Modeling of a horizontal circulation open loop in two-phase helium

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Outline

- Cooling large superconducting detector magnet
- Vertical circulation loop
- The R3B-Glad magnet
- Circulation loop with horizontal heat exchanger

- Experimental facility and ranges of the study

- Model

- Evolution of the p, T and x along the loop

- Comparison with experimental results (m_t and x_s)

- Conclusions and future work

Cooling large superconducting detector magnet

- Large scale "Dry" magnet
  - Large stored energy and small thermal losses
  - T_{max} and ∇T to minimize the mechanical constraints
    - Larger thermal stabilizer cross-sectional needed
  - Fully impregnated coil
  - Reduction of the quantity of cryogen


CMS magnet

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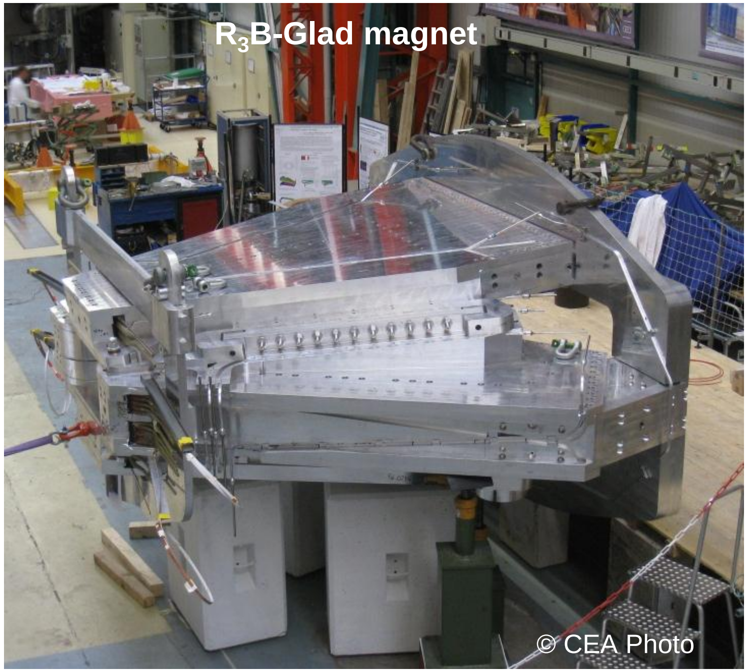
R_3B-Glad magnet

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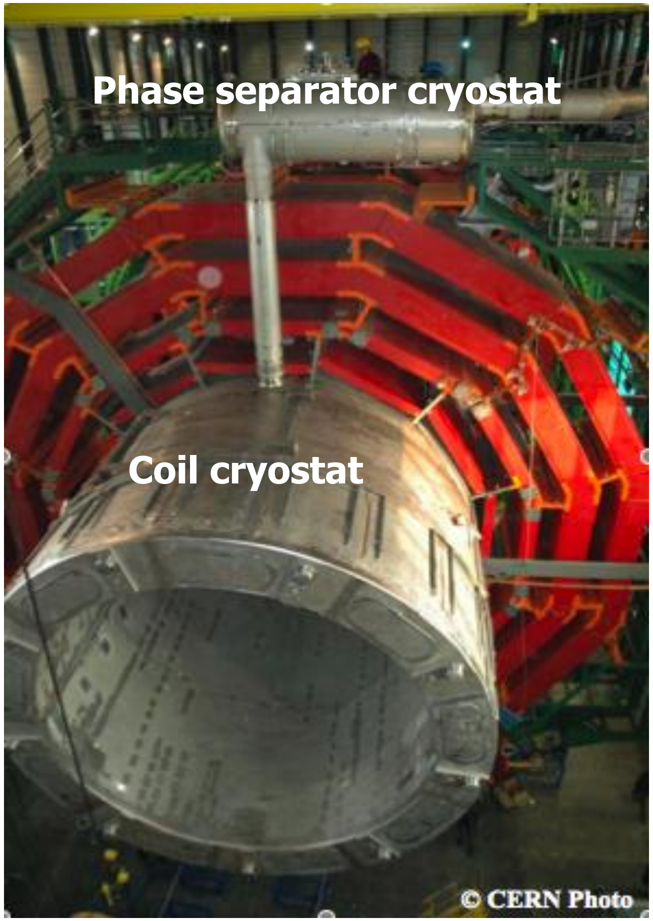
- Heat transfer
  - External cooling is sufficient
  - Two-phase flow of He I
  - Natural circulation loop or forced convection

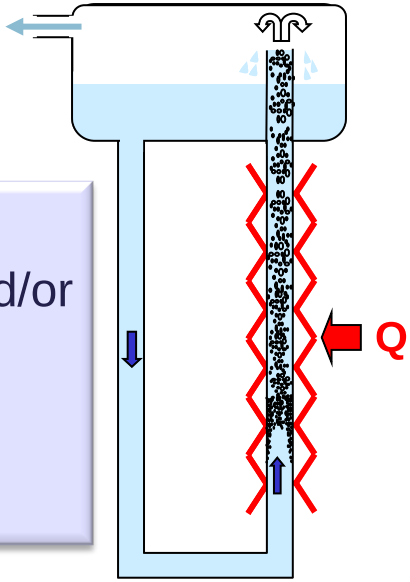

CMS magnet coil

Open circulation loop (1/2)

