European Space Thermal Engineering Workshop
ESA/ESTEC, Noordwijk, Netherlands, 9 – 11 September 2025

Candidacy of Cryogenic Pulsating Heat Pipes for Space Applications

Tisha DIXIT[1]

Lorenzo MARELLI[2], Gilles AUTHELET[1], Bertrand BAUDOUY[1]

[1]Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Paris-Saclay Centre, France
[2]Centre national d'études spatiales (CNES), Toulouse, France

Session : Heat Transport

09 September 2025

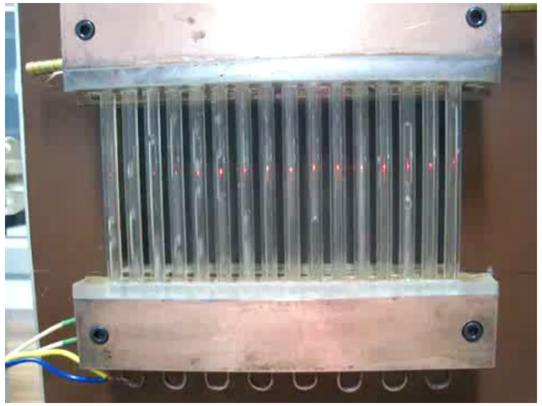
Outline

- PHPs
  - Working mechanism
  - Non-cryogenic PHPs already in space
- Cryogenic PHPs
  - Motivations in the superconductivity world
  - Specific characteristics
  - State-of-the-art at CEA Paris-Saclay
    - Mono-sized 0.4 m long neon (C_{th} *~6 W/K*) and helium PHP (C_{th} *~1 W/K*)
    - First demonstrator of HTS-MI magnet (*10 T, 30 K)* cooled by cryogenic PHP
- Collaborative project with CNES
  - Objectives; first such project aimed for miniature cryogenic PHPs in space
  - Commissioning of on-ground test facility
- Take-away ideas

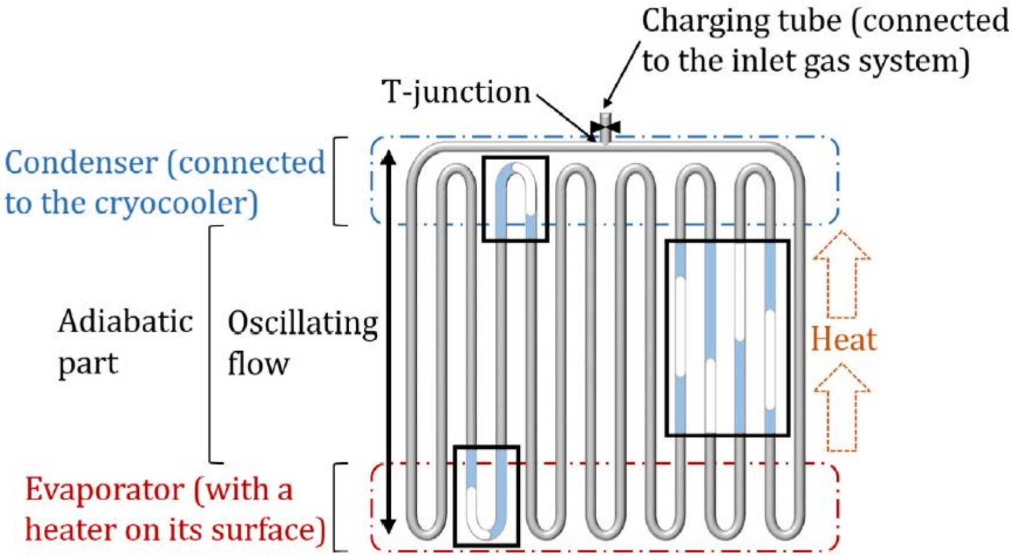
PHPs: Working Mechanism

What is a pulsating heat pipe (PHP) / oscillating heat pipe (OHP)?

- Two-phase passive heat transport device patented by Akachi in 1990
- Filled partially with working fluid operating around its saturation conditions
- Thermal transport carriers: oscillating train of vapor bubbles and liquid slugs



Visualization of water PHP in working
Credits: Prof. S Khandekar, IIT Kanpur, India



Attractive traits for space industry:

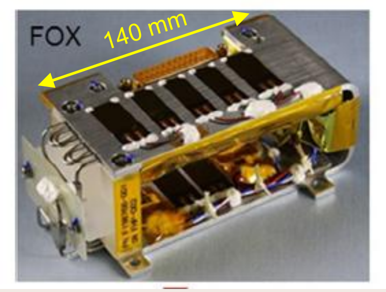
- ✓ High and variable heat transport capability: HT mechanism entails both in sensible and latent heat
- ✓ Ease of construction, lightweight, no moving parts
- ✓ High effective thermal conductivity compared to metallic counterparts
- ✓ « Independent » of gravity
- ✓ Possible heat switch

PHPs: Non-cryogenic PHPs already in Space

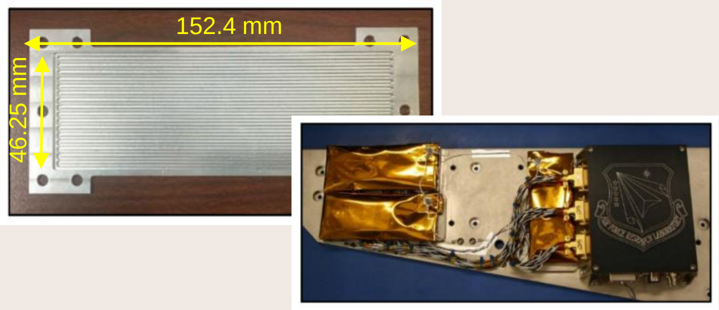
Two long-term reliability and operation on-orbit demonstrators of non-cryogenic PHPs by *JAXA* and *U.S. AFRL*

Several micro-/hyper gravity experiments aboard parabolic flights and sounding rockets by collaboration b/n institutes in Italy (*Università di Bergamo, Università di Parma, Università di Pisa, Politecnico di Milano*), UK (University of Brighton), France (*Institut Pprime CNRS – ENSMA – Université de Poitiers*), ESA Academy

	JAXA FOX on SDS-4	U.S. AFRL + ThermAvant Technologies ASETS-II
Type pf OHP	Tubular with check valves	Flat plate
Material	Al alloy	Al alloy
Working fluid	HFC-134a	Butane, R134a
Test duration	2012 – 2016	2017 – 2019

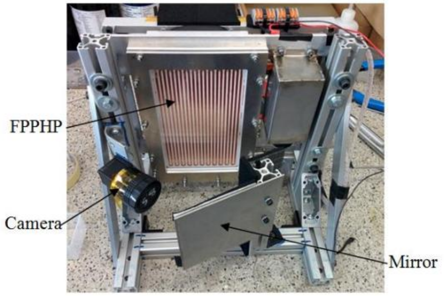


Ando et al. Applied Therm. Eng. 130 (2018) 552-560



Drolen et al. J. Thermophys Heat Trans. 36 (2) (2022) 314-327

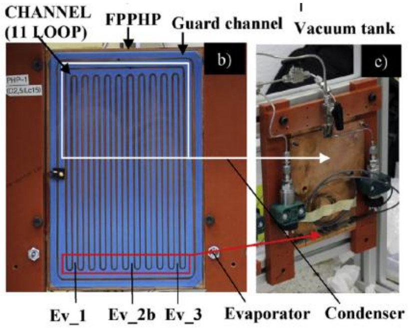
62nd, 64th ESA Parabolic Flight Campaign



