EASISchool 2 on Cryogenics

CEA (France)

September 30th – October 4th 2019

New cryogenic cooling techniques

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Overview

I. Existing cryogenic cooling techniques

II. New cryogenic cooling techniques

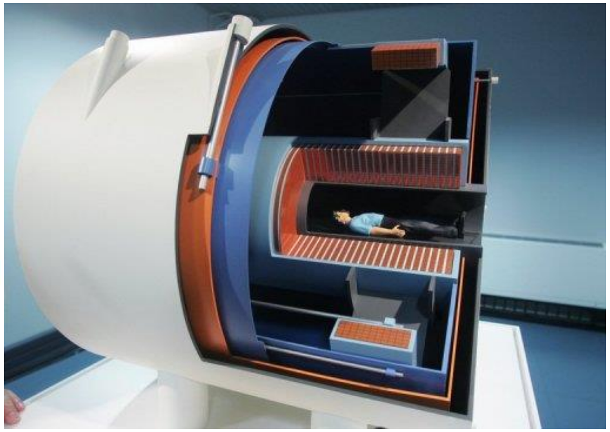
III. The SR2S project

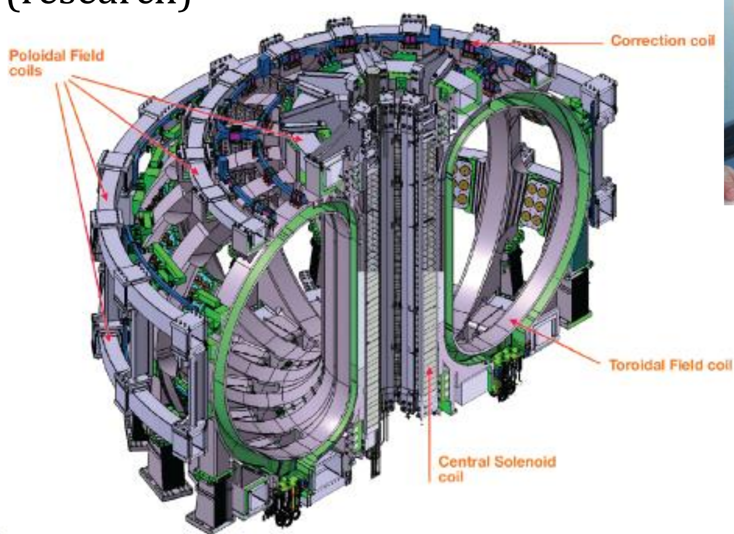
IV. The PHPs at the CEA

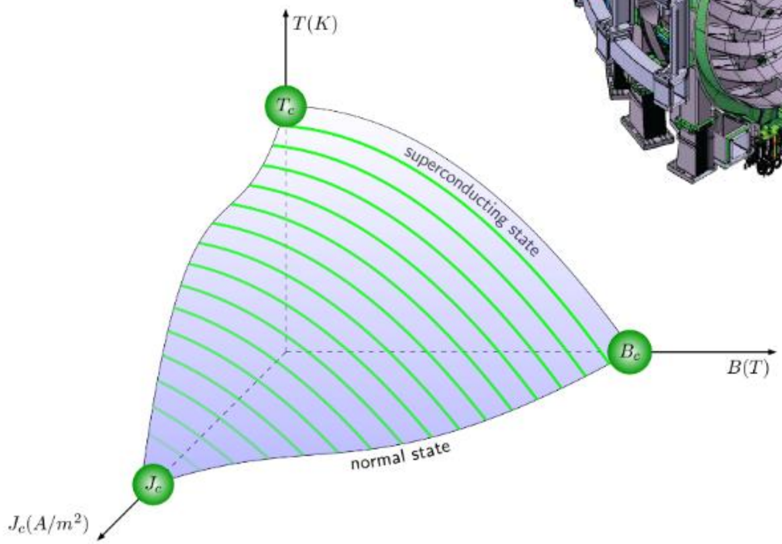
V. Other configurations and applications

I. Cryogenic cooling techniques

- **Superconducting magnets** extensively used in high magnetic field applications:
  - Plasma confinement (fusion)
  - MRI (medical)
  - Beam focalization (accelerators)
  - Particle detection (research)







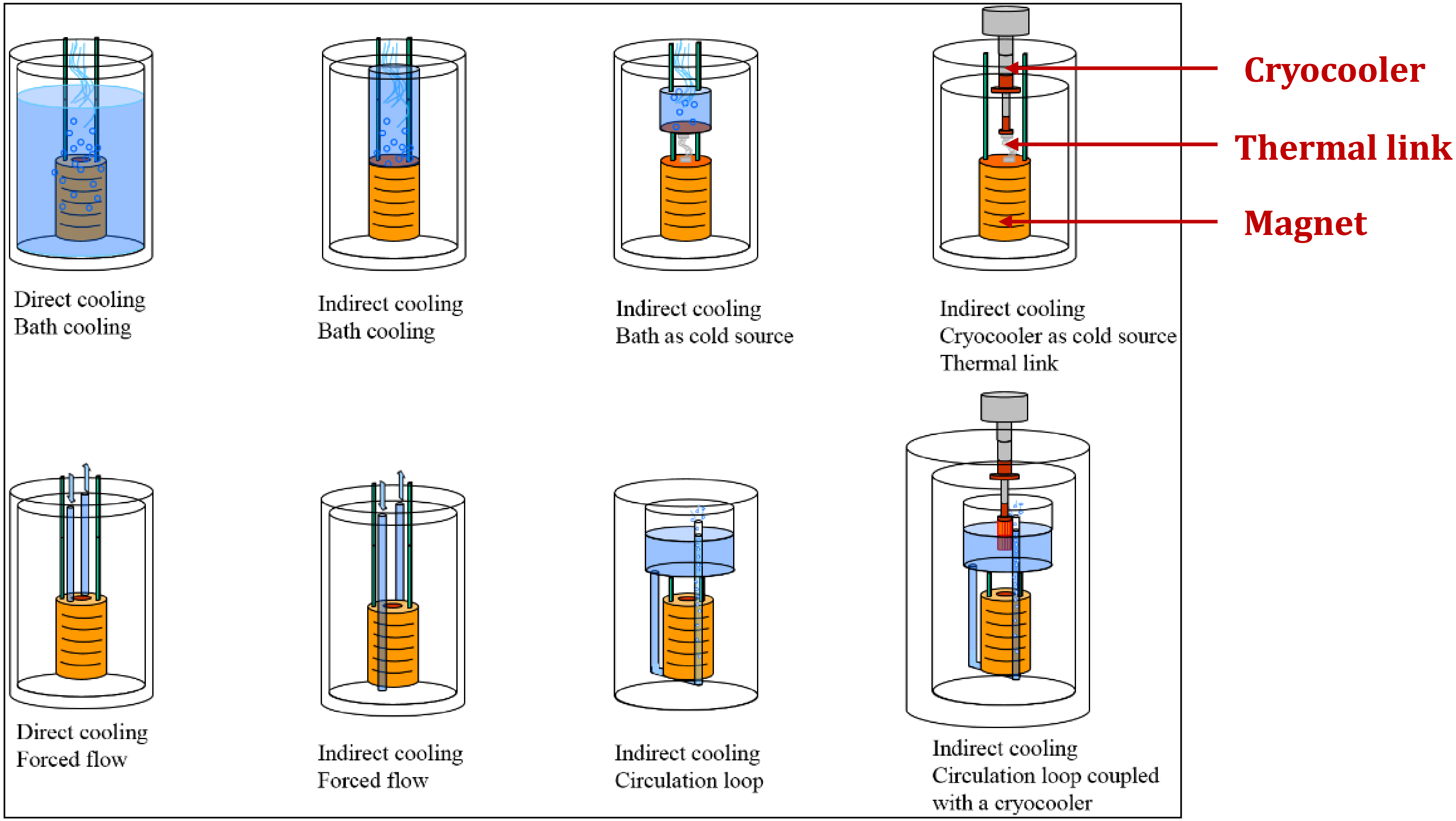
- Superconducting state reached in the "**superconducting region**" (Bc, Tc and Jc)

⇩

- Need of cryogenic cooling techniques

I. Cryogenic cooling techniques

- Cryogenic cooling techniques: **direct** and **indirect** methods

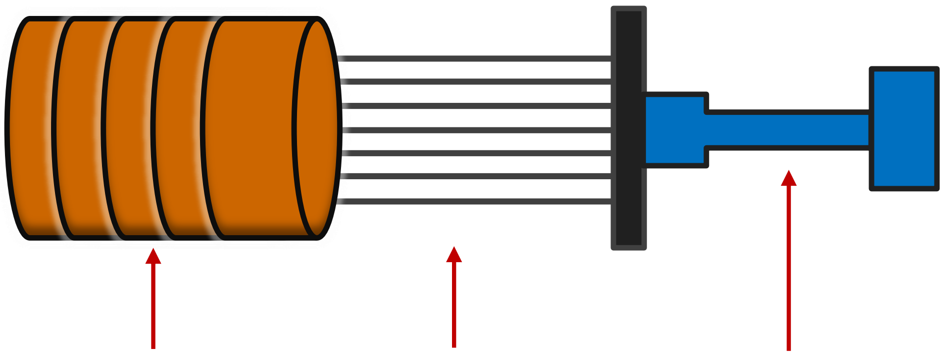


Courtesy of B. Baudouy. Heat transfer and cooling techniques at low temperature, 2013.

II. New cryogenic cooling techniques

New requirements:

- **Small quantity of working fluid** (to avoid He scarcities)
- **Lightness** and **gravity independence** (for space applications)
- **Simple configuration**
- To separate the magnet from the fringe field (distance around 1m)



Cooling solution: **Cryogenic Pulsating Heat Pipes**

II. New cryogenic cooling techniques

Example of a novel cryogenic cooling technique:

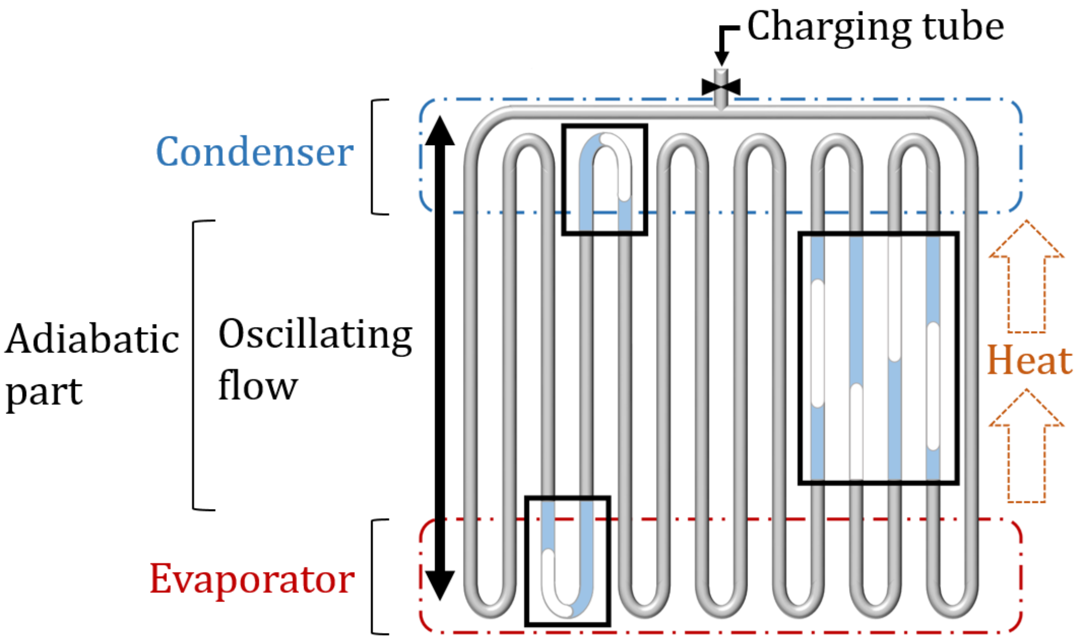
- **P**ulsating (or **O**scillating) **H**eat **P**ipes (PHP or OHP): **two-phase thermal links** consisting of a long **capillary** channel bent into many U-turns

