Cryogenic developments for very high field magnets

Reduced gravity: Simon Bagnis, Clément Lorin, Hugo Reymond, Steffen Kramer (LNCMI)
PHP: Tisha Dixit, Gilles Authelet, Charles Mailleret, Florian Gouit, Vadim Stepanov

Bertrand Baudouy

Université Paris-Saclay, CEA, IRFU, Département des Accélérateurs, de la Cryogénie et du Magnétisme

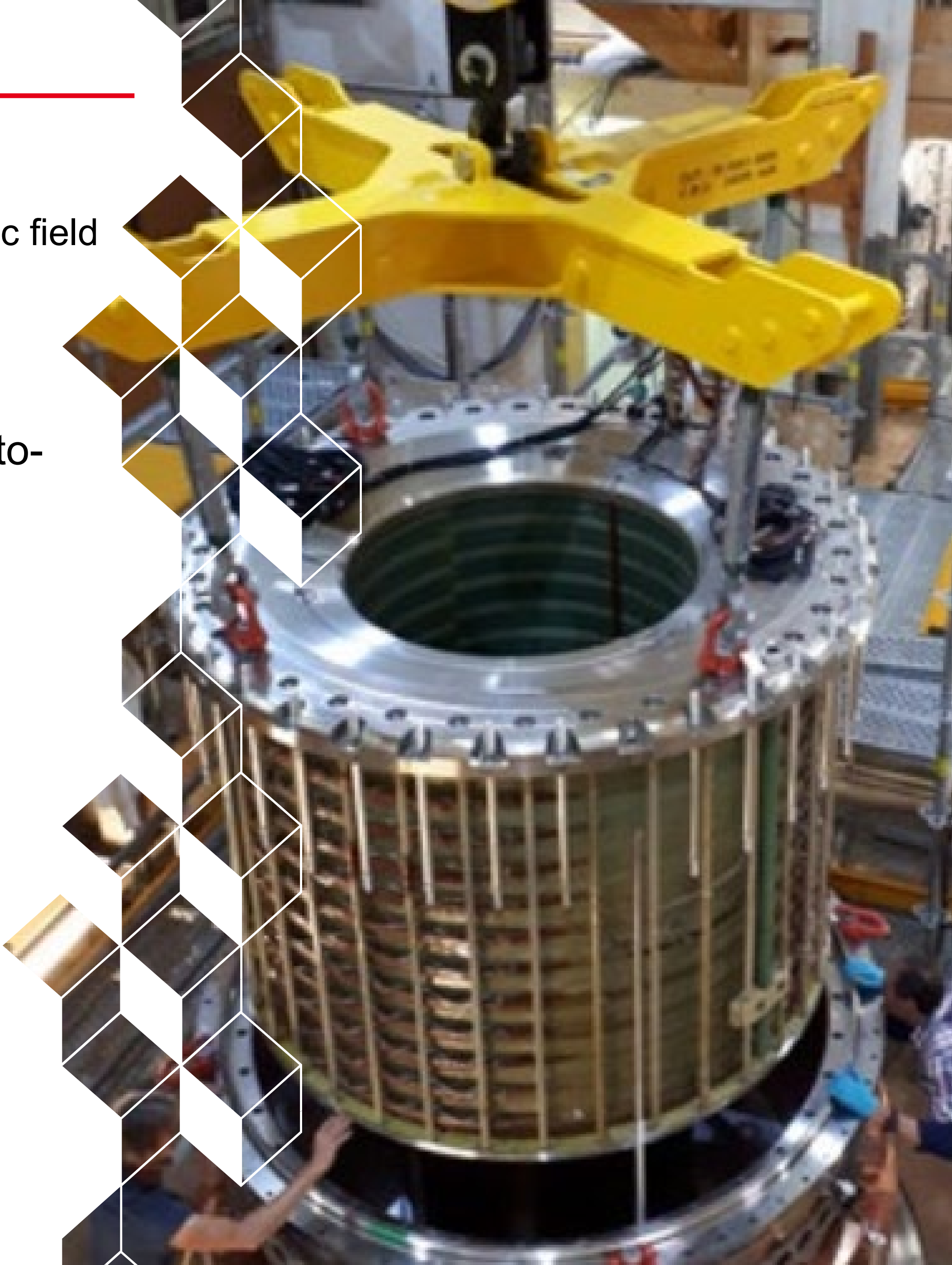
bertrand.baudouy@cea.fr

Outline

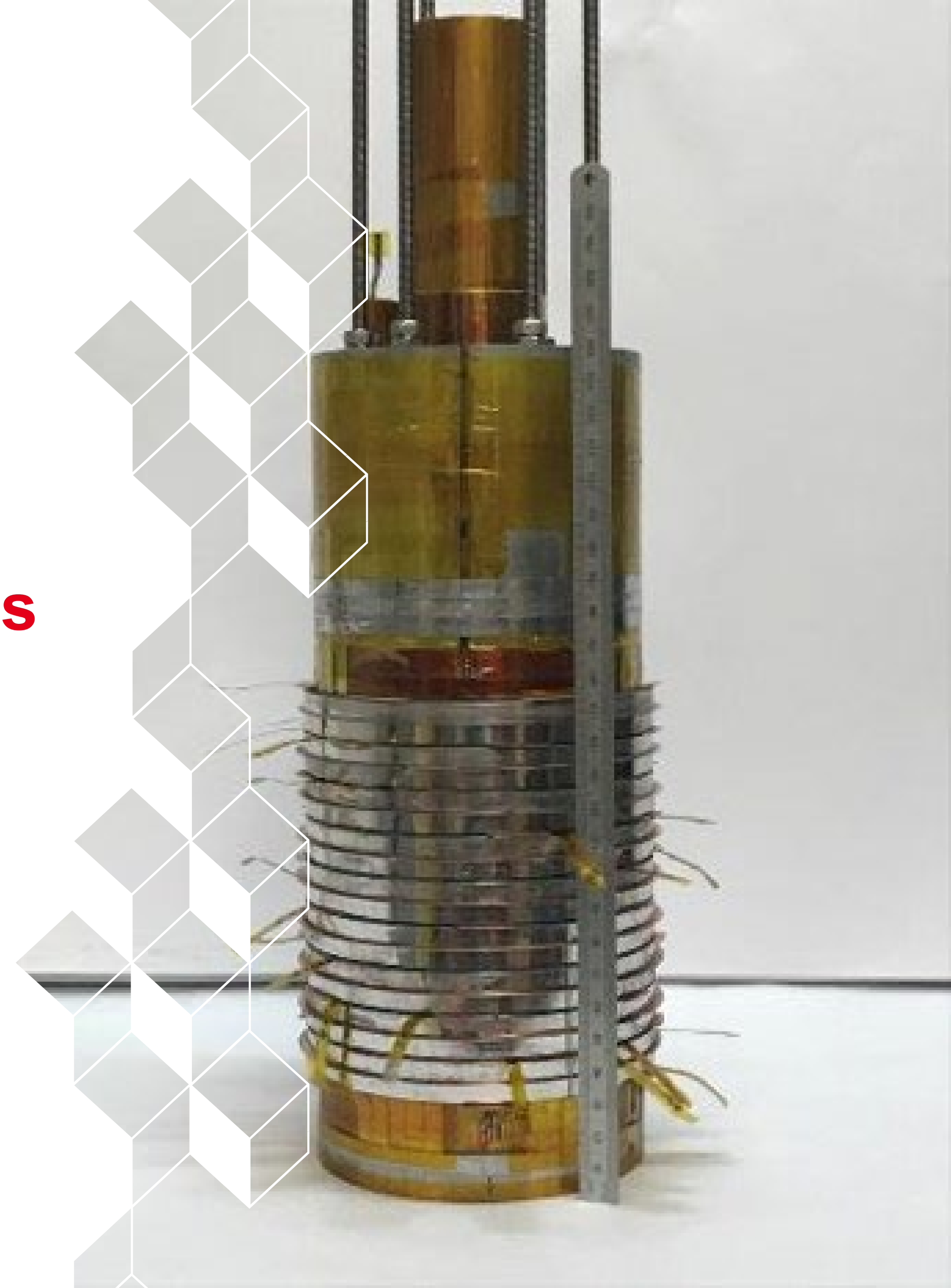
- Very high field magnets cooling
  - Cooling issue for very high magnetic field
  - Heat transfer disturbance due to magneto-gravitational forces

- Helium pool boiling under magneto-gravitational forces
  - Experimental study
  - Results under modified gravity

- Cryogenic cooling of a 10T HTS magnet
  - Cryogenic pulsating heat pipe
  - Cooling a 10T HTS magnet without gravity at 27 K



