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Helium two-phase flow in a thermosiphon open loop

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Outline

☐ Missions of SACM (Accelerator, Cryogenics and Magnetism Division)

☐ Context : The Large Hadron collider at CERN, Geneva

☐ Cooling large superconducting magnet
☐ Thermosiphon open loops for cooling superconducting magnets

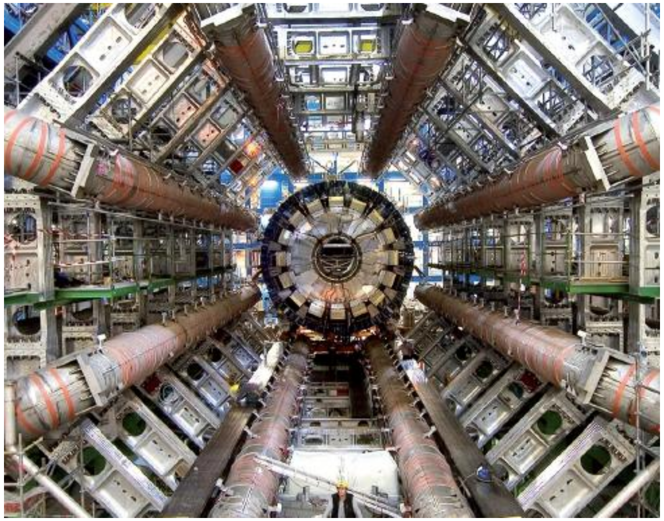
☐ Experimental facility and ranges of the study

☐ COMSOL Multiphysics Modeling
☐ Results with COMSOL Multiphysics

☐ Comparison with experimental results

Missions of SACM

- ☐ SACM is developing and realizing …
  - ○ particle accelerators
  - ○ cryogenic systems
  - ○ superconducting magnets
- ☐ … for in-house and international scientific programs in the fields of astrophysics, nuclear physics, and particle physics



- ☐ SACM is mainly involved in large scale projects
  - ○ International Linear Collider (ILC)
  - ○ Light source XFEL
  - ○ IPHI project (high-intensity proton accelerator)
  - ○ Spiral 2 project (rare isotope beams)

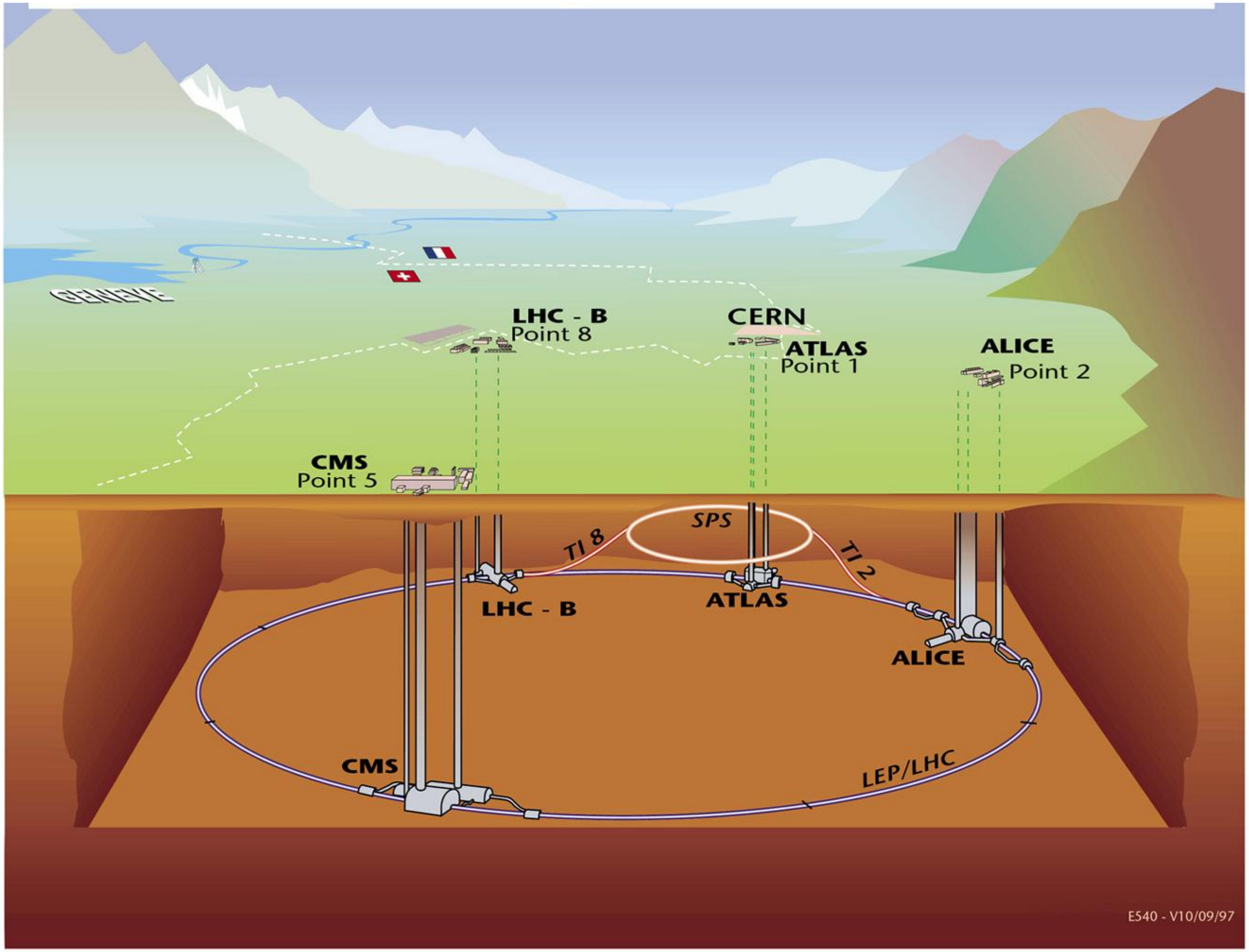
  - ○ Neurospin Iseult, MRI solenoid
  - ○ R_3B Glad spectrometer
  - ○ Large Hadron Collider (LHC) accelerator and detector construction at CERN with the quadrupoles magnets, the Atlas toroid and **the CMS solenoid**