- **Condenser** and **evaporator** separated by an **adiabatic part**

- Maximum **inner diameter** defined using the **Bond dimensionless number**

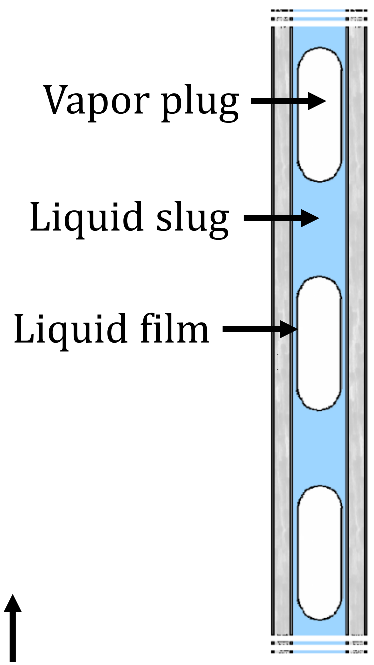
$$Bo = \frac{(\rho_l - \rho_v) g D^2}{\sigma} \leq 4$$

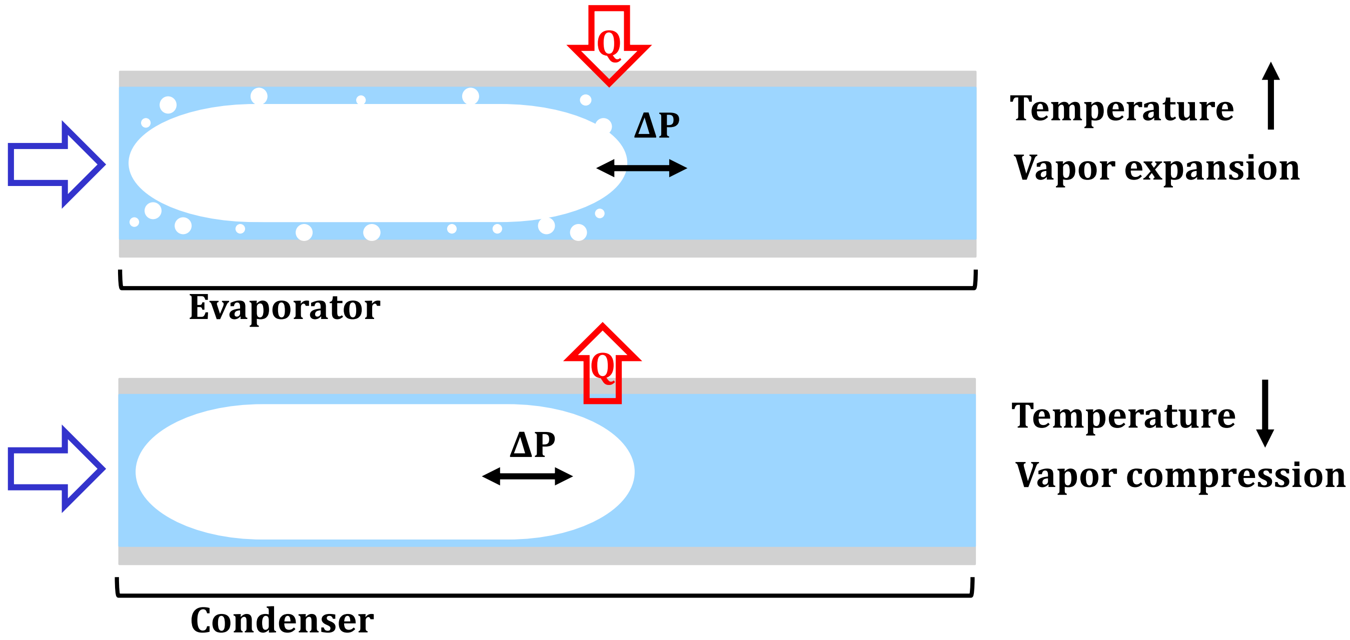
$$D_{crit} \leq 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}$$



II. New cryogenic cooling techniques

- **Two-phase** working fluid close to phase **change conditions**
- Distribution of the working fluid in **alternating liquid slugs and vapor plugs**
- **Liquid film** enables circulation of the vapor plugs sliding through the tube
- Thermally driven by an **oscillating flow** of liquid slugs and vapor plugs





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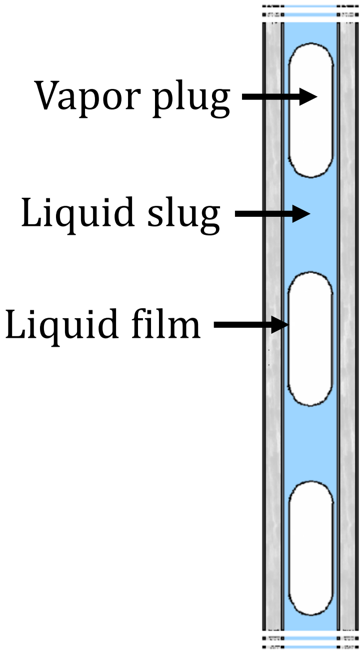
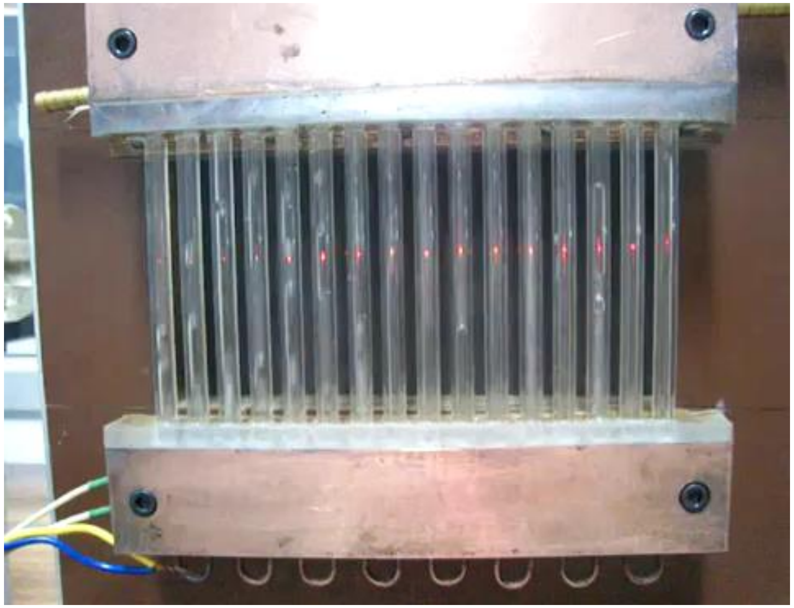




***Sameer Khandekar (2010)**

III. The SR2S project

Space travel missions…

<u>The problem:</u> harmful radiation effects on biological tissues… as an example… **A mission to Mars (2 years) has up to 40% risk of cancer death**…

- Solar Particle Events (SPE)
  Protons and helium from Sun (High Flux – Low Energy)
- Galactic Cosmic Rays (GCR)
  Protons, helium and ions (Low Flux – High Energy)

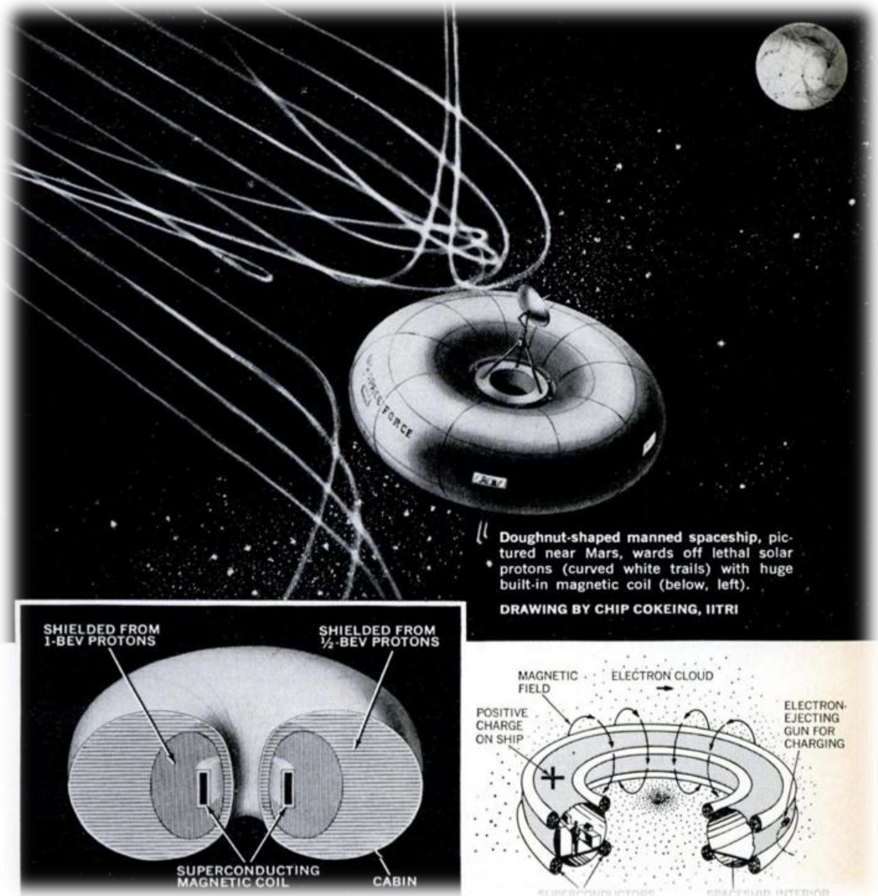
<u>One possible solution:</u>

Active shield ... like the earth does! Deviating "bad" particles with the magnetic field!

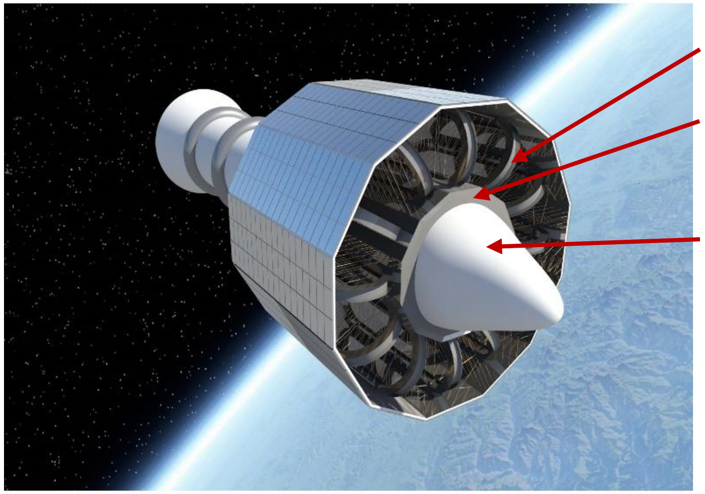
Superconducting magnets surrounding space rockets !