Very high field magnets cooling



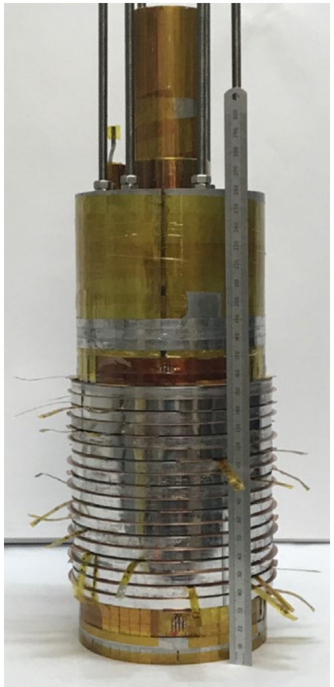
Cooling disturbance at high magnetic field (1/2)

- Cooling problems with certain high-field magnets cooled with saturated liquid helium at 4.2 K
  - NHMFL: 33,8 T [1]
  - Magnet temperature not stabilized at 4.2 K

  - CEA/CNRS: 32,5 T [2]
  - Magnet temperature not stabilized at 4.2 K

  - HMFLCAS: 31,5 T [3]
  - Continuous rise in temperature until a "quench" is reached

- Phenomenon already observed at MIT in 1986 in liquid helium [4]



NOUGAT magnet [2]

Assumption: Heat transfer disturbances due to magneto-gravitational forces

[1] : W. D. Markiewicz et al. 33.8 TESLA WITH A YBa2Cu3O7 SUPERCONDUCTING TEST COIL, 2010
[2] : Philippe Fazilleau et al. 38 mm diameter cold bore metal-as-insulation HTS insert reached 32.5 T in a background magnetic field generated by resistive magnet. Cryogenics, 2020
[3] : Donghui Jiang et al. Energizing behaviors of a no-insulation and layer-wound REBCO coil in high magnetic field Cryogenics, 2019
[4] : L. G. Rubin et al, 33.6 T dc magnetic field produced in a hybrid magnet with Ho pole pieces,1986

Cooling disturbance at high magnetic field (2/2)

- Magnetic forces and other associated physical parameters

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

	T (K)	G_{0g} (T²/m)
H_2	20	-1000
He	4,2	-4170
H_2O	293	-2721
N_2	77	-4425

- Resulting acceleration ←→ resulting gravity

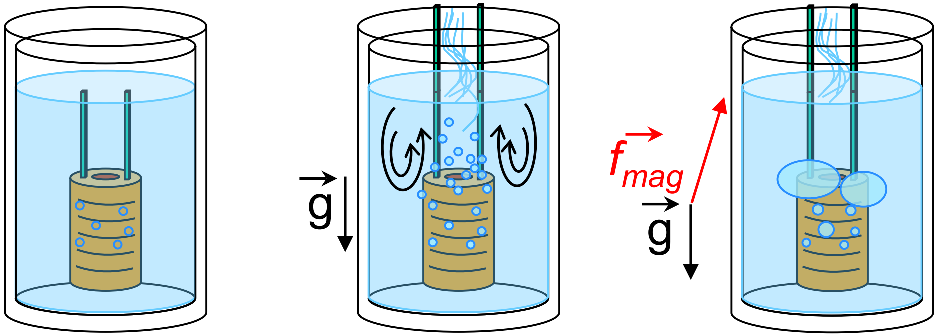
$$\rho\overrightarrow{g^*} = \frac{\chi}{2\mu_0}\vec{G} + \rho\vec{g} = \vec{0}$$

