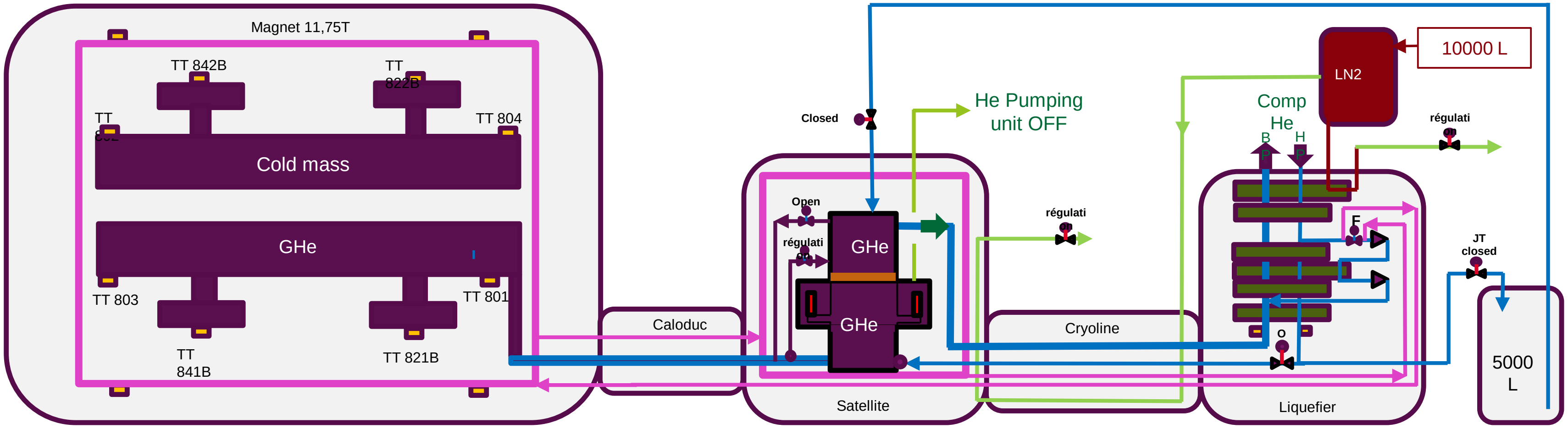
# FIRST step of cooling down : 300-120 K

