DE LA RECHERCHE À L'INDUSTRIE

Dynamic simulation of high transients in a forced flow Supercritical helium loop for the sizing of an experimental set-up dedicated to the study of loss of vacuum

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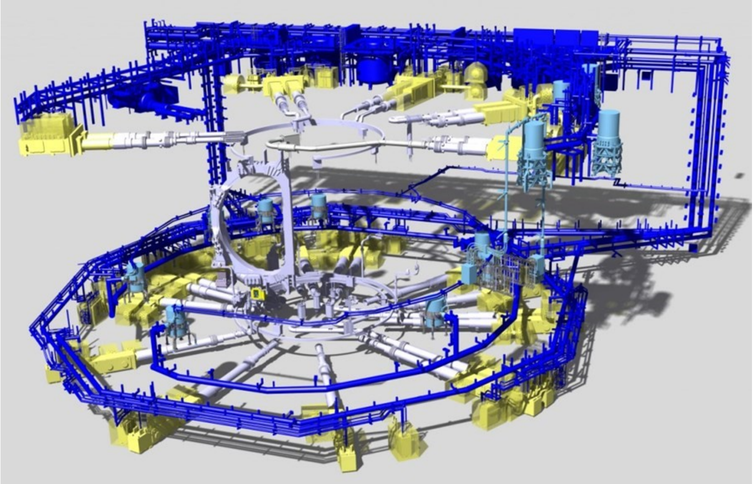
Safety in cryogenics

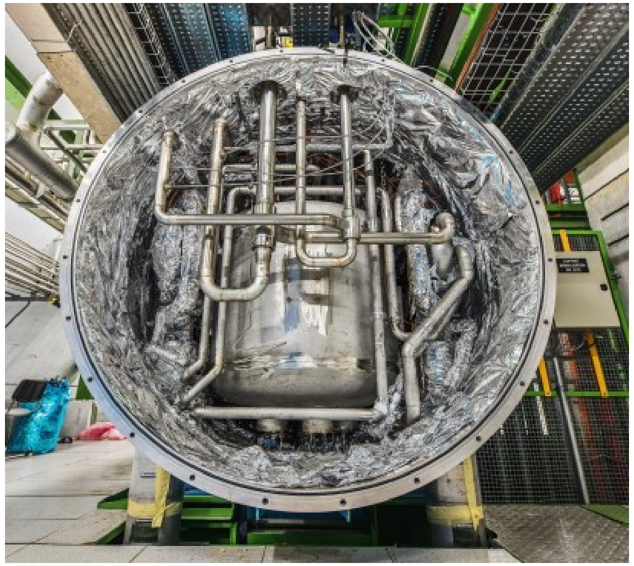
- Insulating vacuum failure is a major accident scenario
  - Large break on the Cryostat
  - Outside atmospheric air rushes into the vacuum space and condenses on cold surfaces
  - Very high heat load transferred to the cryogenic fluid
- Cryogenics devices have to be protected against overpressure
  - By using safety valves or rupture disks
- For instance, safety relief devices are sized by using a constant heat flux value :
  - Helium tank in diphasic discharge, without insulation: 3.8W/cm²
  - Helium tank in supercritical discharge, without insulation: 2W/cm²
- Reference values of heat flux have just been measured for tank

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

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

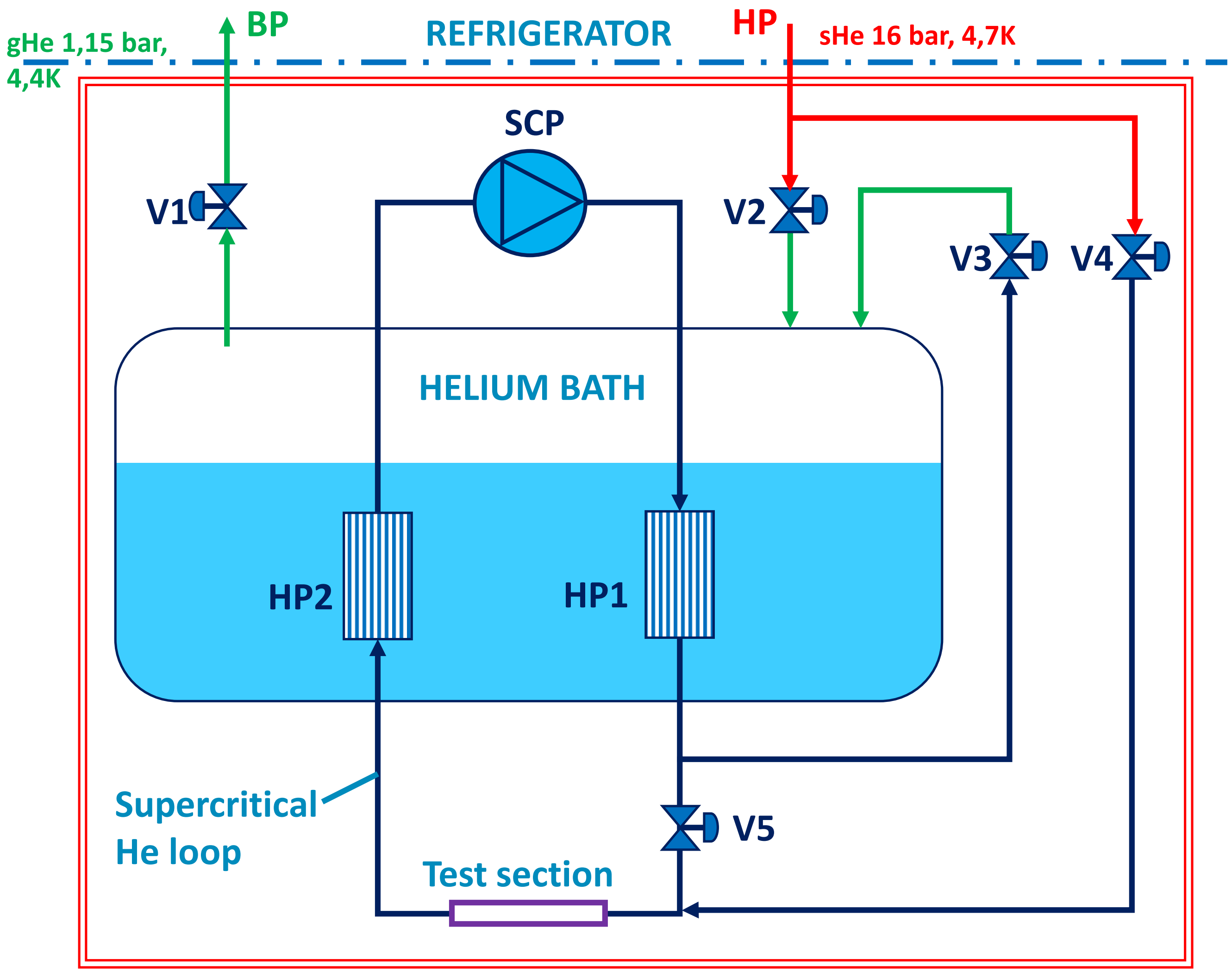


Iter's Cryolines and cold boxes (iter.org)



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

The HELIOS loop



- HELIOS is composed of two main parts:
  - 1 supercritical helium loop
  - 1 saturated helium bath
- 2 heat exchangers ⇨ thermal coupling bath/loop
- Bath connected to the refrigerator (by HP & BP)
  - Cooling power available: 320 W
- Why Helios is used ?
  - Supercritical helium loop is already available
  - Cold centrifugal pump ⇨ imposes forced convection
  - Saturated helium bath ⇨ Interface with refrigerator + Thermal buffer

The test section

How to generate a « controlled » loss of insulating vacuum with HELIOS ?