Magneto-gravity potential

$$\Sigma_{mg} = z - \frac{\chi}{2\mu_0}B^2$$

- Compensation of gravity if

$$\vec{G} = \overrightarrow{G_{0g}} = -\frac{2\rho\mu_0}{\chi}\vec{g}$$



Example for a superconducting solenoid

- For a diamagnetic fluid $\chi < 0$

$$\overrightarrow{f_{mag}} = \frac{\chi}{2\mu_0}\vec{G}$$

- In the upper part, vertical magnetic forces oppose gravity

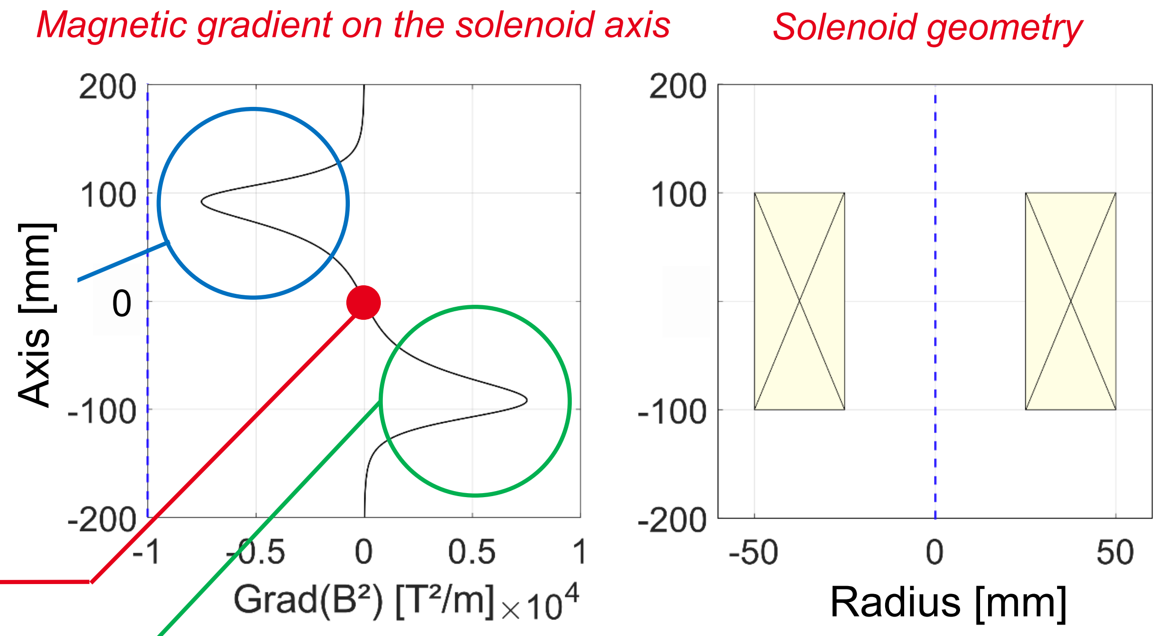
$$g^* < 1g$$

- At the magnet center, magnetic forces are null

$$g^* = 1g$$

- In the lower part, vertical magnetic forces add to gravity

$$g^* > 1g$$



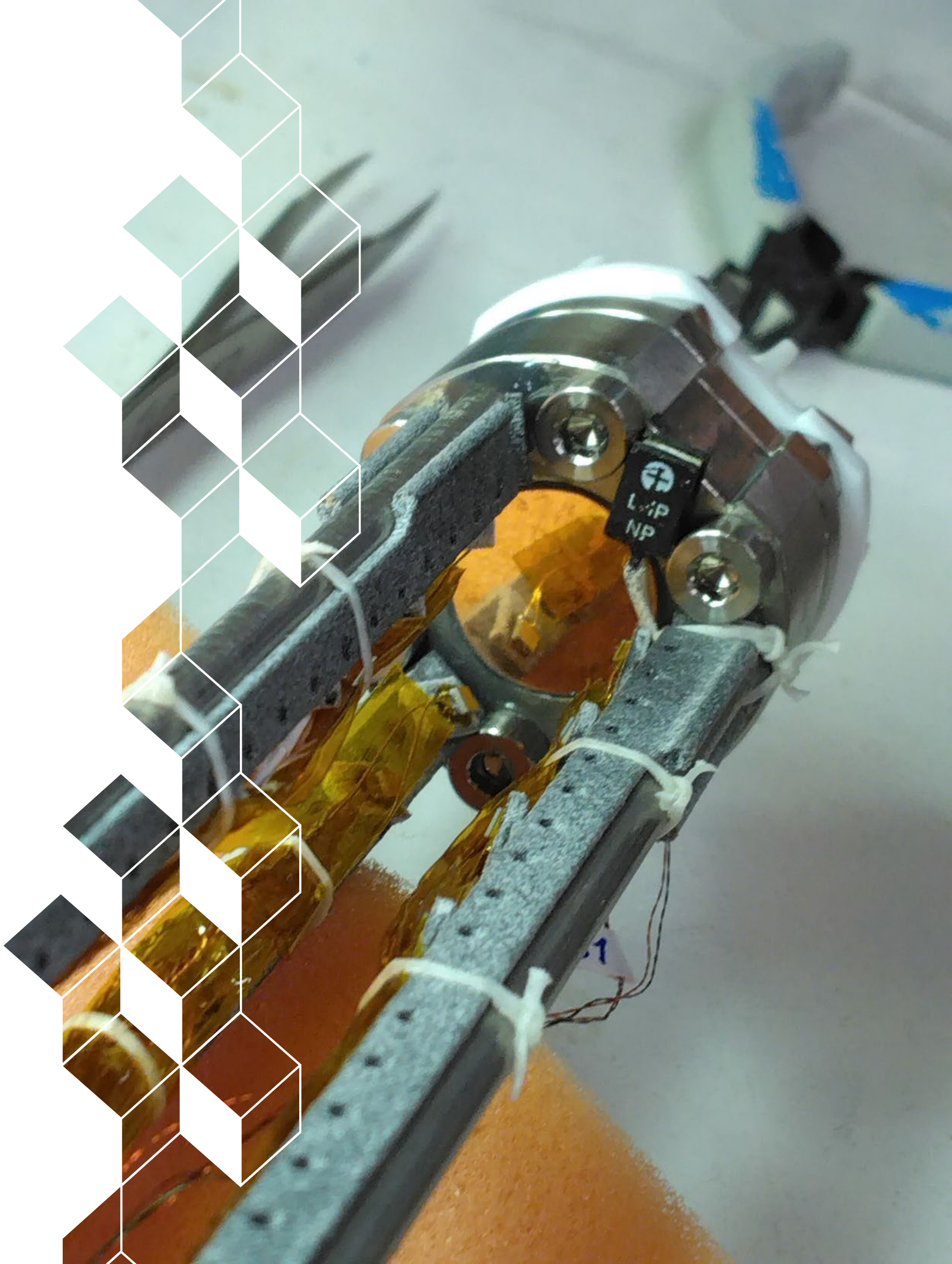
Magnetic gradient on the solenoid axis

Solenoid geometry

$$\overrightarrow{G_{0g}} = -\frac{2\rho\mu_0}{\chi}\vec{g} \quad \text{avec} \quad \chi < 0$$

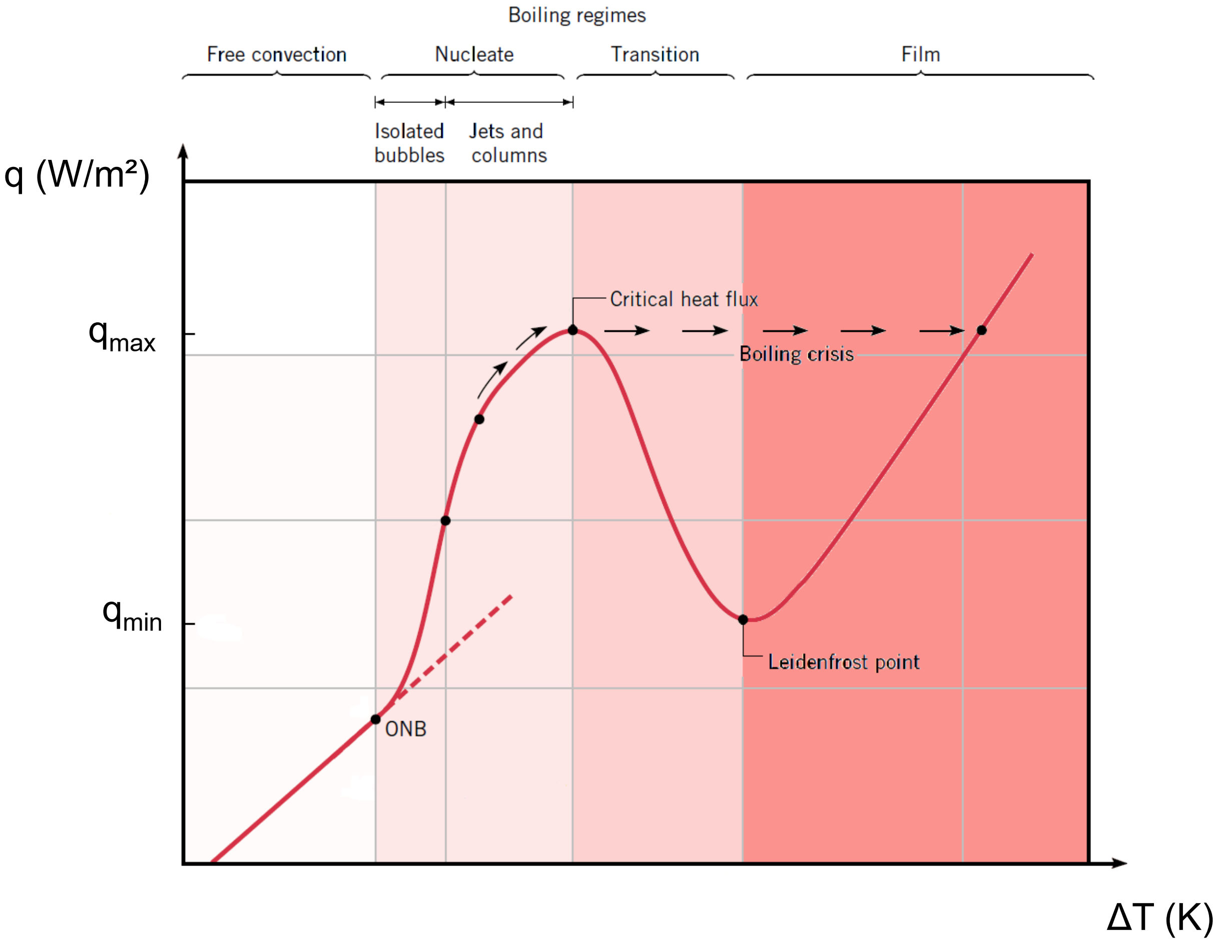
→ Diamagnetic levitation is only possible in the upper part

He pool boiling under magneto-gravitational forces



He pool boiling under magneto-gravitational forces

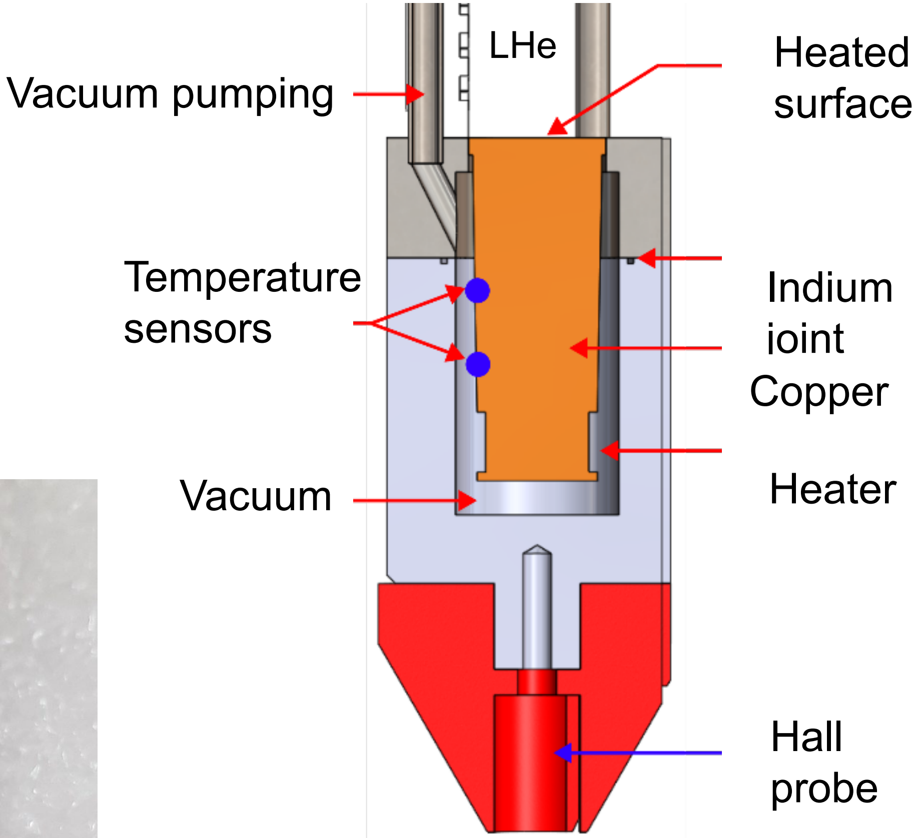
- Experimental study of He pool boiling under modified gravity with magneto-gravitational forces
- Measurement of the boiling curve (Nukiyama) for different g*