Tubular Cu PHP, FC-72

Ayel et al. Heat Tranf. Eng. 40 (2018) 227-237

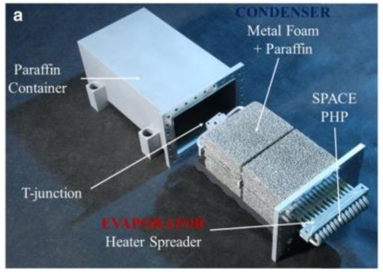
65th ESA Parabolic Flight Campaign



Flat Cu PHP, water+SRWF

Cecere et al. Acta Astronautica 147 (2018) 454–461

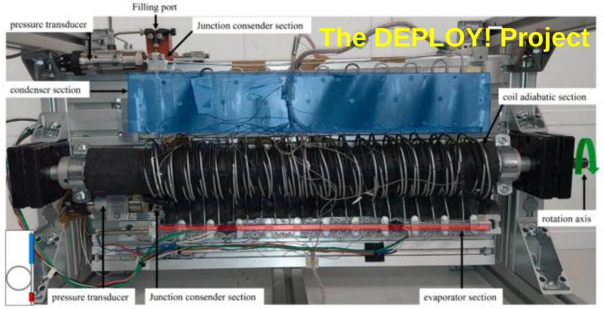
ESA REXUS 22 Sounding Rocket



Tubular Al 6060 hybrid LT /PHP, perfluorohexane

Mameli et al. Microgravity Sci. Tech. 31 (2019) 249-259

79h ESA Parabolic Flight Campaign



Deployable tubular Al 6063 PHP, HFE-7000

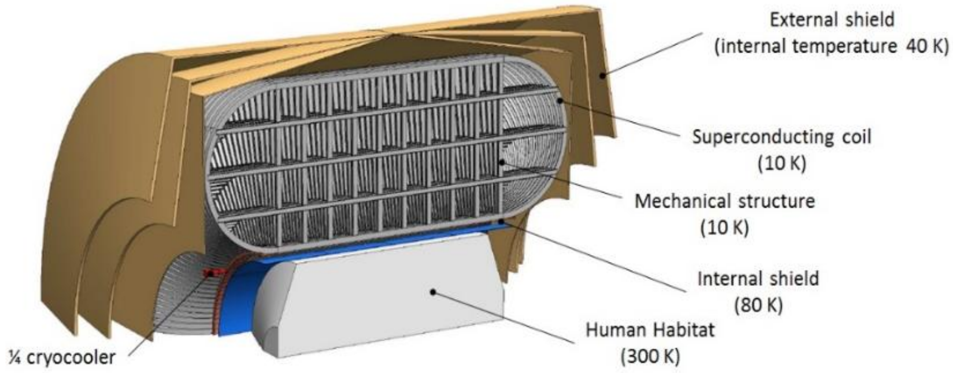
Perna et al. Therm. Sci. Engg. Prog. 61 (2025) 103479

Cryogenic PHPs: Motivations in Superconductivity World

Migration of PHPs in cryogenics in 1998: investigations began at CEA in 2014

Efficient heat transfer device in "zero gravity" environment

- Cooling superconducting system for space application – CEA conceptual idea
- Cooling very high magnetic field superconducting magnet (B>20 T) where magnetic force can oppose gravity – CEA R&D

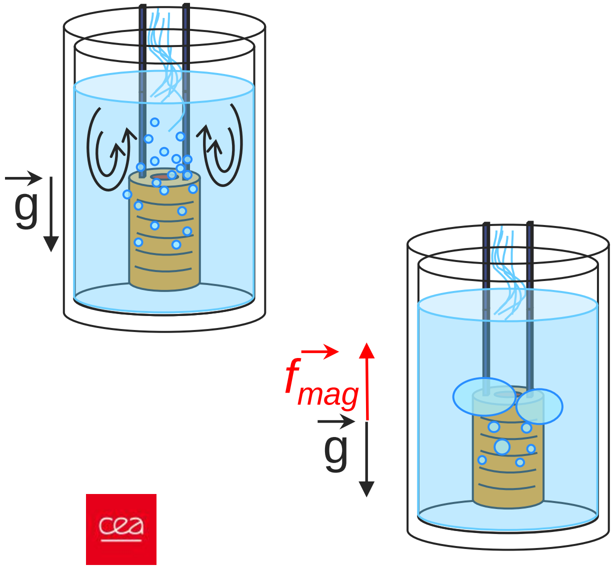


European Commission Grant ID:313224,
Project duration 2013 – 2015
Proposal to cool thermal shield b/n human habitat and superconducting magnet with nitrogen PHP in space

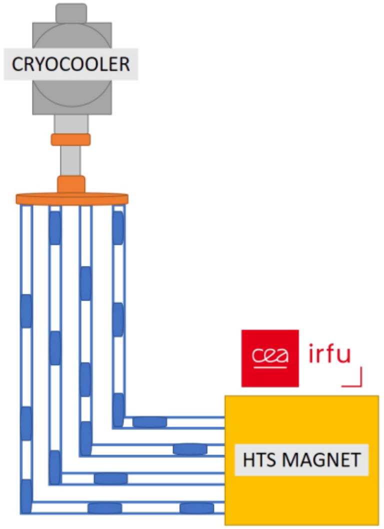
Liquid helium bath cooled 32.5 T solenoid HTS magnet NOUGAT

Fazilleau et al., Cryogenics 106 (2020) 103053

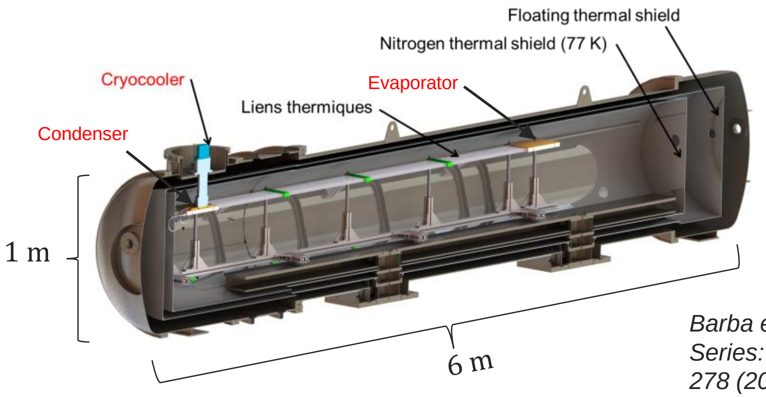
$$\overrightarrow{f_{mag}} \propto \frac{\chi}{2\mu_0}\overrightarrow{grad}(B^2)$$



