CERN **A**ccelerator **S**chool

"Superconductivity for Accelerators"

Ettore Majorana Foundation and Centre for Scientific Culture
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Heat transfer and cooling techniques at low temperature

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Outline

- Heat transfer at low temperature (Lecture 1)
  - Conduction
  - Radiation
  - Convection

- Cooling techniques at low temperature (Lecture 2)
  - Different classifications of system with respect to cooling
  - Different methods of cooling
  - Some examples

Cooling methods at low temperature (Lecture 2)

- Content
  - Introduction
  - Different classifications of system with respect to cooling
  - Review of the different cooling methods
  - Examples of system

- Just a few words in this lecture
  - Superfluid helium cooling methods

- Not included in this lecture
  - Cooling below 2 K

- Present until the end of the school, do not hesitate to ask

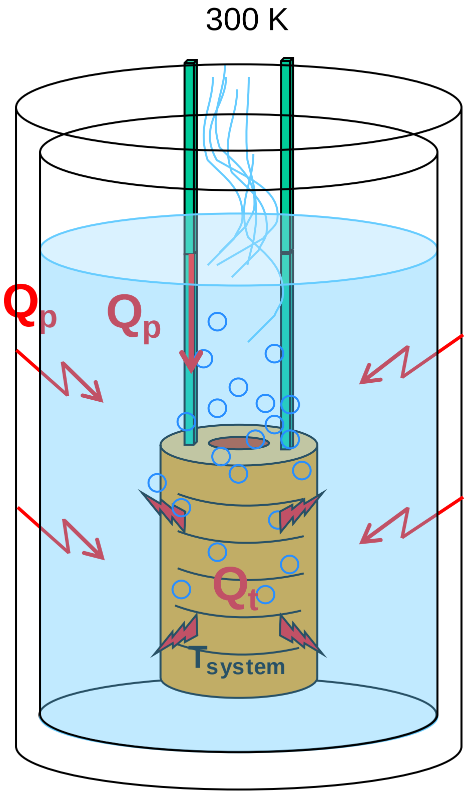
Cooling to the low temperature (1/3)

- Primary goal : maintain a system at temperature T≪ room temperature
  - Thermal stability in steady-state regime → T_{system} ≈constant
  - Protection of your system against transient events →T_{system}<T_{max}

- System defined by thermophysical properties, geometry, orientation, environment, confinement…

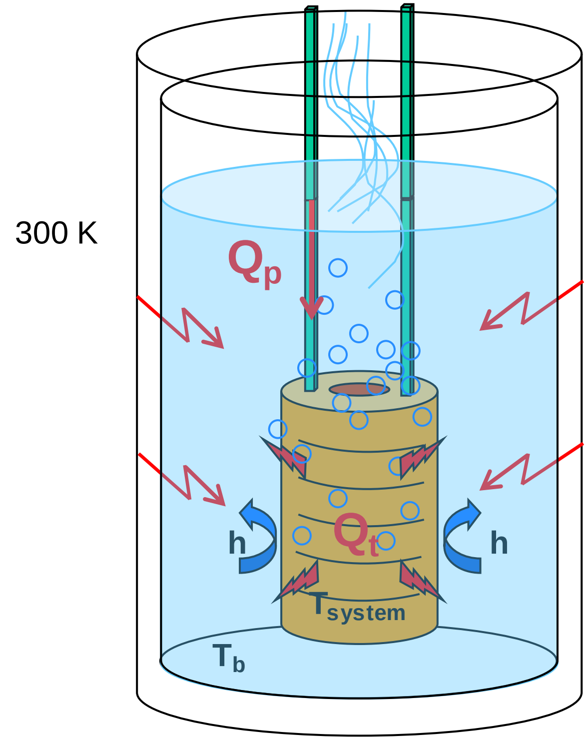
- System subjected to permanent heat input (heat losses), Q_p
  - Thermal radiation (room temperature to T_{system})
  - Conduction through supports, current leads, …
  - Internal dissipation (Joule effect, AC losses, beam losses…)

- System subjected to transient heat perturbation, Q_t
  - Quench of a superconducting cavity or magnet



Cooling to the low temperature (2/3)

- Cooling power provided to the system, Q_R
  - Direct contact with cryogen (wet system, cavities,…)
    - Thermophysical properties of the cryogen
    - Contact heat transfer coefficient, ***h*** [W/m^2]
  - Indirect contact with cryogen
    - Thermal link (liquid or gas, flow or no flow)
    - Heat exchanger (series of tubes, ….)
  - Without cryogen (Dry magnet, cryogen-free system)
    - Performance and the temperature range of the cryocooler
    - Heat distribution system, thermal links

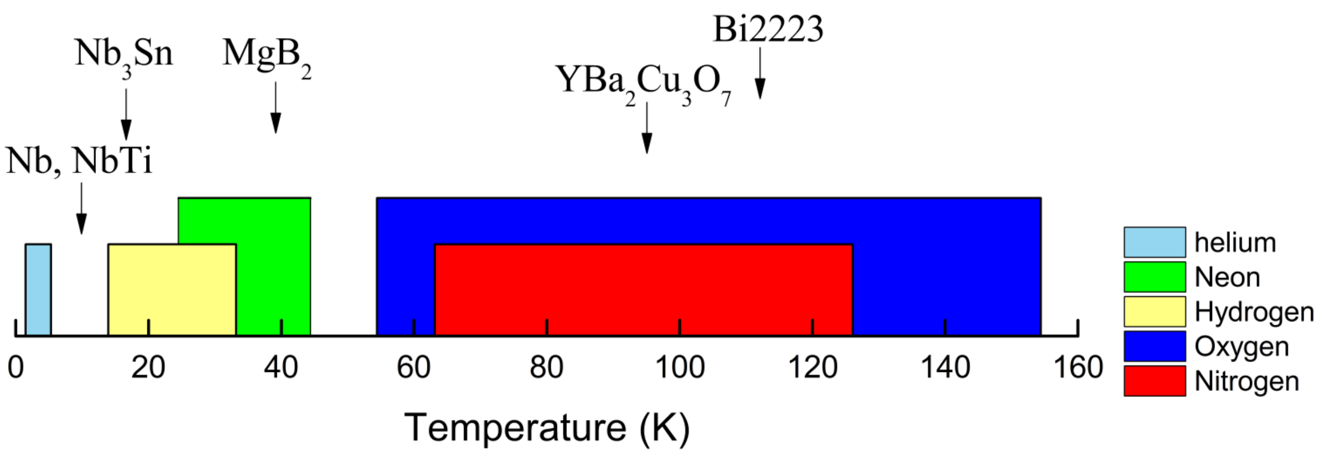


- System design at low temperature
  - Minimize the heat input
    - Minimization of the heat transfer at a constant temperature difference
  - Maximize the heat extraction (cooling Q_R)
    - Minimization of the temperature difference for a constant heat transfer

Cooling to the low temperature (3/3)

- Common cryogenic fluids and "usable" superconductors

Fluid	He^4	H_2	Ne	N_2	O_2
Boiling temperature @ 1 atm (K)	4,2	20,4	27,1	77,3	90,2
Latent heat of vaporization (kJ/kg)	21	452	86	199	213
Sensible heat from 300 K and $T_{boiling}$ (kJ/kg)	1550	3800	280	233	193
Power to evaporate 1 liter	0,7	9,0	29,0	45	68
Approximate price €/liter	*7*			*0,15*	



Outline | Different classifications of system

- Cooling methods at low temperature (Lecture 2)

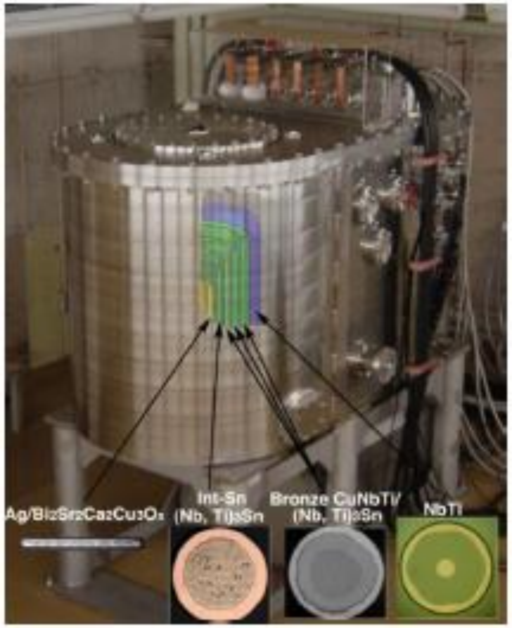
  – Different classifications of system with respect to cooling
    - Dry systems
    - Indirect cooling
    - Wet systems

  – Different methods of cooling
    - Baths
    - Forced flow
    - Two-phase flow
    - Cryogen free cooling
    - Coupled systems

  – Some examples
    - Large detector magnets
    - Superconducting RF cavities
    - Accelerator magnets
    - Fusion magnets
    - Life science magnets

Cooling classification | Dry Systems

- Cryogen-free (no cryogen)
  - Conduction only in the system
- Cold source
  - Cryocooler
- Reasons
  - Non cryogenic environment preferred
  - Small heat load
  - Slow perturbations process
- Examples
  - Room temperature bore magnets
  - Small MRI magnets
  - …



Cryogenfree 18 T superconducting magnet with a Bi2223 insert

18 T cryogen free magnet with HTc
K. Watanabe, J Supercond Nov Magn (2011) 24: 993–997

Cooling classification | Indirect cooling

- No direct contact between the cryogen and the system
  - Conduction in the system: important parameter
  - Surface heat transfer: less important

- Cold source
  - Liquid bath
  - External flow of cryogen

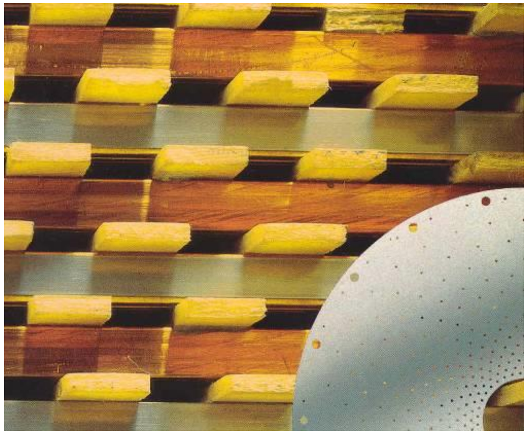
- Reasons
  - Moderate heat load – no need to have an “overall” large heat transfer rate
  - No “vaporization” zone in confined geometry
  - Reduction of the cryogen quantity
  - Slow perturbations process

- Examples
  - Large detector magnet like CMS or Atlas at CERN

Coil cross section of the CMS magnet
Two-phase helium flow external cooling ©CERN

Cooling classification | Wet Systems

- Direct contact between the cryogen and the conductor
  - Heat transfer in the system (coil for magnet)
  - Enthalpy reserve in the liquid (in the system)

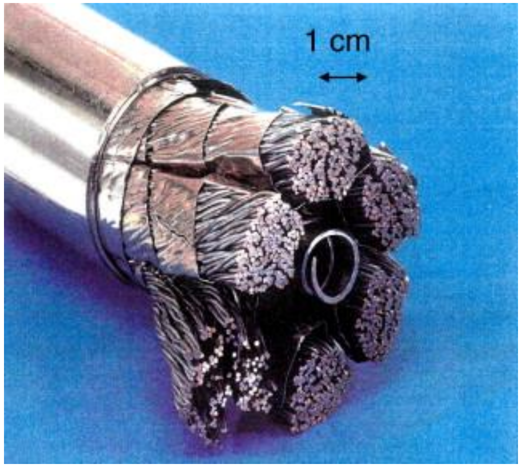


Iseult – 11.7 T whole body MRI (CEA Saclay) Coil model

- Cold source
  - Liquid bath
  - Stagnant coolant (He II pressurized or saturated)
  - Single phase flow (supercritical)

