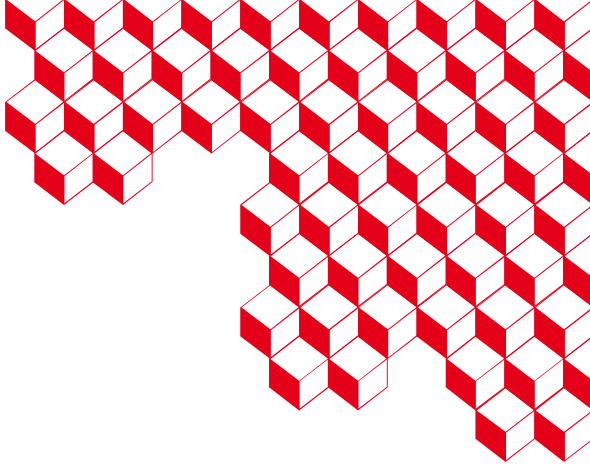

Industry Workshop on Cryogenics in Big Science

Cité International Universitaire de Paris

April 17 2024

Recent developments in cryogenic pulsating heat pipes for magnets, space and medicine

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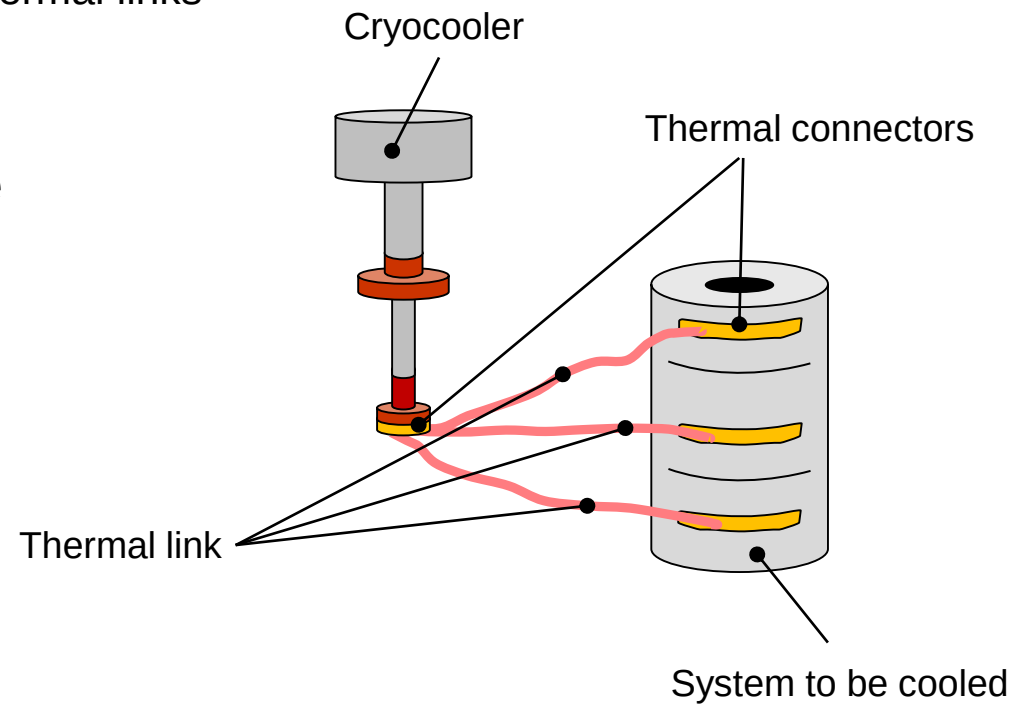
Cooling with a cryocooler

- 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

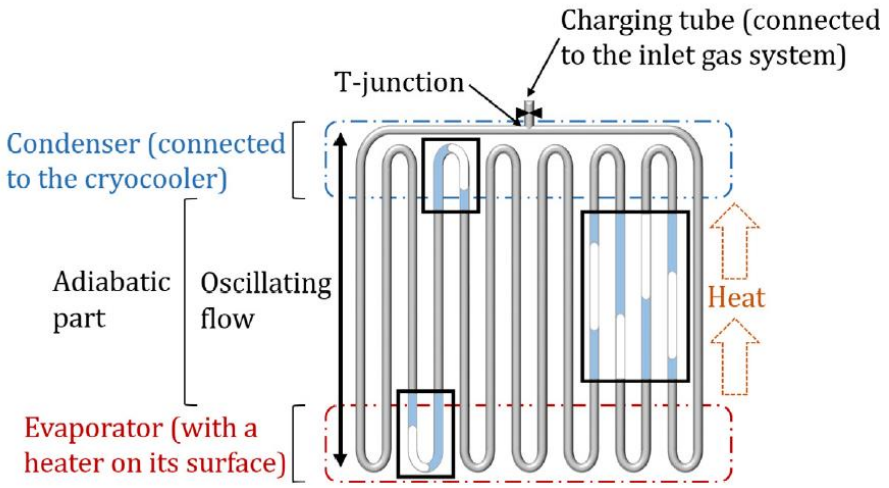
- Solid thermal links are the standard
  - “Large” ΔT
  - Slow due to thermal diffusion
  - Heavy