- A test section (TS) will be included in the helium loop of HELIOS
- Vacuum loss in a restricted area thanks to a secondary vacuum vessel
  - Vacuum break with N2 at atmospheric pressure/temperature
- Vertical upward supercritical helium flow

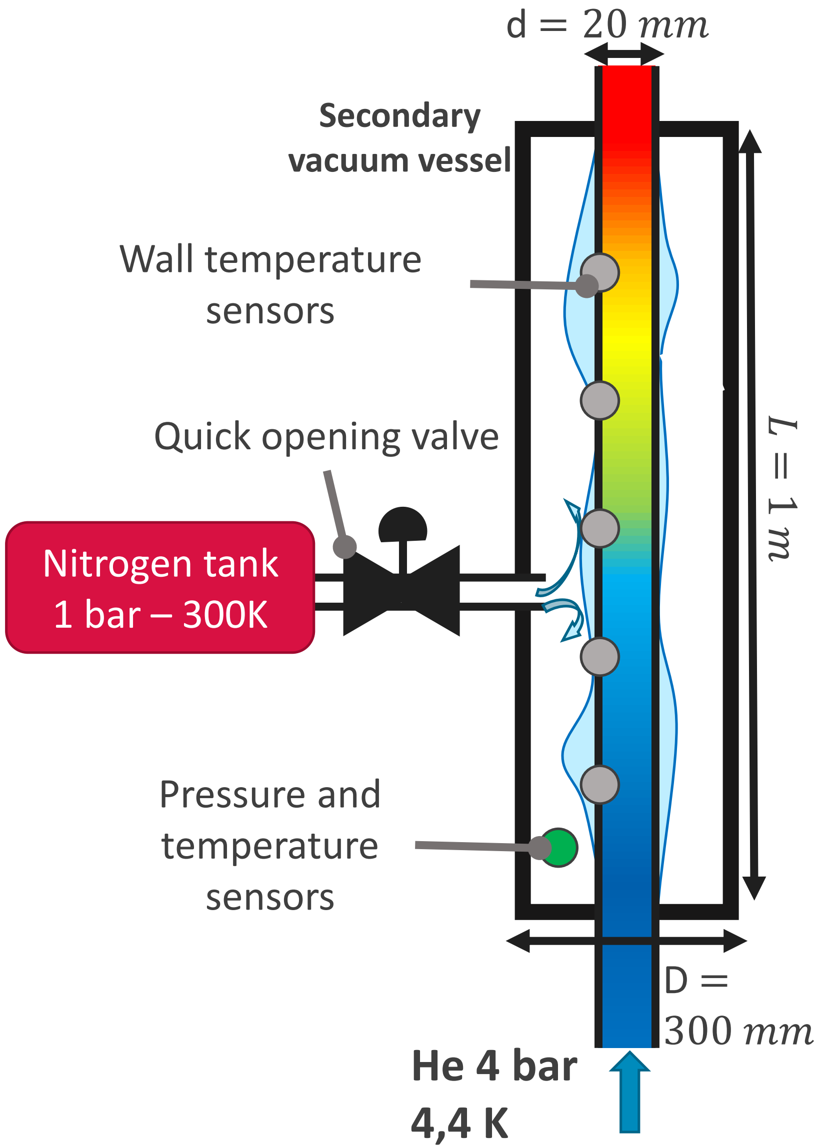


Diagram of the test section

Hypothesis for the sizing of the experiment :

- $h_{condensation} \gg h_{forced\ convection}$
- Wall temperature imposed to 77K
- Supercritical He flow: 20g/s
- Dittus Boelter correlation

⇨ Heat load received by supercritical He **~ 2,7kW** (4,25W/cm²)

Sizing of the new HELIOS loop

HELIOS has to be adapted to this new experiment

- Orders of magnitudes :
  - Estimated power transmitted to supercritical He in the test section : 2700W
  - Cooling power available : 320W

$$P_{section} \gg P_{refrigerator}$$

⇨ Thermal buffer need to be sufficient to store the energy injected during the loss of vacuum

- Last version of HELIOS :
  - Volume of the loop : ~30L
  - Volume of the bath : 310L

⇨ Not enough to keep the maximal pressure under the safety valve opening pressure (Pmax = 9 bar)

- Sizing parameters :
  - Volume of the loop
  - Transit time between the test section and heat exchanger
  - Thermal exchange loop/bath
  - Volume of the bath (thermal buffer)

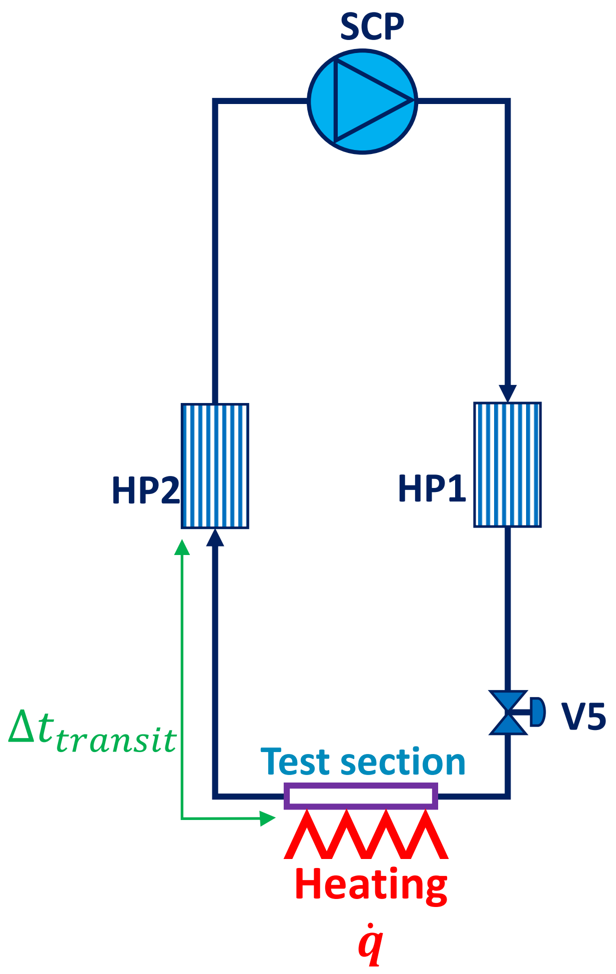
Geometry of the loop

- The pressure increases due to the stored energy

$$U_f = U_i + \frac{\dot{q} * \Delta t_{transit}}{m_{loop}}$$

$$\Delta t_{transit} = \frac{\rho V_{TS \to HP2}}{\dot{m}}$$

- Volume distribution
  - Remove volume between TS and HP2 to reduced $\Delta t_{transit}$
  - Cold volumes to be added : HP2 – SCP and HP1 – TS



