PSI Center for Accelerator Science and Engineering

VDL ETG

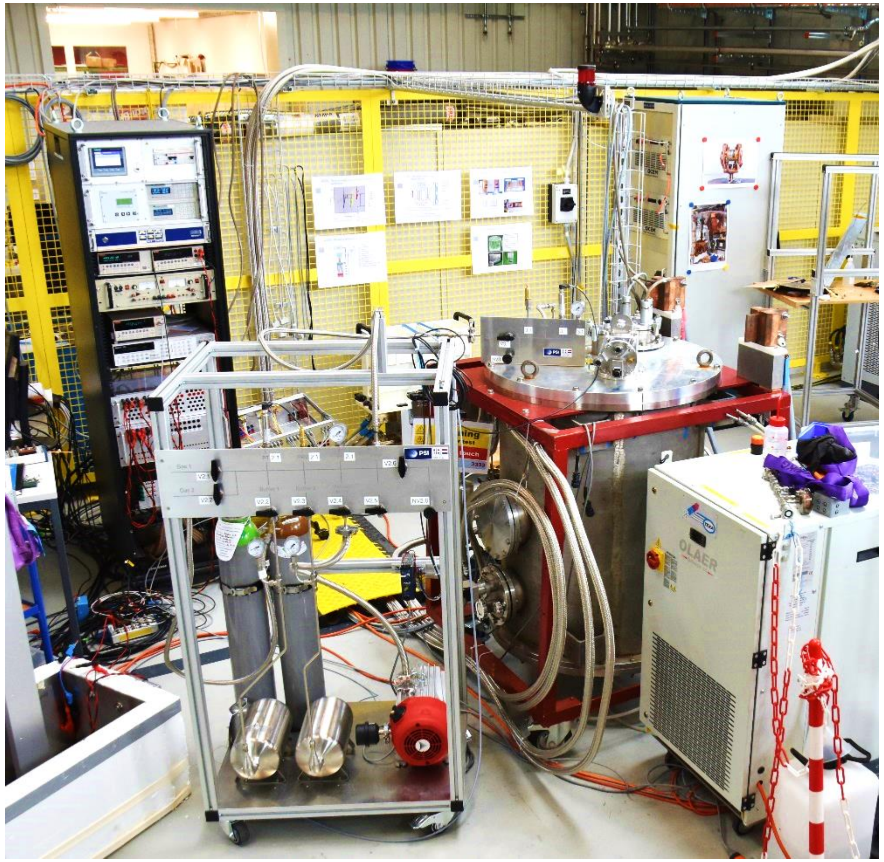
Commissioning and first results of an experimental setup for the characterization of cryogenic pulsating heat pipes

C. Zoller, M. Duda, Q. Gorit, J. C. Maris

ICEC29/ICMC2024, Geneva, 24 July 2024

Outline

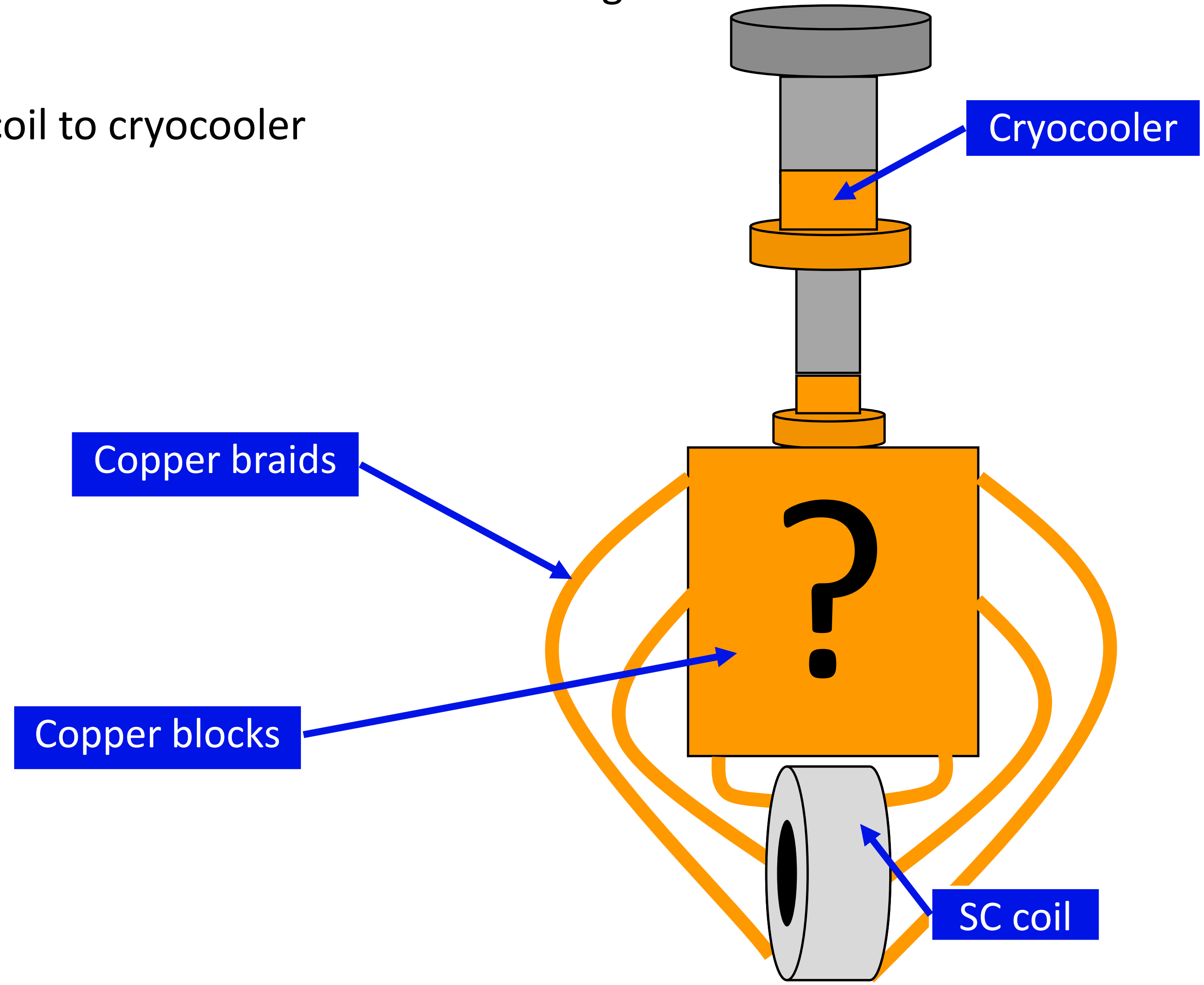
- Motivation and Principle
- Experimental setup
- Exemplary results
- Conclusion and Outlook



Experimental test setup, PHP project

Motivation

- <u>Trend:</u> Cryocoolers increasingly favored over traditional immersion bath cooling for superconducting (SC) components
- <u>Challenge:</u> Transport heat efficiently from SC coil to cryocooler
- <u>State of the art:</u> Copper links (heavy, bulky)