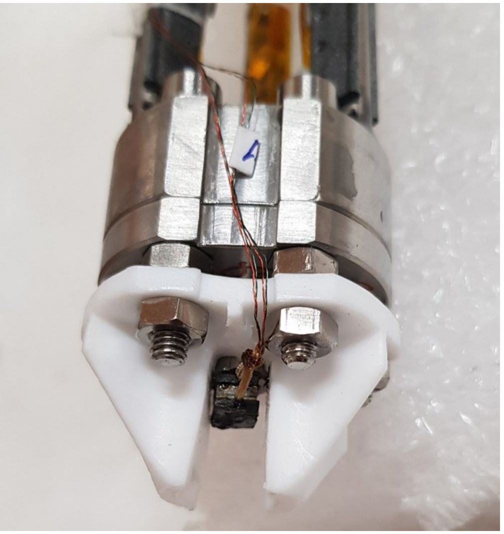


He pool boiling under magneto-gravitational forces

- Magnetically transparent Experimental cell
  - Titanium vacuum can
  - Copper heated surface

  - Temperature sensors to determine the surface temperature
  - Hall probe to evaluate the field and cell positioning

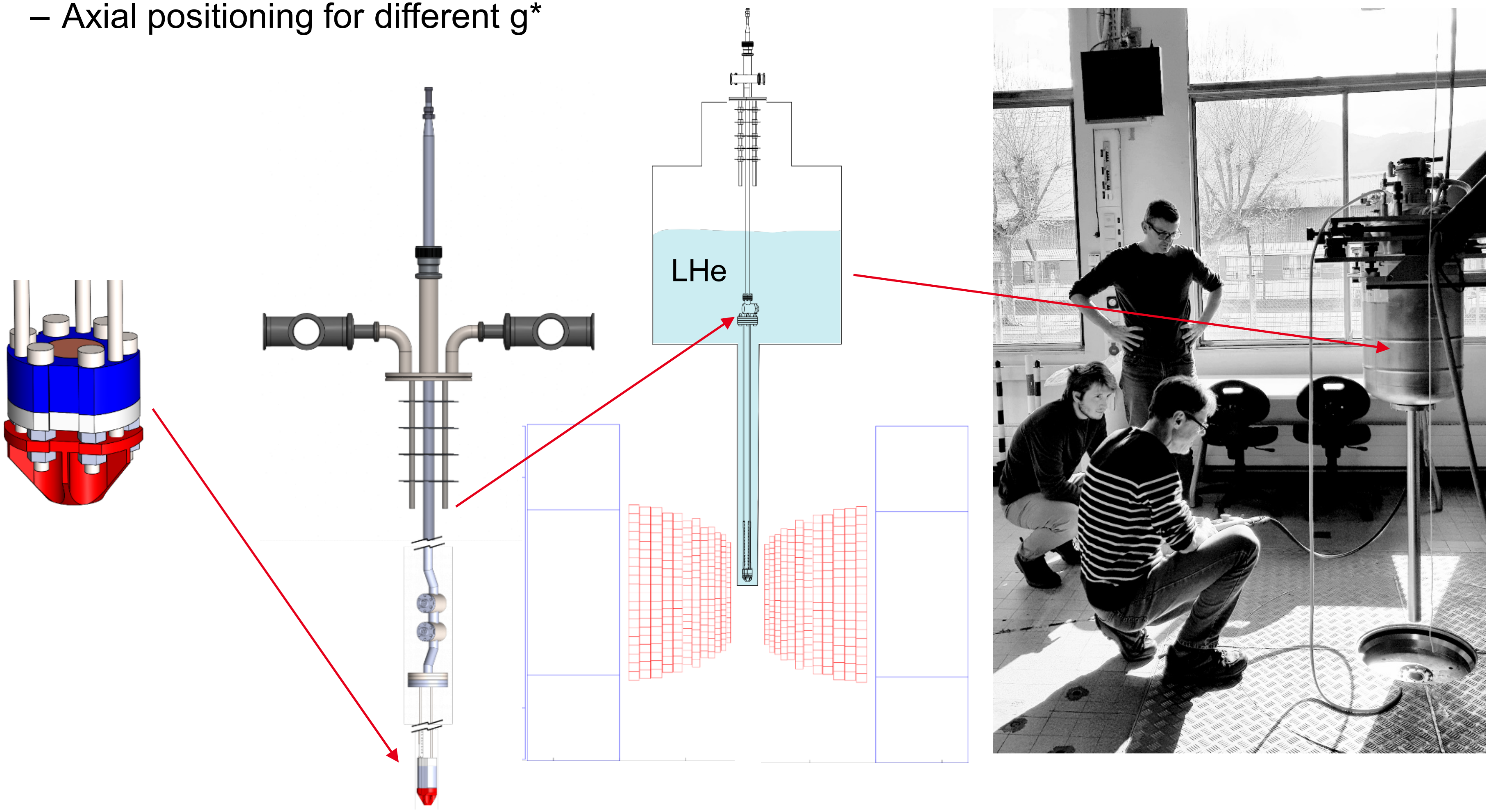




S. Bagnis. PhD .org/10.1016/j.ijheatmasstransfer.2023.125107

He pool boiling under magneto-gravitational forces

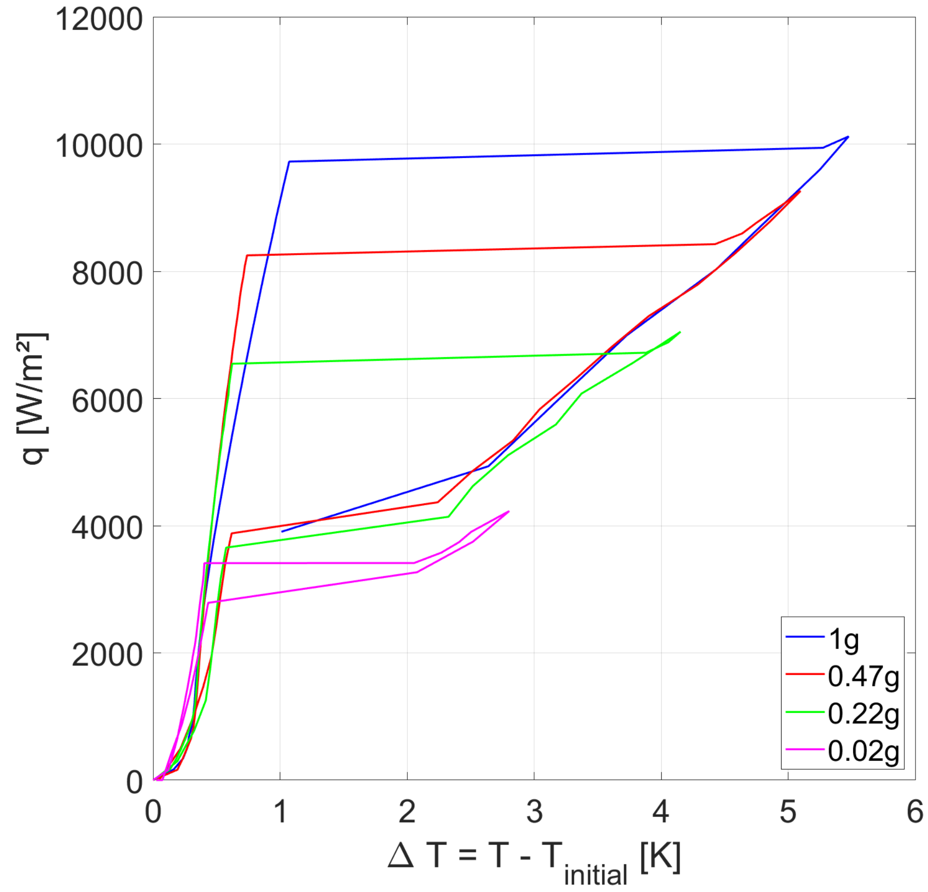
- Tests at LNCMI (Grenoble) in a 30 T resistive magnet
  - 38 mm warm bore
  - Axial positioning for different g*