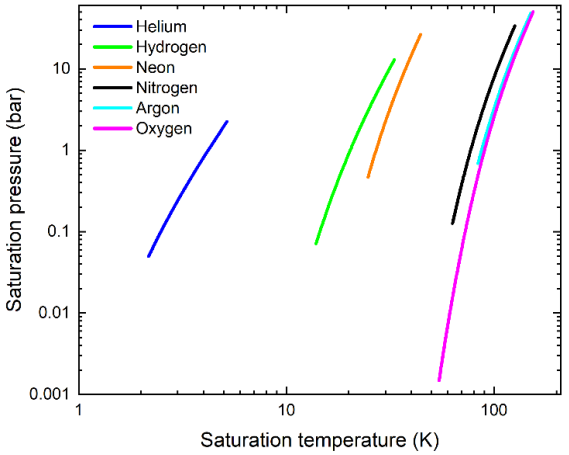


- Alternative thermal link = Two-phase cryogenic PHP

Cryogenic Pulsating Heat Pipe

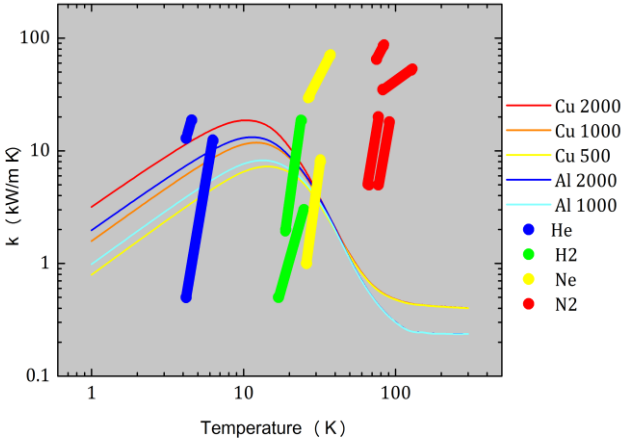
- Two-phase passive heat transfer device
  - having oscillating train of liquid slugs and vapor bubbles as thermal transport carriers
  - Filled partially with working fluid operating at its saturation condition





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

- Why a pulsating heat pipe (PHP)?
  - High heat transfer rate and light
  - Easy to construct, bendable, flexible….
  - Almost gravity independent
  - Some drawbacks…



Cryogenic Pulsating Heat Pipe

- Vapor bubbles and liquid plugs oscillations
  - Capillary force creates liquid and vapor structures
  - Δp 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

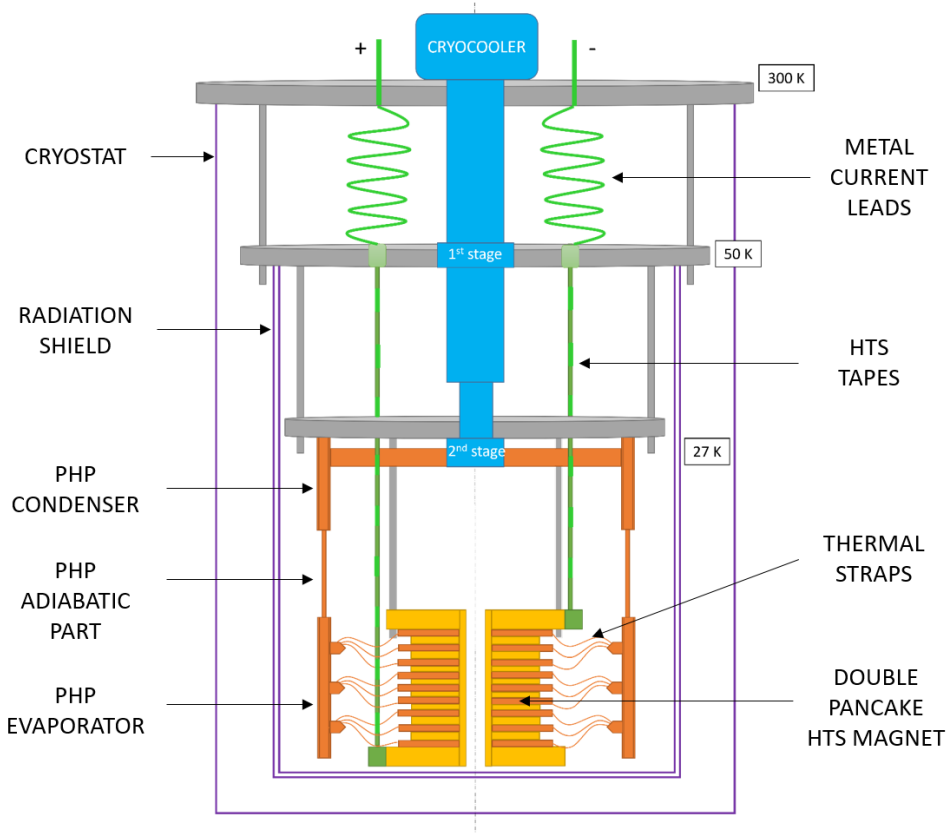
Gravity force

- 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)