- Reasons
  - Need of a large overall heat transfer rate due to large heat loads (steady-state or transient)
  - Need of surface temperature uniformity

- Examples
  - Accelerator magnets (LHC magnets)
  - CICC magnets (ITER, 45T NHMFL magnet)
  - He II cooled magnet (Tore Supra, Iseult)
  - Superconducting cavities

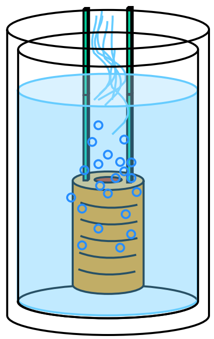


ITER Cable-In-Conduit conductor

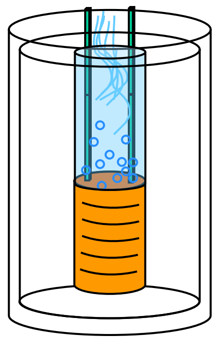
Outline | Different methods of cooling

- Cooling methods at low temperature (Lecture 2)
  - Different classifications of system with respect to cooling
    - Dry systems
    - Indirect cooling
    - Wet systems
  - Different methods of cooling
    - Baths
    - Forced flow
    - Circulation loop
    - Cryogen free cooling
    - Coupled systems
  - Some examples
    - Large detector magnets
    - Superconducting RF cavities
    - Accelerator magnets
    - Fusion magnets
    - Life science magnets

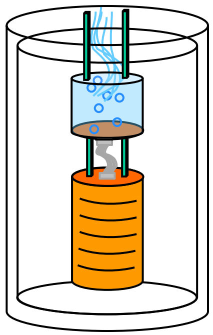
Cooling methods



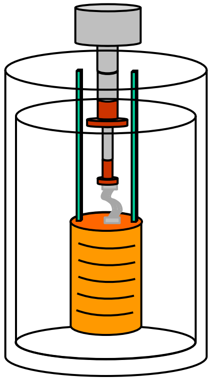
Direct cooling
Bath cooling



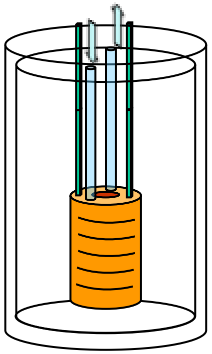
Indirect cooling
Bath cooling



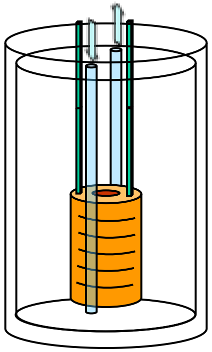
Indirect cooling
Bath as cold source



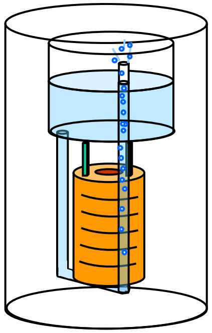
Indirect cooling
Cryocooler as cold source
Thermal link



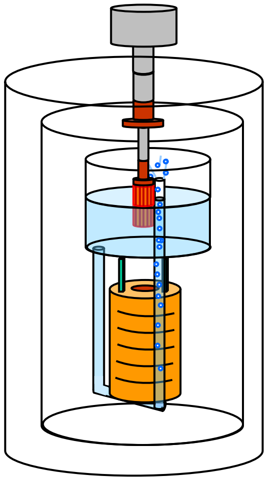
Direct cooling
Forced flow



Indirect cooling
Forced flow

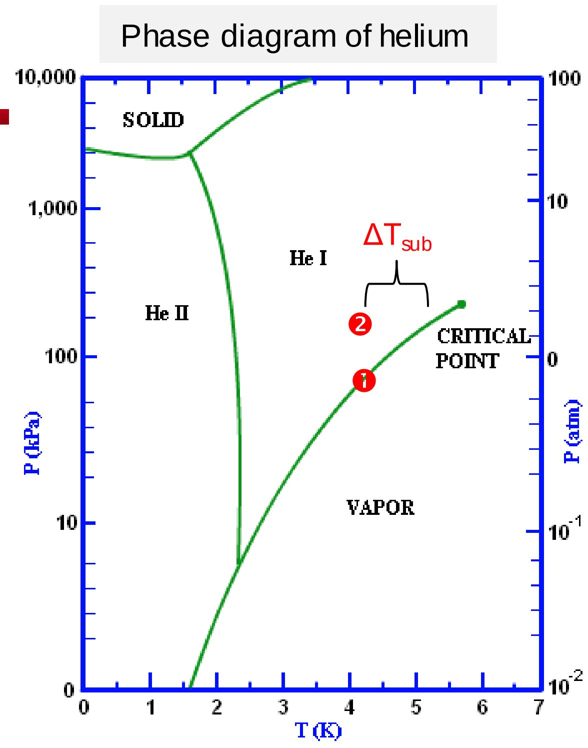


Indirect cooling
Two-phase thermosiphon



Indirect cooling
Two-phase thermosiphon
Coupled with a cryocooler

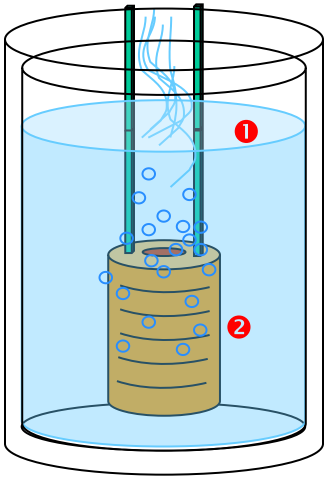
Cooling methods | Baths (1/2)



- **Saturated bath** (P=1 Atm and $T \approx T_{sat}$)
  - Latent heat cooling (phase change)
  - Sensible heat (if subcooled)
  - No cryogen flow
  - Direct and indirect cooling

  - Advantages
    - Simple design and operation for cryogenics
    - Almost **constant surface temperature** (ΔT small)
    - **High heat transfer** (nucleate boiling)
    - If sub-cooling then extra ΔT_{sub} before boiling (natural convection)

  - Disadvantages
    - **Discrete temperature cooling** (He 4.2 K, H_2 20.4 K, N_2 77.3 K…)
    - Large quantity of cryogen to handle in case of quench (pressure rise)
    - **Non uniform cooling if vapor formation**
    - If $q>q_{cr}$ then film boiling (an order of magnitude smaller heat transfer)
    - h dependent on orientation and gravity



Cooling methods | Baths (2/2)

- **Superfluid helium bath**
  - Heat transfer in He II (conduction-like in liquid)
  - Surface heat transfer (Kapitza resistance)
  - Direct and indirect cooling

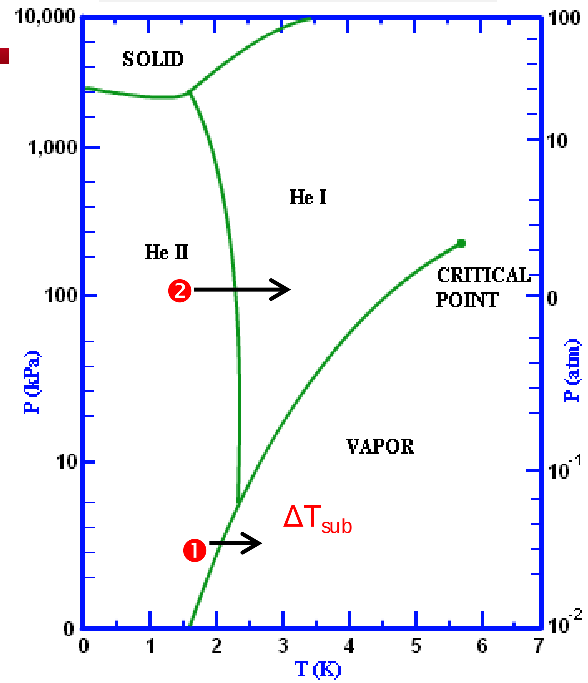
  - Advantages
    - **Huge heat transfer** rate: k≈10^5 W/m.K
    - *h* independent of orientation and gravity

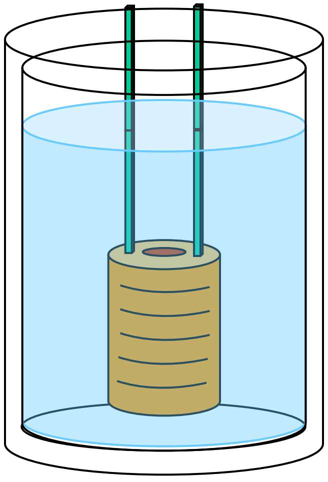
  - Disadvantages
    - Thermal (Kapitza) resistance between solid and He II
      - R_k=3 10^{-4} K.m²/W for Cu and R_k= 10^{-3} K.m²/W for Kapton
    - Large quantity of cryogen to handle in case of quench

  - Saturated bath (superconducting cavity)
    - If sub-cooling then extra ΔT_{sub} before boiling ❶
    - Large volume below atmospheric pressure (leaks)

  - Pressurized bath (for LHC magnets)
    - Finite ΔT (0.3 K) before reaching He I ❷
    - Costly and complicated design and operation
      - Heat exchanger needed

Phase diagram of helium

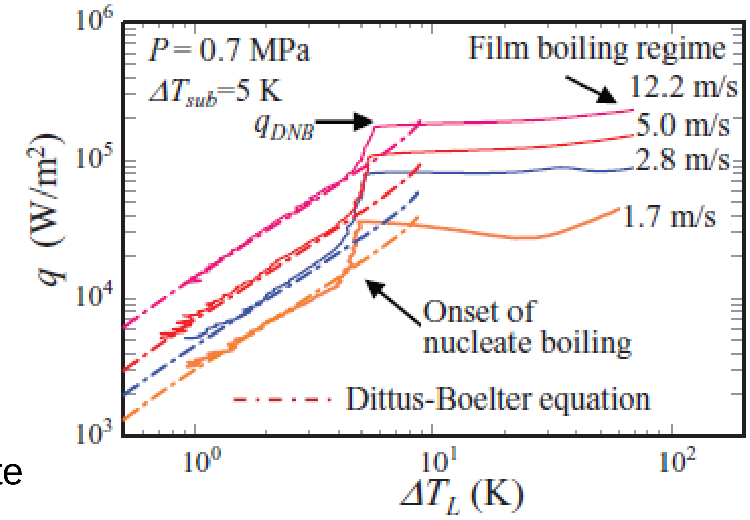




Huge Heat transfer : no boiling in he II

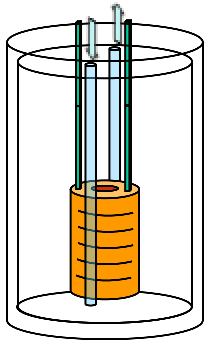
Cooling methods | Forced flow (1/4)

- **Single phase forced flow**
  - Sensible heat, advection
  - Indirect and direct cooling
  - Advantages
    - Smaller amount of cryogen if external circuits
    - Save space and weight in the system design
    - High heat transfer rate adjustable with mass flow rate



Tatsumoto H, et al. Forced Convection Heat Transfer of Liquid Hydrogen Through a 200-mm Long Heated Tube. Physics Procedia. 2012;36(0):1360-5.