S. Bagnis. PhD Physics, University Paris-Saclay, https://theses.hal.science/tel-04227350

He pool boiling under magneto-gravitational forces

- LHe pool boiling curve measurement in a quasi static mode

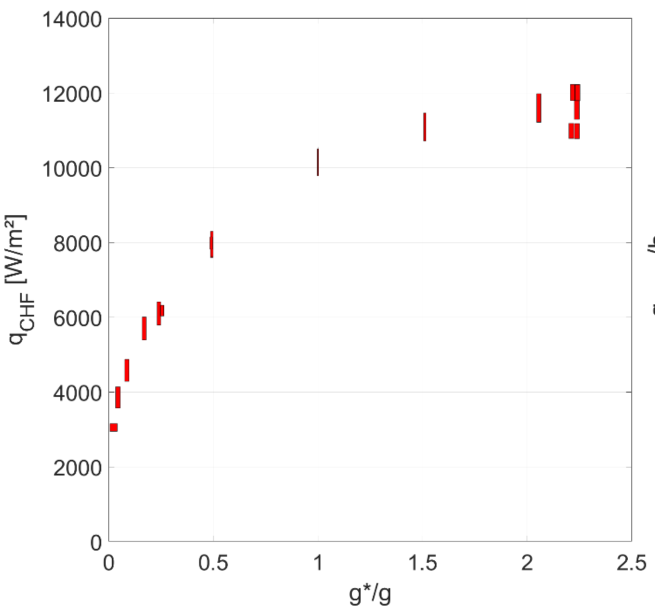


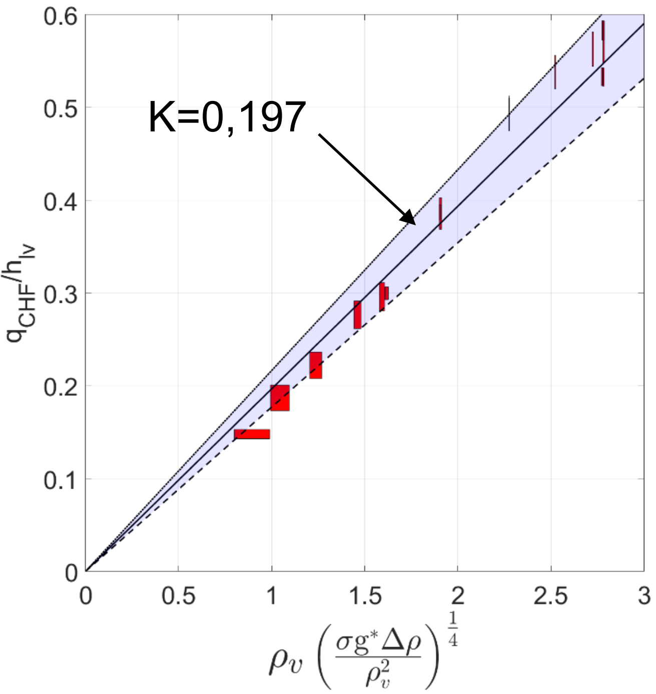
- Entire boiling curve covered
- Nucleate boiling regime
  - 170 W/m² per min
- Critical heat flux detection
- Film boiling regime (q↑)
  - 500 W/m² per min
- Film boiling regime (q↓)
  - 500 W/m² per min
- Detection of minimum heat flux (recovery heat flux)

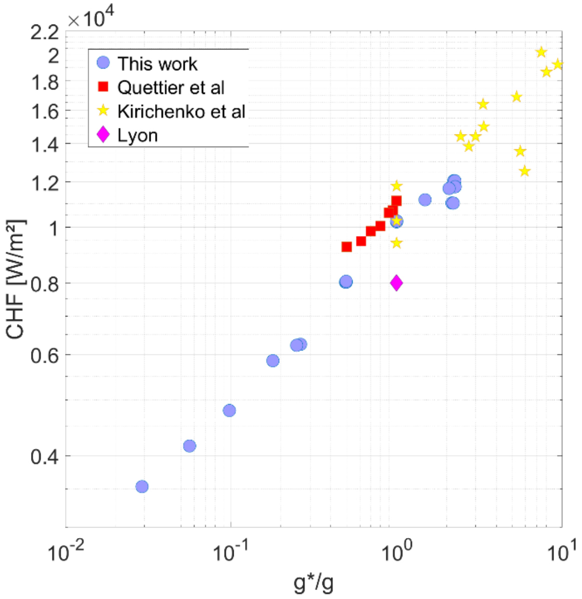
S. Bagnis et al. Helium pool boiling critical heat flux under various magnetically controlled gravity levels, *International Journal of Heat and Mass Transfer*, Volume 221, 2024, 125107
https://doi.org/10.1016/j.ijheatmasstransfer.2023.125107

He pool boiling under magneto-gravitational forces

- LHe pool boiling critical heat flux
- Corrélation avec la forme de Kutateladze: $q_{CHF} = K\rho_v h_{lv}\left(\frac{\sigma g(\rho_l-\rho_v)}{\rho_v^2}\right)^{1/4}$




K=0,197



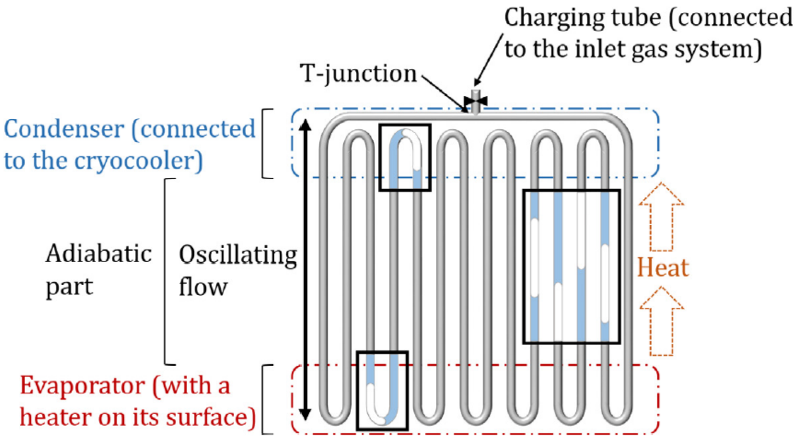
- Good accuracy with the correlation from 0.03g to 2,2g
- K very close to literature value

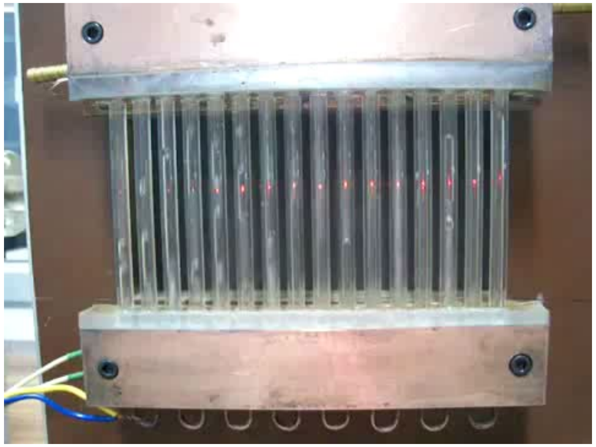
S. Bagnis et al. Helium pool boiling critical heat flux under various magnetically controlled gravity levels, *International Journal of Heat and Mass Transfer*, Volume 221, 2024, 125107
https://doi.org/10.1016/j.ijheatmasstransfer.2023.125107

Cryogenic cooling of a 10T HTS magnet

Cryogenic PHP

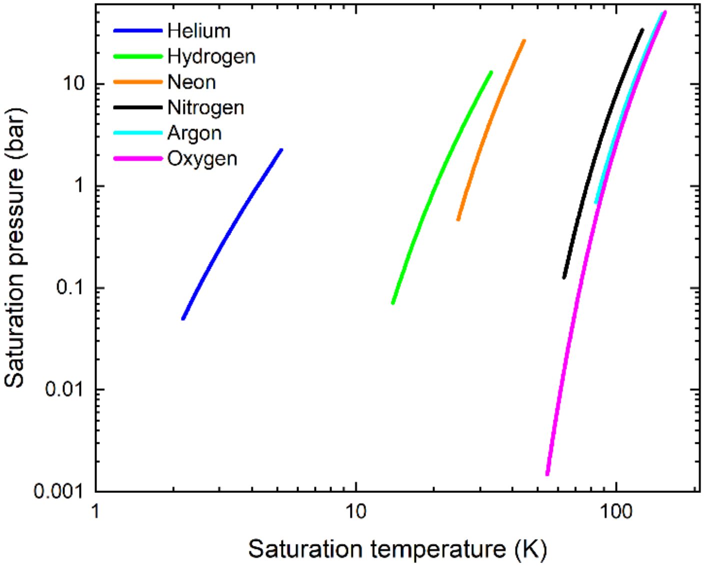
- Two-phase passive heat transfer device
  - having oscillating train of liquid slugs and vapor bubbles as thermal transport carriers
  - Filled partially with working cryo-fluid operating at its saturation condition