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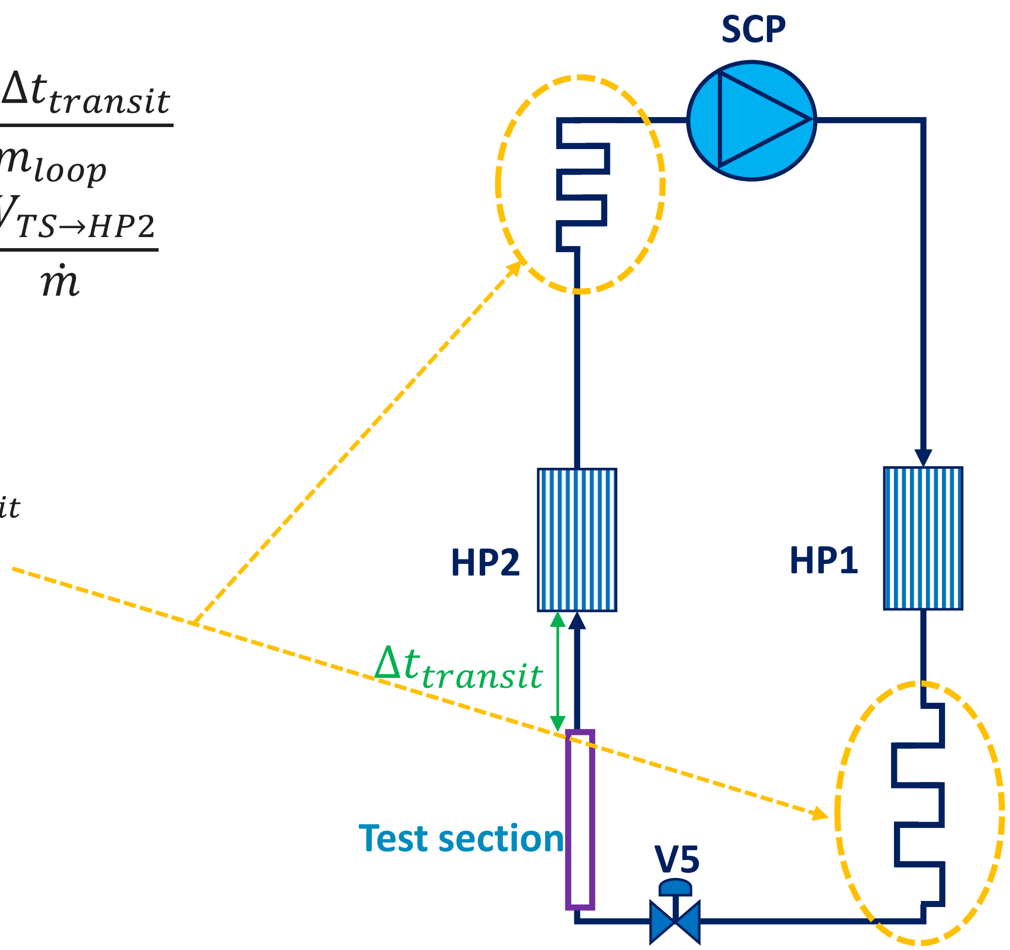
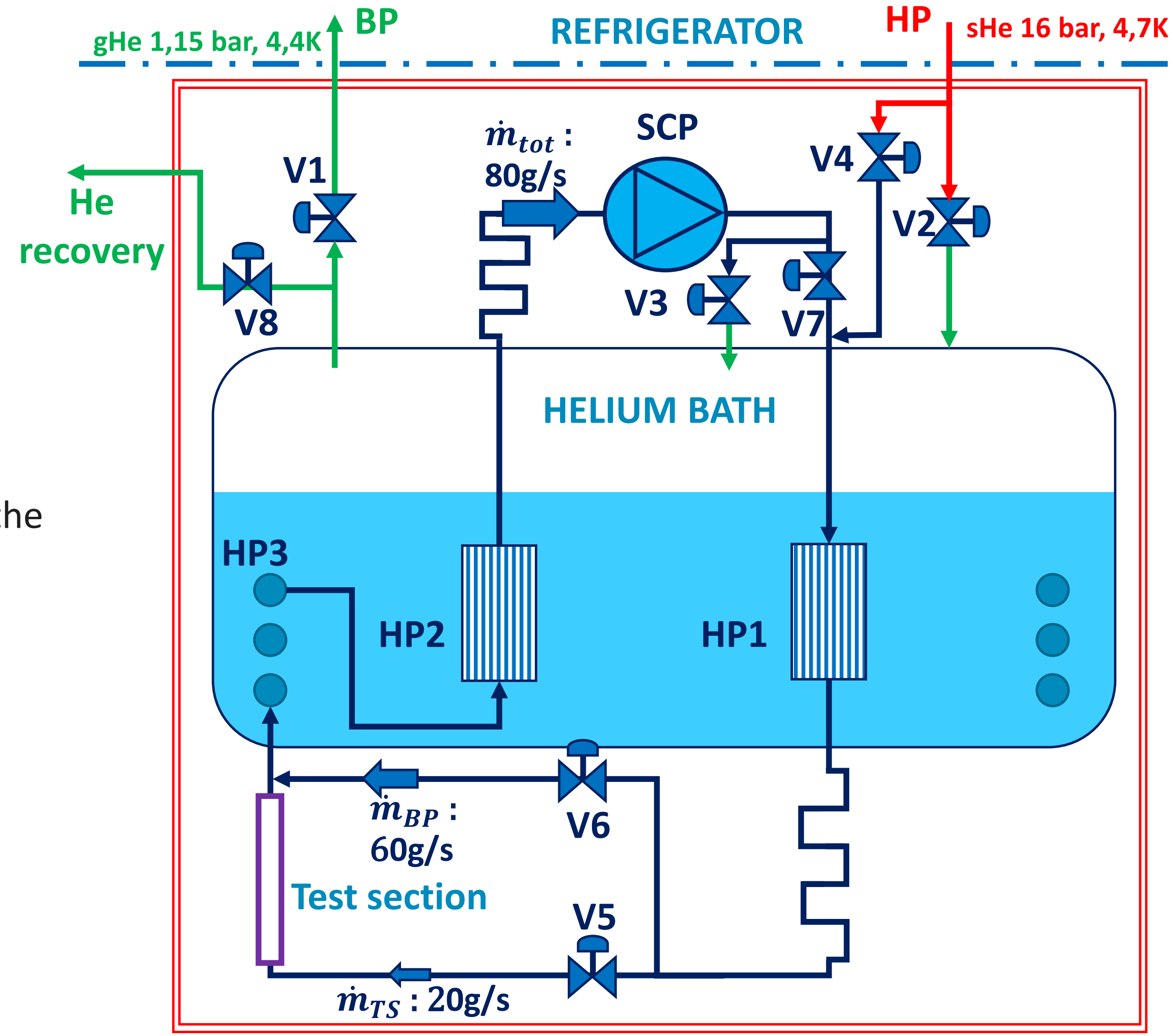
- In the new loop design, the volume reaches 170L

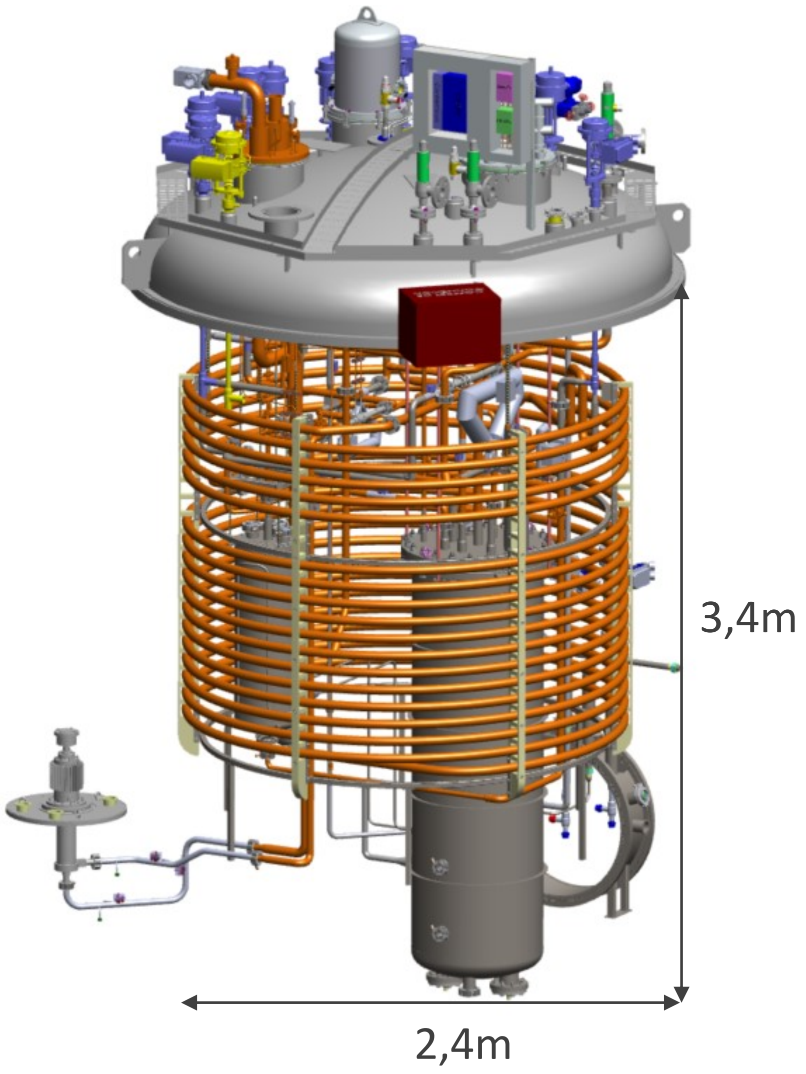


Additional modifications to the HELIOS loop

- A new heat exchanger has been added (HP3) :
  - Power injected in the TS >> Heat load used for the sizing of HP2
  - The new heat exchanger is placed between TS and HP2
  - 3 parallel copper coils immersed in the bath
- The by-pass line :
  - Large part of the flow by-passes the TS
  - Improves the additional heat exchanger (HP3) performances
  - The cold circulator can be used on an extended operation field
- The bath has been connected to the helium recovery system
  - Cold He gas can be evacuated from bath without passing through the refrigerator
- The bath volume was increased from 310L to 510L :
  - Space to include the new heat exchanger
  - Increased thermal storage