  - Disadvantages
    - Pressurization system or circulation pumps to implement and maintain at low temperature
    - Heat exchanger to sub-cool the fluid
    - Range limitation due to finite sub-cooling
  - Sign of the JT coefficient $\left(\frac{\partial T}{\partial p}\right)_H$ important
    - If JT coefficient negative then in a flow ΔP ↘ implies ΔT ↗ (T_{fluid} ↗)
    - If JT coefficient positive then (T_{fluid} ↘)

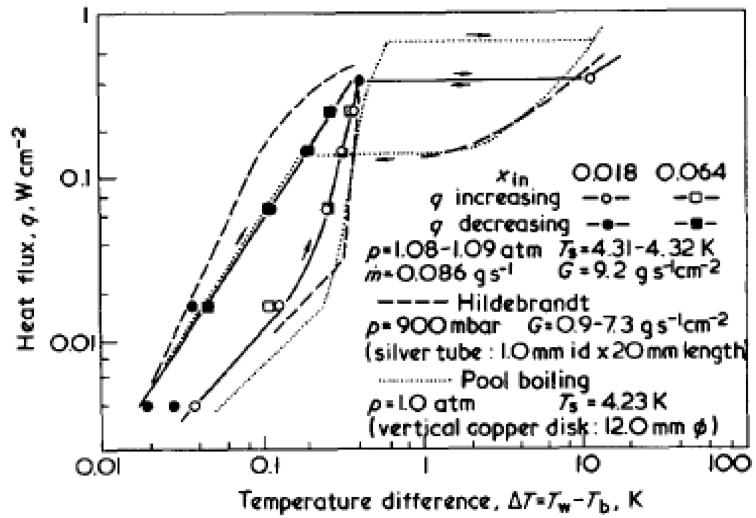


Cooling methods | Forced flow (2/4)

- **Two-phase saturated forced flow**

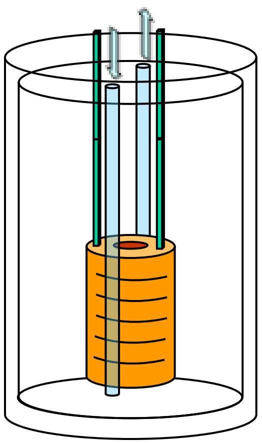
  – Latent heat
  – Sensible heat, advection
  – Indirect cooling

Ogata, Forced convection heat transfer to boiling helium in a tube, Cryogenics July 1974, p. 375



  – Advantages
    - **Almost isothermal flow**
    - High heat transfer rate up to high vapor quality
    - Save space and weight in the system design
    - Smaller amount of cryogen because of external circuits
    - Helium : q_{max}≈3.10^3 W m^{-2} Ø10 mm m=610^{-3} kg s^{-1} and ΔT≈1 K; no sub-cooling Mahé, PhD CEA Saclay 1991

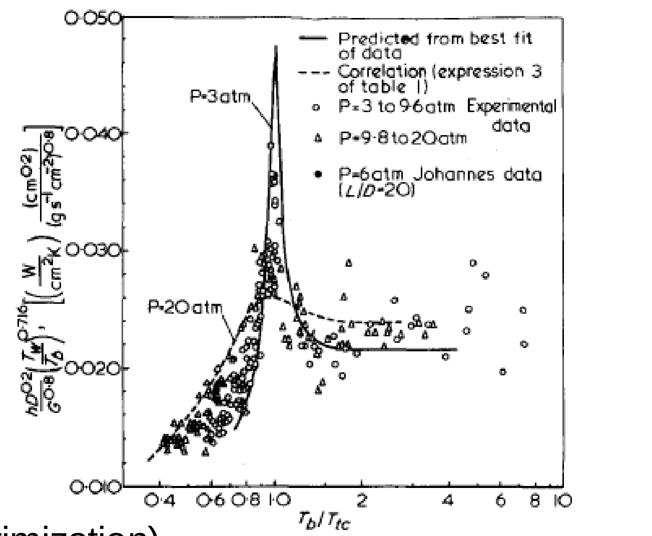
  – Disadvantages
    - Discrete temperature cooling (He 4.2 K, N_2 77.3 K et H_2 20.4 K, …)
    - **Non uniform cooling if vapor formation**
    - If $q > q_{cr}$ then film boiling (an order of magnitude smaller heat transfer)
    - h dependent on orientation and gravity



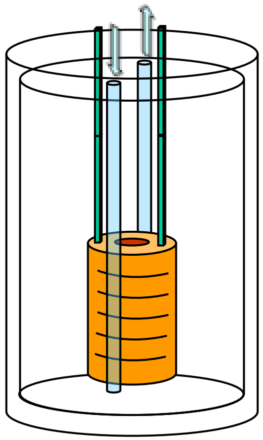
Cooling methods | Forced flow (3/4)

- **Supercritical forced flow (helium)**
  - Sensible heat, advection
  - Direct and indirect cooling

Giarratano, Forced convection heat transfer to supercritical Helium, Cryogenics, Oct. 1971 p. 385

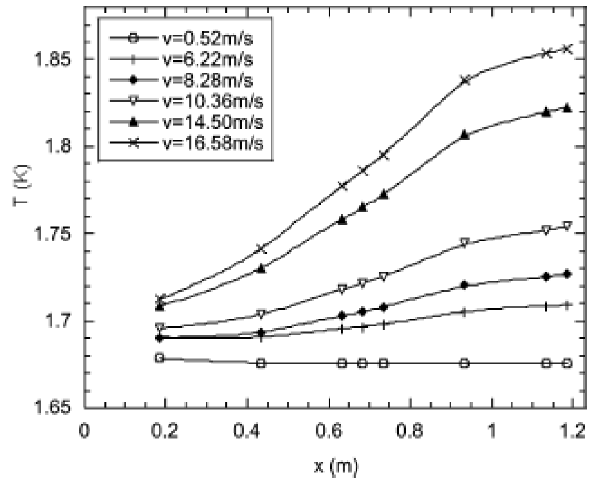


  - Advantages
    - **Single phase flow** (no vapor formation)
    - Comparable heat transfer coefficient to pool boiling
      - Classical heat transfer $q \approx 10^4$ W/m^2 for $\Delta T \approx 1$ K
      - JT coefficient positive or negative
    - Adjustable heat transfer with mass flow (temperature optimization)
    - Cooling system can be « plugged » to refrigeration plant and be used for cooling from 300 K
  - Disadvantages
    - Pressurization system
      - Absolute pressure P≈3-8 bar + extra ΔP in the system
    - Periodic re-cooling for operation (series of large magnets)



Cooling methods | Forced flow (4/4)

- Superfluid helium forced flow (helium)
  - He II heat transfer and advection
- Advantages
  - Same advantages as static He II
  - Large heat transfer
  - Classical frictional Δp up to Re≈10^7
- Disadvantages
  - Negative JT coefficient close to saturation
  - Needs specific pumps, heat exchanger, more complicated cooling scheme
  - Transition velocity for advection effect (1m/s @ 1.8 K)
- JT effect
  - Smooth tube : Dh=10 mm, Δp=0.3 bar →ΔT=0.1 K
- Never applied in accelerator magnets



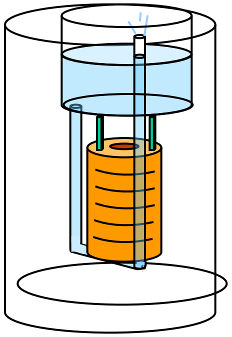
S. Fuzier, et al., Cryogenics, Volume 41, Issues 5–6, Pages 453-458

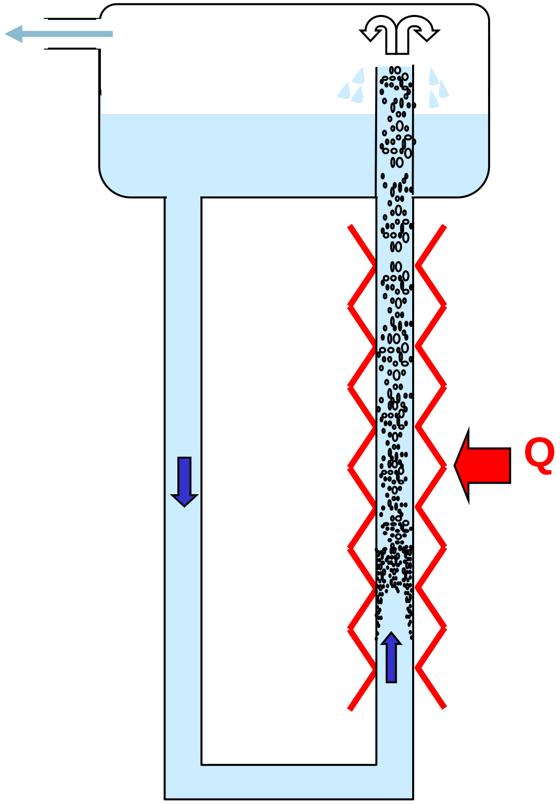
Cooling methods | Natural circulation loop

- **Natural circulation loop**
  - Flow is created by the weight unbalance between the two branches due to vaporization or decreased density
  - Mass flow rate linked to the heat flux
  - No pumps or pressurization system
  - Auto-tuned mass flow rate

  - « Open loop »
    - Vapor goes out of the system
    - Reservoir must be filed to avoir dry-out

  - « Closed loop »
    - Vapor is re-condensed in the reservoir

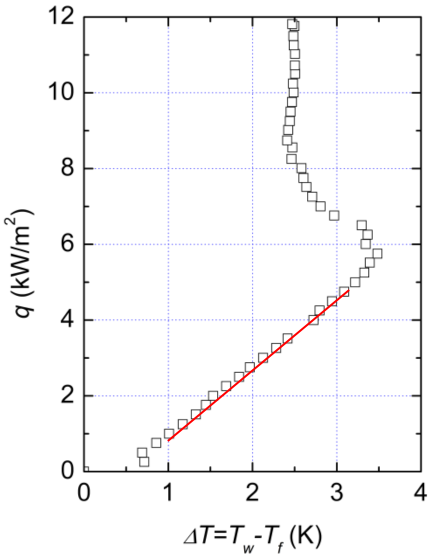




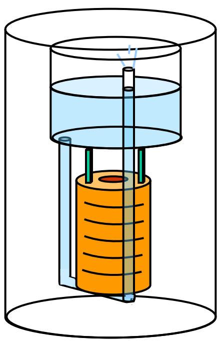
Case of a two-phase circulation loop

Cooling methods | Natural circulation loop

- **Single phase natural convection**
  - Buoyancy
  - Direct and indirect cooling
  - Advantages
    - No pressurization system
    - High heat transfer rate
    - In a circulation loop
      - Nitrogen flow $q_x \approx 4 10^3$ Wm^{-2} for Ø10 r
      - m=40 gs^{-1} and $\Delta T \approx 3$ K