*Simon Bagnis, **PhD Thesis**, Analysis of the effect of magneto-gravitational forces on liquid helium cooling of high magnetic field superconducting magnets, CEA/IRFU/DACM Université Paris-Saclay 2023*



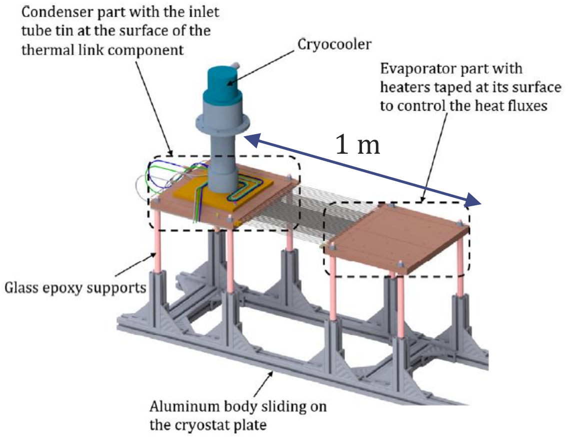
Cryogenic PHPs: CEA State-of-the-Art 2014-till date



3.7 m

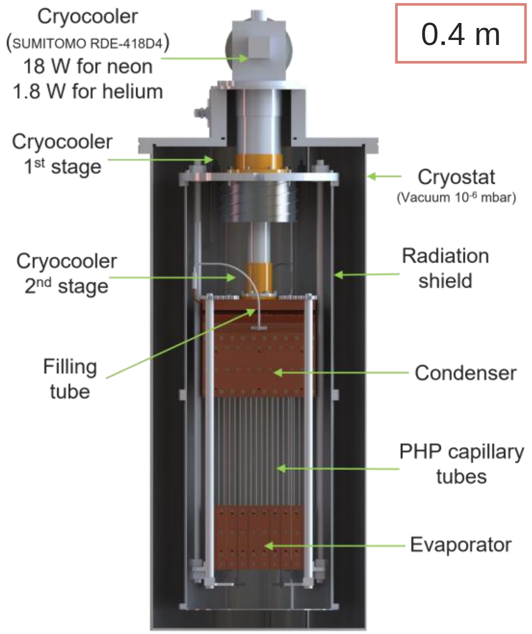
Barba et al. IOP Conf. Series: Mater. Sci. Eng. 278 (2017) 012156

European Commission Grant ID 313224, 2013 – 2015

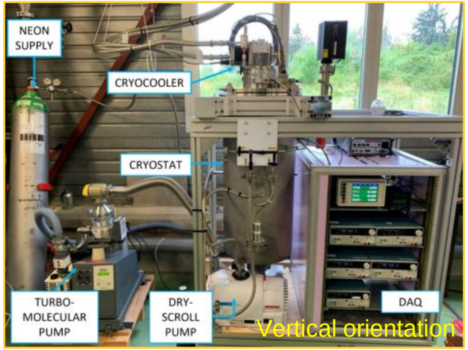


1 m

*Maria Barba, **PhD Thesis**, Study of meter-scale horizontal cryogenic pulsating heat pipes, Université Paris-Saclay, 2019*



0.4 m



Dixit et al. Cryogenics 132 (2023) 103670
Dixit et al. App. Therm. Eng. 251 (2024) 123613

Cryogenic fluids tested:
- Argon (87.3 K or -185.9°C)
- Nitrogen (77.3 K or -195.8°C)
- Neon (27.1 K or -246.1°C)
- Hydrogen (20.3 K or -252.9°C)
- Helium^4 (4.2 K or -268.9°C)

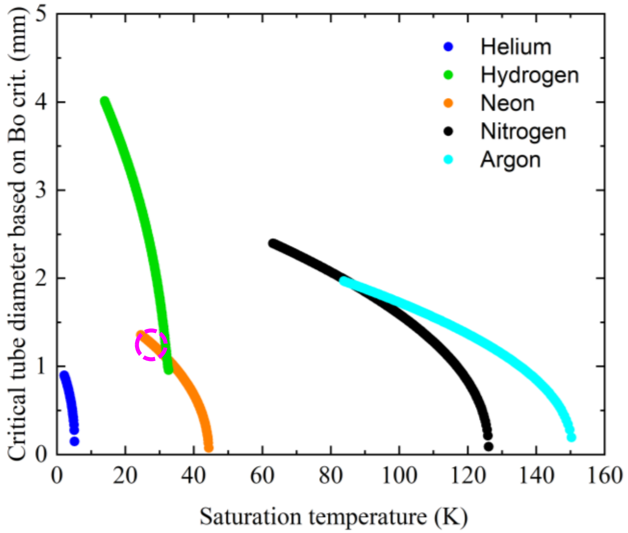
Cryogenic PHPs: CEA State-of-the-Art Mono-sized neon & helium PHP

Design parameters

- Not straightforward – jugging of several parameters
- Guidelines not streamlined – still primarily dependent on experimental investigations

Physical characteristics
- ✓ Capillary tube inner diameter
- ✓ Number of tubes
- ✓ Length of evaporator/condenser/ adiabatic part (1:1:1 or 1:2:1 or …)

Operational characteristics
- ✓ Working fluid
- ✓ Condenser temperature
- ✓ Filling ratio
- ✓ Evaporator heat load



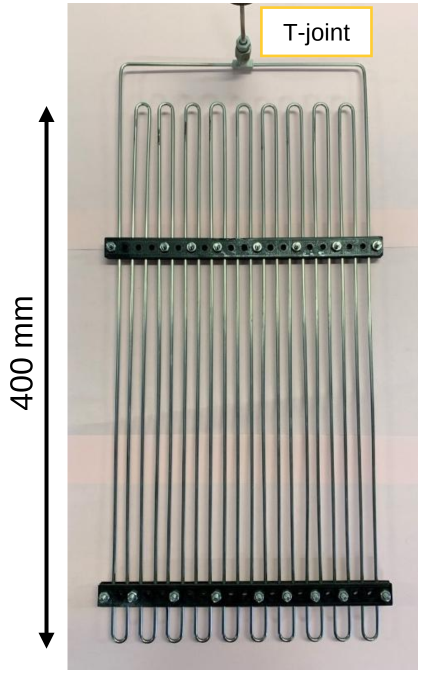
Choice of PHP capillary tube diameter based on widely accepted, fluid property dependent Bond number criterion

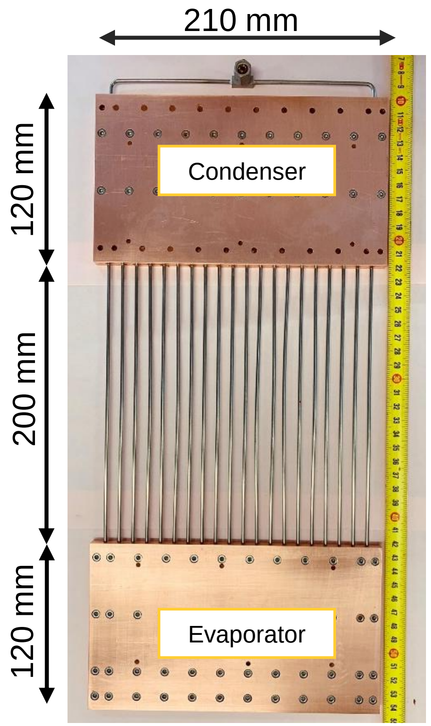
$$Bo = \frac{g(\rho_l - \rho_v)D^2}{\sigma} < 4$$

