The Physics Beyond Colliders Study Group

4th Technology Workshop

CERN

September 28 2022

Effective passive thermal links for cryocooling

Bertrand Baudouy

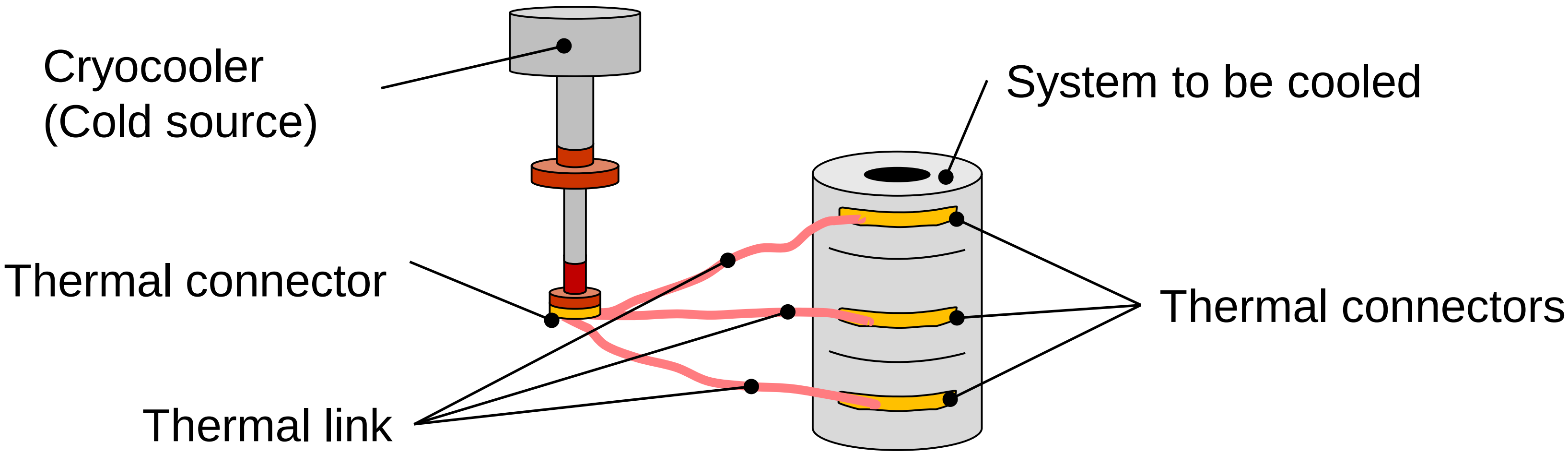
bertrand.baudouy@cea.fr

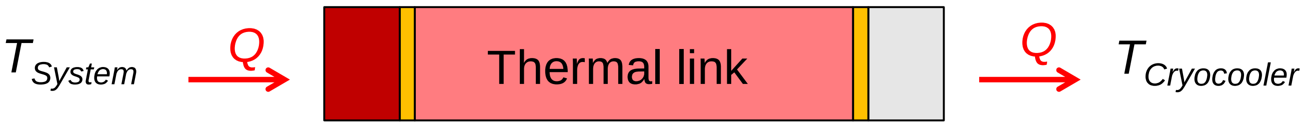
Outline

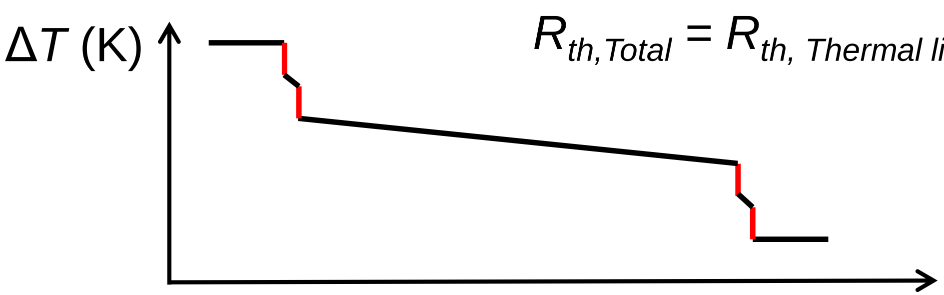
- Cryocooling
- Possible thermal links for cryocooling
- Gravity assisted circulation loop
- The example of the WAVE magnet
- Pulsating heat pipe
- The example of the HTS magnet cooled by a neon PHP project

Cooling with a cryocooler (1/4)

- Indirect cooling method
  - Thermal contact resistances between the different solid component of the thermal link







$$R_{th,Total} = R_{th,\ Thermal\ link} + R_{th,\ Contact}$$

$$R_{th,\ Contact} \approx R_{th,\ Thermal\ link}$$

At low temperature

Cooling with a cryocooler (2/4)

- Limited cooling power

Typical max power for Gifford-McMahon, Pulse tube, Stirling,… cryo-cooler

Temperature (K)	4.2	10	20	77
Power (W)	2	5-10	10-30	500

  - Cryogenic design must be accurate (accurate heat load estimation)
  - If higher heat load than designed, working temperature (and pressure if two-phase thermal link) higher

- A small cooling area
  - Cooling cross-section between 10 cm² to 85 cm²
  - Cooling power distribution needed : thermal links
  - Active and passive thermal links

- Passive thermal links are preferable
  - Automation of the cooling scheme
  - Cryogen-free system
  - Possibility to use cryogen

Gifford-MacMahon type Cryocooler

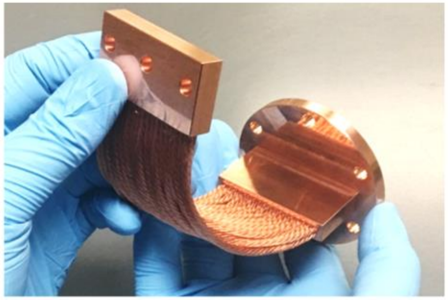
Pulsed Tube type Cryocooler

Cooling with a cryocooler (3/4)

- Cooling without a cryogen (Cryogen-free cooling)

- Solid thermal links
  - Conduction between cold source and the system
  - Thermal contact and heavy (Cu, Al,…)
  - Small heat load especially at low temperature
  - Slow (diffusion) and low thermal perturbations
  - Easy implementation

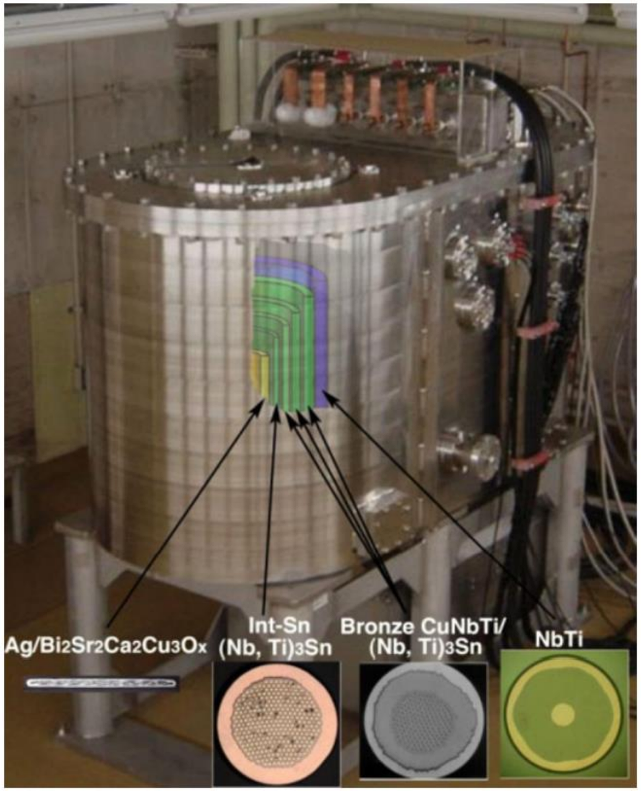
https://thermal-space.com



https://www.techapps.com

- Examples
  - Detector for space
  - Superconducting magnet with cold bore
  - Instrumentation for medical imaging
  - Physics instruments
  - HTc current leads