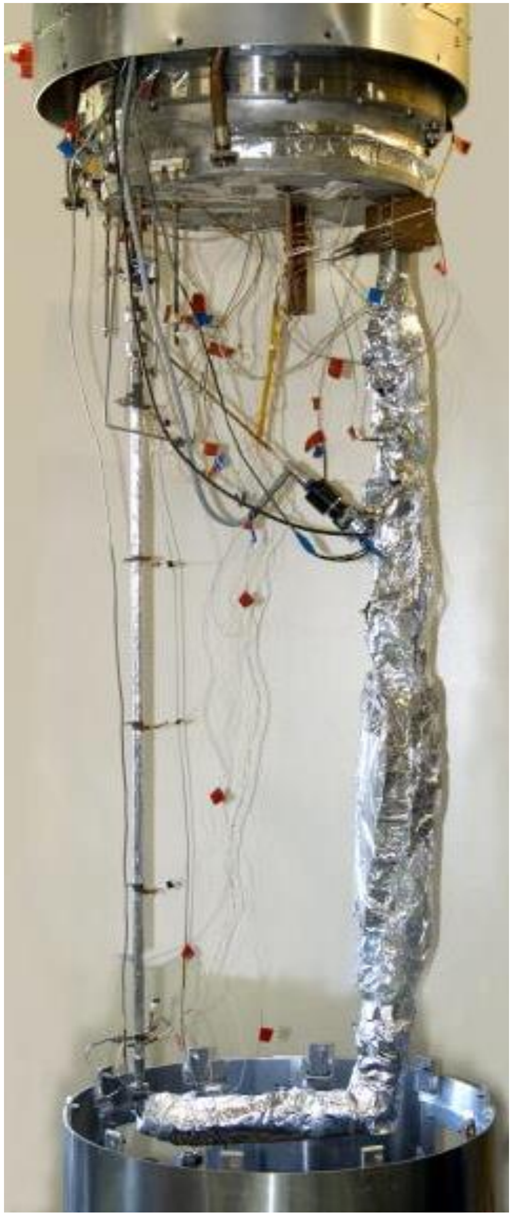
  - Disadvantages
    - Must have gravity!
    - In a circulation loop, mixed convection
      - Forced convection reduces natural convection



$$\frac{Nu_z}{Nu_{FC}} = 3.2\left(\frac{Gr}{Re^2}\frac{D}{z}\right)^{0.25}$$

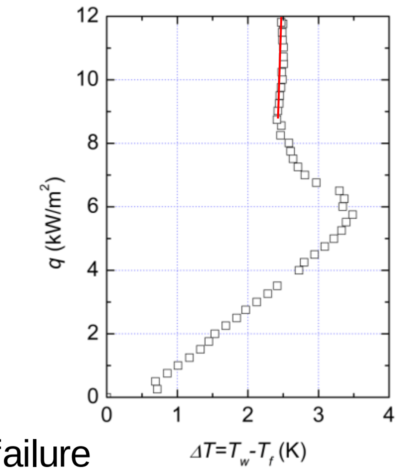
Mixed convection correlation
Nitrogen

Baudouy B. Experimental study of a nitrogen natural circulation loop at low heat flux. Adv. in Cryo. Eng. 55A, AIP Conf. Proc. 1218; 2010. p. 1546-53



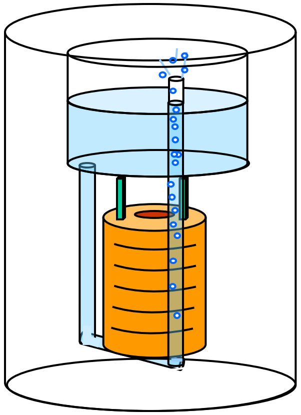
Cooling methods | Two-phase circulation loop (1/2)

- **Open vertical two-phase circulation loop**
  - Latent heat, sensible heat, advection
  - Indirect cooling
  - Advantages
    - No pressurization system (no pump and its associated maintenance)
    - Auto-tuned mass flow rate
    - Reservoir above the liquid serves as a reservoir in case of cryogenic failure
    - Reduced cryogen quantity
    - High heat transfer rate
      - Nitrogen flow $q_x \approx 10^4$ Wm^{-2} for Ø10 mm m=40 gs^{-1} and ΔT≈2.5 K
      - Helium flow $q_{max} \approx 10^3$ Wm^{-2} for Ø10 mm m=20 gs^{-1} and ΔT≈0.3 K
  - Disadvantages
    - Must have gravity!
    - Reservoir high enough above the circuit to create a sufficient ΔP (driving force)
    - Requires permanent refill to avoid dry-out in the cooling branches
    - One order of magnitude lower critical heat flux compared to pool boiling



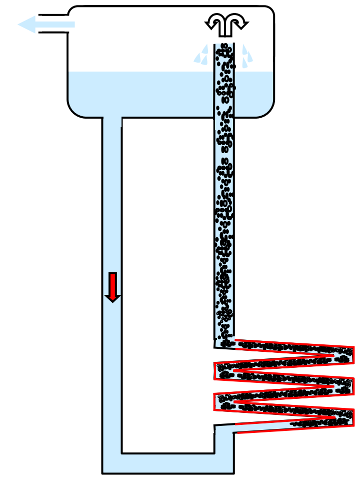
Baudouy B. Experimental study of a nitrogen natural circulation loop at low heat flux. In: Adv. in Cryo. Eng. 55A, AIP Conf. Proc. 1218; 2010. p. 1546-53.

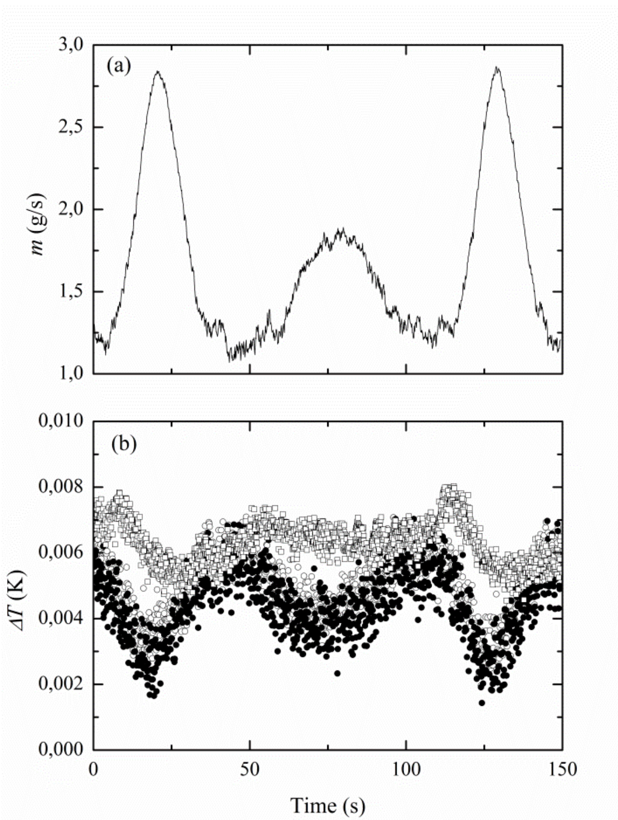
Benkheira L, et al. Heat transfer characteristics of two-phase He I (4.2 K) thermosiphon flow. IJHMT, 2007;50(17-18):3534-44

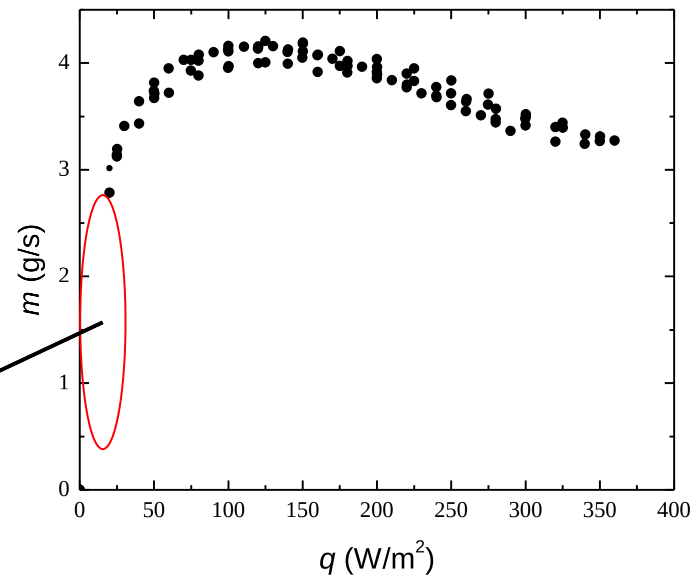


Cooling methods | Two-phase circulation loop (2/2)

- Open **horizontal** two-phase circulation loop
  - Circulation loop with horizontal parts possible (but not at the bottom)
    - Instability at low heat flux
    - But high heat transfer







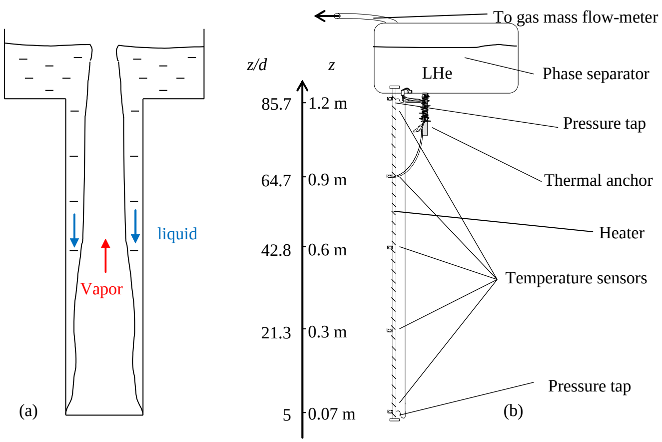
B. Baudouyet al. Modeling of a horizontal circulation open loop in two-phase helium, *Cryogenics, Volume 53, January 2013, Pages 2-6*

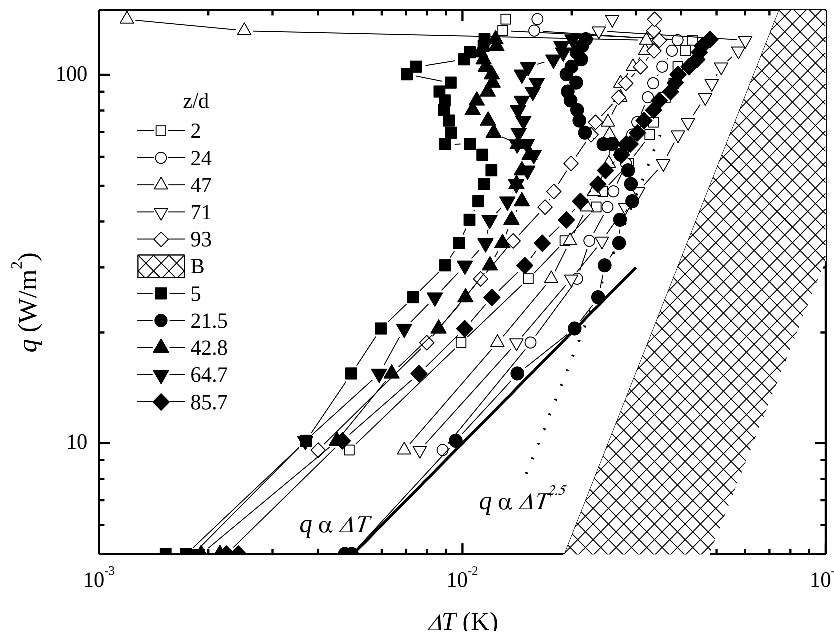
Gastineau B, et al. R3B-GLAD magnet R&D tests program: Thermosiphon loop with horizontal section, superconducting cable joints at 3600 A, and reduced scale "coil in its casing" mock-up. IEEE Transactions on Applied Superconductivity. 2012;22(3):900-1004.

Evolution of the total mass flow rate (a) and wall Δ*T* (b) at the bottom and top of Ø10 mm tube at 3.508 m from the entrance of the tube for 5 W/m²

Cooling methods | Large open thermosiphon

- Open thermosiphon with a closed tube
  - Counter-current two-phase flow
  - Indirect cooling
  - Advantages
    - Even simpler design and less cryogen
    - Large heat transfer rate
  - Disadvantages
    - **Low critical heat flux**
    - Flooding, instability
  - Helium case
    - 1 m long, Ø 10 mm
    - h~10^4 W/m^2.K
    - q_c ~100 W/m^2

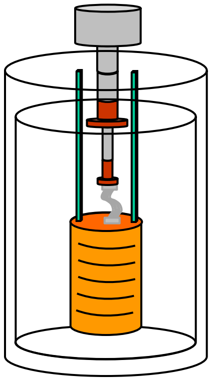


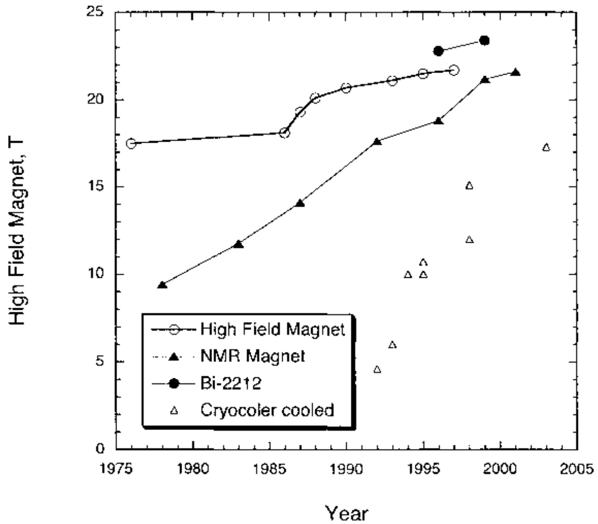


Baudouy B. Experimental study of heat transfer in a vertical uniformly heated closed-end tube submerged in saturated liquid helium. In: Proceedings of the 21th ICEC 2006. p. 381-4.