ρ_l = fluid saturation liquid density (kg/m^3)
ρ_v = fluid saturation vapour density (kg/m^3)
σ = fluid surface tension
D = tube inner diameter (m)

Good starting point but validity of theory deliberated!
Dixit et al. "Oversized diameter helium pulsating heat pipe" Applied Thermal Engineering 251 (2024) 123613

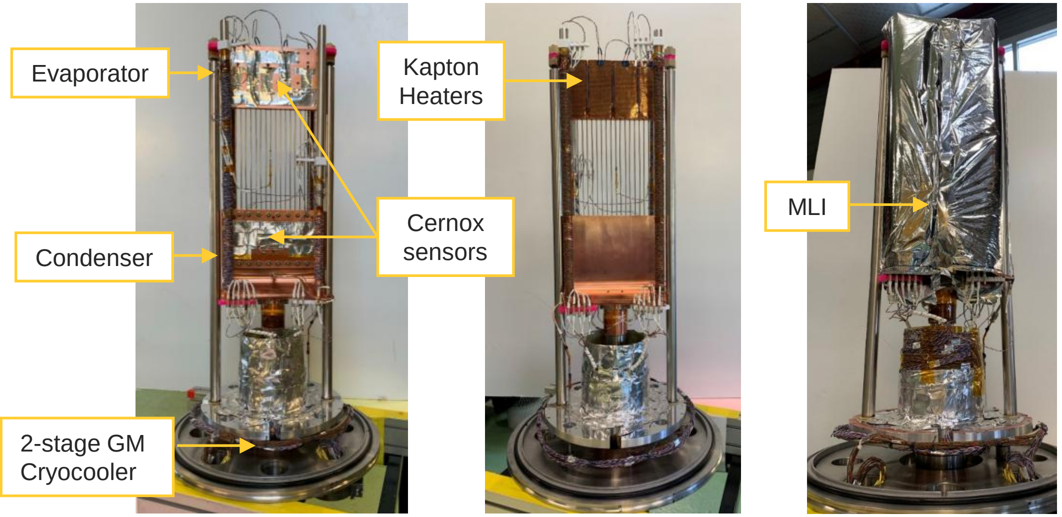
Chosen neon PHP parameters:
- Inner diameter = 1.0 mm (Bo ~ 2.5 at 27.1 K)
- Number of tubes = 20
- Projected length = 0.4 m
- Condenser/evaporator material = CuC2
- Tube material = SS316 L annealed
- Turns enclosed within the condenser/evaporator

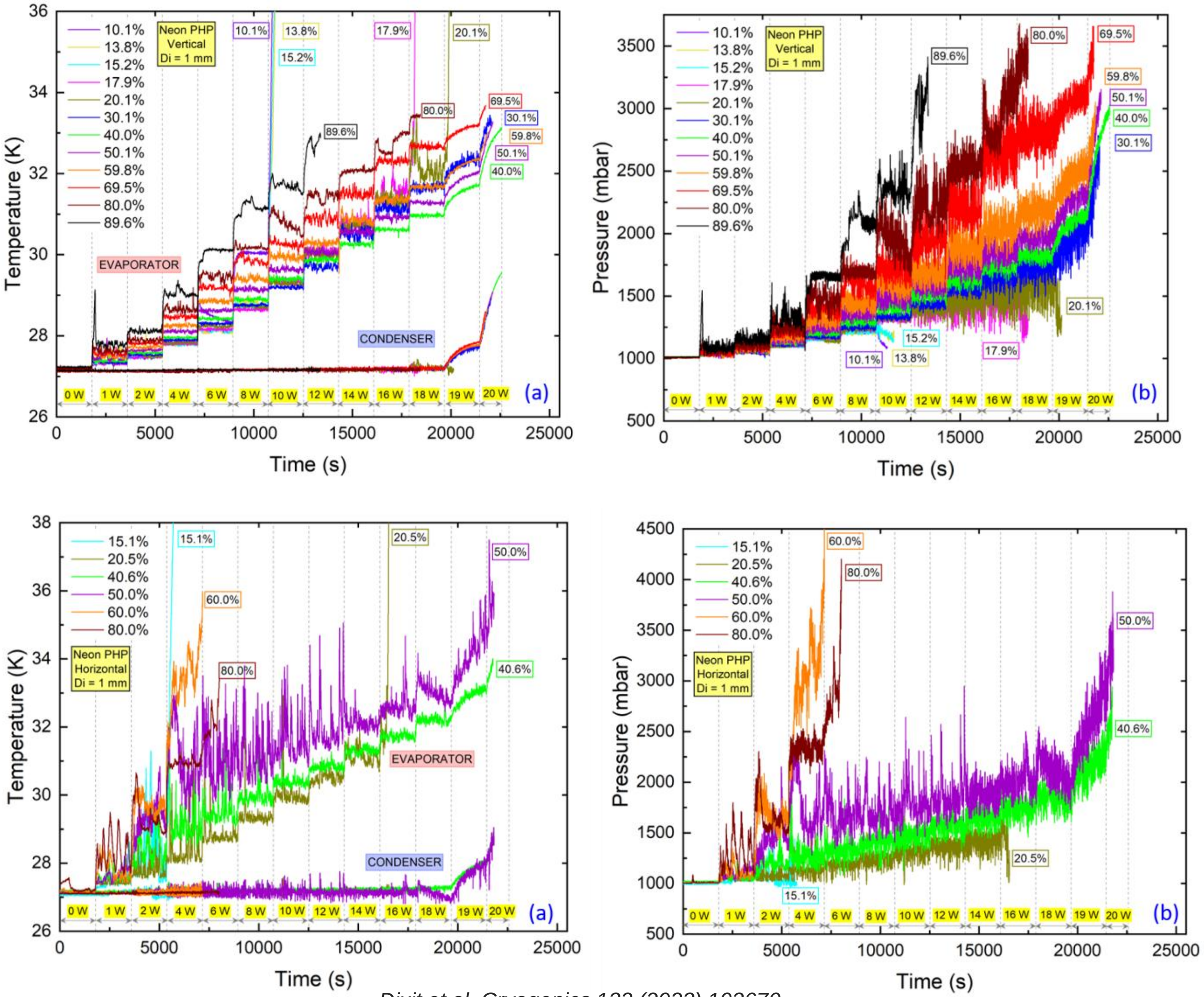




Cryogenic PHPs: CEA State-of-the-Art Mono-sized neon & helium PHP

Neon PHP





- Evaporator temperature, (regulated) condenser temperature, global pressure measurement
- Vertical and horizontal orientation
- Filling ratio (FR) of 10% - 90%