Some illustrations



3D view of the experimental setup

Photography of the 3 heat exchangers

Photography of the bath

The CATHARE code

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

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

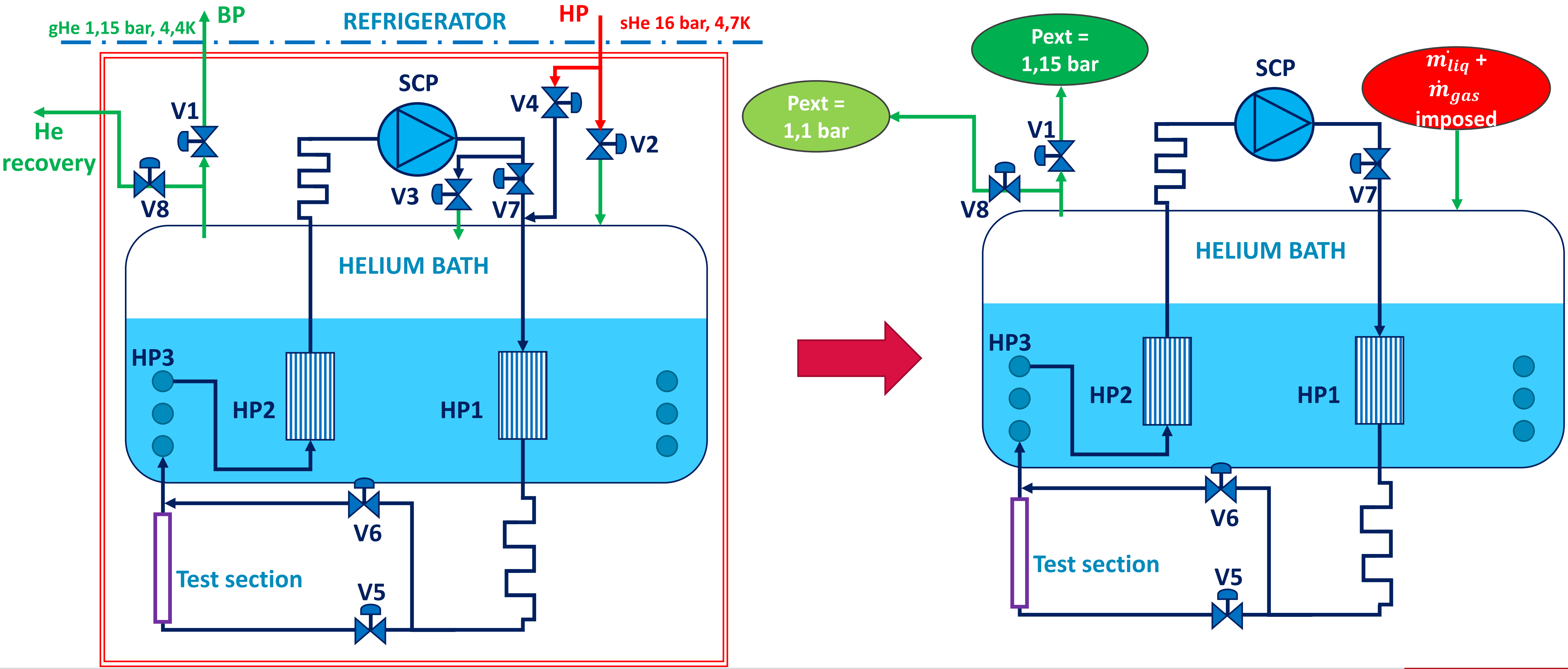
- Devoted to thermal hydraulic simulation of multiphase flow transient at the system scale

- 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

▶ Some simplifications are made on the modelling, using relevant boundary conditions

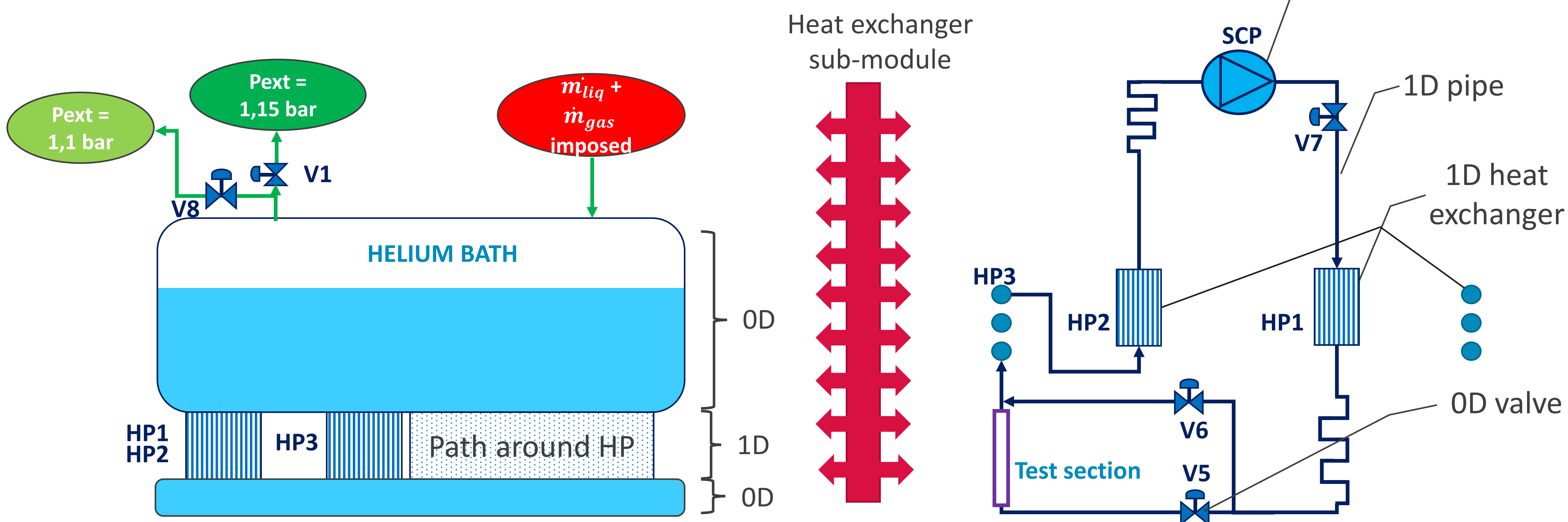


Dynamic modelling of the HELIOS facility

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

→ Using closure law for water except for nucleate boiling (Kutateladze)

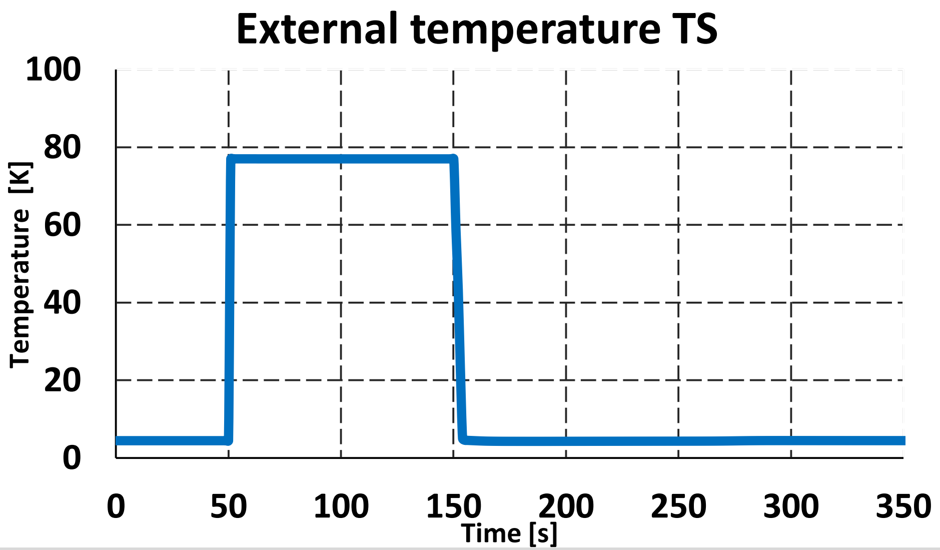
☑ Comparison performed on a former experiment (cf article)

