TESLA TECHNOLOGY COLLABORATION 2020

WG4: New Fabrication Methods and Alternative Cooling Techniques

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An effective thermal link for cooling cryo-magnetic systems : The Pulsating Heat Pipe (PHP)

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Outline

- Cryo-cooling and passive thermal links
- Pulsating heat pipes
- Cryogenic Pulsating heat pipes
- Thanks to people involve or involved at CEA Paris-Saclay
  - Maria Barba (maria.asuncion.barba.higueras@cern.ch)
  - Antoine Bonelli
  - Romain Bruce
  - Aurélien Four
  - Clément Hilaire

Cryo-cooling and Thermal links (1/2)

- Cooling with cryocoolers
  - Importance of the thermal link between the cold source and the system
  - Indirect cooling (ΣΔT due to thermal contact resistance, …)

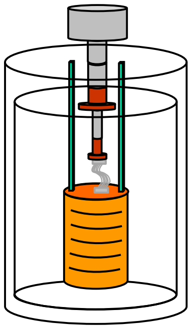
- Advantages
  - **Easy implementation** (no liquefaction unit, no heat exchanger, no transfer line, …)
  - **Easy working conditions** (cryogenist-free system)

- Disadvantages
  - **Limited cooling power** - thermal design must be accurate
    if the heat load to be extracted exceeds the cryocooler power capacity then T↗
  - GM Cryocooler characteristics
    - 4 K two-stage cryocooler - 2nd stage 1.8 W at 4.2 K and 1st stage 45 W at 50 K
    - 20 K two-stage cryocooler - 2nd stage 9,5 W at 20 K and 1st stage 75 W at 60 K
    - 77 K single stage cryocooler; several 100 W!
  - **A point-source of cold** (35 cm^2 to 85 cm^2)
    - A distribution of cooling power must be implemented
  - **Maintenance** (20000 hours)

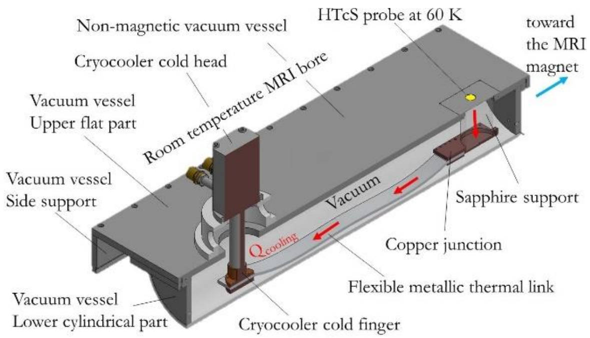
RDE-418D4 4K from SHI cryo

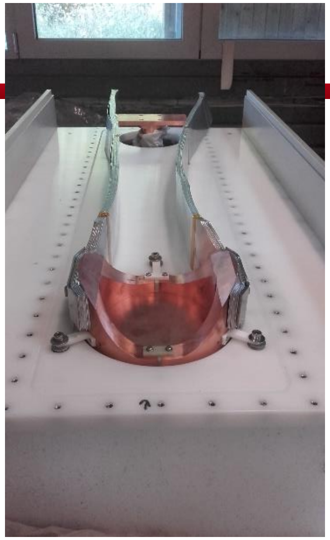
Cryo-cooling and Thermal links (2/2)

- Conductive thermal links



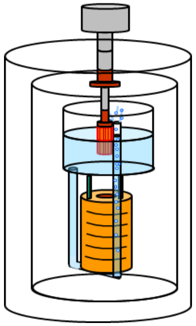
- HTS coil @ 60 K for MRI
- Thermal contact with silver paint and indium
- 7 kg 5N aluminum bars



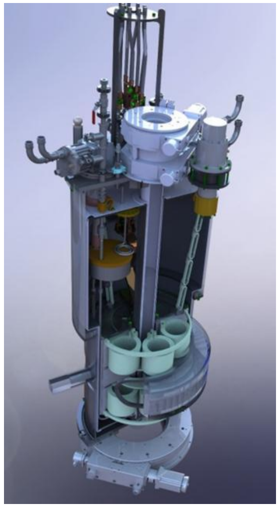


G. Authelet et al., All polymer cryogen free cryostat for mu-MRI application at clinical field, IOP Conference Series-Materials Science and Engineering, Volume: 502, Article Number: 012156, DOI: 10.1088/1757-899X/502/1/012156