The MagicPHP project @ CEA

- Demonstrate the generation of 10 T with a double pancake SC magnet at 27 K cooled by a neon PHP as a thermal link with a cryocooler



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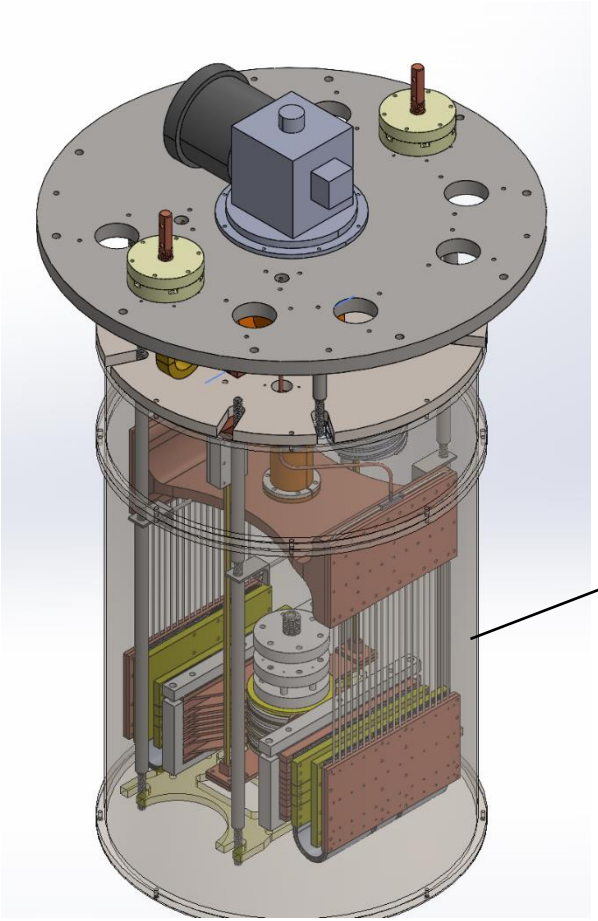
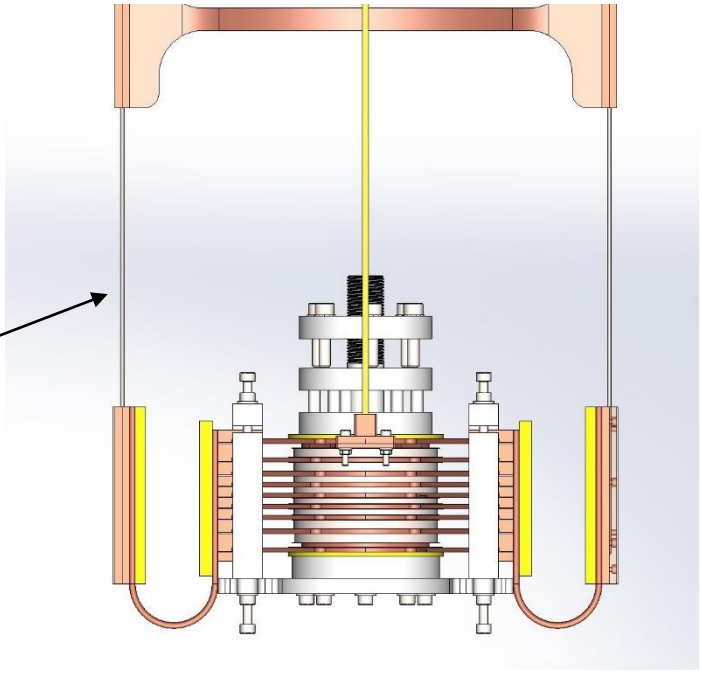
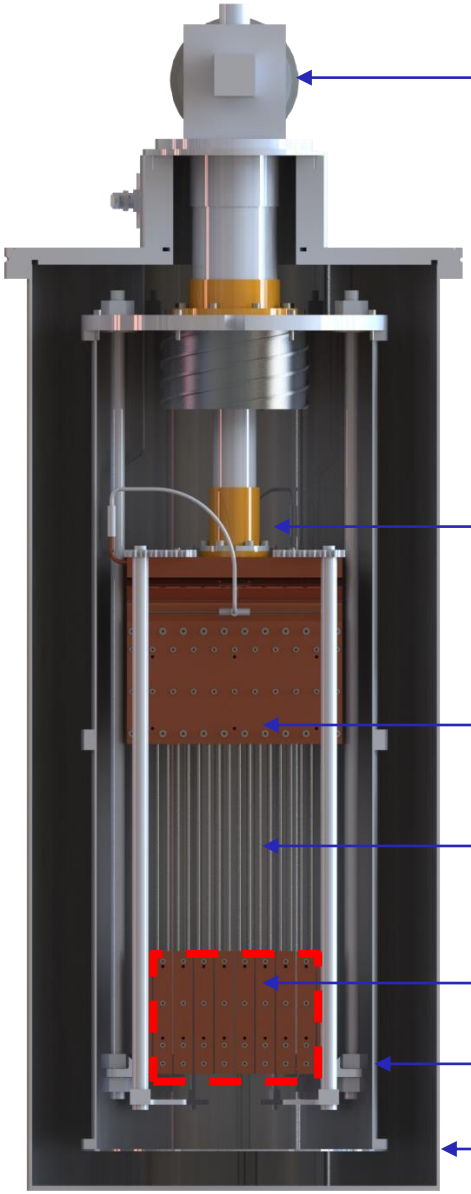
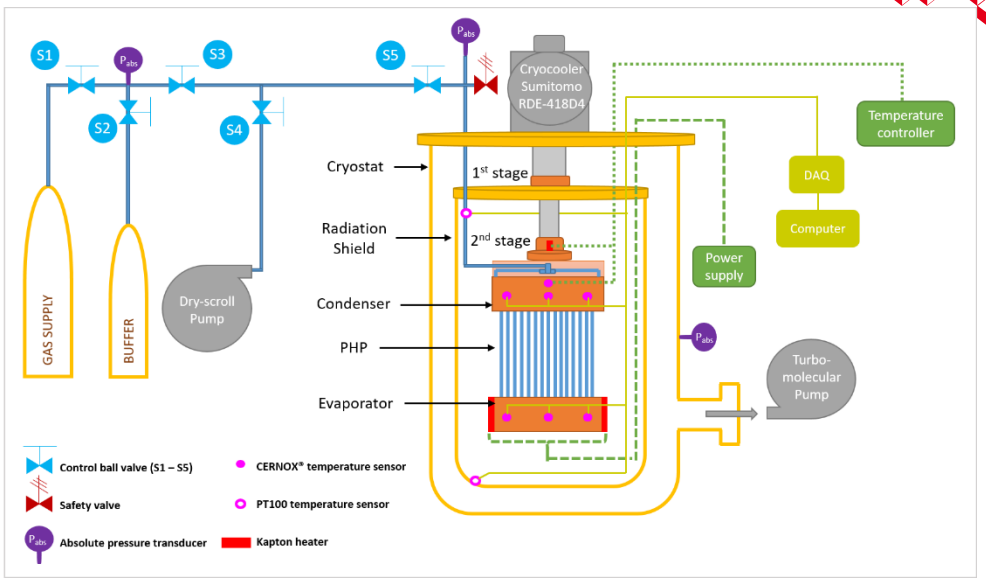