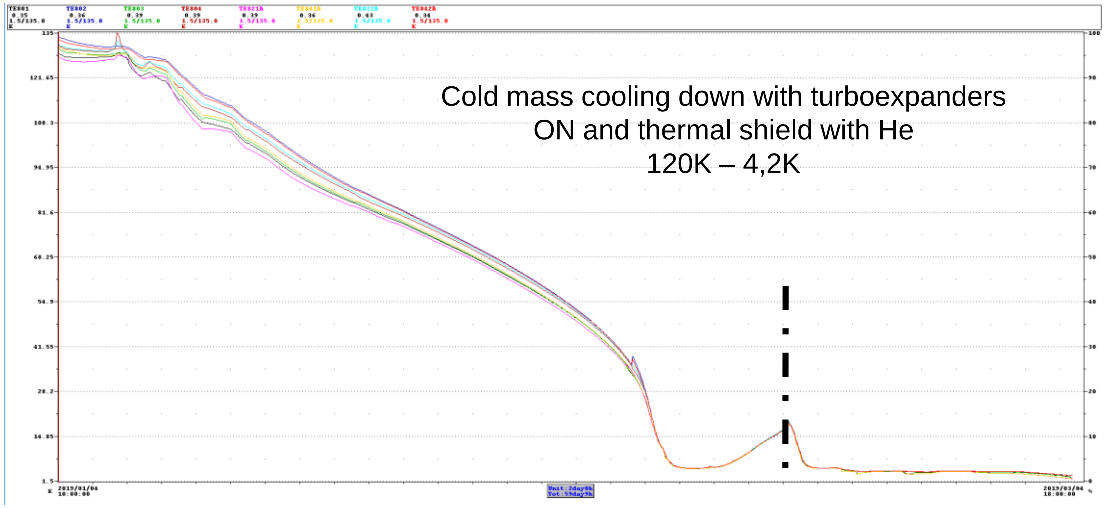


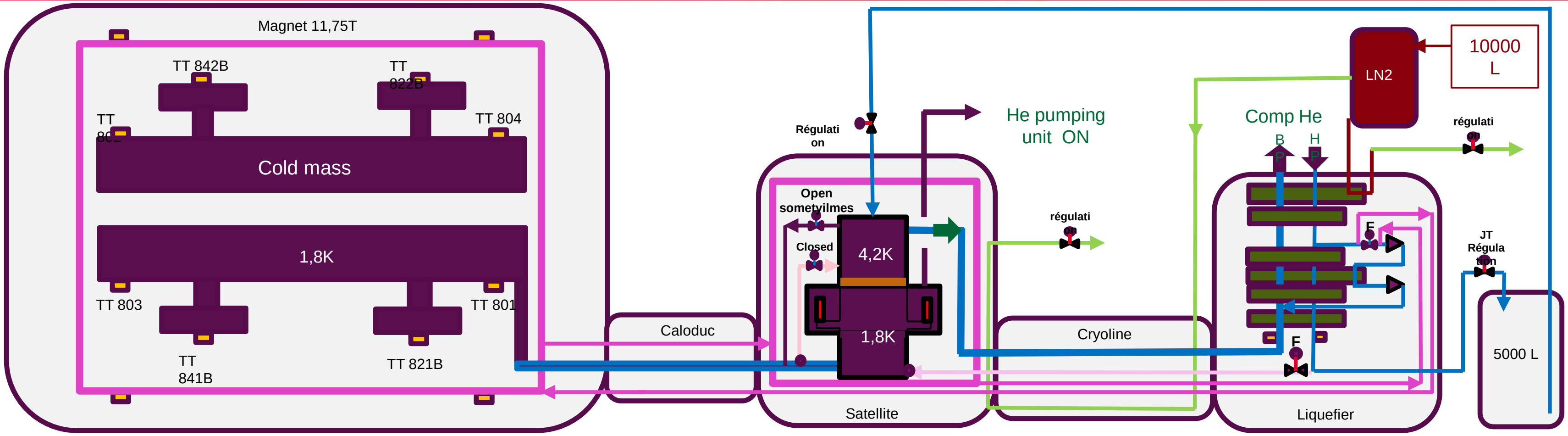

- **110 tons to be cooled from 300 K to 120K**
- **210 000 liters of LN2**
- **7 weeks**

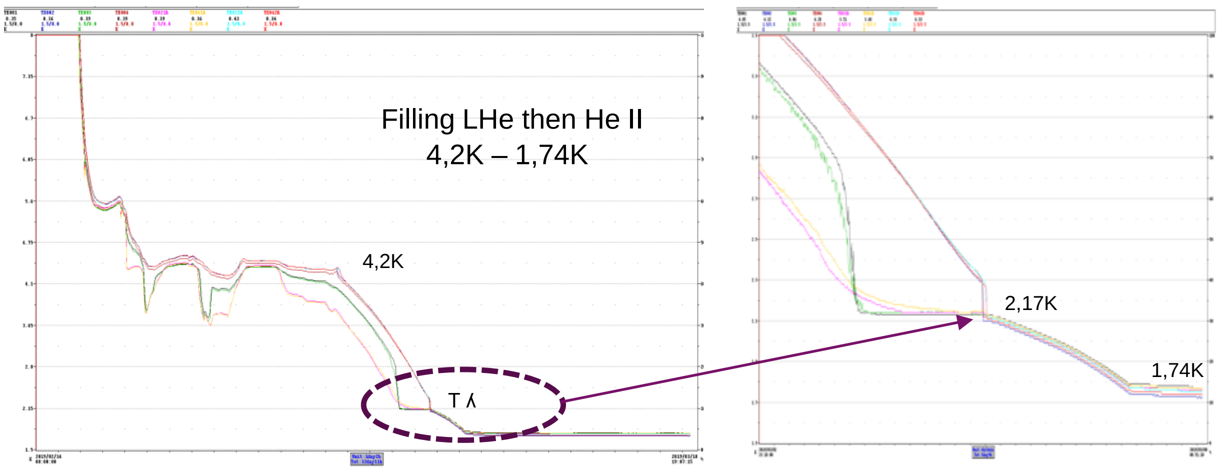
# SECOND STEP OF COOLING DOWN : 120 – 4.2 K



