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Thermal Study of a one-meter long Neon Cryogenic Pulsating Heat Pipe

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OVERVIEW

- Goal
- Definition of PHP
- Description of the cryogenic experimental facility
- Experimental results
- Conclusions
- Future work

GOAL

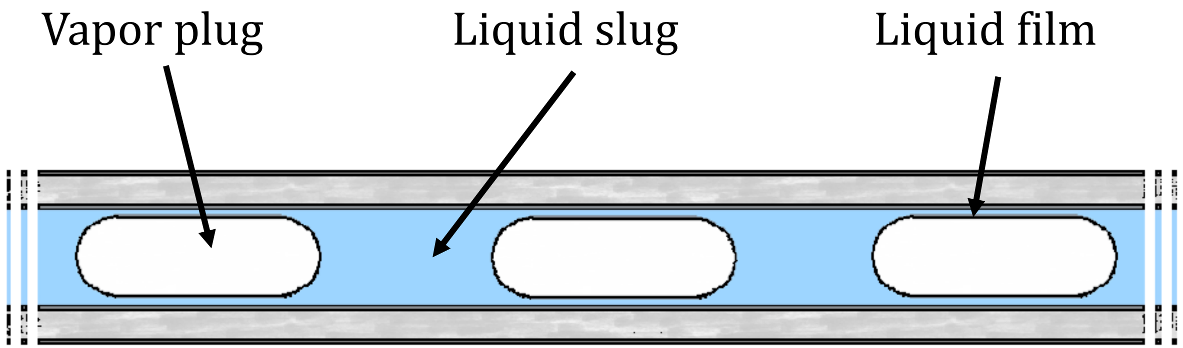
To develop cryogenic technologies for cooling superconducting magnets with the following characteristics:

- Light and simple construction
- Low cryogenic fluid consumption
- Transfer heat without any additional power systems
  (such as pumping systems, etc…)
- Enough distance between the magnet and the cryocooler
  (to avoid any damage in the cryocooler by the magnetic field)
- Able to work at different ranges of temperature
- Able to work under zero-gravity conditions for future space applications

PULSATING HEAT PIPES (PHP)

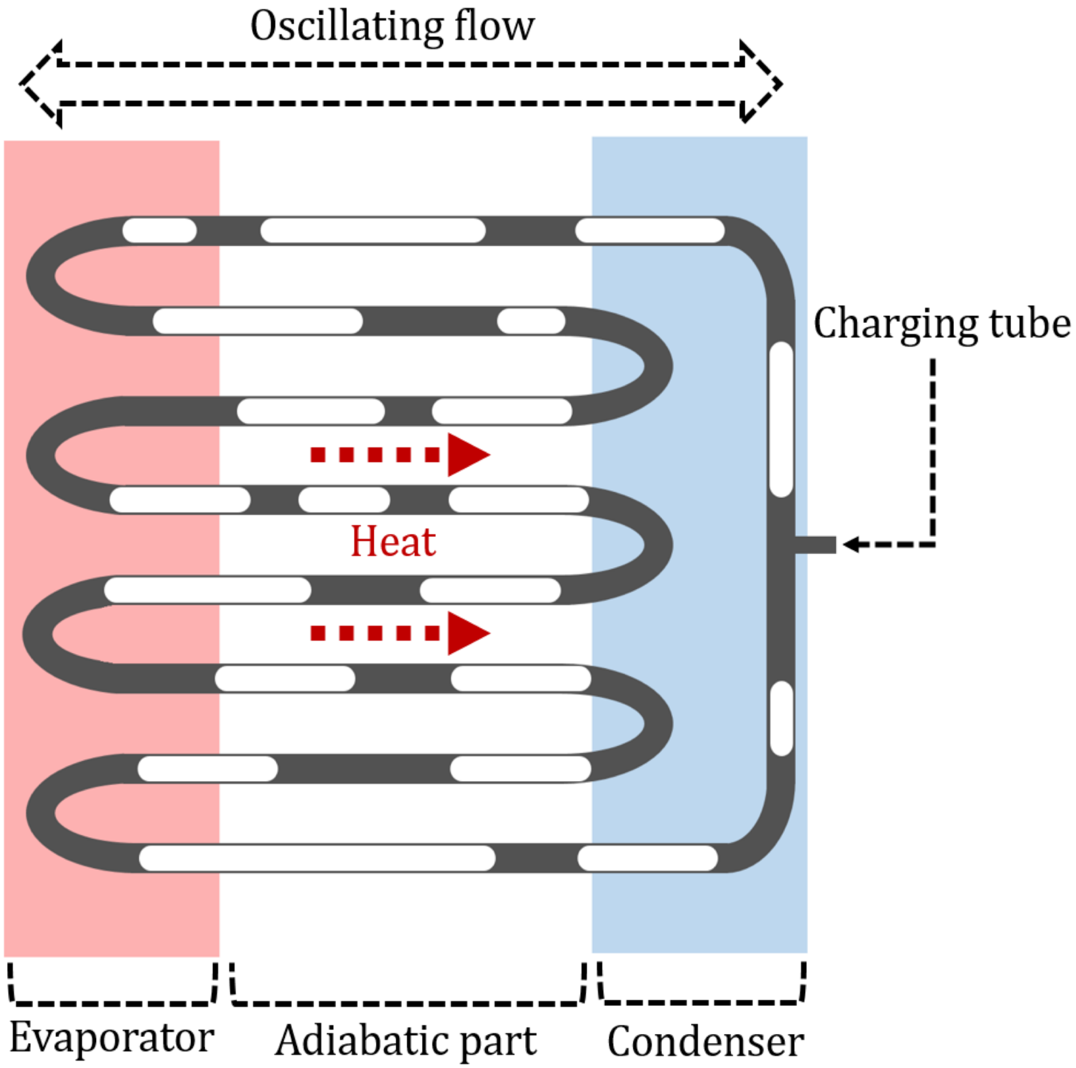
- **P**ulsating (or **O**scillating) **H**eat **P**ipes (PHP or OHP) are **two-phase thermal links** consisting of a long **capillary** channel bent into many U-turns