18T cryogen-free superconducting magnet



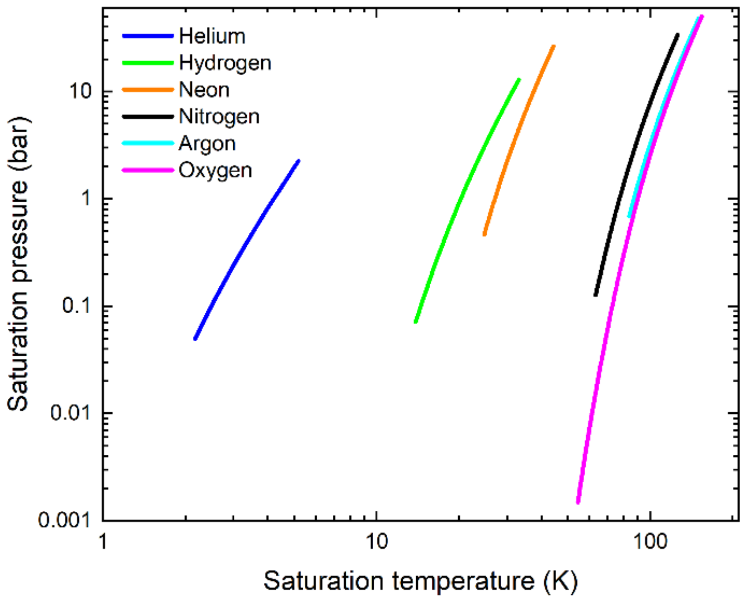
K. Watanabe, J Supercond Nov Magn (2011) 24: 993–997,
https://doi.org/10.1007/s10948-010-0871-0

Cooling with a cryocooler (4/4)

- Cooling with a cryogen

- Thermal links with gas, liquid or two-phase mixture with or without a forced circulation
  - Heat transfer by phase change (closed to saturation)
  - Heat transfer by advection (pump..)
  - Lighter and higher heat transfer rates (phase change + advection…) than for the solid thermal links
  - Limited temperature and pressure ranges for two-phase thermal links (at saturation)

- Examples
  - Small superconducting magnet
  - Liquid targets for nuclear physics

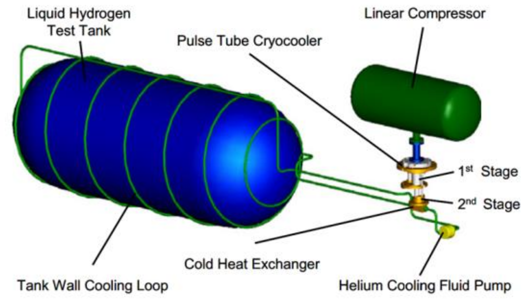


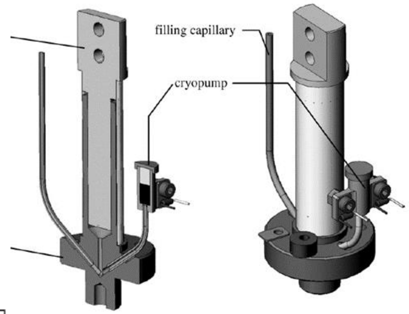
Superconducting magnet cooled by a helium gravity assisted circulation loop

C. Berriaud et al., IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1-4, June 2016, Art no. 4102804, doi: 10.1109/TASC.2016.2517338
T. Robillard et al. Journal of Neutron Research 22 (2020) 379–391 379, https://content.iospress.com/articles/journal-of-neutron-research/jnr200167

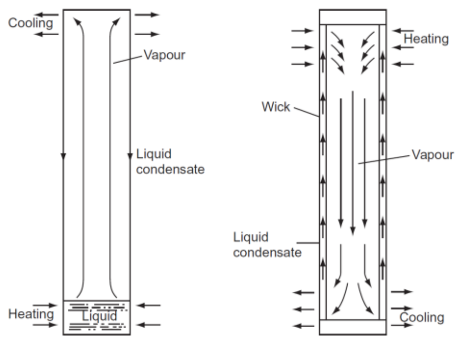
Two-phase thermal links

- **Active thermal links**
  - Forced flow circulation loop
  - Heat switch (mechanical, gas, magnetic,…)

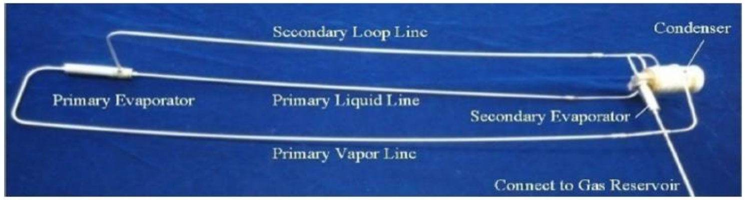


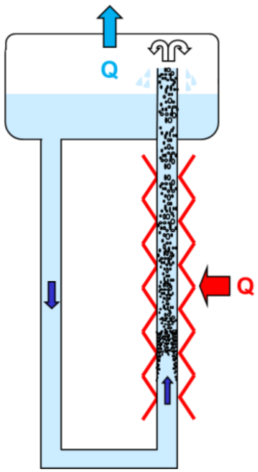


- **Passive thermal links**
  - Thermosiphon
  - Heat pipe
  - Loop heat pipe
  - Gravity assisted circulation loop
  - Pulsating heat pipe



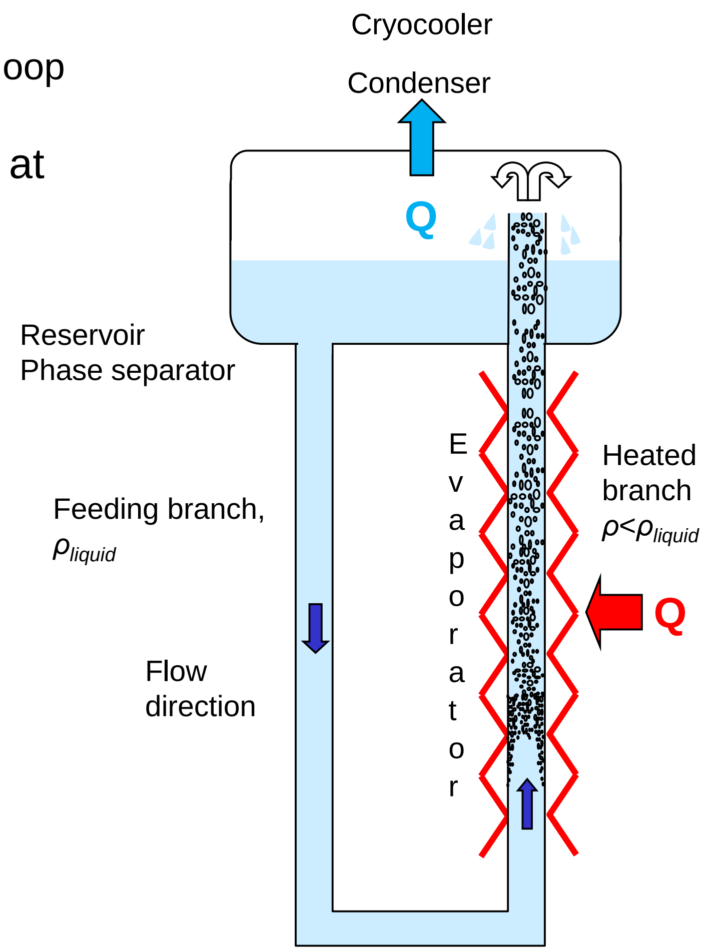
(a) Thermosyphon (b) Heat pipe





Two-phase thermal links | Gravity loop (1/4)