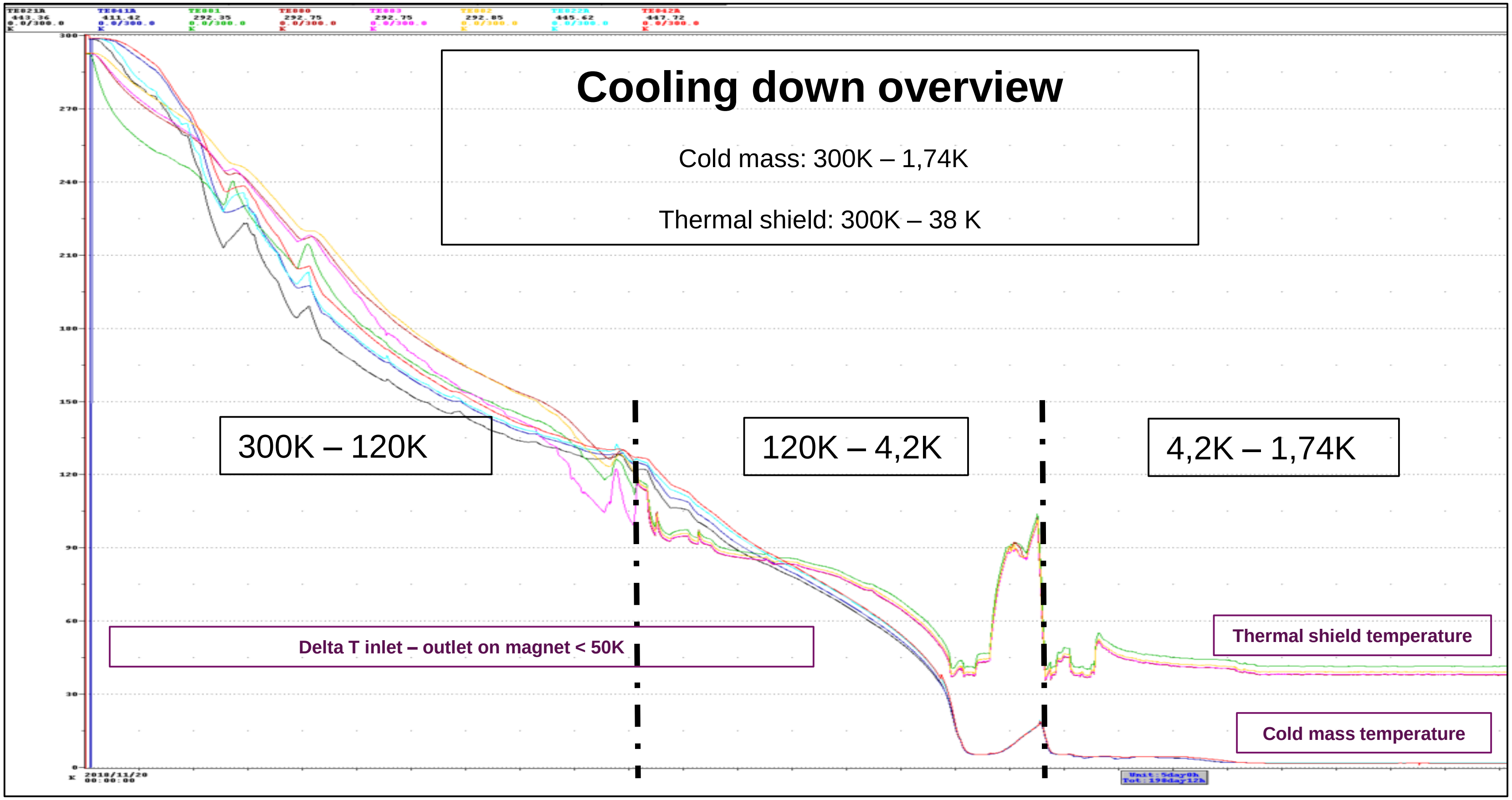

- **110 tons to be cooled 120 K – 4.2K**
- **50000 liters of LN2**
- **5 weeks**




- **Filling the magnet with 7400 liters of He II**
- **Cooling down from 4,2K to 2.17 K then from 2.17 K to 1.8 K**
- **Complete the 5000 liters LHe Dewar**
- **Vaporiser 13 bidons de 1000 litres d'hélium dans le cycle**
- **25000 liters of LN2**
- **4 weeks**