- □ Gravity powered device
  - ○ Reservoir of liquid above the loop (phase separator)
  - ○ No re-condensation of the vapor (open reservoir)



- □ Power to be extracted
- □ Decrease in liquid density and/or vaporization
- □ Branch weight unbalance
- □ Flow induced

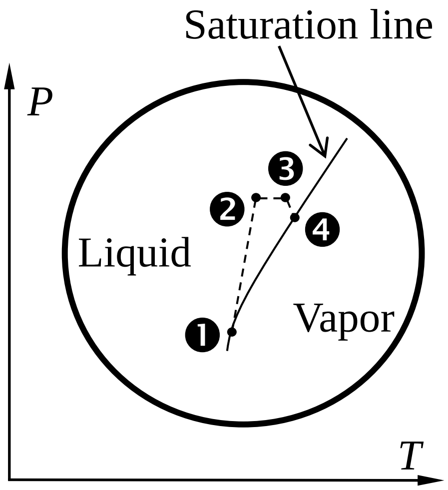


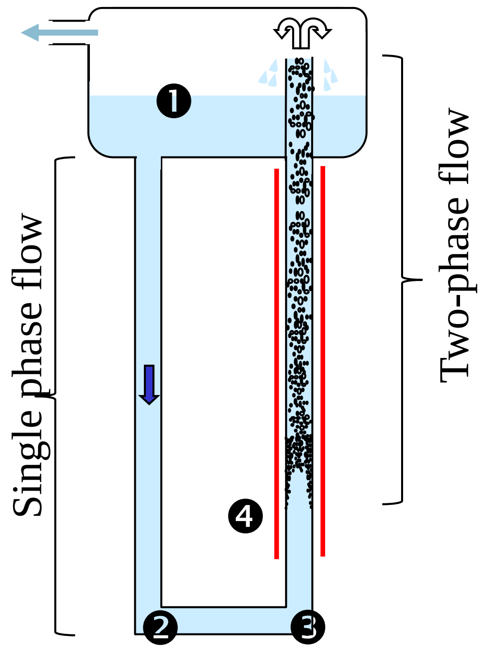
- □ Suppression of pressurization system
- □ Self-sufficient mass flow rate system

- □ Liquid level needs to be controlled to avoid dry-out
- □ Minimum heat flux to start a stable mass flow rate
- □ Flow oscillations at low heat flux

Vertical open circulation loop

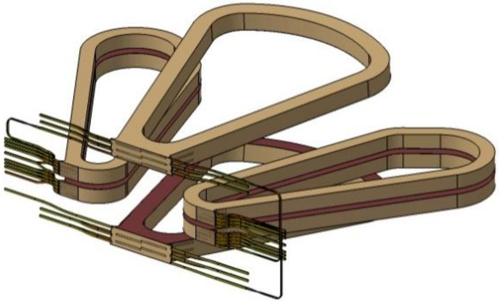
- Single phase flow in the feeding branch (❶- ❷ and ❷ to ❸)
  - Adiabatic branch and the liquid is sub-cooled
  - Pressure and the temperature increase from ❶ to ❷
  - Pressure and the temperature constant from ❷ to ❸
- The upward branch is heated partially and above it is adiabatic (the riser)
  - Flow is first in single phase from ❸ to ❹
  - Fluid reaches the saturation temperature at point ❹
  - Fluid temperature follows the saturation line down to ❶
- Point ❹ is the onset of nucleate boiling
  - Then the flow above ❹ is two-phase

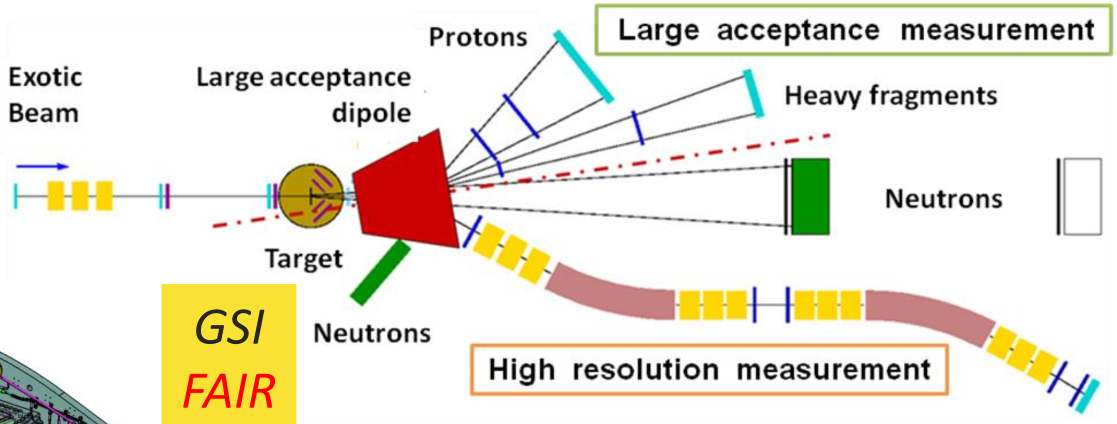




The R3B-Glad magnet (1/2)