Cooling methods | Conduction (1/2)

- Cryogen-free cooling
  - Conduction between the cold source and the system
  - Indirect cooling
  - Advantages
    - Easy implementation (no liquid, no heat exchanger, no transfer line, …)
    - Suitable for small power system without large transient event
  - Disadvantages
    - **Finite cooling power** - thermal design must be accurate
      if real power to be extracted exceeds the cryocooler power, then what?
    - **A point-source of cold** (distribution of cooling power)
    - Conductive diffusion limit for transient
  - Examples
    - 10T magnet class commercialized since 1990
    - 18T NbTi and Nb_3Sn magnet (MIMS, Toshiba et TIT)





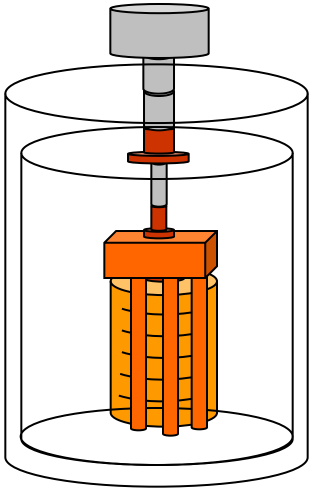
A. Sato, MiMS

Cooling methods | Conduction (2/2)

4K class cryocooler

- GM Cryocooler characteristics
  - 4K two-stage cryocooler
    - 2nd stage 1.5 W at 4.2 K
    - 1st stage 30 W at 50 K
  - 20K two-stage cryocooler
    - 2nd stage 10 W at 20 K
    - 1st stage 35 W at 77 K
  - 77 K single stage cryocooler; several 100 W!

- Cryocoolers are point-source of cold systems and a power distribution is needed (thermal links)



- Conductive links
- Small loops with Two-phase fluid

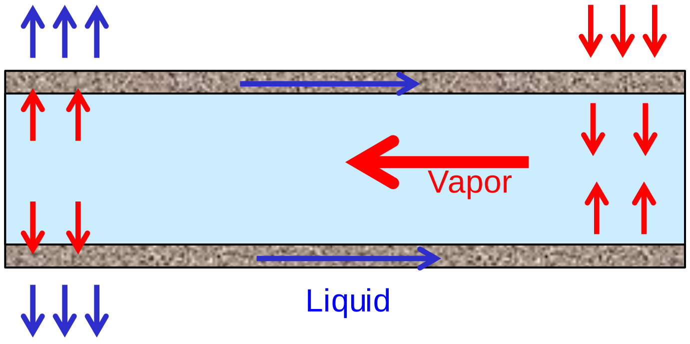
10K and 77K class cryocoolers

Cooling methods | Capillary pumped device (1/2)

- Flow is created by capillary pressure in porous media at the liquid/vapor interface

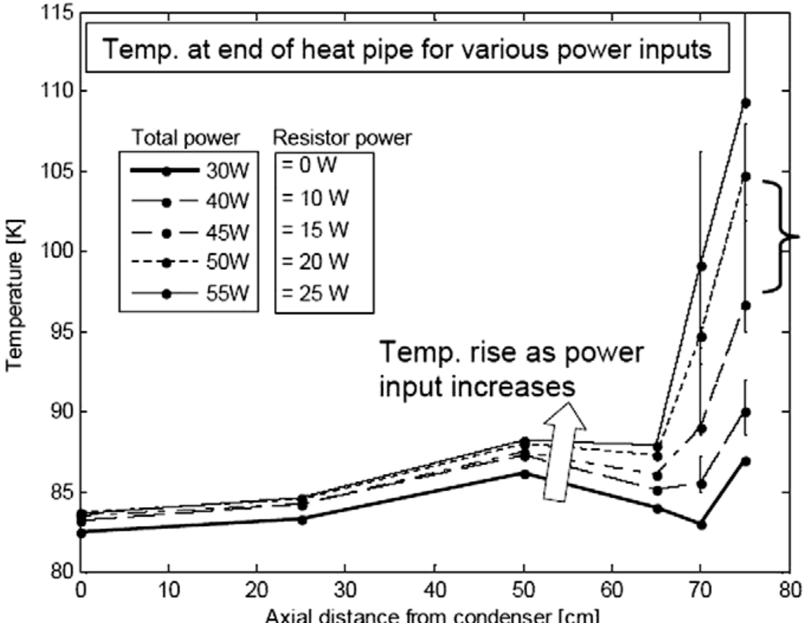
- **Wick-based heat pipe**
  - Large ΔT between condenser and evaporator

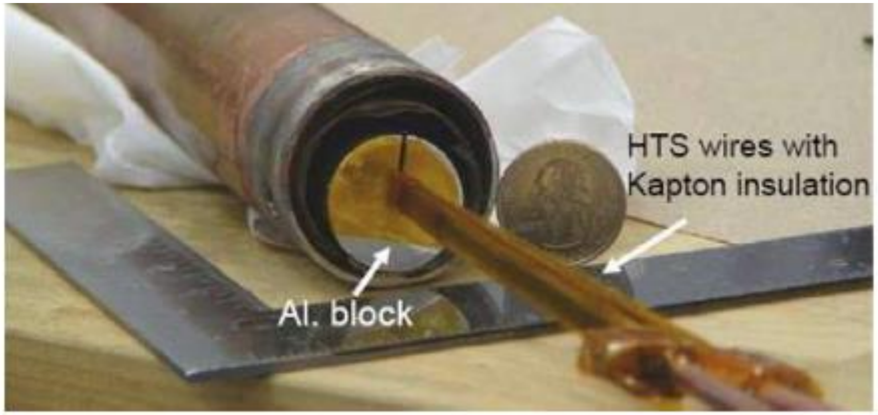
(Evaporator)
(System to be cooled) Heating



Cooling (cryocooler)
(condenser)

Nitrogen heat pipe
Heat pipe length 85.5 cm
Pipe diameter 4 cm
Wick material stainless steel mesh

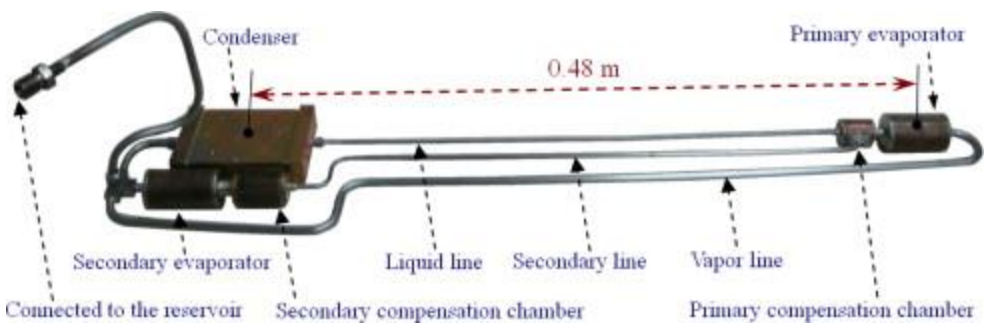


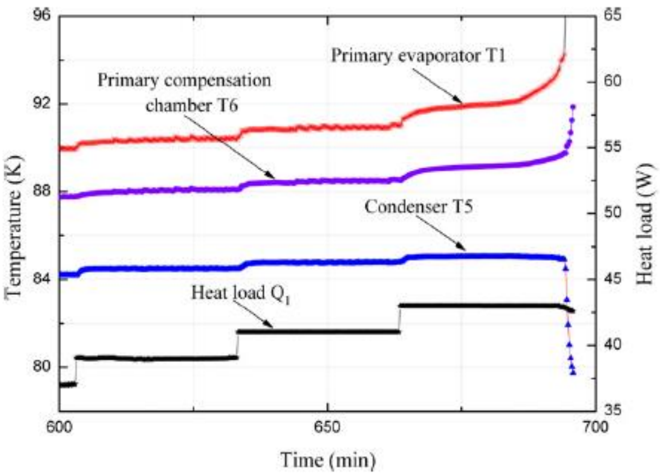


D.W. Kwon et al. Cryogenic heat pipe for cooling high temperature superconductors, Cryogenics, Volume 49, Issue 9, September 2009, Pages 514-523

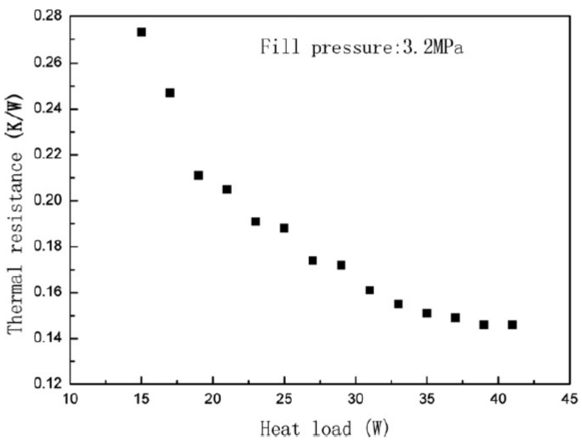
Cooling methods | Capillary pumped device (2/2)

- **Cryogenic loop heat pipe**
  - Heat pipe in a loop configuration (mass flow)





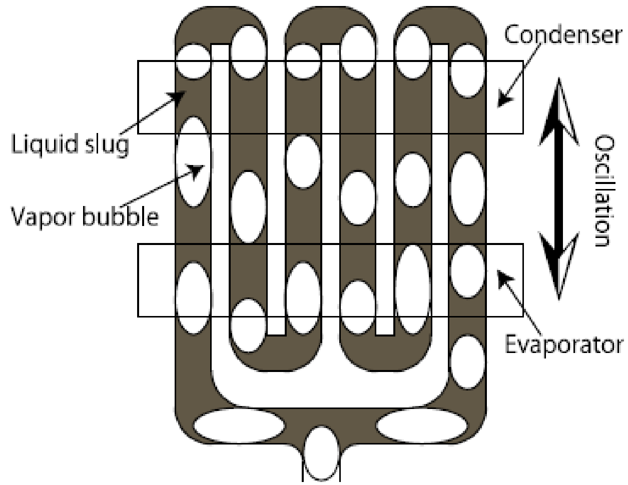
- Heat transfer in Nitrogen
  - ΔT=6 K for 40 W for 0.5 m long
  - R_{th} ↘ for the heat load



Y. Zhao, et al. Experimental study on a cryogenic loop heat pipe with high heat capacity, Int J Heat Mass Transfer, 54 (2011), pp. 3304–3308

Cooling methods | Oscillating Heat Pipe

- Pressure change due to volume expansion and contraction at phase transition
- Oscillation of liquid slugs and vapor bubbles between the evaporator and the condenser