- Gravity assisted two-phase fluid thermal link



- Circulation loop coupled to a cryocooler
- Vapor re-condensed in an upper reservoir
- High heat transfer in boiling convection or single phase flow
- "Faster" heat transfer than conductive link
- Autonomous cooling method for cryo-systems

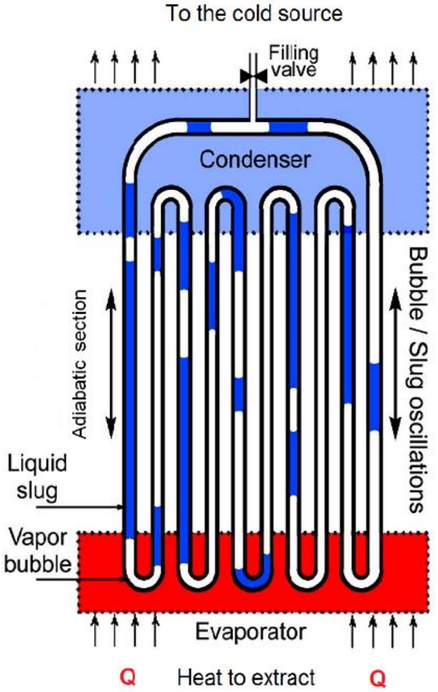


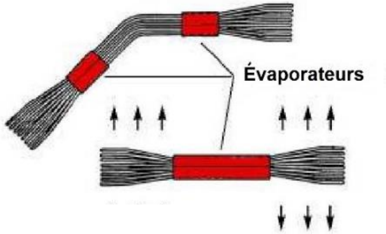
Y. Song et al. Nucleate boiling heat transfer in a helium natural circulation loop coupled with a cryocooler, Int. Journal. Heat Mass Trans. 66 Pages: 64-71 DOI: 10.1016/j.ijheatmasstransfer.2013.07.002

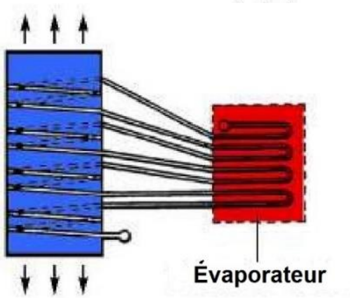
4.2 K loop for the Wave vectorial magnet at CEA Paris-Saclay

Pulsating heat pipes (1/2)

- PHP = **Pulsating Heat Pipe** or Oscillating Heat Pipe
  - Oscillating two-phase heat pipe
- Passive heat exchanger made of a plain capillary tube
  - No additional structure inside the tube
- Tube is arranged in several U-turn loops between a evaporator and a condenser separated by an adiabatic section
  - Simple and versatile design
- Tube partially filled with the working fluid in a two-phase state close to the saturation conditions
- Tube diameter designed → Dominant capillary forces
  - Gravity independent
- Random distribution of liquid and vapor structures







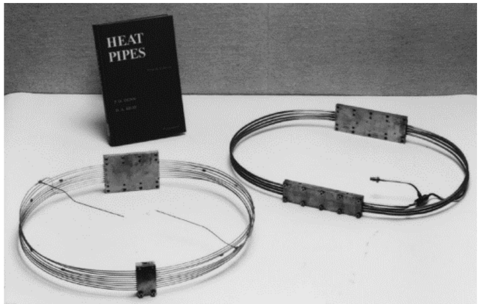
Pulsating heat pipes (2/2)

- 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
    - Vaporization in the evaporator creates overpressure
    - Movement of the vapor plugs surrounded by a liquid film
    - Liquefaction of the vapor in the condenser
- Combination of phase change and advection heat transfer
  - Advection: sensible heat carried mainly by the liquid
  - Phase change: latent heat due to all phase changes between the two phases and with the condenser or evaporator
- Used in numerous domains at different temperatures
  - Electronics
  - Space
  - …

Khandekar, Sameer et al. “Closed loop pulsating heat pipes Part B: visualization and semi-empirical modeling.” (2003).

Cryogenic pulsating heat pipes (1/4)

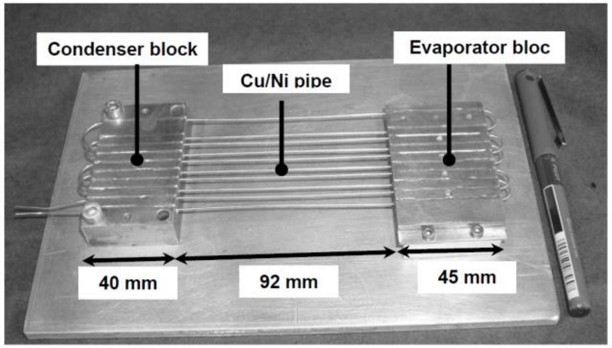
- Chandratilleke *et al.*
  - Round PHP, Ø 0.5 mm SS tubes, 10 turns
  - Condenser and evaporator section : 100 mm and 30 mm
  - Adiabatic section: 516 mm long



Fluid	Diameter (mm)	Heat input (W)	Condenser temperature (K)	Evaporator temperature (K)	Keff (kW/m.K)
He	0.5	0.2	4.2	4.6	**12.9**

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

- Bonnet *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

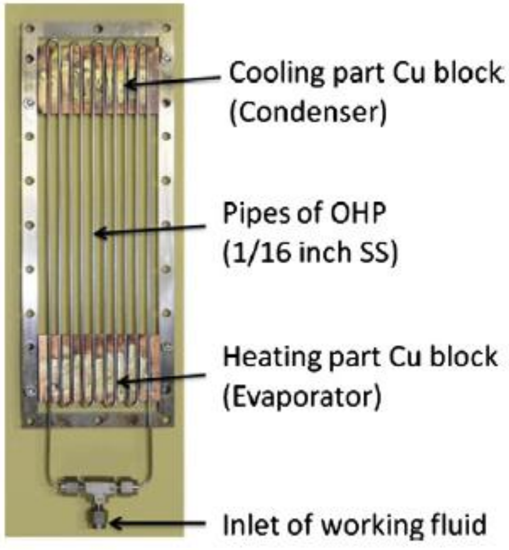


Fluid	Diameter (mm)	Heat input (mW)	Condenser temperature (K)	Evaporator temperature (K)	Keff (kW/m.K)
He	0.5	15-145	4.2	4.6	**18.7**

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.

Cryogenic pulsating heat pipes (2/4)

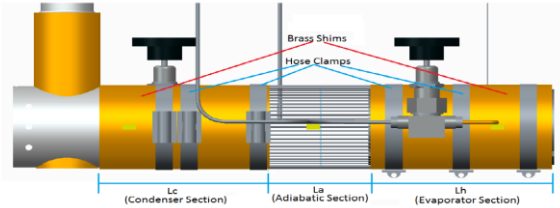
- Natsume *et al.*
  - Flat PHP, Ø 0.78 mm SS tubes, 10 turns
  - Condenser and evaporator section : 30 mm long
  - Adiabatic section: 100 mm long



Fluid	Heat input (W)	Condenser temperature (K)	Evaporator 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**

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

- Fonseca *et al.*
  - Round 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)	Condenser temperature (K)	Evaporator temperature (K)	Keff (kW/m.K)
He	3-86	4.2	?	**1.8-2.45**

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

Cryogenic pulsating heat pipes (3/4)

- Xu D. *et al.*
  - Flat PHP, Ø 0.5 mm SS tubes, 8 turns
  - Condenser and evaporator section : 50 mm long
  - Adiabatic section: 100 mm long

Fluid	Heat input (mW)	Condenser temperature (K)	Evaporator temperature (K)	Keff (kW/m.K)
He	72	4.2	4.7	**9.5**

Xu, D at al. Experimental investigation on the thermal performance of helium based cryogenic pulsating heat pipe, Experimental Thermal And Fluid Science, Volume: 70, Pages: 61-68, 2016, DOI: 10.1016/j.expthermflusci.2015.08.024

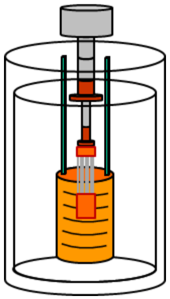
- Li M. *et al.*
  - 3 PHP, Ø 0.5 mm SS tubes, 48 turns
  - Condenser and evaporator section : 50 mm long
  - Adiabatic section: 100 mm long

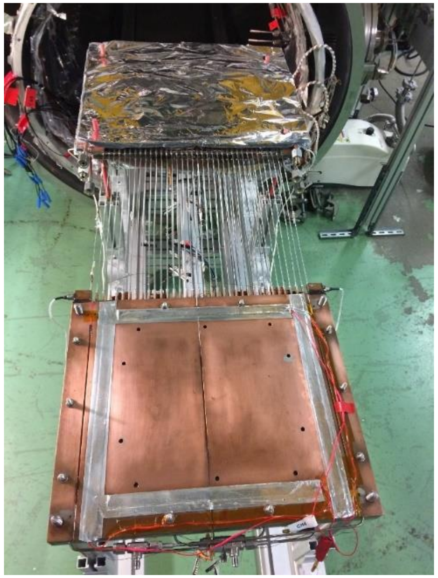
Fluid	Heat input (mW)	Condenser temperature (K)	Evaporator temperature (K)	Keff (kW/m.K)
He	375	3.4	4.5	**5**

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

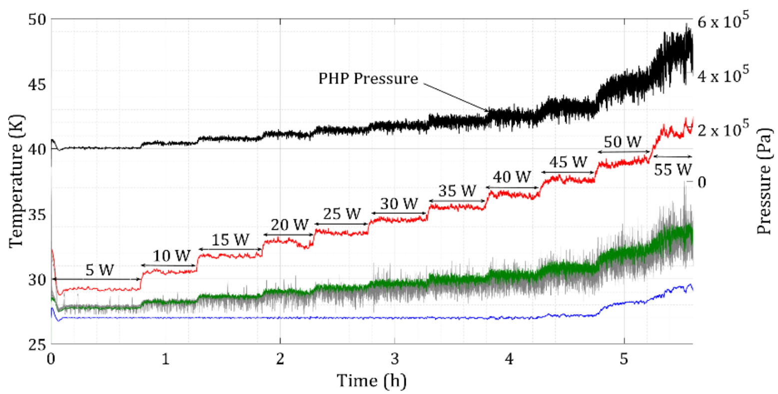
Cryogenic pulsating heat pipes (4/4)

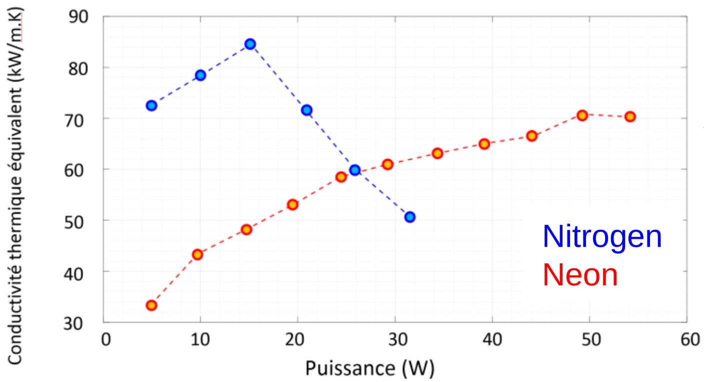
- Bruce *et al.* and Maria Barba PhD
  - Flat PHP horizontal , Ø 1.5 mm SS tubes, 36 turns
  - Condenser and evaporator section : 330 mm long
  - Adiabatic section: 300 mm long
  - Nitrogen, neon and argon





Fluid	Heat input (W)	Condenser temperature (K)	Evaporator temperature (K)
Ne	50	27	37
N2	25	75	82

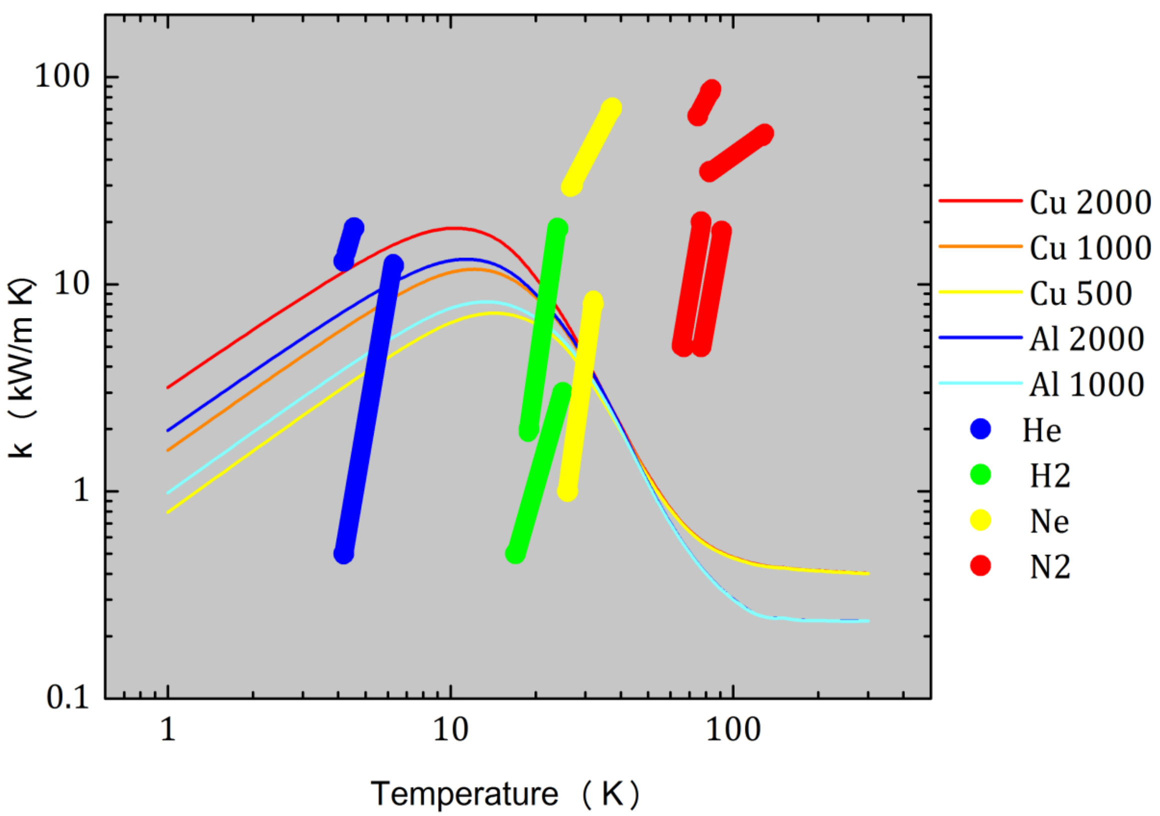




30 W
Cu 200 = 60 kg
PHP = 400 g

Bruce R., Thermal performance of a meter-scale horizontal nitrogen Pulsating Heat Pipe, Cryogenics, Volume: 93, Pages: 66-74, 2018, DOI: 10.1016/j.cryogenics.2018.05.007
M. Barba, Study of Meter-scale Horizontal Cryogenic Pulsating Heat Pipes, PhD Université Paris-Saclay, 18 Septembre 2019

Conclusion



100
10
1
0.1
k （kW/m K）
1
10
100
Temperature （K）
Cu 2000
Cu 1000
Cu 500
Al 2000
Al 1000
He
H2
Ne
N2