R3B-GLAD





GSI
FAIR

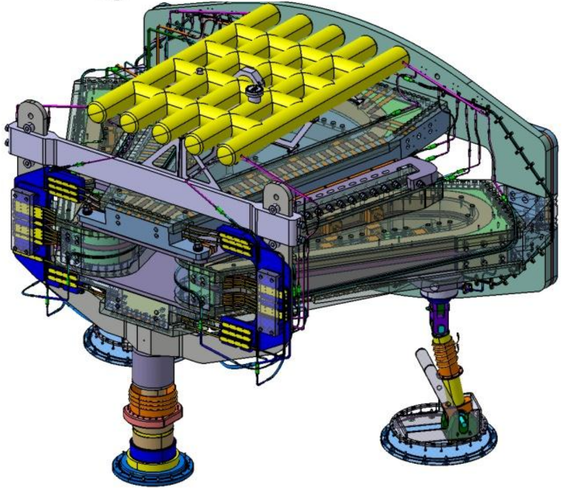
Cable
Rutherford
Cu–NbTi
17 km, 5.2 tons

Cold mass
Al 5083
22 tons

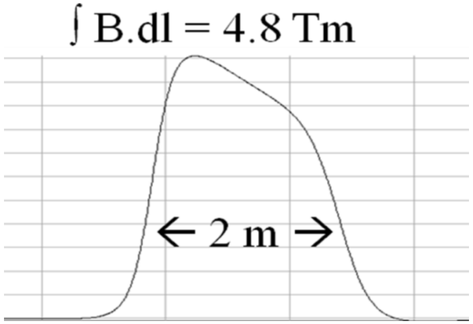
Thermosiphon
Liq-Helium 4.6 K

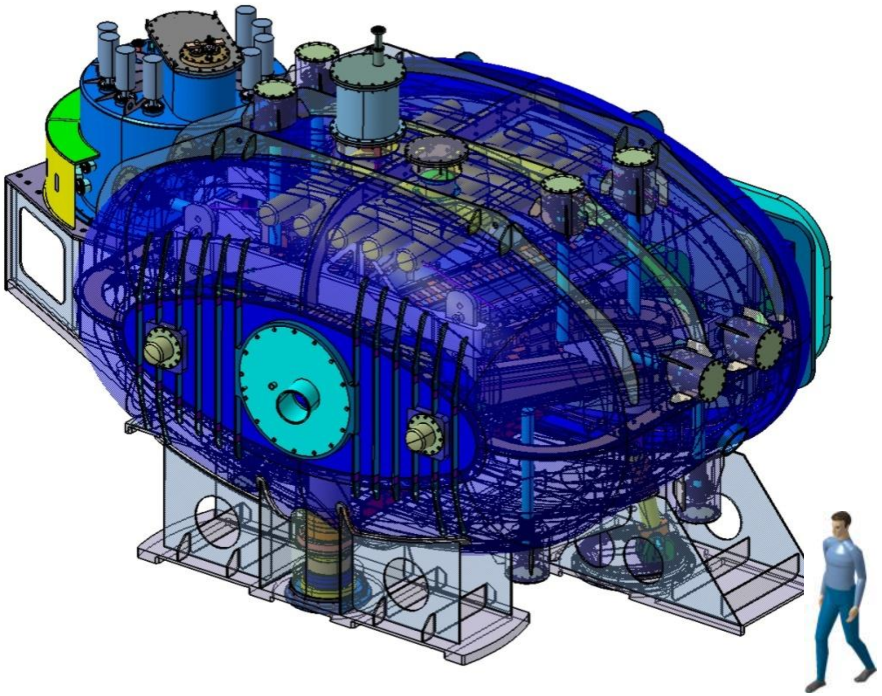
Magnet **~ 60 t**

Active shielding
Target area
< 20 mT



$\int B.dl = 4.8\ \mathrm{Tm}$





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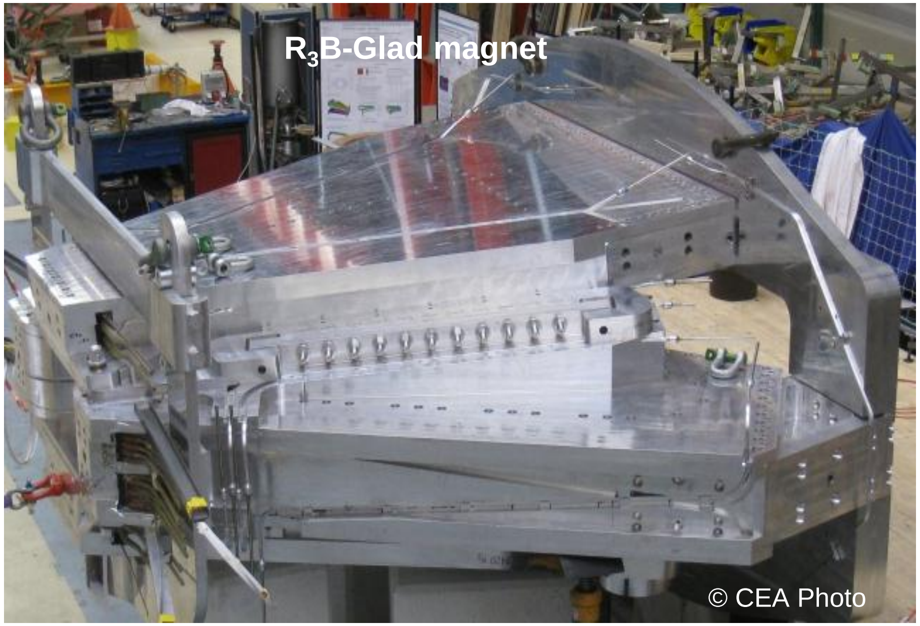
The R3B-Glad magnet (2/2)