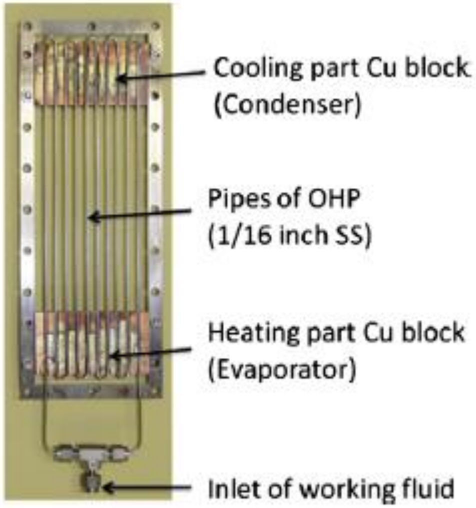


- Advantages
  - Easy to implement
  - Large heat transfer

$$D_{crit} = 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$$

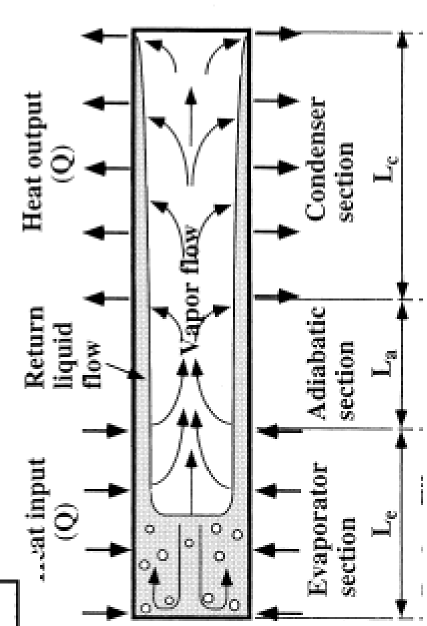
K. Natsume, Heat transfer performance of cryogenic oscillating heat pipes for effective cooling of superconducting magnets, Cryogenics, Volume 51, Issue 6, June 2011, Pages 309-314

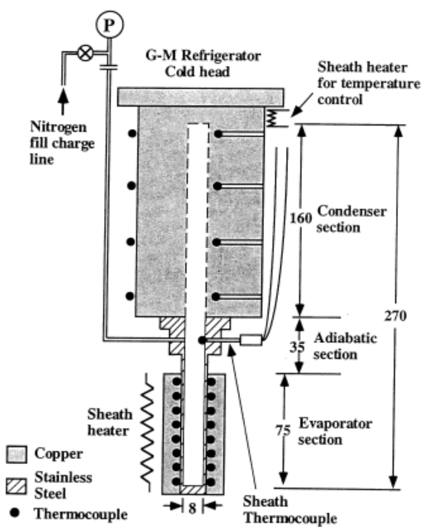
Fluid	Heat input (W)	Cooling part temperature (K)	Heating part temperature (K)	Keff (kW/m.K)
H2	0-1.2	17-18	19-27	0.5-3.5
Ne	0-1.5	26-27	28-34	1-8
N2	0-7	67-69	67-91	5-18

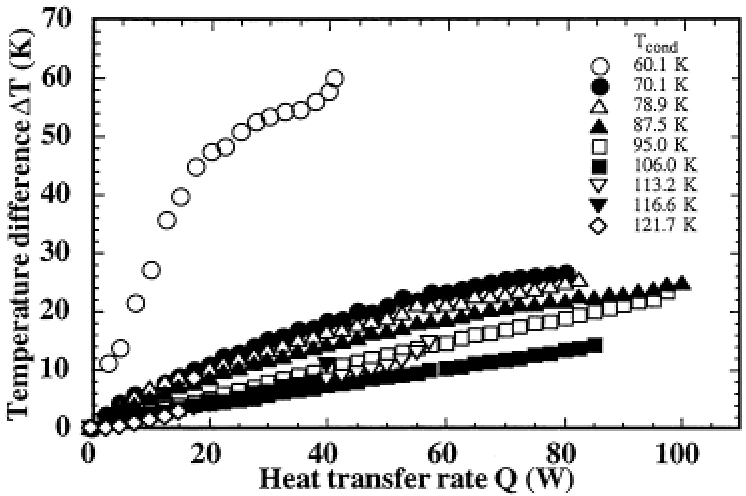


Cooling methods | Thermosiphon

- Counter-current two-phase flow
- Same advantages as the open large thermosiphon
- **Autonomous loop**
- Heat transfer in nitrogen
  - R_{th}=0.5 K/W for 20 W and ΔT=10 K



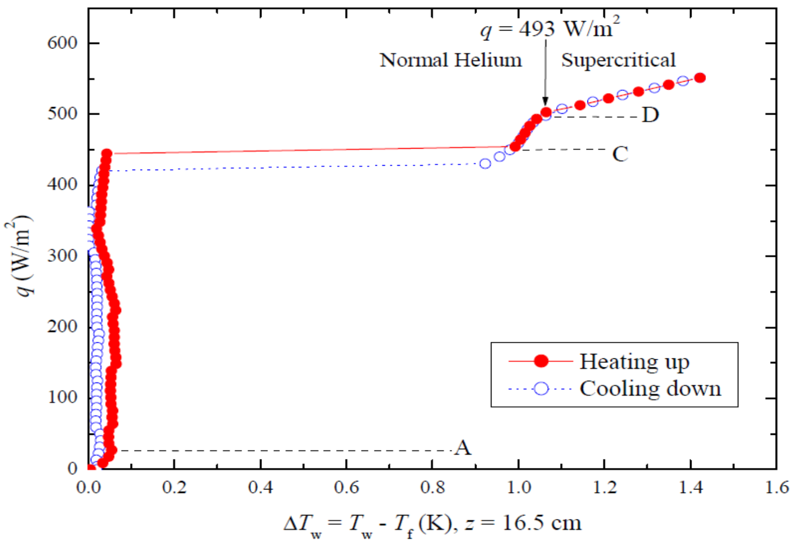


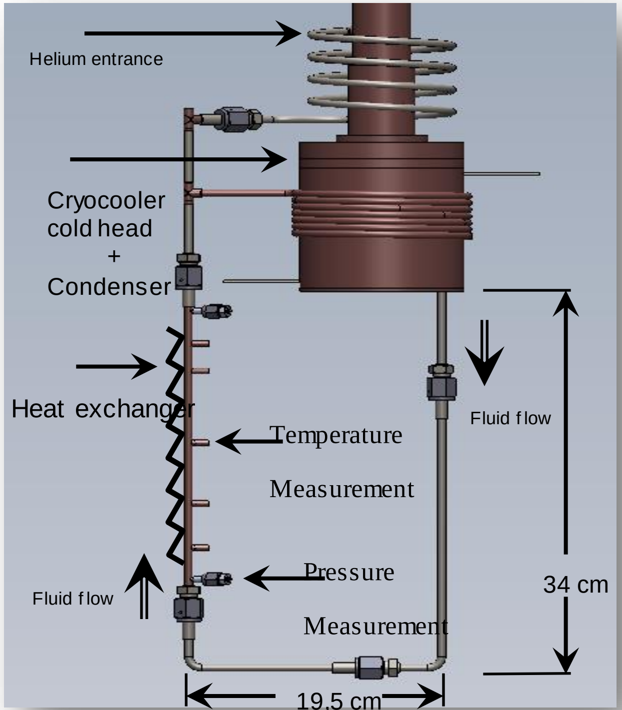


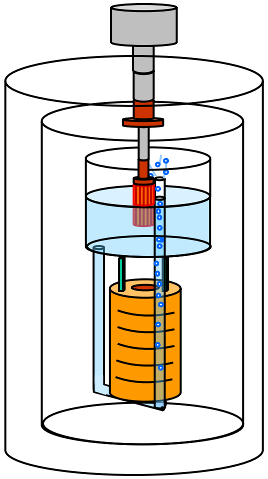
A. Nakano, et al. An experimental study of heat transfer characteristics of a two-phase nitrogen thermosyphon over a large dynamic range operation, Cryogenics, Volume 38, Issue 12, December 1998, Pages 1259-1266

Cooling methods | Natural circulation close loop

- Co-current two-phase flow
- Same advantages than the open natural circulation loop
- **Autonomous loop**
- Heat transfer in helium Ø4 mm
- Around 4.2 K at saturation
  - h~5000 W/m^2K
  - q_c=500 W/m^2





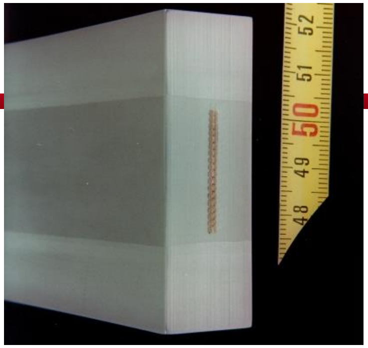


Y. Song et al. submitted to IJHMT 2013

Outline|

- Cooling methods at low temperature (Lecture 2)
  - Different classification of system with respect to cooling
    - Dry systems
    - Indirect cooling
    - Wet systems
  - Different methods of cooling
    - Baths
    - Forced flow
    - Two-phase flow
    - Cryogen free cooling
    - Coupled systems
  - Some examples
    - Large detector magnets
    - Superconducting RF cavities
    - Accelerator magnets
    - Fusion magnets
    - Life science magnets

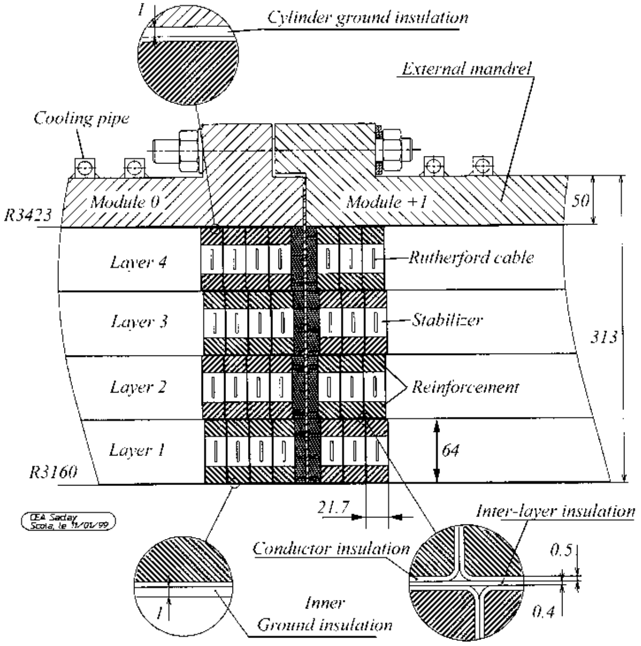
Large detector magnets



- Large scale magnet
  - Large stored energy and small thermal losses
  - Large thermal stabilizer cross-section needed
  - T_{max} and ∇T must be controlled to minimize the mechanical constraints

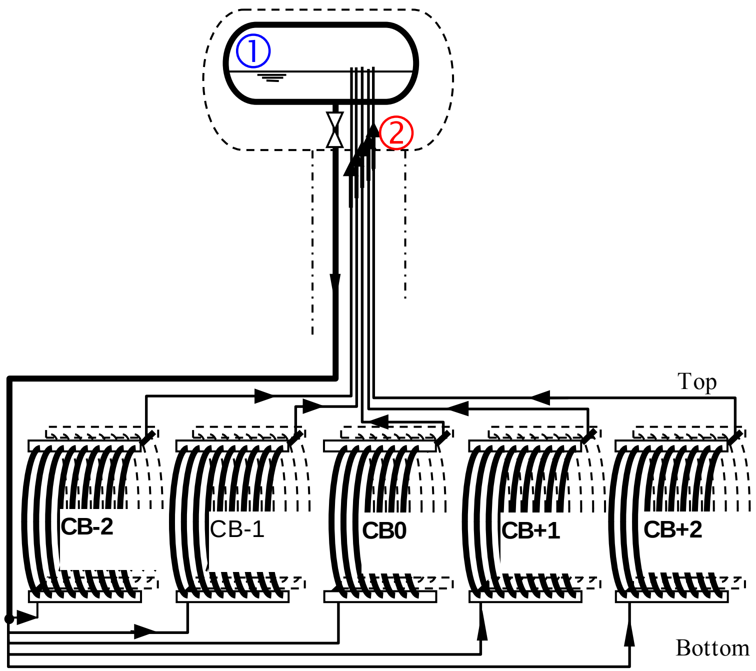
- Indirect cooling "Dry coil" magnet
  - Reduced cryogen quantity
  - Fully impregnated coil with epoxy resin
  - High purity aluminum stabilized conductor