SR2S
Space Radiation Superconducting Shield

(European project)



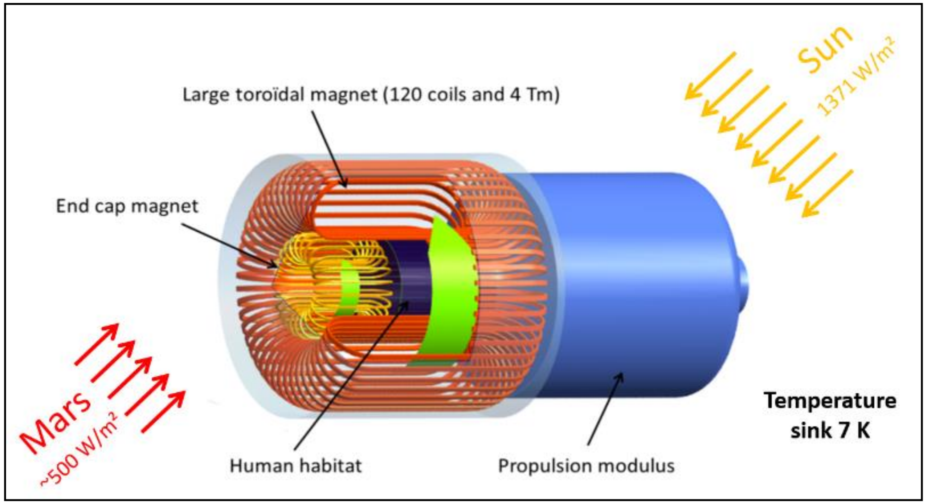
III. The SR2S project

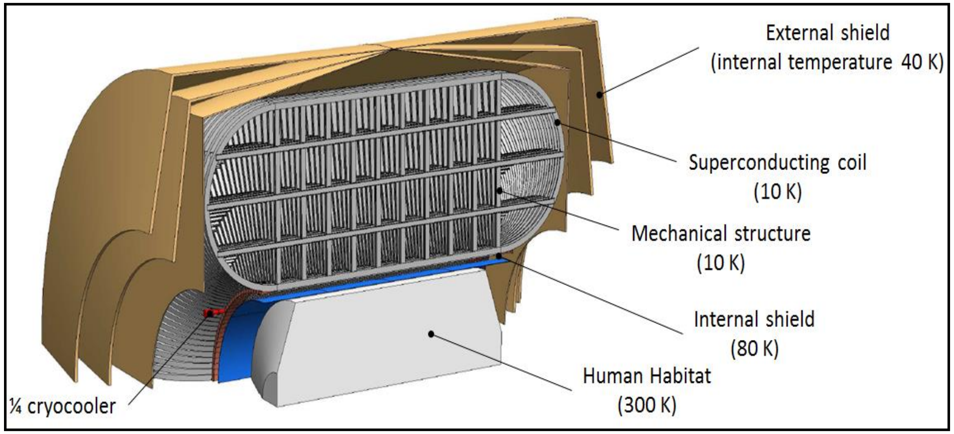


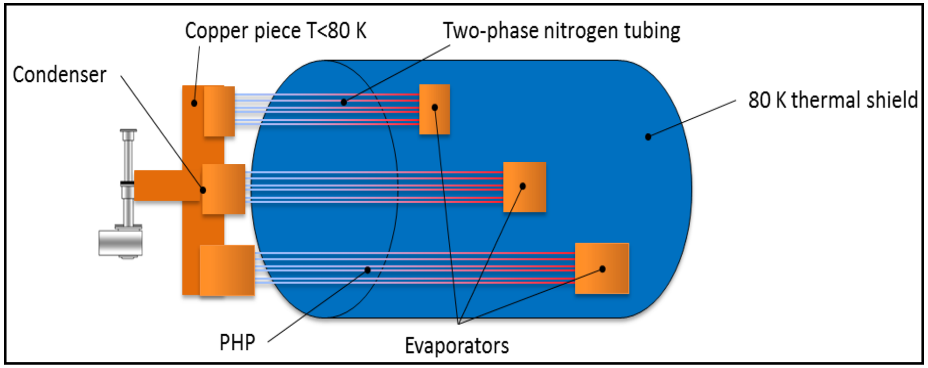
Coils (10 K)

Internal shield (80 K) and cryogenic cooling system

Human habitat (300 K)

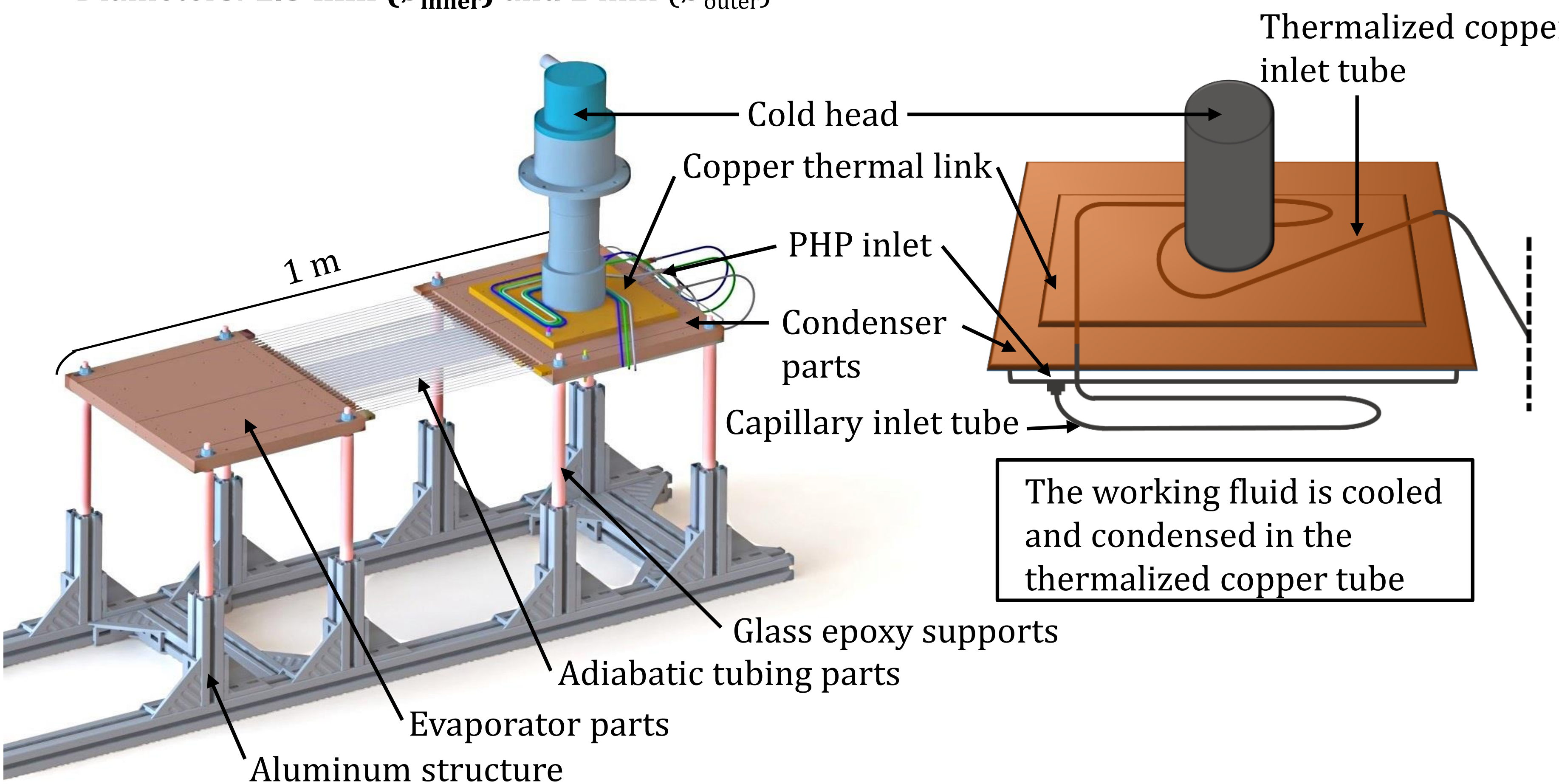






IV. The PHPs at the CEA

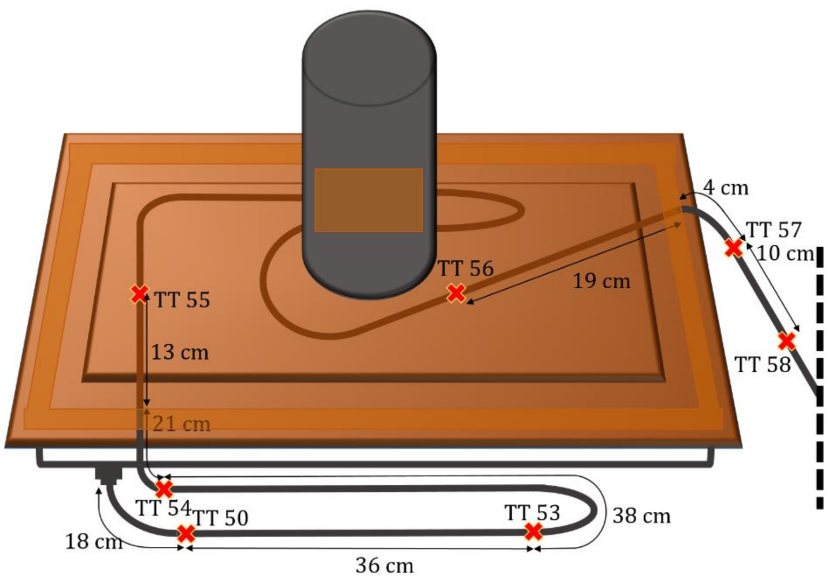
- **Three** PHPs with **12, 24** and **36 stainless steel capillary tubes** (poor thermal conduction)
- **Horizontal** position (closest configuration to zero-gravity)
- **1 m** long closed-PHP
- Diameters: **1.5 mm (ø$_{inner}$)** and 2 mm (Ø$_{outer}$)