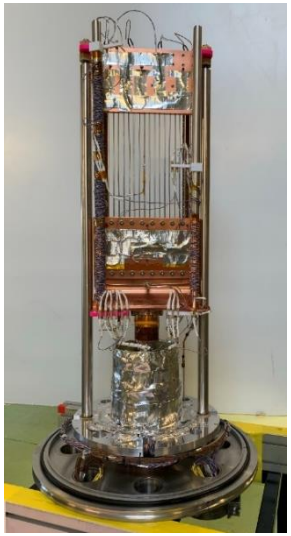
Cryostat 3D CAD model

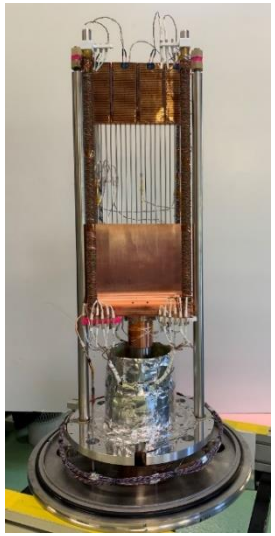


Ne PHP developments







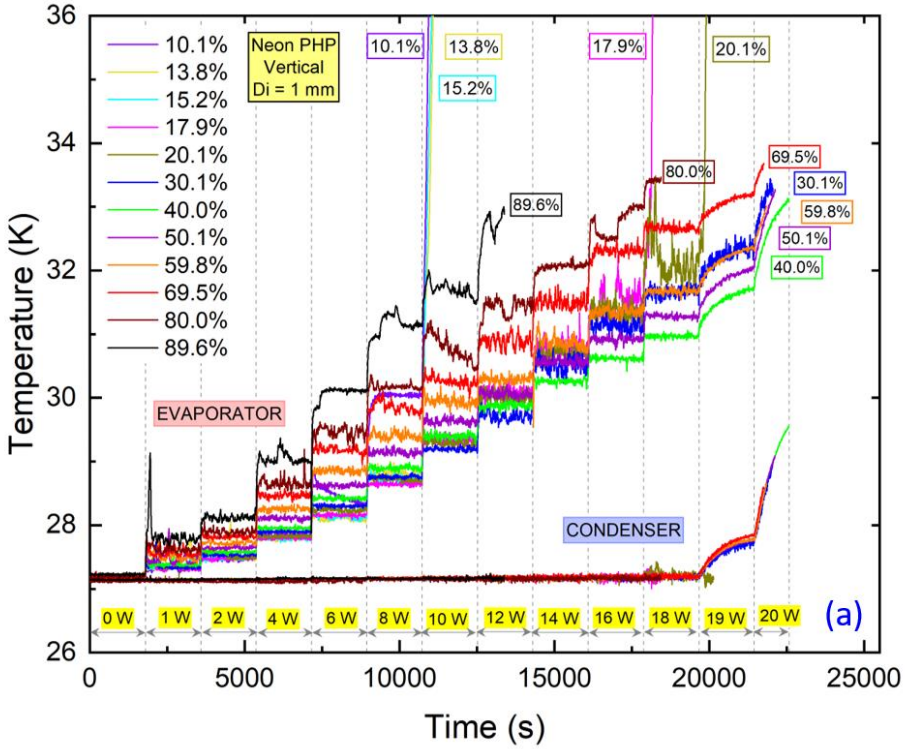


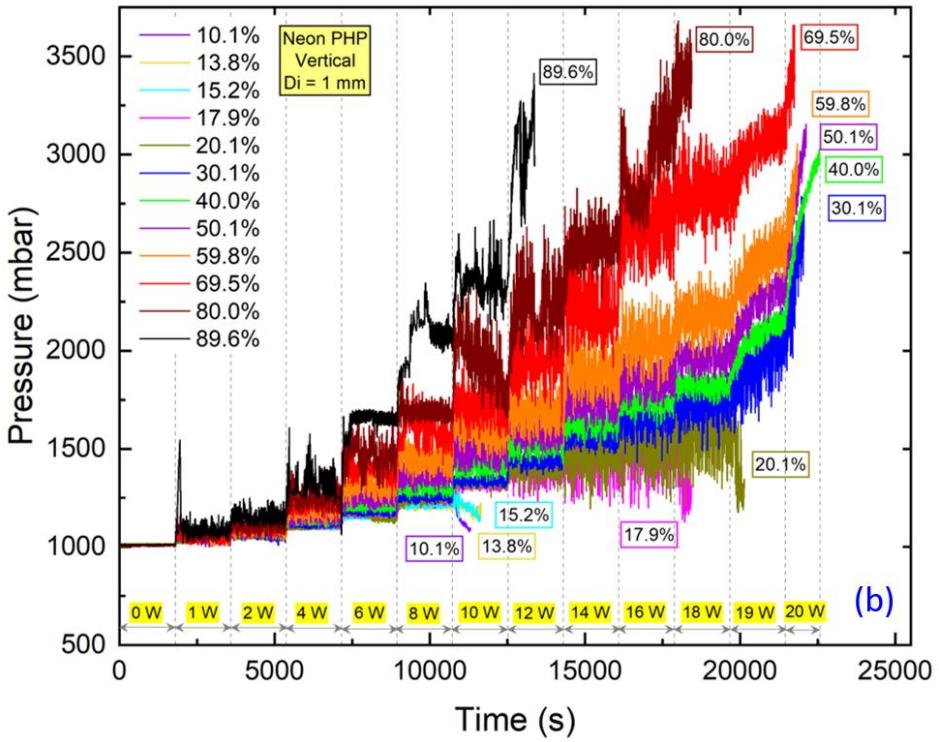
Chosen PHP parameters

Working fluid = NEON
Material = SS316L_ann
Inner diameter = 1.0 mm
Outer diameter = 2.5 mm
Number of tubes = 20
Length = 400 mm

Ne PHP developments

- Results for 18 W class neon PHP ($T_{condenser}$ = 27.1 K)





Dixit et al., Cryogenics 132 (2023) 103670, https://doi.org/10.1016/j.cryogenics.2023.103670