- Heat transfer
  - Cold source : He reservoir / phase separator
  - Two-phase flow of He I in external tubes
    - Forced flow or natural two-phase flow



Detector Magnets | CMS

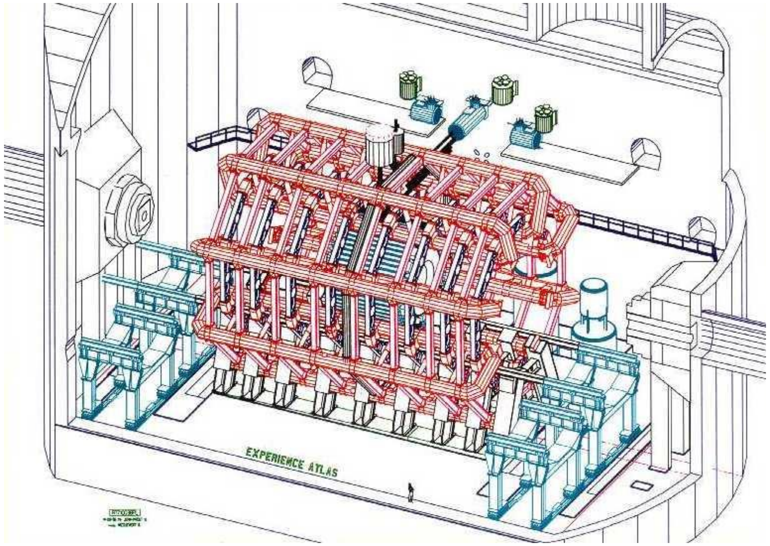
- Two-phase convection in **thermosiphon mode**
  - Solenoid with “vertical parts”
- Heat transfer
  - 180 W of static load
  - ① 4.4 K at 1.25 bar (saturated)
  - ② 4.4 K at 1.25 bar (Two-phase)



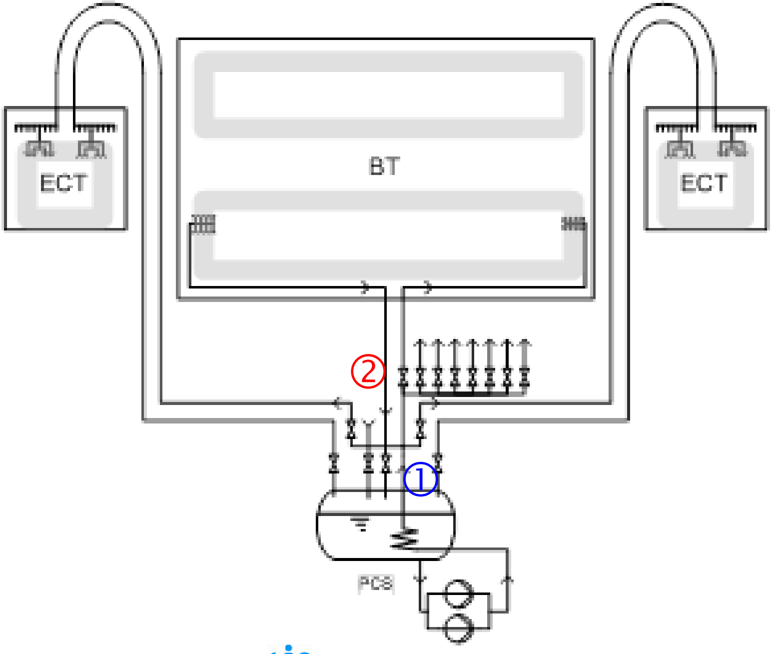
- Mass flow rate 0.2 -0.4 kg/s
- Vapor quality 5-10%

Detector Magnets | ATLAS

- Helium two-phase **forced convection and thermosiphon**
  - "Air" toroid with long horizontal parts
  - Central solenoid



- Heat transfer in the toroid
  - 8x80 W of static load (barrel)
  - 2x200 W of static load (end-cap)
  - ① 4.65 K at 1.7 bar (sub-cooled)
  - ② 4.8 K at 1.67 bar (Two-phase)



- Mass flow rate 0.7 kg/s in the barrel
- Mass flow rate 0.5 kg/s in the end-cap
- Vapor quality up to 8%

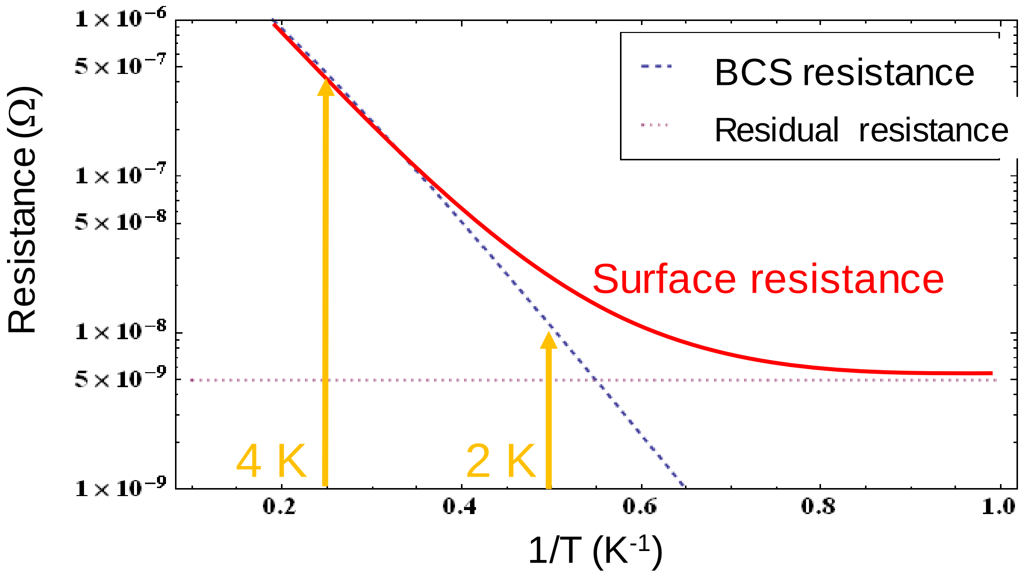
Superconducting RF cavities (1/2)

- Direct cooling with liquid helium (He I or He II) in saturated bath

- Heat dissipation mainly in the metallic cavity wall

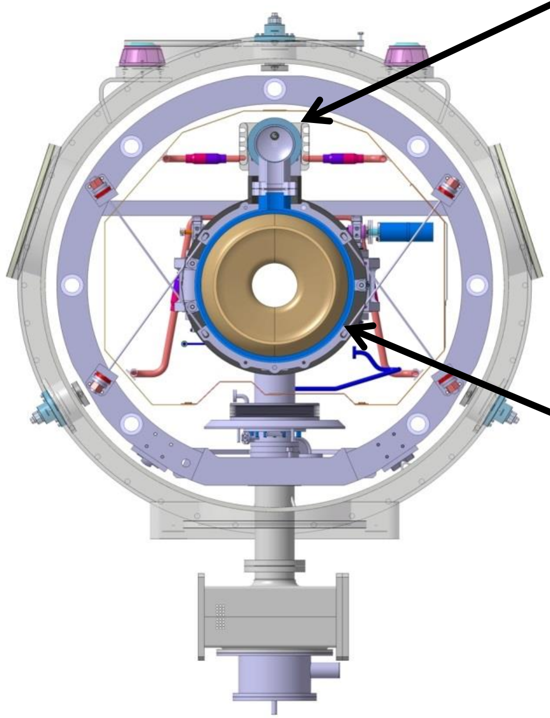
$$Q \propto \int_S R_s H_s^2 dS$$

  – Surface resistance of a cavity is $R_S = R_{BCS} + R_{residual}$



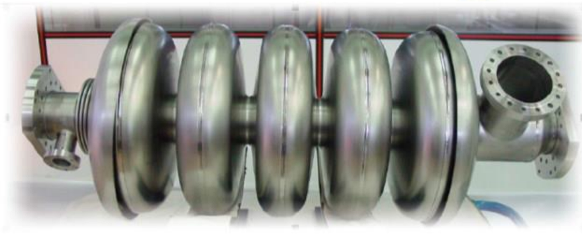
  – R_{BCS} decreases with decreasing temperature
  – R_{BCS} is proportional to f^2
  – 4.2K → 2K R_{BCS} est divided by 50

Superconducting RF cavities (1/2)



XFEL general Cryo design

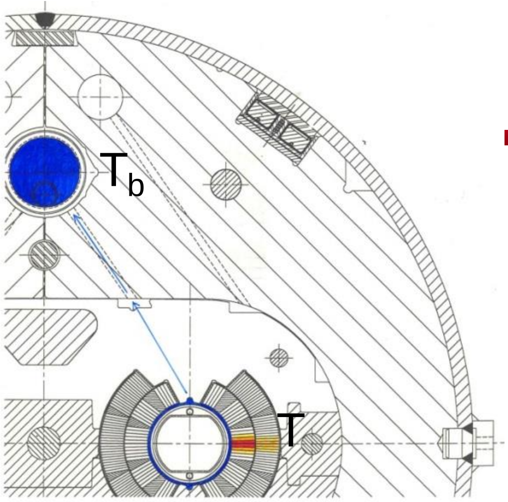
- Two-phase helium distribution pipe
  - Vapor/ He II at saturation
- Pumping line
- Heat exchanger + JT valve to feed the He II bath from 4.2 K
- He II saturated Bath
  - Pumping is a simple way to control temperature via pressure
    (δp~1 mbar → δT~1 mK)
  - Stability in Temperature



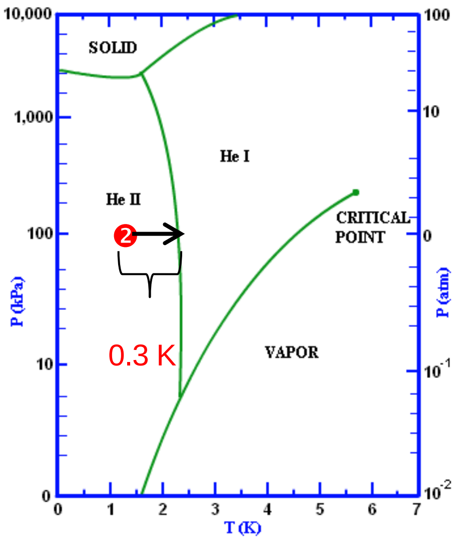
704 MHz SC elliptical cavity
β 0.65
[CEA/CNRS]

Accelerator magnets

- "Wet" magnets with "heat exchanger"
  - Large internal losses and smaller stored energy
  - "Beam losses" in LHC (10 mW/cm^3 or 0.4 W/m (cable))
  - Cooling source : Internal tube heat exchanger
  - Single phase coolant in contact with conductor



- LHC He II cooling
  - Two-phase He II for the exchanger, T_b
  - Stagnant He II for the magnet



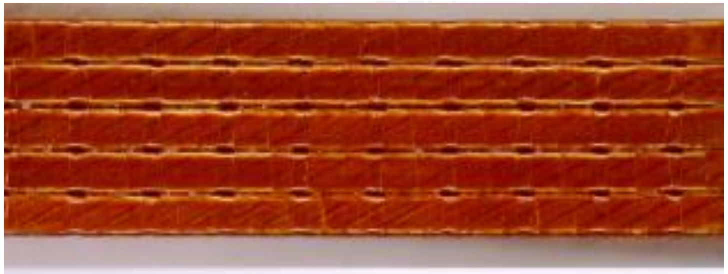
- Heat transfer between the conductor and the cooling source determines the working conditions temperature margin, $\Delta T = T - T_b$
  - $T_b = 1.9$ K → $\Delta T = T - T_b < 0.3$ K!