Water PHP Credits: Prof. Sameer Khandekar, IIT Kanpur, India

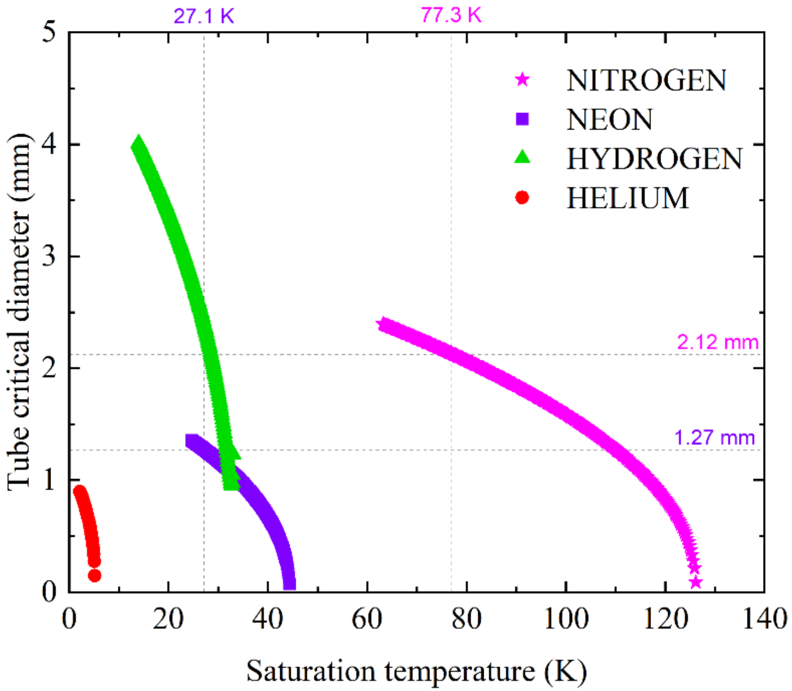
Saturation curves (P,T)



- Why a pulsating heat pipe (PHP)?
  - High heat transfer rate and light
  - Heat transfer/weight ⟶ 100 better than eq. copper
  - Easy to construct, bendable, flexible….
  - Almost gravity independent
  - Some drawbacks…

Cryogenic PHP design

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



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

ρ_l = fluid saturation liquid density
ρ_v= fluid saturation vapour density
σ = fluid surface tension
D = tube inner diameter

Good starting point but validity of theory deliberated!

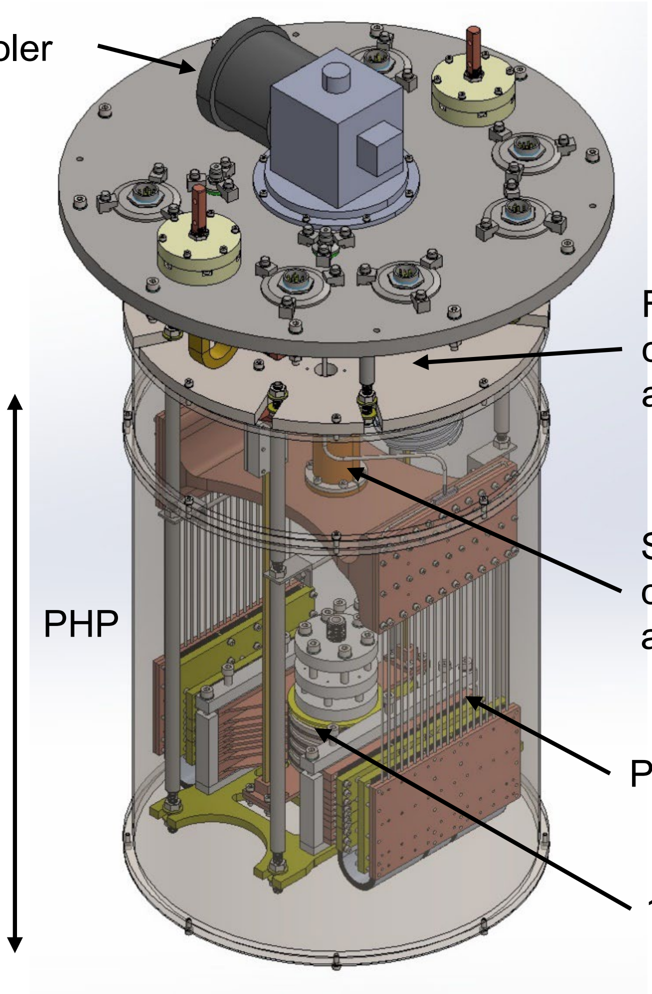
Dixit et al. "Oversized diameter helium pulsating heat pipe" ATE 2024 (under review)

Governing phenomena not completely understood: currently choice based on results of experiments. 1D/2D numerical models being developed

- Choice of other physical characteristics:
  - Length of condenser, adiabatic part and evaporator
  - Material of condenser/evaporator, of capillary tube
  - Number of PHP turns

Cooling high field magnet

- Demonstrate the generation of 10 T with a double pancake SC magnet at 27 K cooled by a cryocooler and 2 neon PHP as thermal links