- Gravity assisted circulation loop
  - Heat exchange due to advection and boiling
    - Evaporator : one of the branch of the loop
    - Condenser : cryocooler + heat exchanger
    - Evaporator and condenser inserted in a vertically oriented loop
  - Flow created due to phase change or density decrease at evaporator
    - Lighter evaporator branch ($\rho < \rho_{liquid}$) than feeding branch
    - Circulation due to loop configuration
    - Co-current flow of liquid and vapor in the evaporator

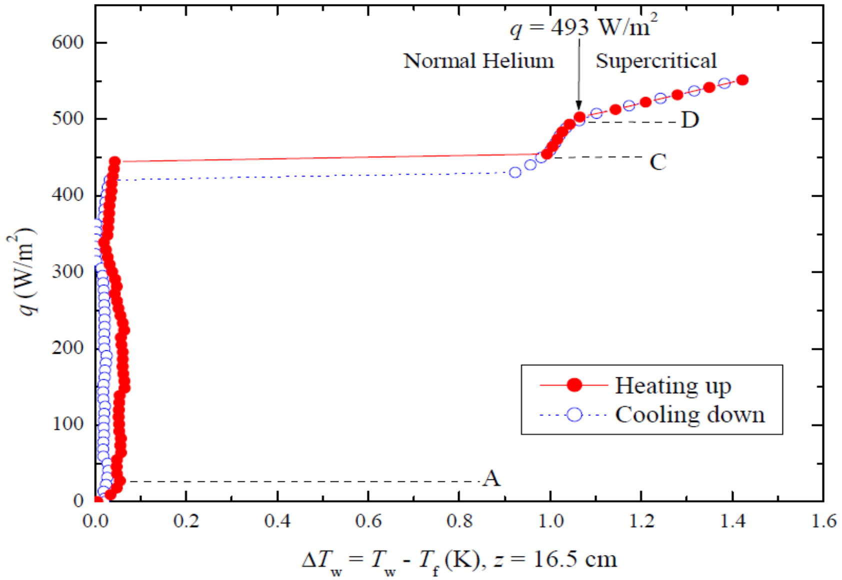


- Advantages
  - Easy construction and implementation
  - No pumping system
  - Self-adjusting flow rate
- Disadvantages
  - Gravity dependent
  - Lower heat transfer than pool boiling

Two-phase thermal links | Gravity loop (2/4)

- 0.5 m autonomous loop in helium
  - Two-stage GM Cryocooler: 1.5 W at 4.2 K
  - 1st stage
    - Radiation shield
    - Precooling of the gas with a heat exchanger
  - 2nd stage
    - Copper finned tube exchanger in the reservoir

- Test in helium around saturation for a Ø4 mm tube
  - h~5000 W/m^{2}K et q_c≈500 W/m^2



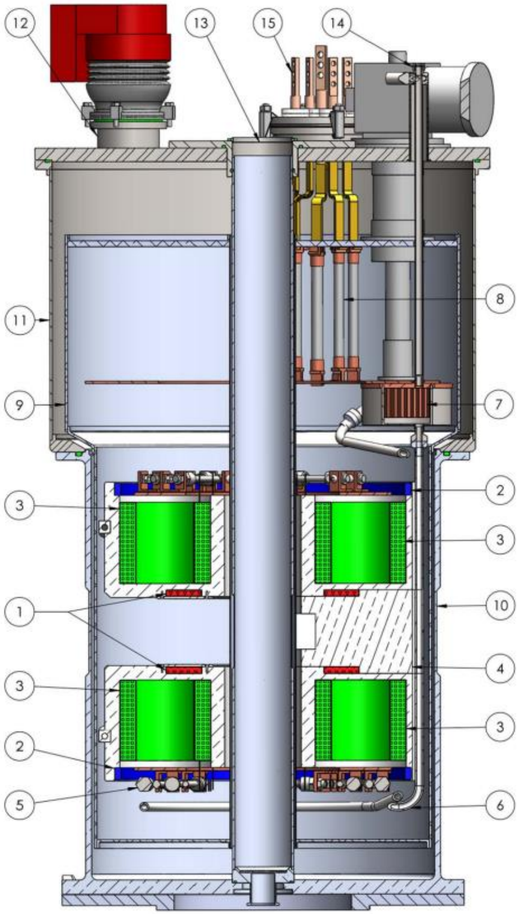
Y. Song et al., International Journal of Heat and Mass Transfer, Volume 66, November 2013, Pages 64-71,
https://doi.org/10.1016/j.ijheatmasstransfer.2013.07.002

Two-phase thermal links | Gravity loop (3/4)

- Example of the superconducting magnet WAVE (Wide Aperture Vector Magnet)
  - – 1 T superconducting vector magnet for neutron scattering experiment

- Cold sources
  - – Single-stage 100 W at 50 K cryocooler
    - Pre-cooling and Radiation shield
  - – Two-stage 35 W @ 50 K and 1.5 W @ 4.2 K cryocooler
    - Radiation shield and circulation loop

- Gravity circulation loop in helium at 4.5 K
  - – Copper tank (phase separator) of 1.5 liters with heat exchanger on the 2nd stage of the cryocooler
  - – Aluminum magnet cold mass (cryo-stability)
  - – Heat exchanger by aluminum tubes (Ø10 mm) with square section (16x16 mm²) glued on the cold mass in spiral
  - – Helium tank of 200 liters and 6 bar max
    - Initial charge of helium gas for condensation
    - Helium recovery in case of quench



C. Berriaud et al., IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1-4, June 2016, Art no. 4102804, doi: 10.1109/TASC.2016.2517338
T. Robillard et al. Journal of Neutron Research 22 (2020) 379–391 379, https://content.iospress.com/articles/journal-of-neutron-research/jnr200167

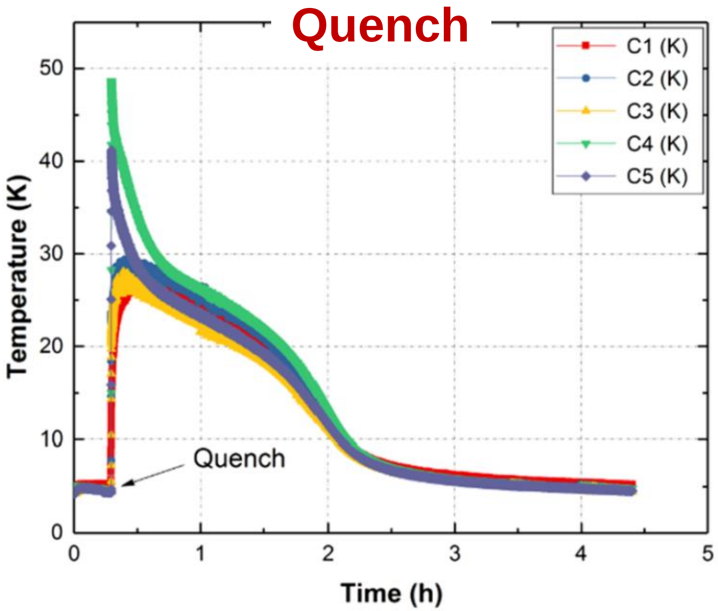
Two-phase thermal links | Gravity loop (4/4)