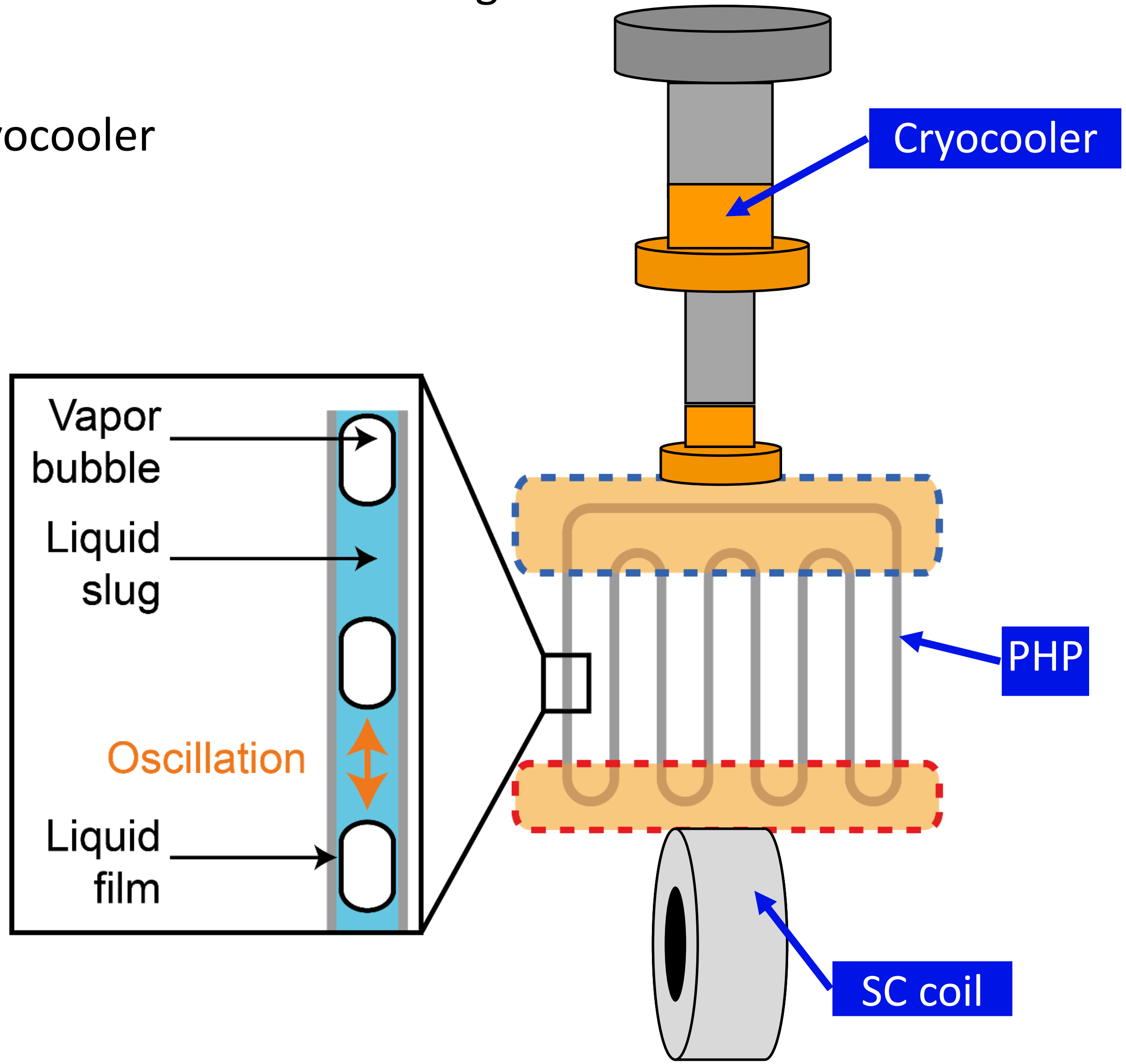


Motivation

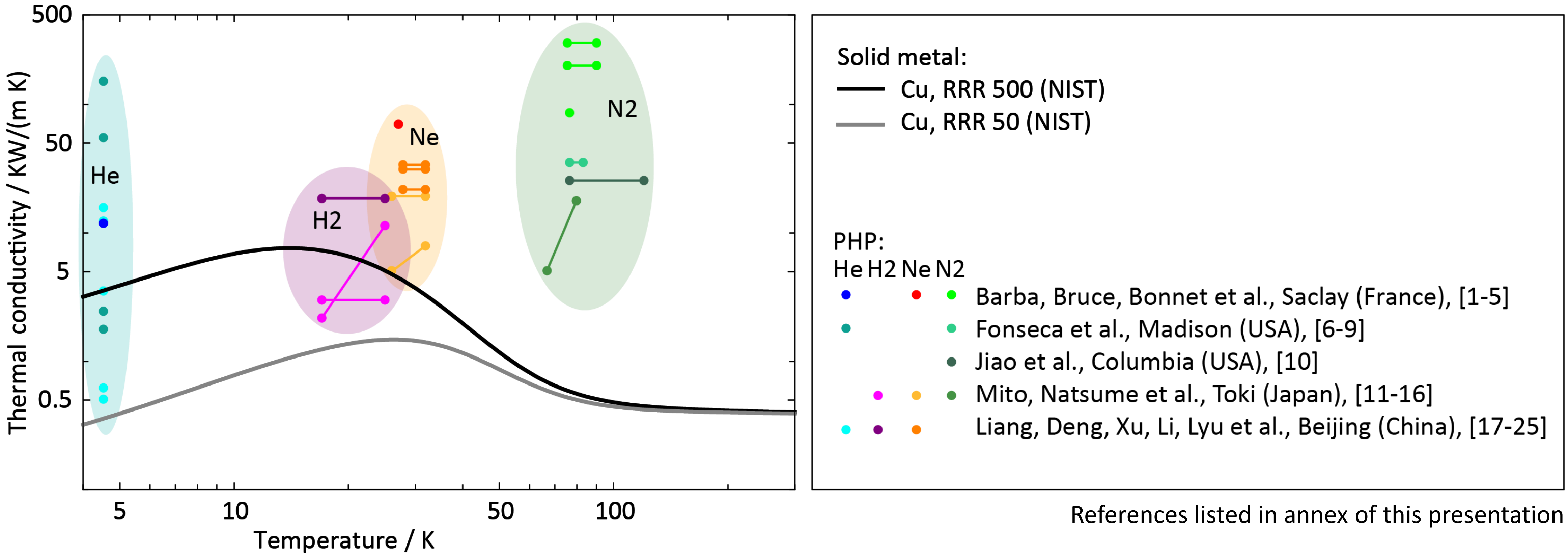
- Trend: Cryocoolers increasingly favored over traditional immersion bath cooling for superconducting (SC) components
- Challenge: Transport heat efficiently from SC coil to cryocooler
- State of the art: Copper links (heavy, bulky)
- Proposed solution:
  - Use **pulsating heat pipes (PHP)** filled with neon (for HTS) or helium (for LTS)
- Principle:
  - Transfer heat from "warm" evaporator to cold condenser using two-phase flow

    → latent heat (enthalpy of phase change) +

    → sensible heat (advection and convection)



Equivalent thermal conductivity (*k*) of PHP for cryogenic application



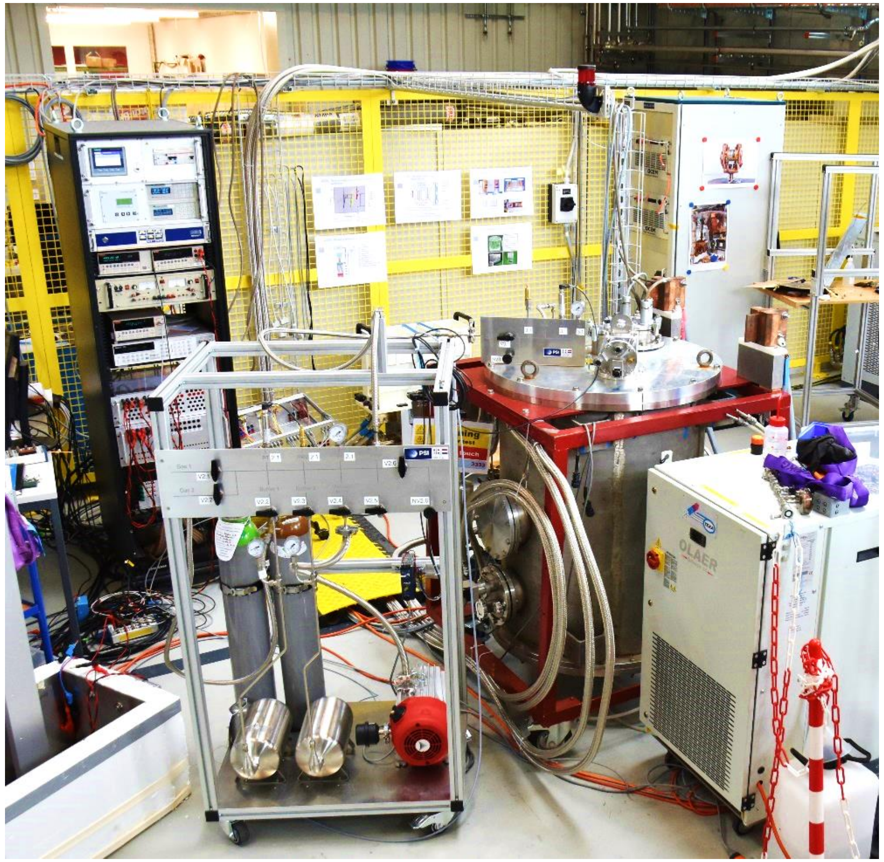
References listed in annex of this presentation

- Helium PHP for LTS application
- Neon PHP (24.5 … 44.4 K) for HTS application

$$k = \frac{Heat\ transferred}{Temperature\ difference} \times \frac{Distance}{Fluid\ cross\ sectional\ area}$$

