"Superconductivity and other new Developments in Gantry Design for Particle Therapy"

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Cooling methods and cryogenic systems for rotating superconducting magnets

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Outline

- Some considerations for the cryogenic design
- An example :the CEA-Saclay Gantry cryogenic pre-design
- Thermal links for cryocooling
- Conductive thermal links for cryocooling
- Two-phase cryogen thermals link for cryocooling

Considerations for cryogenic design (1/3)

- Magnet submitted to rotation
  - No fluid in the SC coil (dry coil)
  - Gravity assisted cooling system prohibited
    - No cryogenic fluid : Cryogen-free design
    - With cryogenic fluid : Gravity “independent” cooling system design

- System used by non cryogenists
  - Best cold sources are cryocoolers
    - Cooling of the main magnets
    - Cooling of the auxiliary components (radiation shields and current leads)
  - Passive thermal links between the cryocooler and the cold parts
    - Conductive (cryogen free)
    - Gravity independent two-phase cryogen thermal link

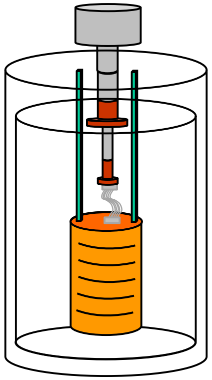
- Medical or commercial environment
  - Importance of the cool-down duration
  - Importance of the recovery duration after a quench

Considerations for cryogenic design (2/3)

- Cooling with cryocoolers
  - Thermal link between the cold source and the system
  - Indirect cooling ($\Sigma\Delta T$ due to thermal contact resistance, …)

- Advantages
  - Easy implementation (no liquefaction unit, no heat exchanger, no transfer line, …)
  - Easy working conditions

- Disadvantages
  - **Limited cooling power** - thermal design must be accurate
    if the heat load to be extracted exceeds the cryocooler power capacity, then T↗
  - **A point-source of cold** (35 cm² to 85 cm²)
    A distribution of cooling power must be implemented



Considerations for cryogenic design (3/3)

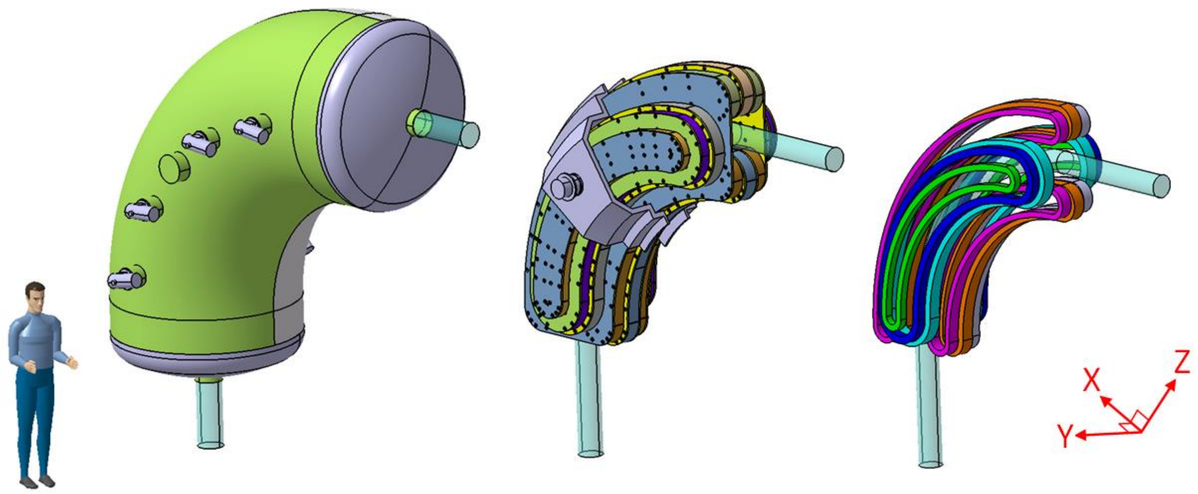
- GM Cryocooler characteristics
  - 4K two-stage cryocooler
    - 2^{nd} stage 1.5 W at 4.2 K
    - 1^{st} stage 30 W at 50 K
    - Cold source area ~35 cm^2
  - 20K two-stage cryocooler
    - 2^{nd} stage 10 W at 20 K
    - 1^{st} stage 35 W at 77 K
  - 77 K single stage cryocooler; several 100 W!
    - Cold source area ~ 85 cm^2
- Maintenance (20000 hours)

4K class cryocooler
© SHI Cryogenics Group

300W @ 80 K cryocooler
© CryoMech

CEA-Saclay Gantry cryogenic pre-design (1/4)