- Superconducting magnet WAVE (Wide Aperture Vector Magnet)

- Total heat input of 0.240 W on the superconducting magnet
  - Conduction in the supports
  - Current leads (conduction and resistive heat loads)
  - Radiation

- Magnet cooling in 8 days in total autonomy (cryocooled only!)
  - Helium tank loaded with helium gas

- Quench of the magnetic system
  - Temperature increase
  - Vaporization of liquid helium
  - Gas recovery in the helium tank
  - 4 hours to re-condense the vapors and recover the operating temperature



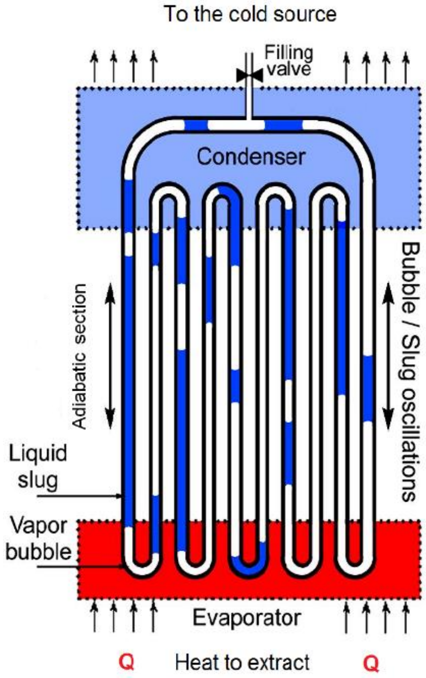
C. Berriaud et al., IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, pp. 1-4, June 2016, Art no. 4102804, doi: 10.1109/TASC.2016.2517338
T. Robillard et al. Journal of Neutron Research 22 (2020) 379–391 379, https://content.iospress.com/articles/journal-of-neutron-research/jnr200167

Two-phase thermal links | Pulsating Heat Pipe (1/5)

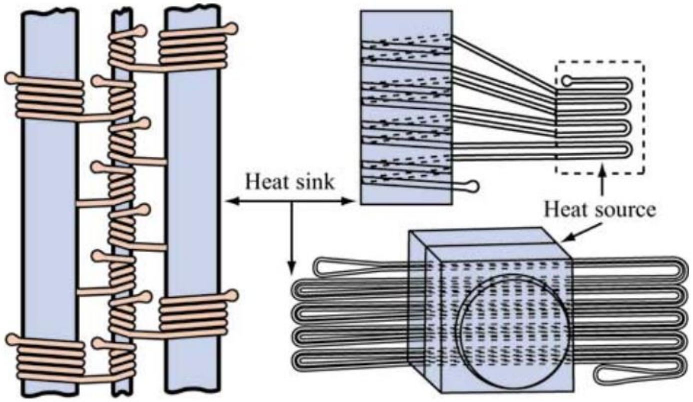
- Heat pipe with a capillary oscillating flow

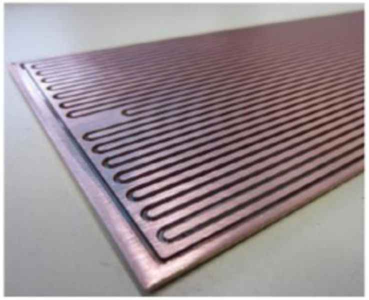
- Passive heat pipe constructed with a single capillary tube
  - No extra structure on the wall of the tube
  - Tube winding in turns between an evaporator and a condenser separated by an adiabatic section

- Tube partially filled with a two-phase mixture close to saturation
  - Random distribution of vapor bubbles and liquid plugs
  - Oscillation of vapor bubbles and liquid plugs between the evaporator and condenser



- Advantages
  - Easy construction
  - Geometry independant
  - Gravity independent





- Disadvantages
  - Start-up scenario (long PHP)
  - No full understanding / rules for design

Two-phase thermal links | Pulsating Heat Pipe (2/5)

- Vapor bubbles and liquid plugs oscillations
  - Capillary force creates liquid and vapor structures
  - Δ*p* due to expansion and contraction of phase transitions
    - Vaporization at evaporator creates overpressure
    - Movement of vapor bubbles lubricated by a wall liquid film
    - Vapor liquefaction at the condenser

- Liquid/vapor fraction important (Filling Ratio = V_{liquid}/V_{total})

- Maximal diameter to create the "slug" flow

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

Surface tension

Gravity force

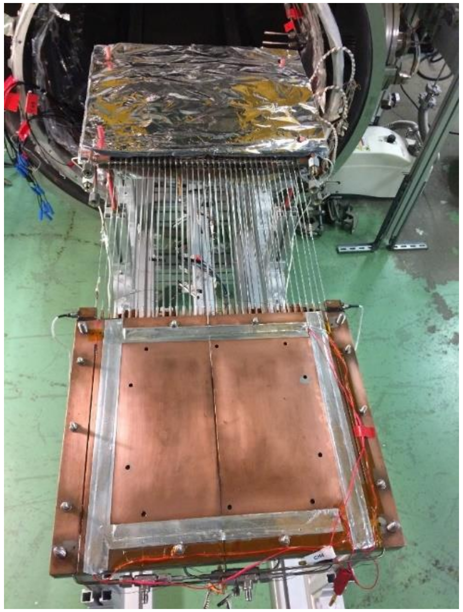
- High heat transfer
  - Phase change and advection heat transfer combination
  - Advection: Sensible heat essentially carried by the liquid
  - Phase change: latent heat due to phase changes within the mixture and with the solid (at evaporator and condenser)

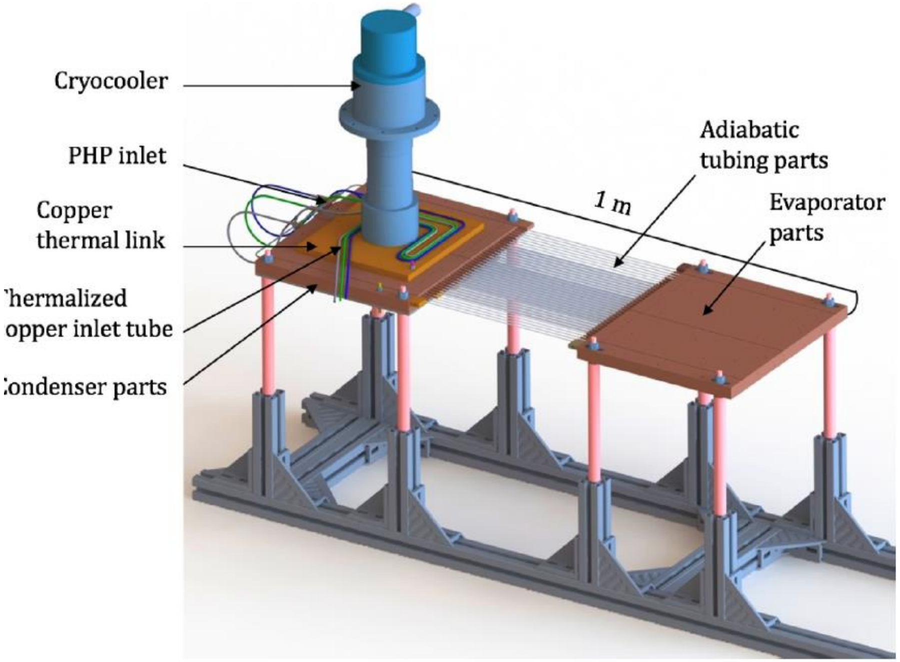
K Sameer et al. Applied Thermal Engineering Volume 23, Issue 16, November 2003, Pages 2021-2033"https://doi.org/10.1016/S1359-4311(03)00168-6 (2003)