- They are thermally driven by an **oscillating flow** of **liquid slugs** and **vapor plugs**



Maximum inner tube diameter Ø (from the Bond number):

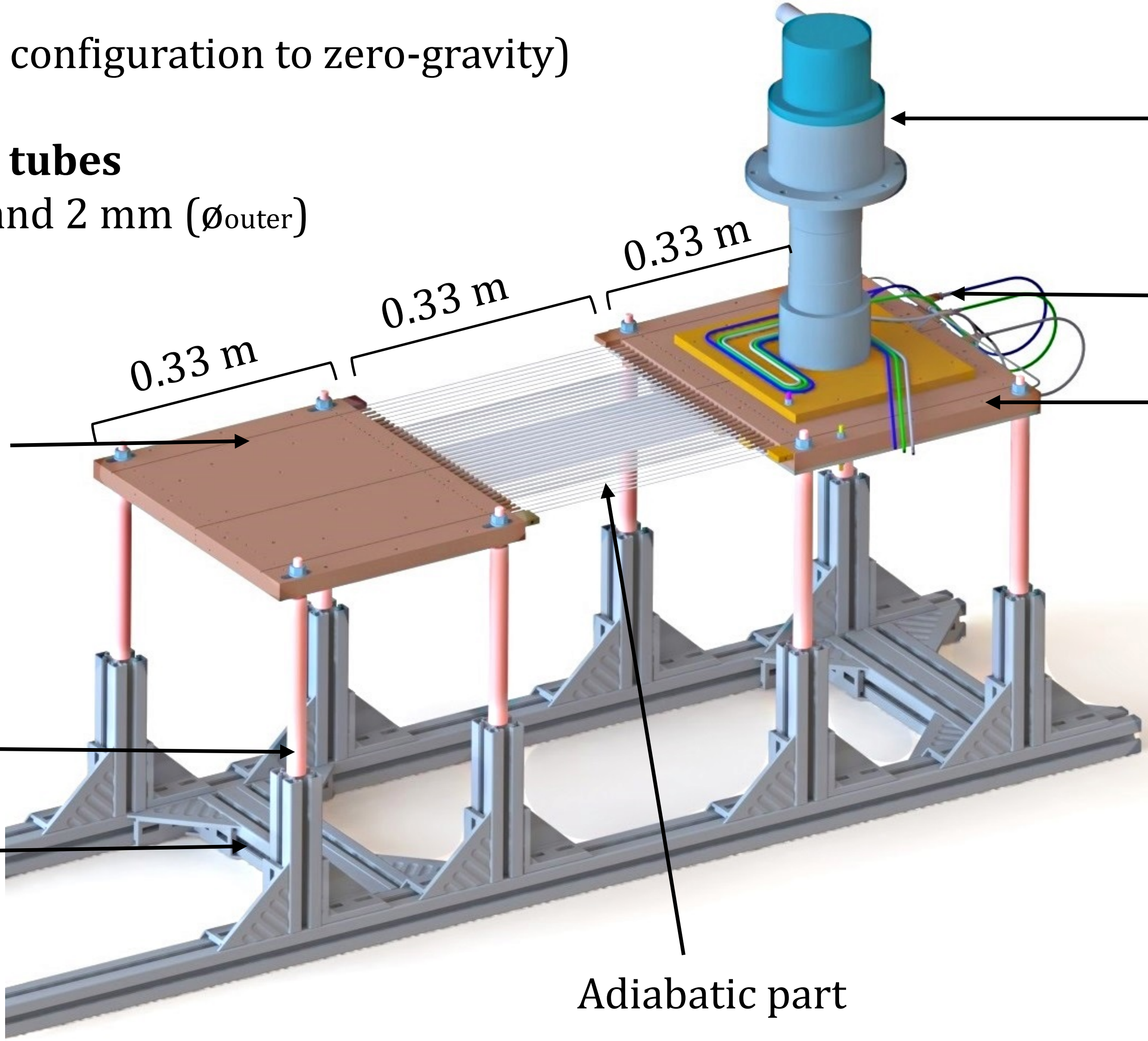
$$Bo = \frac{(\rho_l - \rho_v) g D^2}{\sigma} \leq 4 \qquad D_{crit} \leq 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$$

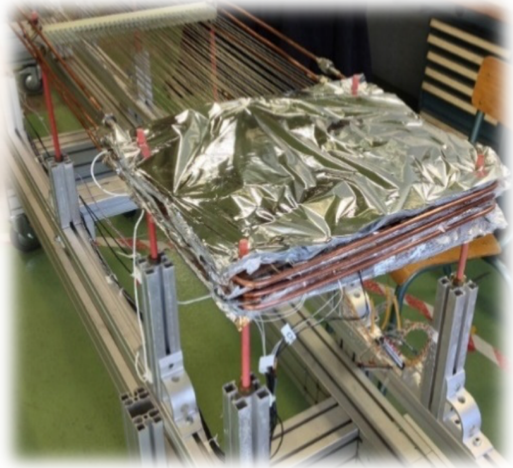


CRYOGENIC PHP: EXPERIMENTAL SETUP (1/4)

Characteristics:

- **Horizontal** position (closest configuration to zero-gravity)
- **1 m** long closed-PHP
- **36 Stainless steel capillary tubes**
- Diameters: **1.5 mm (øinner)** and 2 mm (øouter)