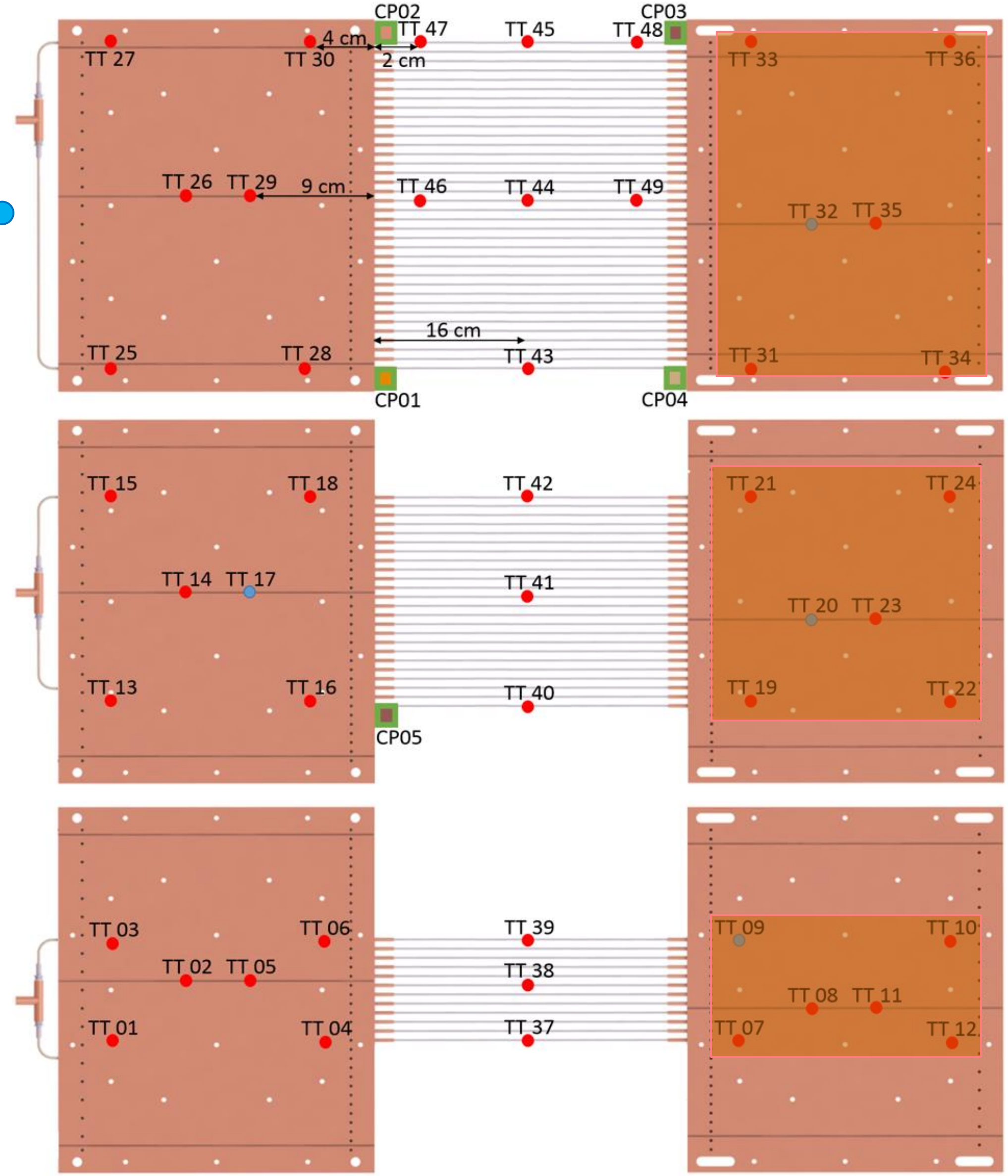


The working fluid is cooled and condensed in the thermalized copper tube

IV. The PHPs at the CEA

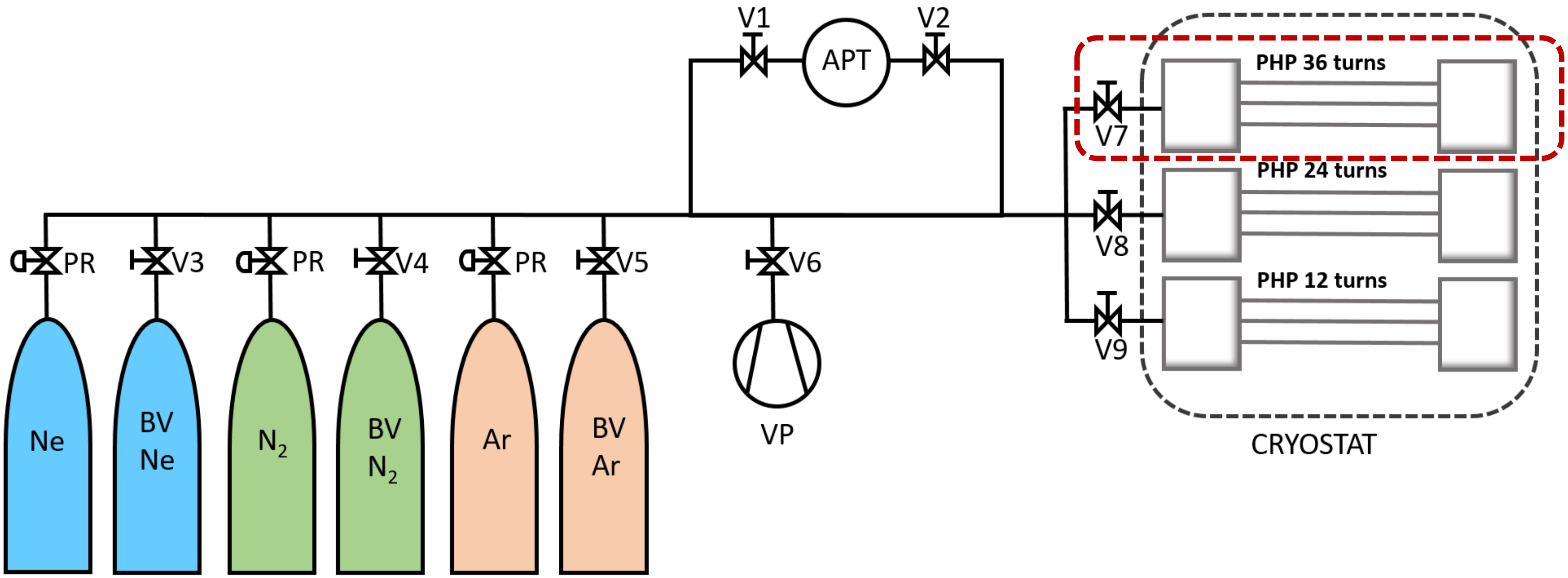
- 5 heaters (0 – 100 W)
  (temperature controller and input power)
- 56 temperature sensors
  - **Cernox (4 – 300 K) (±10mK - ±16mK)**
  - **Pt100 (37 – 300 K) (±0.15 K)**
- 6 pressure sensors
  - **Kulite (0 – 7.10^5 Pa) (±0.1%)**
  - **MKS (100 – 7.10^5 Pa) (±0.5%)**
- 1 vacuum sensor
  MKS (1.10^{-6} – 2.10^5 Pa)





IV. The PHPs at the CEA

- **Gas supply system** (gas tanks and buffer volumes 0.05 m^3 each)
- Thermal shields and cryostat (estimated undesirable heat inputs 1 W)
- Pumping systems (ensure vacuum environment 10^{-4} - 10^{-6} Pa)
- Data acquisition systems (sensors, acquisition cards, Labview program, etc.)
- Power supply systems