Large Hadron Collider

- Large Hadron Collider
  - Largest physics instrument in the world
  - 27 km of circumference
  - Proton-proton collider (14 Tev)
- LHC will describe with increasing detail the fundamental particles that make up the Universe and the interactions between them
  - What is mass?
  - What is 96% of the universe made of?
  - Where is the anti-matter now?
  - What was matter like within the first seconds of the Universe's life?
- Magnets at…
  - Over 8000 magnets for the ring
  - Few gigantic magnets for detection
- …100 m underground!

Large Hadron Collider

- Detectors at LHC



Why magnetic field for particle detection?

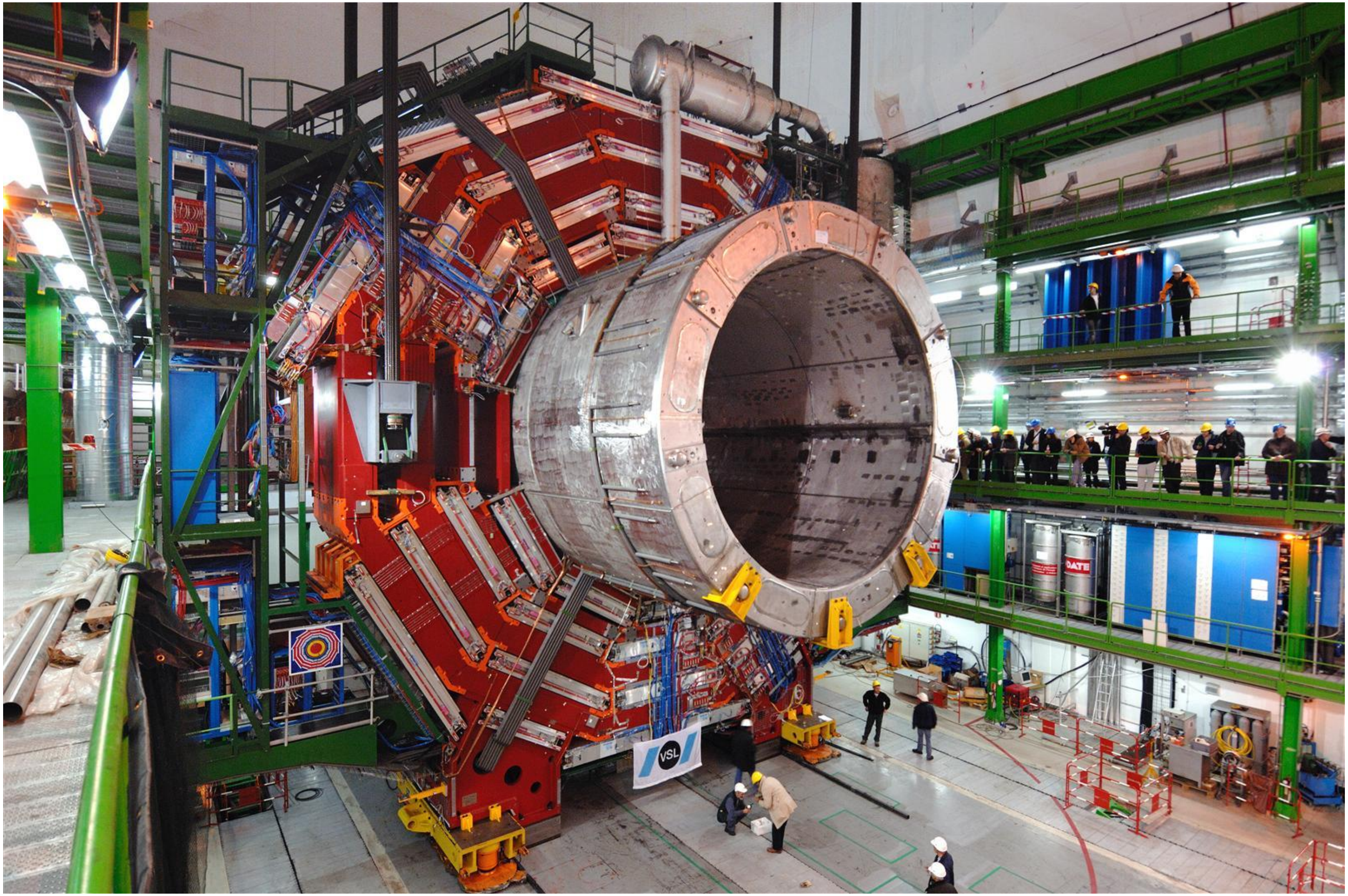
- For a charged particle (q) moving in a magnetic field (B) over a distance L
  - momentum $p=mv=q\rho B$ (ρ=bending radius)
  - **Precision on the measurement of $p \sim BL^2/p$**

- Increasing the magnetic field and the dimension of detection (the magnet itself) improves the precision on particle detection

- Magnets must be superconducting
  - **Reduction in energy consumption** to energize the magnet
  - Higher current density with superconducting cables making the **magnetic design feasible in reasonable space**
  - **"Transparency"** for the detection

- Still, these magnets are **gigantic** and needs to be cooled with **liquid helium**!

Example : The Compact Muon Solenoid



Cooling large superconducting magnet

- Compact Muon Solenoid magnet
  - 7 m diameter and 12.5 m long
  - 4 T at the center
  - Liquid helium temperature cooling (4.2 K)

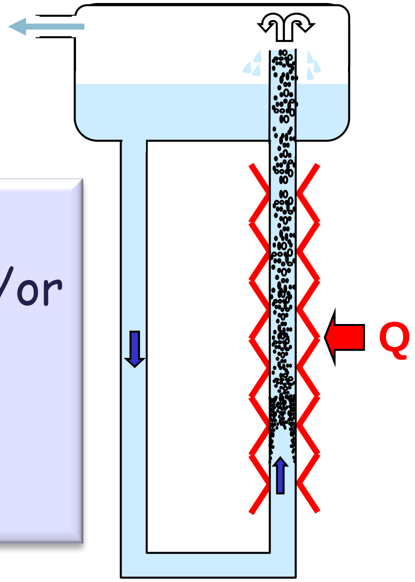
- Unique magnet of large scale
  - Reduction of the quantity of cryogen
    - Lower the cost of operation
  - Protection in case of quench
    - Lv ≈ $2\ 10^4$ J/Kg
    - Phase change $\rho_l/\rho_v \approx 7$