- Cryogenics
  - Base temperature 4.45 K
  - 17 W @ 4 K
  - Reservoir @ 0.5 m above the cooling tubes
    - 460 l reservoir (50% of liquid)
  - 24 cooling tubes on the cold mass
    - 5° orientation (quasi-horizontal)
    - 2 m long
    - 10 mm diameter



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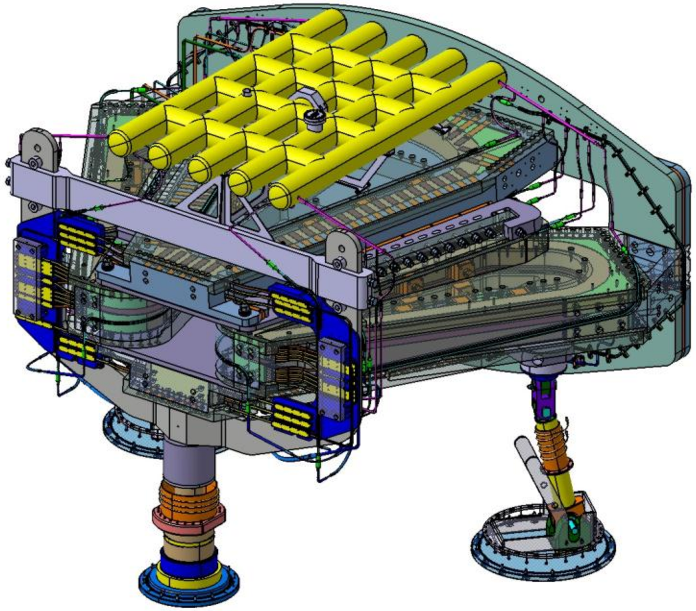
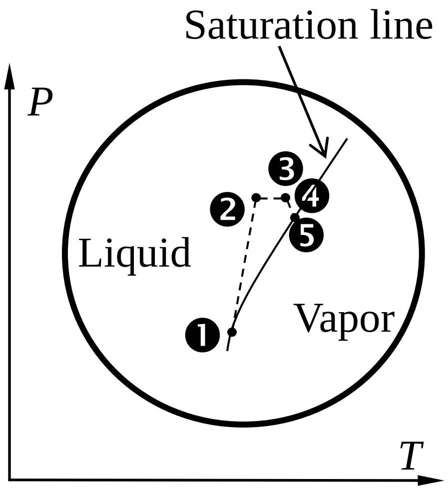
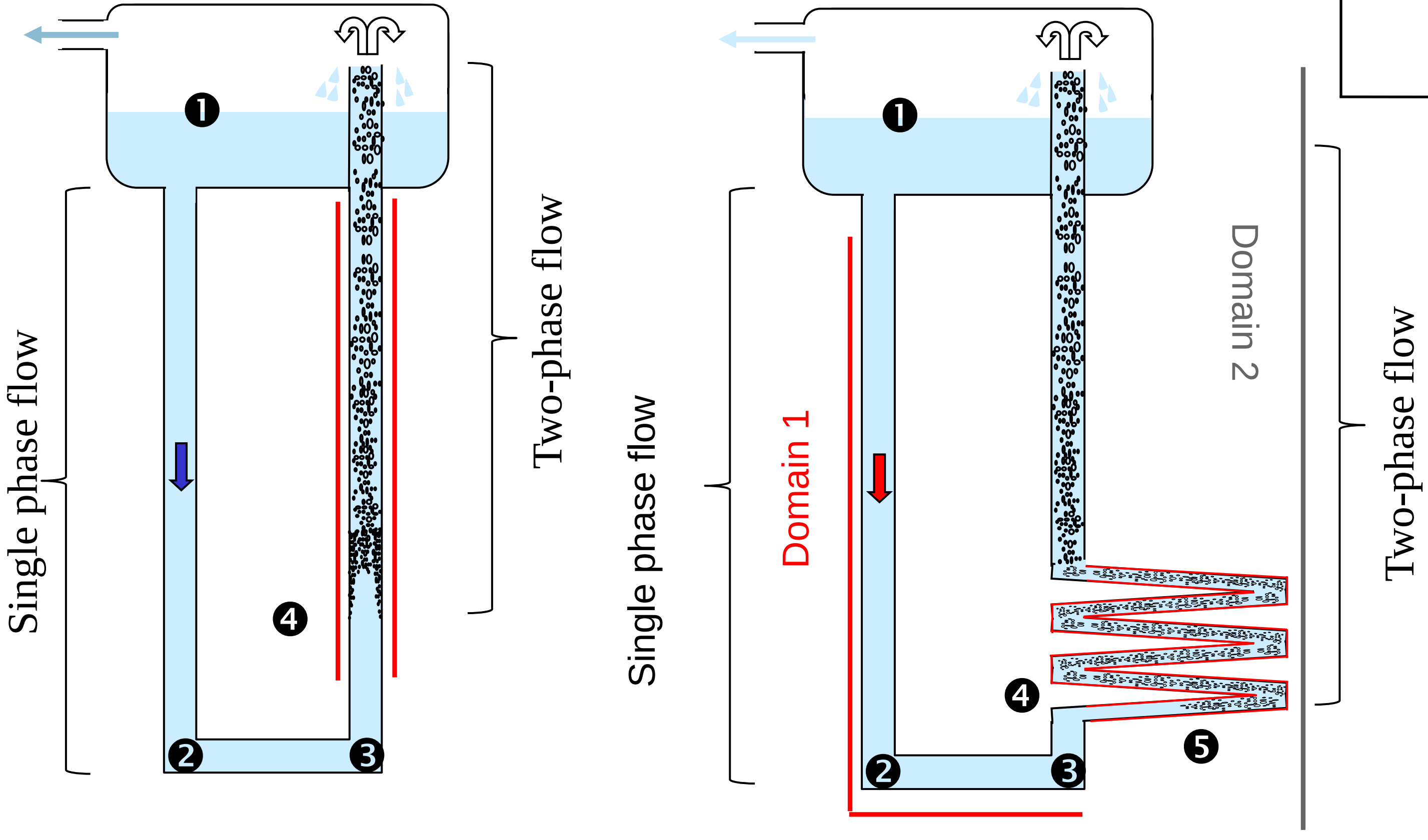