PR: Pressure Regulator

BV: Buffer Volume

APT: Absolute Pressure Transducer

VP: Vacuum Pump

PHP: Pulsating Heat Pipes

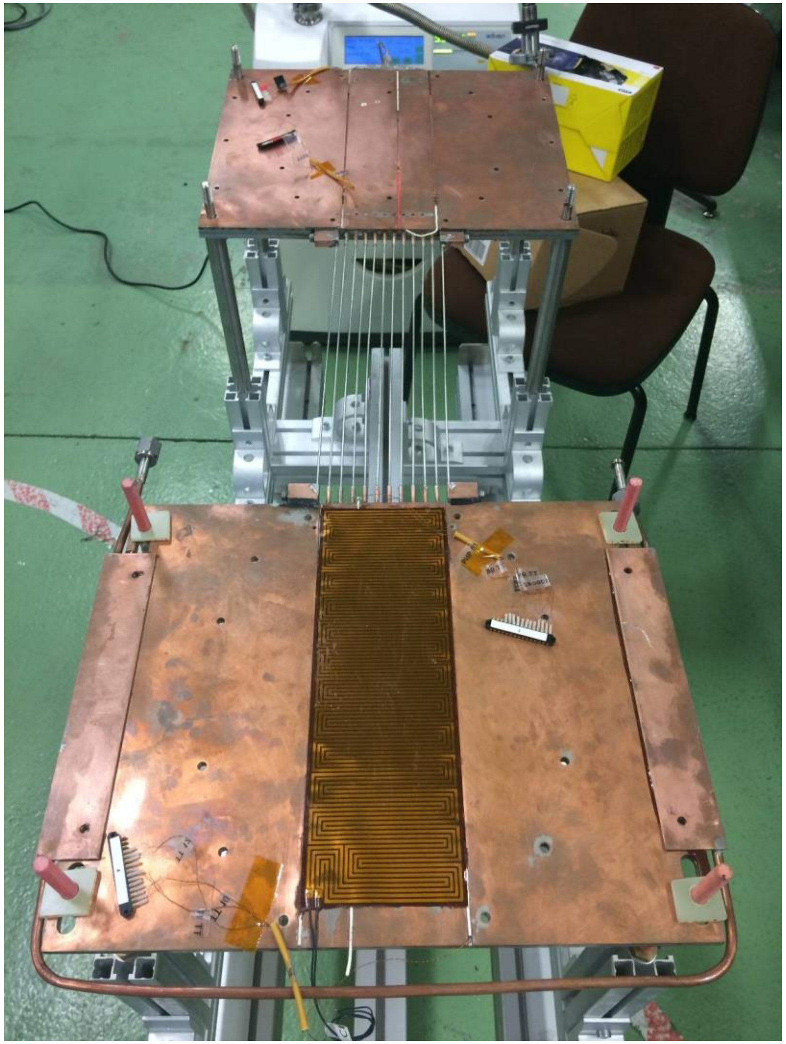
V1, 2, … : Valves

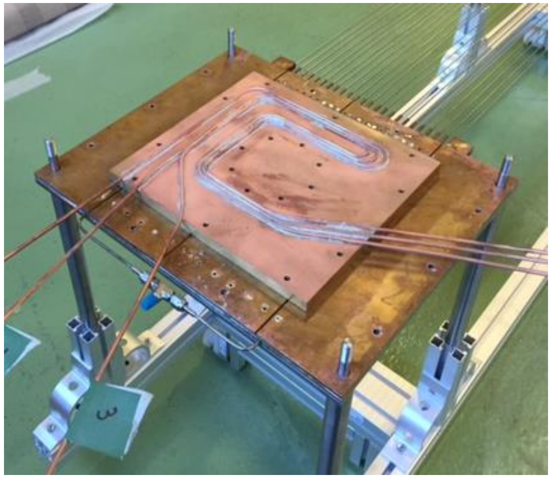
Ne: Neon gas tank

N_2: Nitrogen gas tank

Ar: Argon gas tank

IV. The PHPs at the CEA





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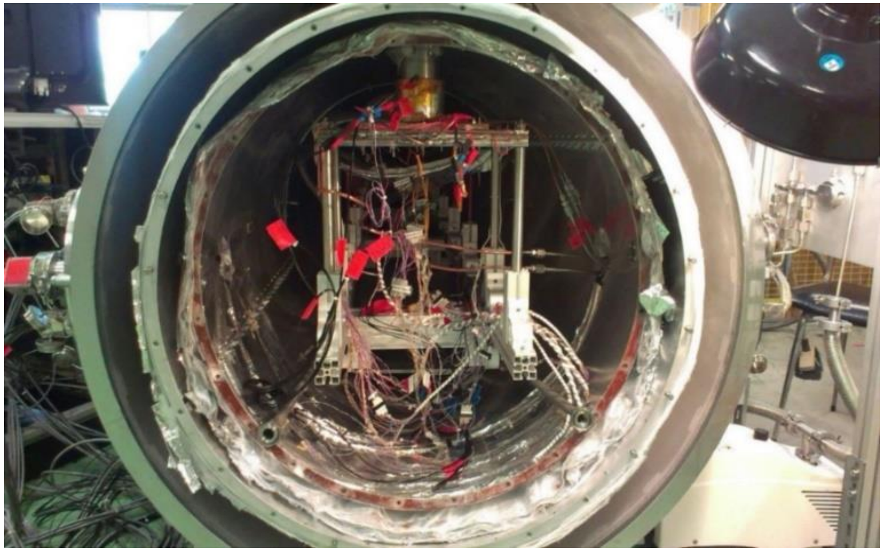
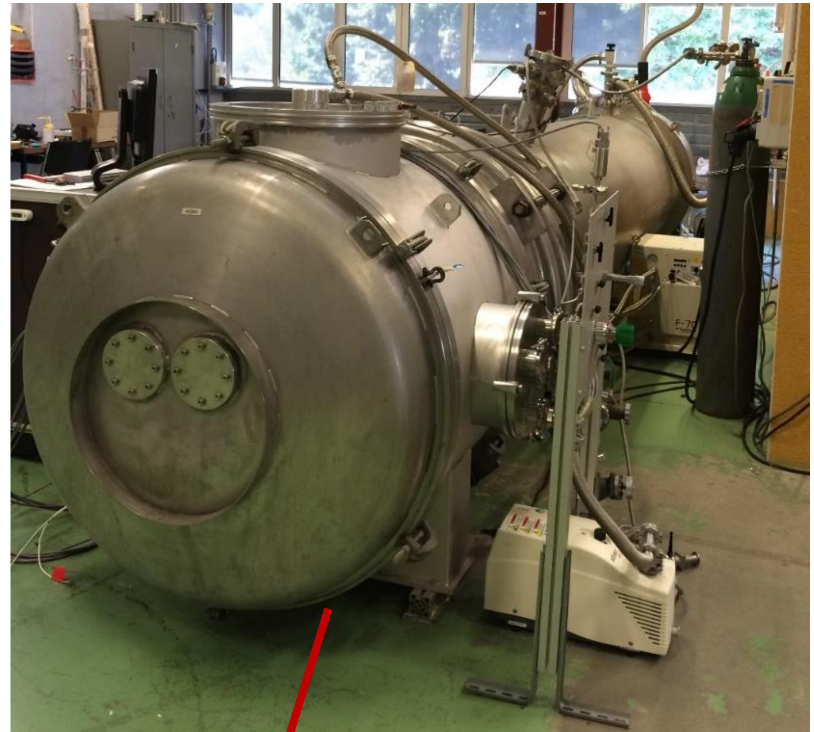
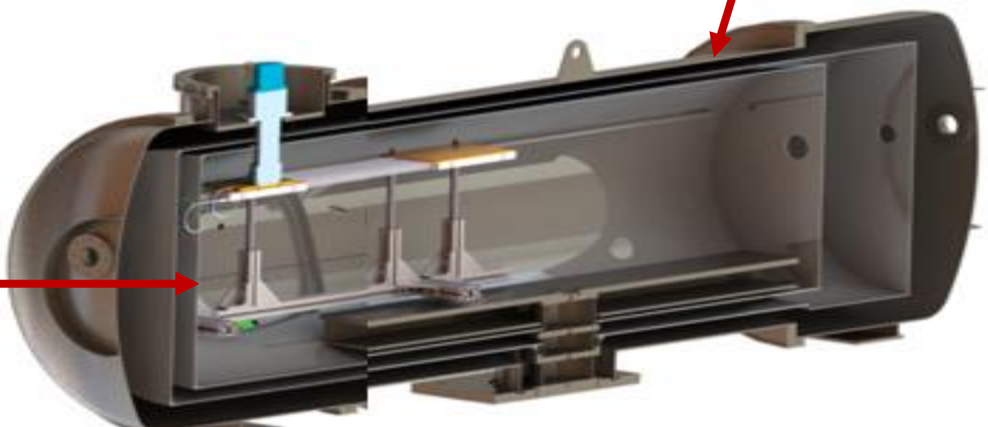


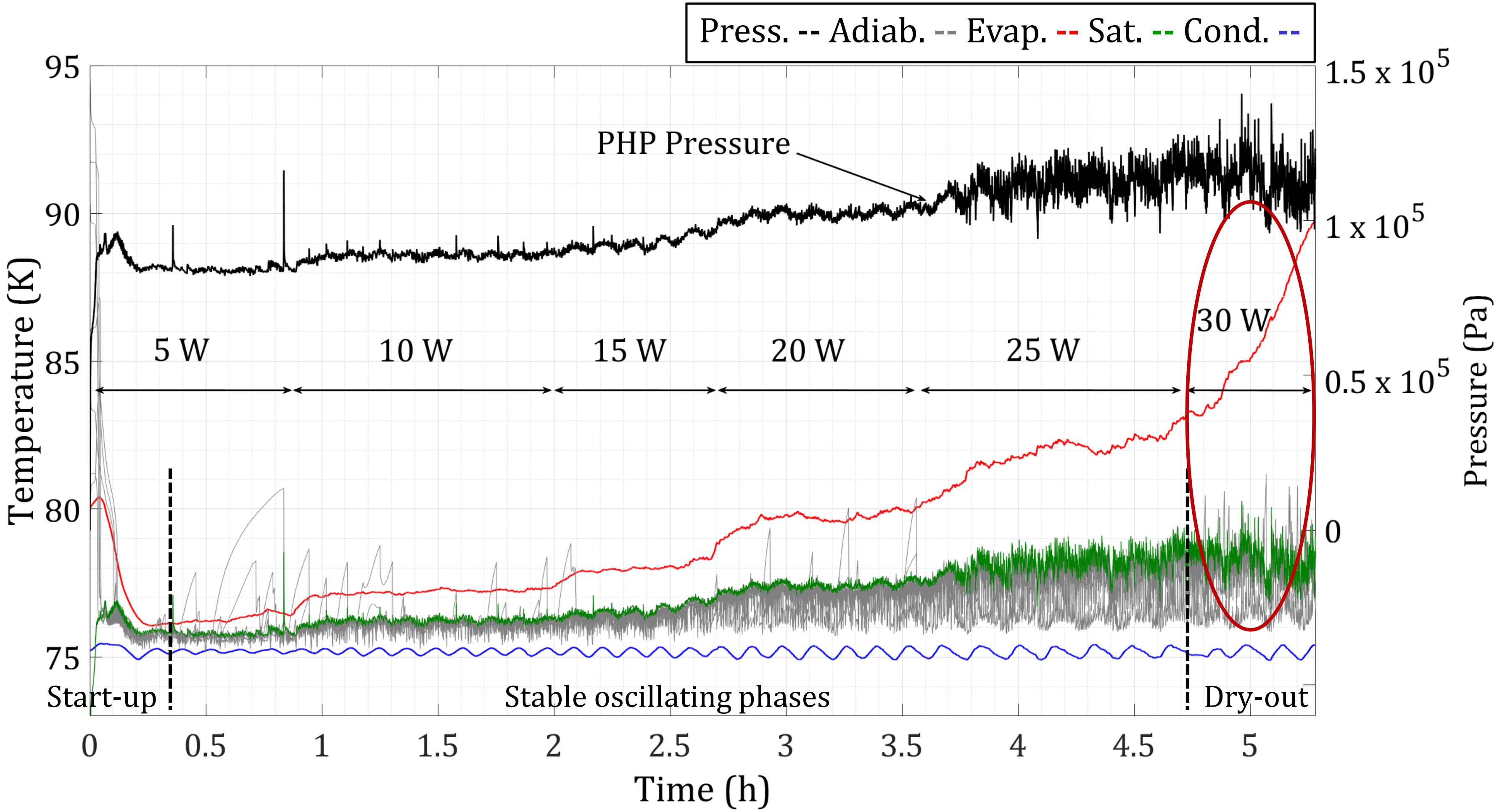




IV. The PHPs at the CEA

Progressive heat load tests: **Nitrogen**

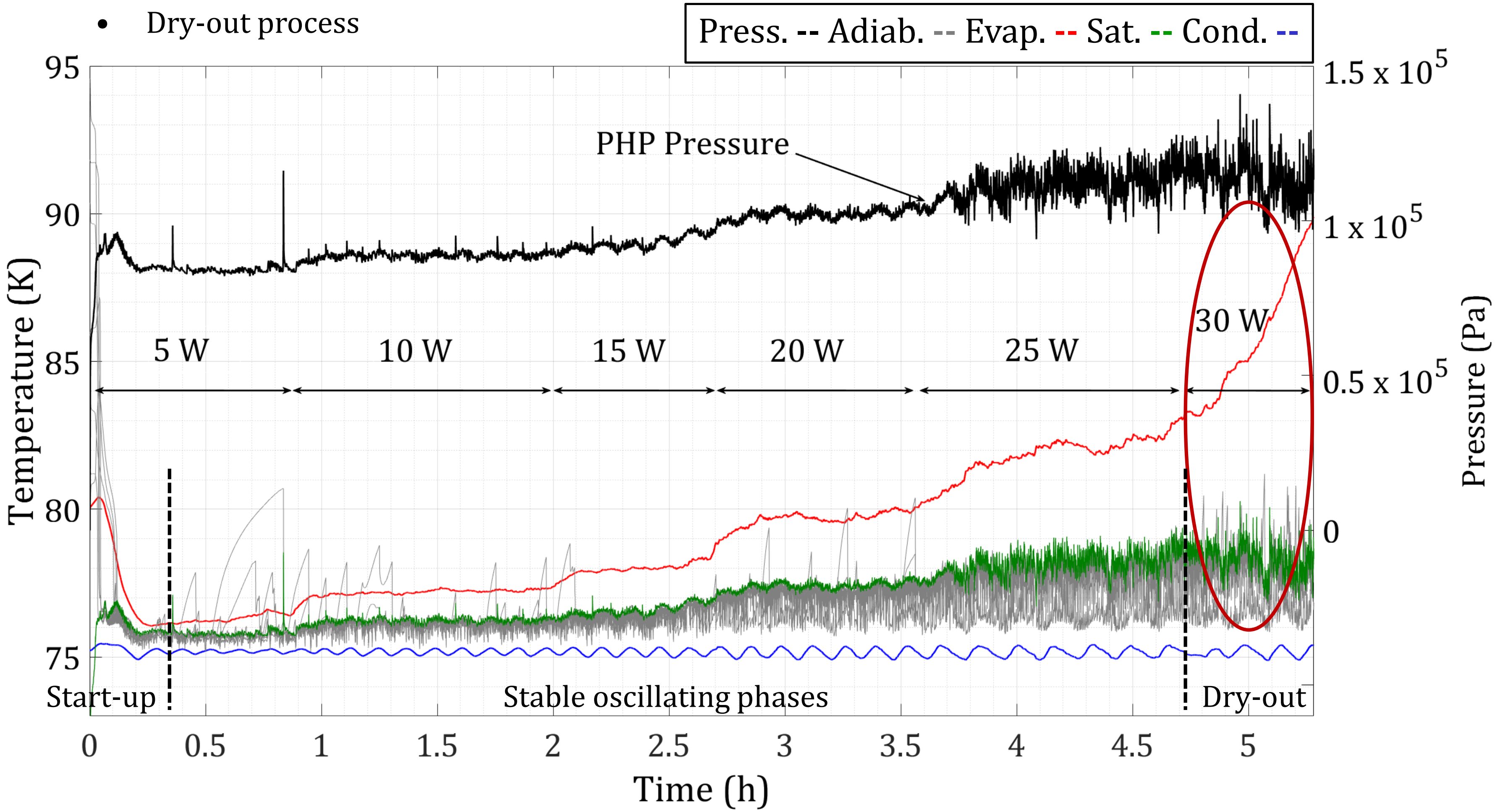
- Specific filling process and initial conditions (ΔTi = 5 K and 5 W)
- Condenser fixed at 75 K / FR 42-43 % / closed configuration
- Heat load increased every 40 min (5-watts steps)



IV. The PHPs at the CEA

Fluid's behavior and thermodynamic characterization:

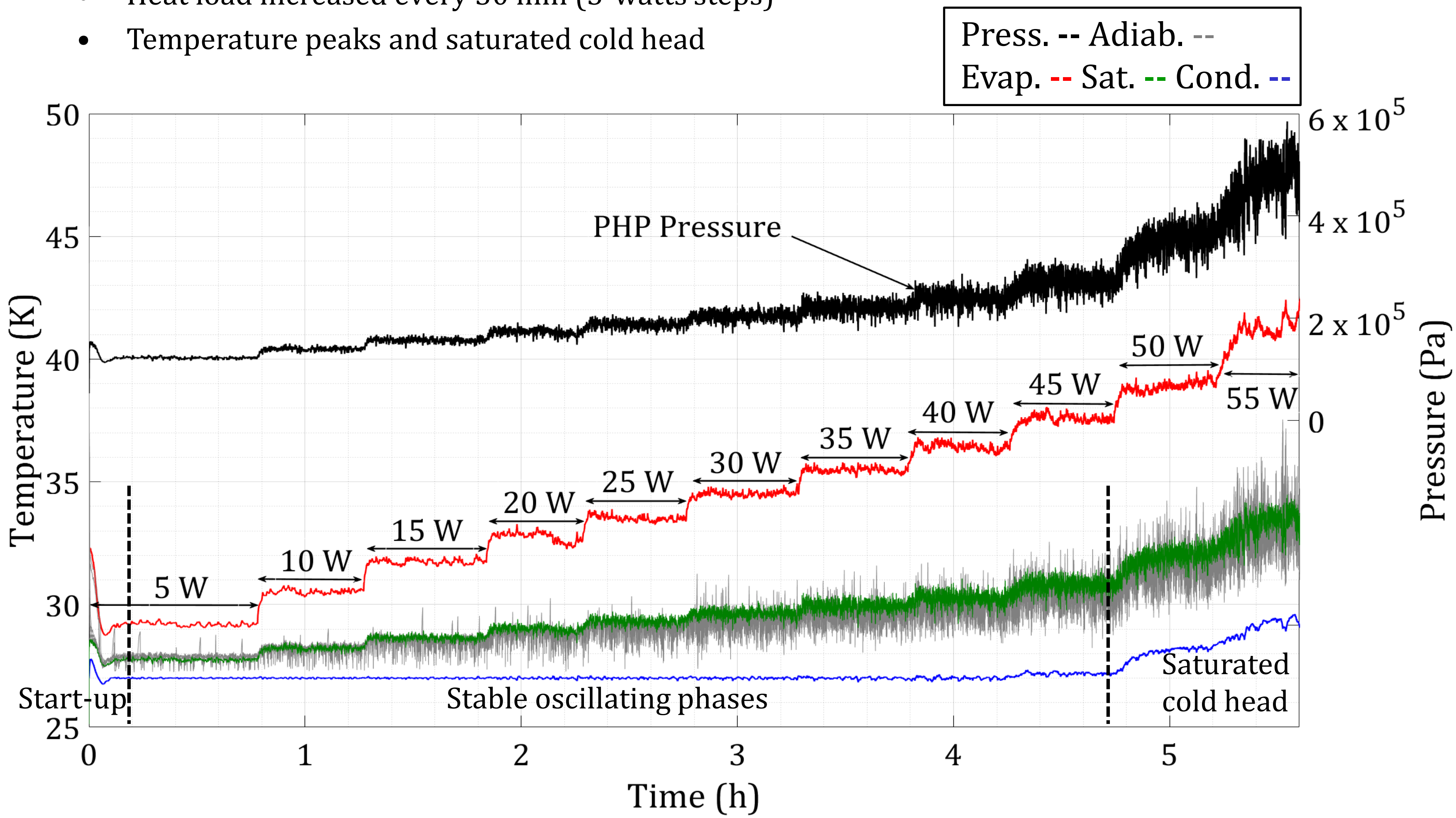
- Same pressure everywhere considered at saturation conditions
- Subcooled state of liquid parts
- Temperature peaks: local dry-outs and adiabatic compressions
- Dry-out process



IV. The PHPs at the CEA

Progressive heat load tests: **Neon**

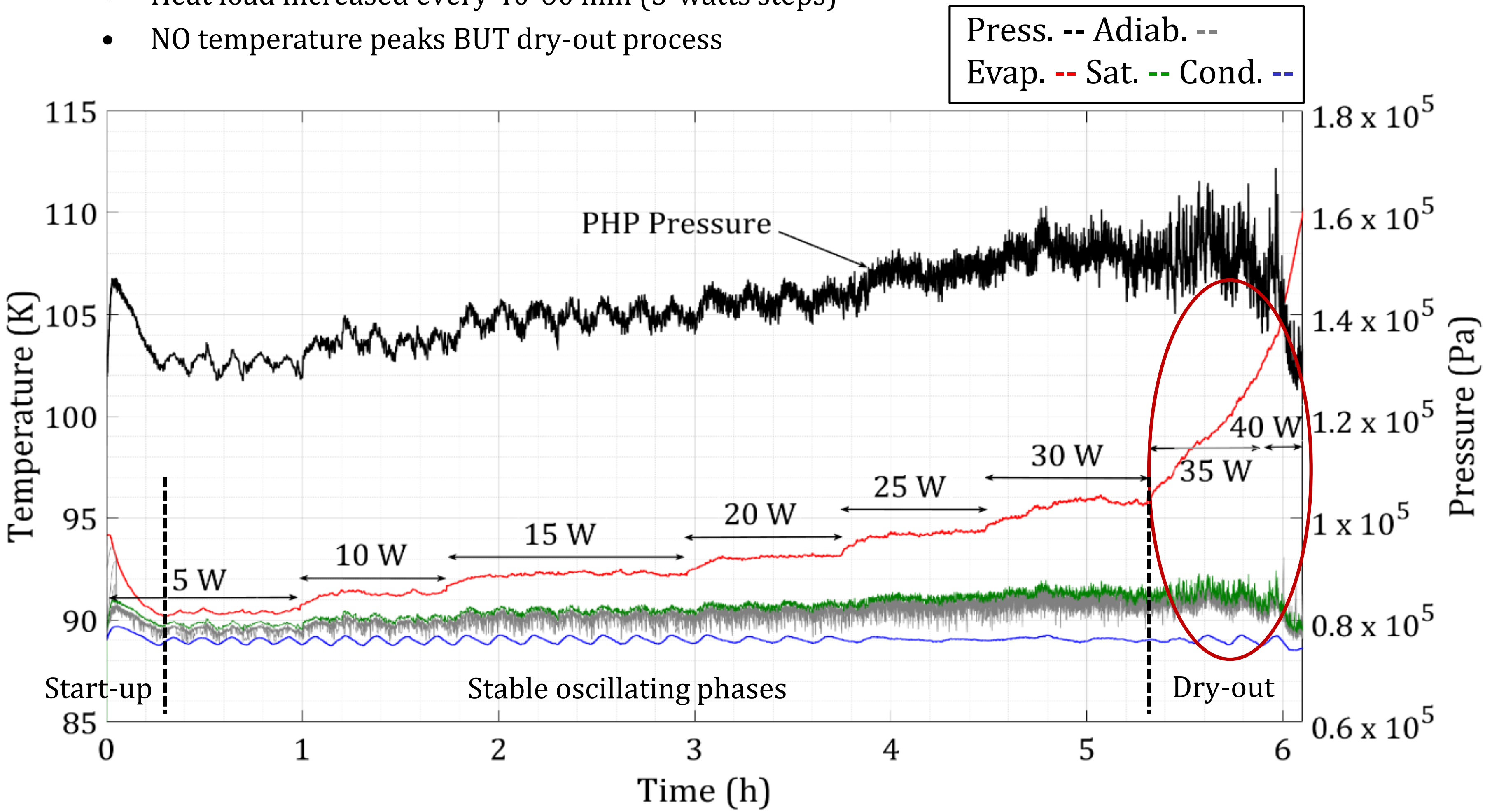
- Specific filling process and initial conditions (ΔTi = 5 K and 5 W)
- Condenser fixed at 27 K / FR 25 % / closed configuration
- Heat load increased every 30 min (5-watts steps)
- Temperature peaks and saturated cold head



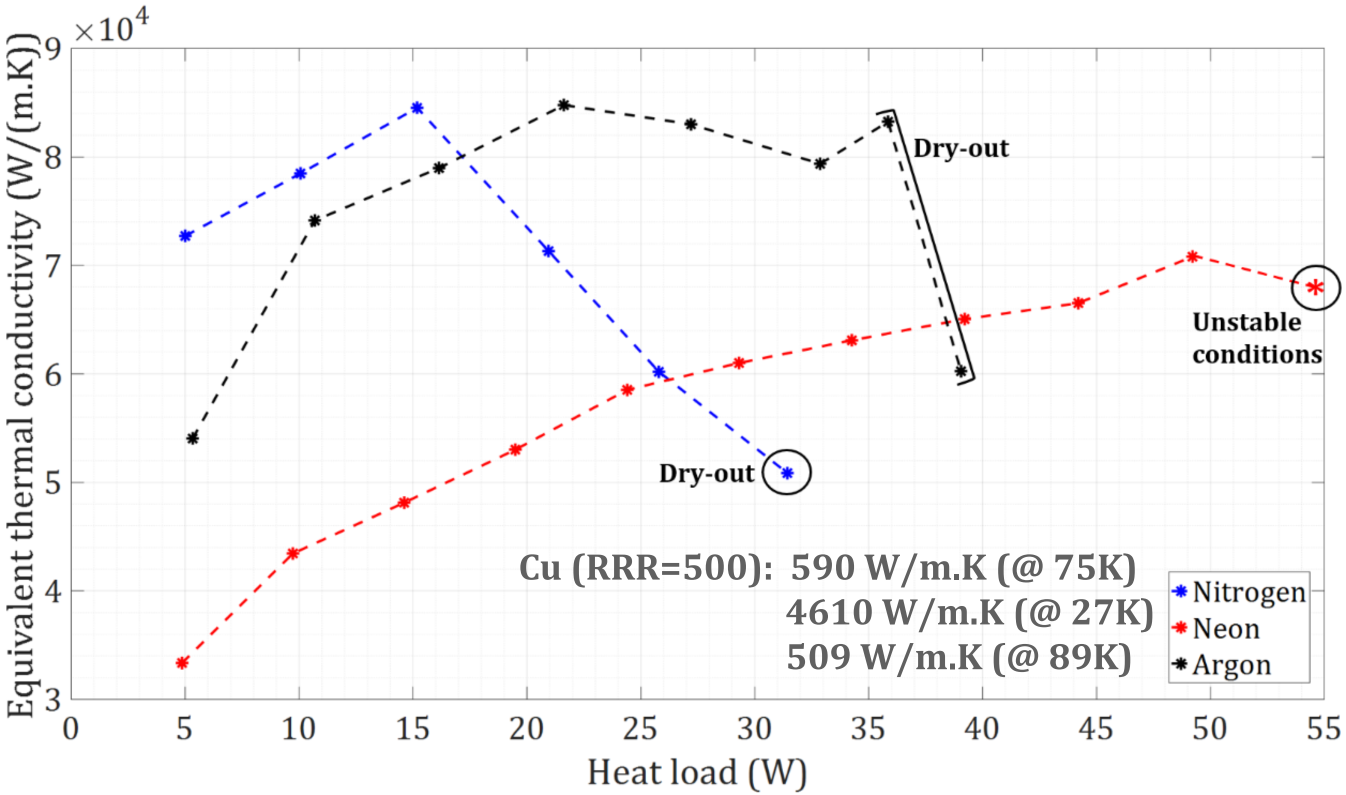
IV. The PHPs at the CEA

Progressive heat load tests: **Argon**

- Specific filling process and initial conditions (ΔTi = 5 K and 5 W)
- Condenser fixed at 89 K / FR 29-30 % / closed configuration
- Heat load increased every 40-60 min (5-watts steps)
- NO temperature peaks BUT dry-out process