Outline

- Motivation and Principle
- **Experimental setup**
- Exemplary results
- Conclusion and Outlook



Experimental test setup, PHP project

Design features

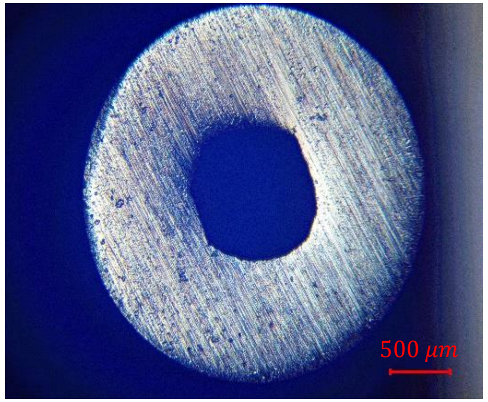
Pipes:

Material: 316 L steel

Diameters: $D_\mathrm{i} = 1\ \mathrm{mm}$, $D_\mathrm{o} = 3\ \mathrm{mm}$

Adiabatic length: $L = 195\ \mathrm{mm}$

→ similar to Dixit et al. [1]



Pipe cross-section
Courtesy of A. Brem, PSI

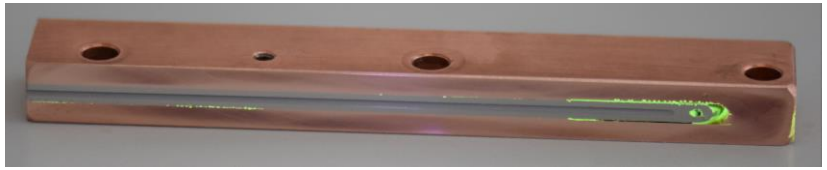
Evaporator and condenser:

Material: High purity copper

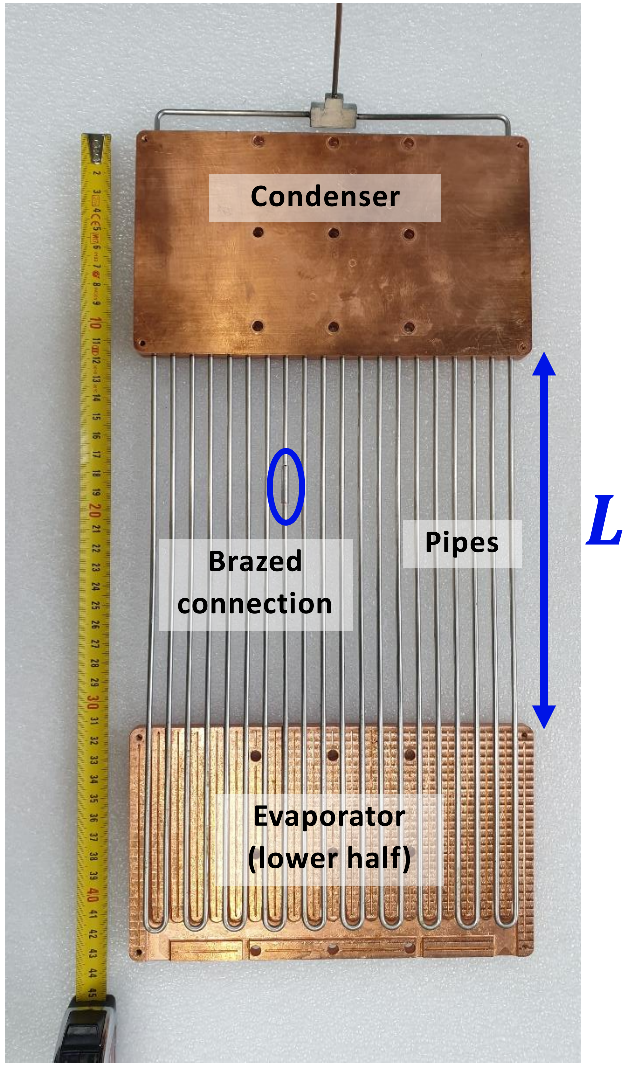
Thickness: $e = 2 \times 5\ \mathrm{mm}$

Width: $W = 115\ \mathrm{mm}$

Contact to tubes: Apiezon N grease



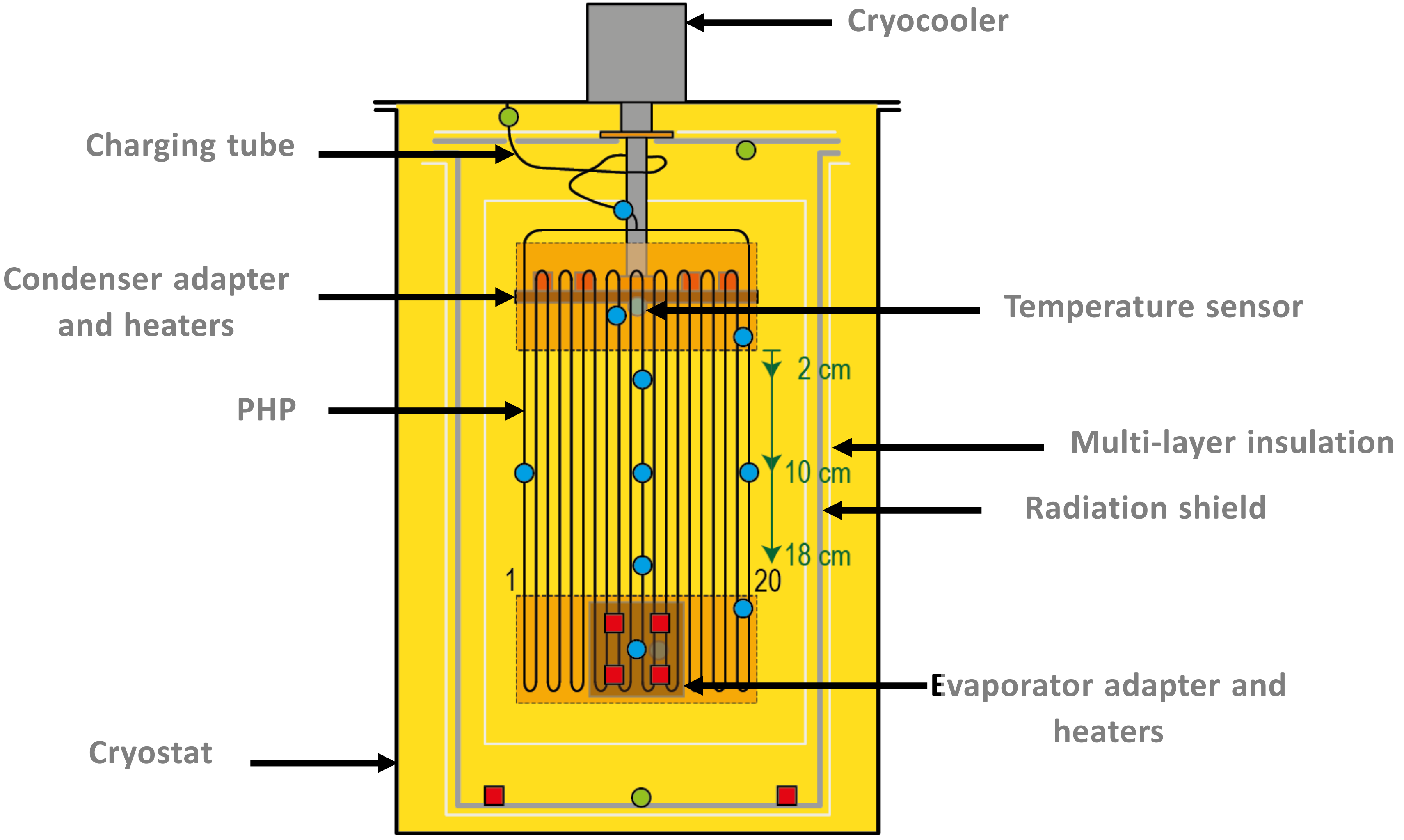
Evaporator cross-section



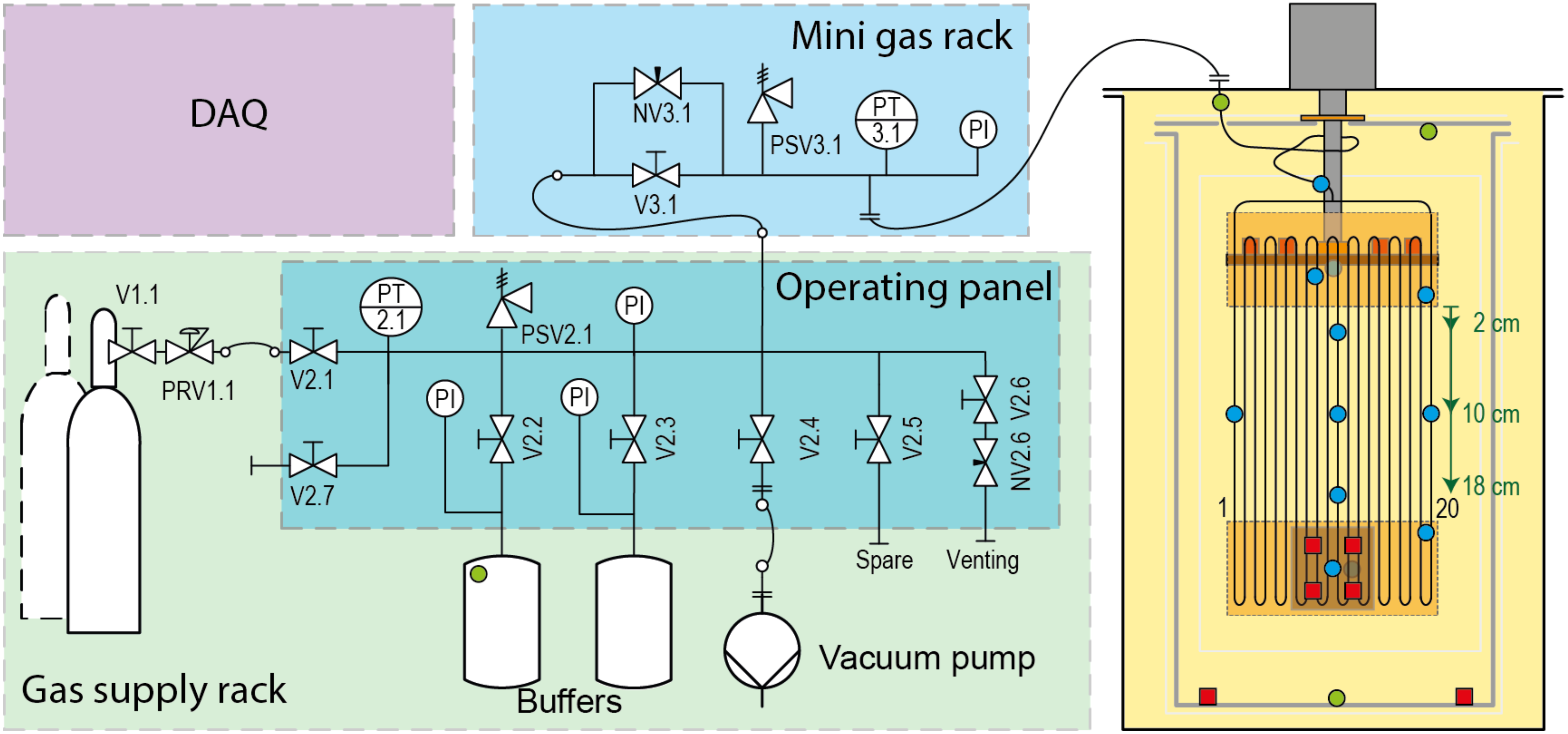
20-tube-PHP

[1] Dixit T, Authelet G, Mailleret C, Gouit F, Stepanov V and Baudouy B 2023 Cryogenics 132, 103670 ISSN 0011-2275 URL https://doi.org/10.1016/j.cryogenics.2023.103670

Experimental set-up

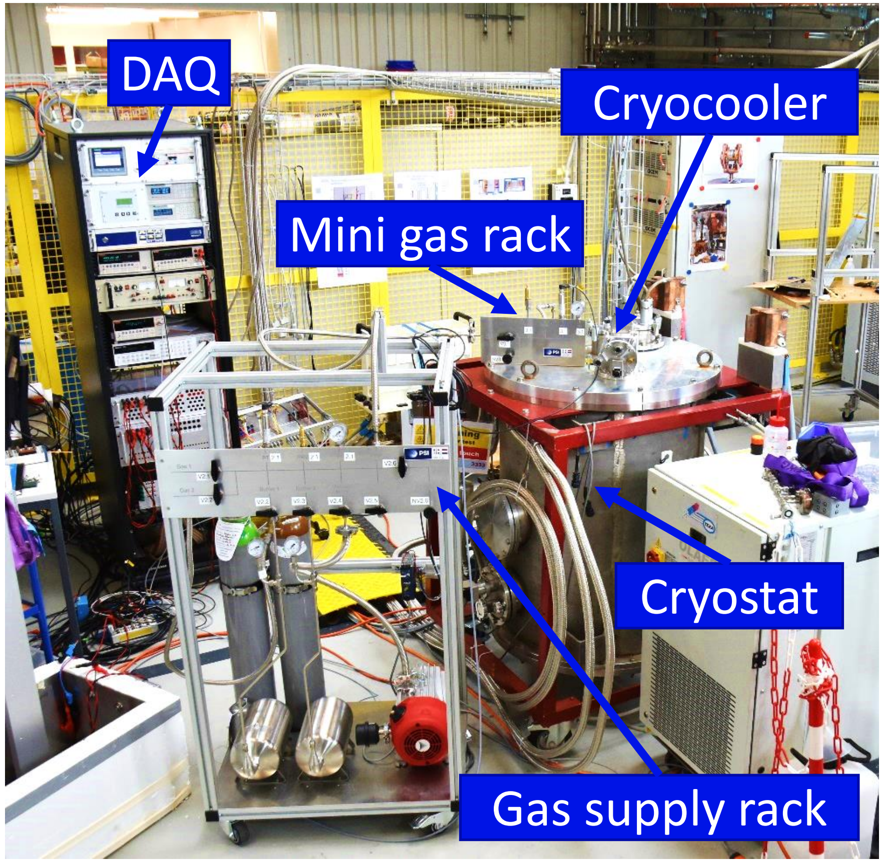


Experimental set-up



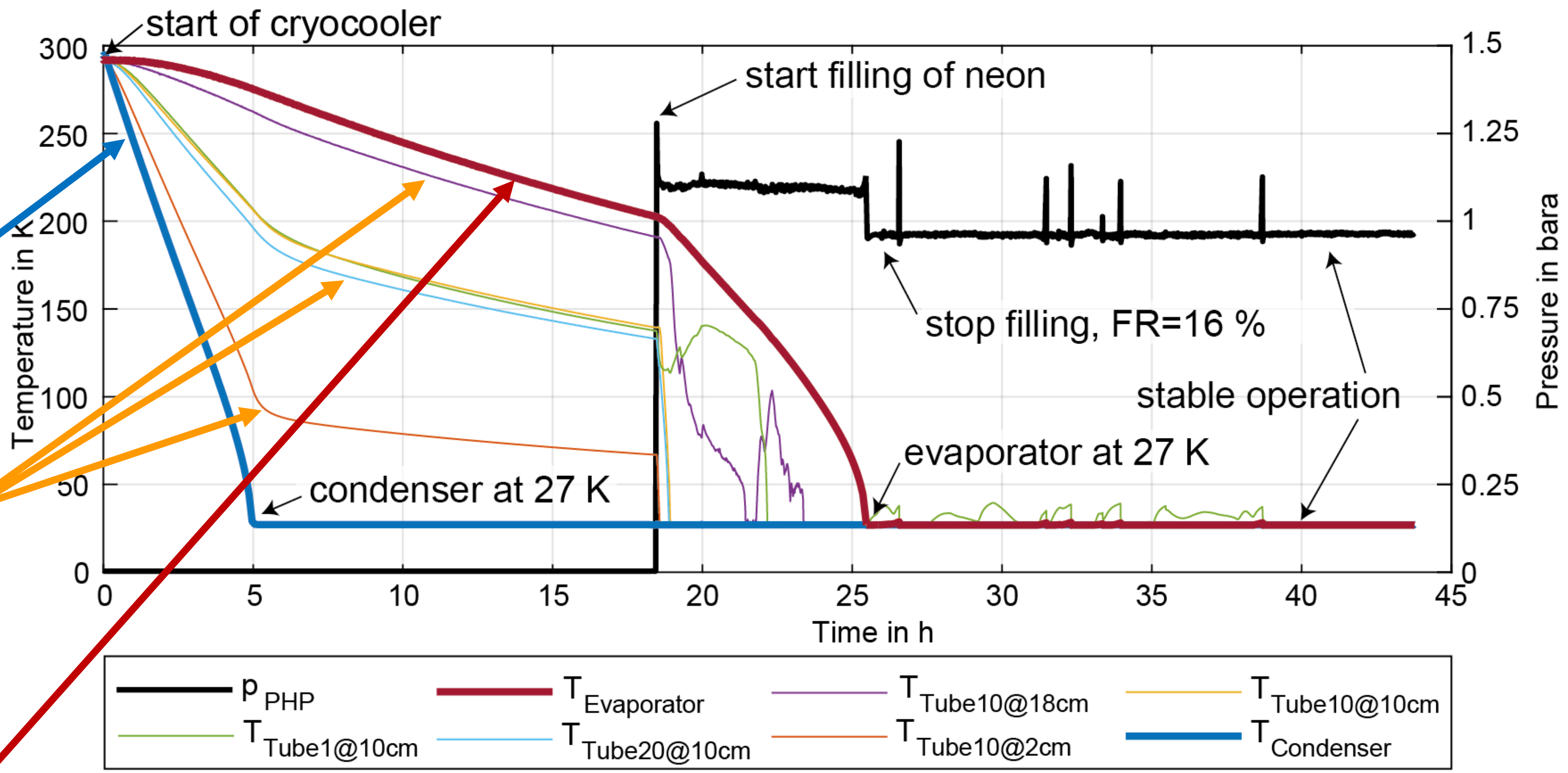
Outline

- Motivation and Principle
- Experimental setup
- Exemplary results
- Conclusion and Outlook



Experimental test setup, PHP project

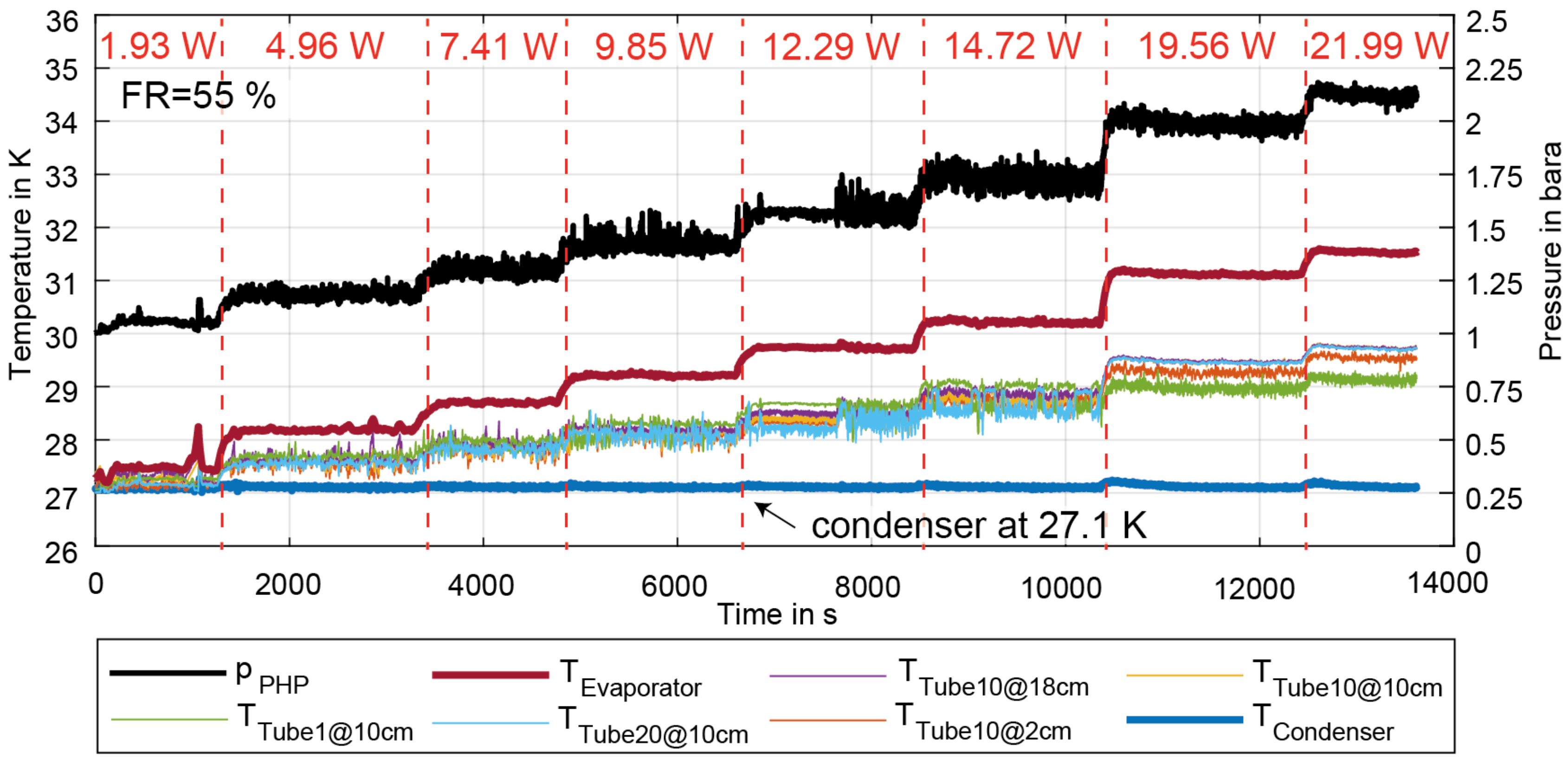
Exemplary cooldown



Characterization results

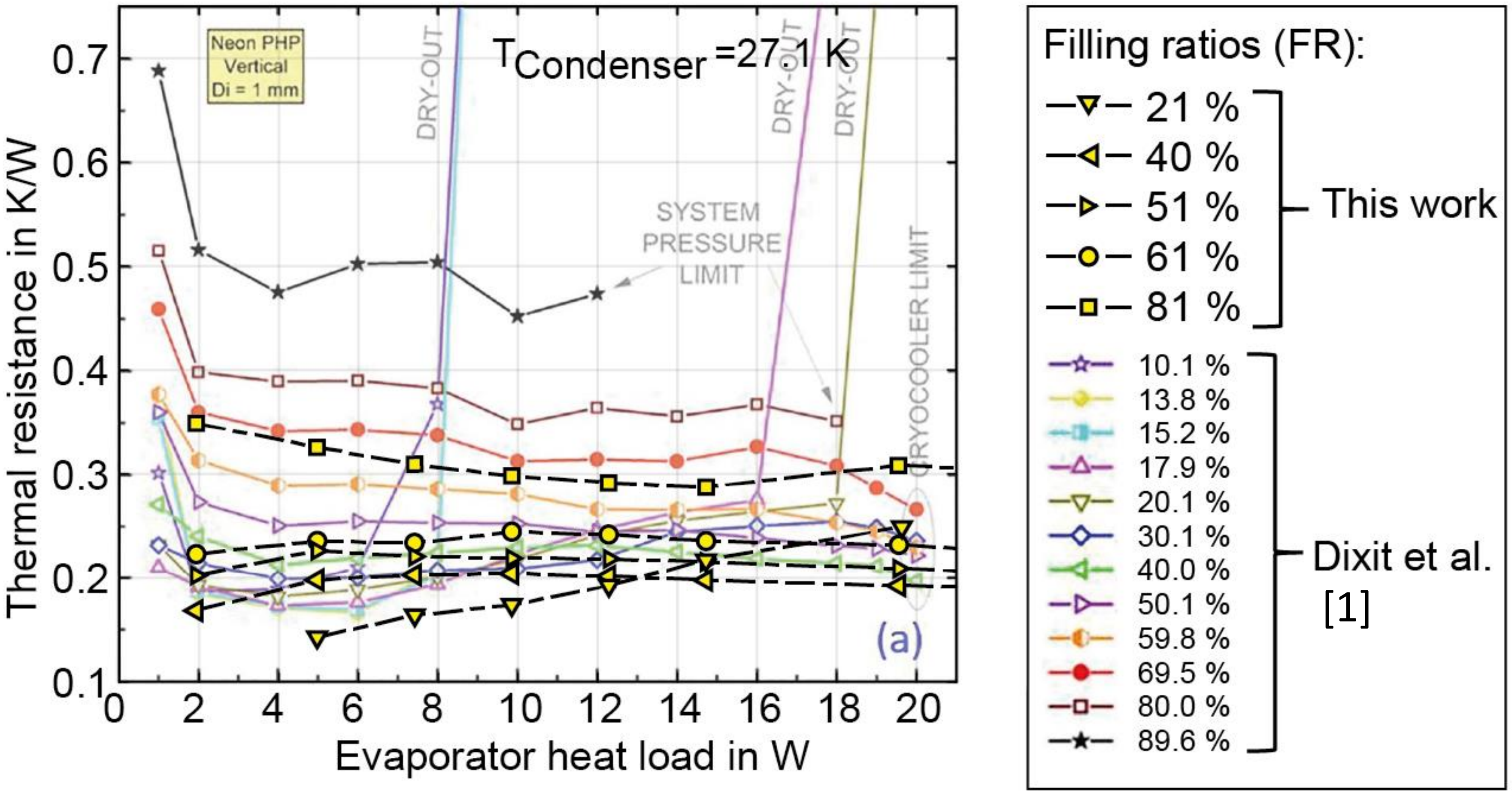
VDL ETG PSI

- Example of characterization in pseudo-steady state (simulate operated coil)



- 20 tube **neon PHP works very well** with condenser temperature at 27 K, 27.1 K and 30 K
- Maximum of **22 W transferred**
- Measured PHP performance was mostly **limited by test setup** (cryocooler or pressure limits) instead of PHP limit (dry-out phenomenon)
- Fast **transient experiments** simulating a **quenched coil** showed also promising results

Comparison of thermal resistance (R_{th}) with experimental results from Dixit et al. [1]



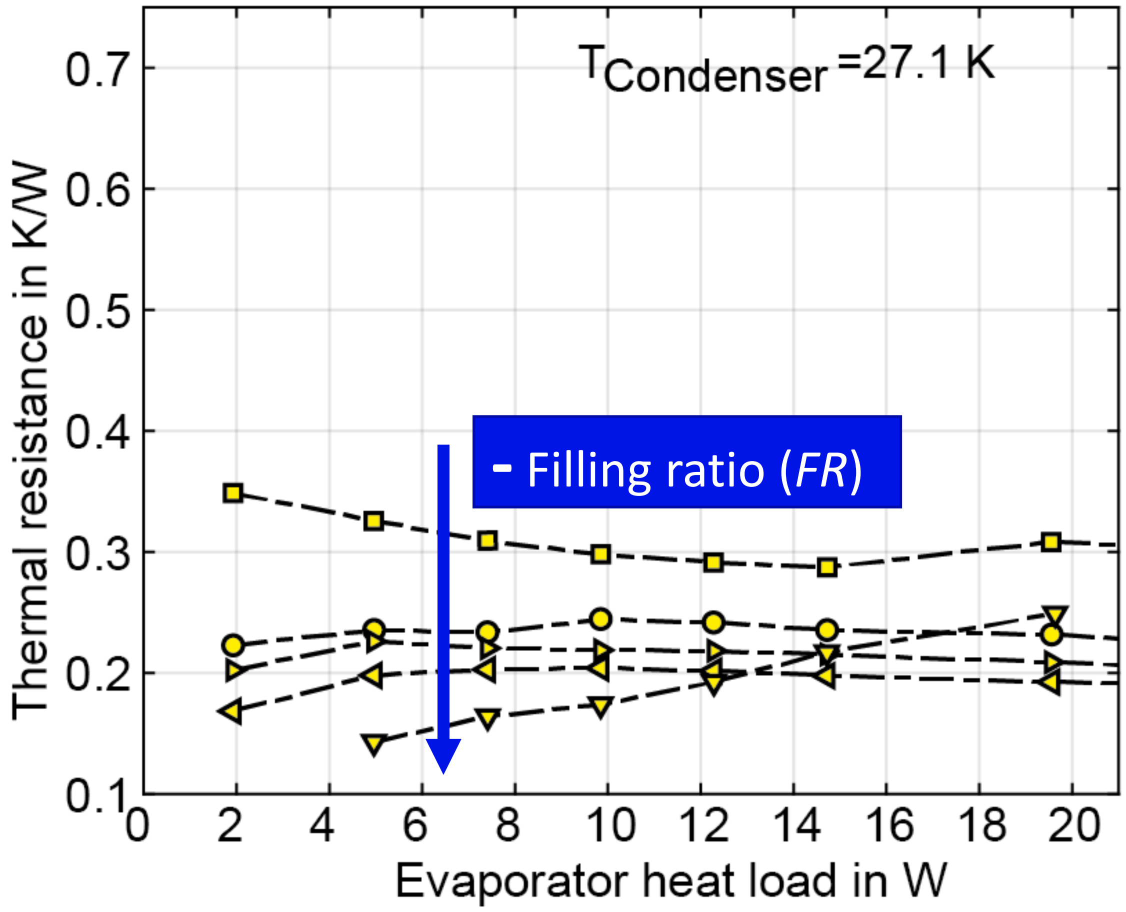
- Similar results
- Slightly lower thermal resistance can be explained by
  - Slightly different geometry
  - Different assembly method
- Best values for 40 % filling ratio in both cases

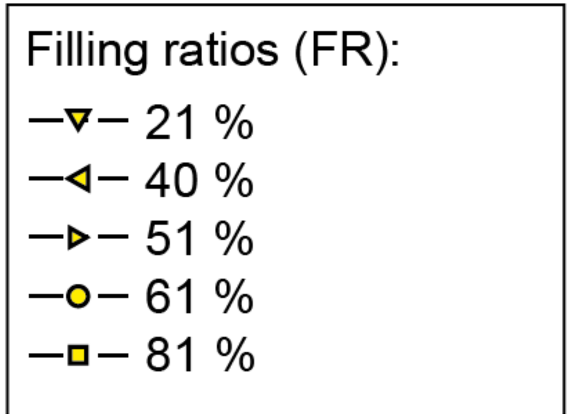
$$R_{\text{th}} = \frac{Temperature\ difference}{Heat\ transferred}$$

[1] Dixit T, Authelet G, Mailleret C, Gouit F, Stepanov V and Baudouy B 2023 Cryogenics 132, 103670 ISSN 0011-2275 URL https://doi.org/10.1016/j.cryogenics.2023.103670

Thermal resistance (R_{th}) dependence on filling ratio (FR) and condenser temperature ($T_{Condenser}$)

VDL ETG PSI





$R_{th} \downarrow$ with $FR \downarrow$ (but danger of dry-out)

$R_{th} \downarrow$ with $T_{Condenser} \uparrow$

Benchmarking:

- $R_{th,PHP,this\ study} = \mathbf{0.10\ ...\ 0.46\ K/W}$
- $R_{th,PHP,Ne,literature} = 0.11\ ...\ 32\ K/W$
- $k_{PHP,this\ study} = 40.8 ...\ \mathbf{182.6\ kW/(m \cdot K)}$
- $k_{PHP,Ne,literature} = 0.8\ ...\ 149.8\ kW/(m \cdot K)$
- $k_{Cu(27\ K, 0\ T, RRR=50...500)} = 1.5\ ...\ 4.5\ kW/(m \cdot K)$

→ factor 30...40 better than Cu

Conclusion & Outlook

- New test stand for cryogenic pulsating heat pipes built and commissioned
- Promising first results for 20-tube neon PHP
  - Better thermal performance with filling ratio ↓ (but danger of premature dry-out) and with condenser temperature ↑
- Successful benchmarking with results from Dixit et al. (CEA Saclay)
- Next steps:
  - Parametric studies, e.g. on number of tubes, working fluids
  - Operation of 2 PHP in parallel
  - Cooldown and operation of HTS coil

PSI Center for Accelerator Science and Engineering

VDL ETG

We would like to thank:

- **PSI GFA** and **VDL ETG** for their ongoing commitment
- **PSI technicians** for their support in manufacturing, assembly and, vacuum-, volume- and pressure tests
- **CHART team**, **A. Brem** and **R. Riccioli** for discussions and microscopy
- **B. Baudouy** and the **CEA Saclay team** for their kind support during the planning of the test setup.

C. Zoller, M. Duda, Q. Gorit, J. C. Maris

References Saclay, France

[1] Bonnet F, Gully P, Nikolayev V. Development and test of a cryogenic pulsating heat pipe and a pre-cooling system. In: Advances in cryogenic engineering, vol. 1434; 2012. p. 607–14.

[2] Romain Bruce, Maria Barba, Antoine Bonelli, Bertrand Baudouy, Thermal performance of a meter-scale horizontal nitrogen Pulsating Heat Pipe, Cryogenics, Volume 93, July 2018, Pages 66-74

[3] Barba, M., Bruce, R., Bouchet, F., Bonelli, A. & Baudouy, B. Thermal Study of a one-meter long Neon Cryogenic Pulsating Heat Pipe. IOP Conf. Series: Materials Science and Engineering 502 (2019). (doi.org/10.1088/1757-899X/502/1/012152)

[4] Bruce, R., Barba, M., Bouchet, F., Bonelli, A. & Baudouy, B. Transient thermal behavior of a neon Pulsating Heat Pipe (PHP). IEE Transactions on Applied Superconductivity, Volume 29, Issue 5 (2019). (doi.org/10.1109/TASC.2019.2902978)

[5] Maria Barba, Romain Bruce, Florent Bouchet, Antoine Bonelli, Bertrand Baudouy, Effect of the thermo-physical properties of the working fluid on the performance of a 1-m long cryogenic horizontal pulsating heat pipe, International Journal of Heat and Mass Transfer, Volume 187, 2022, 122458, https://doi.org/10.1016/j.ijheatmasstransfer.2021.122458.

References Missouri and Wisconsin, USA

[6] Fonseca LD, Miller F, Pfotenhauer J. Design and operation of a cryogenic nitrogen pulsating heat pipe. In: Advances in cryogenic engineering, vol. 101; 201

[7] Luis Diego Fonseca, Franklin Miller, and John Pfotenhauer, "A helium based pulsating heat pipe for superconducting magnets", AIP Conference Proceedings 1573, 28-35 (2014) https://doi.org/10.1063/1.4860679

[8] Luis Diego Fonseca, John Pfotenhauer, Franklin Miller, Results of a three evaporator cryogenic helium Pulsating Heat Pipe, International Journal of Heat and Mass Transfer, Volume 120, 2018, Pages 1275-1286, ISSN 0017-9310, https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.108.

[9] Luis Diego Fonseca, John Pfotenhauer, Franklin Miller, Short communication: Thermal performance of a cryogenic helium pulsating heat pipe with three evaporator sections, International Journal of Heat and Mass Transfer, Volume 123, 2018, Pages 655-656, ISSN 0017-9310, https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.013.

[10] Jiao AJ, Ma HB, Critser JK. Experimental investigation of cryogenic oscillating heat pipes. Int J Heat Mass Transf 2009; 52(15–16):3504–9.

References Tokio, Japan

PSI

[11] Mito T., Natsume K., Yanagi N., Tamura H., Tamada T., Shikimachi K., Hirano N., Nagaya S., Development of highly effective cooling technology for a superconducting magnet using cryogenic OHP (2010) IEEE Transactions on Applied Superconductivity, 20 (3), art. no. 5433248, pp. 2023 - 2026, DOI: 10.1109/TASC.2010.2043724

[12] K. Natsume et al., "Development of Cryogenic Oscillating Heat Pipe as a New Device for Indirect/Conduction Cooled Superconducting Magnets," in IEEE Transactions on Applied Superconductivity, vol. 22, no. 3, pp. 4703904-4703904, June 2012, Art no. 4703904, doi: 10.1109/TASC.2012.2185029.

[13] Mito T., Natsume K., Yanagi N., Tamura H., Tamada T., Shikimachi K., Hirano N., Nagaya S. Achievement of high heat removal characteristics of superconducting magnets with imbedded oscillating heat pipes (2011) IEEE Transactions on Applied Superconductivity, 21 (3 PART 2), art. no. 5699953, pp. 2470 – 2473, DOI: 10.1109/TASC.2010.2100356

[14] Kyohei Natsume, Toshiyuki Mito, Nagato Yanagi, Hitoshi Tamura, Tsutomu Tamada, Koji Shikimachi, Naoki Hirano, Shigeo Nagaya, Heat transfer performance of cryogenic oscillating heat pipes for effective cooling of superconducting magnets, Cryogenics, Volume 51, Issue 6, 2011, Pages 309-314, ISSN 0011-2275, https://doi.org/10.1016/j.cryogenics.2010.07.001.

[15] Mito T, Natsume K, Yanagi N, Tamura H, Tamada T, Shikimachi K, et al. Development of highly effective cooling technology for a superconducting magnet using cryogenic OHP. IEEE Trans Appl Supercond 2010;20(3):2023–6.

[16] Mito T, Natsume K, Yanagi N, Tamura H, Terazaki Y. Enhancement of thermal properties of HTS magnets using built-in cryogenic oscillating heat pipes. IEEE Trans Appl Supercond 2013;23(3):4602905.

References Beijing, China

[17] Qing Liang, Yi Li, Qiuliang Wang, Experimental investigation on the performance of a neon cryogenic oscillating heat pipe, Cryogenics, Volume 84, 2017, Pages 7-12, ISSN 0011-2275, https://doi.org/10.1016/j.cryogenics.2017.03.004.

[18] Liang, Q., Li, Y., & Wang, Q. (2017). Cryogenic oscillating heat pipe for conduction-cooled superconducting magnets. IEEE Transactions on Applied Superconductivity, 28(3), 1-5.

[19] Qing Liang, Yi Li, Qiuliang Wang, Effects of filling ratio and condenser temperature on the thermal performance of a neon cryogenic oscillating heat pipe, Cryogenics, Volume 89, 2018, Pages 102-106, ISSN 0011-2275, https://doi.org/10.1016/j.cryogenics.2017.12.002.

[20] Q. Liang , Y. Li , Q. Wang , Study on a neon cryogenic oscillating heat pipe with long heat transport distance, Heat Mass Transf. 54 (2018) 1721–1727 .

[21] Deng HR, Liu YM, Ma RF, Han DY, Gan ZH, Pfotenhauer JM. Experimental investigation on a pulsating heat pipe with hydrogen. In: Advances in cryogenic engineering, vol. 101; 2015.

[22] Dong Xu, Laifeng Li, Huiming Liu, Experimental investigation on the thermal performance of helium based cryogenic pulsating heat pipe, Experimental Thermal and Fluid Science, Volume 70, 2016, Pages 61-68, ISSN 0894-1777, https://doi.org/10.1016/j.expthermflusci.2015.08.024.

[23] M. Li, L. Li, D. Xu, Effect of number of turns and configurations on the heat transfer performance of helium cryogenic pulsating heat pipe, Cryogenics, Volume 96, December 2018, Pages 159-165.

[24] Monan Li, Laifeng Li, Dong Xu, Effect of filling ratio and orientation on the performance of a multiple turns helium pulsating heat pipe, Cryogenics, Volume 100, 2019, Pages 62-68, ISSN 0011-2275, https://doi.org/10.1016/j.cryogenics.2019.04.006.

[25] Bingkun Lyu, Dong Xu, Wei Wang, Jijun Xin, Yaran Shi, Zhichun Fang, Chuanjun Huang, Rongjin Huang, Laifeng Li, Experimental investigation of a serial-parallel configuration helium pulsating heat pipe, Cryogenics, Volume 131, 2023, 103668, ISSN 0011-2275, https://doi.org/10.1016/j.cryogenics.2023.103668.