- Heat transfer
  - Cooling tube receive (5 to 20 W/m^2) in nominal operation
  - Even at this low heat flux, two-phase induced
    - Mass flow rate periodic but not null
    - ΔT = few mK

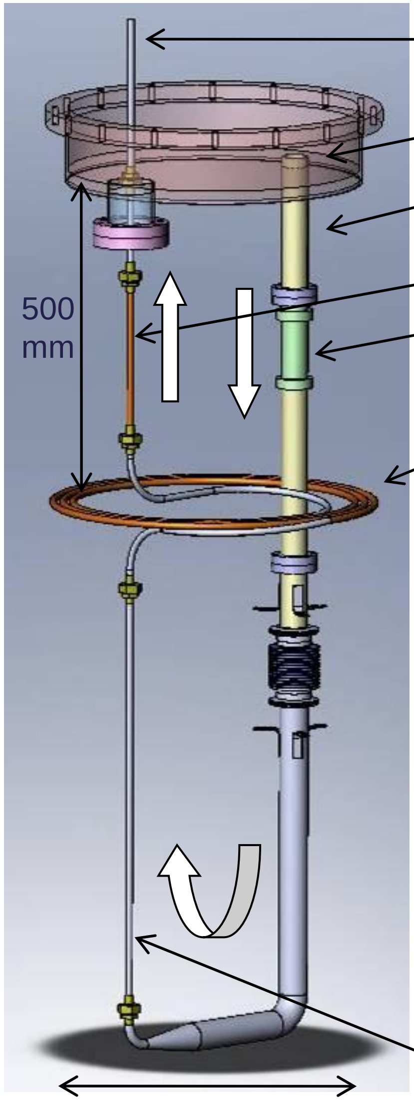
Circulation loop with horizontal HX section

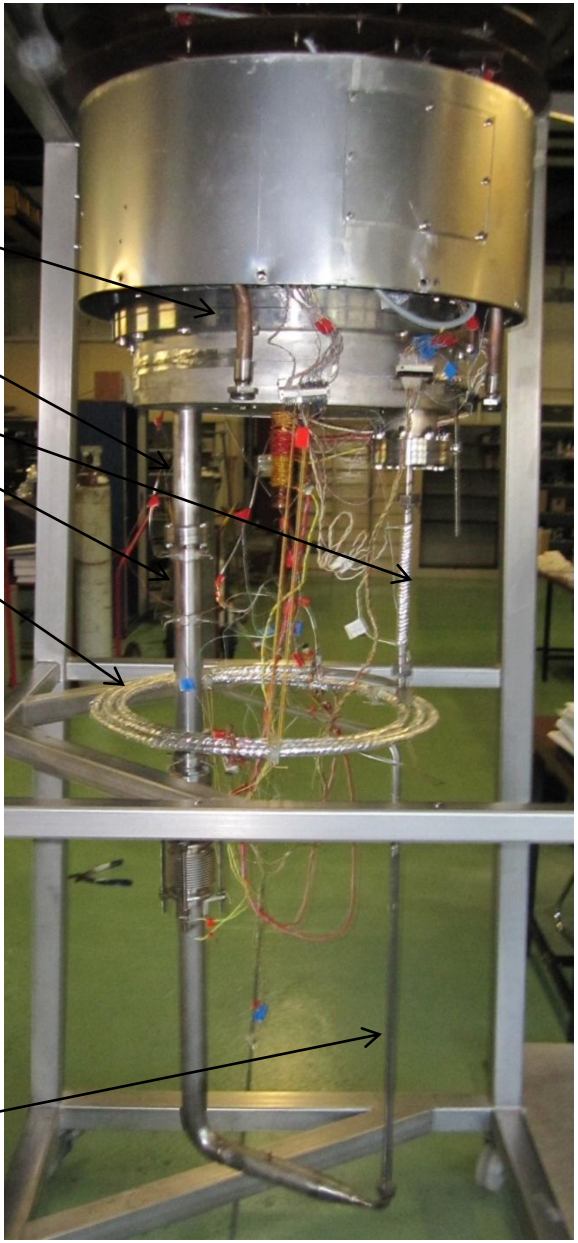
- ☐ One more vertical section ❸ to ❹
- ☐ Onset of nucleate boiling is in the horizontal section ❺