# Cooling down



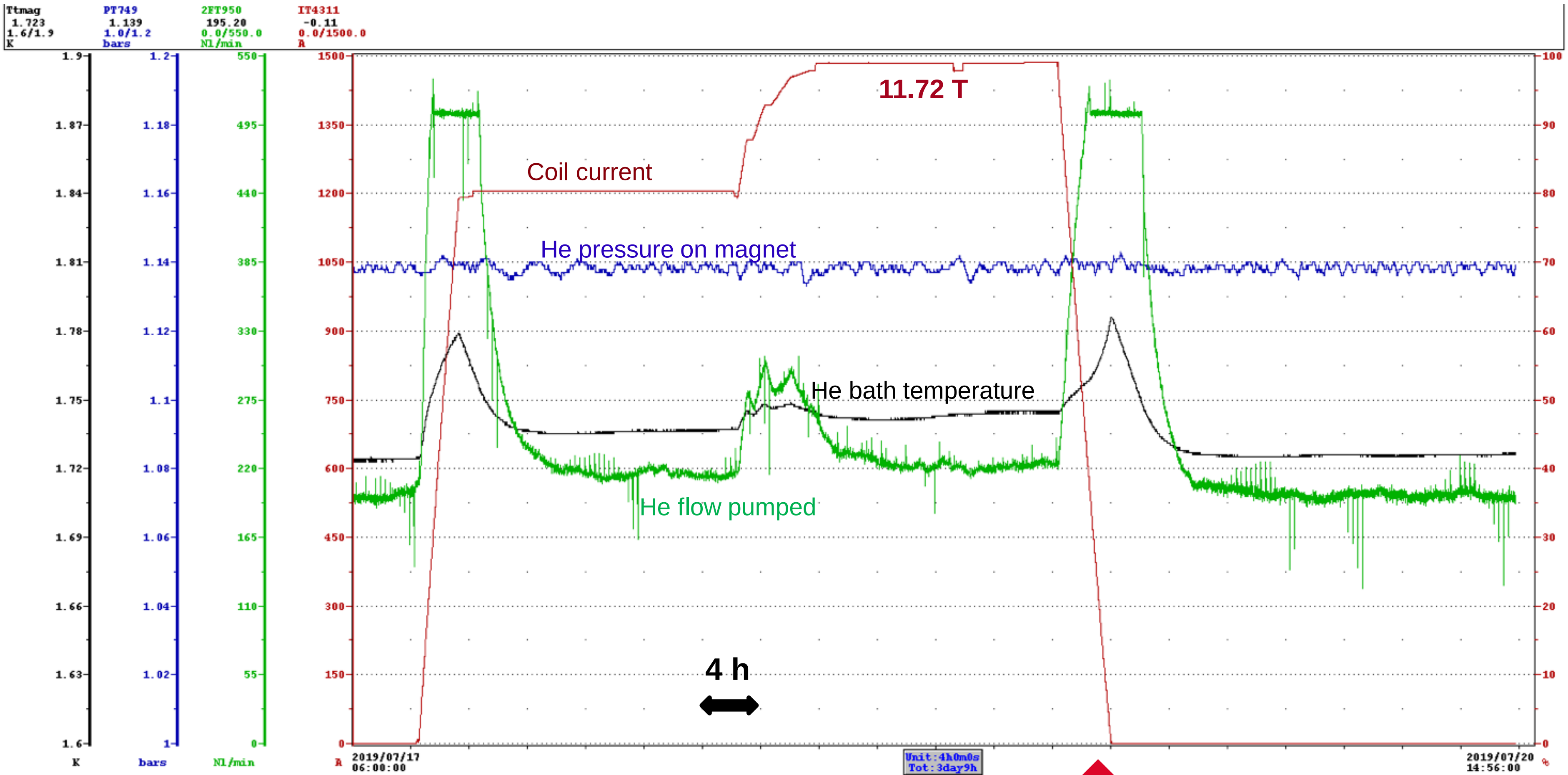

A little bit long ☹ but unique ☺ and with no He leak or unexpected heat loads : ☺