Cryocooler

First stage cryocooler at 50 K

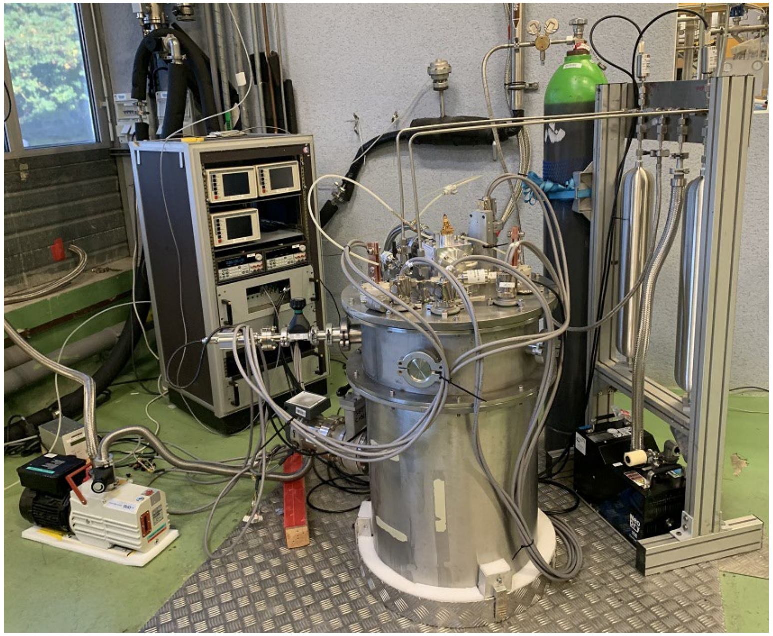
Second stage cryocooler at 27 K

PHP

1.15 m

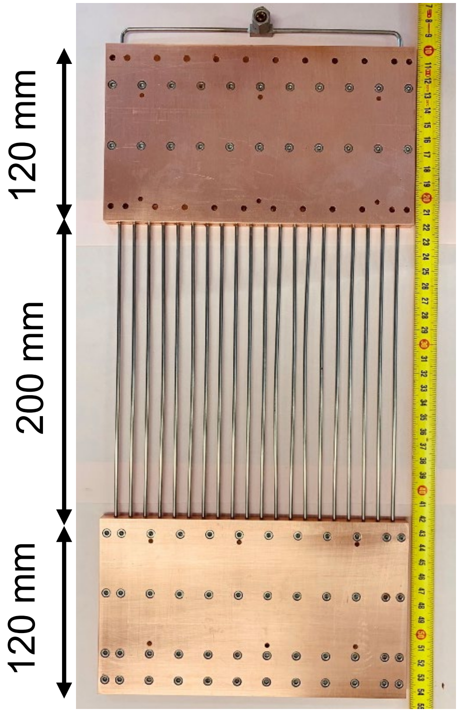
PHP

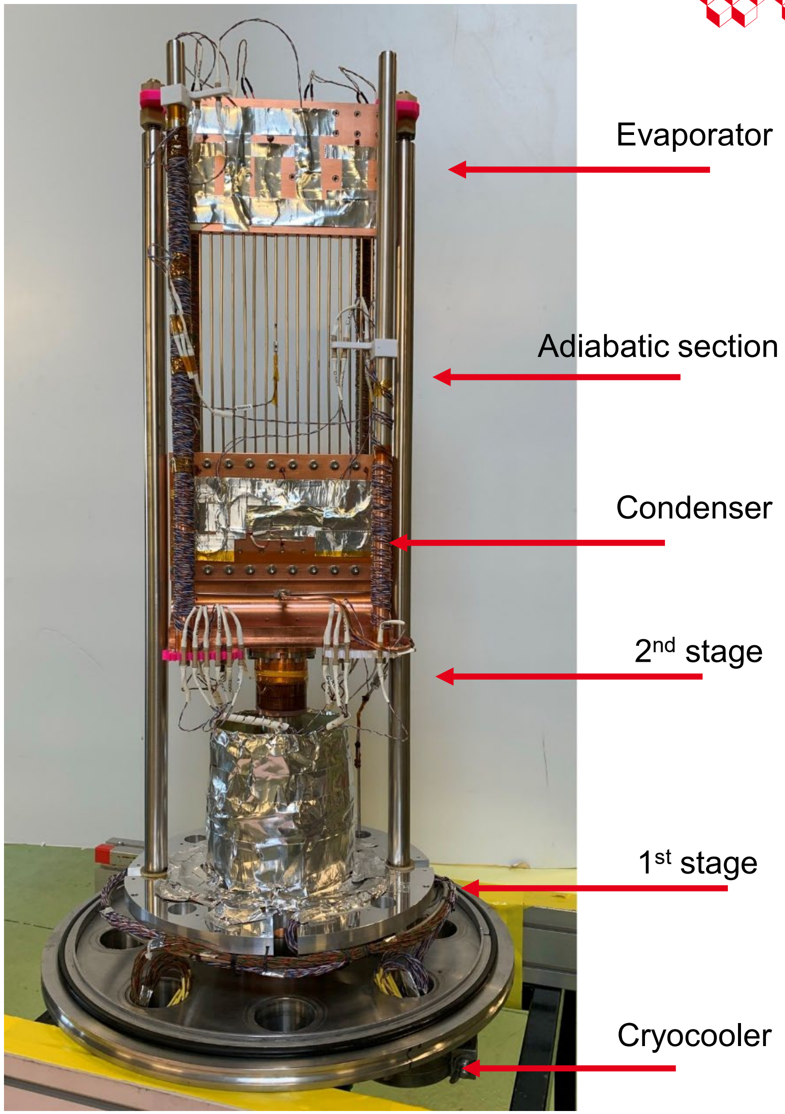
10 T superconducting magnet



Neon PHP for HTS magnet

Chosen PHP parameters
Material = SS316L
Inner diameter = 1.0 mm
Outer diameter = 2.5 mm
Number of tubes = 20
Length = 440 mm
Bo ≈ 2,5



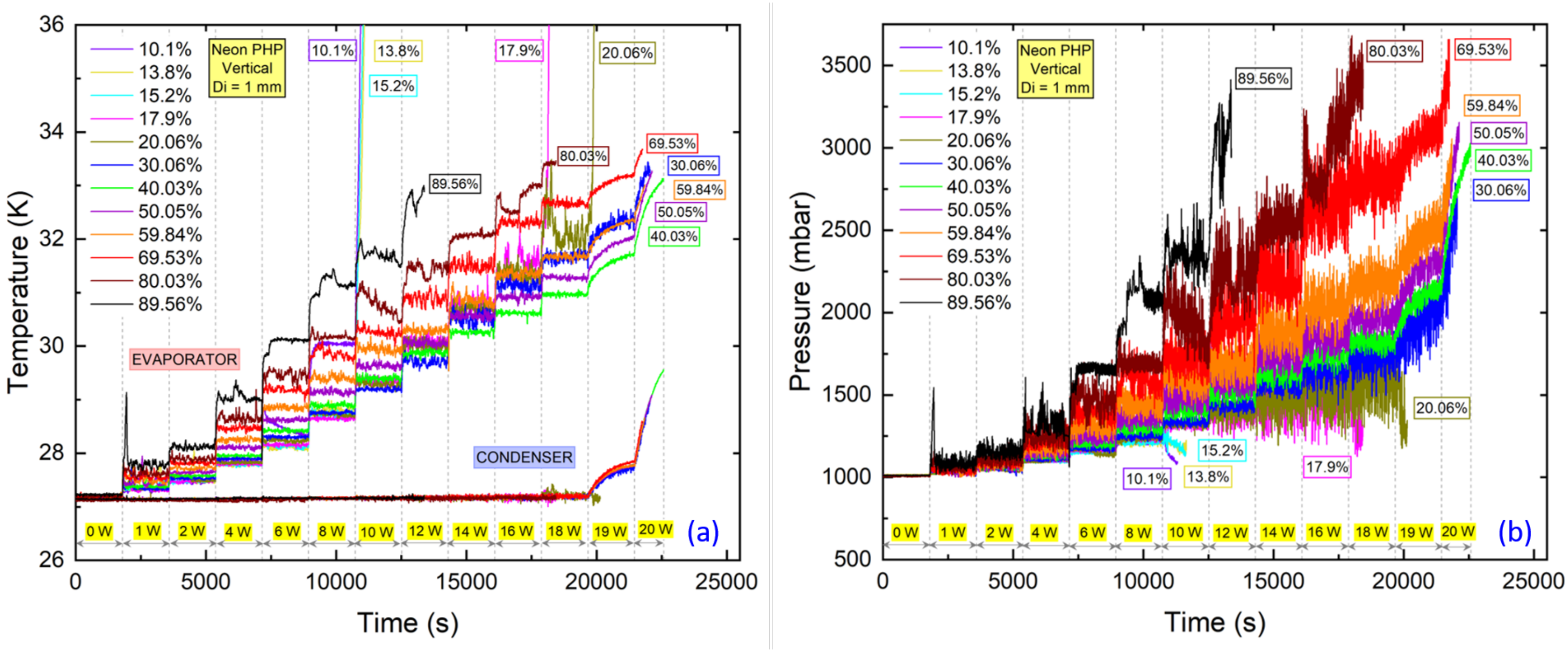


T Dixit et al 2022 IOP Conf. Ser.: Mater. Sci. Eng. 1240 012076

Neon PHP for HTS magnet

- Evaporator and condenser temperature measurement
- Pressure outside of the cryostat
- Vertical and horizontal orientations
- 18 W is reached at @ $T_{condenser}$ = 27.1 K due to cryocooler max capability

$$FR = V_{liquid}/V_{total}$$

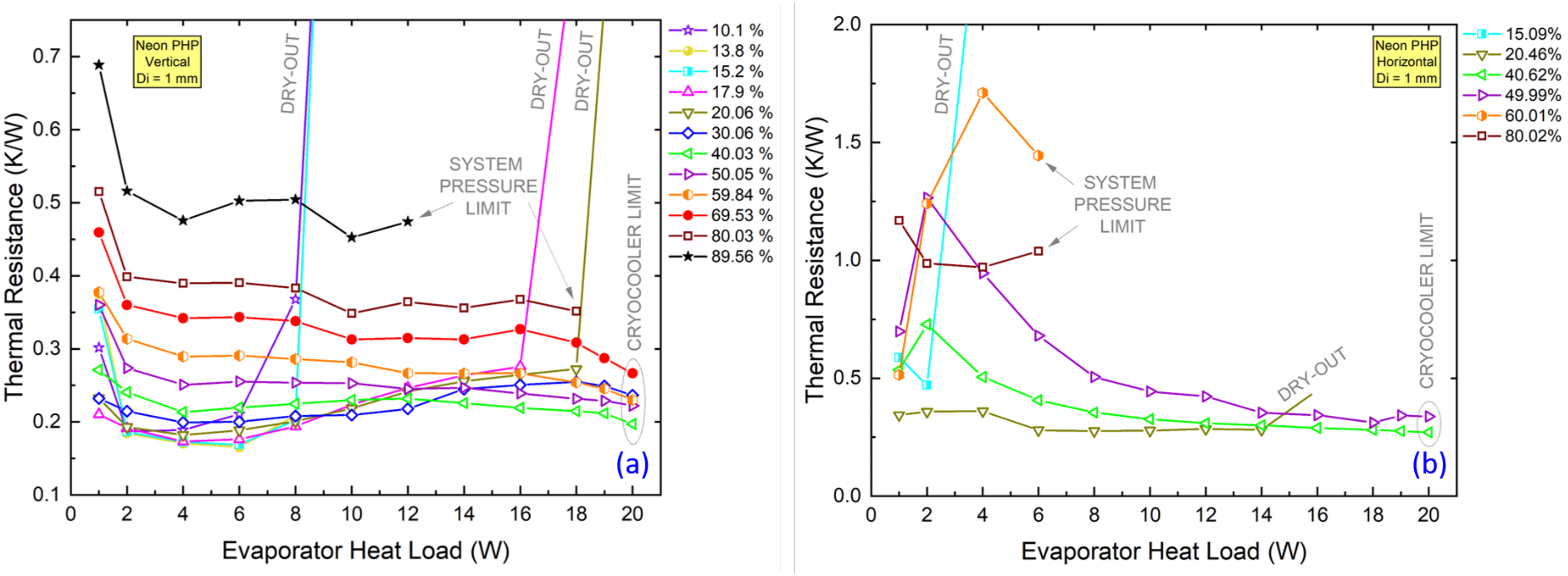


Dixit et al., Cryogenics 132 (2023) 103670, https://doi.org/10.1016/j.cryogenics.2023.103670