Experimental facility and ranges





Two-phase He outlet

Reservoir He

Downward branch

Riser

Venturi mass flow meter

Horizontal heat exchanger tube

Upward branch

- Test section
  - 10 mm inner diameter
  - ~4 m heated length
  - Spirally coiled

- Ranges
  - P: 1.004 ± 0.006 10^5 Pa
  - q: 0-300 W/m^2
  - m: 0-4 g/s
  - x: 0 – 65%

Model (1/4)

- Conservation equations based on the homogeneous model for *u*, *p*, *T* and *x*
  - Small statification ($\Delta T_{high} > \Delta T_{low}$ by 10%)
  - One velocity field, *u*
  - Thermodynamical equilibrium between the phases, one temperature field, *T*
  - 1 dimensional model

- Mass $$\frac{d}{dz}\left(\rho_m \frac{du}{dz}\right) = 0 \qquad \text{with} \quad \frac{1}{\rho_m} = \frac{x}{\rho_v} + \frac{1-x}{\rho_l}$$
- Momentum $$\frac{dp}{dz} = \rho_i u \frac{du}{dz} - \rho_i g \cos\theta + \left(\frac{dp}{dz}\right)_f$$
- Energy $$4\frac{q}{D} = \rho_m u \frac{d}{dz}\left(h(x) + \frac{u^2}{2} + gz\cos\theta\right) \quad \text{with} \quad h(x) = C_pT + L_v x$$

- The same set of equations is used either for two-phase and single phase

$$\text{when } x = 0 \text{ then } \rho_m = \rho_l,\ \phi = 1 \text{ and } h(x) = C_pT$$

Model (2/4)

- Friction term in the homogeneous model $$\left(\frac{dp}{dz}\right)_f = \frac{f}{D}\phi_{lo}\rho_m\frac{u^2}{2}$$
  - ○ Blasius regular friction factor for straight tube $$f = \frac{0.316}{Re_l^{0.25}} \qquad Re_l = \frac{\rho_l u D}{\mu_l}$$
  - ○ Lockhart-Martinelli two-phase multiplier $$\phi_{lo} = \left[1 + x\left(\frac{\rho_l}{\rho_v} - 1\right)\right]\left[1 + x\left(\frac{\mu_l}{\mu_v} - 1\right)\right]^{-1/4}$$
  - ○ Regular friction factor for “curved tube” in single phase flow

    Ito’s friction factor $$f_{Ito} = \frac{0.304}{Re_l^{0.25}} + 0.029\left(\frac{D}{D_{coil}}\right)^{0.5}$$

    White’s Friction factor $$f_{White} = \frac{0.320}{Re_l^{0.25}} + 0.048\left(\frac{D}{D_{coil}}\right)^{0.5}$$
  - ○ Two-phase friction factor for “curved tube” constructed as $$\left(\frac{dp}{dz}\right)_f = \frac{f_{Ito}}{D}\phi_{lo}\rho_m\frac{u^2}{2}$$

Model (3/4)

□ Closure equations

- ○ Equation system not sufficient to model our system since there are four independent variables *u*, *p*, *T* and *x*

- ○ We use 2 energy conservation equations, one for *T* and one for *x*

  - ○ Energy equation for *T*

$$\text{for } x = 0 \text{ then } 4\frac{q}{D} = \rho_l u \frac{d}{dz}\left(C_p T + \frac{u^2}{2} + gz\cos\theta \right) \quad \text{for } x > 0 \text{ then } T = T_{sat}(p)$$

  - ○ Energy equation for *x*

$$\text{for } x > 0 \text{ then } T = T_{sat}(p); \quad 4\frac{q}{D} = \rho_m u \frac{d}{dz}\left(C_p T_{sat}(p) + L_v x + \frac{u^2}{2} + gz\cos\theta \right)$$