Ne PHP developments

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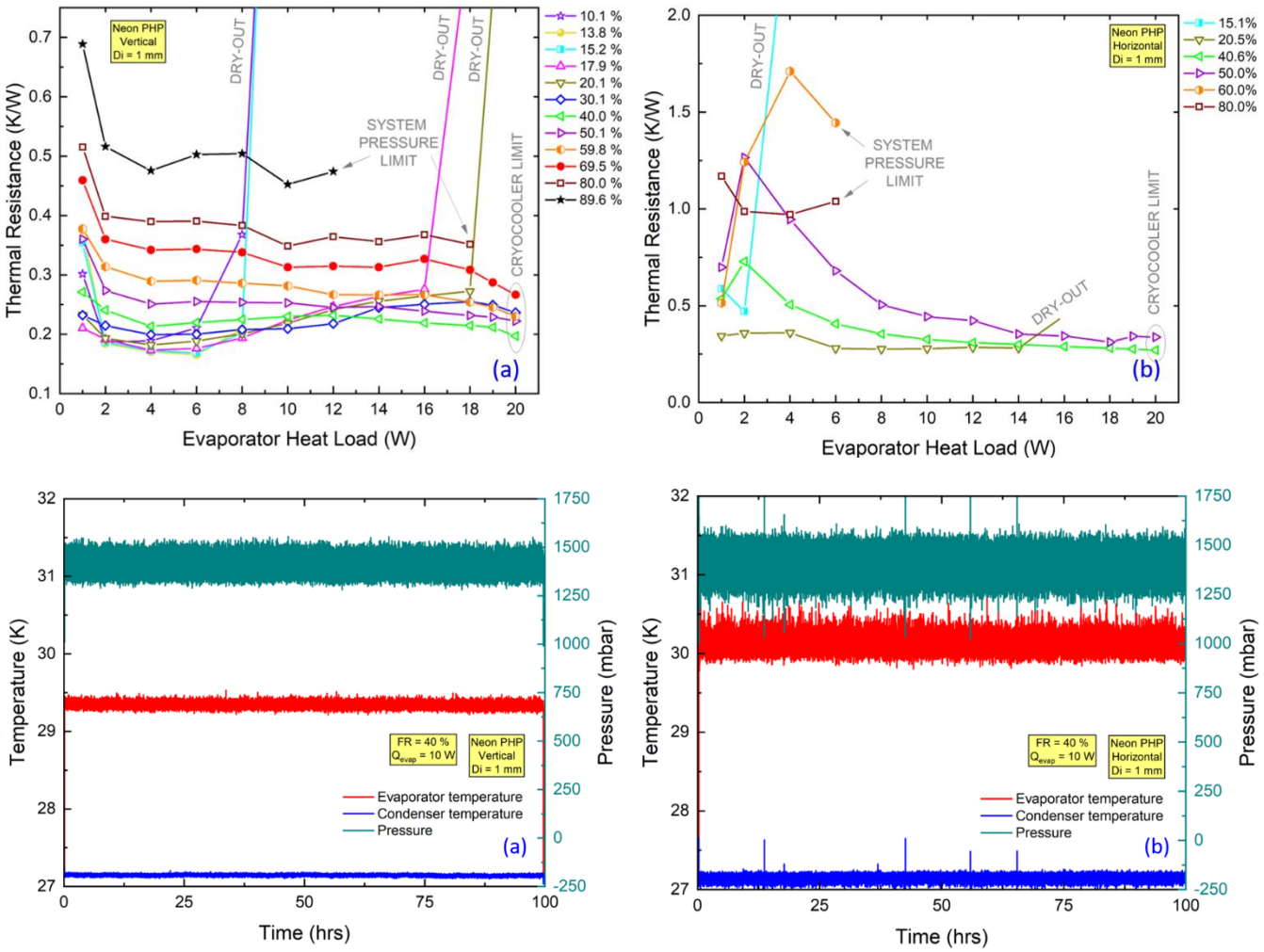
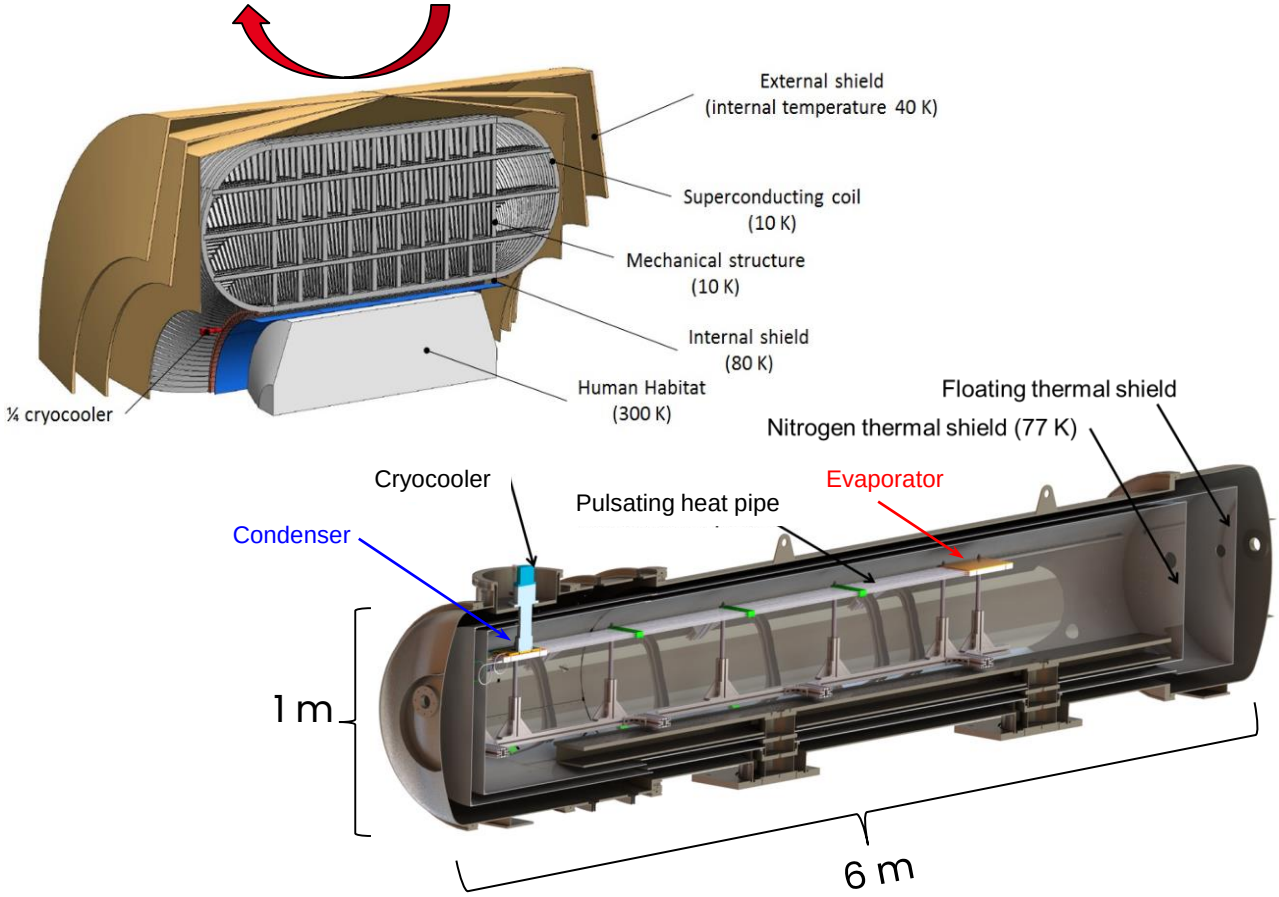