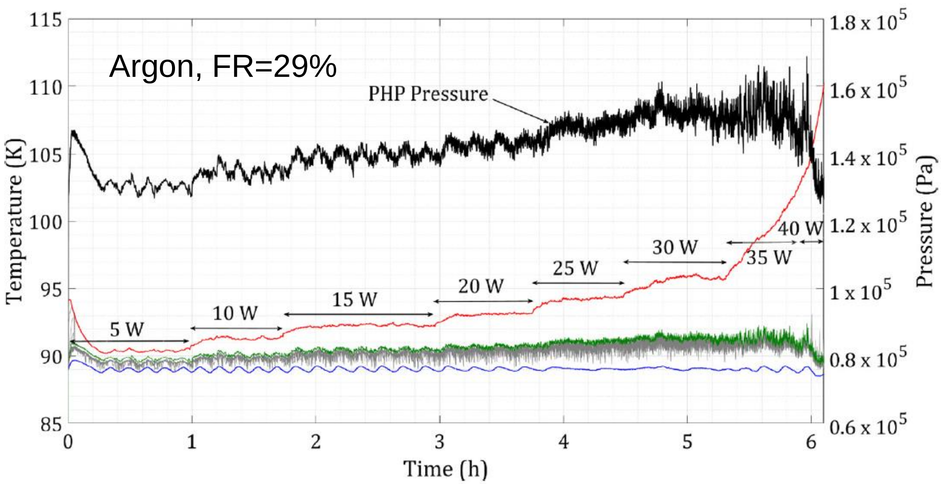
Two-phase thermal links | Pulsating Heat Pipe (3/5)

- 1 m long horizontal PHP
  - SS tube with Ø1.5 mm and 36 turns
  - Condenser and evaporator: 330 mm long
  - Adiabatic section : 300 mm long

- Fluids : Nitrogen (77 K), neon(27 K) and argon (87 K)



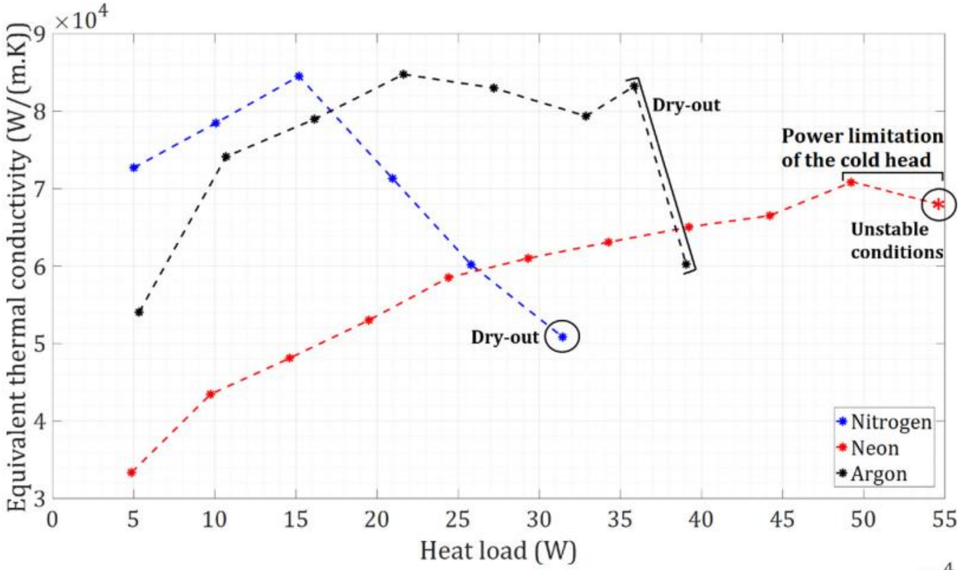




Maria Barba et al. International Journal of Heat and Mass Transfer, Volume 187, 2022, 122458, https://doi.org/10.1016/j.ijheatmasstransfer.2021.122458
Maria Barba et al. Applied Thermal Engineering, Volume 194, 2021, 117072, https://doi.org/10.1016/j.applthermaleng.2021.117072.

Two-phase thermal links | Pulsating Heat Pipe (4/5)

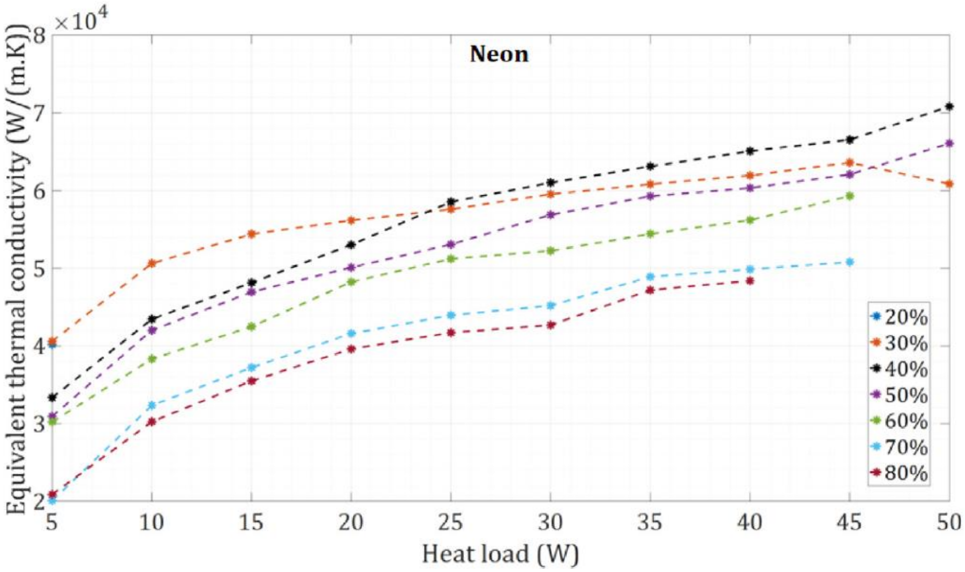
- 1 m long horizontal PHP with Ø1.5 mm and 36 turns