Neon PHP for HTS magnet

- At 18 W, Lower thermal resistance for FR=40 %
- Orientation effect
  - – ΔT = 3.9 K for vertical orientation
  - – ΔT = 5.1 K for horizontal orientation

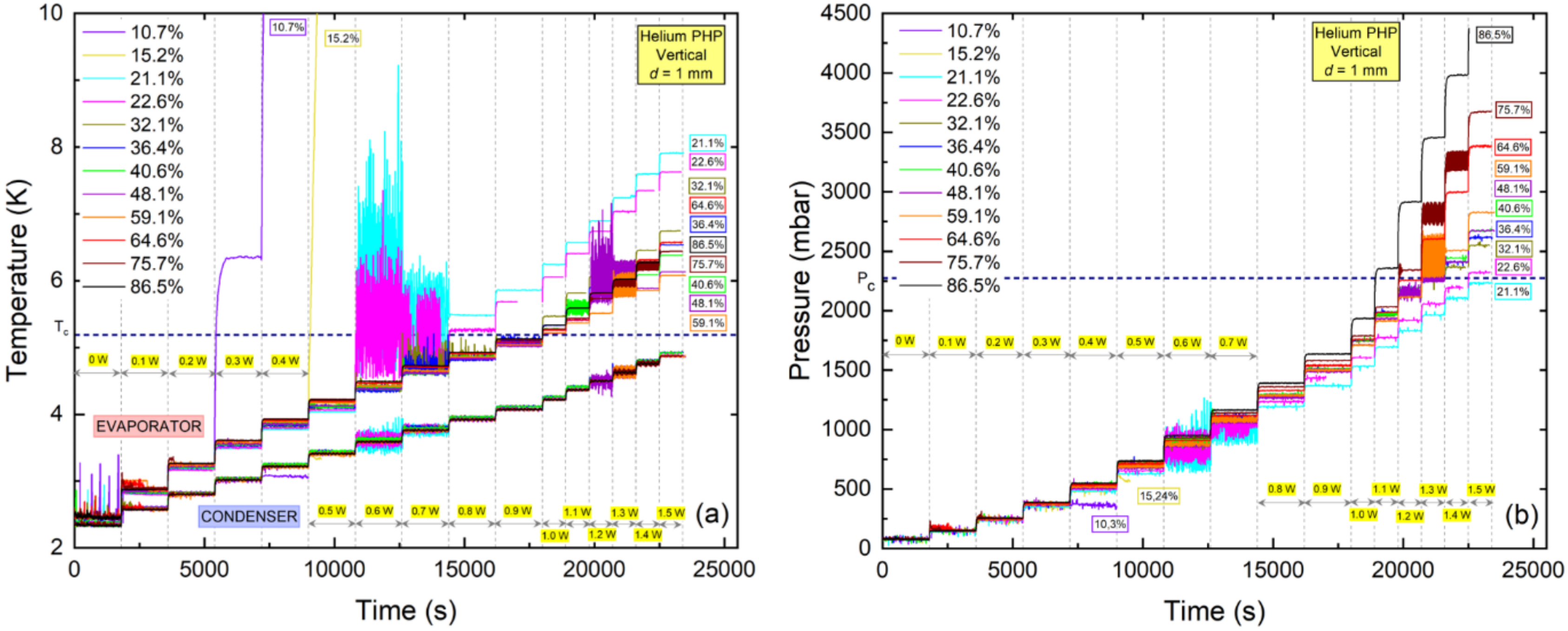
$$R_{th} = \frac{T_{Evap} - T_{Cond}}{Q}$$



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

He PHP

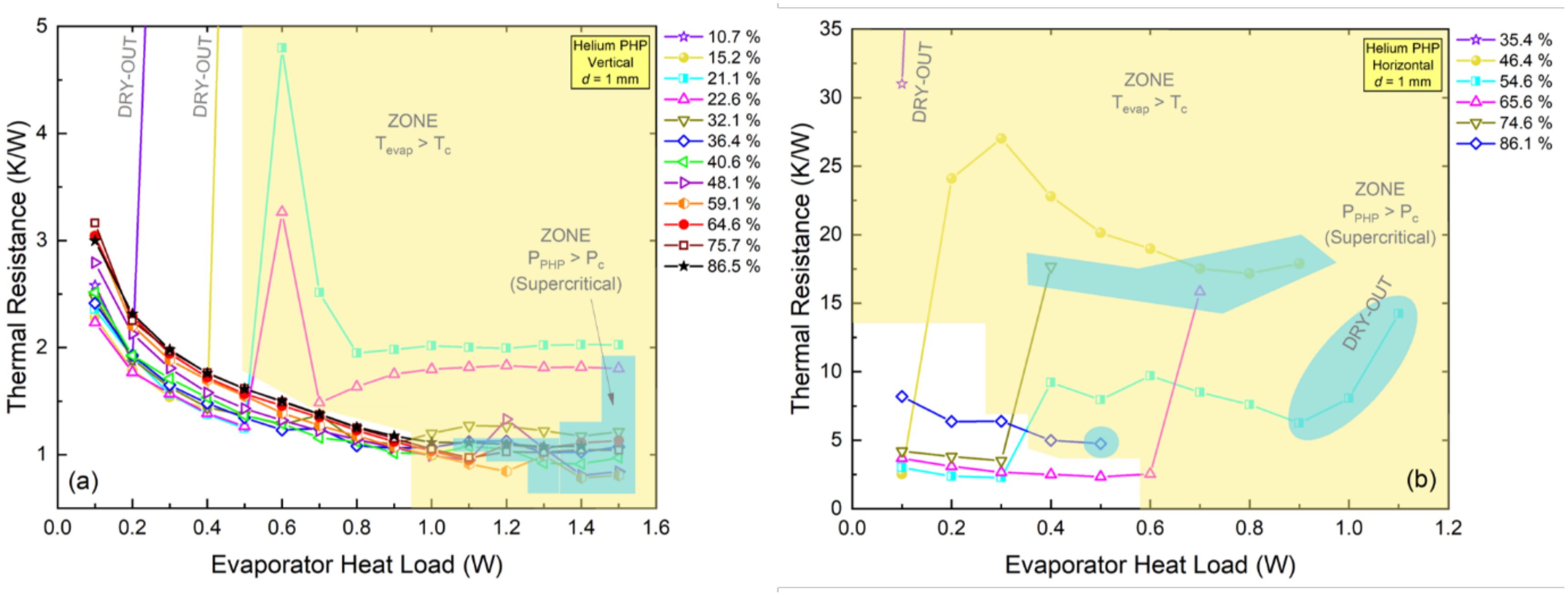
- Bo number based on the critical diameter where vapor structure is trapped as a bubble in a capillary tube and starts to move
- But “plug flow” exists for non null velocity, i.e. for Bo>4 ⟶ Limit?
- **Test in helium and 1 mm diameter ⟶ Bo≈12**



Dixit et al., Applied Thermal Engineering 251 (2024) 123613 https://doi.org/10.1016/j.applthermaleng.2024.123613

He PHP

- Stable working condition in **pressurized liquid state** in evaporator (T>T$_c$)
- Stable working condition in **supercritical state** in evaporator
- Visualization is needed to identify the flow regimes



- Stable working conditions for 65 hours
  - FR = 40.6% and 0.6 W in vertical orientation
  - FR = 64.6% 0.2 W in horizontal orientation

Dixit et al., Applied Thermal Engineering 251 (2024) 123613 https://doi.org/10.1016/j.applthermaleng.2024.123613

Future work

- Study of the diameter size effect on the thermal performance
  - Max diameter size?

- Velocity bubble measurement with capacitance method
- Visualization with shadowgraph method

- Flexible PHP to match the geometry of our devices
  - Evaporator geometry
  - Bending effect…

- Miniaturization of PHP for space detector application (15 cm long)

- Collaboration with S. Pietrowicz group at WUST with a co-PhD (Marcin Opalski) on the numerical and experimental study of small cryogenic PHP