# Measurements at nominal mode

**Measured heat losses**:

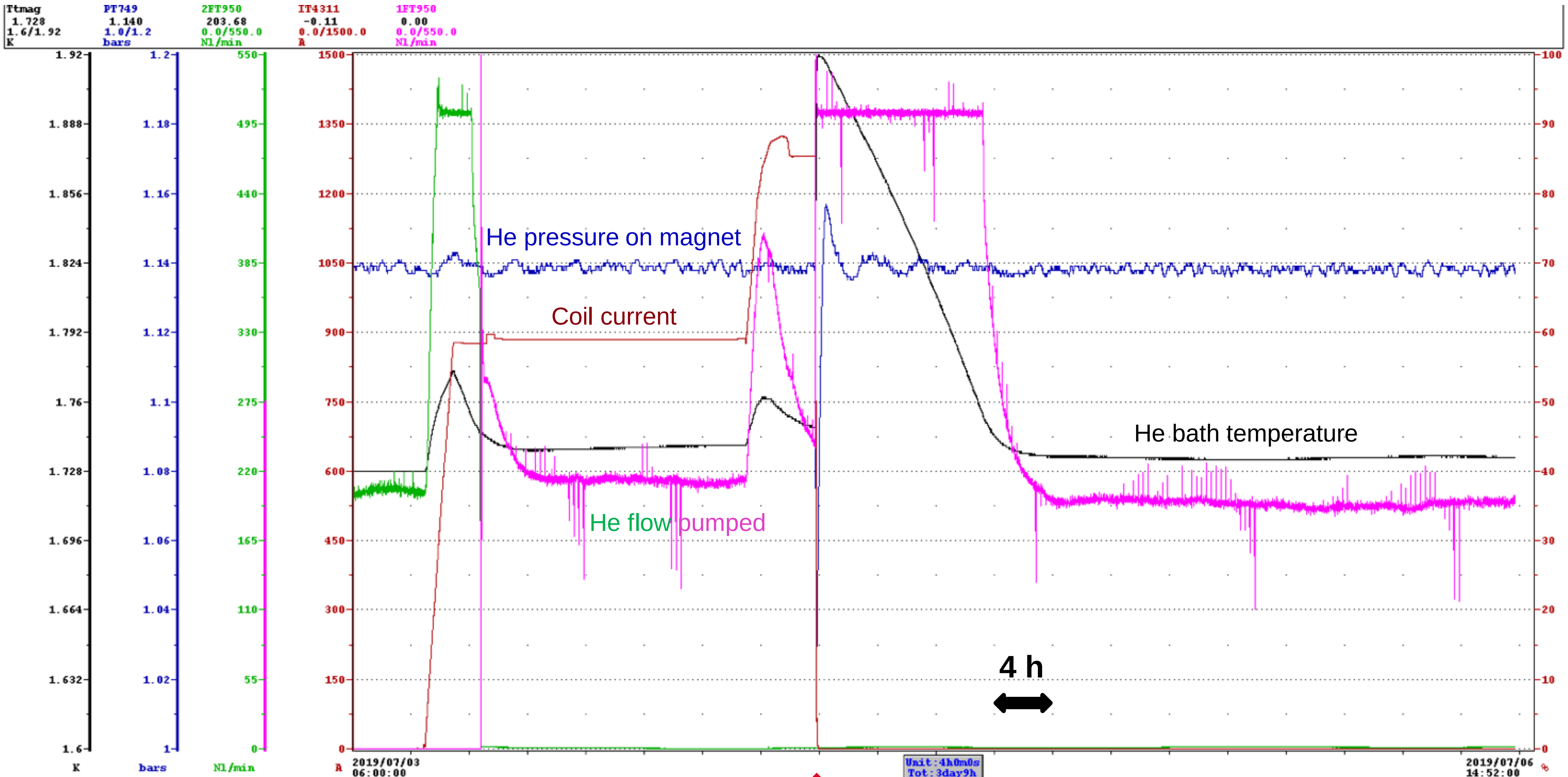
- 12 W @ 1.8 K without current
- **14 W @ 1.8 K** with 1483 A (20 W estimated)
- > 16 W @ 4.4 K (tbc)
- **8.1 l/h** for currents leads (8 l/h estimated)
- **572 W** with 38 K on magnet ThS and 41 K on satellite ThS (570 W estimated…)