Fluids difference

$$k_{eff} = \frac{QL}{A\Delta T}$$

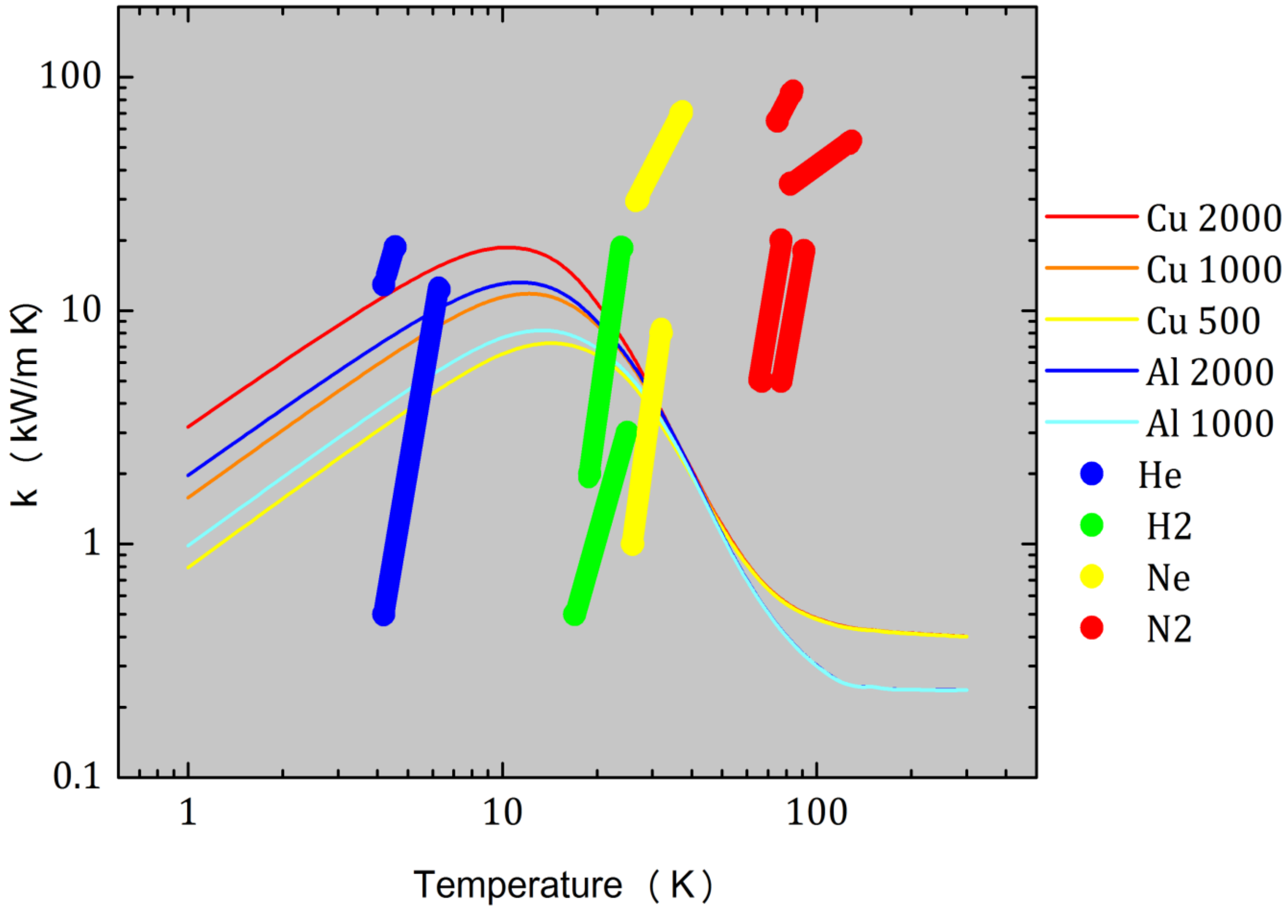
FR effect



Maria Barba et al. International Journal of Heat and Mass Transfer, Volume 187, 2022, 122458, https://doi.org/10.1016/j.ijheatmasstransfer.2021.122458
Maria Barba, Applied Thermal Engineering, Volume 194, 2021, 117072, https://doi.org/10.1016/j.applthermaleng.2021.117072.

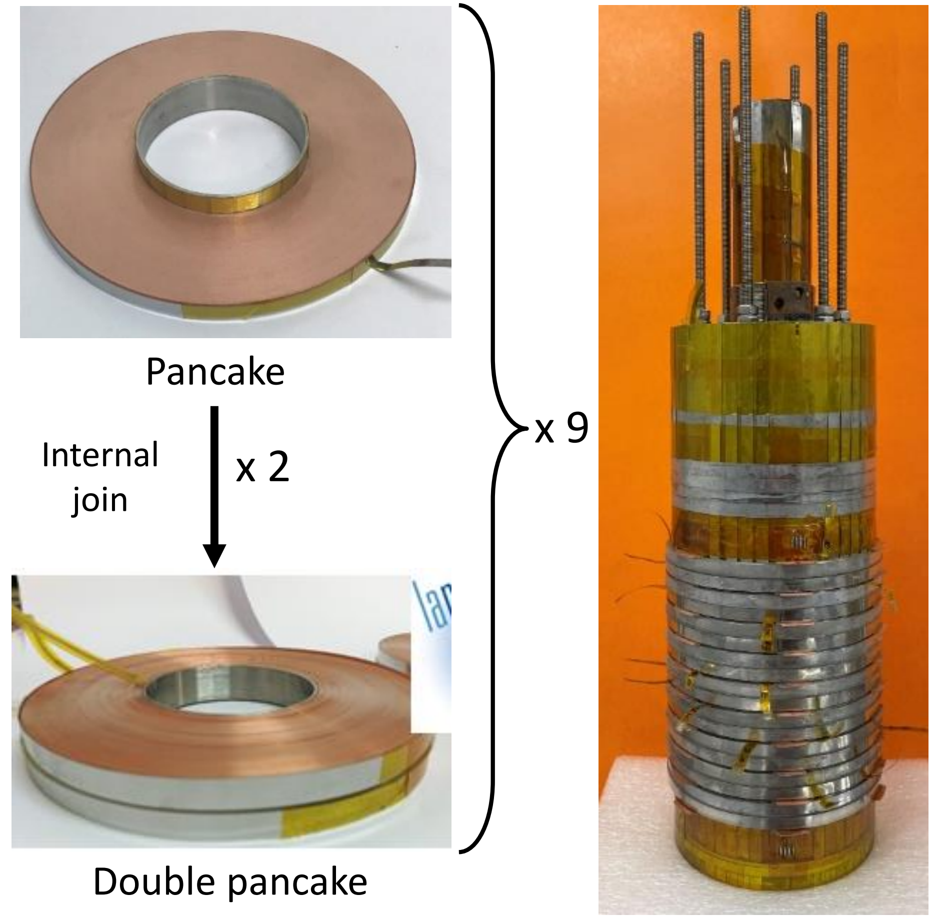
Two-phase thermal links | Pulsating Heat Pipe (5/5)

$$k_{eff} = \frac{QL}{A\Delta T}$$



Two-phase thermal links | Neon PHP for magnet (1/5)