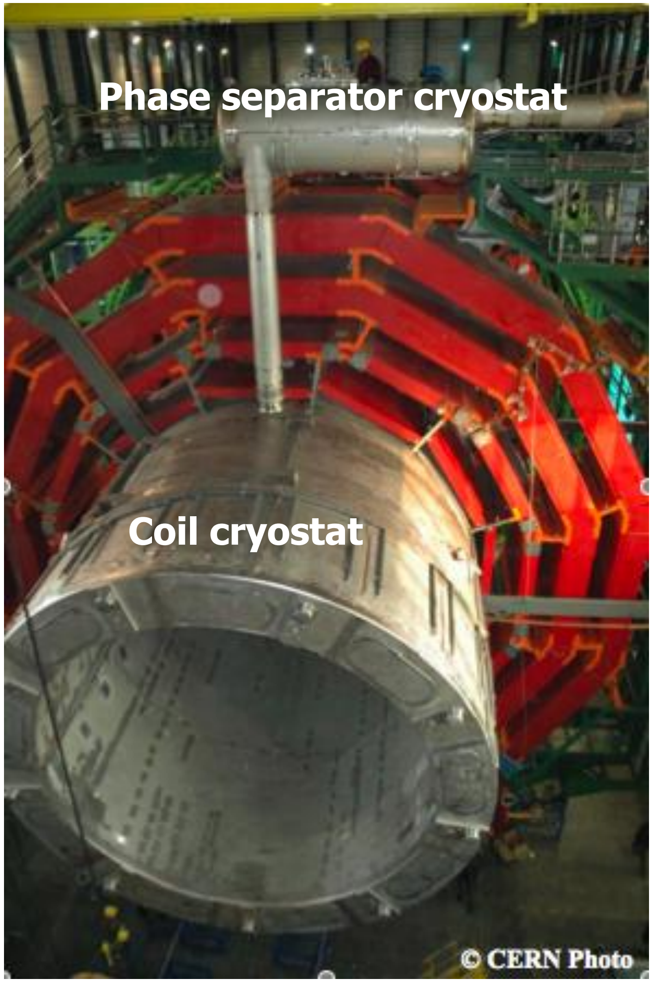
- External cooling

- Two-phase thermosiphon cooling method

Thermosiphon open loops (1/2)

- Open reservoir/phase separator
  - No re-cooling of the warm liquid or re-condensation of the vapor





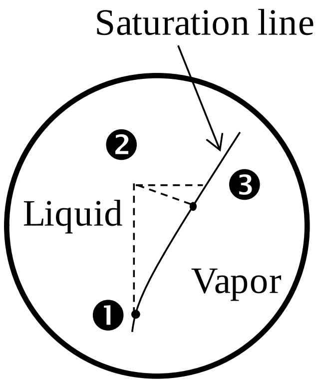
- Power to be extracted
- Decrease in liquid density and/or vaporization
- Branch weight unbalance
- Flow induced

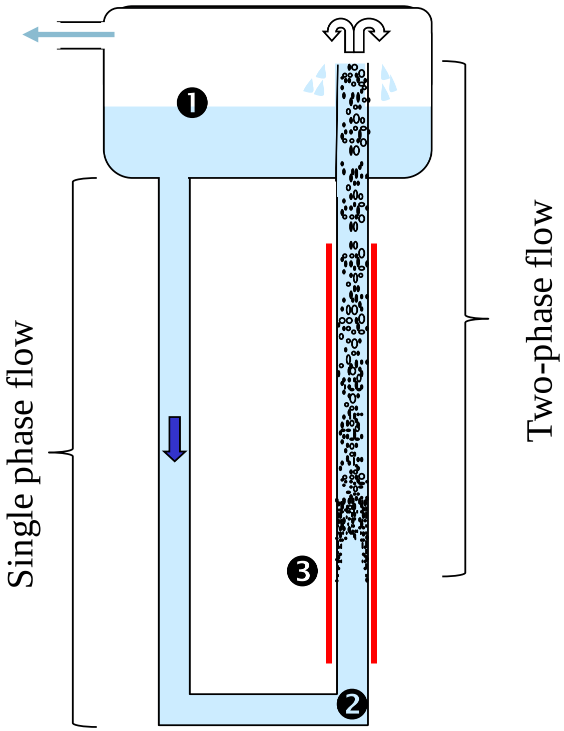
- Suppression of any pressurization system

- Liquid level needs to be controlled to avoid dryout
- Minimum heat flux to start the flow
- Flow oscillations at low heat flux