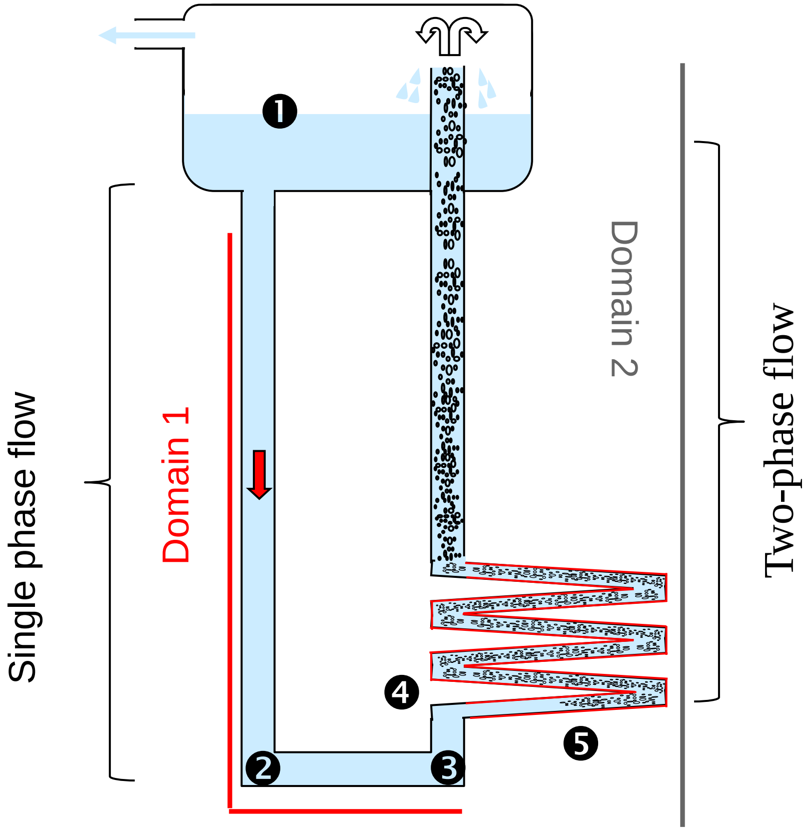
Model (4/4)

- □ Modeling strategy
  - ○ The entire loop is modeled in two domains
    - Domain 1: feeding tube (Ø40 mm)
    - Domain 2: upward branch, heat exchanger and the riser (Ø10 mm)
  - ○ FEM code (Comsol)
    - "Damped-Newton" solver in segregated mode
    - 3 groups: (*u*, *p*), *T* and *x* solved in that order
    - 960 nodes
    - Convergence 10^{-6}
- □ Boundary conditions
  - ○ Entrance of the loop (❶)

$$p = p_o + \zeta_1 \rho_m \frac{u_1^{\,2}}{2}; \quad T = T_{sat}(P_o); \quad \frac{\partial u}{\partial z} = 0; \quad x = 0$$

  - ○ Between domains
    - Conservation of mass flow
    - Pressure drop due to singularities
  - ○ Exit of the loop (point ❶)

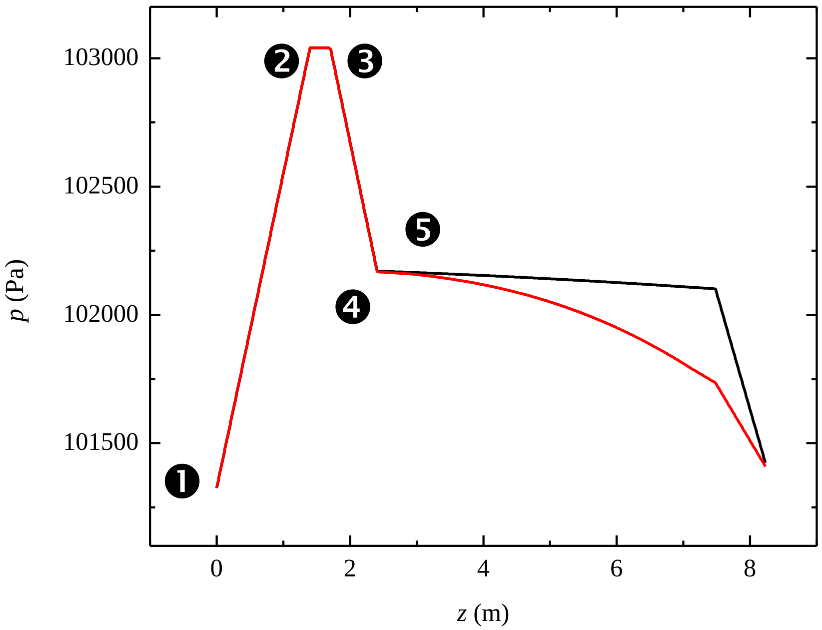
$$p = p_o + \zeta_4 \rho_m \frac{u_1^{\,2}}{2}; \quad \frac{\partial T}{\partial z} = 0; \quad \frac{\partial u}{\partial z} = 0; \quad \frac{\partial x}{\partial z} = 0$$