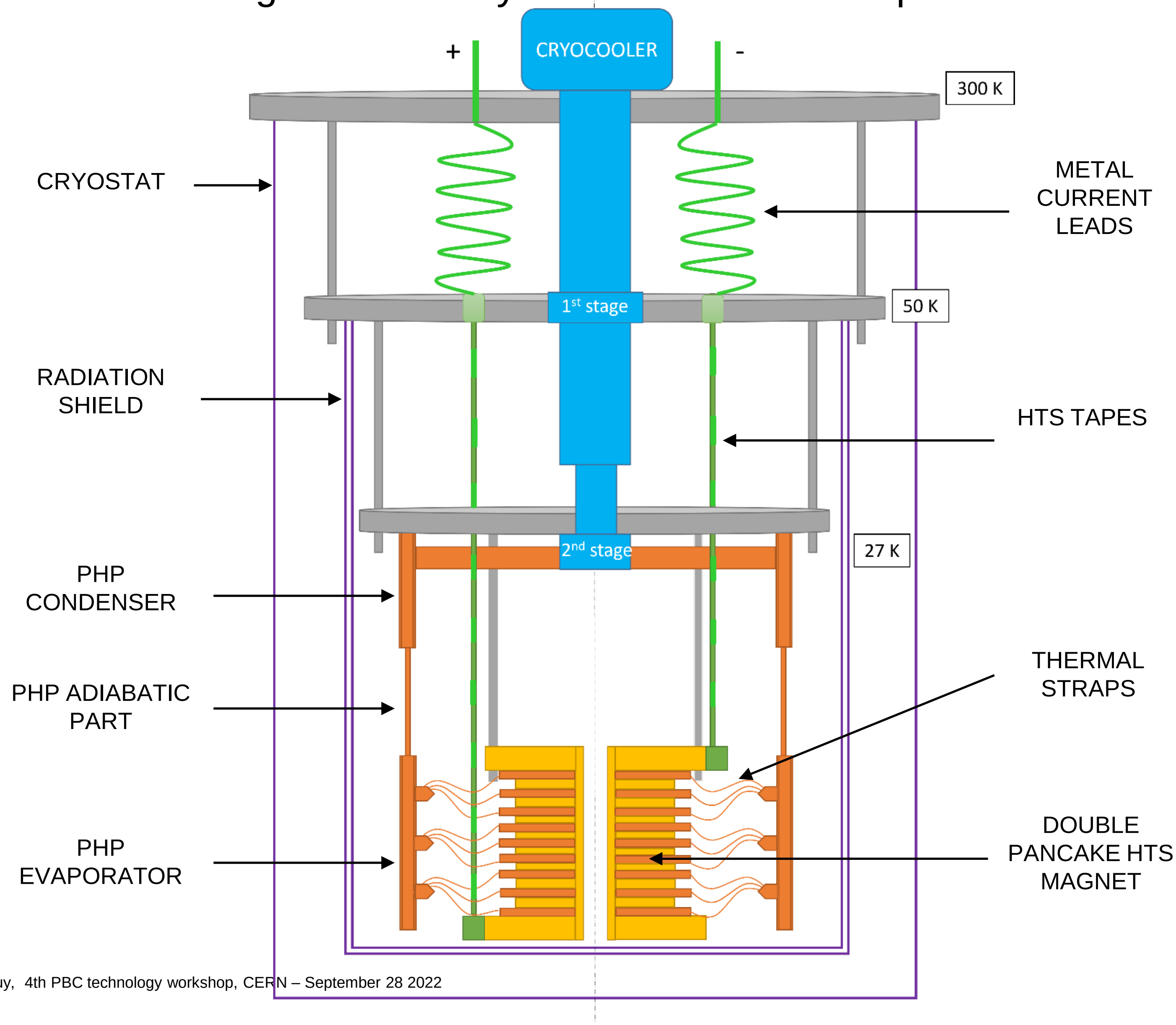
- 10 T class HTS magnet cooled by an PHP at Neon temperature
- MI for Metal-as-Insulation technique
  - A resistive metallic tape is co-wound with RebCo tape
- Magnet like the NOUGAT magnet project (2015-2018, CNRS-CEA ANR)
- MI-HTS magnet at intermediate temperature (27 K)
- Cryogenic scheme based on a PHP link
- Working conditions
- Long-duration stability of cryogenic PHP



Fazilleau, P., Chaud, X., Debray, F., Lécrevisse, T., & Song, J. B. (2020). 38 mm diameter cold bore metal-as-insulation HTS insert reached 32.5 T in a background magnetic field generated by resistive magnet. Cryogenics, 106, 103053.

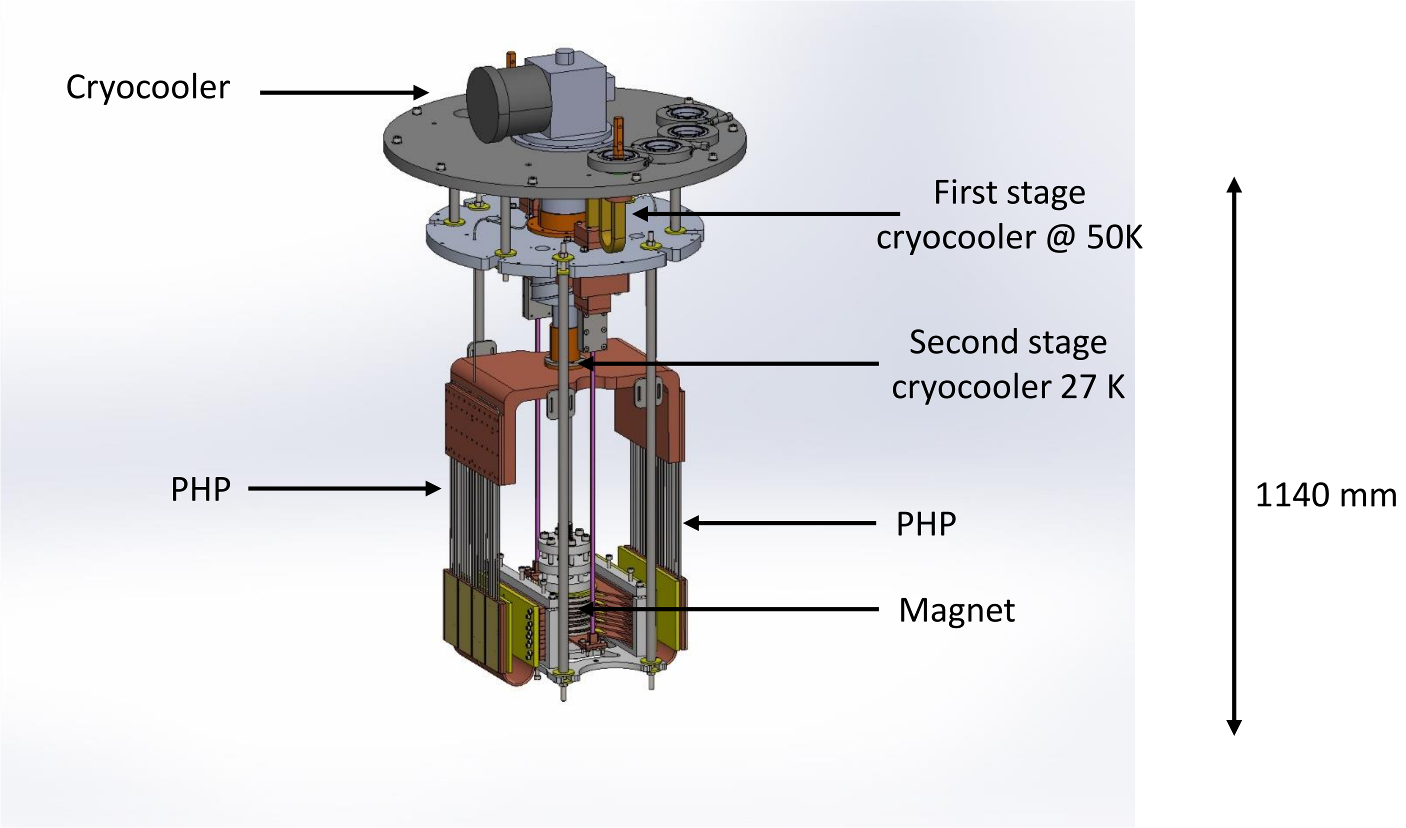
Two-phase thermal links | Neon PHP for magnet (2/5)