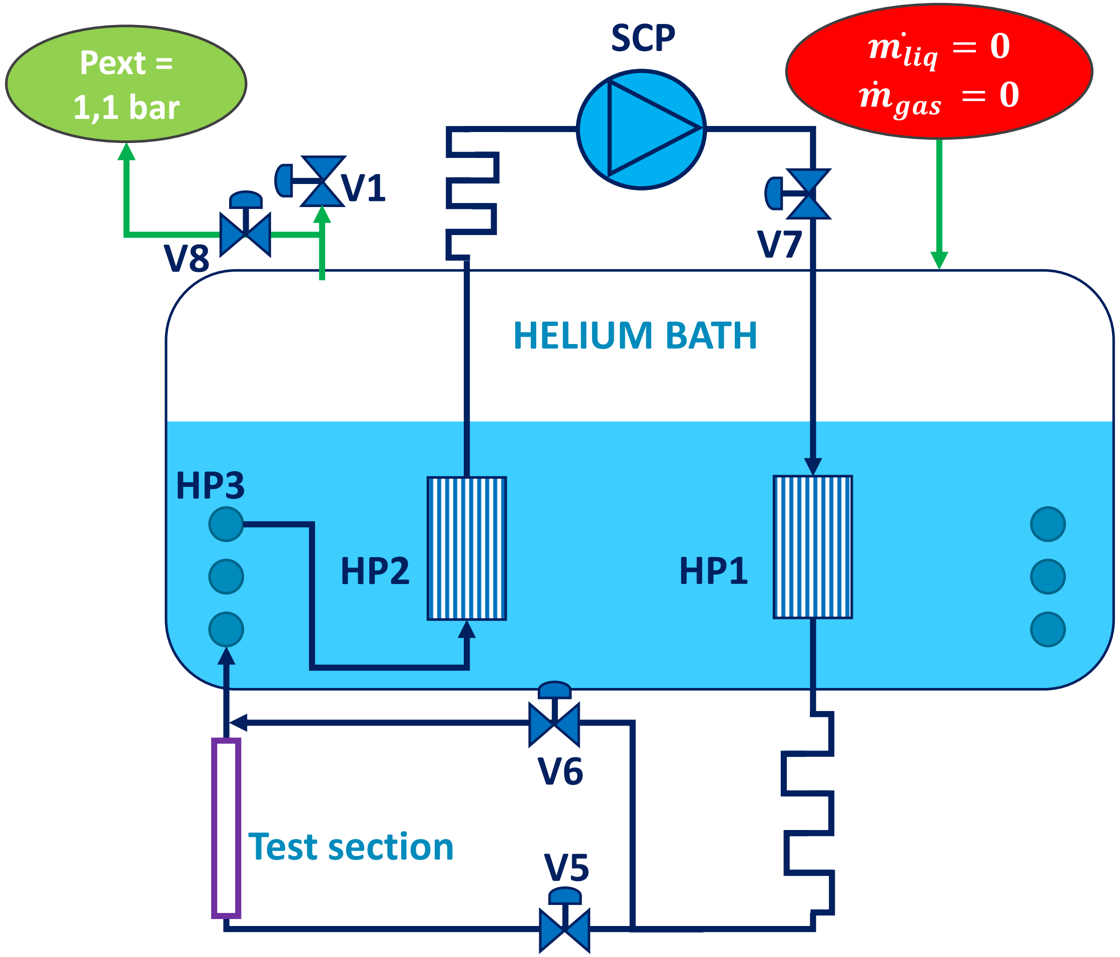


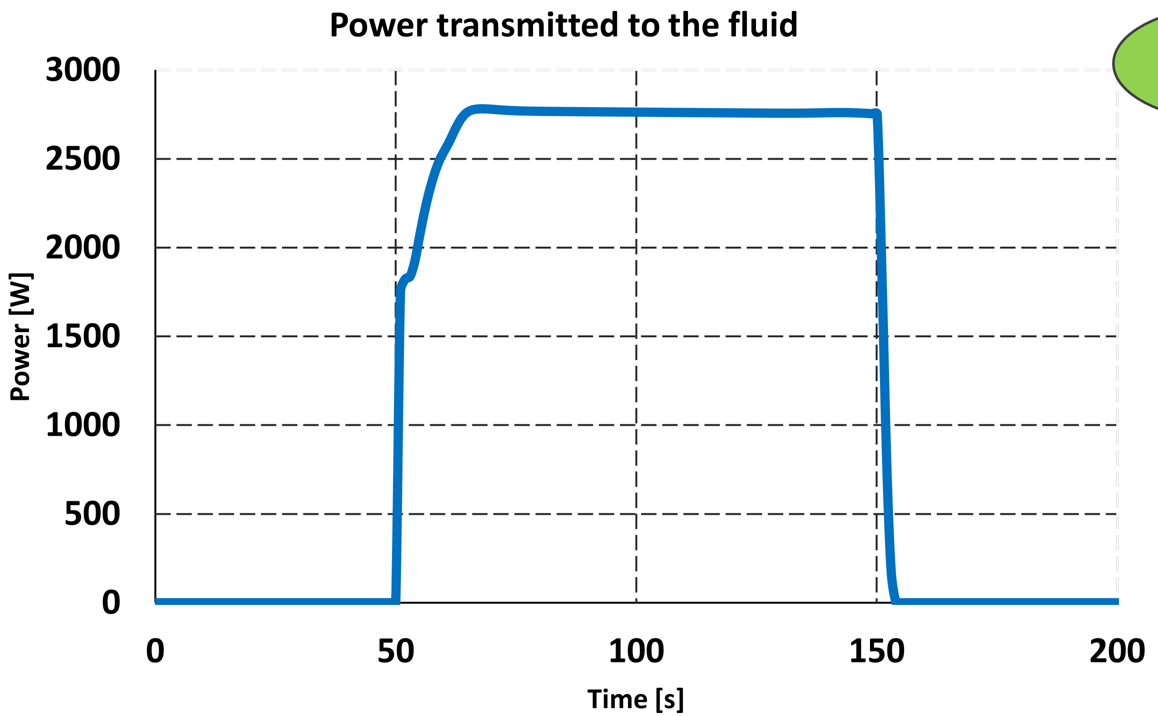
- Transient scenario :
  - $\Delta P_{SCP} = 0{,}85\ bar$ (regulation on V7) / $\dot{m}_{SCP} = 75\ g/s$
  - $\dot{m}_{TS} = 20g/s$ (regulation on V5)

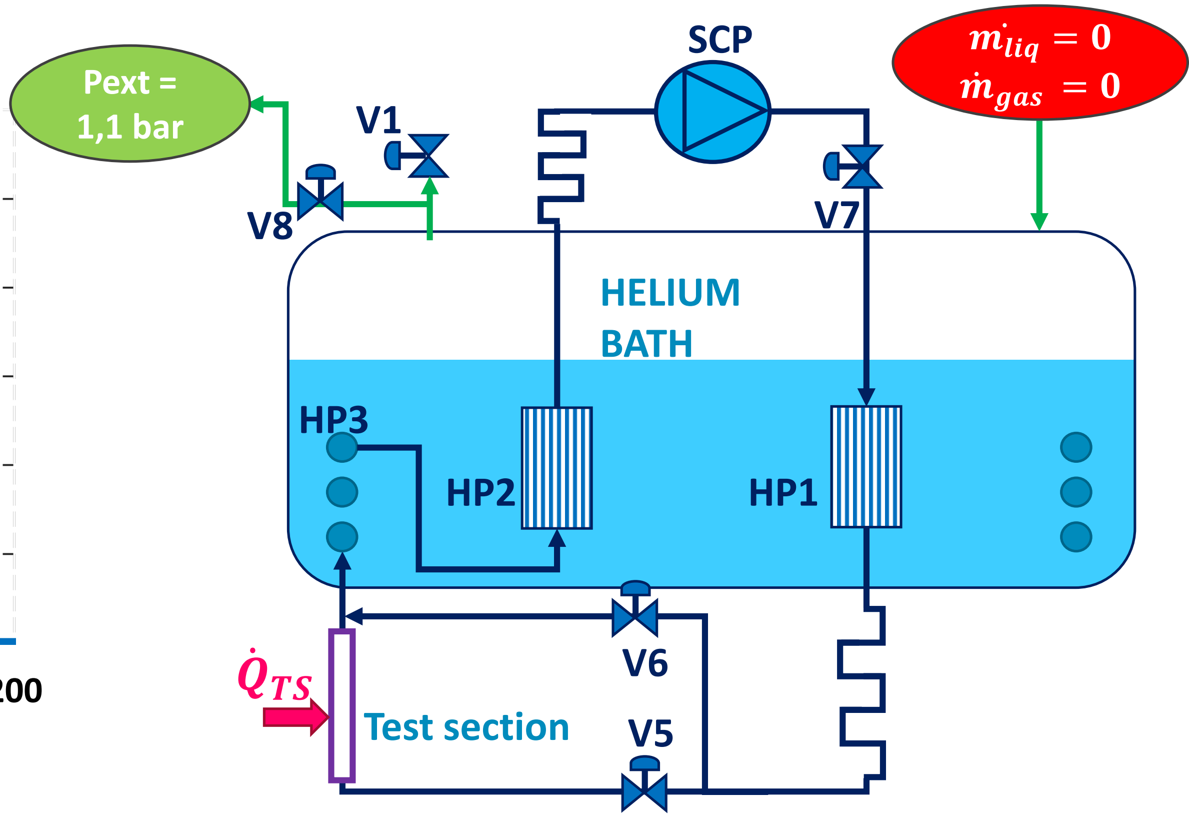
  } Regulation only during the first 50s

  - At t=50s : loss of vacuum
- Loss of vacuum : TS's external wall temperature imposed to 77K
- Bath isolated from the refrigerator, discharge in the He recovery
  - V1 close
  - V8 fully open