# 9.5 T THEN 11.72 T WITH SLOW DISCHARGE




**Slow discharge** (small heat deposit )

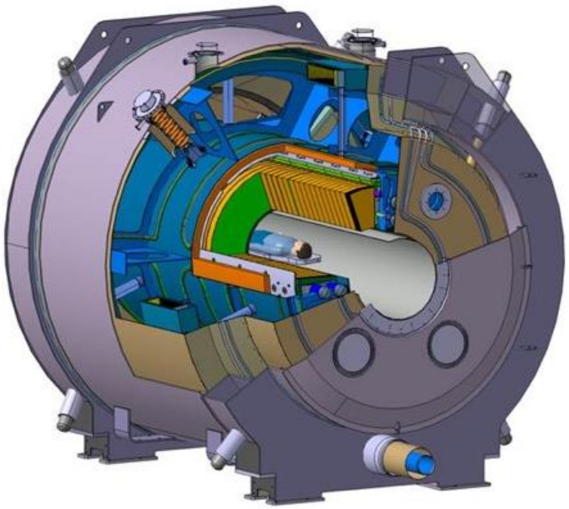
# 7 T THEN 10.5 T WITH FAST DISCHARGE



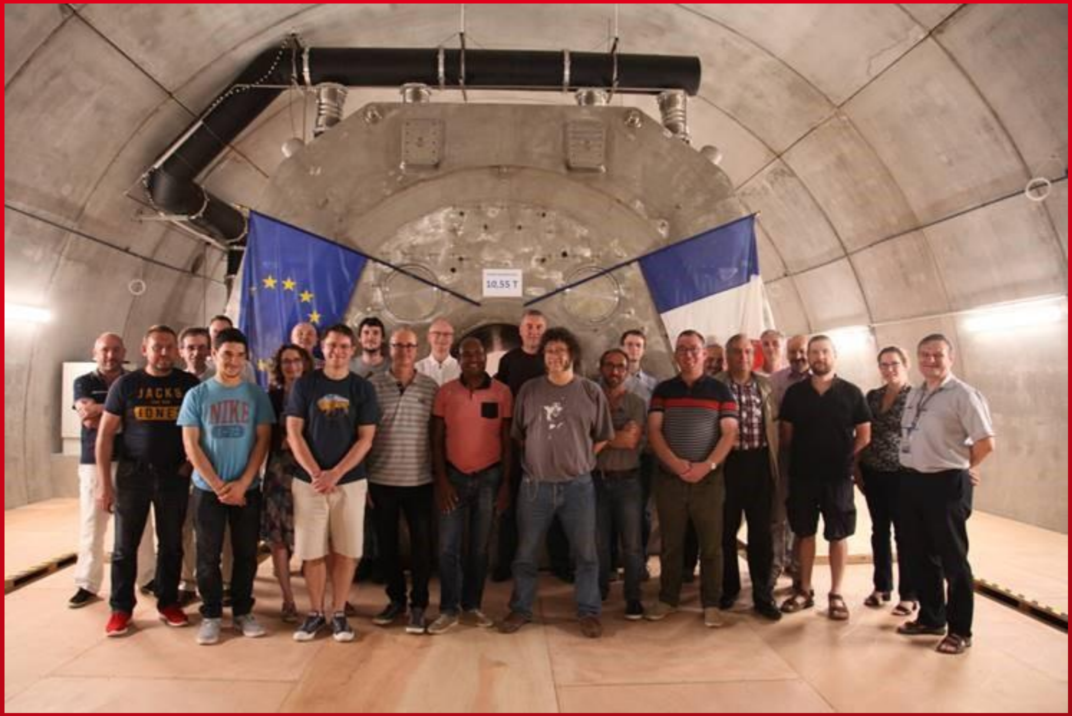

**Fast discharge** *(normal contraction of the HeII bath under a significant heat deposit (eddy currents) !)*

# Next steps

- To continue to consolidate the control-command software by testing and analysing the maximum of fault scenarios modes (several « instructive » failures since one year of continuous mode…)
- To analyse the thermal effect (extra transient heat losses) of the pulsed gradient coils (not yet installed inside the magnet hole)
- To implement all the maintenance procedures, equipment and contracts with manuals for operators



# Thank you  for your attention




And great acknowledgements to all the collaborators involved in this work…

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