IV. The PHPs at the CEA



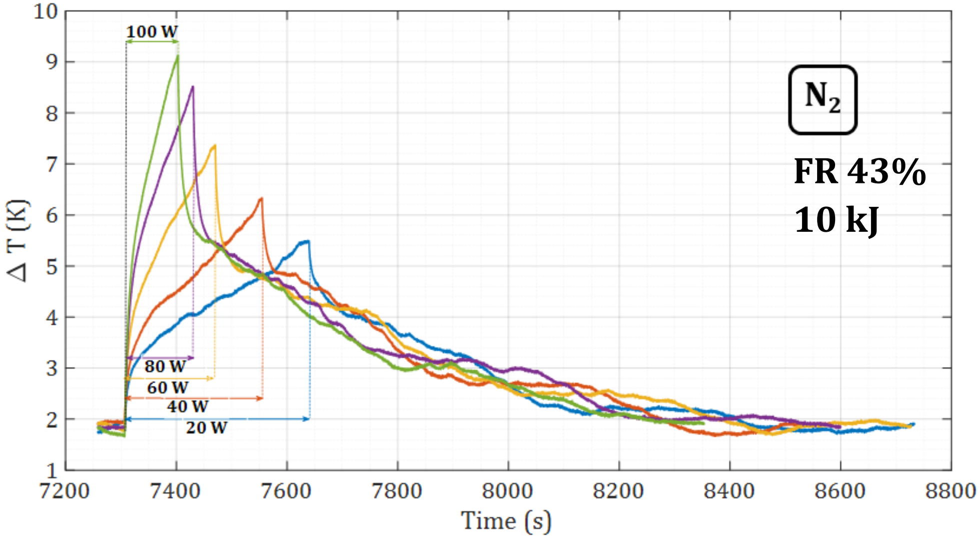
$$\lambda = \frac{Q \cdot L}{A \cdot \Delta T}$$

Between 7 and 170 times higher than Cu!!

Working fluid	Nitrogen	Neon	Argon
Range of working temperatures	**74 – 90 K**	**26 – 42 K**	**88 – 110 K**
Boiling point at 1. 10^5 Pa	**77.3 K**	**27.1 K**	**87.3 K**
Max. heat load (stable conditions)	**20 – 25 W**	**50 W (?)**	**25 – 30 W**

IV. The PHPs at the CEA

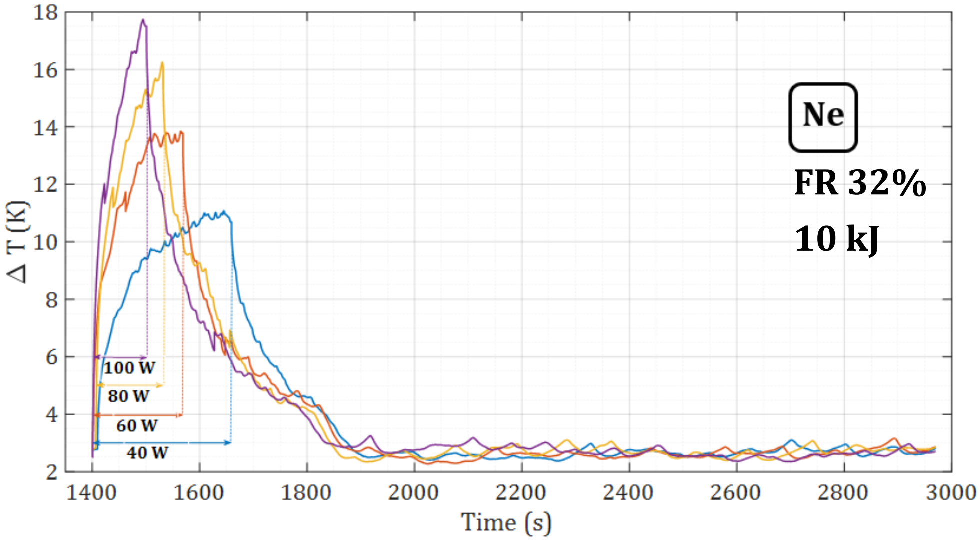
The PHPs for superconducting magnets applications:



Goal: **operating limits** of PHPs during transient heat load tests (**quench situations**)

Transient heat load tests:

5 W ⇨ High heat load ⇨ 5 W



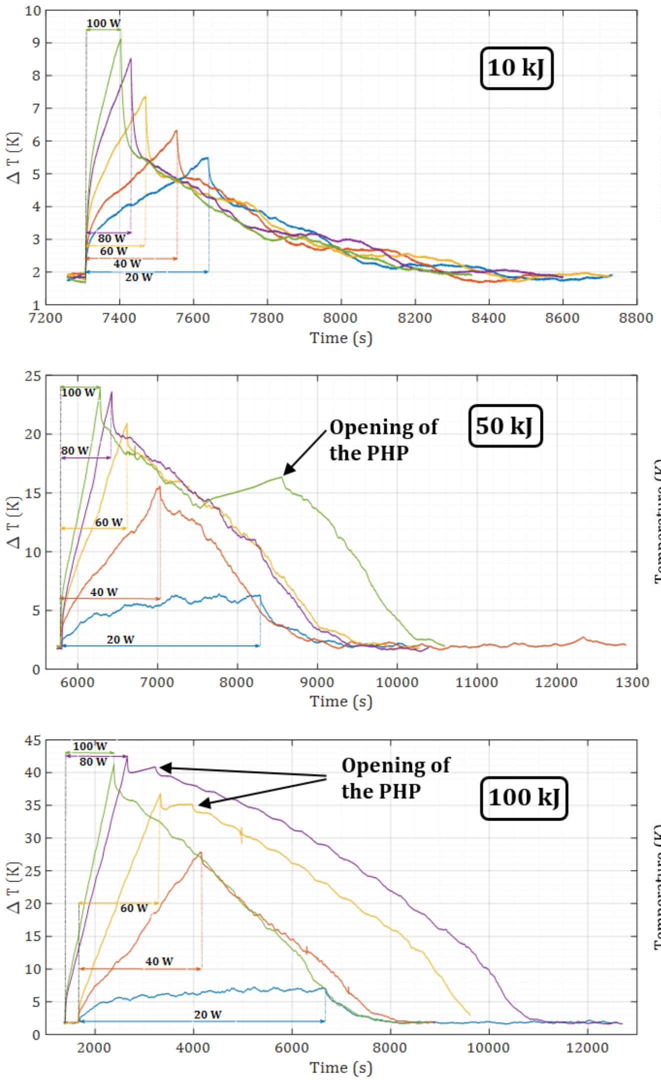
Remarks:

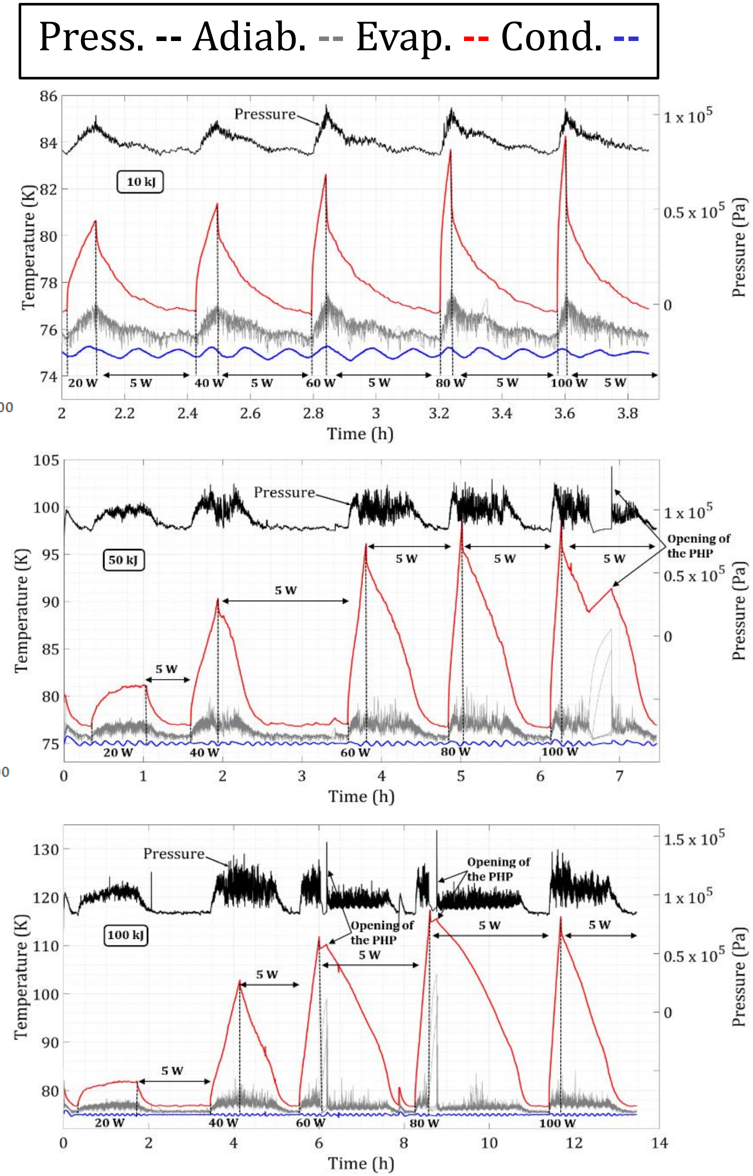
Neon: **higher ΔT** but **lower time duration to recover stable conditions** (neon's steeper slope of the saturation curve)

Cp of copper at the ranges of **working temperatures** (neon's temperatures lower Cp so higher temperature increments)

IV. The PHPs at the CEA

N_2 FR 43 % ± 0.5 %



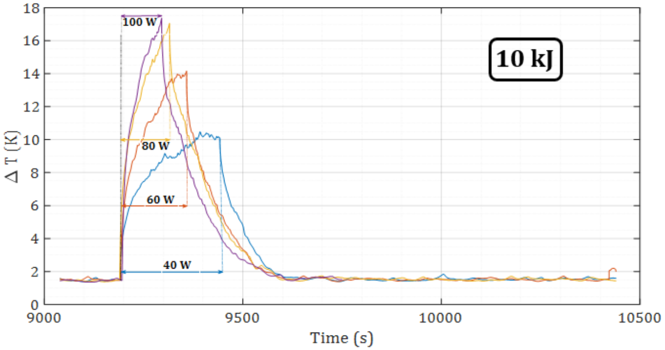


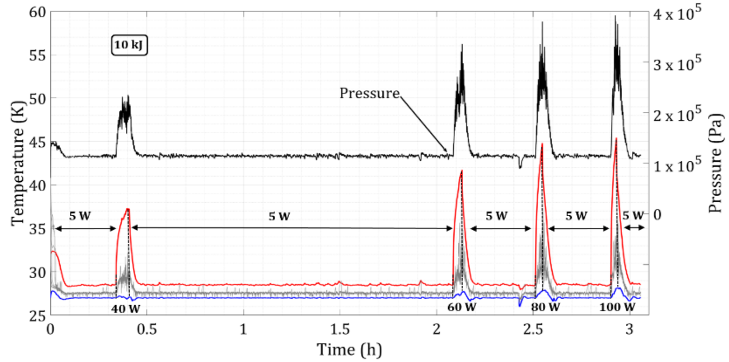
- Oscillations of the adiabatic part (heat transferred)
- Stop-flows and increasing temperature (opening of the PHP)