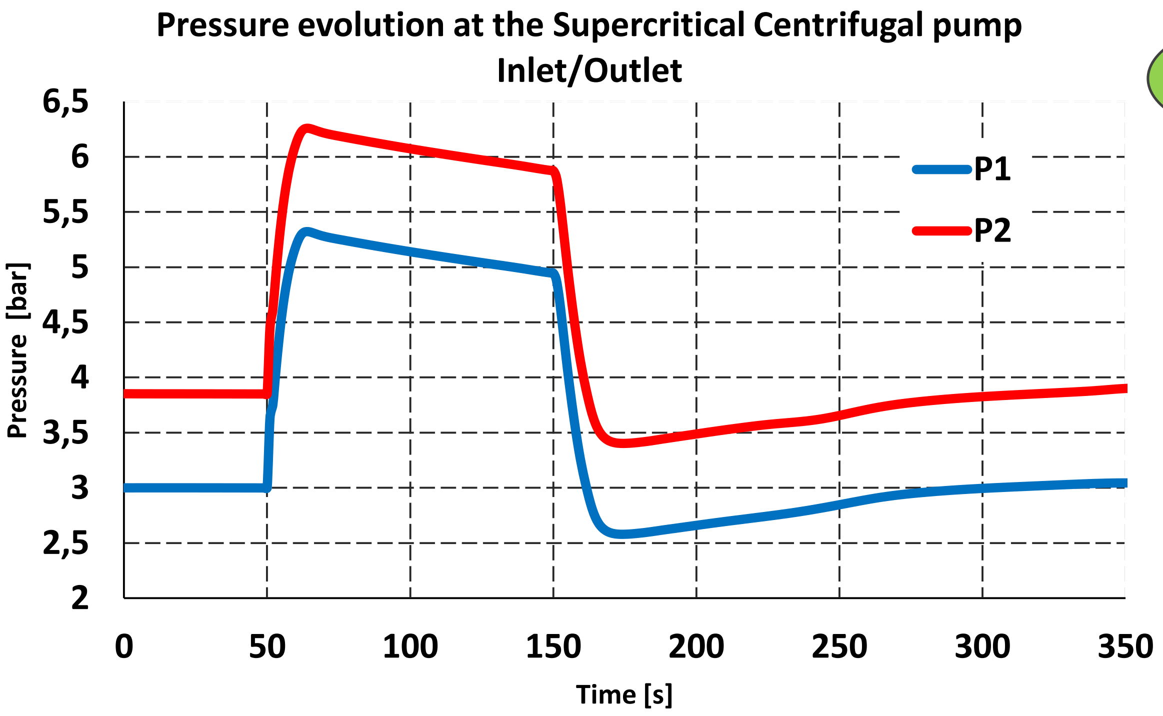


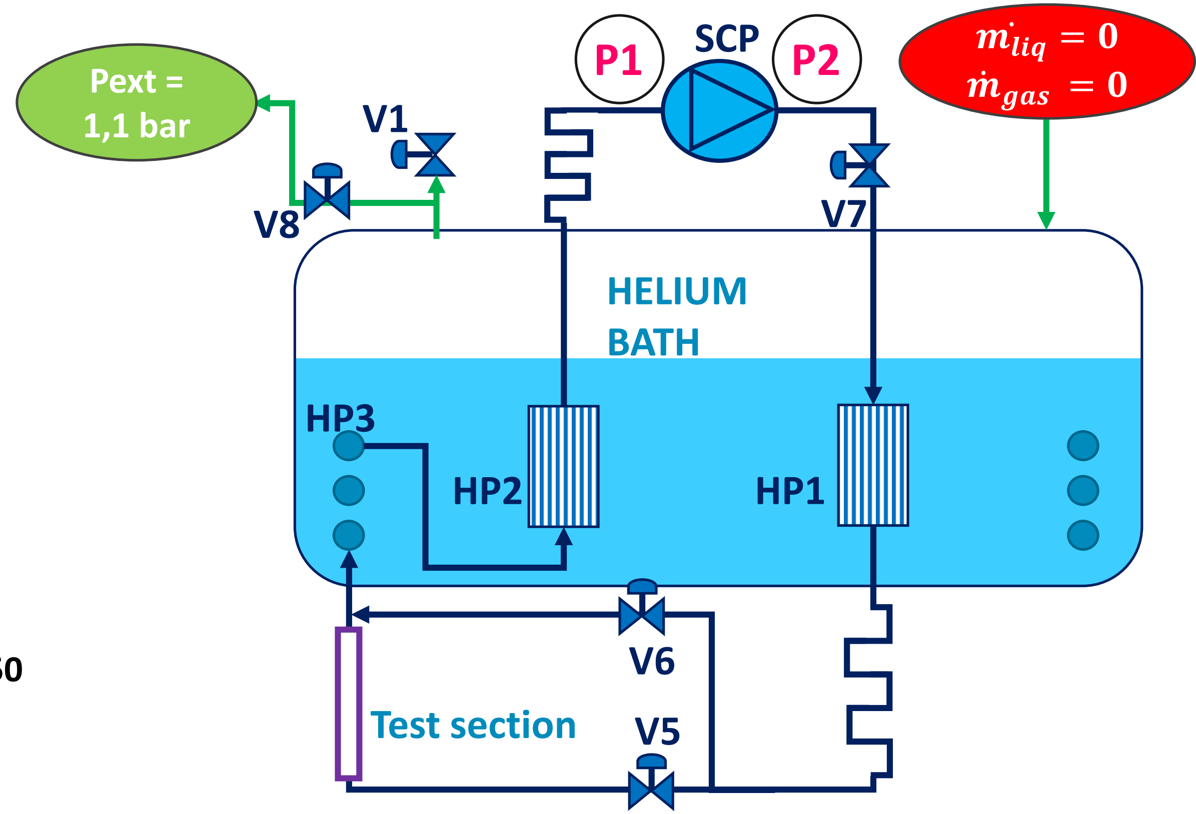




- Maximal power transmitted to the fluid : 2780 W
- Take few seconds to reach its maximum
  - Mass flow decreases in the section due to the expansion of the heated helium

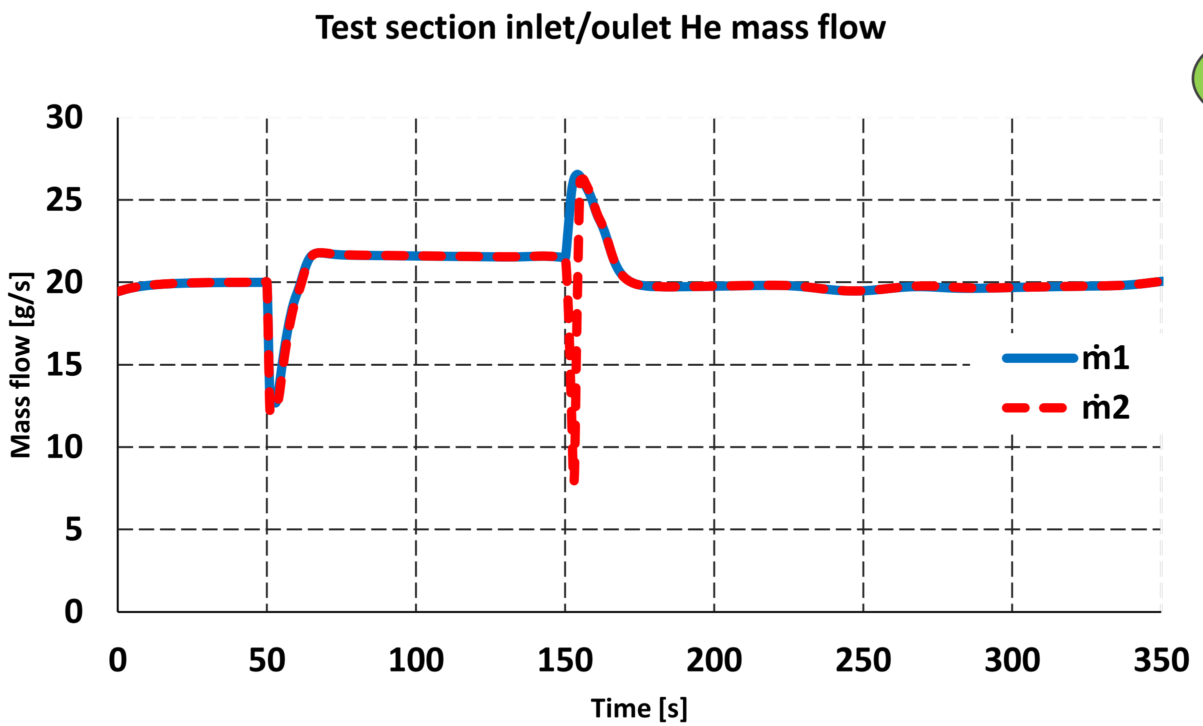
Dynamic modelling of the HELIOS facility