- Temperature range 27.1 K to 37 K
- Q_{evap} 0 - 18 W (cryocooler limit reached)

- Optimum FR of 40% for 18 W capacity

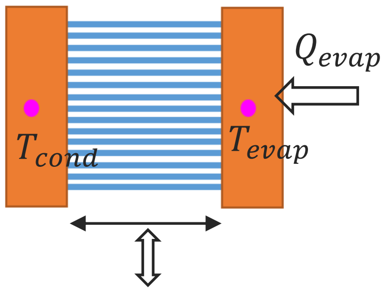
Dixit et al. Cryogenics 132 (2023) 103670

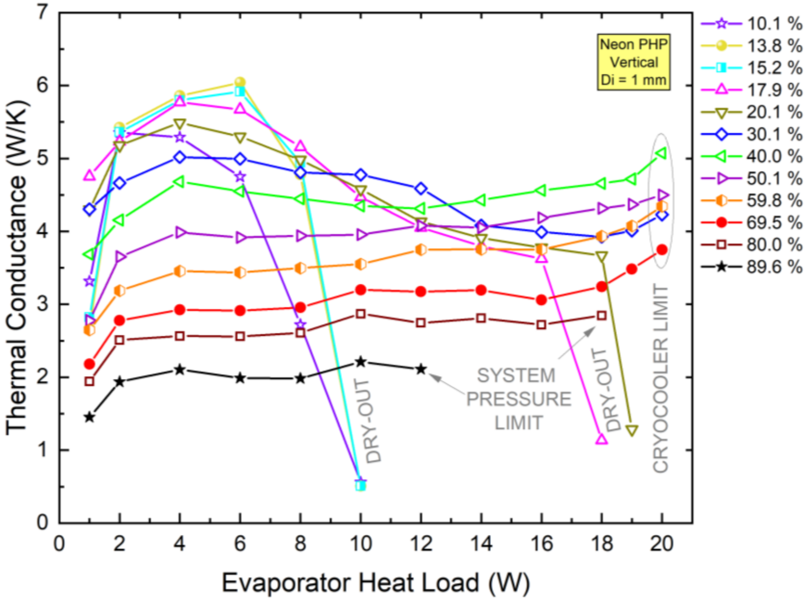
Cryogenic PHPs: CEA State-of-the-Art Mono-sized neon & helium PHP

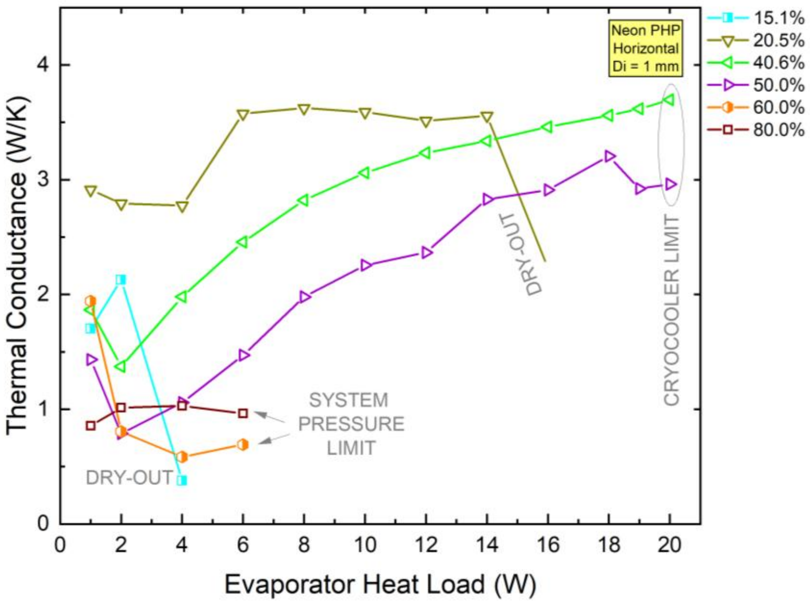
Neon PHP

- Thermal conductance in temperature range 27.1 K to 37 K
  - ✓ Highest C_{th} ~6 W/K in vertical and ~3.7 W/K in horizontal orientation
  - ✓ Best thermal performance ever measured for neon PHPs

$$C_{th} = \frac{Q_{evap}}{T_{evap} - T_{cond}}$$







- Function steadily under non-homogeneous evaporator heat load
- Long run stable functioning ~100 hours at constant FR and Q_{evap}

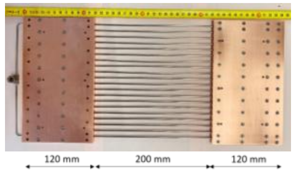
Comparison with classic metallic strap

Mass of PHP adiabatic part • n = 20, L = 200 mm b/n condenser & evaporator • SS316L tube	**132 g**
C_{th} at FR 13.8 % & 6 W	**6 W/K**

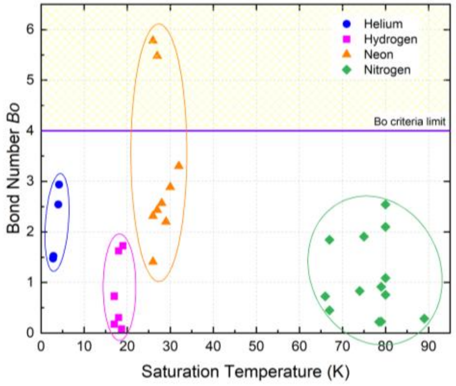
In 30 K temp range	Cu strap (k_{th} 2000 W/mK)	Al Strap (k_{th} 3000 W/mK)
Iso-conductance	**1060 g**	**215 g**
Iso-mass	**0.75 W/K**	**3.8 W/K**

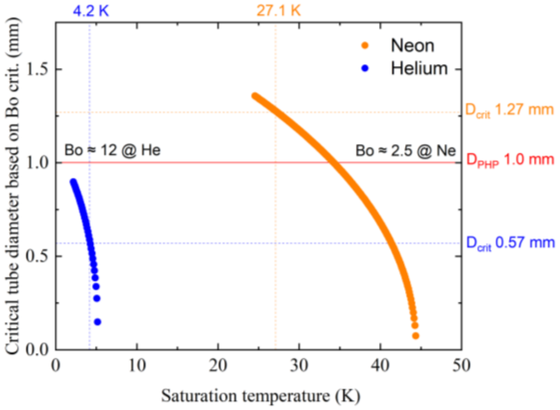
Cryogenic PHPs: CEA State-of-the-Art Mono-sized neon & helium PHP