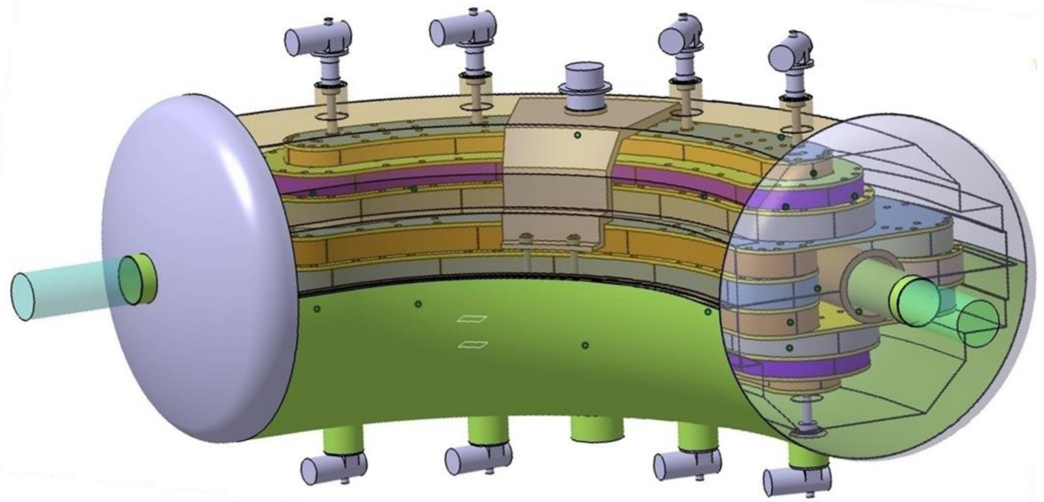
- Carbon ion hadron therapy Gantry magnet studied at CEA Saclay in 2000's
  - Dipole composed of 12 coils, 90° with 2 m curvature radius
  - Active shielding
  - NbTi SC with a 1.25 K temperature margin (T=4.2 K)
  - Central field of 3.2 T, 5.4 T max on the conductor, 12 MJ of stored energy



- Cryocoolers used for the cooling and the normal working condition
  - Possibility to cool-down with cryogen

CEA-Saclay Gantry cryogenic pre-design (2/4)

- Heat load inventory in normal working conditions
  - Heat conduction due to the different supports : 3 W
  - Radiation
    - 21 W @ 80 K
    - 3.5 W @ 4.2 K
  - HTc Current leads (1000 A)
    - 1.3 W between 300 K and 50 K
    - 0.3 W between 50 K and 4.2 K
  - Losses in the conductors : 3 W
  - Total :10 W @ 4.2 K
    : 20 W @ 80 K



- 8 x 1.5 W @ 4.2 K cryocoolers are necessary
  - Safety margin and 10% of performance degradation due to rotation

CEA-Saclay Gantry cryogenic pre-design (3/4)

- Minimization of the cooling time and the recovery time after quench
  - 3 x 580 W @ 80 K cryocoolers
  - 1 100 W @ 30 K cryocooler

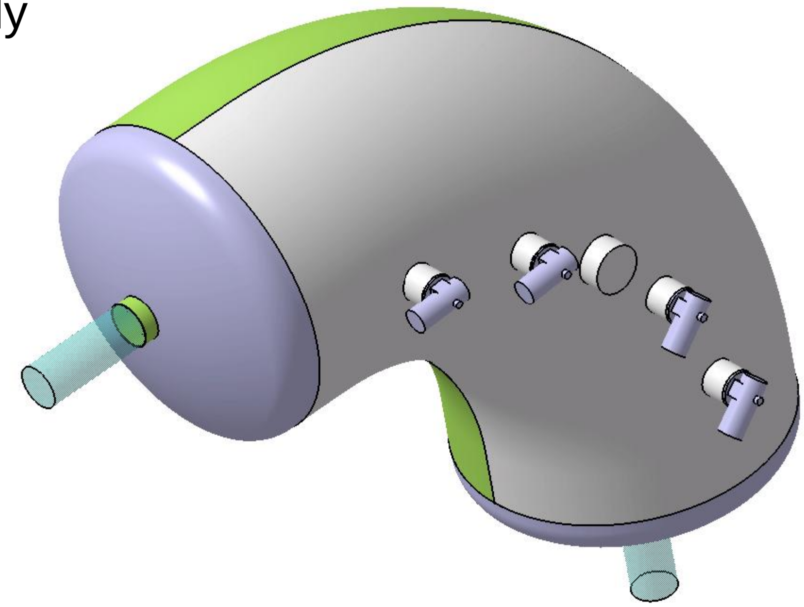
- Enthalpy variation computation only

- Cooling time (300 K to 4.2 K)
  - 4.83 days from 300 K to 80 K
  - 2.7 days from 80 K to 30 K
  - 4.3 days from 30 K to 4 K

  Total 12 days

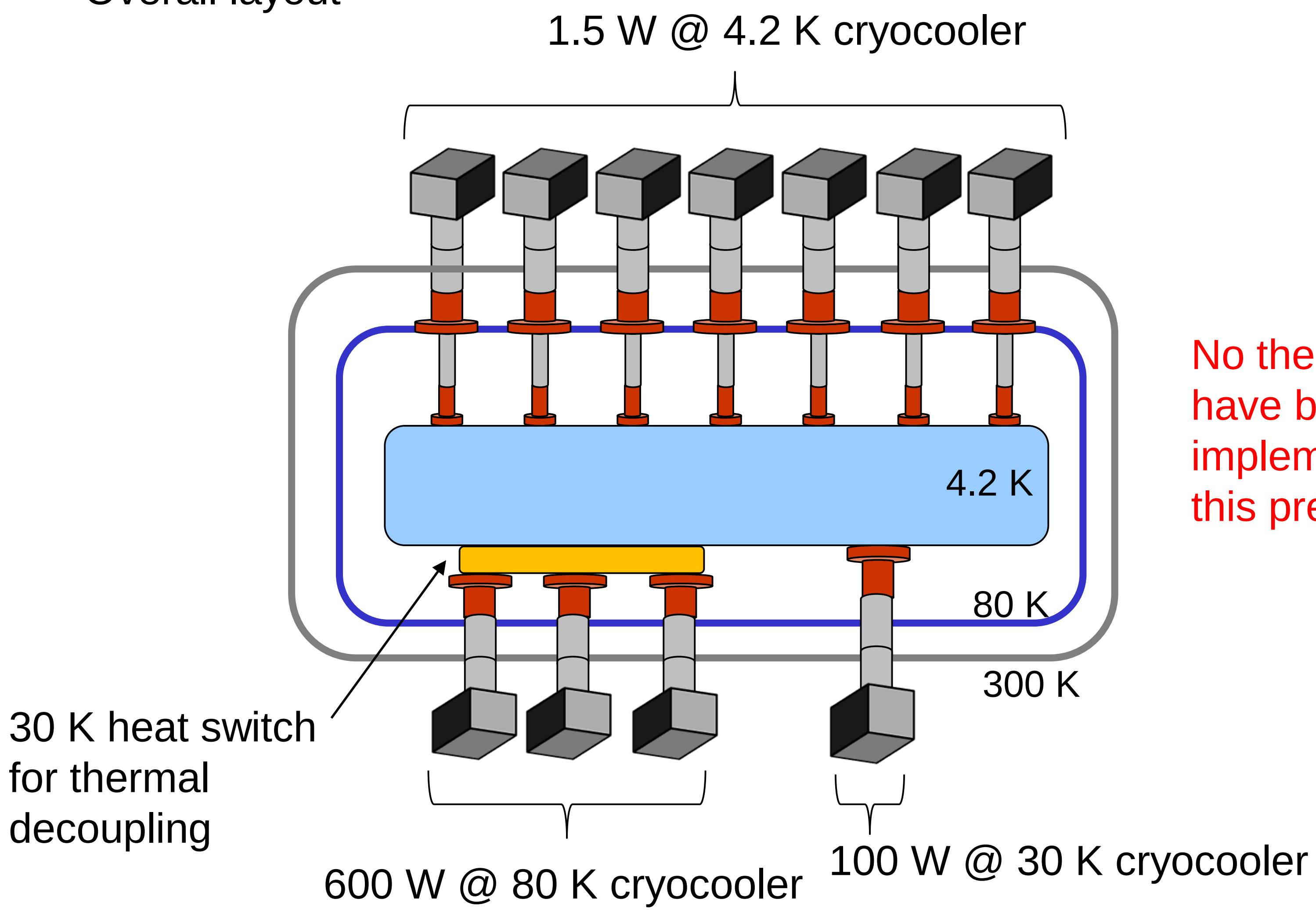
- Recovery time after a quench
  - Average temperature reached 70 K
  - 16 hours to go back to 30 K
  - 23 hours to go down to 4 K

  Total of 40 hours to recover



CEA-Saclay Gantry cryogenic pre-design (4/4)

- Overall layout



No thermal link have been implemented in this pre-design !