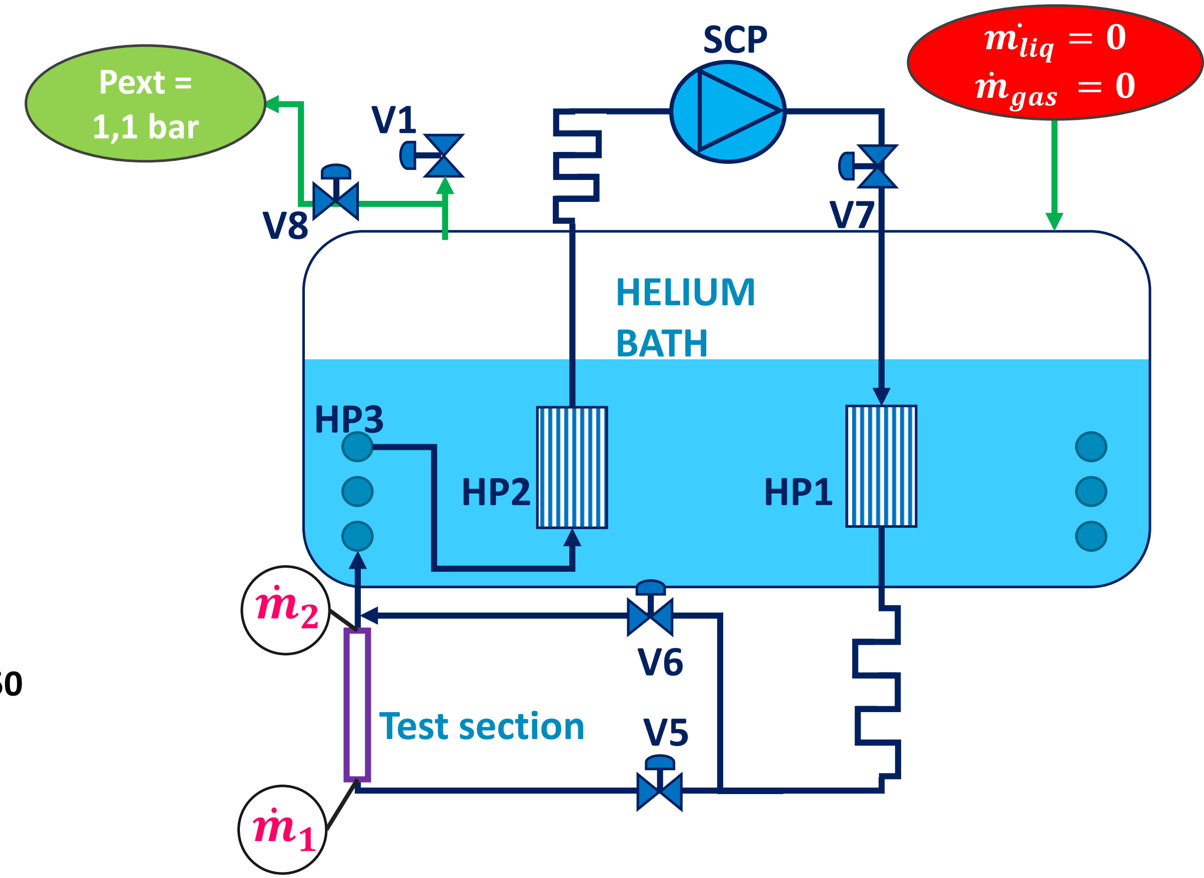




- P2 is the maximal pressure in the loop
- P2 << Pmax (9bar)

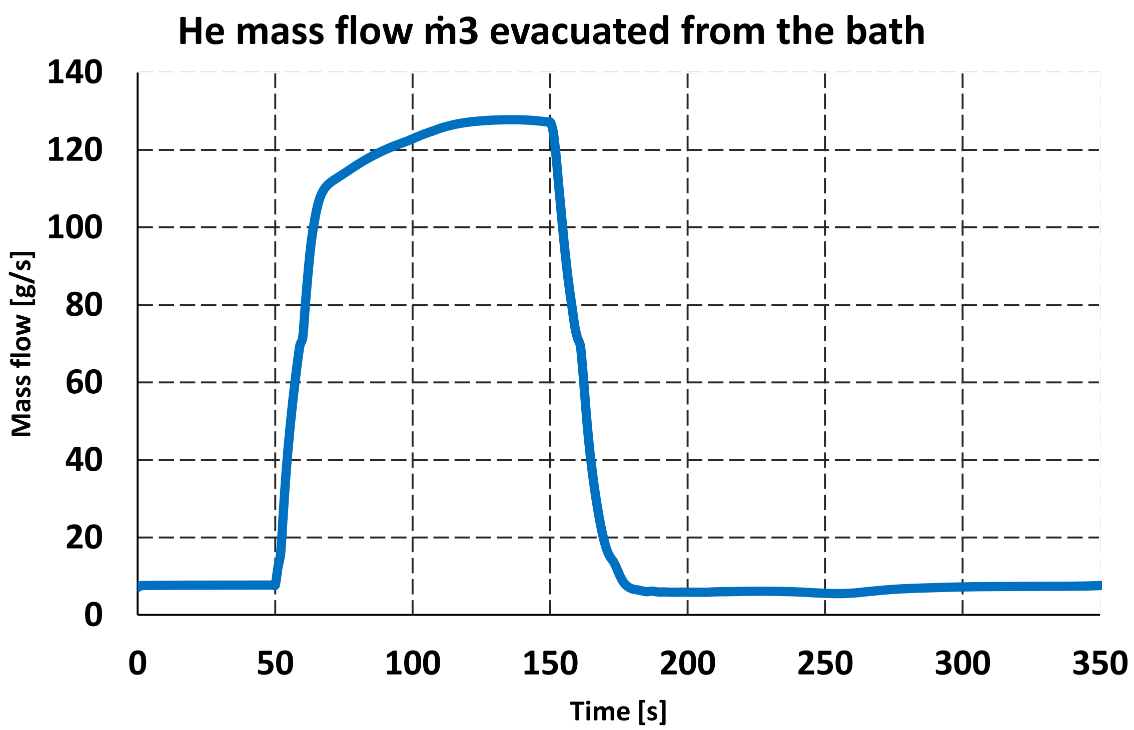
Dynamic modelling of the HELIOS facility

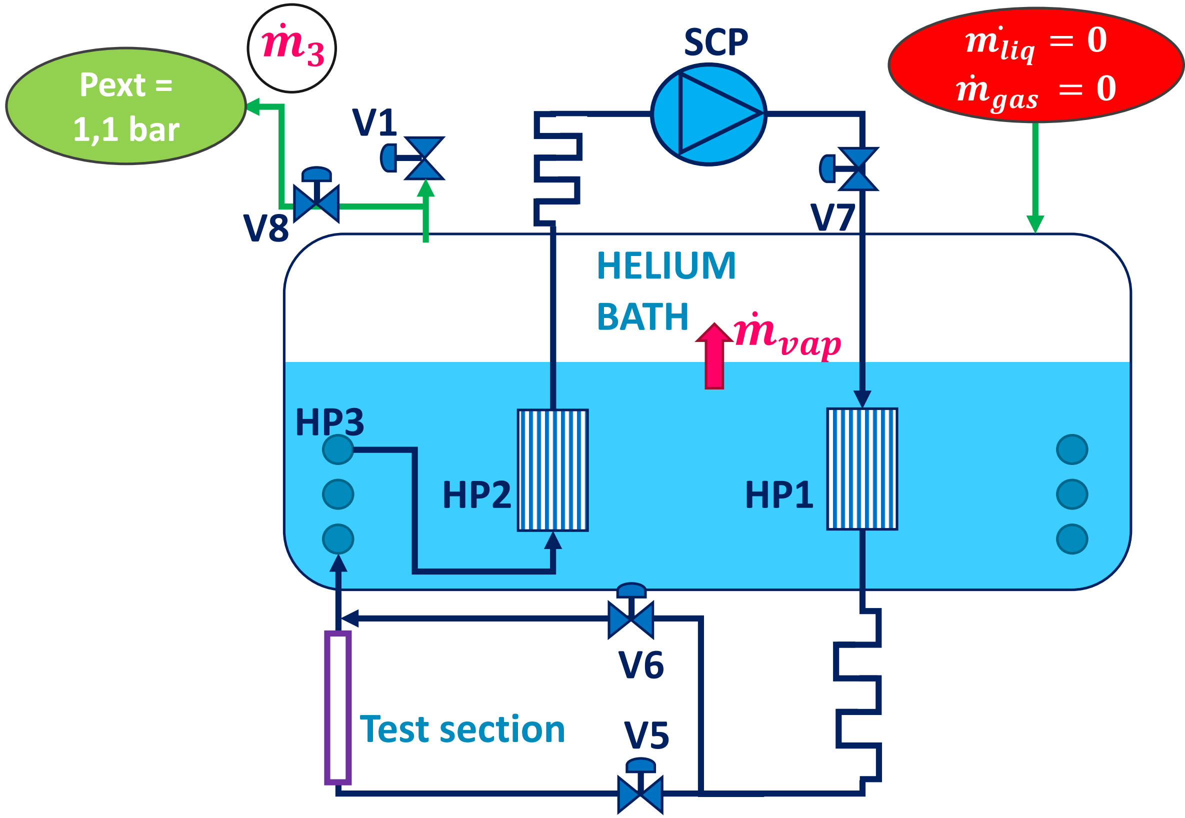




- No reversed flow is observed
- CATHARE predicts a similar inlet and outlet mass flow