Helium PHP



Breaching Bo criteria with helium
D_i = 1 mm ⟶ Bo ≈ 12 @ 4.2 K





Dixit et al. App. Therm. Eng. 251 (2024) 123613

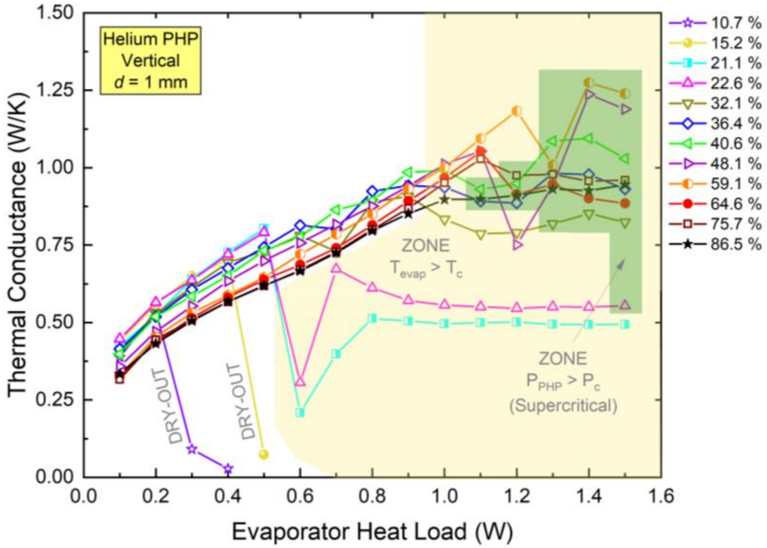
- Evaporator temperature, (unregulated) condenser temperature, global pressure measurement
- Vertical and horizontal orientation

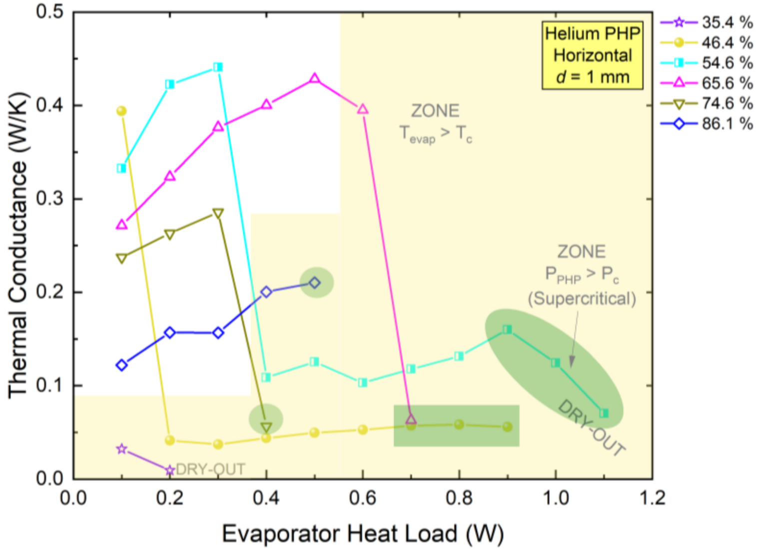
- Temperature range 2.5 K to 10 K
- Q_{evap} 0 - 1.5 W (cryocooler limit reached)

- Successfully transport heat – stable working condition in **supercritical state** in evaporator ($T>T_c$ and $P>P_c$)
- ~65 hours stability test at constant FR and Q_{evap} in vertical/horizontal orientation

Comparison with classic metallic strap

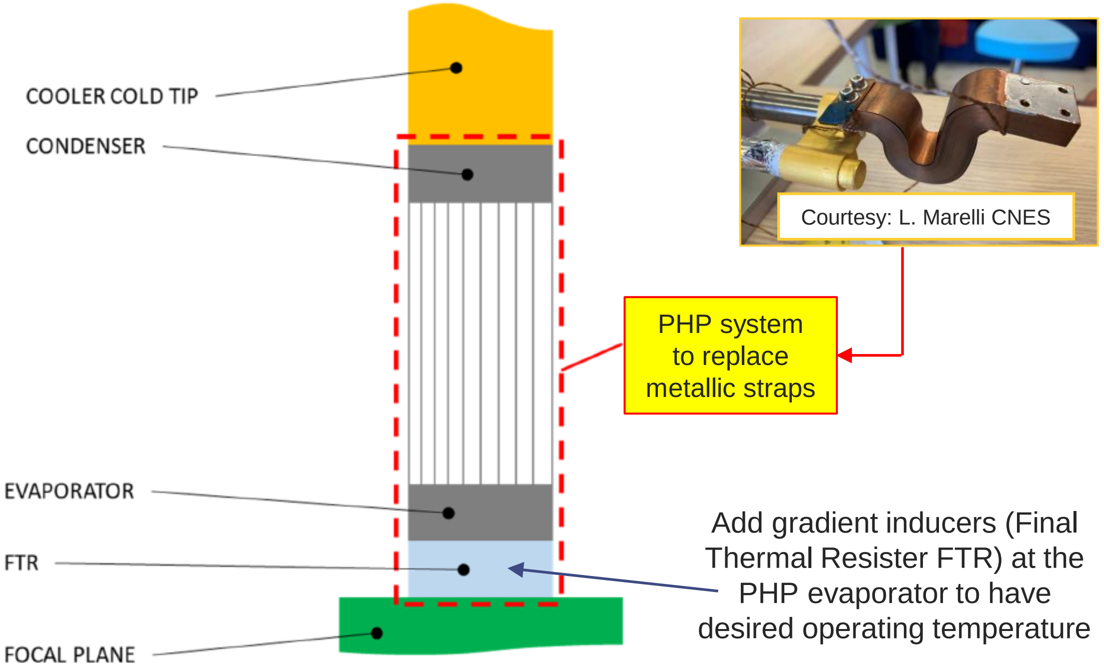
	Present 0.4 m PHP	Cu strap (k_{th} 520 W/mK)	Al Strap (k_{th} 2500 W/mK)
In 4.2 K temp range FR 48% & 1 W	**132 g**	**700 g**	**39 g**
	1.0 W/K	**0.19 W/K**	**3.15 W/K**
Heat switch function	**Yes**	**No**	**No**





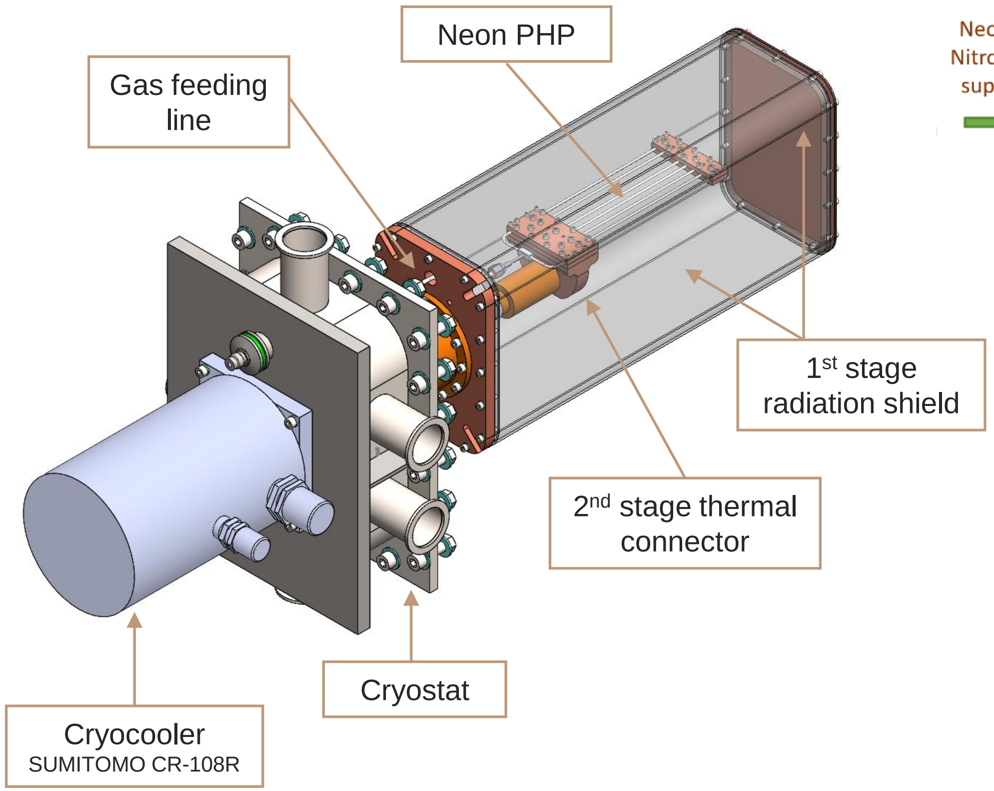
CNES-CEA Collaboration Project: Objectives