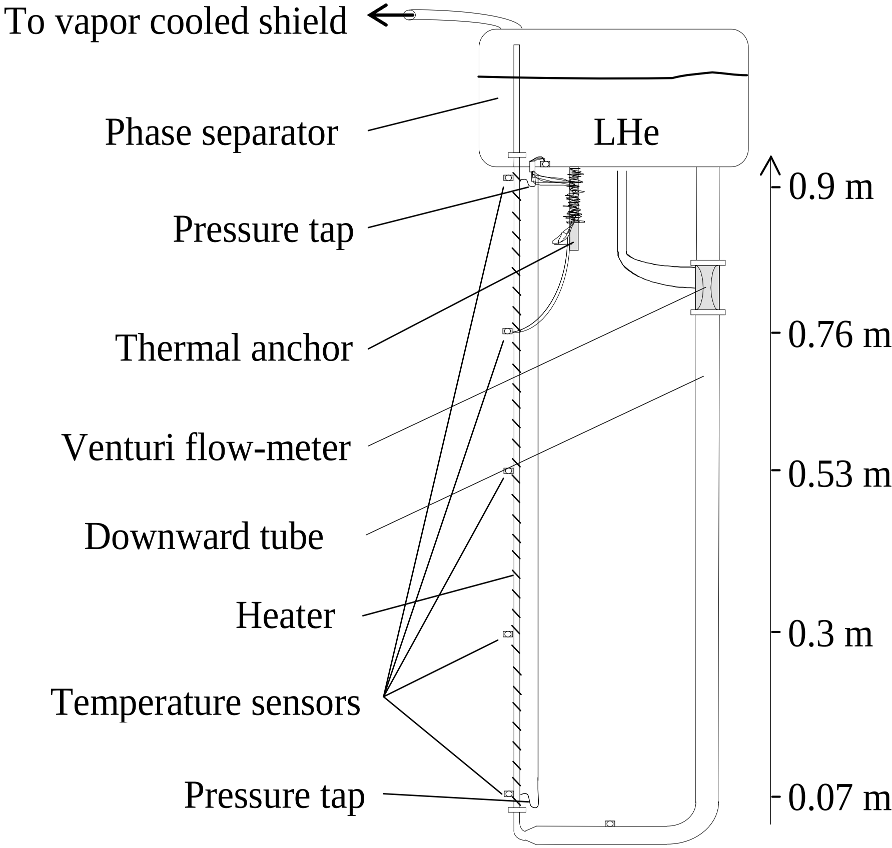
Thermosiphon open loops (2/2)

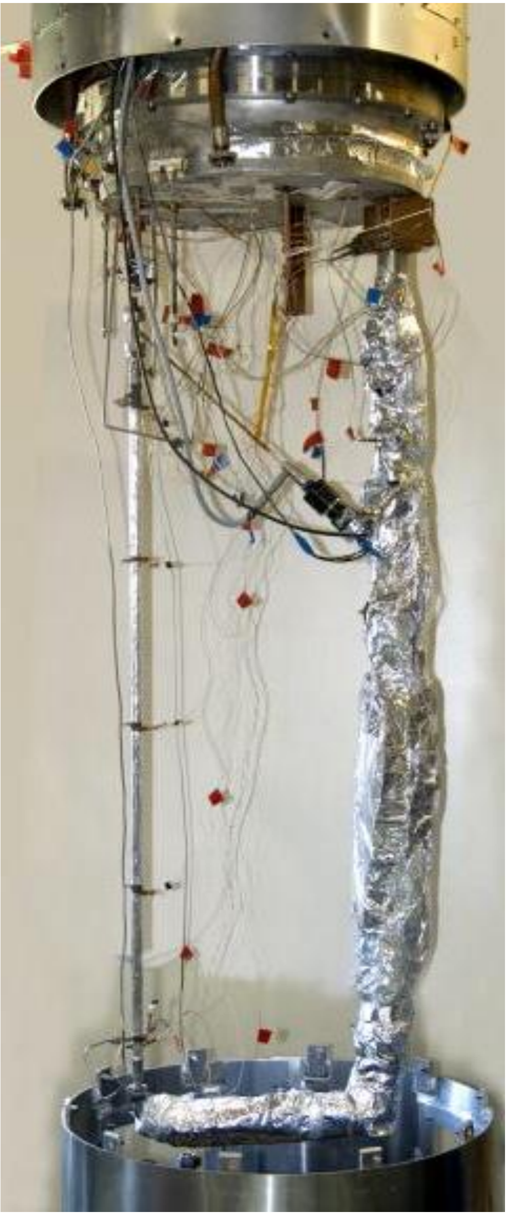
- In the downward branch, the flow is single phase
  - Adiabatic branch and the liquid is sub-cooled
  - Pressure and the temperature increase from ❶ to ❷
- The upward branch is heated partially and above it is adiabatic (the riser)
  - Flow is first in single phase from ❷ to ❸
  - Fluid reaches the saturation temperature at point ❸
  - Fluid temperature also increases up to the saturation line
- Point ❸ is the onset of nucleate boiling
  - Then the flow above ❸ is two-phase
  - Fluid temperature decreases following the saturation line





