Forum on Tracking Detector Mechanics - Universität Tübingen

CO_2 cooling system prototype for the ATLAS ITk Pixel Endcap detector

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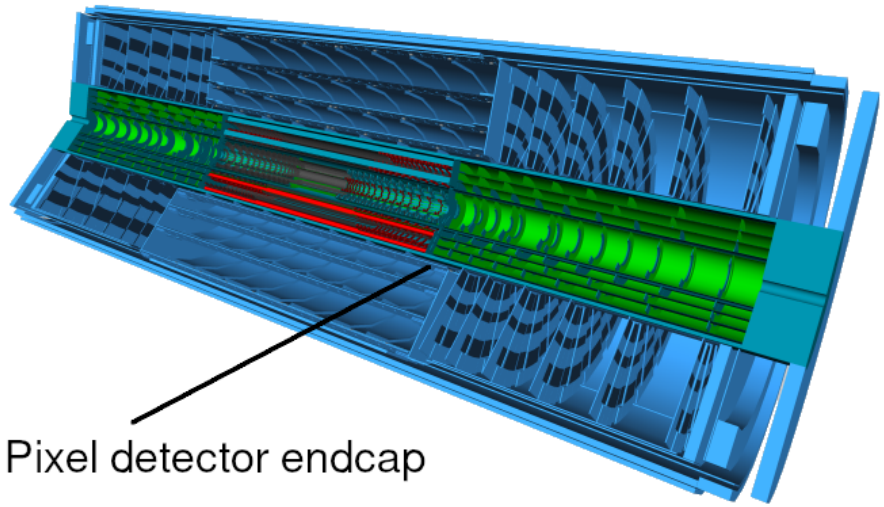
Introduction

- In preparation for **high-luminosity LHC** → ATLAS detector will be upgraded with a **new silicon inner tracker ITk**
- ITk will rely on **evaporative CO_2** based cooling system



- In order to test the key aspects of the cooling, a **prototype for the ITk Pixel Endcap Layer 4 half-shell cooling system** was built in Milan
- Prototype tested at the **CERN CO_2 BabyDEMO cooling plant** → facility is able to provide a flow up to 150 g/s with a temperature as low as –45 °C

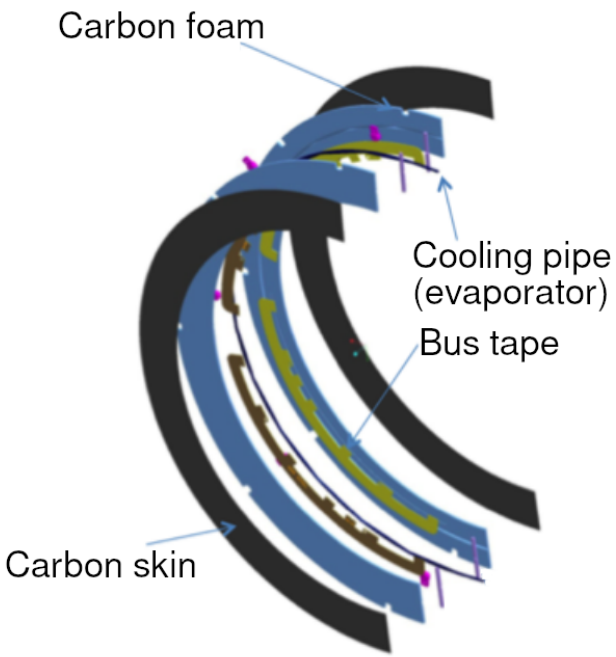
Outline of the talk

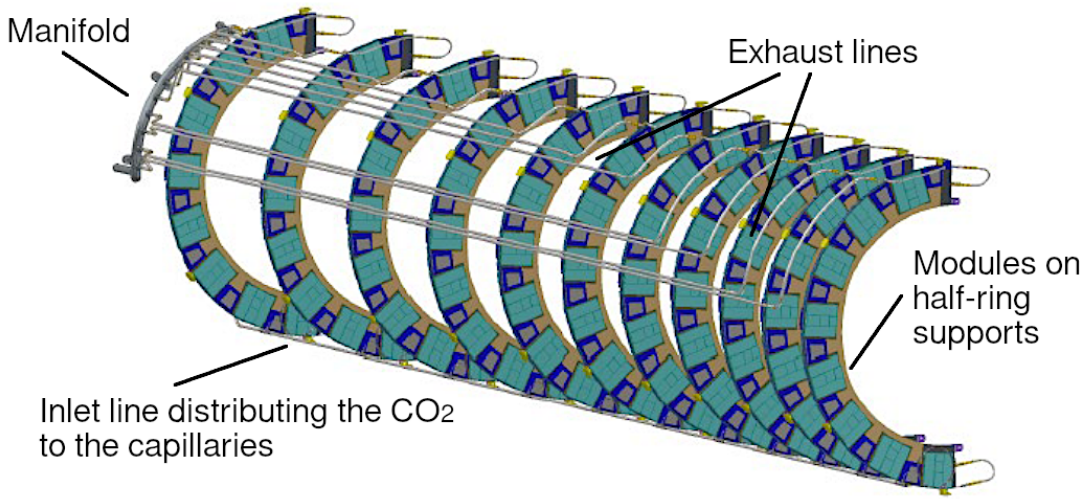
- Introduction to **ITk Pixel Endcap cooling system**
- **Layer 4 prototype**
  - mechanical construction
  - capillary sizing
  - sensors
  - thermal load
- **Measurements performed at BabyDEMO plant**
  - nominal detector operations conditions
  - transient and extreme conditions
- **Conclusions**

ITk Pixel Endcap cooling system

ITk Pixel Endcap: cooling system overview

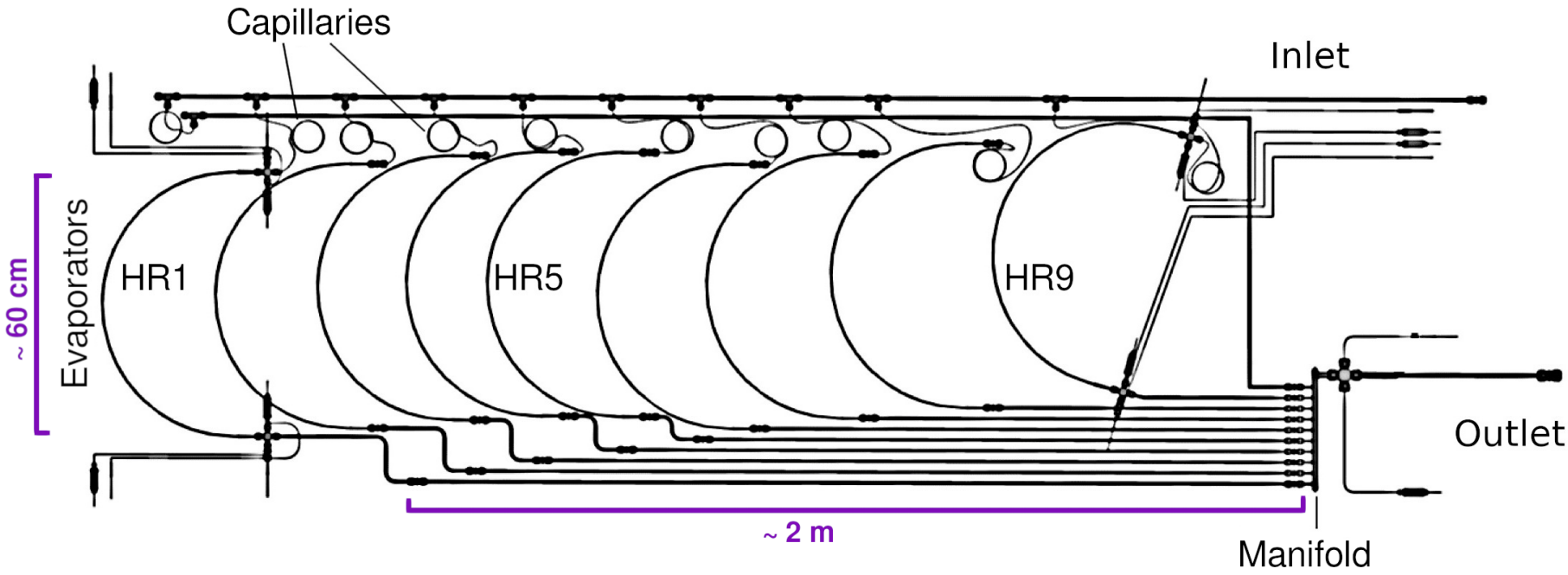
Pixel modules mounted on half-ring local supports.
Injecting liquid CO_2 in the system, the CO_2 reaches the **two-phase state** over the detector local supports evaporator tubes:





Layer 2 CAD by Fred Gannaway (QMUL)

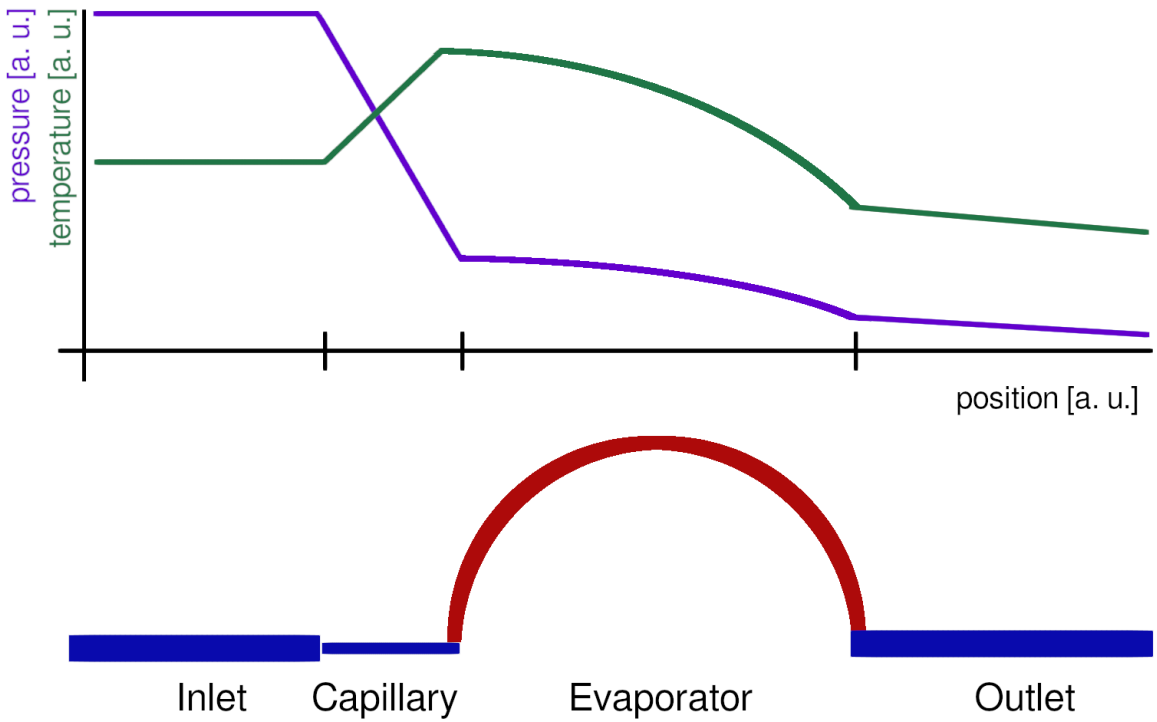
Cooling system and flat Layer 4 prototype overview



- Common **inlet line**
- **Capillaries** distributing CO_2 to all the **half-ring evaporators**
  → capillary crucial both to trigger CO_2 evaporation and to equalize pressure drops in the system
- **Exhaust line** collecting two-phase CO_2 and bringing it to the **manifold**
- Prototype is flat to simplify thermal insulation

Evaporative CO_2

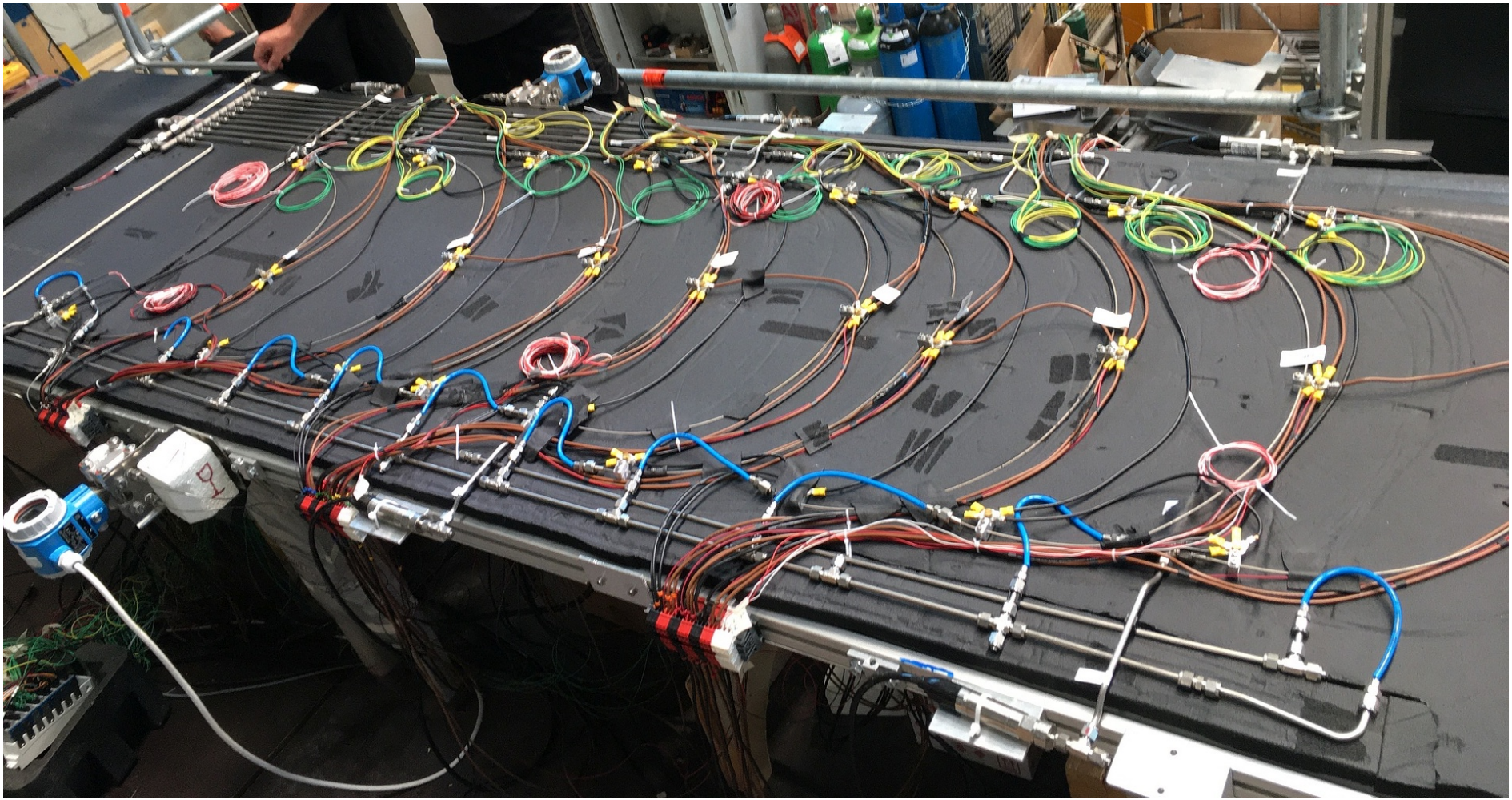
Capillary ensures that the evaporation **starts at the beginning of the evaporator**: liquid very close to saturation, it starts bubbling as soon as it enters the evaporator



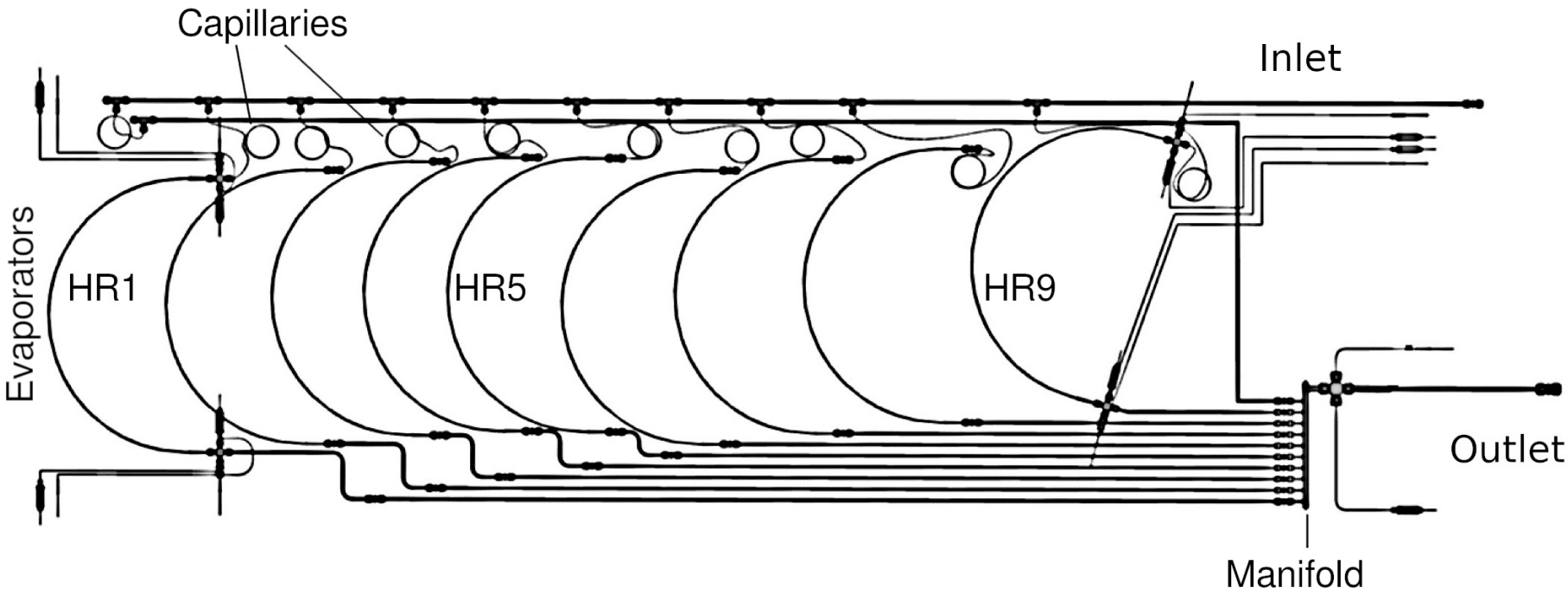
Specifications for the ITk cooling system:

- vapor quality of 30% in the evaporator
- temperature drop within 5°C
- pressure drop in capillary: 8 bar
- pressure drop in evaporator + exhaust line within 2 bar

Mechanical construction of the prototype



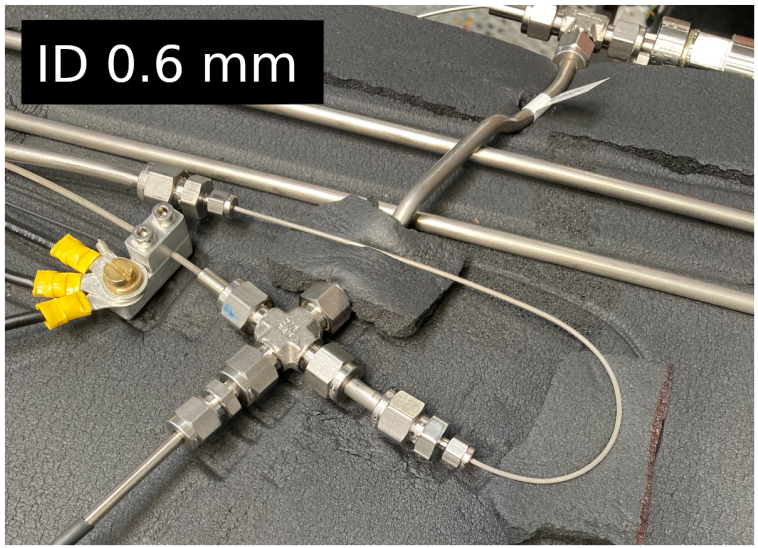
Overview of the Layer 4 prototype



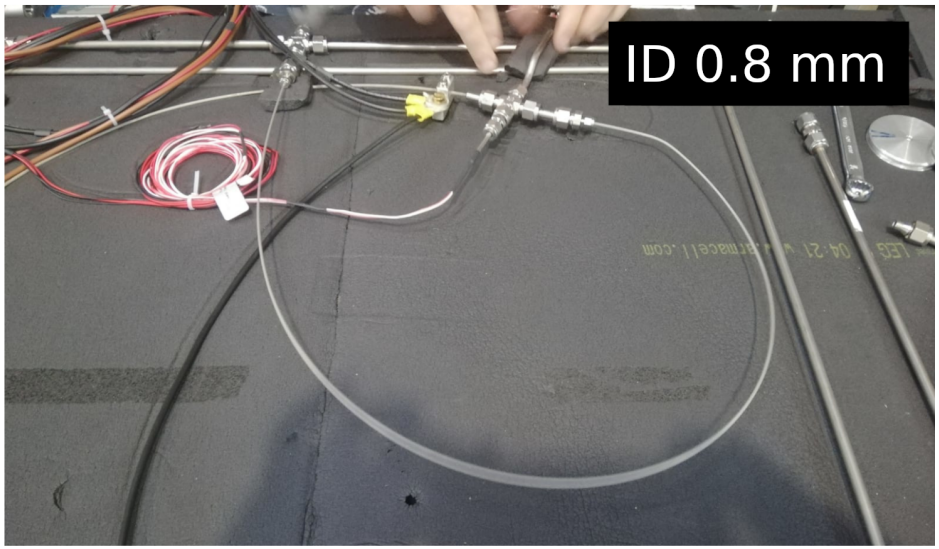
- All tubes are **grade 2 titanium**
- Inlet and outlet lines connected to **BabyDEMO plant**
- **Capillaries** measured and sized at CERN
- 3D printed flat **manifold**
- **Heating system** to simulated detector thermal load
- Temperature and pressure **sensors**

Capillaries

- **Two types of capillaries tested**, both with OD 1/16":
  ID 0.6 mm and ID 0.8 mm.
- Preliminary FLUDY and COBRA simulations to predict length, but dedicated measurements to find correct lengths at BabyDEMO plant to achieve the 8 bar pressure drop



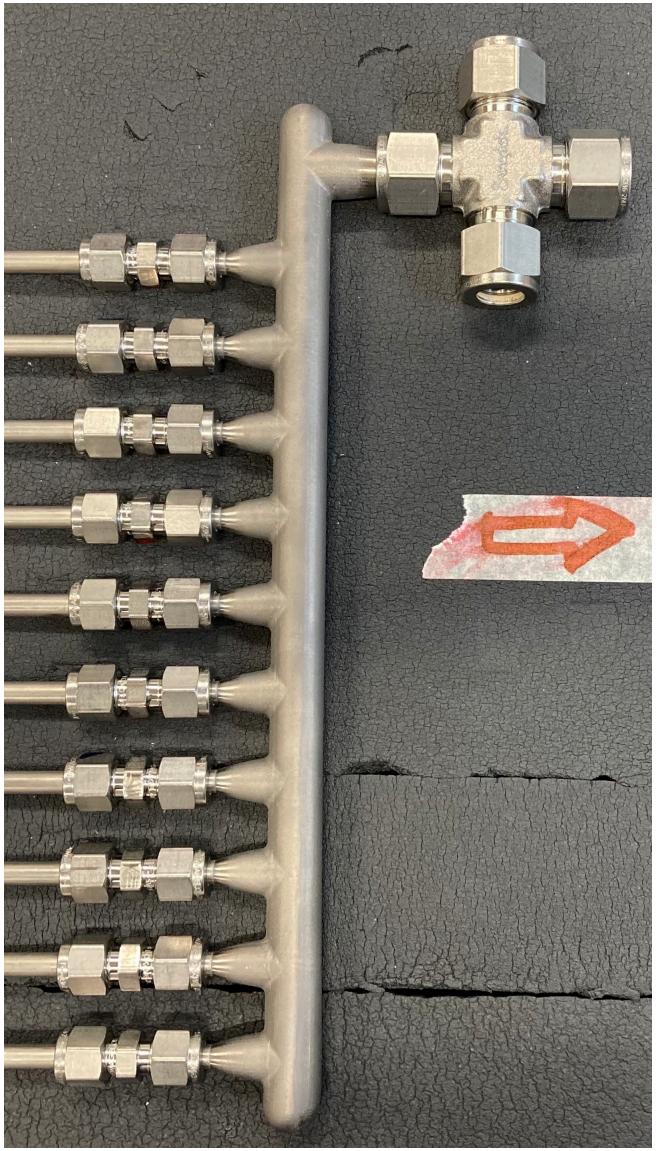
Capillary length: 22.5 cm



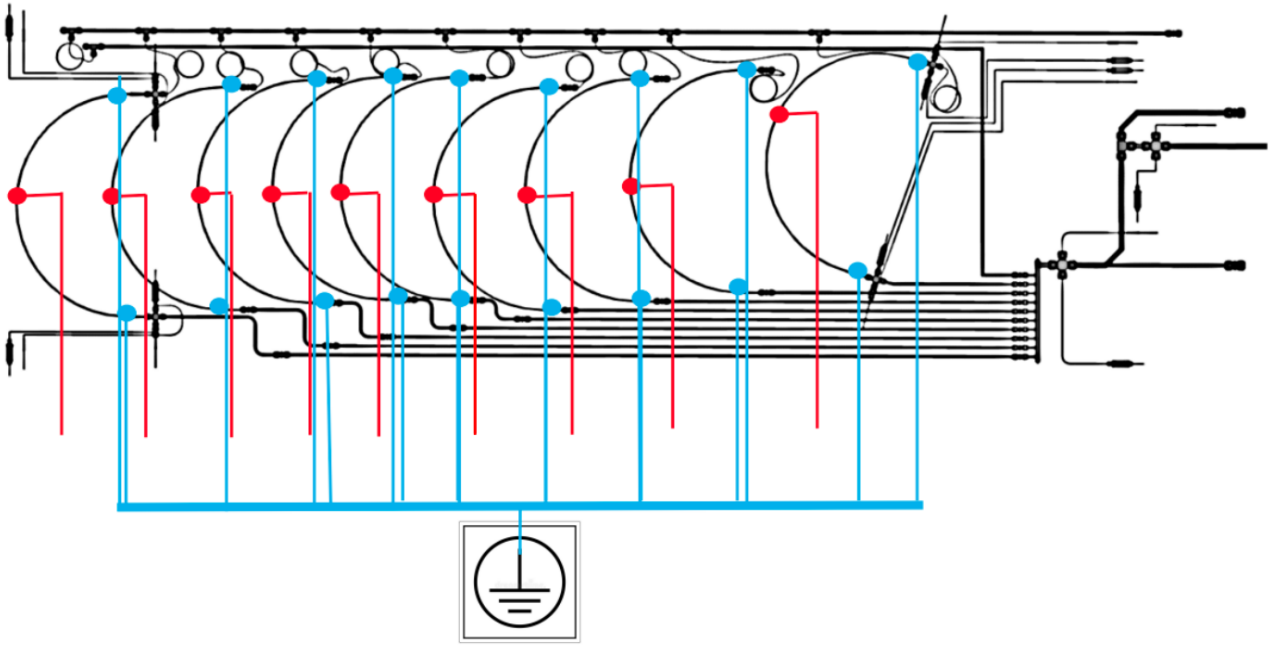
Capillary length: 90 cm

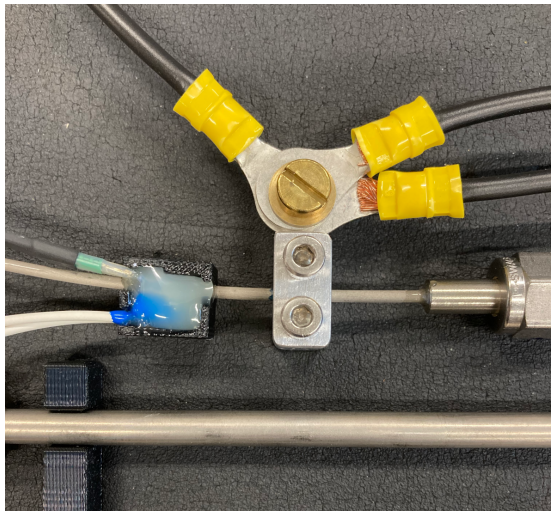
Manifold

- Flat **manifold 3D printed in titanium** at LAMA Labs in Udine
- To prevent debris:
  - thermal treatment
  - cleaning in ultrasonic bath
  - hirtisation foreseen for real detector manifold



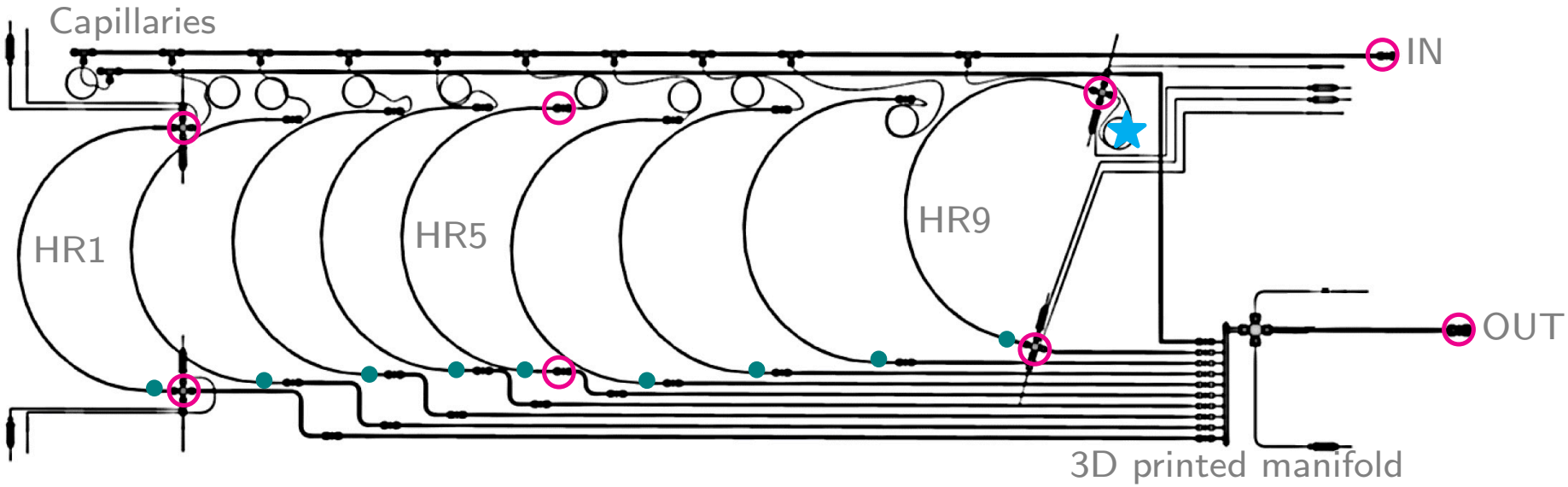
Heating system





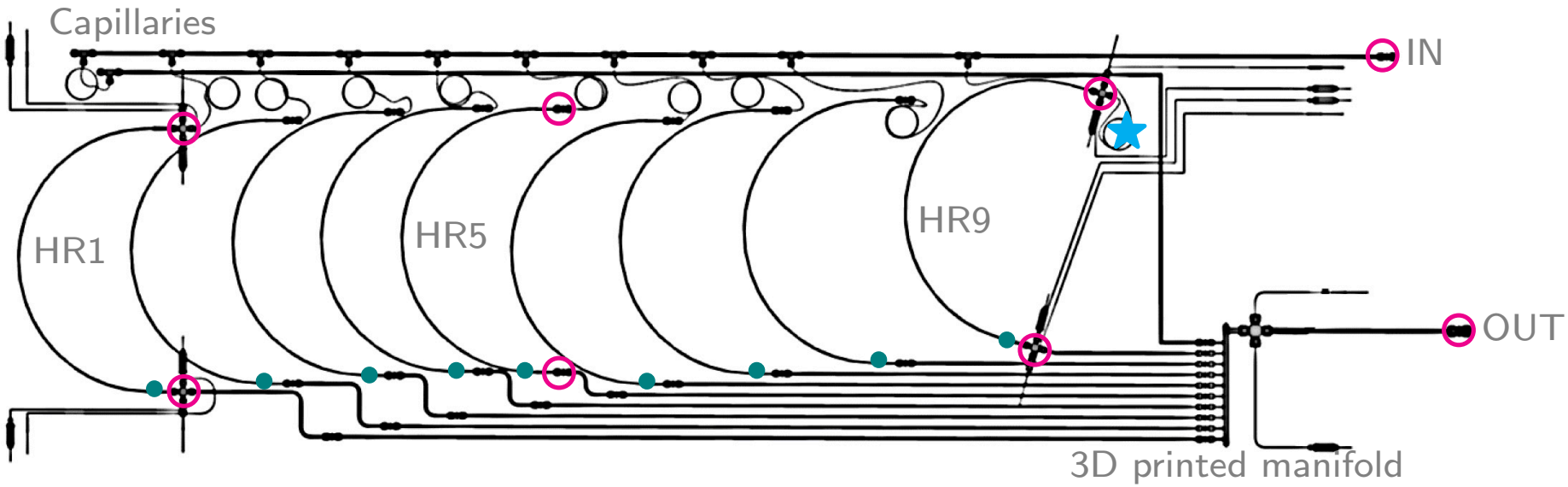
- In order to simulate the **detector thermal load**, HRs connected to power-supplies and treated as resistors
- Nominal power applied to each HR: 300 W (5 V x 60 A), maximum power to be tested estimated to be ~400 W
- Red lines: current injection points
- Blue lines: connection to ground

In-flow sensors

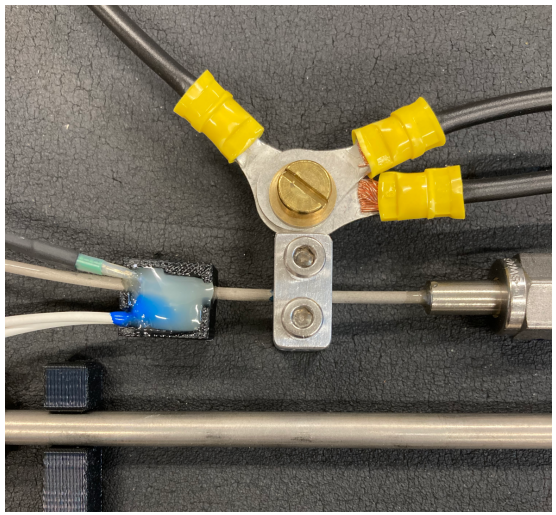


- **In-flow** pressure and temperature sensors (○)
  - Global IN and OUT
  - HRs 1, 5 and 9 IN and OUT
- PT100 temperature sensors
- EPSAS pressure transmitters with ±32 mbar accuracy
- **DeltaBar** (★) for pressure measurement of the capillary of HR9, with ±12 mbar accuracy

External sensors



- **External wall temperature** and interlock temperature sensors (•) glued to each evaporator pipe
- All sensors (except interlock ones) read through LabView

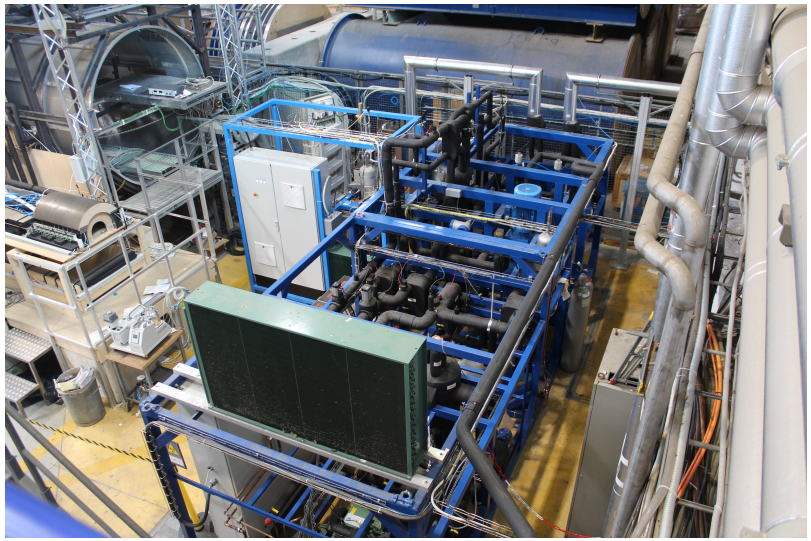


Measurements at BabyDEMO

Summary of measurements [1]

Measurements performed at the BabyDEMO plant:

- First measurements with HR9 evaporator loop only, to **size the capillaries** to give a pressure drop of ~8 bar with 3g/s CO_2 flow
- Full system measurements at **ITk nominal operation conditions:**
  - CO_2 flows 30 g/s and −40 °C
  - thermal loads of 300 W for each evaporator
  - with two different sets of capillaries, ID 0.6 mm and 0.8 mm

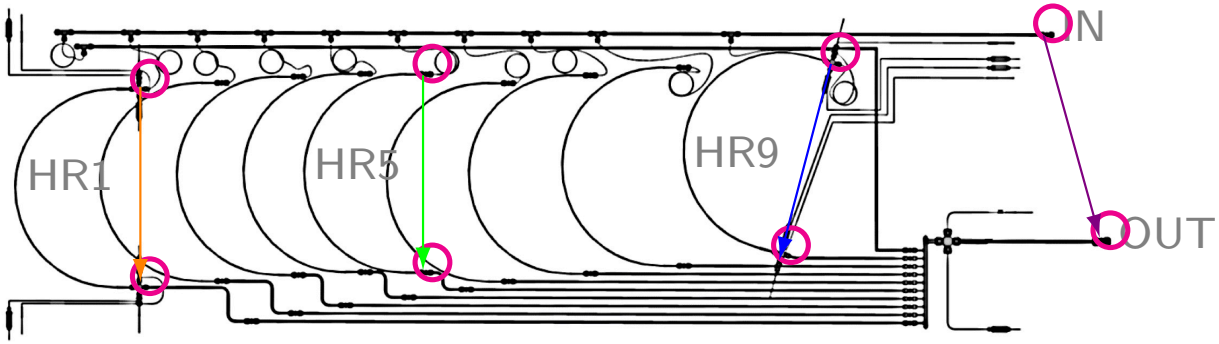


Summary of measurements [2]

- Measurements in **stable conditions** with the full system, at different operating conditions:
  - CO_2 flows [30 g/s and 40 g/s]
  - CO_2 temperatures [−20 °C, −35 °C, −40 °C]
  - thermal loads [0 W, 100 W, 200 W, 300 W and 400 W for each evaporator]
  - two sets of capillaries [ID 0.6 mm and 0.8 mm]
- Measurements of various situation with **transitions**, changing the power to single (or pairs of) evaporators
- Extreme thermal load conditions, up to 700 W for each evaporator
- Finally, measurements decreasing the flow to detect **dry-out** conditions, using nominal power, at 0 °C, −20 °C and −40 °C.

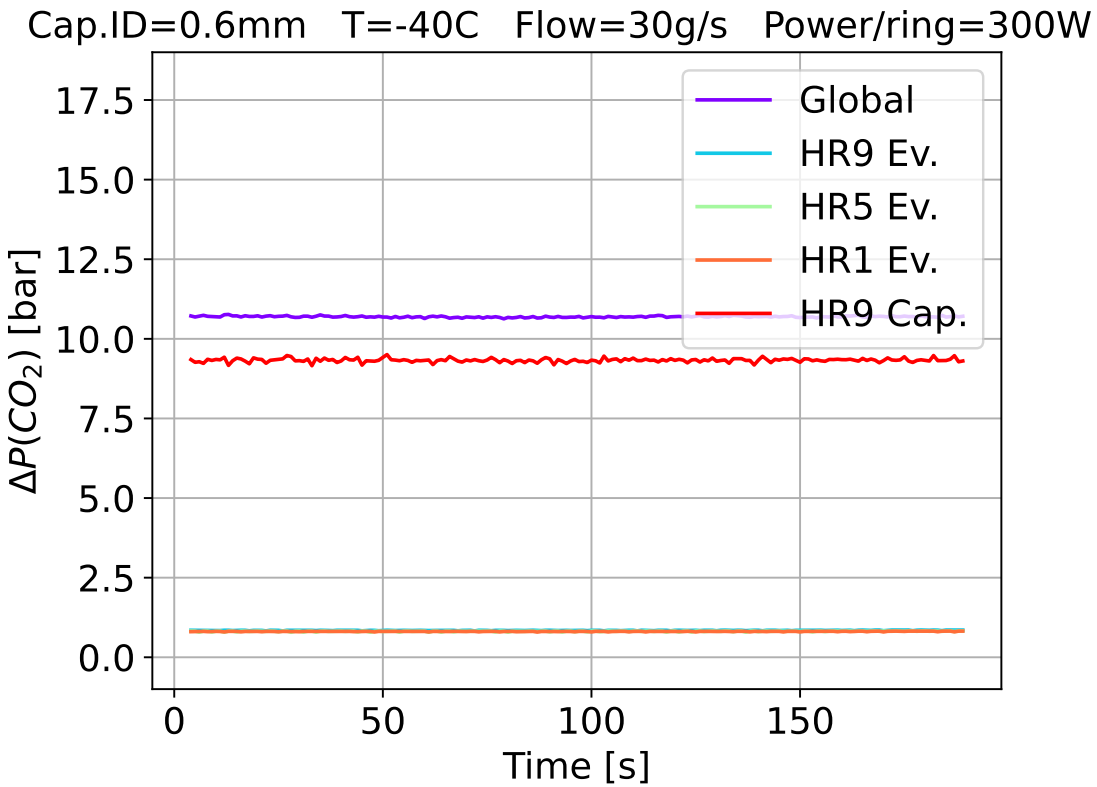
→ Only a selection of the results is shown in the following

Pressure drop after sizing the capillaries ID 0.6 mm

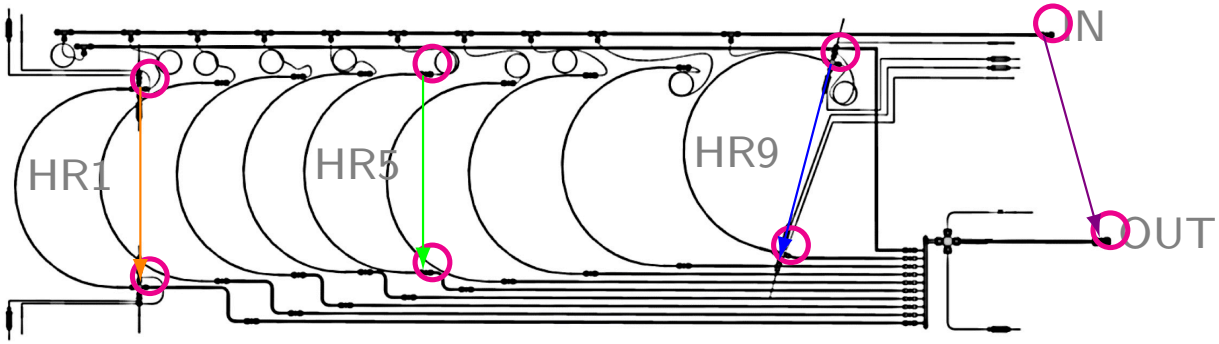


In-flow CO_2 ΔP as a function of time between:
- Global IN and OUT
- HR9, HR5 and HR1 evaporator IN and OUT
- HR9 capillary with DeltaBar

- Nominal conditions, CO_2 $T = -40\,°C$ and $30\,g/s$, using $300\,W$/evaporator
- ΔP around 9.5 bar over capillary, length of $0.225\,m$
- System stable over time
- Same behaviour for the HR evaporators



Pressure drop after sizing the capillaries ID 0.8 mm



In-flow CO_2 ΔP as a function of time between:
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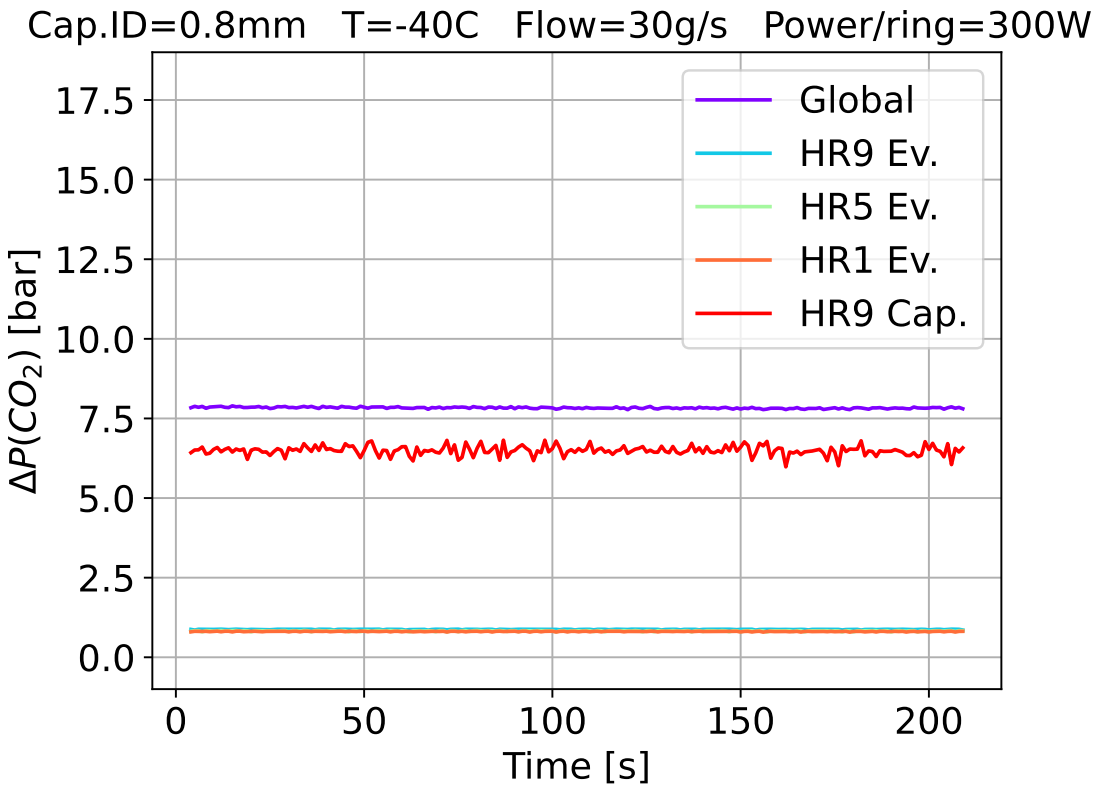
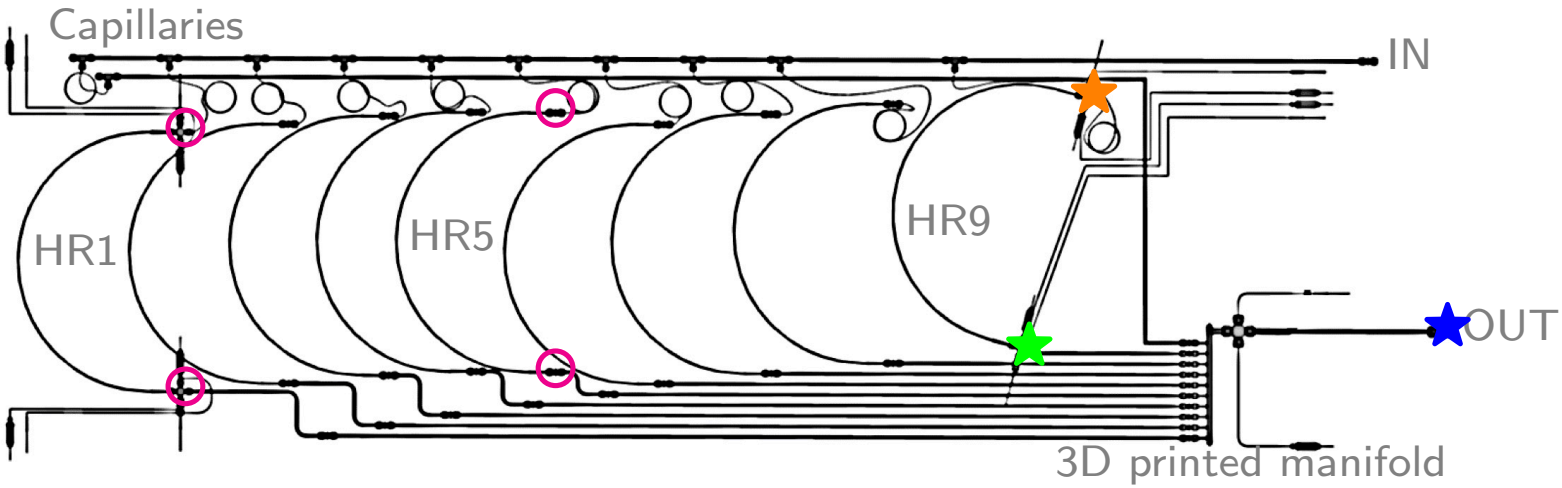
- Nominal conditions, CO_2 $T = -40\,°C$ and $30\,g/s$, using $300\,W$/evaporator
- ΔP around $6.5\,bar$ over capillary, length of $0.9\,m$
- System stable over time
- Same behaviour for the HR evaporators

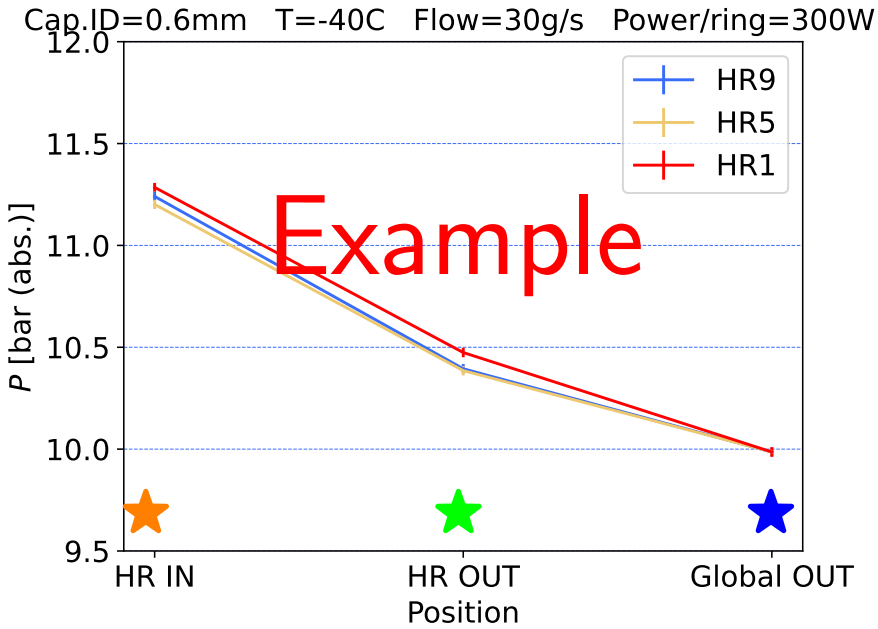


Pressure drop and temperature in HR and exhaust lines



Showing the in-flow CO_2 pressure drop and temperature as a function of the position along the prototype:

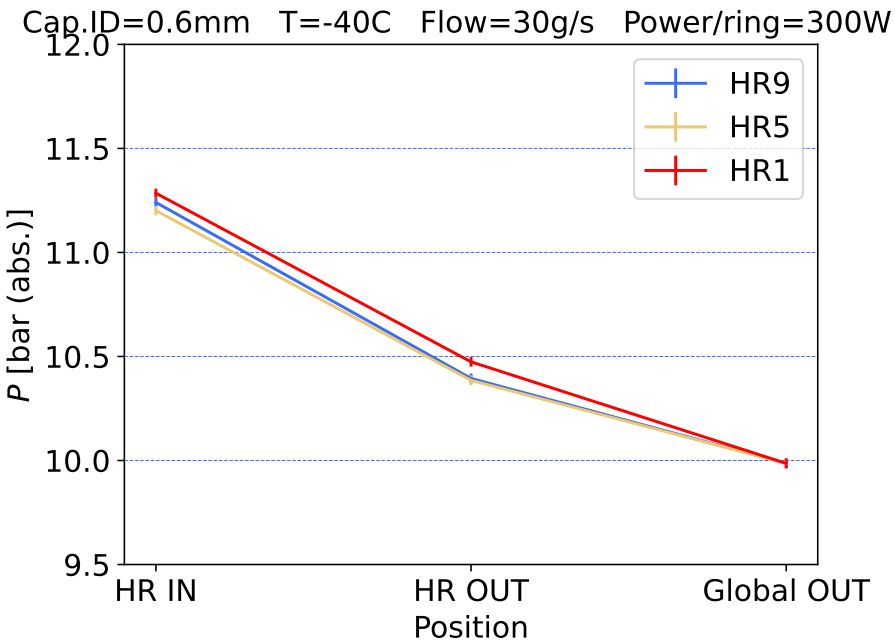
- from HR IN to HR OUT
  → evaporator
- from HR OUT to Global OUT
  → exhaust line



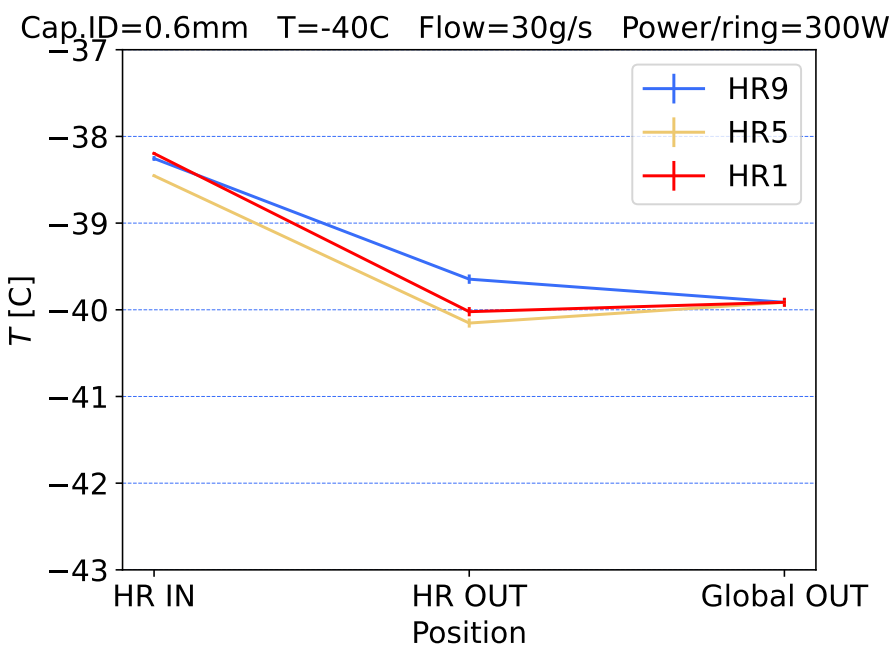
ΔP and T in evaporators and exh. lines - Cap. ID 0.6 mm

CO_2 T = −40 °C and 30 g/s, using 300 W/evaporator

Pressure



Temperature

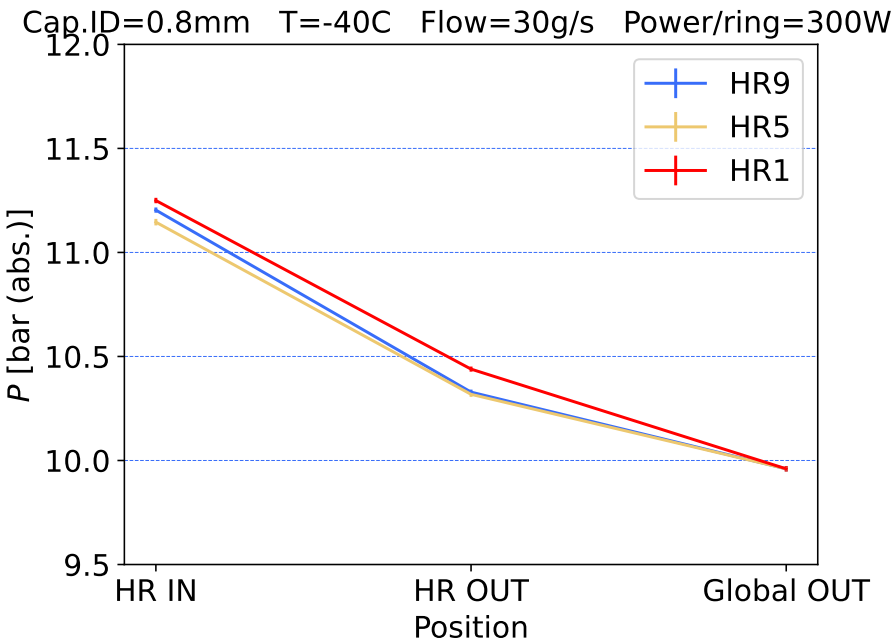


Pressure drop is 1.5 bar, within the 2 bar specification
Temperature difference is 2 °C, within the 5 °C specification

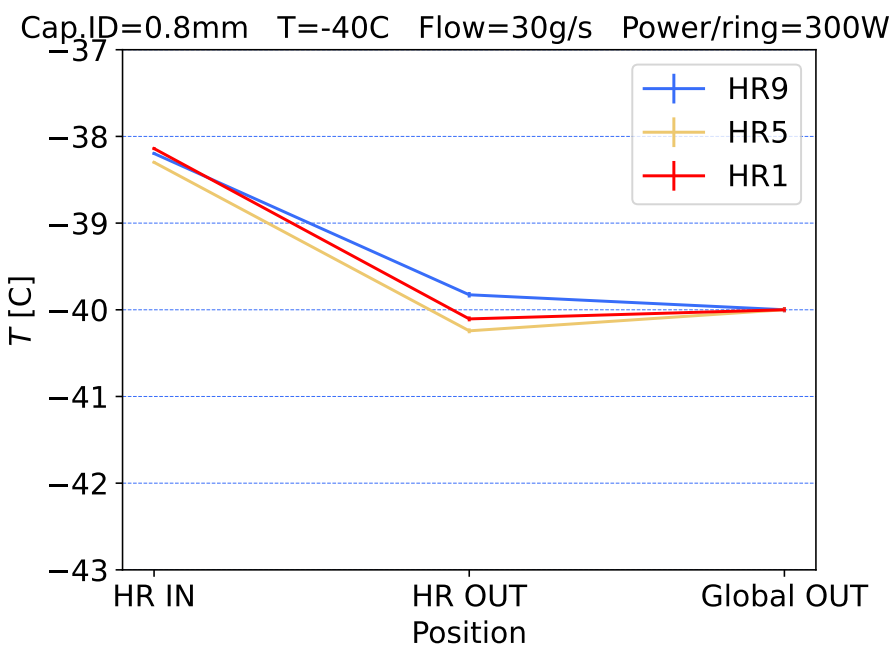
ΔP and T in evaporators and exh. lines - Cap. ID 0.8 mm

CO_2 T = −40 °C and 30 g/s, using 300 W/evaporator

Pressure



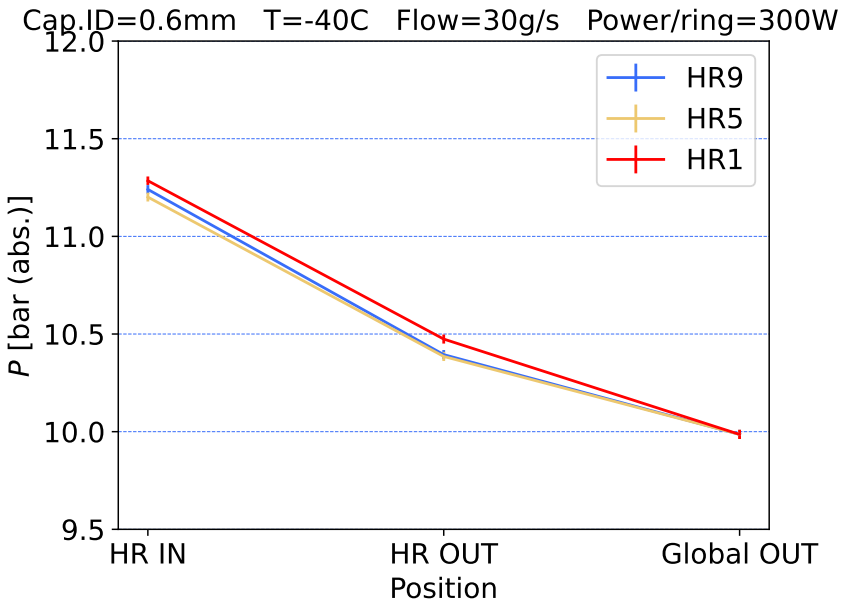
Temperature



Pressure drop is 1.5 bar, within the 2 bar specification
Temperature difference is 2 °C, within the 5 °C specification

Pressure drop in the exhaust lines

Pressure drop at nominal conditions



- At the nominal operating conditions, the pressure drop in the longest exhaust line (HR1) is 0.5 bar
- ID 4.55 mm pipes were used for the exhaust line, since the ID 4 mm ones foreseen for the real system were not available yet
- Need to correct pressure drop for the smaller ID: the correction is a factor 2, computed from analytic formula and FLUDY simulation

Pressure drop is 1 bar in the exhaust line after the correction and 1 bar in the evaporator → total pressure drop is 2 bar

Conclusions

Conclusions

- ITk Pixel Layer 4 cooling system prototype **successfully tested** at the BabyDEMO plant
  - We thank the CERN cooling group and Joao Noite for their support
- Only selected set of measurements shown today, but results show that **the system is operational in all the tested condition**
  - pressure and temperature drops are **within the specification**
  - the **system is stable, even in extreme conditions**, like power variation and temperature/flow condition different from the nominal ones (some reported in the backup slides)
- Group is now moving to the **production of the real detector cooling system**