Thermal links for cryocooling

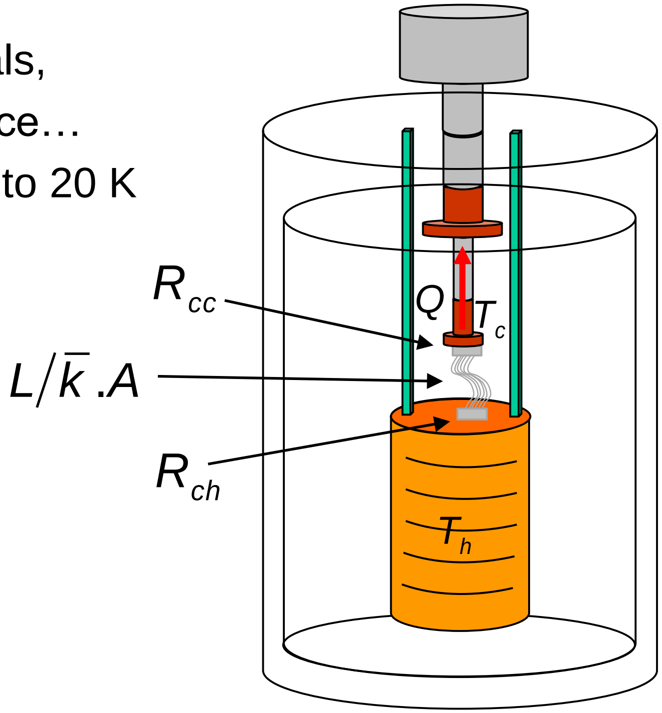
- Whatever the “nature” of the thermal link
  - 2 contact thermal resistances, R_c [K/W]
  - Thermal resistance of the thermal link, $L/\bar{k}.A$

- The thermal resistance of the link itself is easy to designed whether it is conductive or nor

- The contact thermal resistances are not !
  - depend on surface condition, nature of the materials, temperature, interstitial materials, compression force…
  - increase by several orders of magnitude from 200 to 20 K

- In Steady-state $Q = \dfrac{T_h - T_c}{\sum_i R_i} = \dfrac{T_h - T_c}{R_{cc} + \left(L/\bar{k}.A\right) + R_{ch}}$