- 10 T class HTS magnet cooled by an PHP at Neon temperature



Two-phase thermal links | Neon PHP for magnet (3/5)

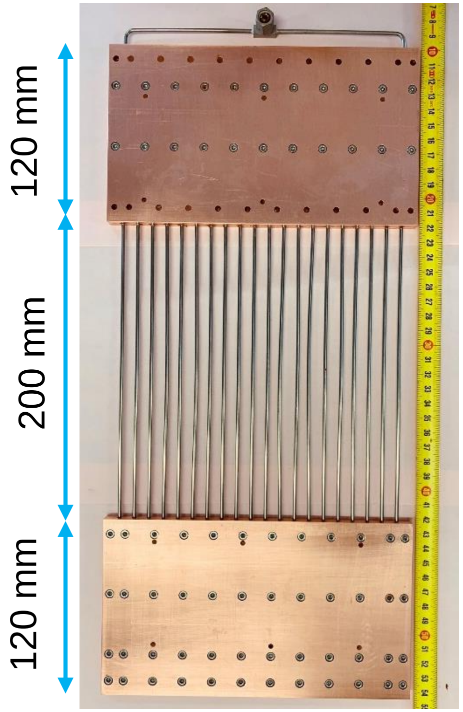
- 10 T class HTS magnet cooled by an PHP at Neon temperature



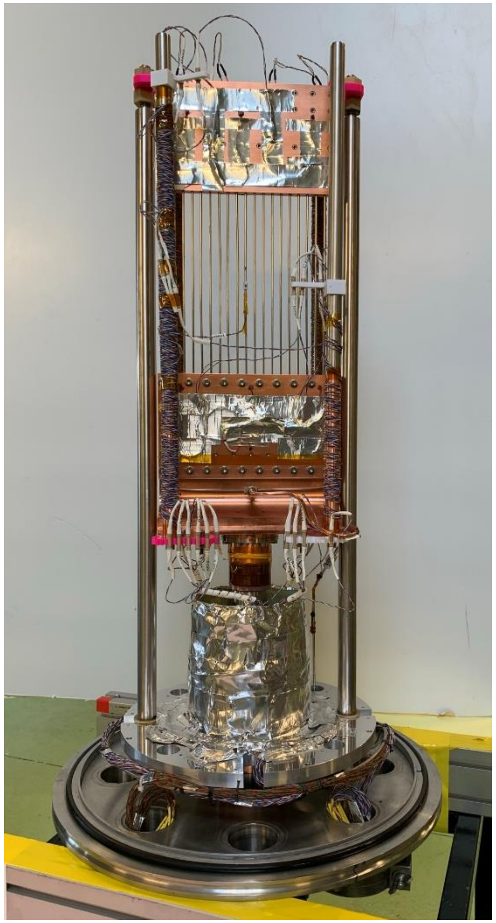
Two-phase thermal links | Neon PHP for magnet (4/5)

- 10 T class HTS magnet cooled by an PHP at Neon temperature

No brazing at
condenser/evaporator



Chosen PHP parameters
Material = SS316L
Inner diameter = 1.0 mm
Outer diameter = 2.5 mm
Number of tubes = 20
Length = 440 mm

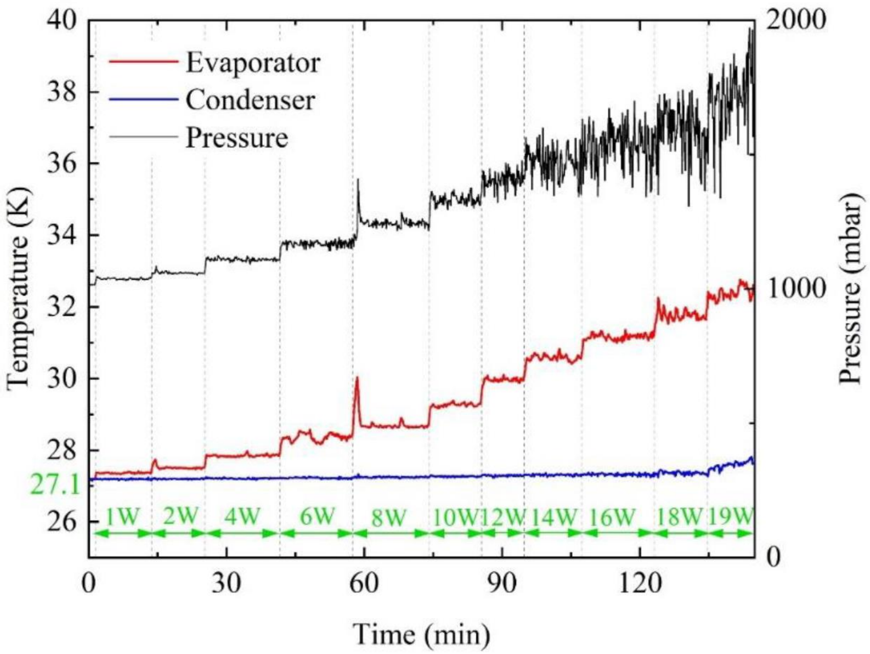


Two-phase thermal links | Neon PHP for magnet (5/5)

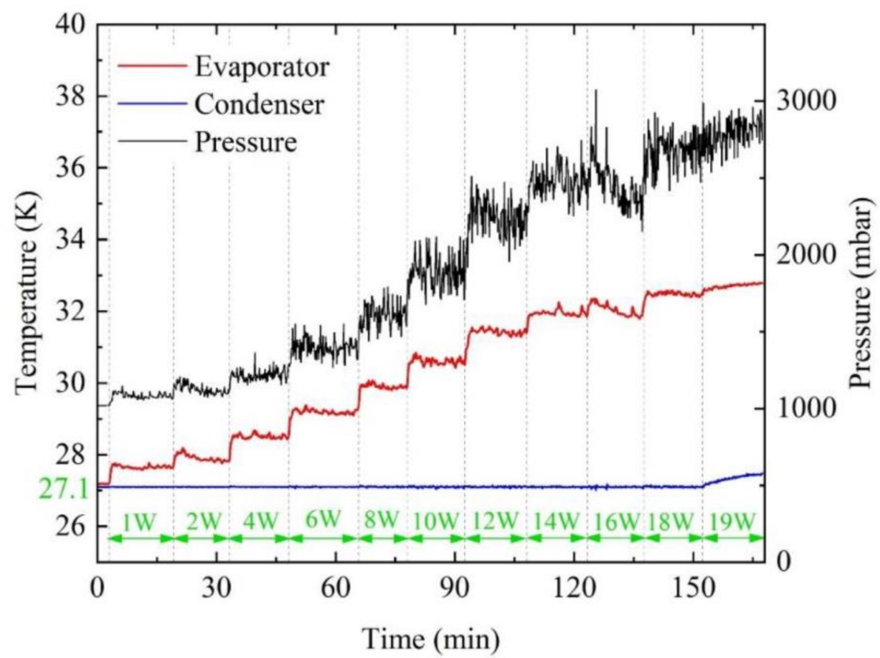
- 10 T class HTS magnet cooled by an PHP at Neon temperature

Vertical tests

FR=20.9%



FR=73.5%



- Maximum capability is reached at 18 W
  - ΔT = 4.4 K for FR = 73.5 %
  - Δ T = 5.4 K for FR = 20.9 %

T Dixit et al 2022 IOP Conf. Ser.: Mater. Sci. Eng. 1240 012076, https://doi.org/10.1088/1757-899X/1240/1/012076