Experimental facility and ranges





- ☐ Test section
  - ○ 10 mm inner diameter
  - ○ ~1 m heated length
  - ○ Tsensor ± 2 mK
- ☐ Ranges
  - ○ P: $1.004 \pm 0.006\ 10^5$ Pa
  - ○ q: 0-25 kW/m^2
  - ○ m: 0-12 g/s
  - ○ x: 0 – 25%

COMSOL Multiphysics Modeling (1/2)

☐ Homogeneous model implemented in Comsol Multiphysics

○ **Mass** $\frac{d}{dz}\left(\rho_i \cdot \frac{du}{dz}\right) = 0$ with $\rho_i = \rho_l$ or $\rho_i = \rho_m$ with $\frac{1}{\rho_m} = \frac{x}{\rho_v} + \frac{1-x}{\rho_l}$

○ **Momentum** $-\frac{dp}{dz} - \rho_i u \frac{du}{dz} + \rho_i g \cos\theta - \left(\frac{dp}{dz}\right)_{f,j} = 0$

$$\left(\frac{dp}{dz}\right)_{f,d} = \left(\frac{f}{D_d} + \frac{\zeta_d}{l_d}\right)\rho_l \frac{u^2}{2} \qquad \left(\frac{dp}{dz}\right)_{f,u} = \left(\frac{f}{D_u} + \frac{\zeta_u}{l_u}\right)\phi_{lo}\rho_m \frac{u^2}{2}$$

$$f = \frac{0.079}{Re_j^{\;0.25}} \qquad \phi_{lo} = \left[1 + x\left(\frac{\rho_l}{\rho_v} - 1\right)\right]\left[1 + x\left(\frac{\mu_l}{\mu_v} - 1\right)\right]^{-1/4}$$

○ **Energy** $4\frac{q}{D_j} = \rho_i u \frac{d}{dz}\left(h_i + \frac{u^2}{2} + gz\cos\theta\right)$ with $h = C_p T$ or $h = C_p T + L_v$

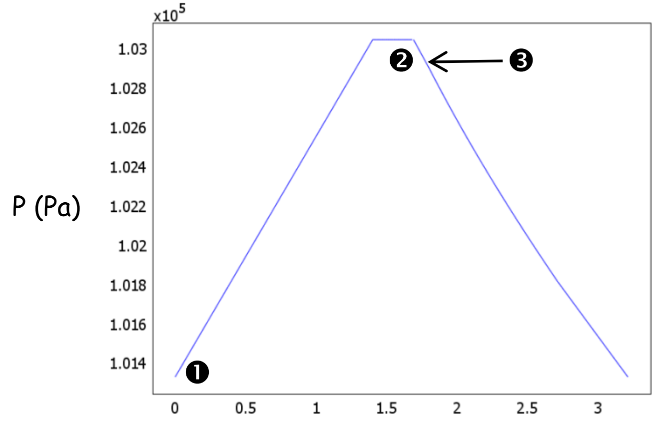
COMSOL Multiphysics Modeling (2/2)