Application to space

- Particles shielding for astronauts for long duration space traveling to avoid cancer
- Superconducting magnet to deviate charged particles from cosmic rays and sun
- Cooling thermal shield between human habitat and the superconducting magnet with long nitrogen PHPs (77 K)



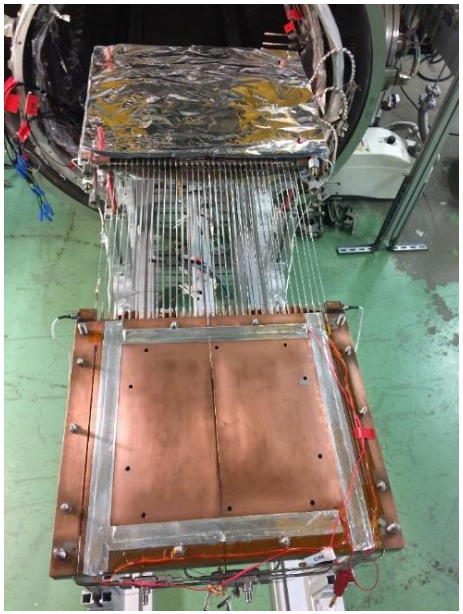
3.7 m long PHP

European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 313224 - SR2S

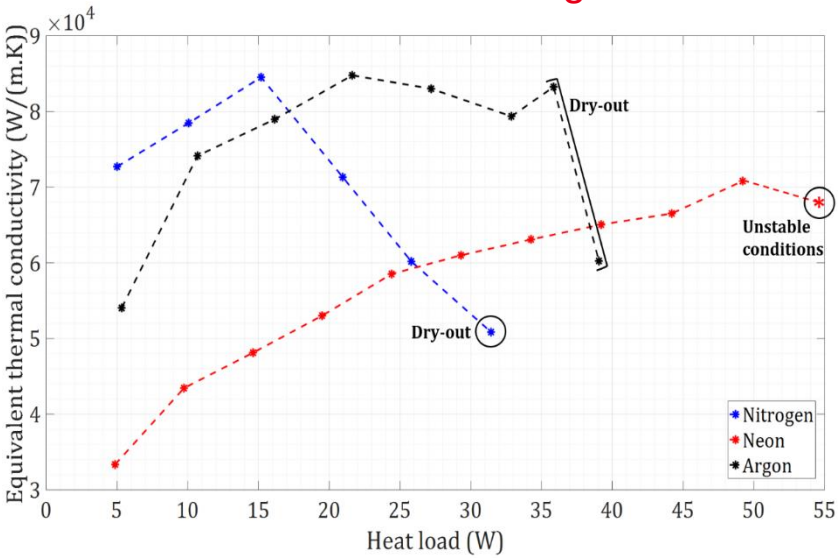
Application to space

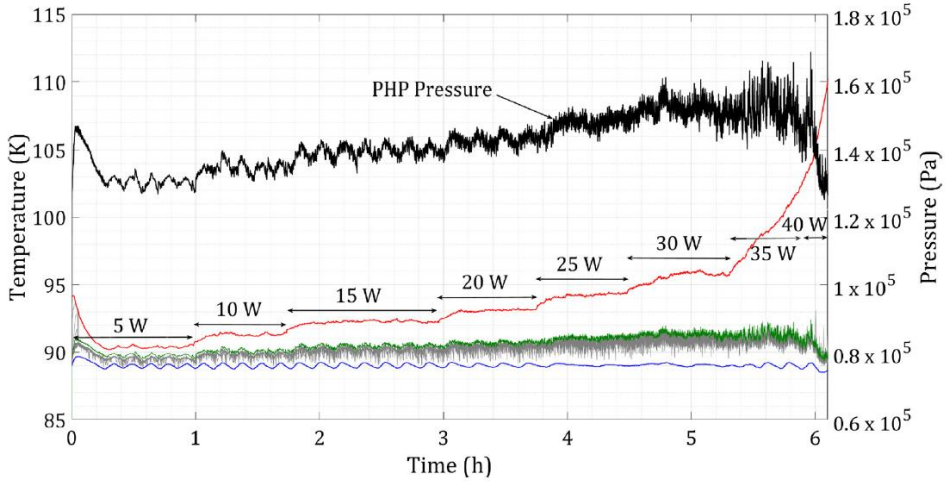
- 1 m long horizontal PHP
  - SS tube Ø 1,5 mm and 36 turns
  - 330 mm long condenser and evaporator
  - 300 mm long adiabatic part

- Fluids : Nitrogen, neon and argon



Between 7 and 170 times higher than Cu!!

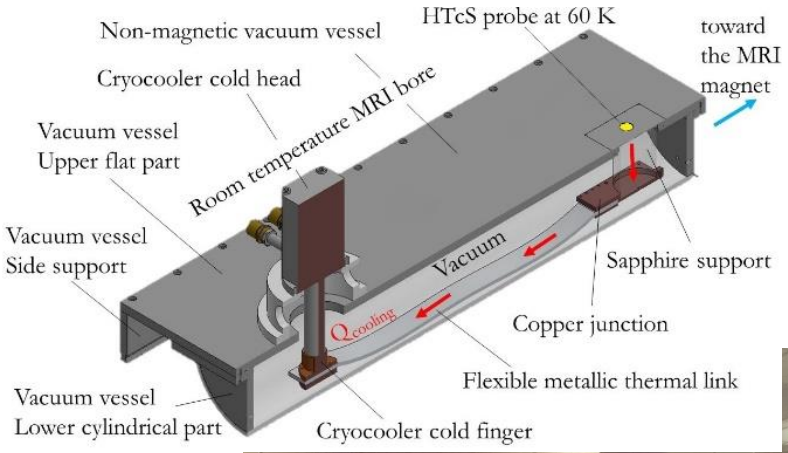




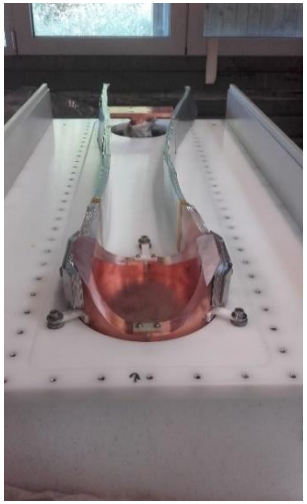
Maria Barba et al. International Journal of Heat and Mass Transfer, Volume 187, 2022, 122458, https://doi.org/10.1016/j.ijheatmasstransfer.2021.122458
Maria Barba et al. Applied Thermal Engineering, Volume 194, 2021, 117072, https://doi.org/10.1016/j.applthermaleng.2021.117072.

Application to medical instruments

- Cooling system for superconducting antennas for micro-MRI
  - Cooling HTS (YBCO) coil at 60K under 1.5 to 3 T
  - Non-invasive imaging technique for oncology, neurology…



Changing the solid thermal link by a PHP



System in operation at Orsay Hospital

French National Research Agency under the grant number ANR14CE17-0003-01