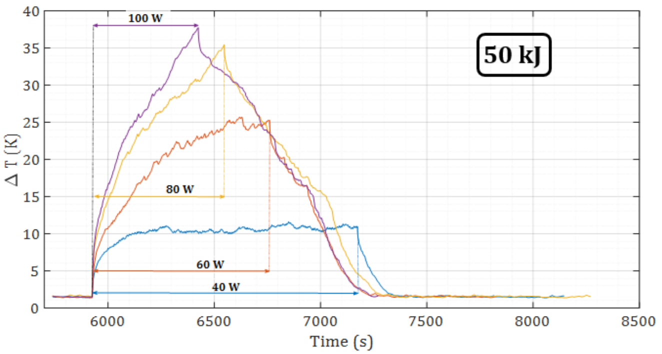
IV. The PHPs at the CEA

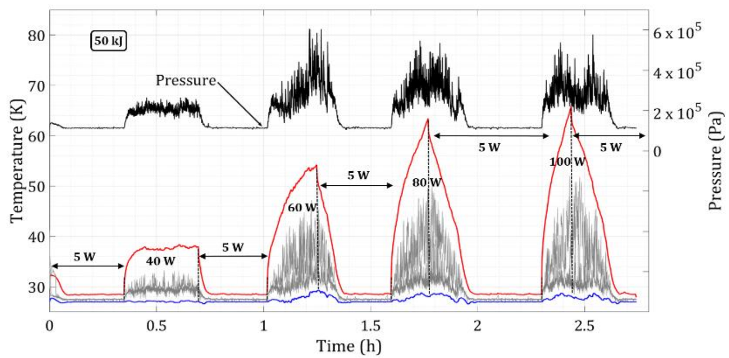
Ne FR 23 %

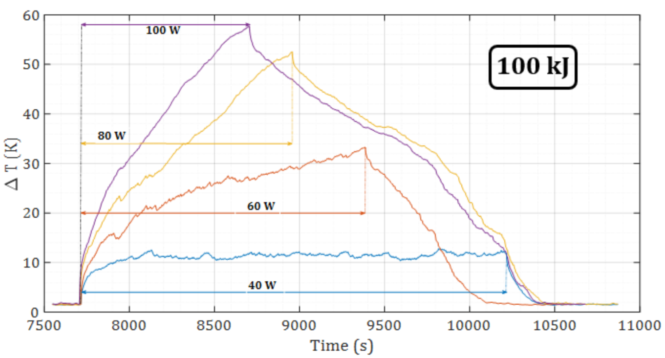
Press. -- Adiab. -- Evap. -- Cond. --

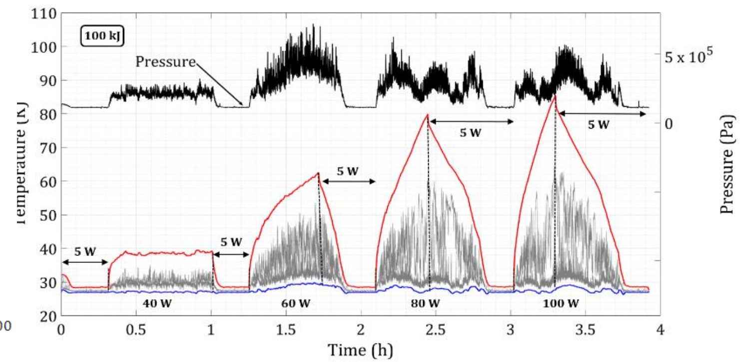






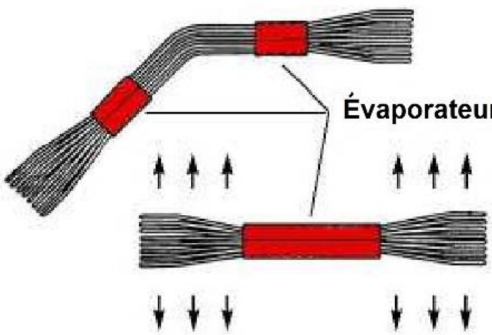


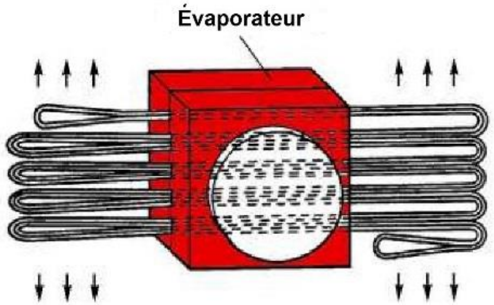


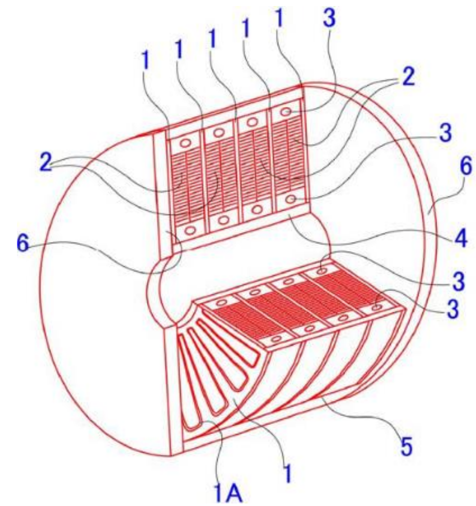


- Oscillations of the adiabatic part (heat transferred)
- NO Stop-flows

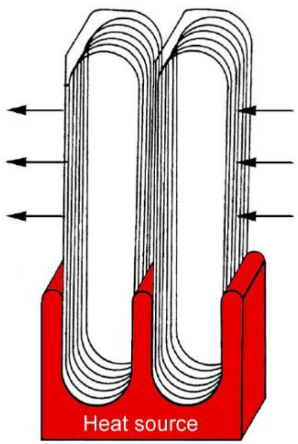
V. Other configurations and applications

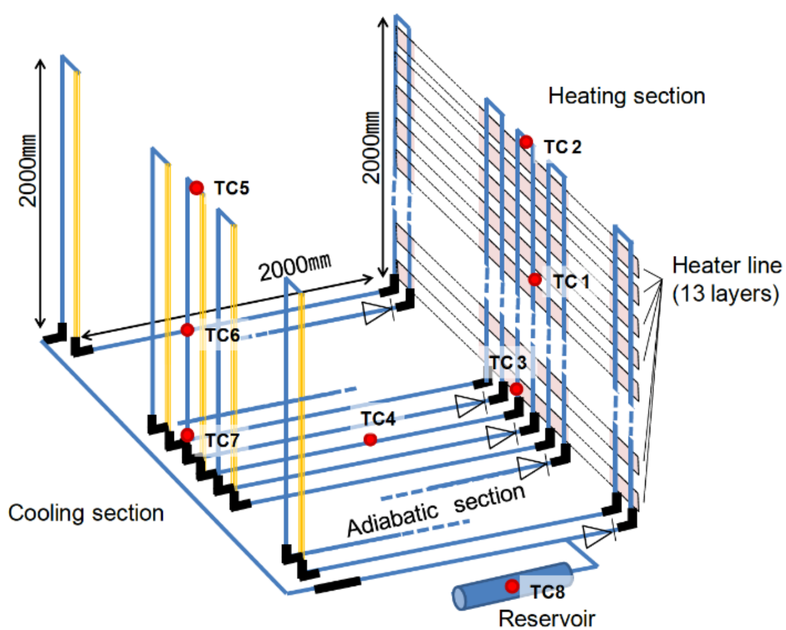


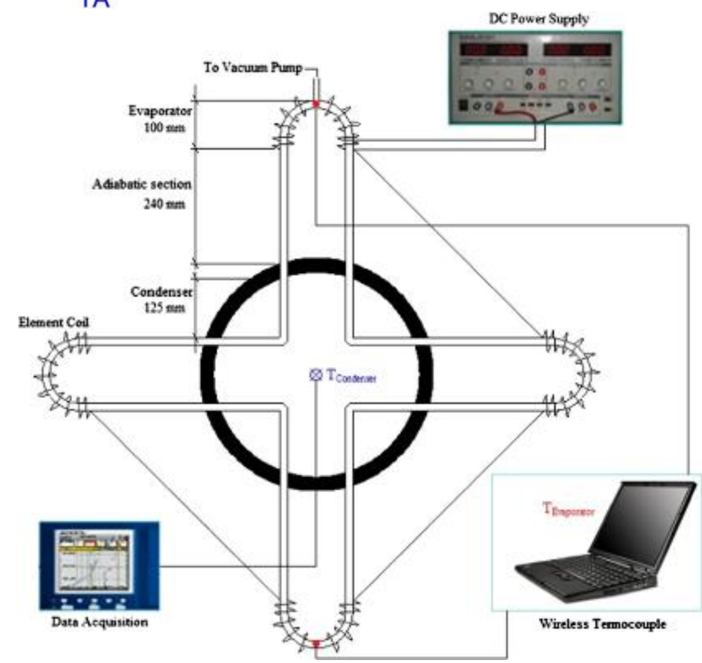




1. Cooling panel
1A.OHP
2. Coil windings
3. Cooling channel of refrigerant
4. Inner bobbin
5. Outer bobbin
6. End plate



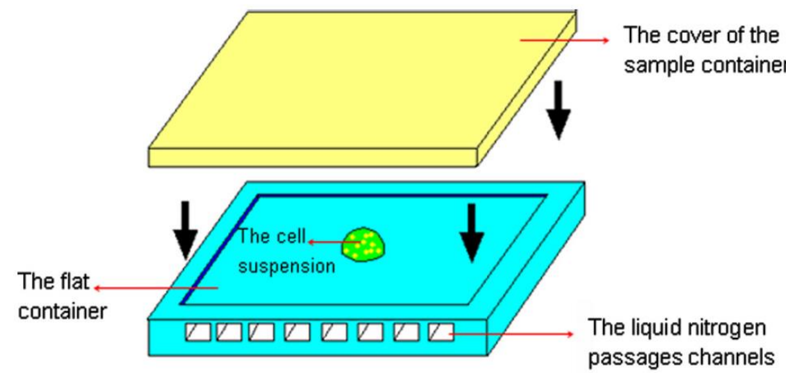




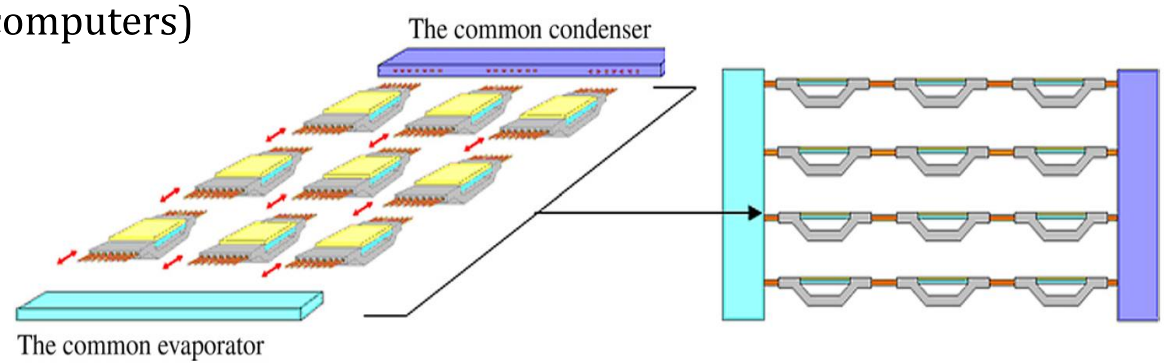
V. Other configurations and applications

Different applications ⟹ different ranges of working temperatures!

- Cryopreservation : conservation of biological samples in cryogenic containers cooled with PHPs.



- Cooling of electronics (quantum computers)



Thank you for your attention!

Appendix

Long stability tests: