Quantification of the heat flux transferred to supercritical helium flowing in tubes after loss of insulating vacuum

Sulayman SHOALA[1], Eric ERCOLANI[1], Jean Marc PONCET[1], Frederic AYELA[2]

[1]CEA/IRIG/DSBT, Grenoble, France

[2] LEGI , Grenoble, France

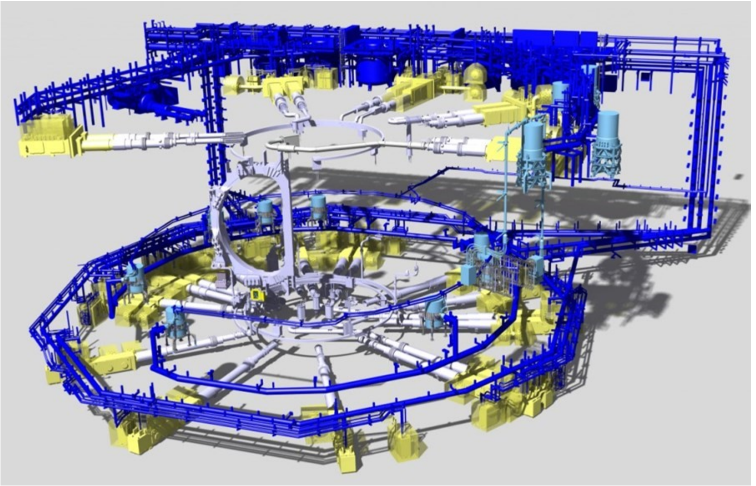
CHATS AS 2023 / 3 – 5 may 2023

Safety in cryogenics

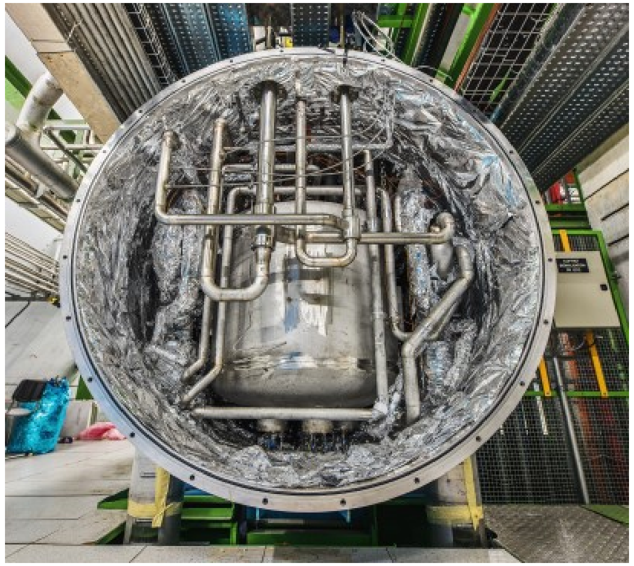
- Insulating vacuum failure is a major accident scenario
  - Large break on the Cryostat
  - Outside atmospheric air rushes into the vacuum space and condenses on cold surfaces
  - Very high heat load transferred to the cryogenic fluid
- Cryogenics devices have to be protected against overpressure by using safety valves or rupture disks
- Safety relief devices are currently sized by using a constant heat flux value :
  - Helium tank in diphasic discharge, without insulation: 3,8 W/cm² [1]
  - Helium tank in supercritical discharge, without insulation: 2 W/cm² [2]
- Reference values of heat flux have just been measured for tanks without long discharge lines

Question: Which value of heat flux has to be considered for supercritical helium flowing in a pipe?

Objective: To develop an experimental device to perform measure of the heat flux



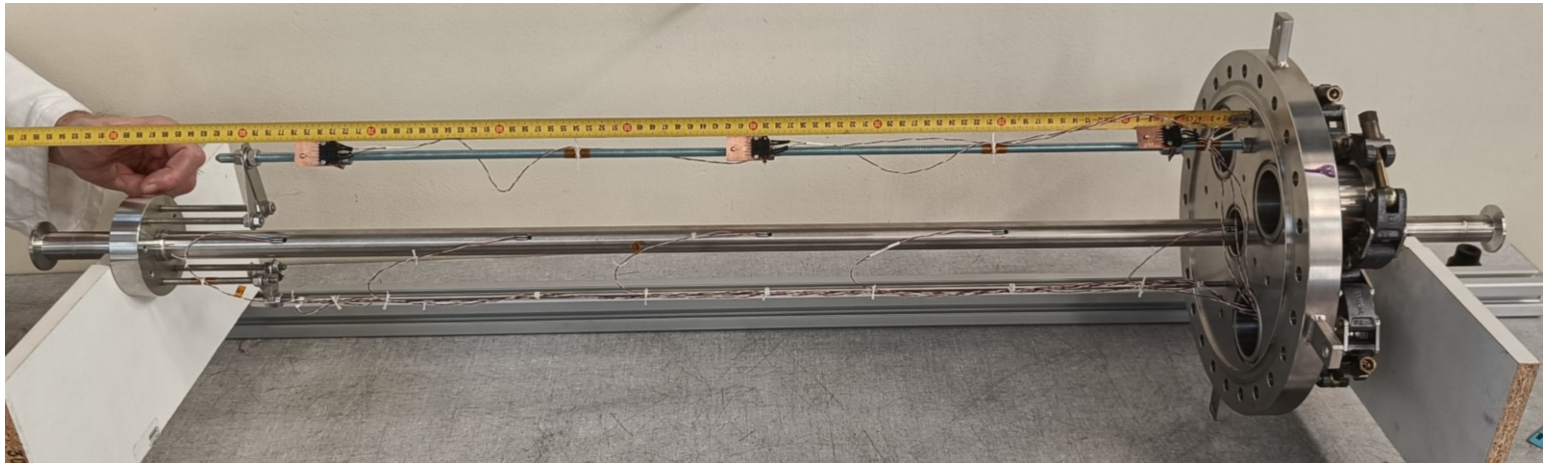
Caption : CERN: 18kW@4.5K cold box (cds.cern.ch)



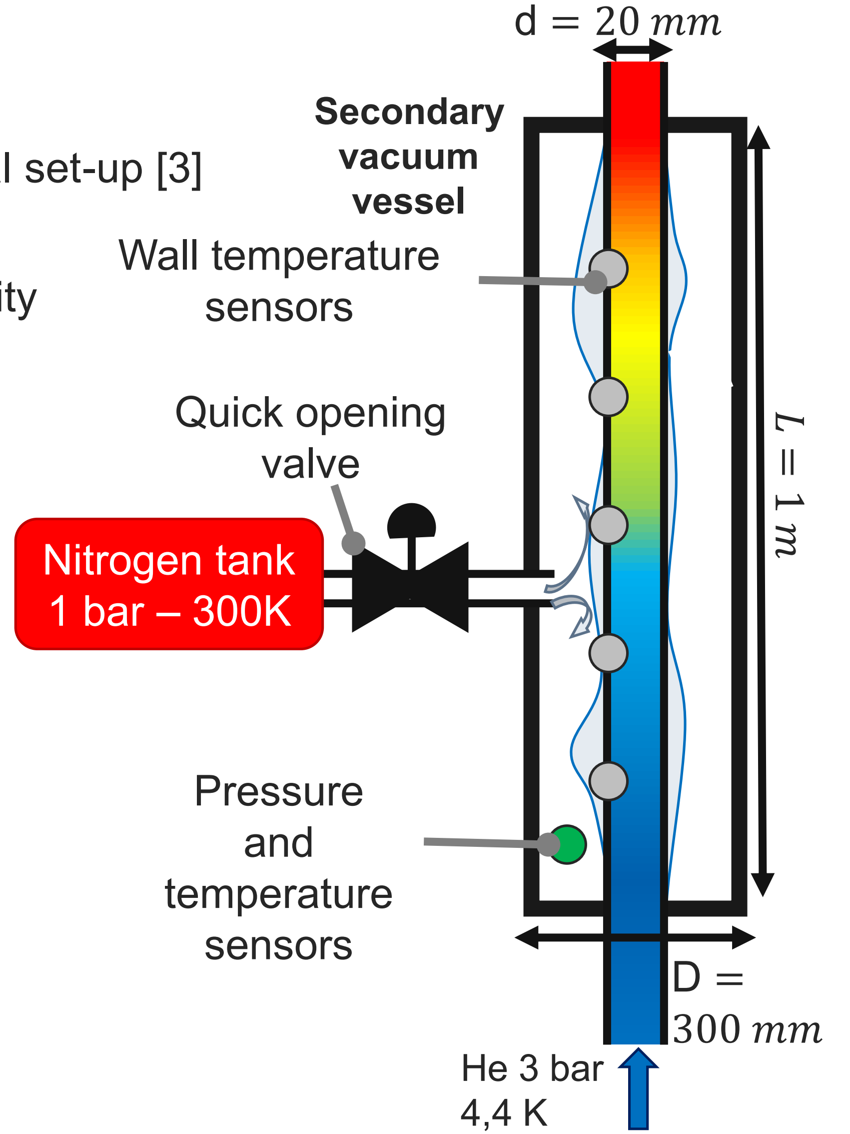
Caption : Iter's Cryolines and cold boxes (iter.org)

The test section

- A test section (TS) has been designed and installed in the HELIOS experimental set-up [3]
- Loss of the insulating vacuum only on a restricted part of the experimental facility
- Vacuum loss in a restricted area thanks to a secondary vacuum vessel
  - Vacuum break with N2 at atmospheric pressure/temperature
- The supercritical helium flow is vertical upwards

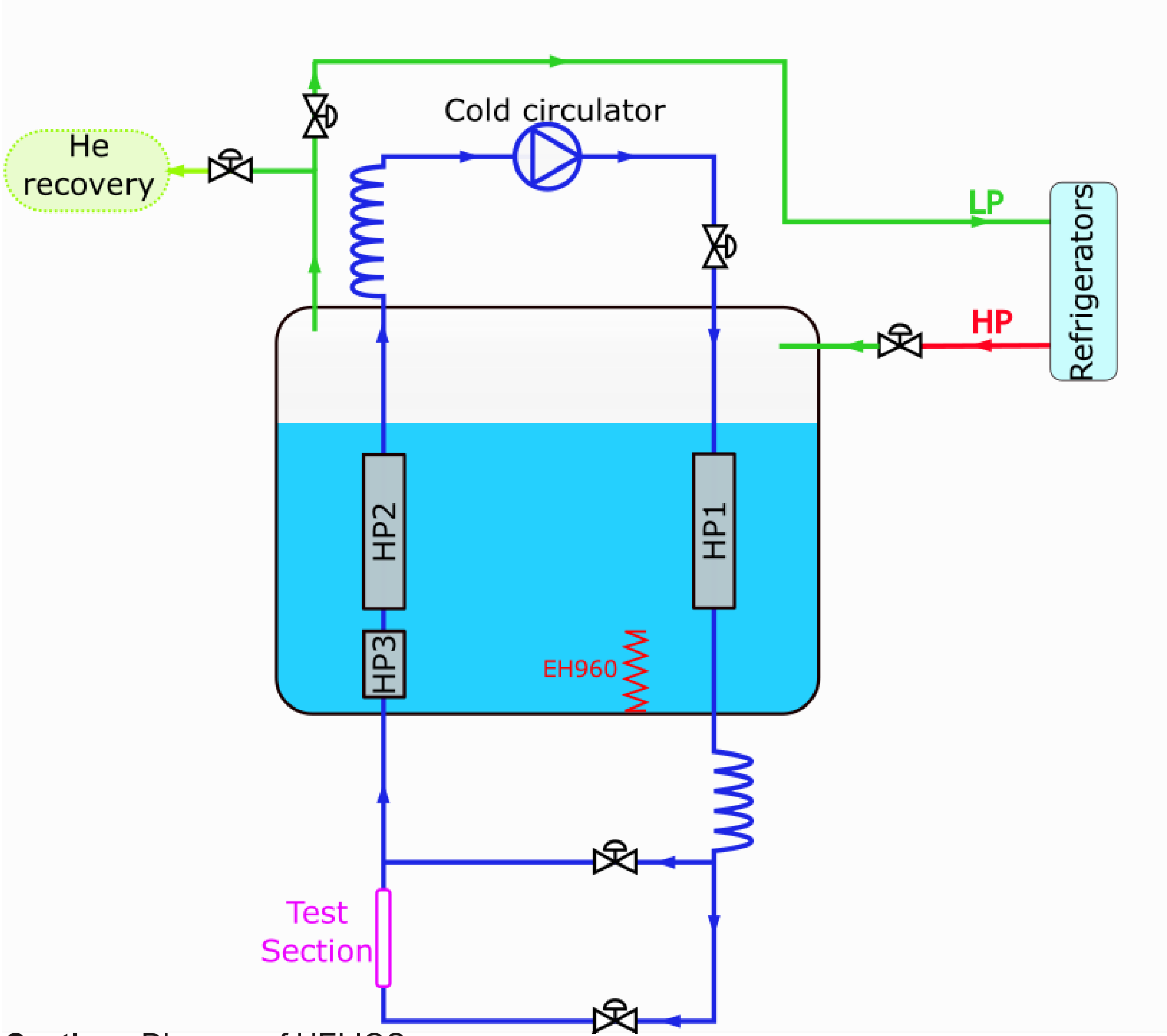


Caption : inner part of the test section



Caption : Diagram of the test section

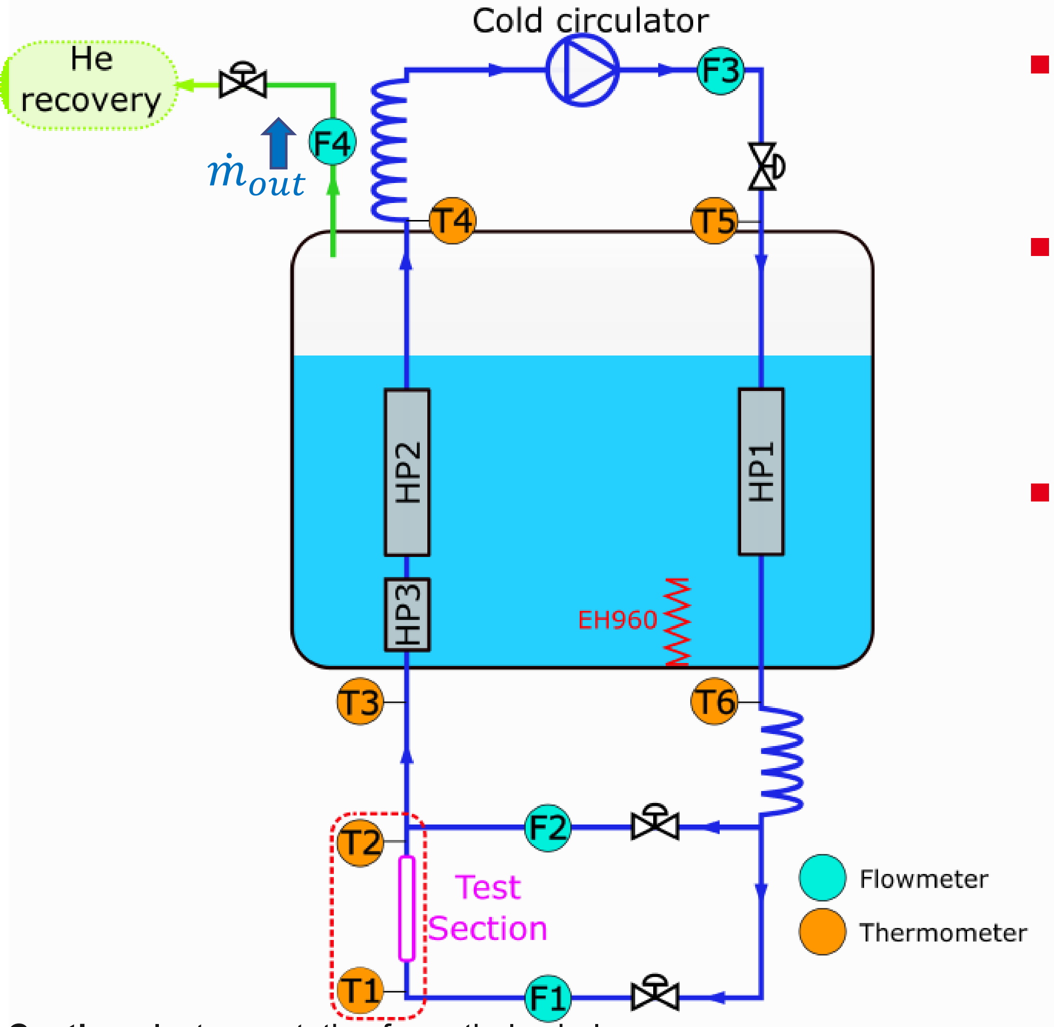
The HELIOS loop



Caption : Diagram of HELIOS

- HELIOS facility is composed of two main parts:
  - 1 supercritical helium loop
  - 1 saturated helium bath
- Bath connected to the refrigerator
  - Cooling power available: 320 W
- Experimental set-up sized with the CATHARE 3 code
  - Major changes in the facility
  - Sized to receive heat pulse loads up to 2,5 kW for 60s
  - Test of the installation control procedures
- Two strategies to store the injected energy during the pulse
  - Closed bath : used as thermal buffer
  - Opened bath : vaporised helium evacuated to the recovery system

Experimental method for measuring thermal power transmitted to the fluid



Caption : Instrumentation for enthalpy balance

- By enthalpy balance in the loop
  - $\dot{Q} = \dot{m}\,(h_{out} - h_{in})$
- By energy balance in the bath :
  - Close system => stored energy is deduced from the pressure rise
  - Open system => energy is deduced from the mass flowrate leaving the bath
- Energy balance in the open bath :
  - $\dot{Q} = \dot{m}_{out} \cdot h_{out} + \frac{d(m_{He} * u_{He})}{dt}$

$\dot{m}_{out} \cdot h_{out}$: Power released by the bath

$\frac{d(m_{He} * u_{He})}{dt}$: Power stored in the bath

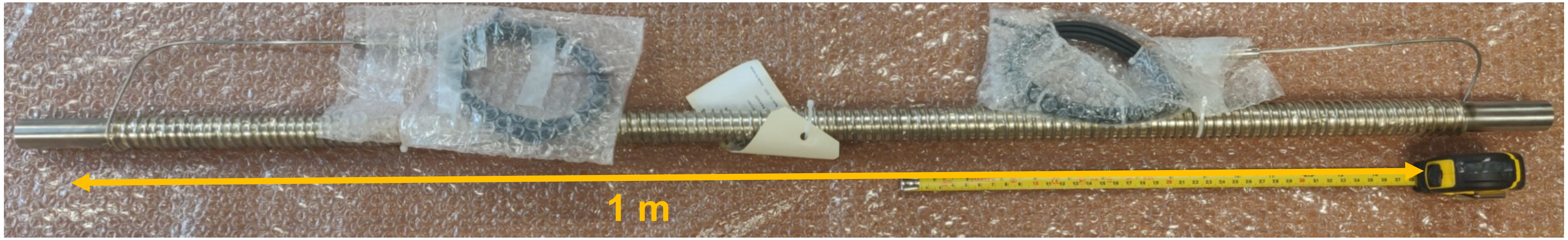
$\dot{m}_{out}$ = leaving mass flowrate
h_{out} = enthalpy of the outgoing gas
m_{He} = helium mass
u_{He} = internal energy

Electrical test section

- A first campaign was conducted with an electrical test section
  - Equipped with the electrical heater to simulate the loss of vacuum with a known heat pulse
  - Positionned in place of the test section used to generate the vacuum loss

- Used to validate the experimental setup:
  - New HELIOS sizing
  - Experimental method for measuring thermal power transmitted to the fluid

- Experimental results can be compared with CATHARE predictions



Caption : Electrical test section

The CATHARE code

- **C**ode for **A**nalysis of **T**hermal **H**ydraulics during **A**ccident and for **R**eactor safety **E**valuation [4]

- CATHARE : Reference tool for safety evaluation of pressurized water reactor, developed by CEA, FRAMATOME, EDF and IRSN since 1979

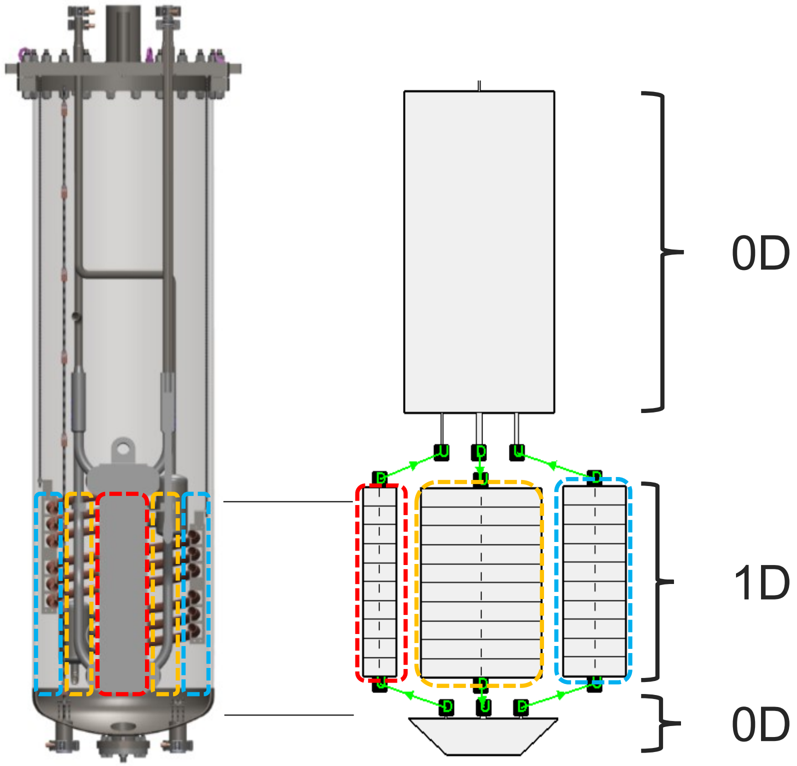
- Devoted to thermal hydraulic simulation of multiphase flow transient at the system scale

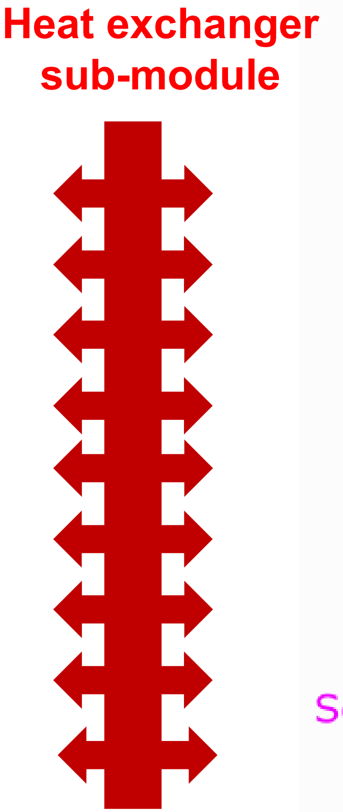
- 2-fluids and 6 equations model :
  - 3 equations for each phase: mass, momentum and energy balance
  - 6 main hydraulic variables: P, Hl, Hg, a, Vl, Vg
  - Taking into account all the flow regimes, mass and heat transfer between each phase or fluid and structure (~200 closure laws)

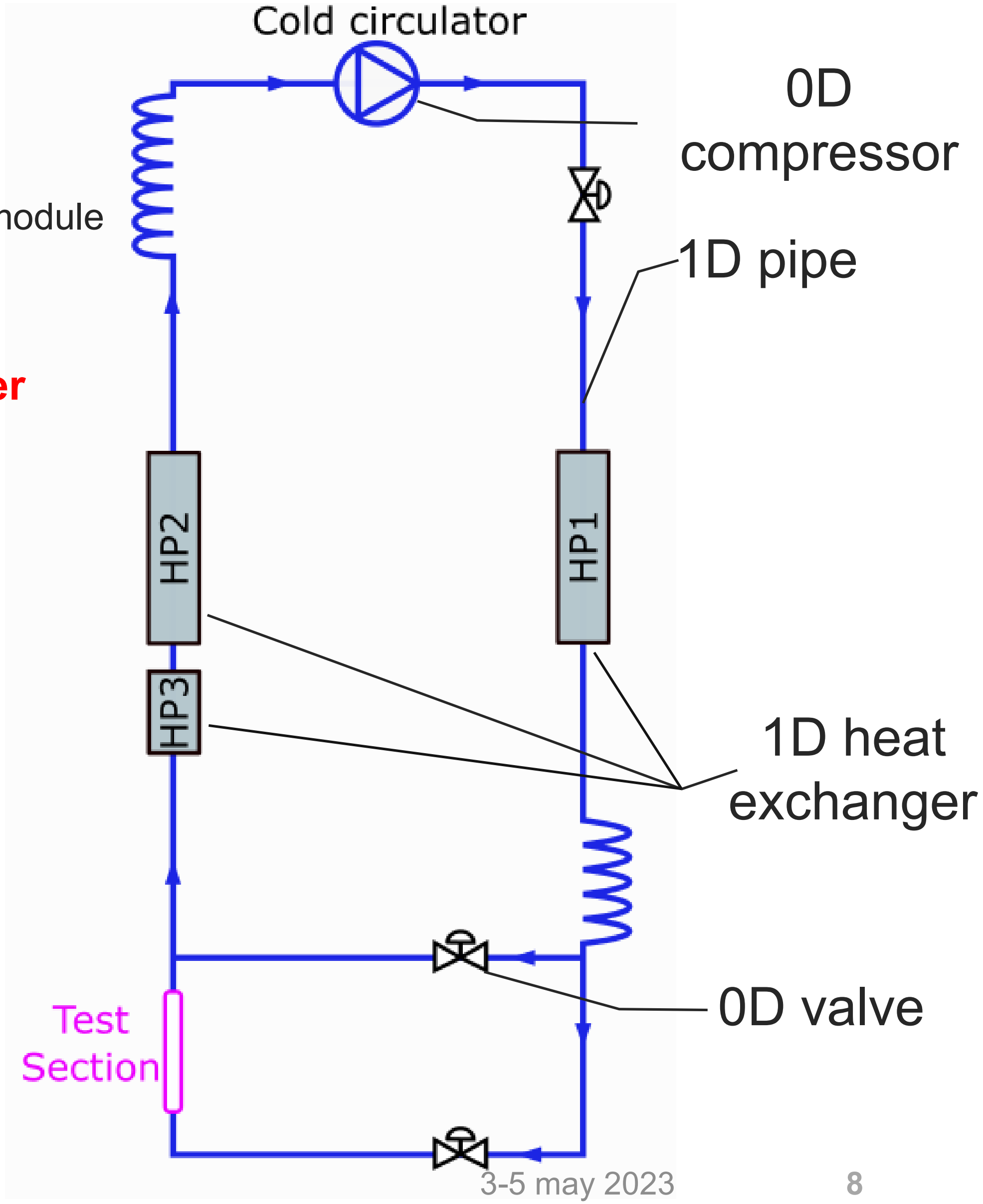
- The default fluid is two-phase water but other options are available:
  - Thermodynamic and transport properties of more than 100 fluids are available including helium (REFPROP database developed by the NIST)

Dynamic modelling of the HELIOS facility

- The loop is modelled with 2 distinct circuits
  - Monophasic flow in the loop (3 bar, 4.4K)
  - 2 phase flow in the bath (1.1 bar, 4.3K)
  - Thermal coupling between bath and loop modelled with the heat exchanger sub-module
  - Refrigerator modelled with boundary conditions

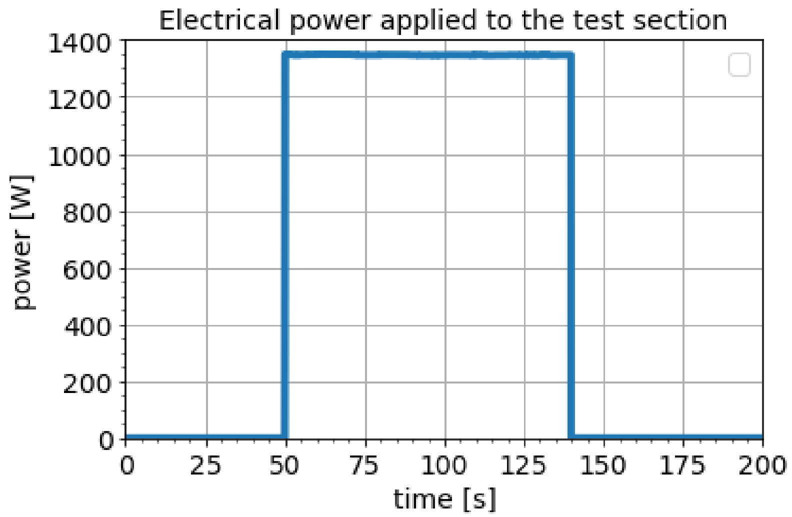






Experimental run with the electrical test section

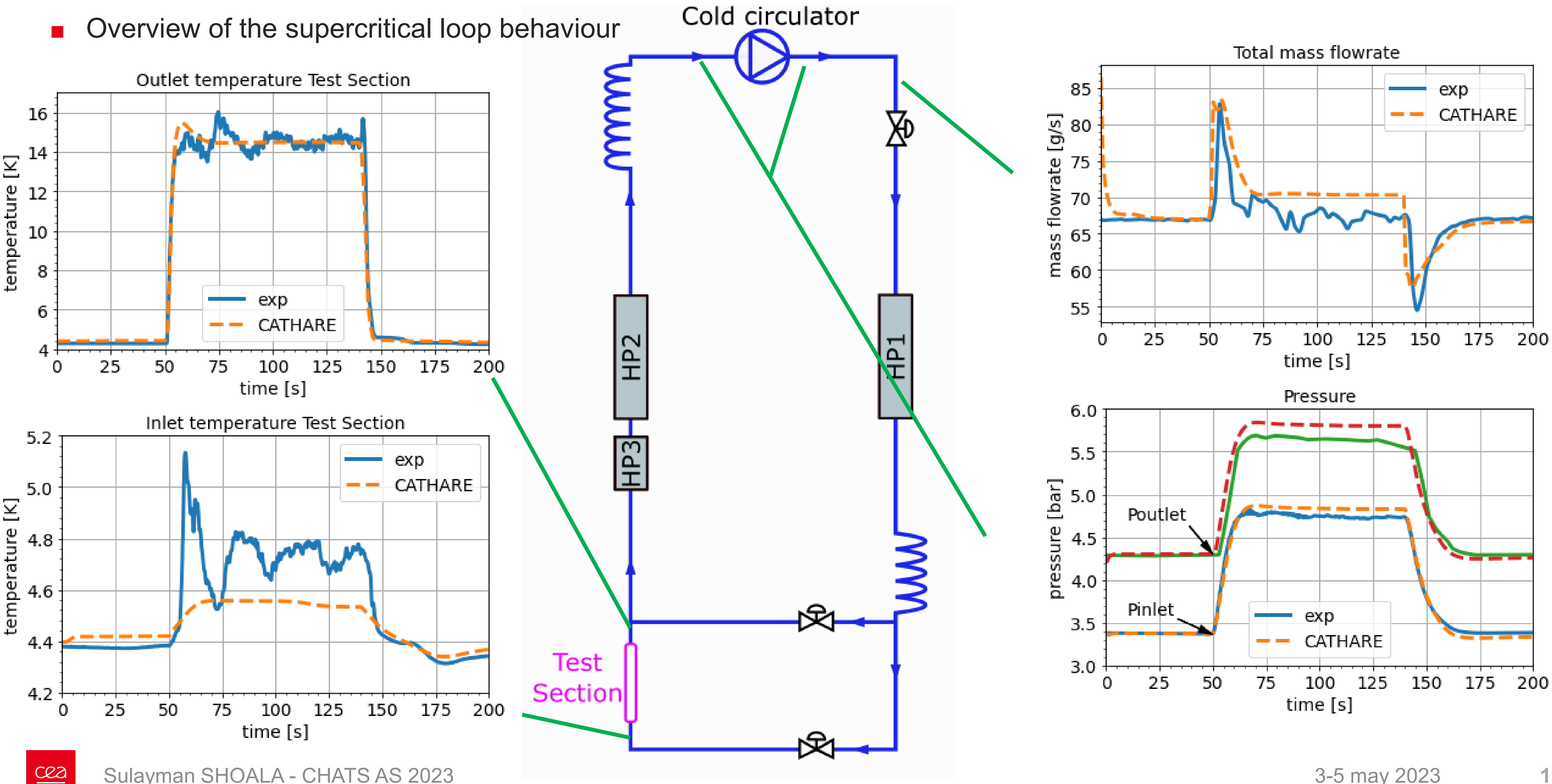
- Experiment carried out on July 30th 2022
- Heat pulse applied : 1,35 kW during 90s
  - 2,15 W/cm² heat flux
- Inital condition in the loop :
  - Pressure at the pump inlet : 3,37 bar
  - Total mass flowrate in loop : 67 g/s
  - Mass flowrate in the test section : 17,5 g/s
  - Open bath



- Experimental initial condition applied in the CATHARE model
  - First seconds used to regulate the mass flowrate and the pump inlet pressure

Experimental run with the electrical test section

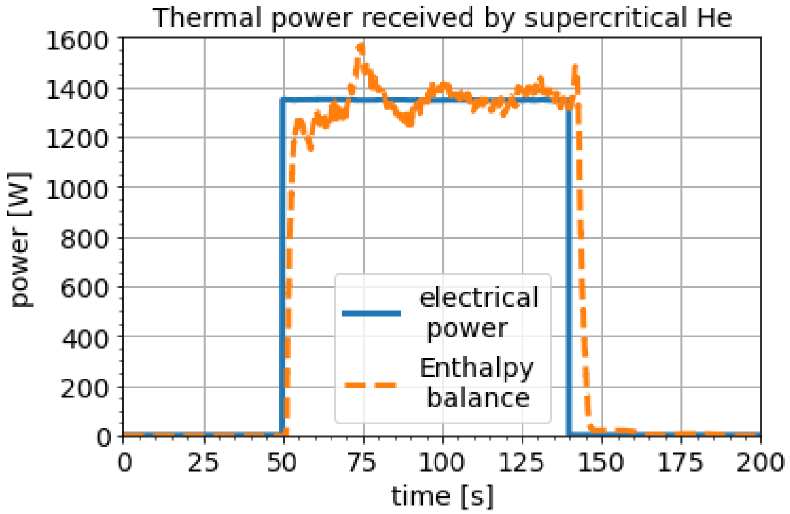
- Overview of the supercritical loop behaviour

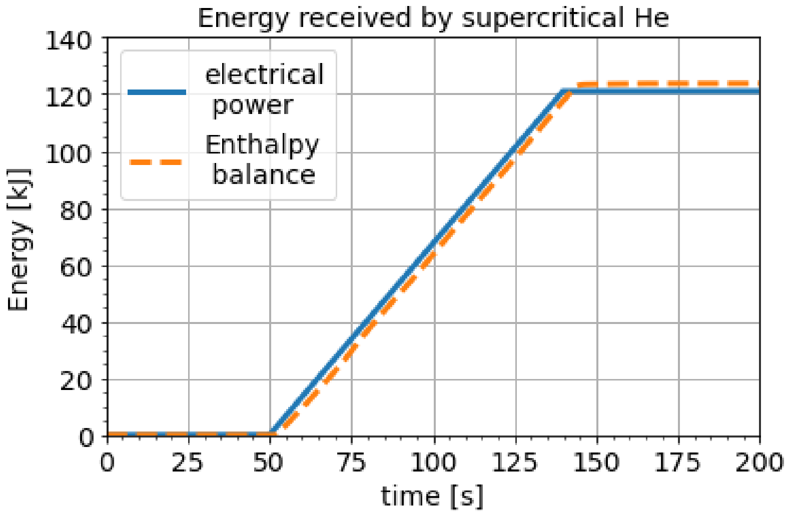


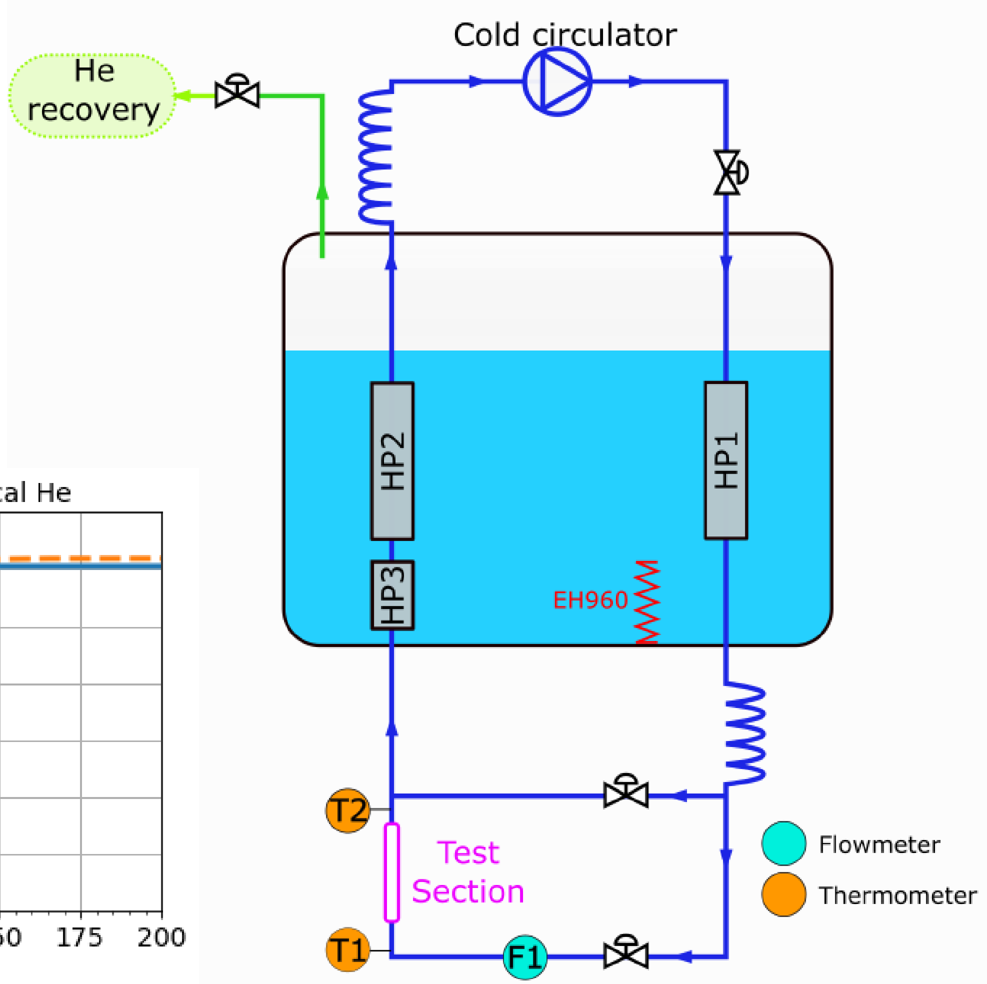
Experimental run with the electrical test section

- Enthalpy balance between T1 and T2 to estimate the thermal power received by supercritical helium
  - Good agreement between the electrical power and the enthalpy balance
  - Thermal inertia effects may be present (still under investigation)
  - Some fluctuations observed at the beginning of the pulse
  - After 25 s, difference between the electrical power and the balance < 100 W

- Total energy transferred through the test section
  - Electrical energy : 121 kJ / Enthalpy balance : 123,6 kJ
  - Mean electrical power = 1,34 kW / Mean power calculated = 1,37 kW

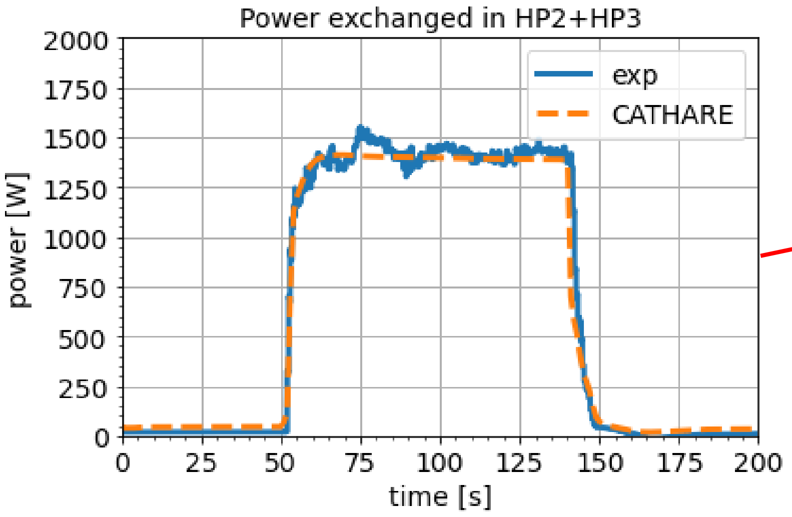


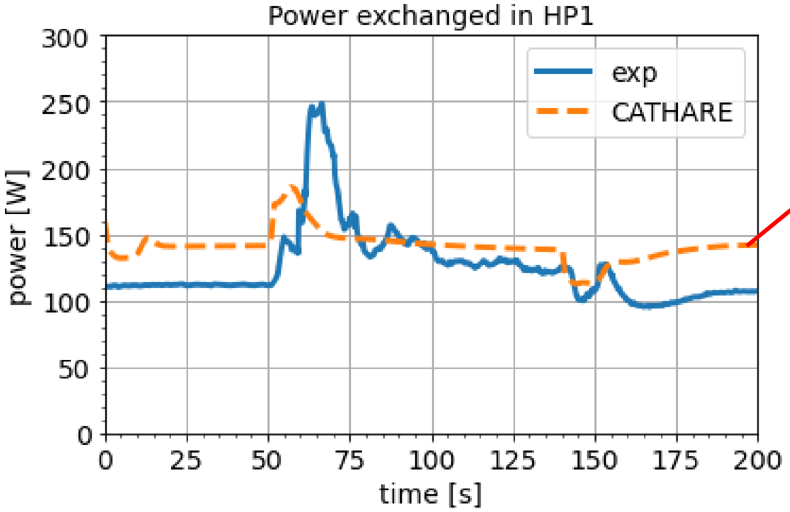


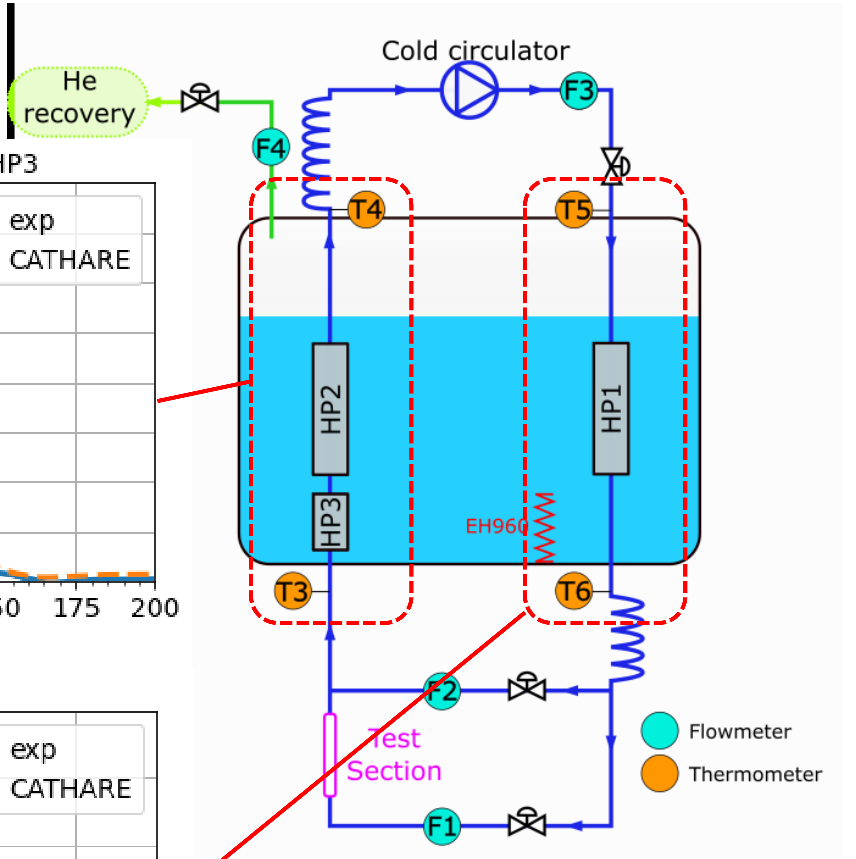


Experimental run with the electrical test section

- Heat exchange between the loop and the bath deduced by enthalpy balance
- CATHARE estimates correctly the power exchanged by HP2+HP3
- Heat transfer through HP1 estimated by CATHARE:
  - Shape close to the experiment
  - Shifted by an almost constant value (deviation in estimated circulator efficiency)
  - Power peak at ~65s supposed to be caused by backflow of hot helium from the circulator casing

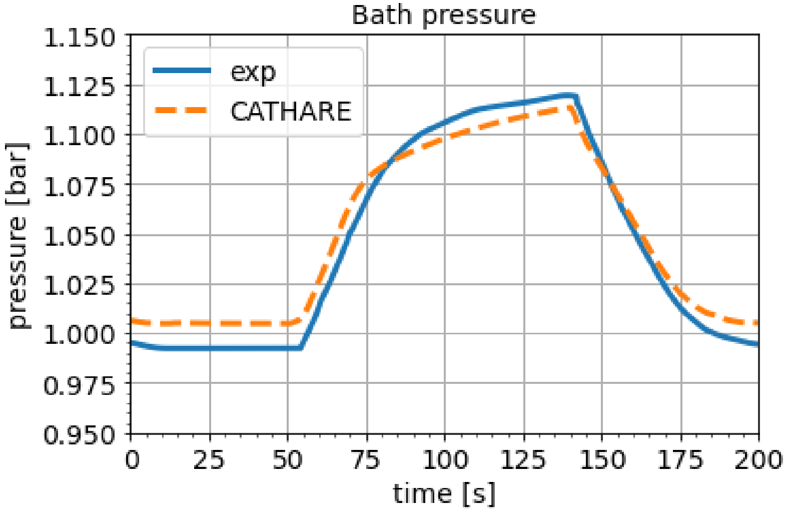


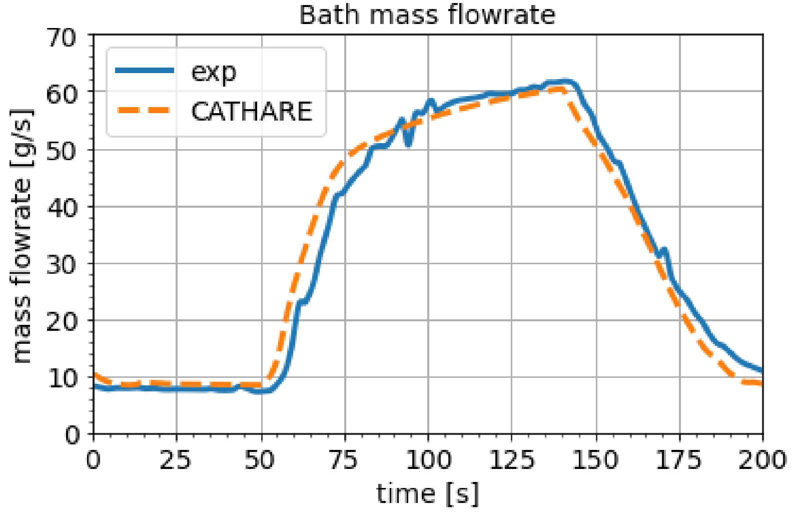




Experimental run with the electrical test section

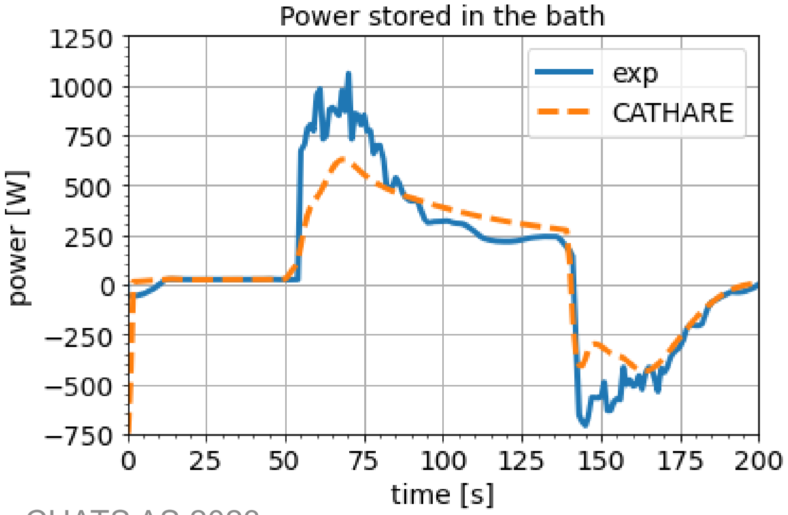
- Energie balance in the bath : contribution of stored power vs released power

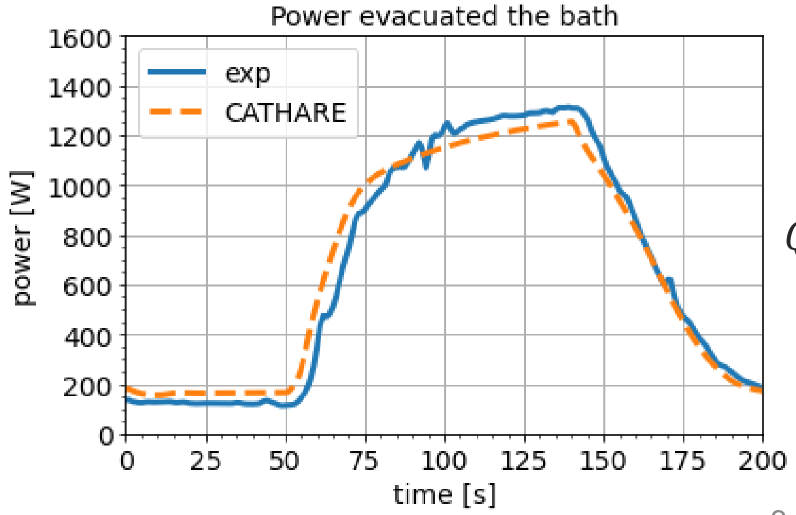




$$\dot{Q}_{stored} = \frac{d(m_{He} * u_{He})}{dt}$$

m_{He} = helium mass
u_{He} = internal energy





$$\dot{Q}_{released} = \dot{m}_{out} \cdot h_{out}$$

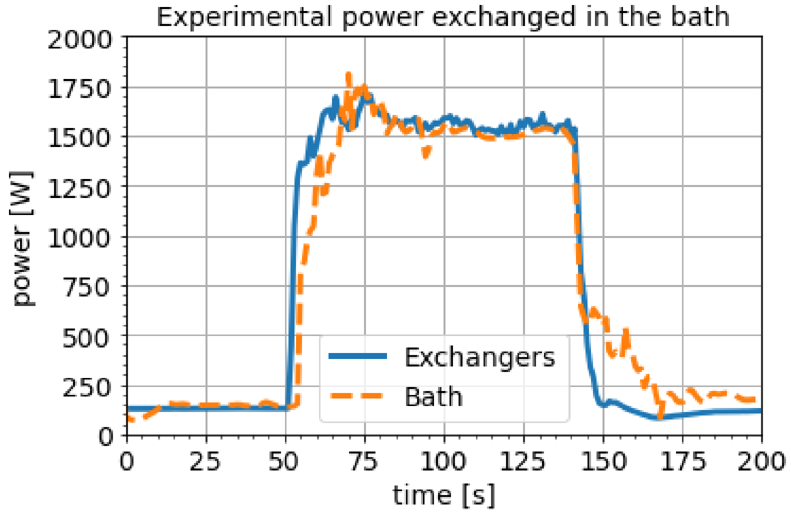
$\dot{m}_{out}$ = leaving mass flowrate
h_{out} = enthalpy of the outgoing gas

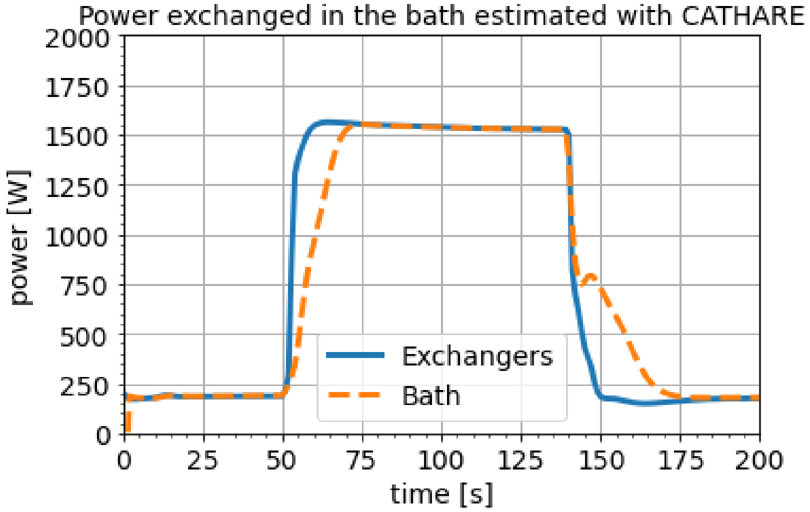
Experimental run with the electrical test section

- Power dissipated in the exchangers in relation to the energy balance in the bath
  - Exchanger : sum of the enthalpy balance for HP1,HP2 and HP3
  - Bath : sum of stored and released power

- Good agreement between the two energy balance, both for the experimental and CATHARE

- The time shift at the beginning of the pulse was expected :
  - Transit time between the first thermometer and the inlet of the heat exchanger
  - Time needed to reach thermal equilibrium in the exchanger

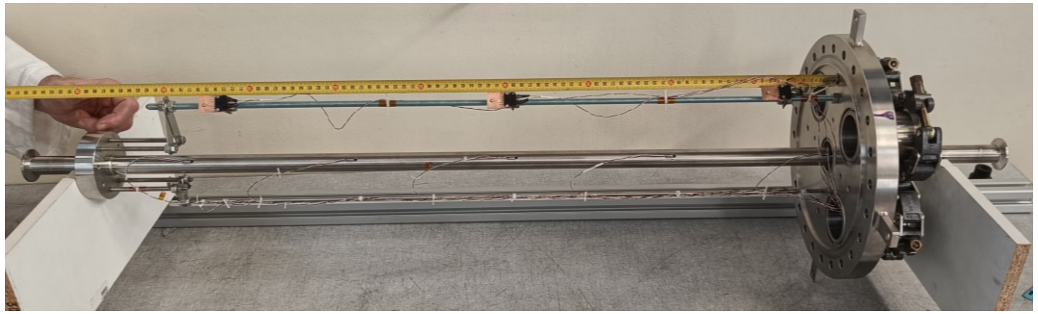




Loss of vacuum experiment

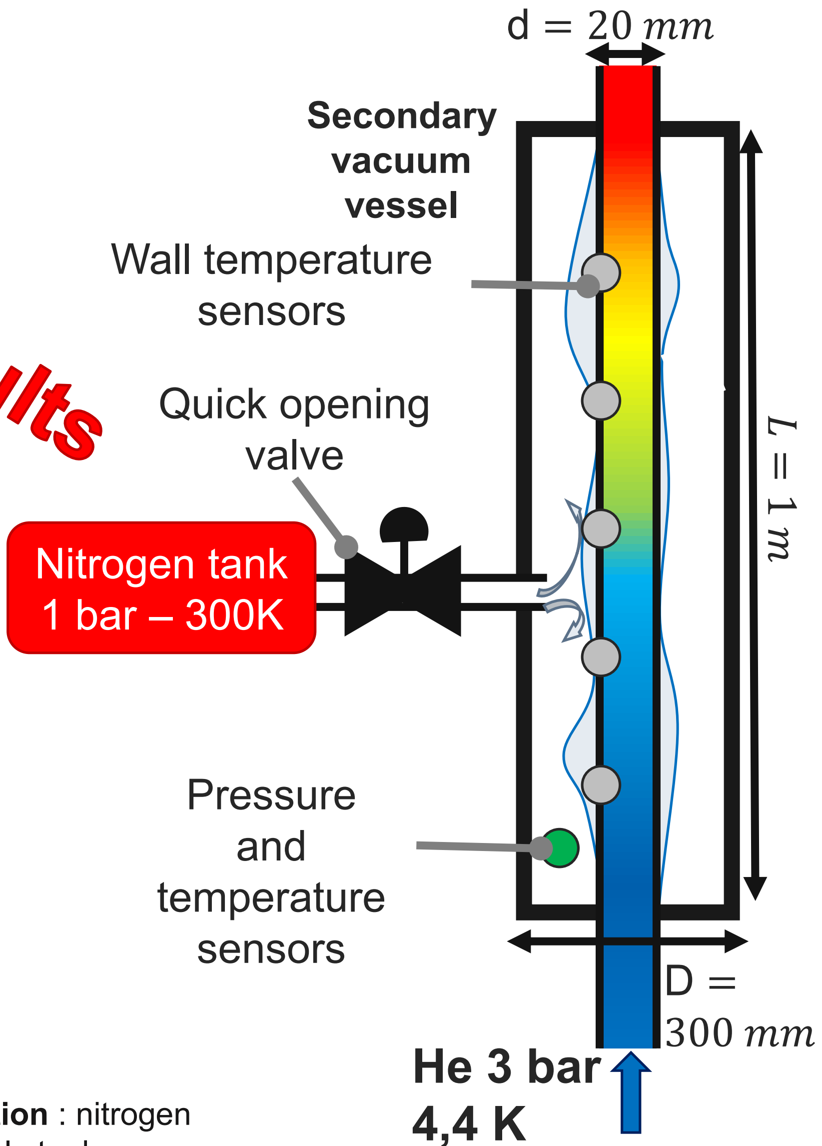
Preliminary results

- Experiment carried out on March 1st 2023
- Loss of vacuum triggered at t=50s
- Venting hole diameter = 50 mm
- Inital condition in the loop :
  - Pressure at the pump inlet : 2,88 bar
  - Total mass flowrate in loop : 92g/s
  - Mass flowrate in the test section : 20g/s



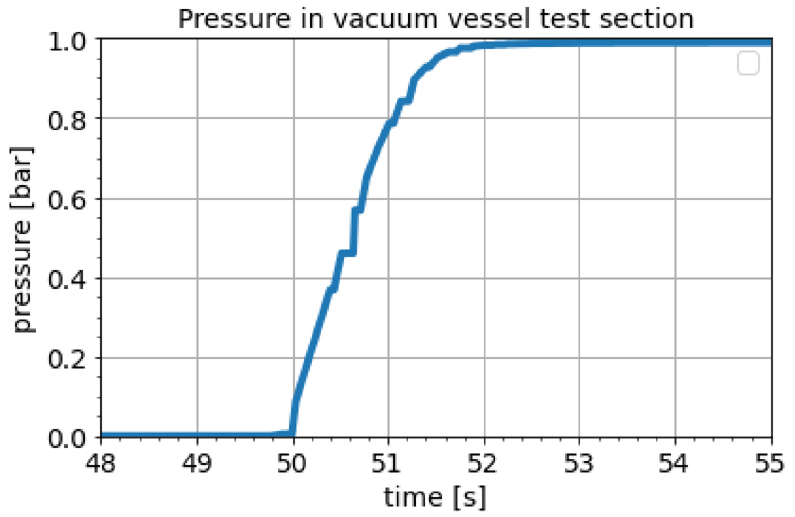
Caption : inner part of the test section

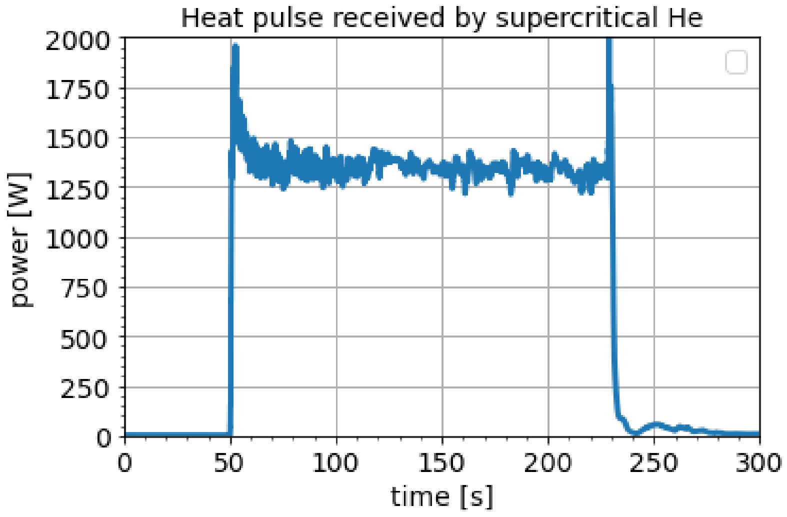
Caption : nitrogen flexible tank



Loss of vacuum experiment

- Ambient pressure reached in the vacuum vessel in about 2 s
- Thermal power received by the supercritical fluid :
  - Estimated by enthalpy balance
  - Initial peak at 2kW / Peak heat flux = 3,2 W/cm²
  - Mean power = 1,35kW / mean heat flux = 2,15 W/cm²
  - The second peak power is not physical (closure of the inlet valve)

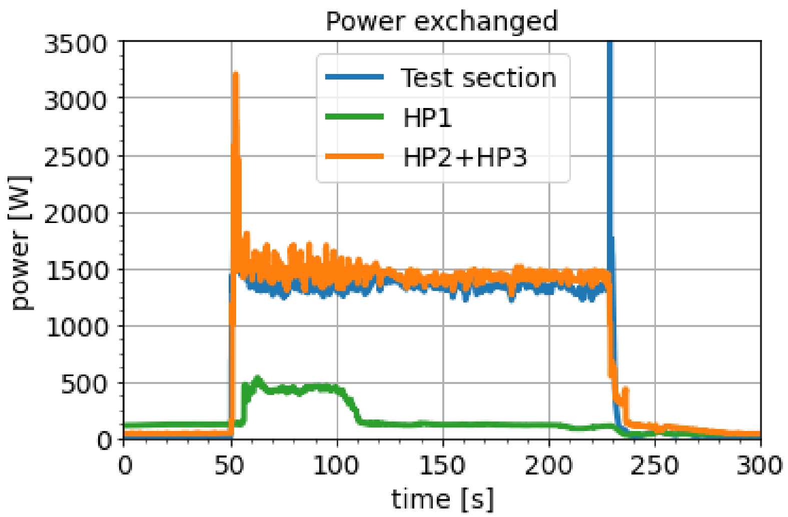


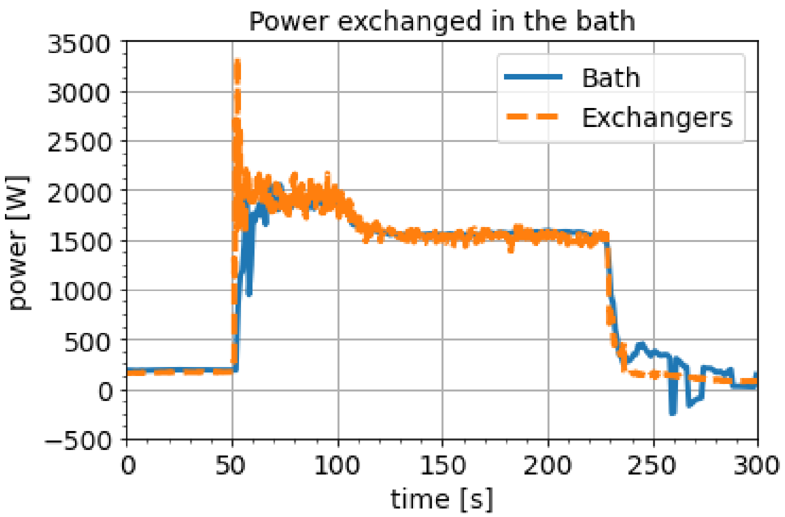


Loss of vacuum experiment

- As observed in the first campaign, additional power is dissipated in the first exchanger at the beginning of the pulse
  - Higher power (~400W)
  - More a plateau than a peak

- Once again, good agreement between the total power balance in the bath and for the exchangers
  - Usefull solution to check the consistency of the various energy balance





Conclusions and perspectives

- Two experimental campaigns have been carry out with HELIOS
  - First with the electrical test section
  - Then with the test section dedicated to the study of insulating vacuum loss

- We have verified that we are able to determine the power deposited by the vacuum break
  - Enthalpy balance on the supercritical loop
  - Energy balance in the liquid bath

- Preliminary simulation with CATHARE contributed to the success of the experimental campaigns
  - The first comparison between CATHARE predictions and experimental results gives encouraging results

- The analysis of the results of the second campaign will be continued :
  - Evolution of wall temperatures
  - Liquid/solid condensation
  - Estimate the dominating heat transfer resistance

- Modelling of the second campaign with CATHARE :
  - Immediate objective : see if CATHARE able to predict correctly the loop behaviour by injecting an equivalent power into the model
  - Long term objective : Implementation of a model to take account the condensation

Bibliography

[1] Lehmann W, Zahn G. Safety aspects for LHe cryostats and LHe transport containers. In: 7. Internat cryogenic engineering conf, ICEC 7, London, July 4–7, 1978. Internat cryogenic engineering conferences, vol. 7. Guildford: IPC Science a.Technology Pr; 1978. 1979. p. 569–79.

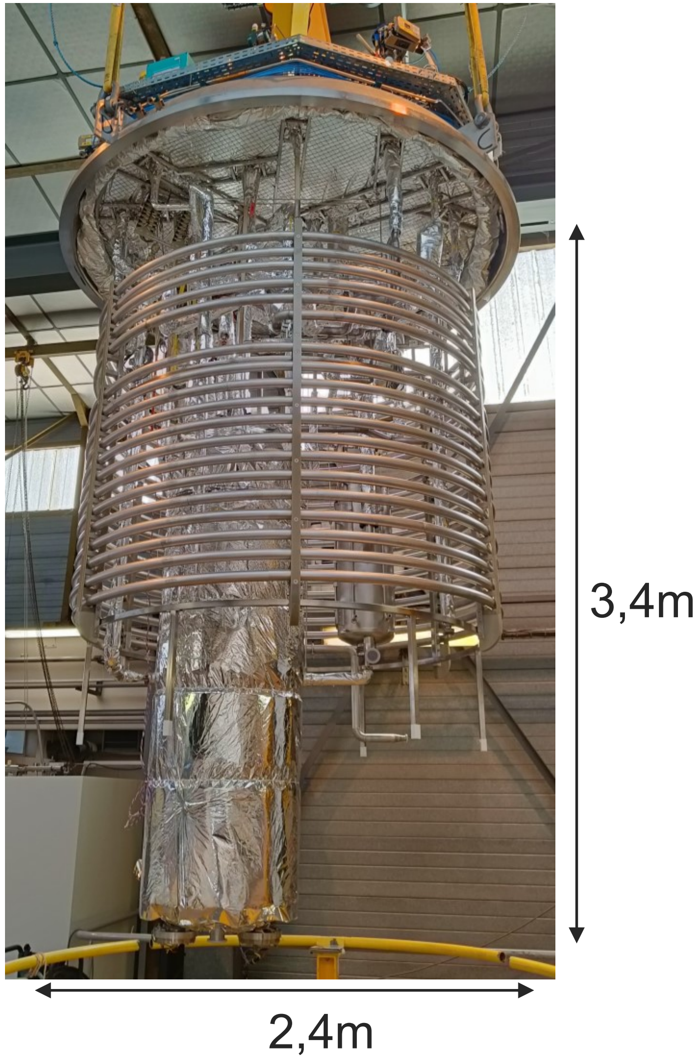
[2] Ercolani E, Gauthier A, Gully P, Poncet JM. Cryogenic safety – HSE seminar (21-23 septembre 2016): quantification of heat flux in supercritical helium · Indico', Indico. <https://indico.cern.ch/event/495194/contributions/2181322/>.

[3] S. Shoala, E. Ercolani, J.-M. Poncet, C. Hoa, F. Ayela, « CATHARE modelling of the HELIOS loop for the study of heat transfer to supercritical helium flowing in pipes following loss of insulating vacuum », Cryogenics, vol. 126, p. 103520, sept. 2022, doi: 10.1016/j.cryogenics.2022.103520.

[4] https://cathare.cea.fr/

Thank you for your attention

Some illustrations



Caption : Photography of the experimental setup

Caption :Photography of the 3 heat exchangers