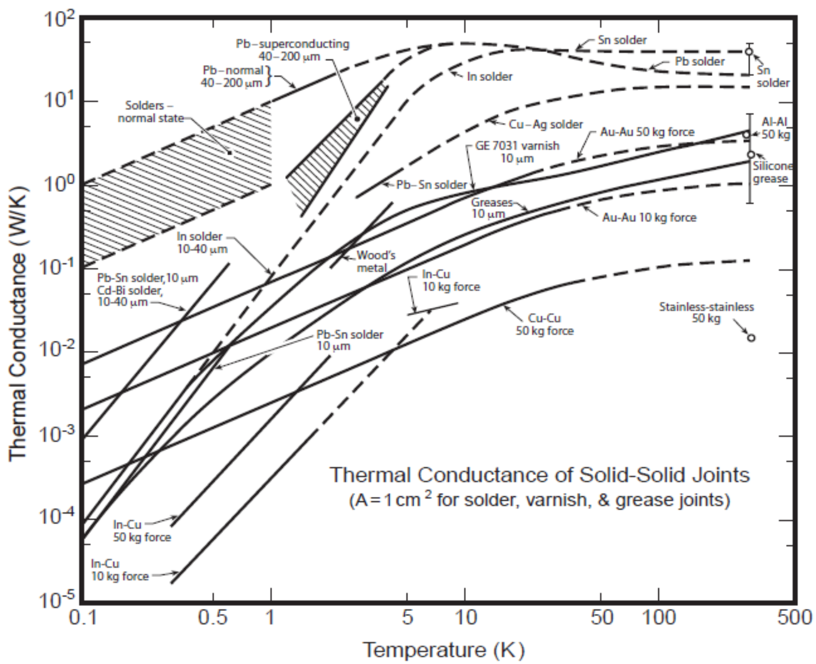
- In transient …

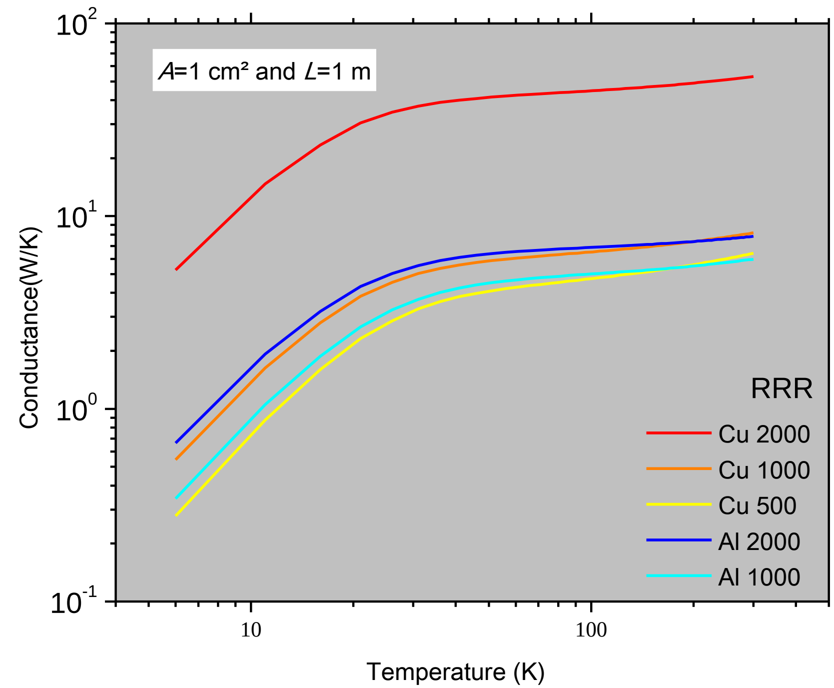


Thermal links for cryocooling | Conductive design

- The thermal contact resistance are most of the time the highest thermal resistance !

$$\frac{Q}{T_h - T_c} = \bar{k}\frac{A}{L}$$





Ekin JW. Experimental Techniques for Low Temperature Measurements. Oxford: Oxford University Press; 2006.

Cryocomp. Eckels Engineering. 3.06. Cryodata Inc. Florence SC, USA 29501

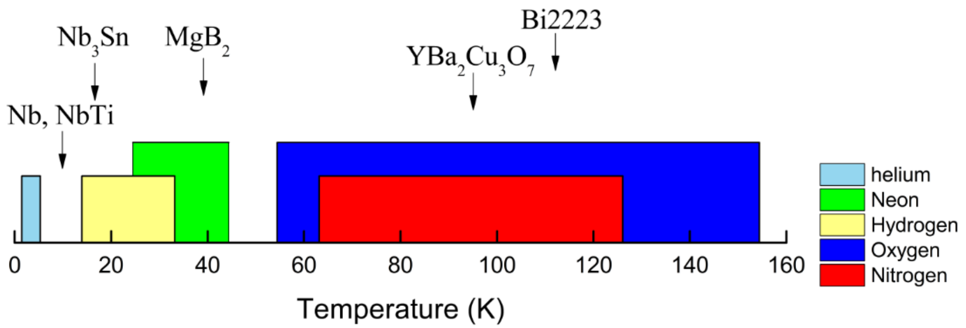
Two phase thermal links for Gantry SC magnets

- Gravity “independent” thermal link with cryogenic fluid
  - Higher heat transfer
  - Higher thermal time constant