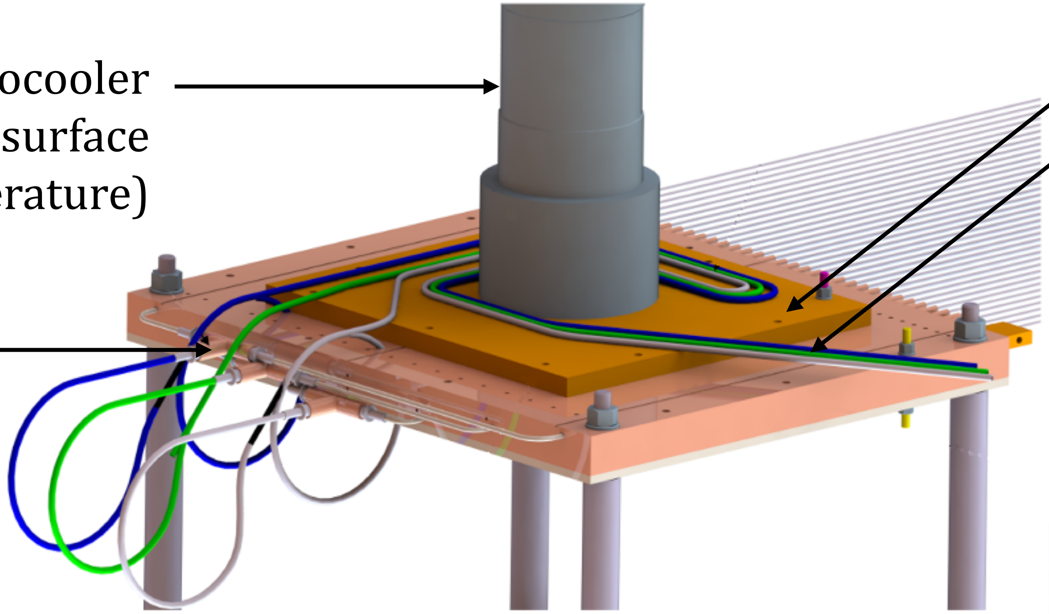


CRYOGENIC PHP: EXPERIMENTAL SETUP (2/4)

<u>Condenser part:</u>

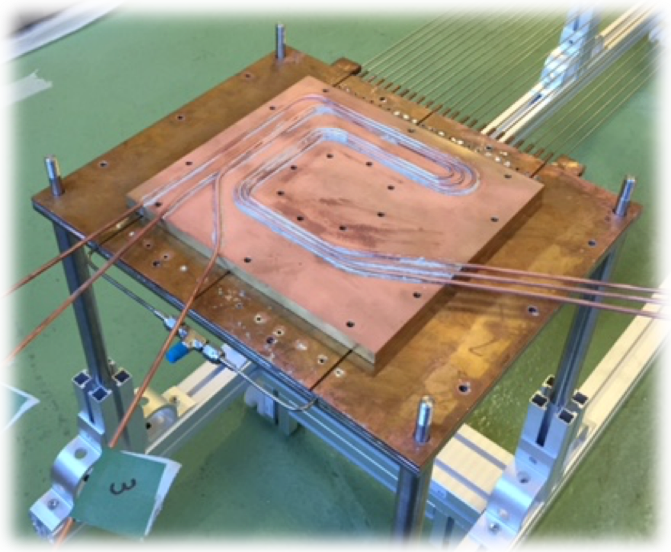
Cryocooler
(with heaters taped at its surface
to control the temperature)

PHP inlet



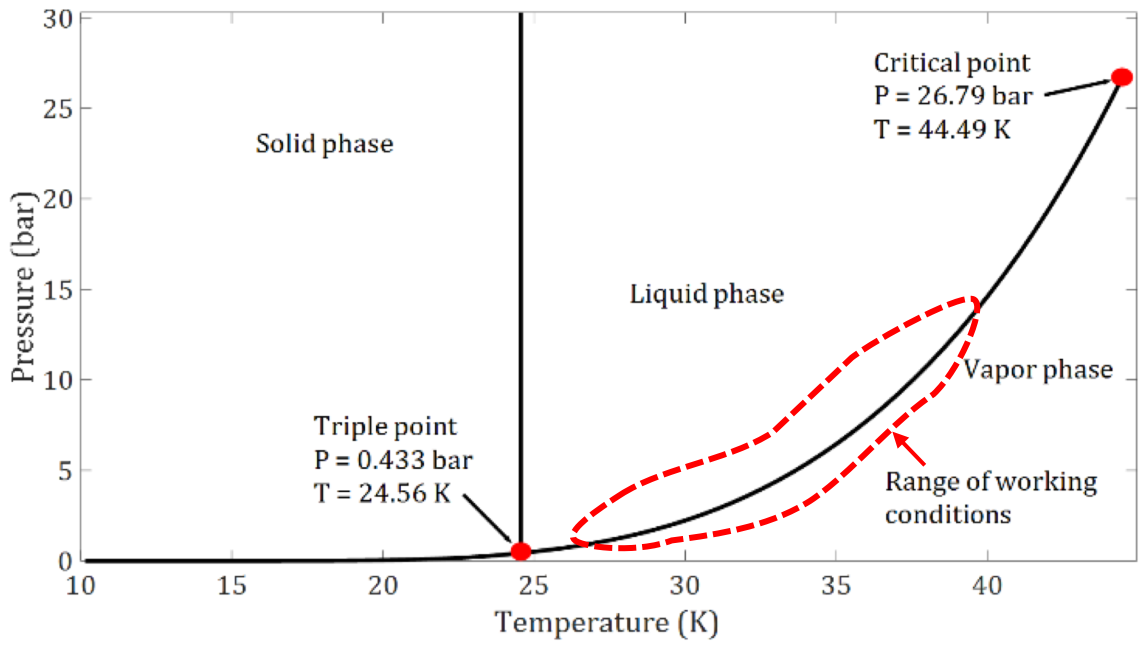
Copper thermal link (with **copper tubes thermalized** at its surface):

The working fluid, coming from outside the cryostat (300 K), is cooled and condensed in the thermalized copper tube and then introduced into the PHP.



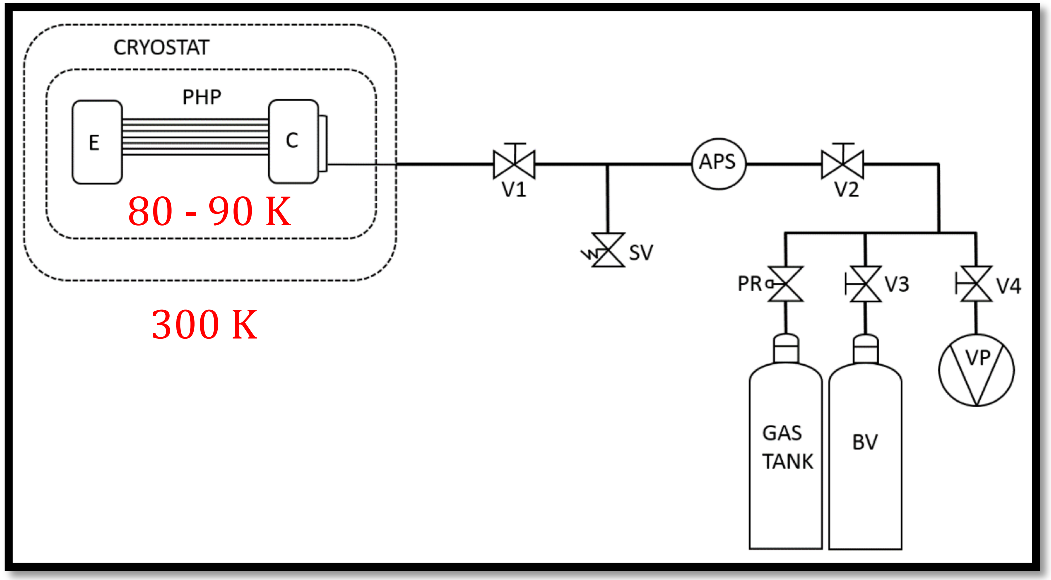
CRYOGENIC PHP: EXPERIMENTAL SETUP (3/4)

- Working fluid: **Neon** (boiling point 27 K @ 1 bar)



- **Specific inlet gas system** to control the liquid/gas filling ratio
  - Pumping process before every test to avoid any impurity inside the system
  - Filling process with a buffer volume to achieve the desired liquid filling ratio

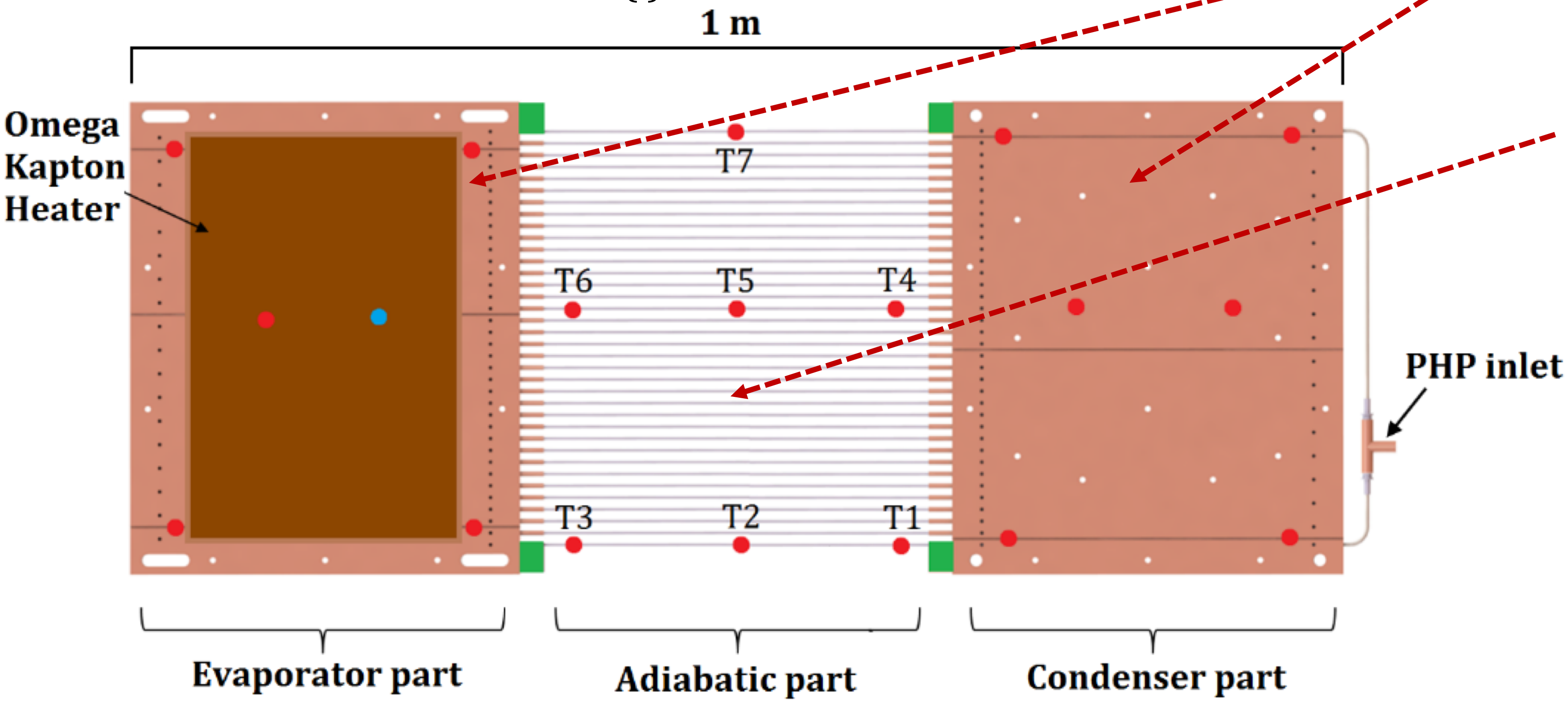
$$FR\ (\%) = \frac{V\ liquid}{V\ php} * 100$$



CRYOGENIC PHP: EXPERIMENTAL SETUP (4/4)

Instrumentation

- Temperature sensors: Pt100 ( )and 1070 CX-SD Cernox ( )
- Pressure sensors: Kulite ( )



CRYOGENIC PHP: EXPERIMENTAL RESULTS (1/4)