- Two-fold objectives:
  - ✓ Feasibility study of <u>replacing metallic straps</u> that thermally couple focal plane of an IR instrument to a cryocooler with <u>miniature cryogenic PHPs</u>
  - ✓ Viability check to see if <u>heat-in-leak</u> arriving from redundant cryocooler can be <u>inhibited</u> by having <u>PHP in “OFF” mode</u>
- Testing at two temperature range of focal planes: 50 K – 65 K and 77 K – 80 K with neon and nitrogen as working fluid

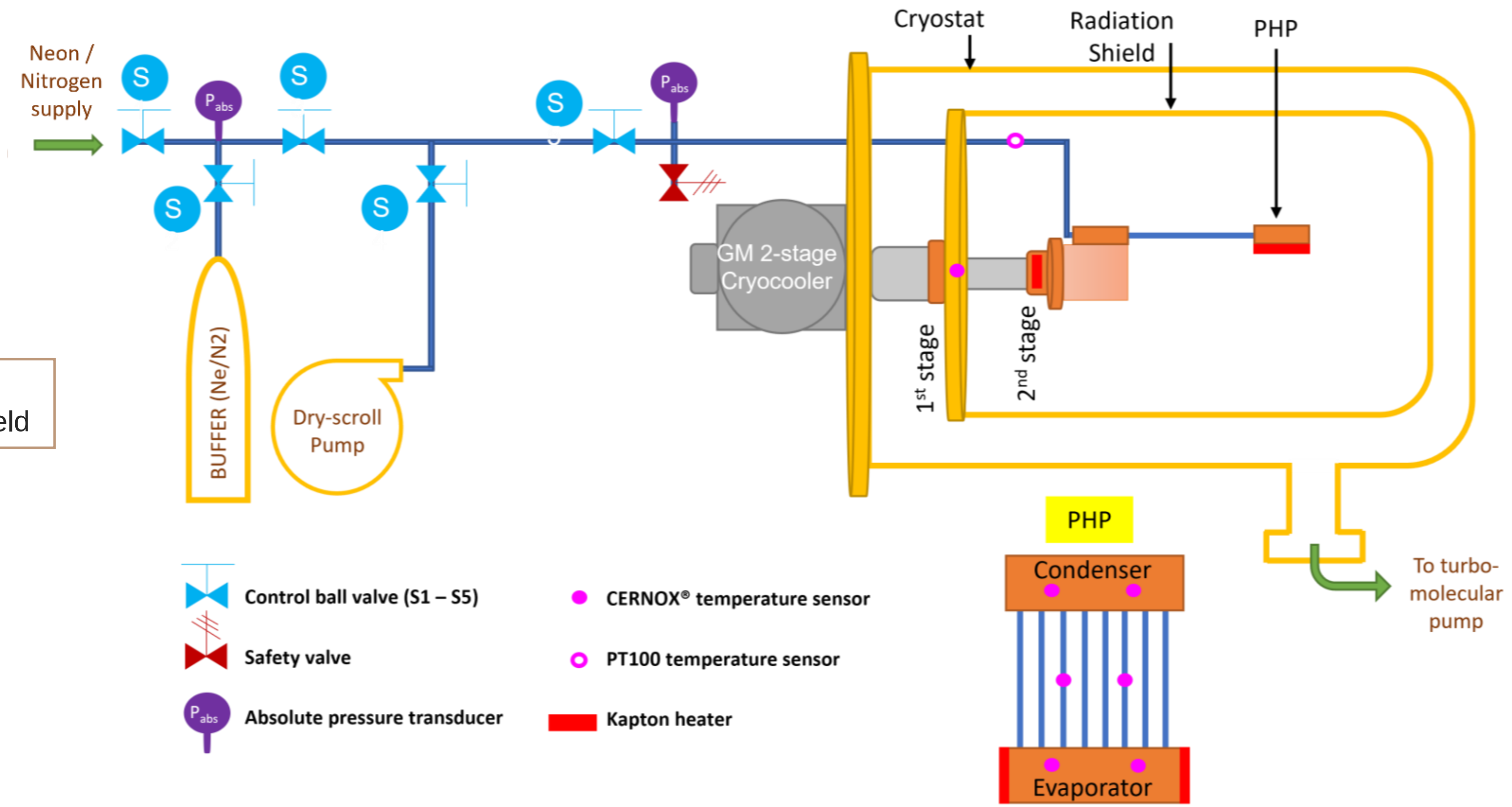


CNES-CEA Collaboration Project: On-ground Test Facility

Cryostat insert



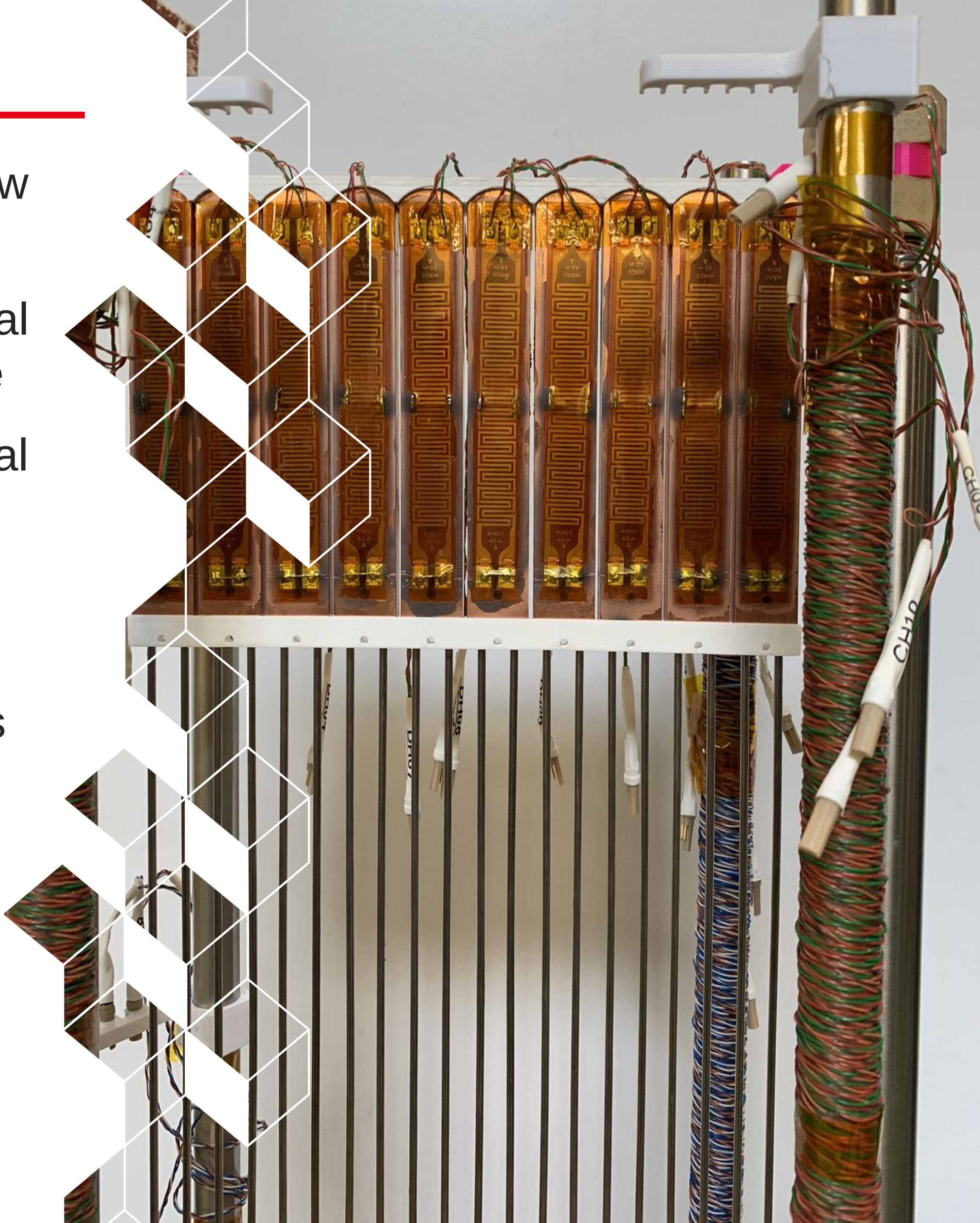
Set-up schematic

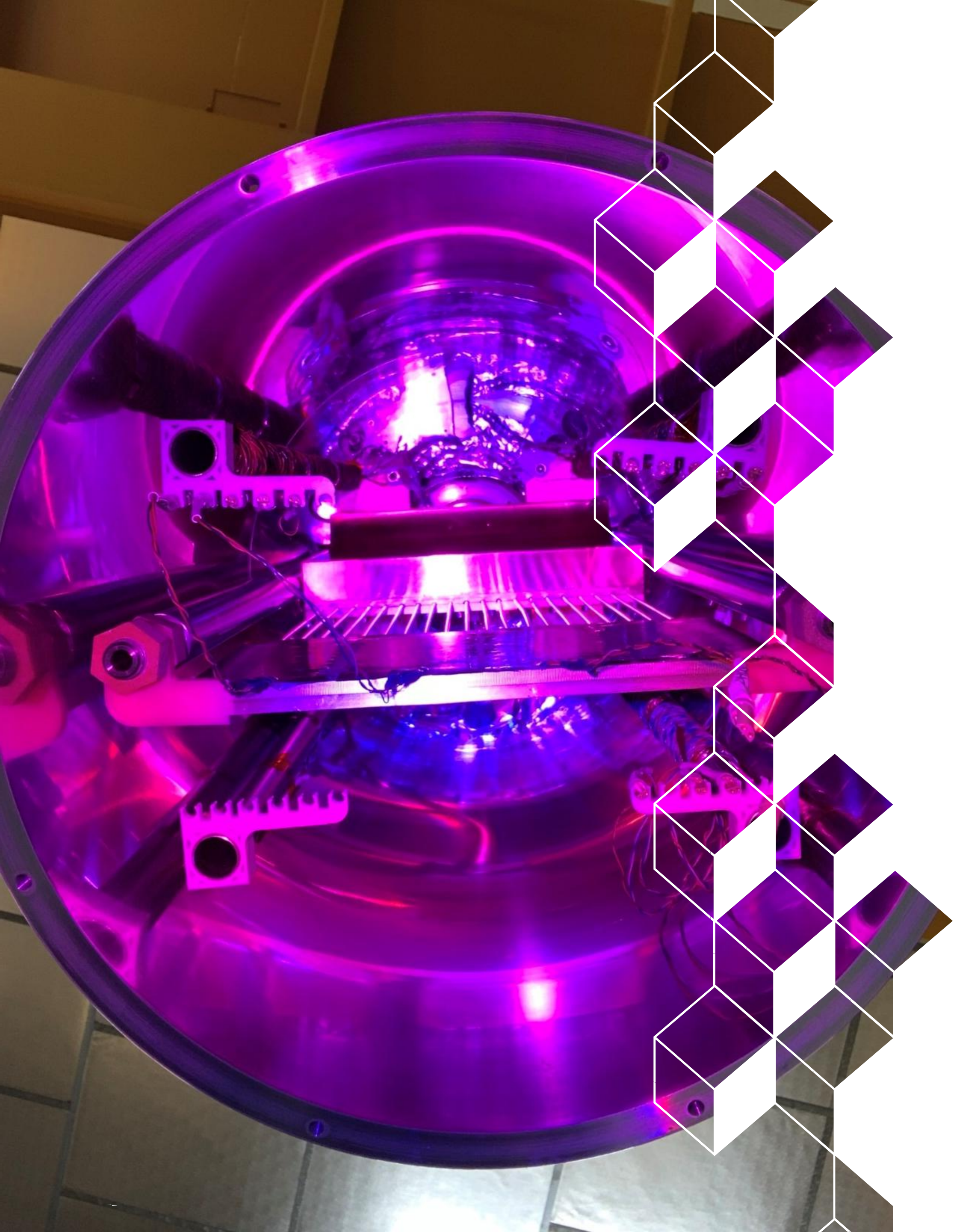


Next step: Manufacturing and Testing… Results next year!

Take-away Ideas: Cryogenic PHPs

- Passive heat transport solution that can serve low temperature range of 2.5 K to 100 K
- Gravity independent – Ground tests in horizontal orientation showcase behavior similar to that in space
- Mono-sized ½ m long PHP is shown to have thermal conductance range
  - 3.7 – 6 W/K for neon 27 – 38 K
  - 0.45 – 1.25 W/K for helium 2.5 – 10 K
- Compared to classical metallic straps, multi-fold times
  - superior thermal performance at iso-mass
  - lighter at iso-conductance
- Heat switch: from insulator to heat transport device!





Thank you for your attention!

tisha.dixit@cea.fr