- Passive cooling method for medical environment

- Two-phase thermal links

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*	

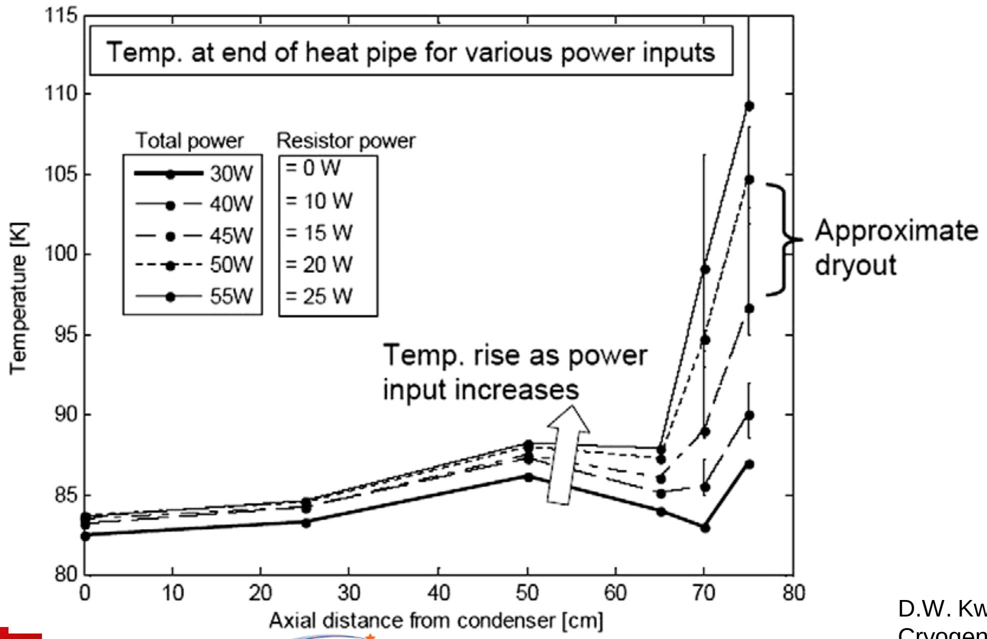


Two phase thermal links for Gantry SC magnets

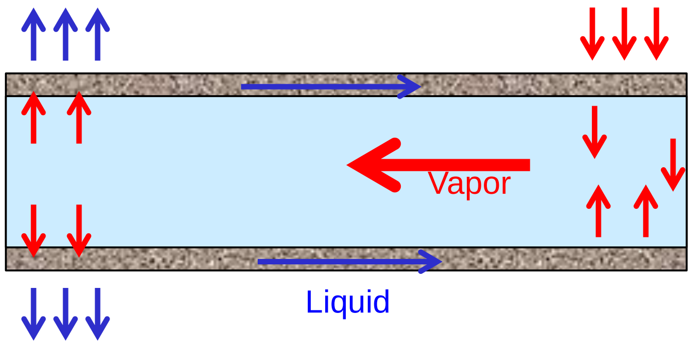
- Several possible heat pipe could serve as thermal for Gantry SC magnet

- Wick-based heat pipe
  - Flow is created by capillary pressure in porous media at the liquid/vapor interface
  - Large ΔT between condenser and evaporator

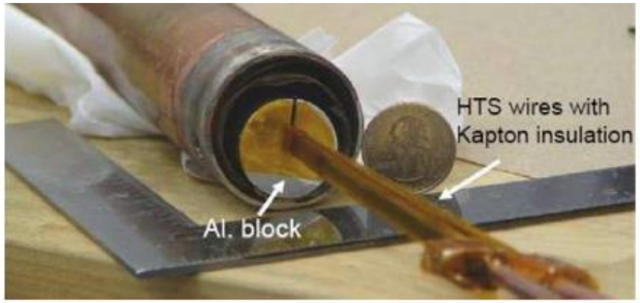
Nitrogen heat pipe
Heat pipe length 85.5 cm
Pipe diameter 4 cm
Wick material stainless steel mesh



(Evaporator)
(System to be cooled) Heating



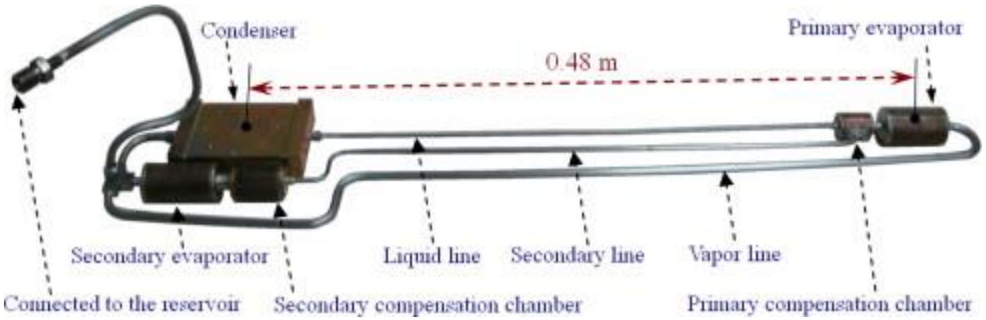
Cooling (cryocooler)
(condenser)

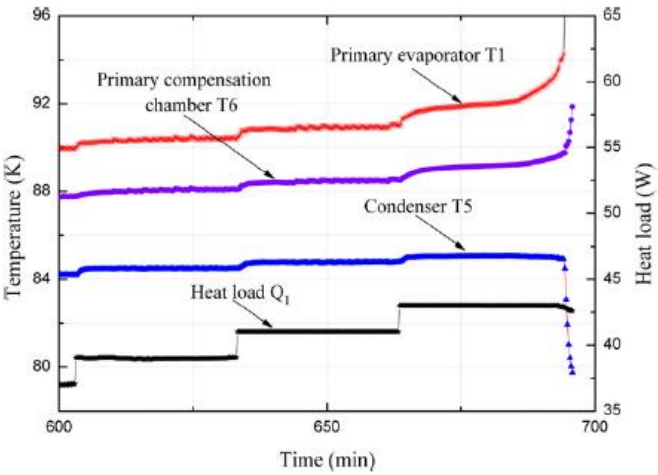


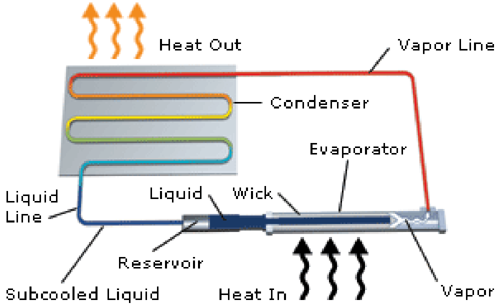
D.W. Kwon et al. Cryogenic heat pipe for cooling high temperature superconductors, Cryogenics, Volume 49, Issue 9, September 2009, Pages 514-523