Comparison with Dixit et al. [4]

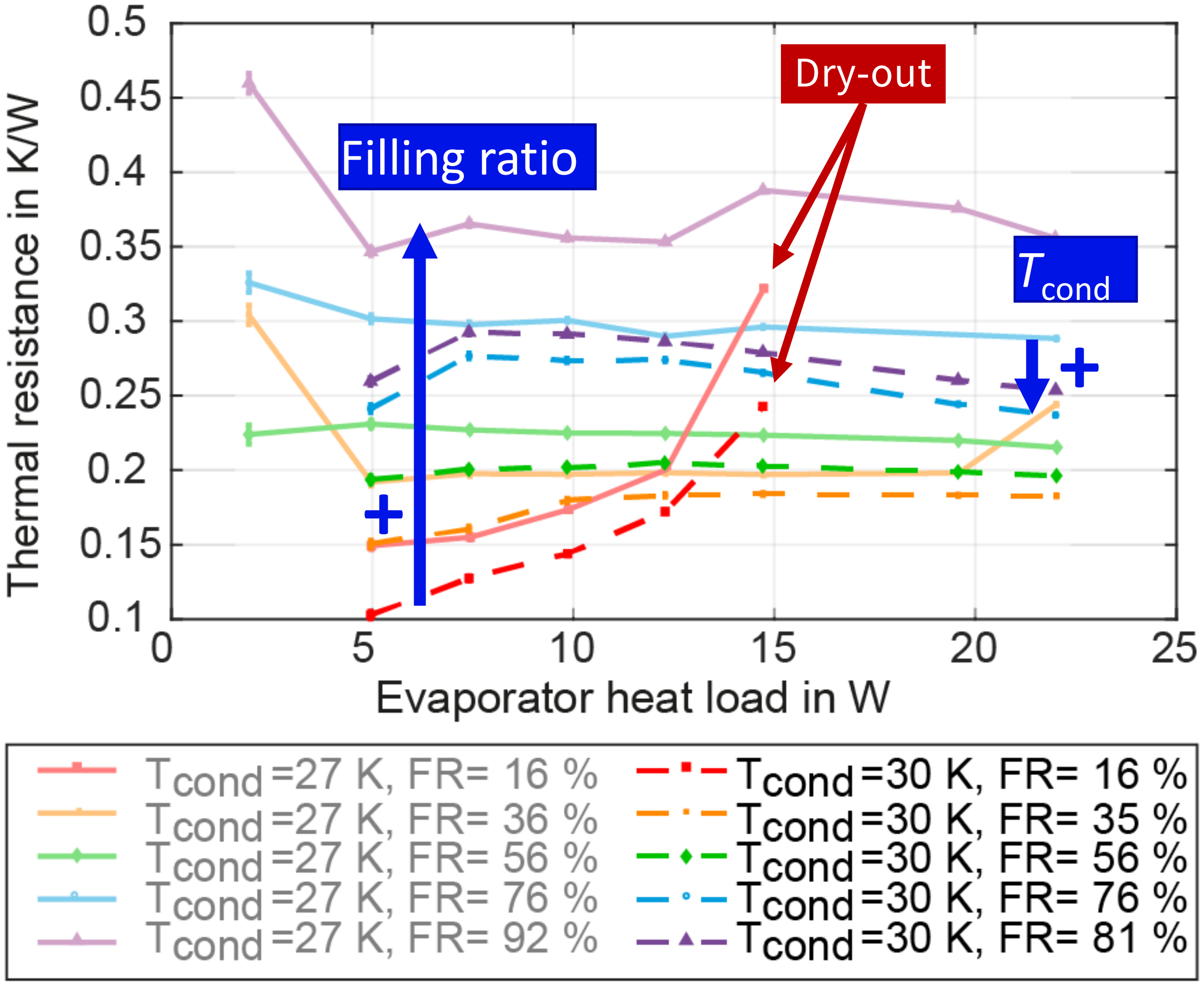
VDL ETG PSI

Table 1: Dimensions and materials of the main PHP components used in this work and in [4].

Component	Parameter	This work	Dixit et al. [4]
Pipes	Inner tube diameter in mm	1	1
	Outer diameter in mm	3	2.5
	Total length in m	8.4	8.5
	Material	SS 316L	SS 316L
	Adiabatic length in cm	19.5	20
	Amount of brazing sleeves	1	0
	Number of parallel tubes	20	20
	Test pressure in bar	10	6
Condenser	Length in mm	120	120
Evaporator	Width in mm	210	210
	Thickness in mm	2×5	2×5
	Thermal contact to tubes	Apiezon® N grease	mix copper particles and high vacuum grease
	Material	OF copper	OFE copper
Cryocooler	Type *Sumitomo*	RDK415D2	RDE418D4

[4] Dixit T, Authelet G, Mailleret C, Gouit F, Stepanov V and Baudouy B 2023 Cryogenics 132, 103670 ISSN 0011-2275 URL https://doi.org/10.1016/j.cryogenics.2023.103670

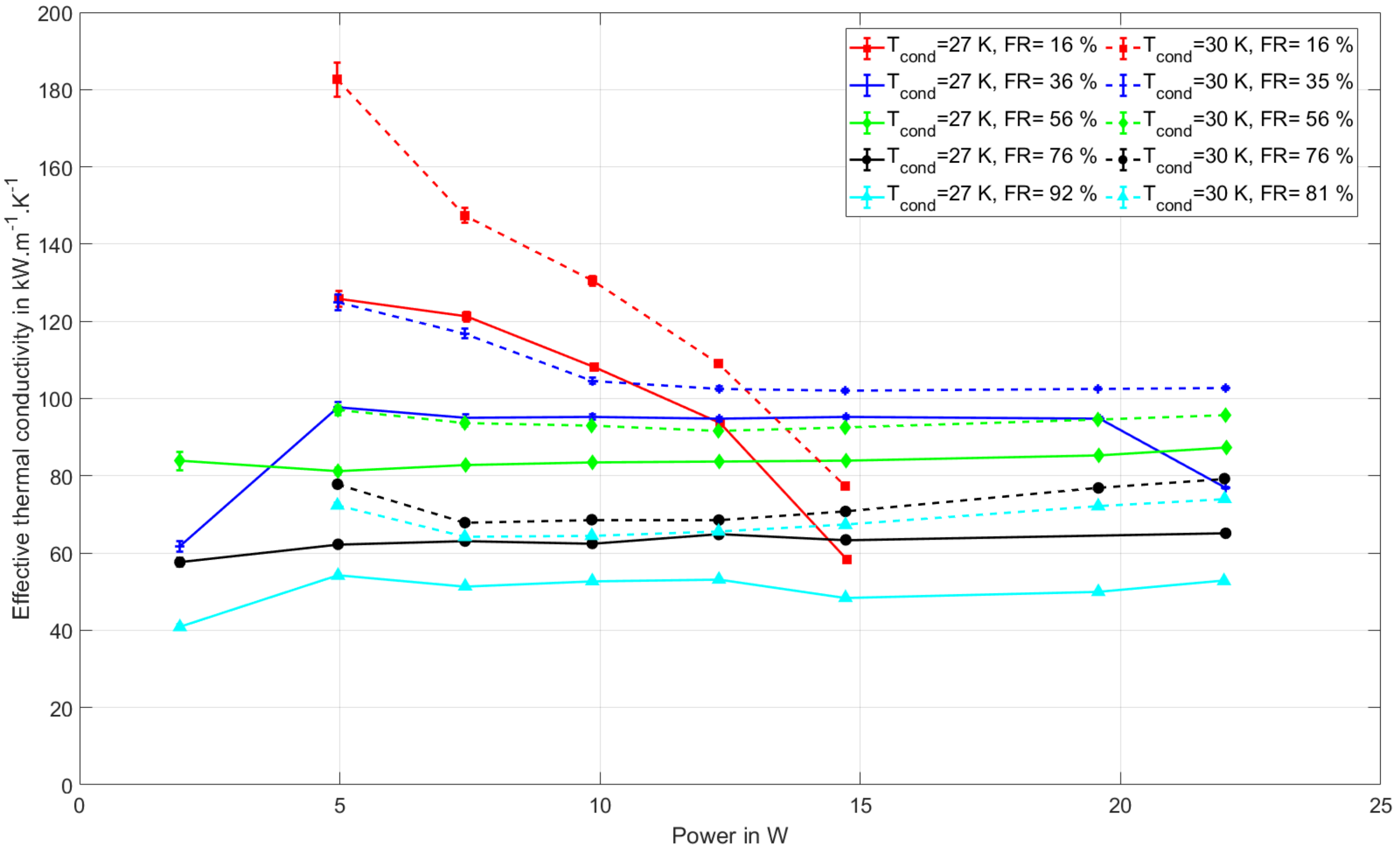
Thermal resistance (R_{th}) dependence on filling ratio (FR) and condenser temperature (T_{cond})



General trend:

- Thermal resistance ↓ with filling ratio ↓ (but danger of premature dry-out) → best 35 %
- Thermal resistance ↓ with condenser temperature ↑

K_eff



Effective thermal conductivity in kW.m^-1.K^-1
Power in W
0
20
40
60
80
100
120
140
160
180
200
0
5
10
15
20
25
T_cond=27 K, FR= 16 %
T_cond=30 K, FR= 16 %
T_cond=27 K, FR= 36 %
T_cond=30 K, FR= 35 %
T_cond=27 K, FR= 56 %
T_cond=30 K, FR= 56 %
T_cond=27 K, FR= 76 %
T_cond=30 K, FR= 76 %
T_cond=27 K, FR= 92 %
T_cond=30 K, FR= 81 %