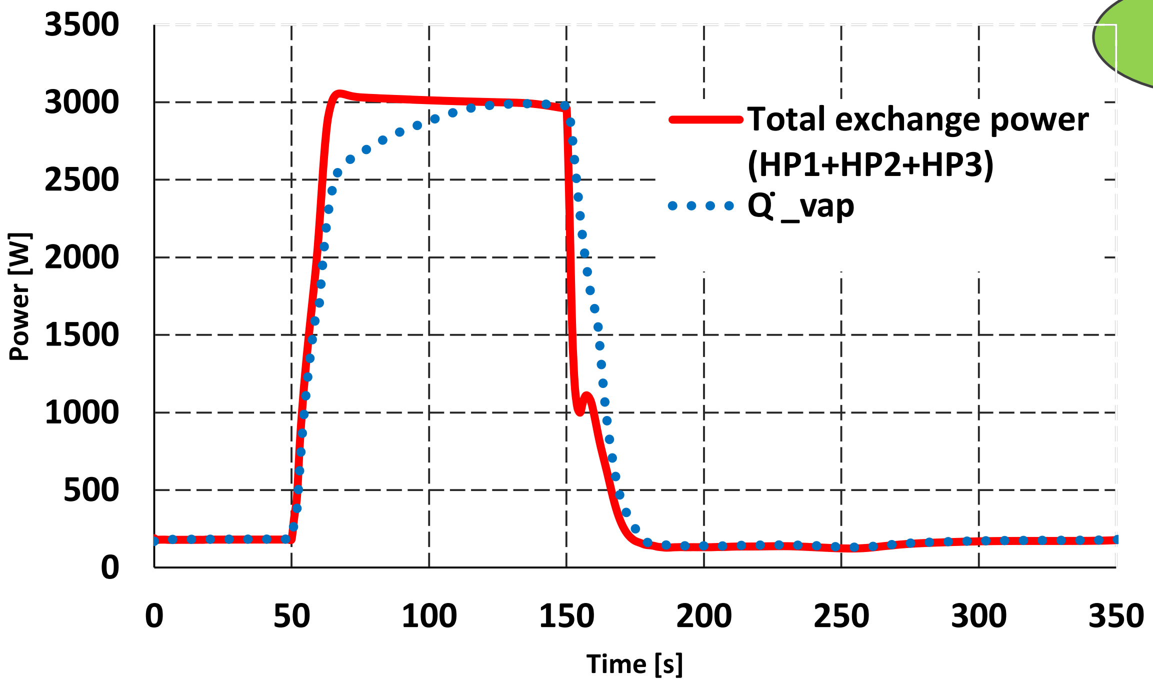
⇨ It seems possible to obtain an enthalpy balance on the TS with only one flow meter placed at the upstream of the section

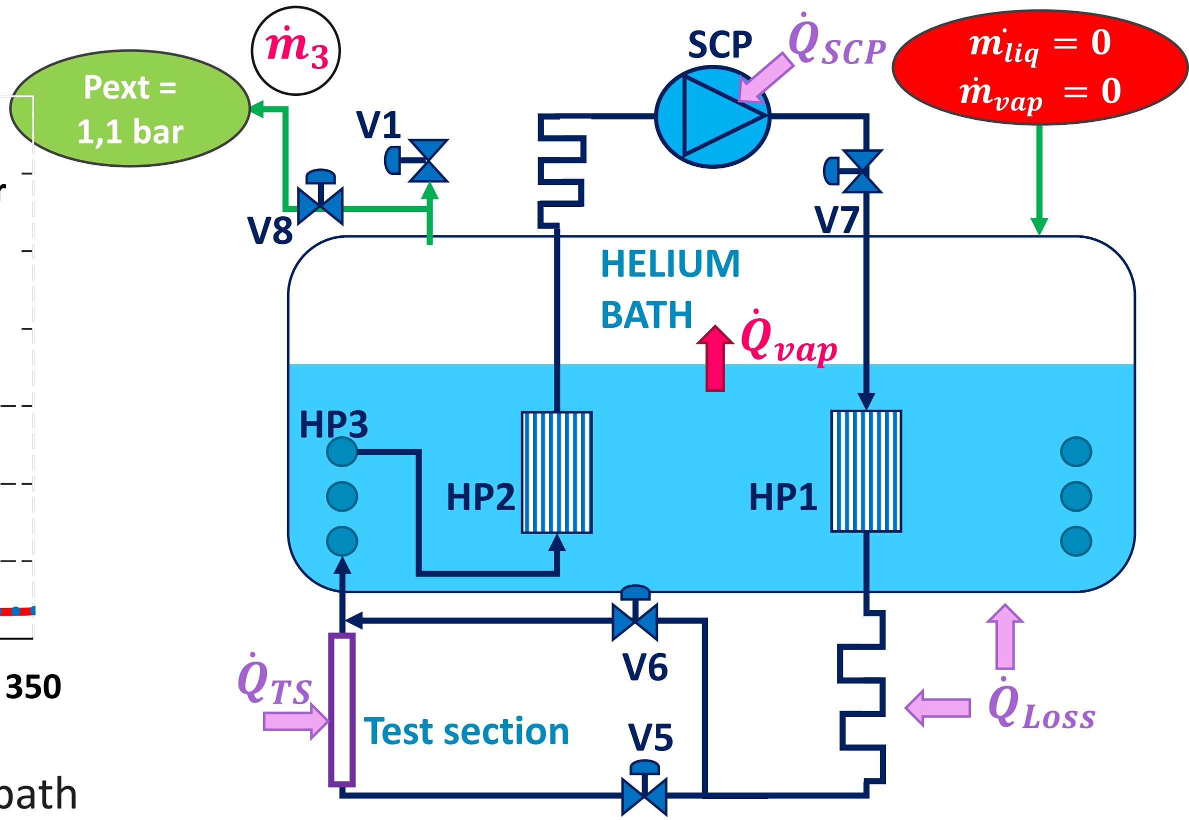




- For a saturated bath with constant pressure :
  - $\dot{m}_{vap}$ is proportionnal to the power received by the bath
- Only $\dot{m}_3$ can be measured :$\dot{m}_{vap} = \dot{m}_3/(1 - \frac{\rho_v}{\rho_L})$
- Due to pressure loss (V8), the flow to reach its nominal value after a delay (P_{bath} increases from 1,1 to 1,17 bar)

Dynamic modelling of the HELIOS facility





- $\dot{m}_3$ can be used to calculate heat power received by the bath
- $\dot{Q}_{vap} = \dot{Q}_{TS} + \dot{Q}_{SCP} + \dot{Q}_{Loss} = \dot{m}_3 \cdot \frac{H_L}{1-\frac{\rho_v}{\rho_l}} = \dot{m}_{vap} \cdot H_L$
- To know the heat flux transmitted at the test section, all additional energy sources must be quantified

Conclusion

- A new design has been defined for the experimental device called HELIOS, in order to perform loss of vacuum on a dedicated test section and carry out experimental measures of heat flux

- CATHARE has been used to modelled HELIOS with its new design
  - The thermal hydraulic behaviour of the loop has been investigated
  - Sizing criteria is respected with the new design
  - Experimental methods to establish the heat flux transmitted the fluid with sufficiently low incertitude has been investigated

- The experimental set up is under construction :
  - Bath and the new heat exchanger are in place
  - Construction of the loop is expected to begin in October

- First experimental campaign expected in 2022

- Experimental result will be compared with CATHARE

Thank you for your attention