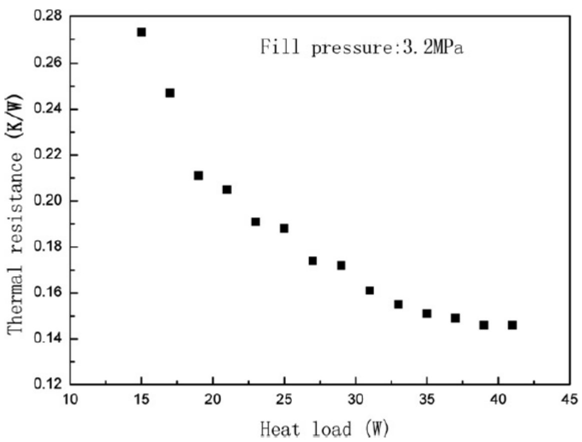
Two phase thermal links for Gantry SC magnets

- **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

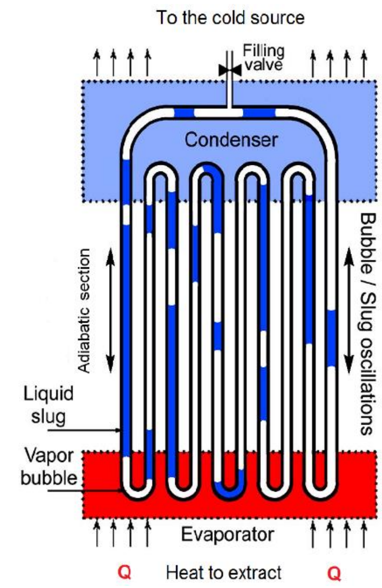
Two phase thermal links | Pulsating Heat Pipe

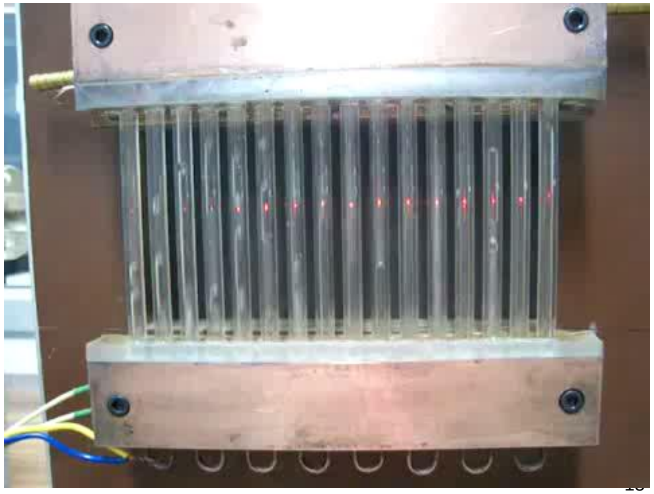
- A PHP consists of a plain meandering capillary tube with many U-turns, partially filled with a working fluid
  - There is no additional structure inside the tube
  - The tube is arranged between an evaporator and a condenser sections with an adiabatic section between

- The closed loop type is the simplest in operation and lightness of the cooling system the tube is joined end-to-end

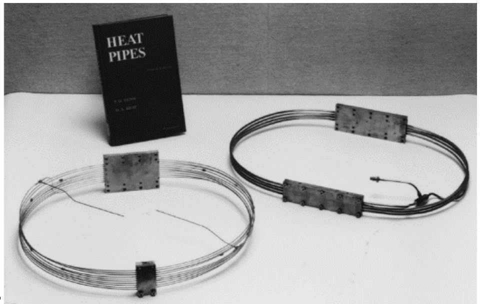
- Oscillations of liquid slugs and vapor bubbles
  - Capillary forces create a separation of liquid slugs and vapor plugs
  - Pressure change due to expansion and contraction at phase transition

- High heat transfer
  - combination of phase change and advection





Two phase thermal links | Cryogenic PHP



- Chandratilleke et al.
  - Rond PHP, Ø 0.5 mm SS tubes, 10 turns
  - Condenser and evaporator section : 100 mm and 30 mm
  - Adiabatic section: 516 mm long

Fluid	Diameter (mm)	Heat input (W)	Cooling part temperature (K)	Heating part temperature (K)	Keff (kW/m.K)
He	0.5	0.2	4.2	4.6	12.9

- Gully et al.
  - Flat PHP, Ø 0.5 mm Cu-Ni tubes, 5 turns for helium
  - Condenser and evaporator section : 45 mm
  - Adiabatic section: 92 mm long

Fluid	Diameter (mm)	Heat input (mW)	Cooling part temperature (K)	Heating part temperature (K)	Keff (kW/m.K)
He	0.5	15-145	4.2	4.6	18.7

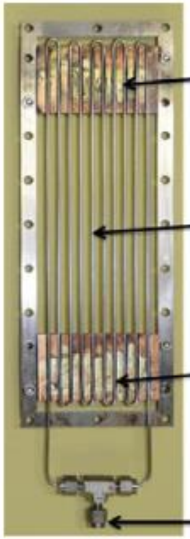
R. Chandratilleke, H. Hatakeyama, and H. Nakagome. Development of cryogenic loop heat pipes. Cryogenics, 38(3):263 { 269, 1998

F. Bonnet, Ph. Gully, and V. Nikolayev. Development and test of a cryogenic pulsating heat pipe and a pre-cooling system. AIP Conference Proceedings, 1434, 2012.

Two phase thermal links | Cryogenic PHP

- Natsume et al.
  - Flat PHP, Ø 0.78 mm SS tubes, 10 turns
  - Condenser and evaporator section : 30 mm long
  - Adiabatic section: 100 mm long

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



- Fonseca et al.
  - Rond Flat PHP, Ø 0.5 mm SS tubes, 32 turns
  - Condenser and evaporator section : 75 and 133 mm long
  - Adiabatic section: 90 mm long

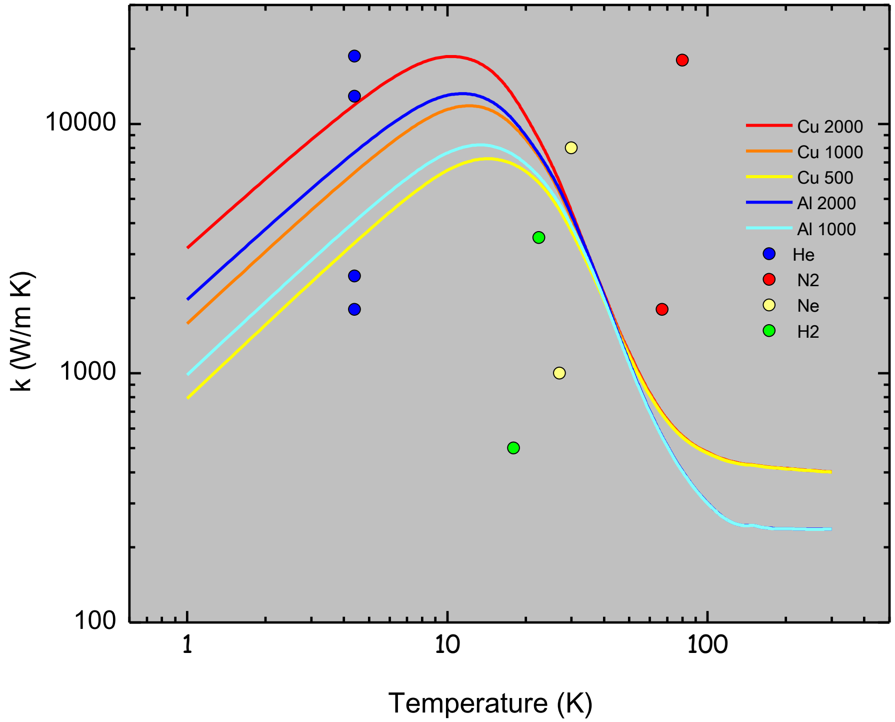
Fluid	Heat input (mW)	Cooling part temperature (K)	Heating part temperature (K)	Keff (kW/m.K)
He	3-86	4.2	?	1.8-2.45

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

Luis Diego Fonseca, Franklin Miller, John Pfotenhauer. A Helium Based Pulsating Heat Pipe for Superconducting Magnets. AIP Conference Proceedings 1573, 2014, 28.

Two phase thermal links | Comparison

- PHP much lighter than any of the solid thermal link
  - Gain of time in the cold-down process
- Equivalent or better performances than solid thermal links
  - Further studies are necessary to improve (or not) the SS performances of PHP
  - Study of the time constant to cool-down
- Simple implementation as the solid thermal link



PHP development at CEA Saclay

- In the frame work of the study of a magnetic shield to protect astronauts during space travelling (FP7-Space SR2S project)
- 77 K thermal shield because PHP are much lighter than any of the solid link
- Study of the numbers of tubing (12, 24, 36) filling ratio, temperature and pressure, length of the adiabatic section…
- Longest PHP ever…