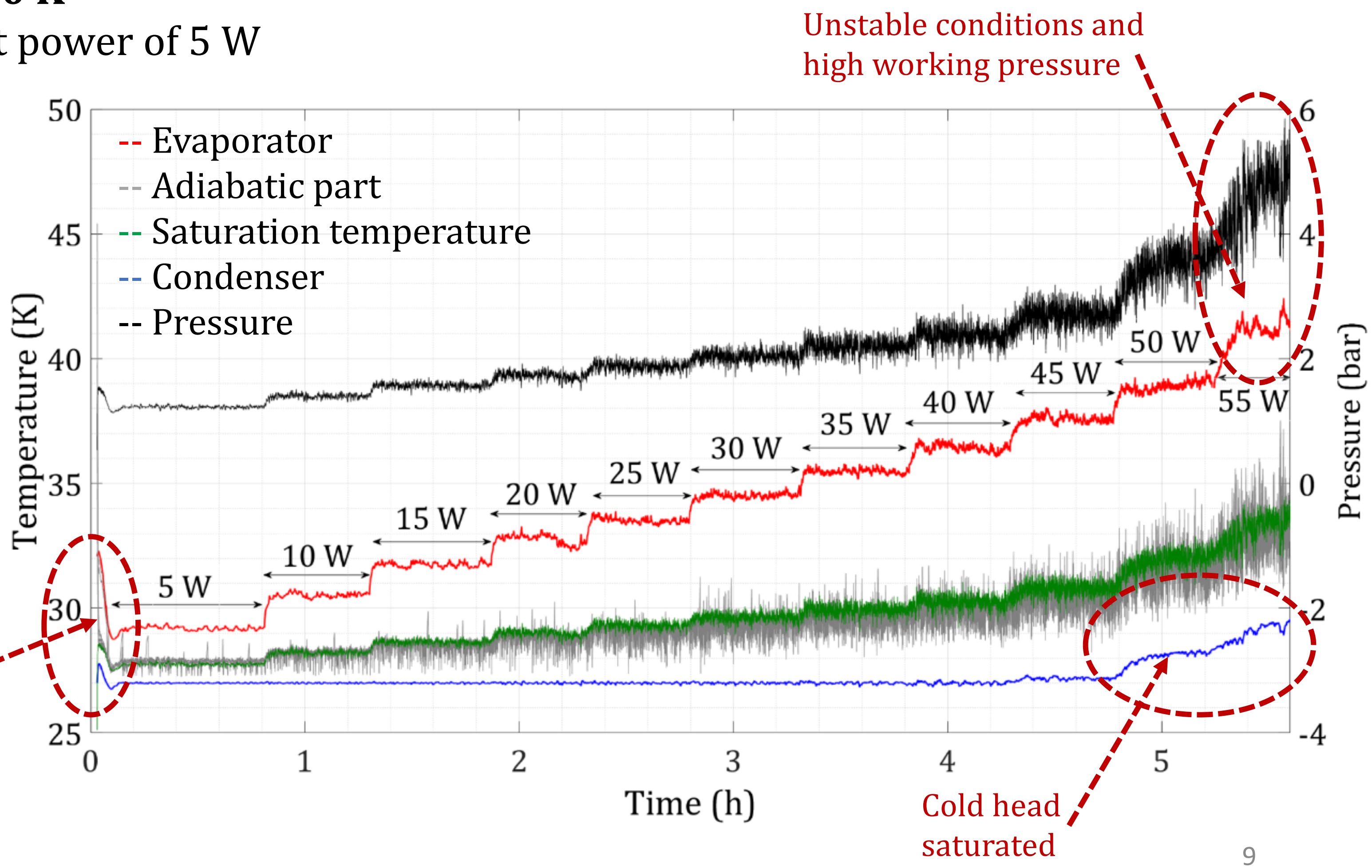
Characteristics of the test:

- Working fluid: **Neon (Ne)**
- Range of working temperatures **27 – 40 K**
- **Initial conditions:** ΔT of 5 K and input power of 5 W
- Condenser temperature fixed @ 27 K
- Filling ratio: **28 %** (V_{liquid}/V_{php})

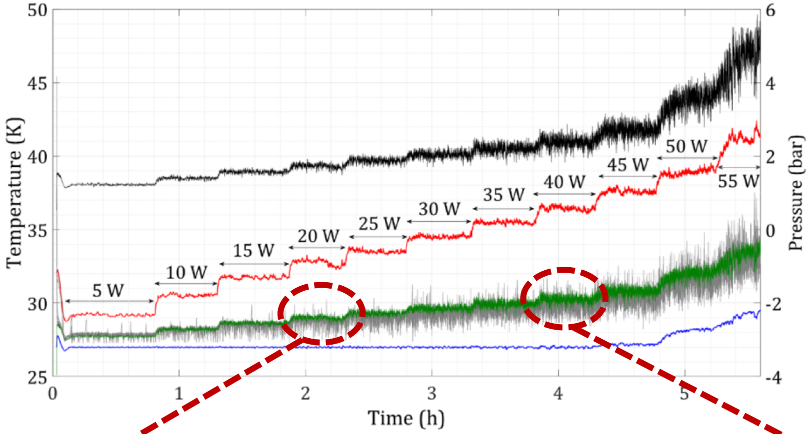
Type of test:

Progressive heat load from 5 to 55 W

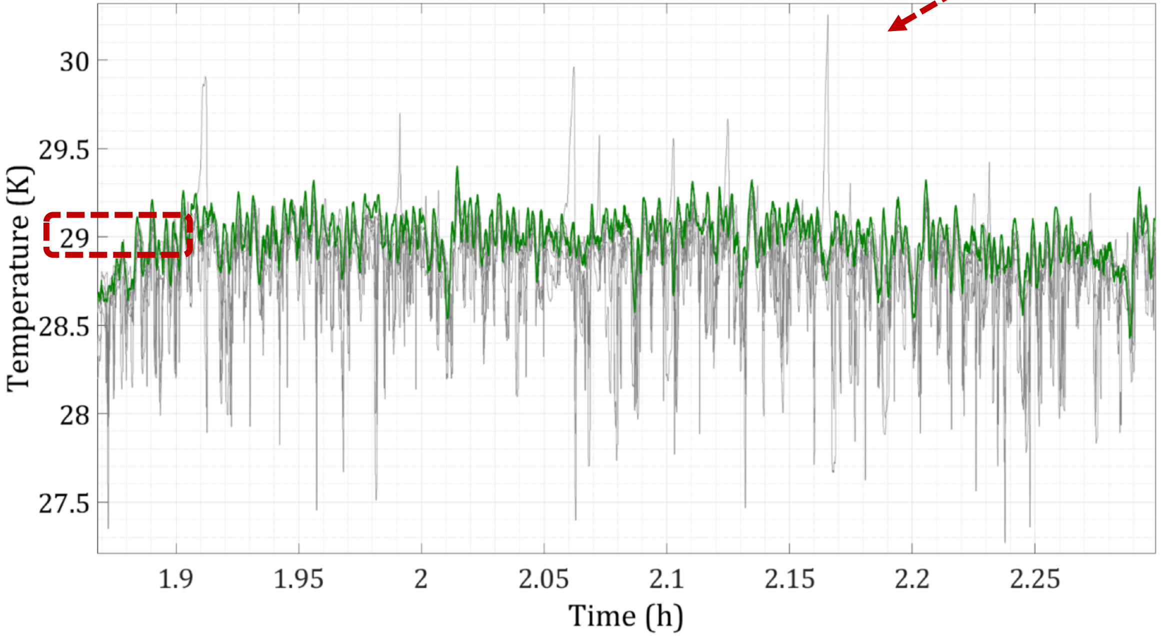
(5 watt-steps every 45 minutes)



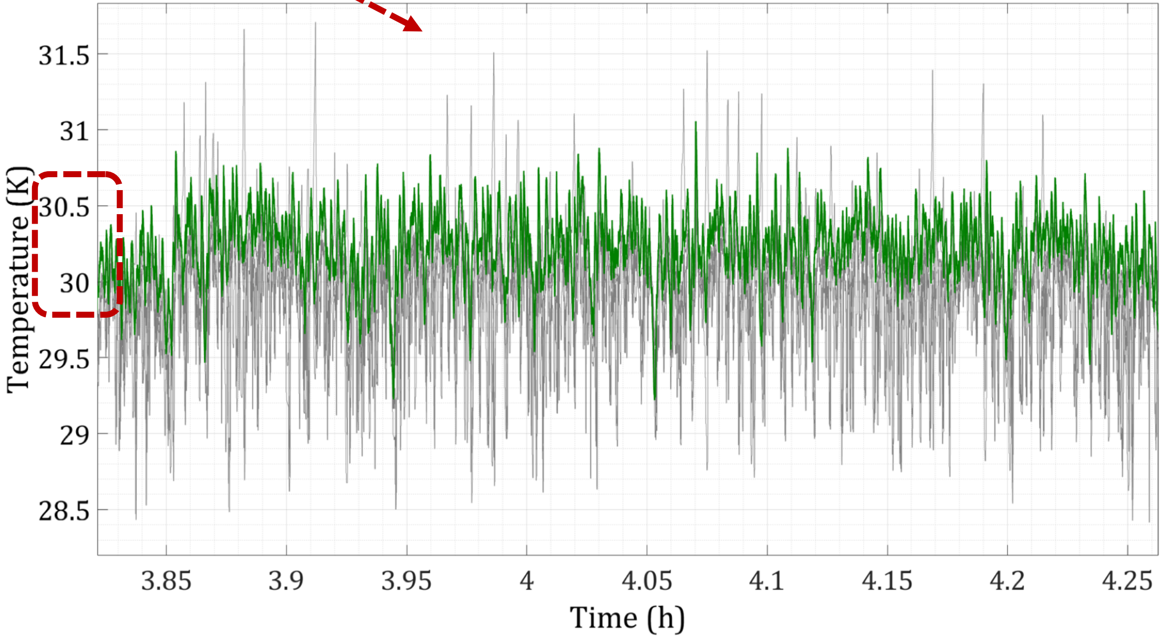
CRYOGENIC PHP: EXPERIMENTAL RESULTS (2/4)



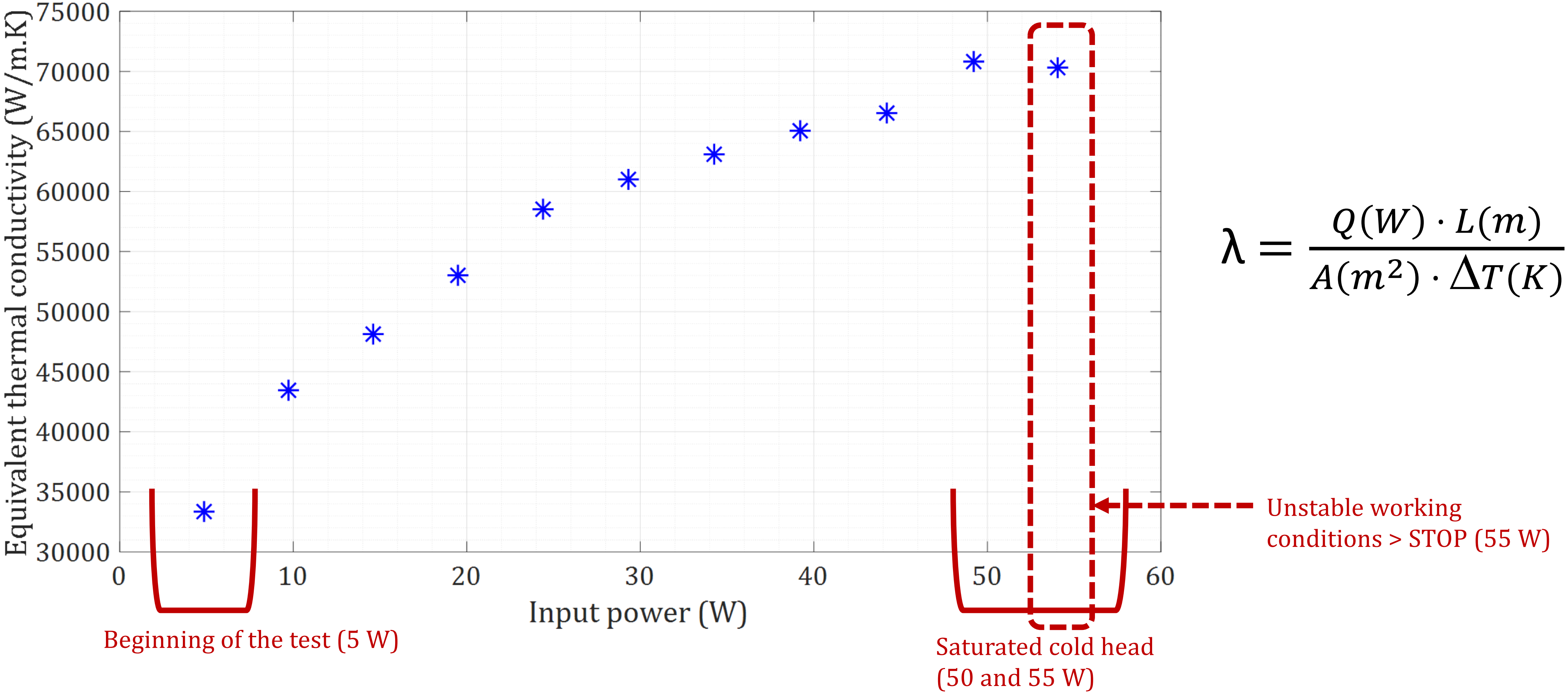
Adiabatic part
Saturation temperature
(from Pressure measurements)



Adiabatic part
Saturation temperature
(from Pressure measurements)



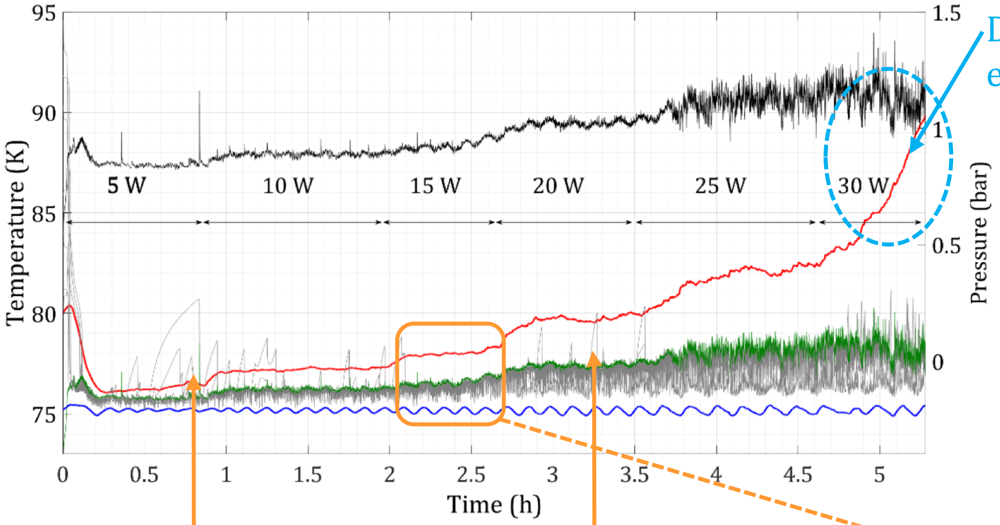
CRYOGENIC PHP: EXPERIMENTAL RESULTS (3/4)



$$\lambda = \frac{Q(W) \cdot L(m)}{A(m^2) \cdot \Delta T(K)}$$

CRYOGENIC PHP: COMPARISON WITH PREVIOUS EXPERIMENTS

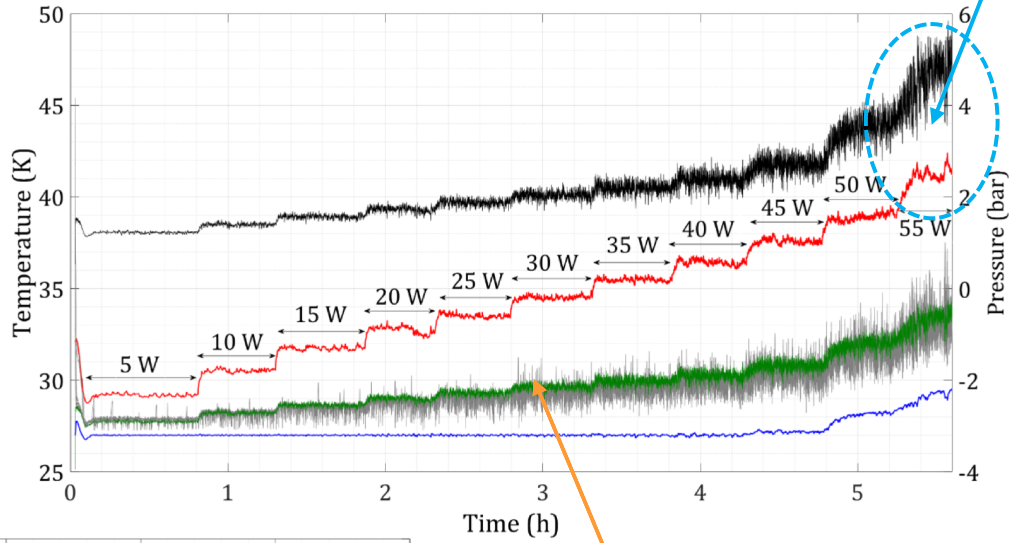
Nitrogen* as working fluid:



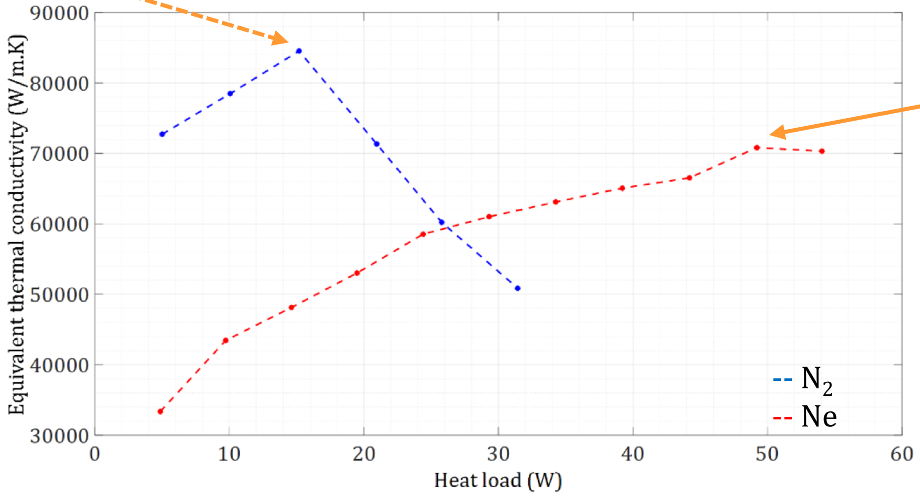
Dry-out at the evaporator

Local dry-outs at low and high heat loads

Neon as working fluid:



Unstable conditions and high working pressure



Temperature peaks and equivalent thermal conductivity increase with the heat load

*Bruce R, Barba M, Bonelli A and Baudouy B 2018, Cryogenics 93 66-74 URL https://doi.org/10.1016/j.cryogenics.2018.05.007

CRYOGENIC PHP: EXPERIMENTAL RESULTS (4/4)

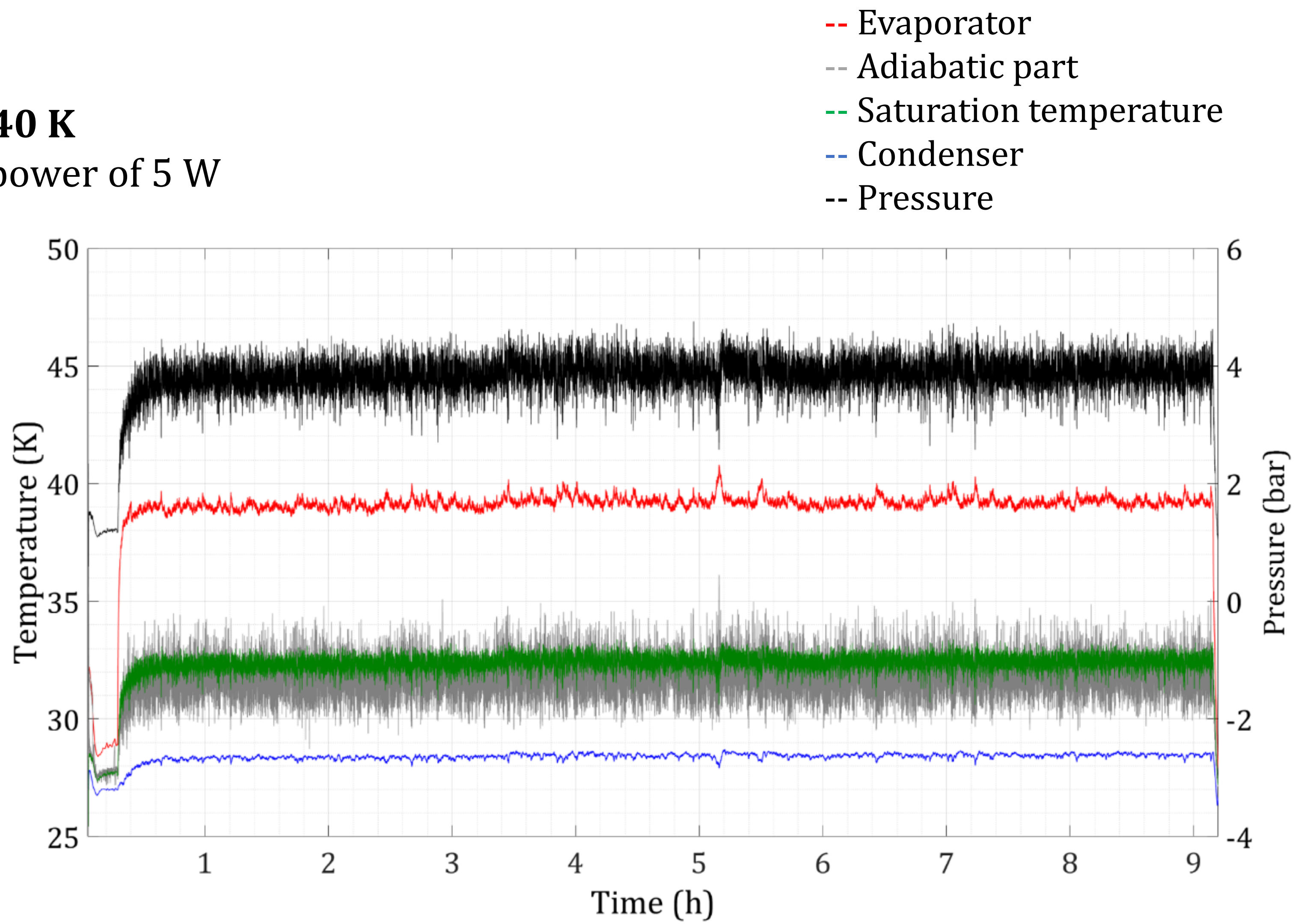
<u>Characteristics of the test:</u>

- Working fluid: **Neon (Ne)**
- Range of working temperatures **27 – 40 K**
- **Initial conditions:** ΔT 5 K and input power of 5 W
- Condenser temperature fixed @ 27 K
- Filling ratio: **29.5 %** (V_{liquid}/V_{php})

<u>Type of test:</u>

Fixed heat load at 50 W during 9 hours

Equivalent thermal conductivity (at 50 W): 70 000 W/m.K



CRYOGENIC PHP: CONCLUSIONS

- Max. heat load transferred in **stable** conditions: **50 W**

- Stability during long periods of time verified

- Maximum **equivalent thermal conductivity** (achieved at 50 W):

  Ne 70 000 W/m.K vs **Cu (RRR = 300) 3500** W/m.K @ 27 K (20 times higher!!)

- **Ne** as working fluid shows impressive **thermal performance** even when the inner diameter of the tubes is **larger** than possible according to the most common criterion found in the literature:

$$Bo \leq 4 \qquad\qquad D_{crit} \leq 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$$

  - Øinner max theorical= **1.25 mm**
  - Øinner of our experimental setup = **1.5 mm**

FUTURE WORK

- Continue the experimental data analysis
- Numerical simulations to compare with experimental results
- Tests using other working fluids (comparative study)
- Quench tests for magnet applications (transient thermal tests)
- Modification of the test bench:
  to increase the length of the adiabatic part

Thank you !

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