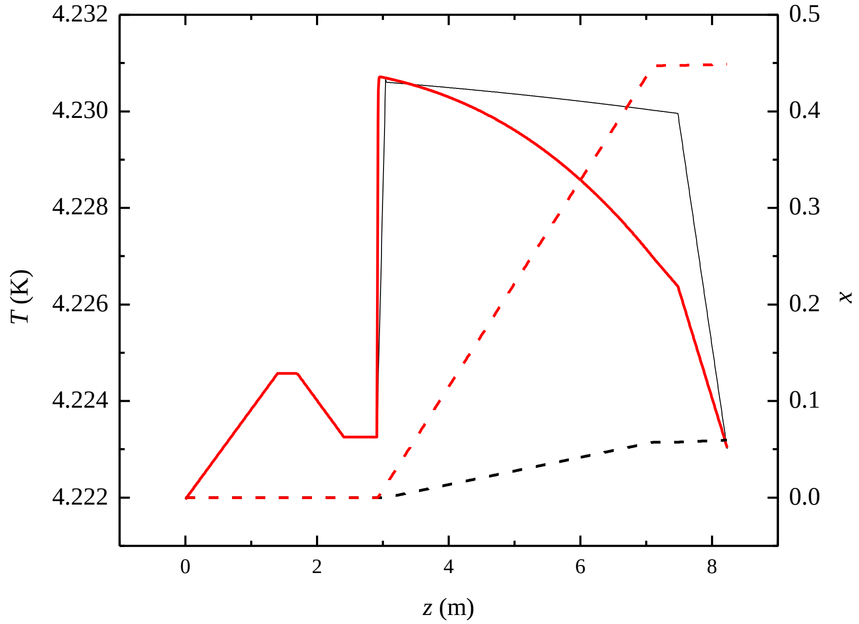


P, *T* and *x* along the loop

- Two cases : 25 W/m^2 and 250 W/m^2
  - Pressure decrease in the HX zone different due to different friction term (x)

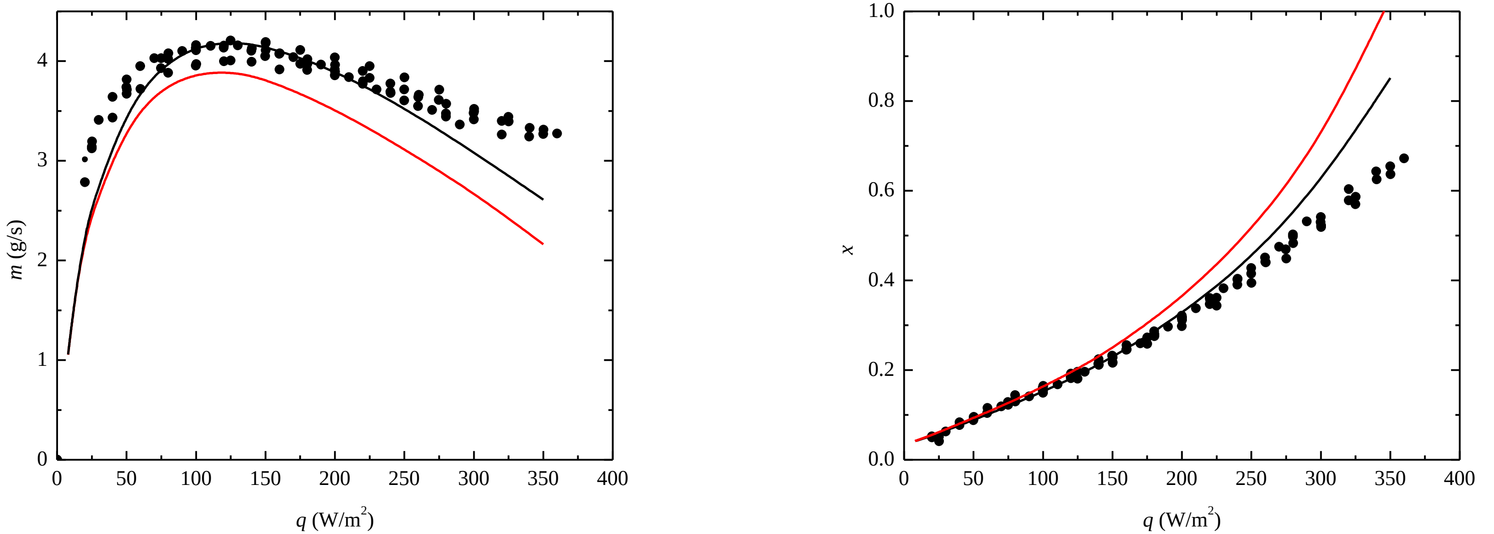
  - Longer sub-cooled zone for 25 W/m^2 since the saturation is reached later
  - Temperature are shifted accordingly
  - Temperature evolution different in the HX zone due to the pressure evolution (T=Tsat(p))
  - *x* still increases in the riser due to decrease of pressure





Comparison with experimental results

- Model reproduces with acceptable accuracy the evolution of the mass flow rate
  - Ito’s correlation gives a better result
  - At low vapor quality, Δp_{grav} is the largest and decreases as increasing x
  - With x increasing, Δp_{fric} increases → m_t decreases



- Above 250 W/m², the model predicts a larger decrease of m_t
  - x is over predicted because above 250 W/m², but there is no film boiling up to 350 W/m²
  - Correlation accuracy problem, singular pressure drop modeling, …
- When q -> 0, $x \neq 0$ because of the riser extension (unstable regime, geysering)

Conclusions and future work

- The numerical model developed predicts with acceptable accuracy the mass flow rate and the vapor quality at the exit for our natural circulation loop in the range of 10 and 250 W/m^2

- Improvement of the modeling of the singular pressure drop and “curved tube” friction factor correlation would be implemented in the code in a near future

- The current model deals with a single tube flow and it is intended to extend this model to parallel multi-tubes to help in the design of large superconducting magnet cooling scheme

- Modification of the equations system to include the modeling of transient process to study cases of quench or any transient disturbance