- 1 D model with downward, horizontal and upward branches

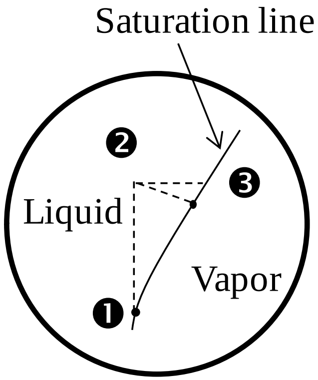
- PDE general form module was used

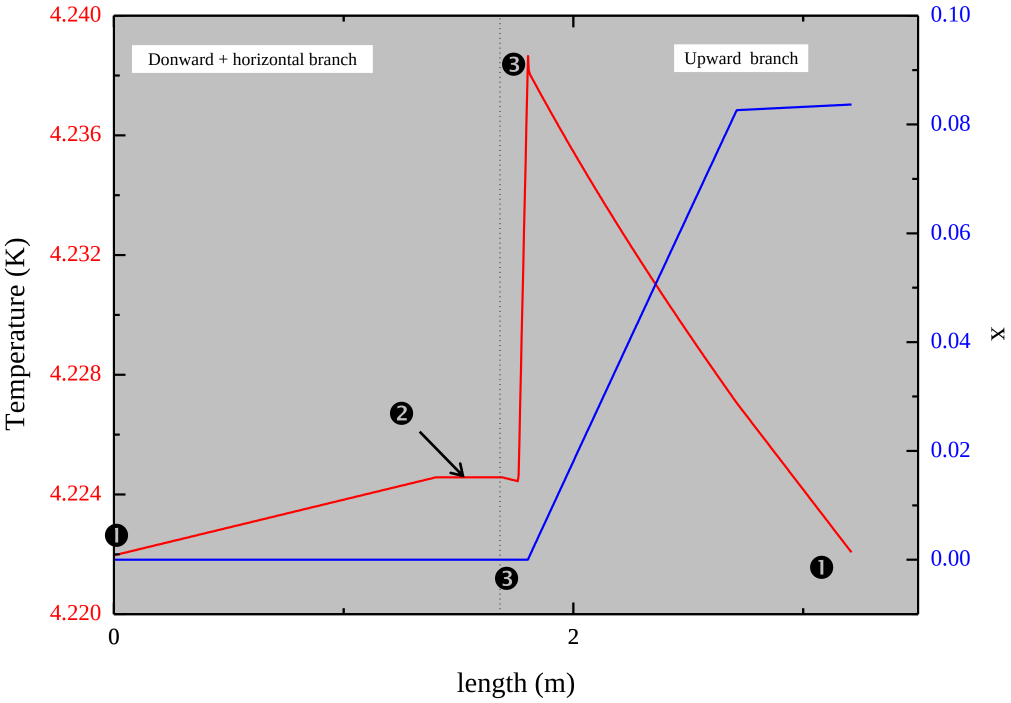
- Segregated mode with three groups
  - First group : conservation of mass and momentum with u and p as variables
    - Pressure fixed at the loop entrance and Neumann condition for other boundaries
    - For velocity, only Neumann conditions are used
  - Second group : Energy conservation equation for T
    - Temperature fixed at the loop entrance and Neumann conditions for other boundaries
  - Third group : Energy conservation equation for the vapor quality, x
    - Quality is set to zero until the saturation temperature is reached