- **Electrical insulation constitutes the largest thermal barrier**

Accelerator magnets | LHC

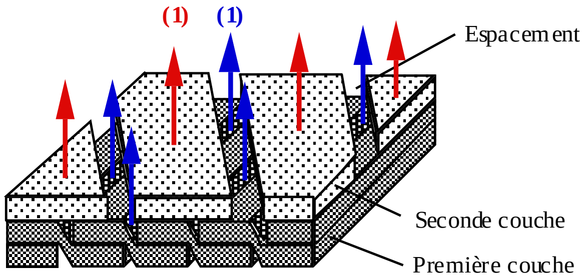
- LHC heat load
  - **ΔT<0.3 K with permeable insulation**
  - ΔT~4 K with monolithic insulation

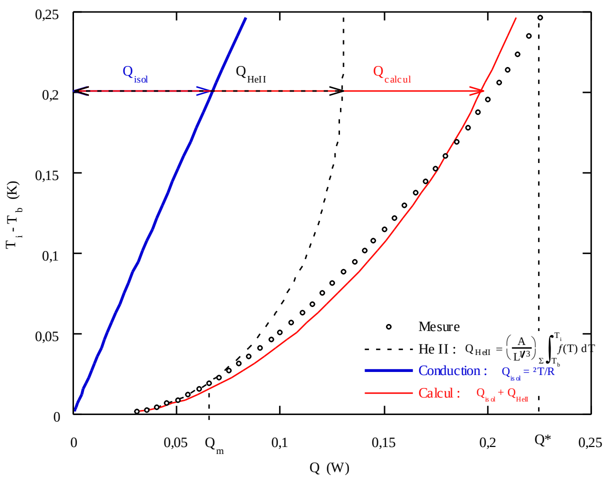
- LHC electrical Insulation
  - triple polyimide wrapping
    - First 2 wrappings without overlap
    - 3rd wrapping with spacing



- Polyimide wrapping creates µ-channels

- Heat transfer in insulation
  - Ø~10 µm, channel length of ~mm
  - **He II in the µ-channels + Conduction/Kapitza**





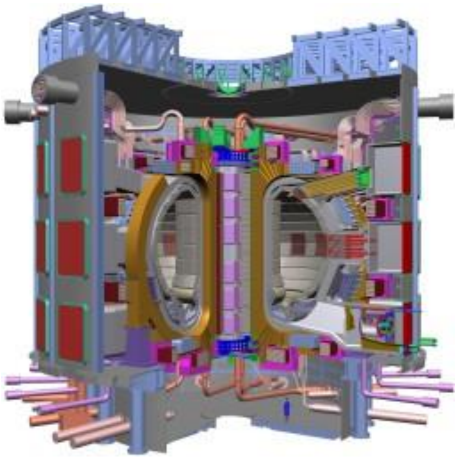
Baudouy B, François MX, Juster F-P, and Meuris C. He II heat transfer through superconducting cables electrical insulation. Cryogenics 2000; 40: 127-136

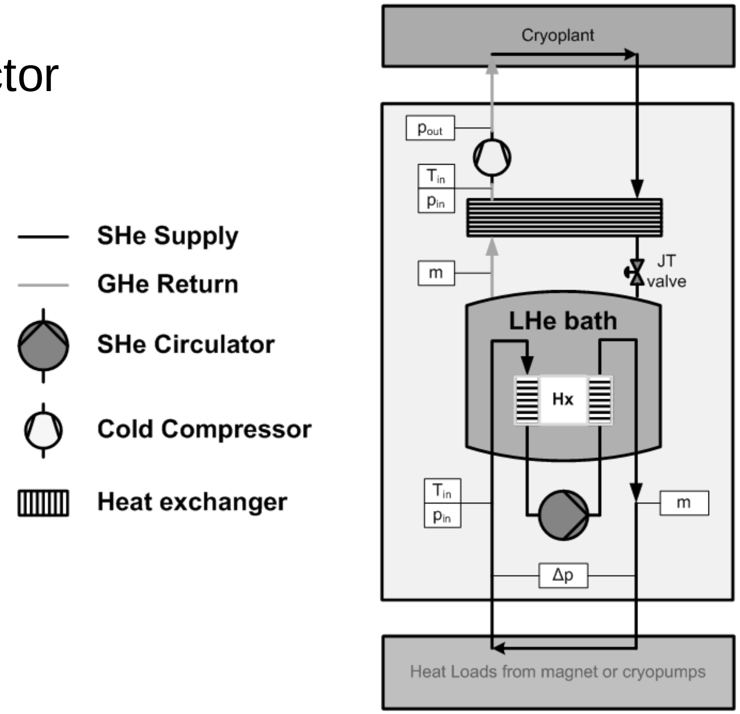
Pier Paolo Granieri, Heat Transfer between the Superconducting Cables of the LHC Accelerator Magnets and the Superfluid Helium Bath, PhD EPFL – CERN, 2012

Fusion Magnets

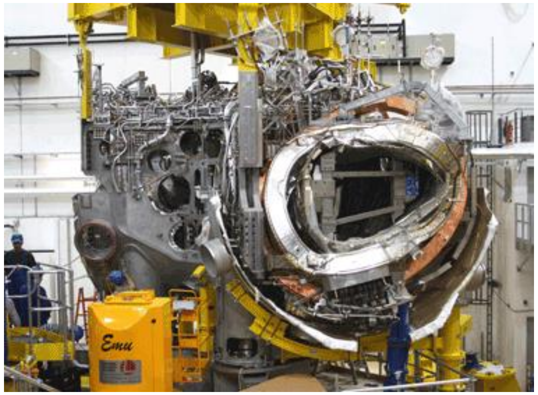
- **Large losses** due to plasma and radiation
- **Direct cooling** within cable in conduit conductor

- ITER
  - Supercritical helium flow at 4.5 K and 6 bars
  - Helium circulator up to 3 kg/s

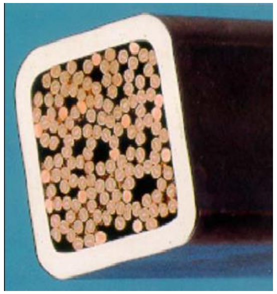




L. Serio, Challenges for cryogenics at iter, Adv. Cryo. Eng. AIP Conf. Proc. 1218, pp. 651-662, 2010

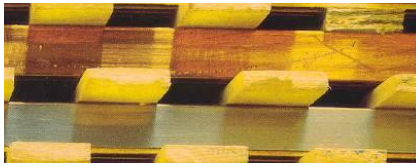


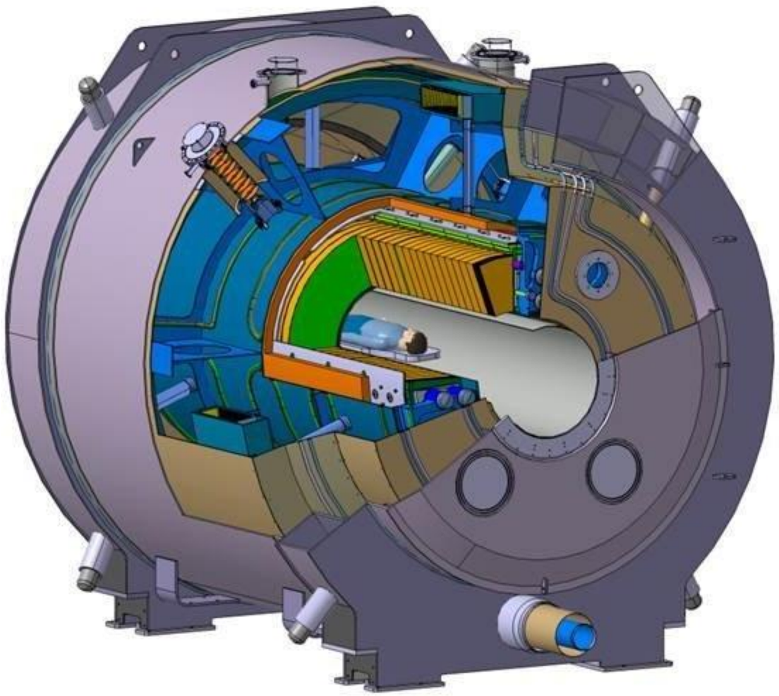
- W7X
  - Supercritical helium at 3.8 K and 6 bars max



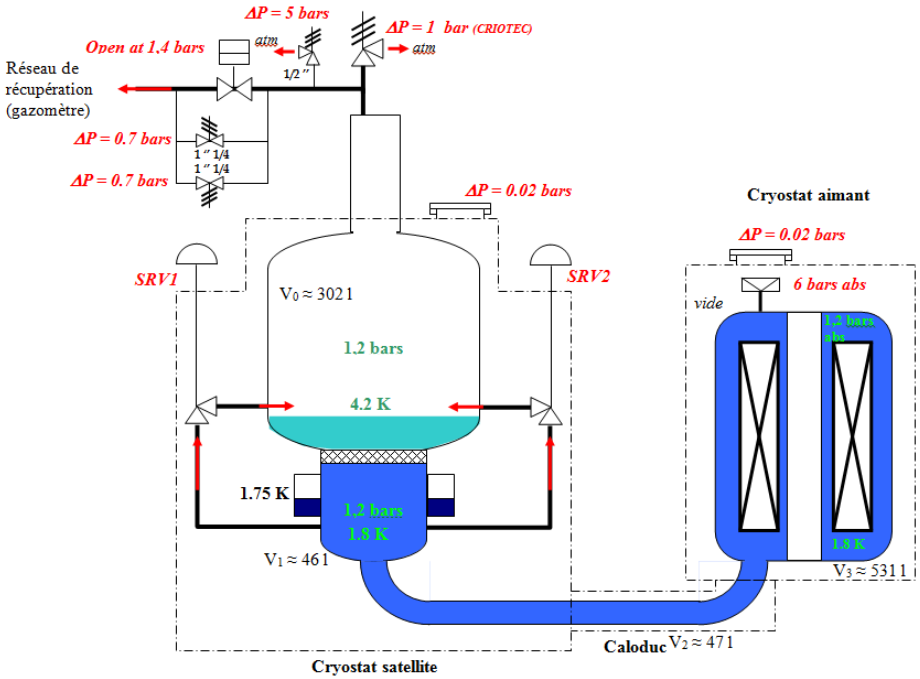
Magnets for life science | Iseult

- "Wet" and "cryostable" magnet
  - Cold source : He II static helium
  - Large He II bath (volume ~ 1000 l)
  - No perturbation for the medical environment!





- Iseult – 11.7 T whole body MRI
  - T=1.8 K at 1.2 bars (caloduc)
  - Insulator/separator of conductors creates channels
  - Channel heat transfer know in He II



Lecture 2 | References & Acknowledgement

- **Journals**
  - *Cryogenics*, Elsevier Science (http://www.journals.elsevier.com/cryogenics/)
- **Conference Proceedings**
  - Advances in Cryogenic Engineering, Volumes 1 – 57, proceedings of the Cryogenic Engineering and International Cryogenic Materials Conference (USA)
  - Proceedings of the International Cryogenic Engineering Conference (Europe/Asia)

- **Acknowledgement**
  - Philippe Brédy (CEA Saclay), Lectures and presentations from CEA Saclay, IPNO and CERN people