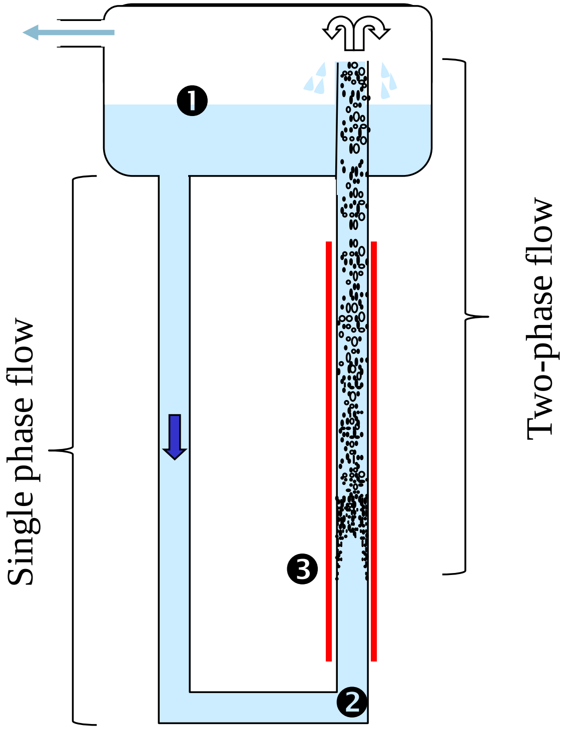
Results with COMSOL Multiphysics



- ☐ Case for 600 W/m^2
- ☐ p=101325 Pa
- ☐ Convergence 10^{-7}
- ☐ 960 elements

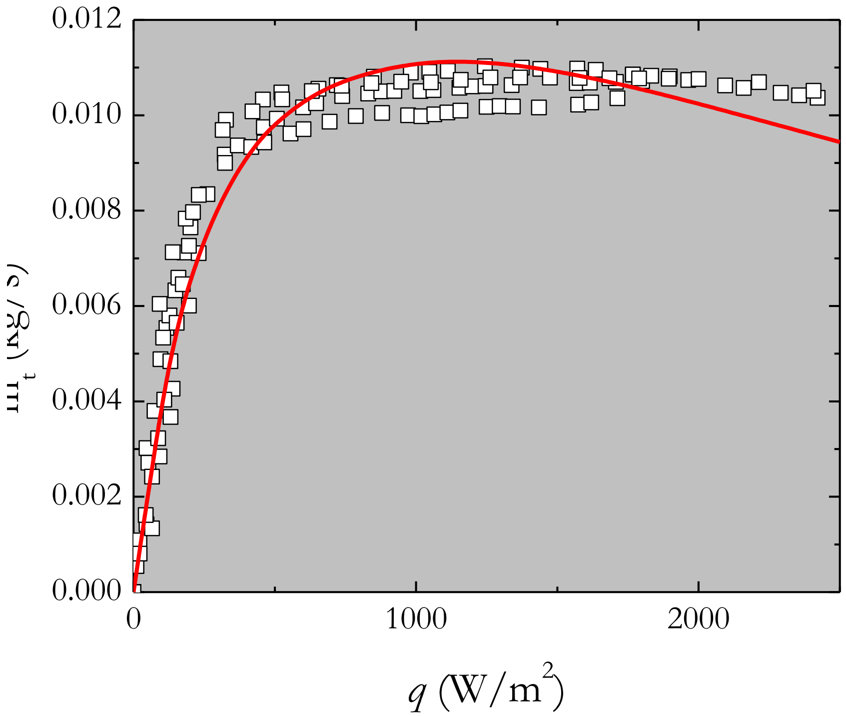






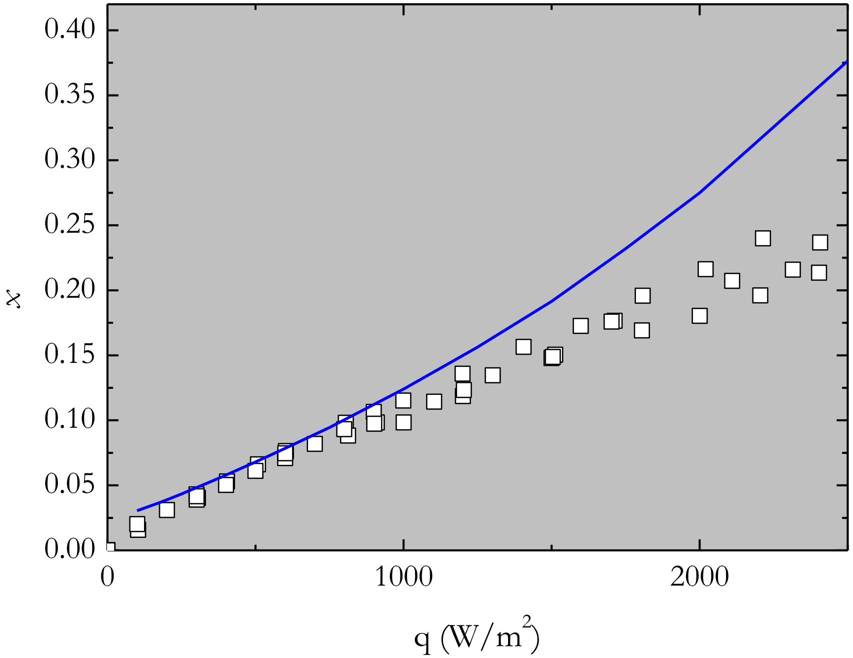
Comparison with experimental results

- At low heat flux, the flow is dominated by the gravity term
- At higher heat flux the friction term increases causing the slight decrease of the total mass flow rate



Comparison with experimental results

- ☐ Vapor quality reproduced with good accuracy up to 1500 W/m^2
  - ○ At 1500 W/m^2 —> film boiling appears
  - ○ No thermodynamic equilibrium between the two phases
  - ○ Homogeneous model no longer holds



- ☐ Model sufficiently accurate to be used for designing cooling system

Conclusions

- ☐ COMSOL easy to handle for non expert
  - ○ Easy implementation and modification of physics models
- ☐ Next is transient
  - ○ Pressure rise due to vaporization in liquid helium
    - Mechanical constraints on the magnet structure
    - Fluid management
  - ○ Adding multi-physics
    - Interaction with the stability of superconductors
    - Magnetic field interaction
- ☐ Going superfluid (He II)…
  - ○ Some magnets are cooled with superfluid helium
  - ○ Heat transfer laws are “super” different
    - Modified Fourier law
    - Non linear boundary condition (Kapitza resistance)