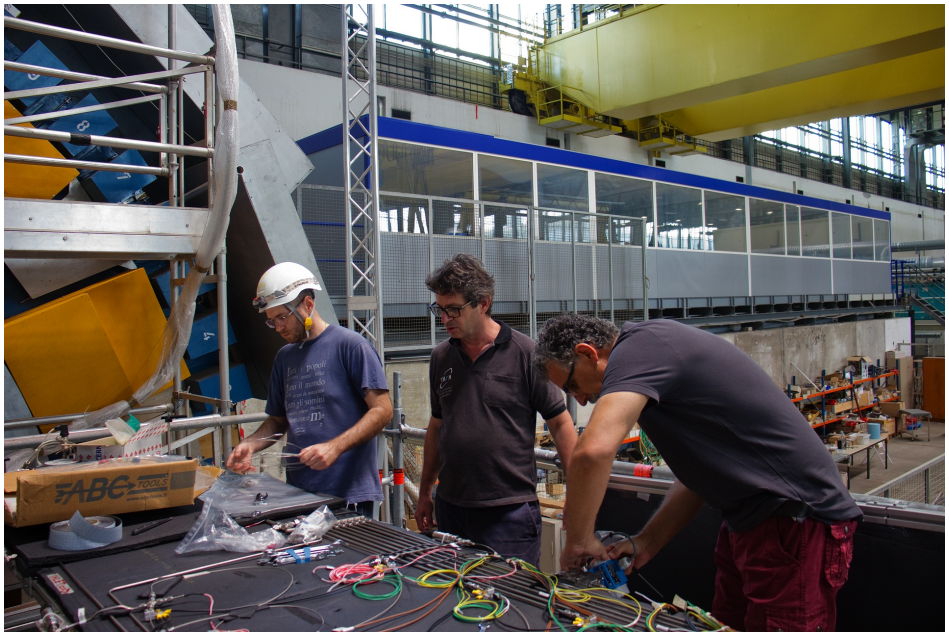
Outlooks

Preparation for **production of the real detector cooling system** for all the layers, challenges:

- 3D **bending** of the pipes
- orbital **welding** of Ti pipes
- preparation of the **capillaries** and brazing to the inlet line

Currently working on 3D prototype for Layer 2 of the system to test the full production process

Prototype of Layer 2 exhaust line and manifold on integration tool


ABC TOOLS


NORMA-TEF

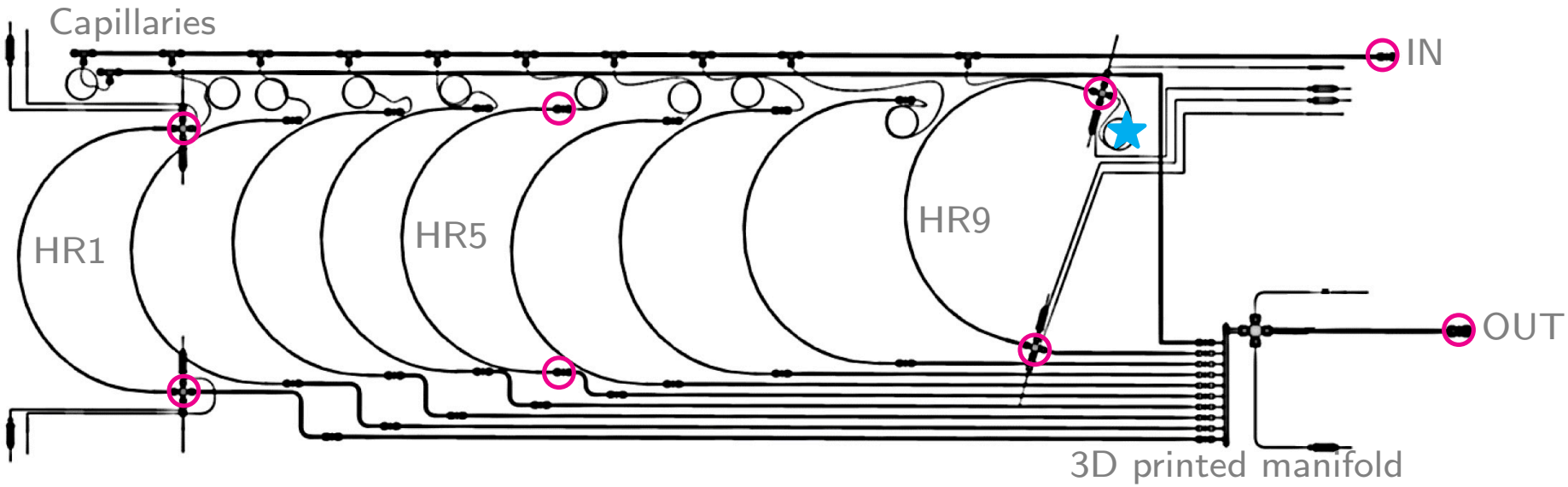
Backup

Mechanics and sensors

Power-supplies

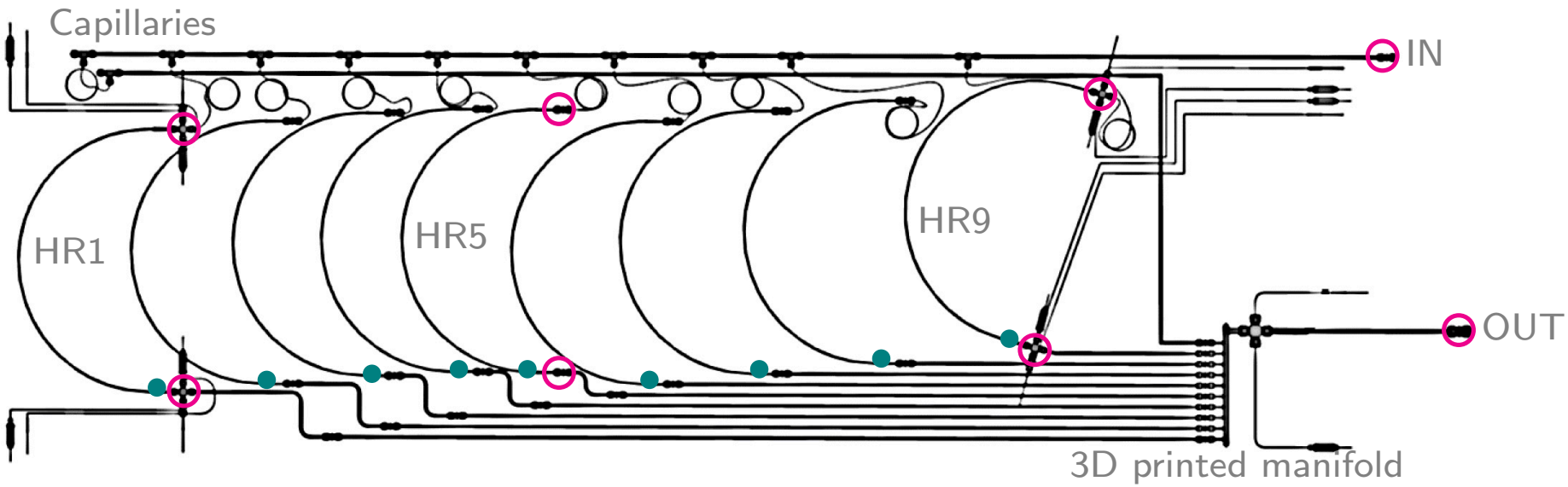
- Each power-supply connected to two HRs, except HR9 that has its own power supply.
  → This ensures the electrical isolation of all the HRs, power consumption only over HRs.
- Using sensing connections: performing measurement of voltage and giving feedback to the power supply itself.
  → This ensure that the voltage and current, read on the power supply, are exactly the ones applied to the HRs.
- Power-supplies used:
  - three Delta Electronic SM 30V-200A power-supplies for HR1-HR2, HR3-HR4 and HR5-HR6,
  - two EA 80V-120A power-supplies connected in series for HR7-HR8,
  - one Delta Electronic SM 15V-100A power-supply for HR9.

Details on pressure sensors



- 8 EPSAS **pressure transmitters**,
  output 4 mA–20 mA, calibration 0 bar–80 bar ABS
  accuracy: 0.04 %, FS = 80 bar → ±32 mbar
- 1 **DeltaBar** PMD75 ENDRES+HAUSER,
  output 4 mA–20 mA, calibration −16 bar/16 bar
  accuracy: max. measurement error 0.075 % → ±12 mbar

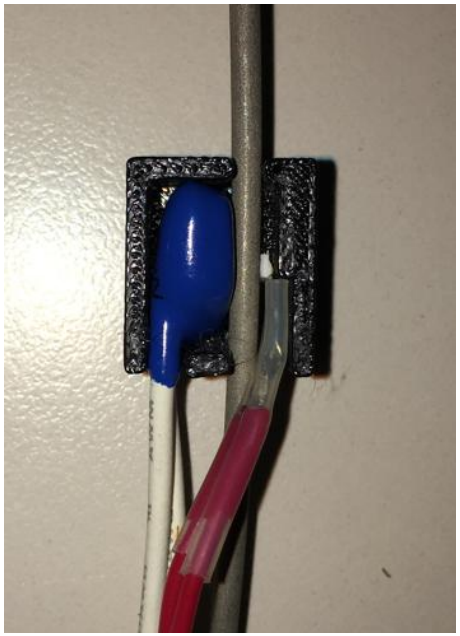
Details on temperature sensors

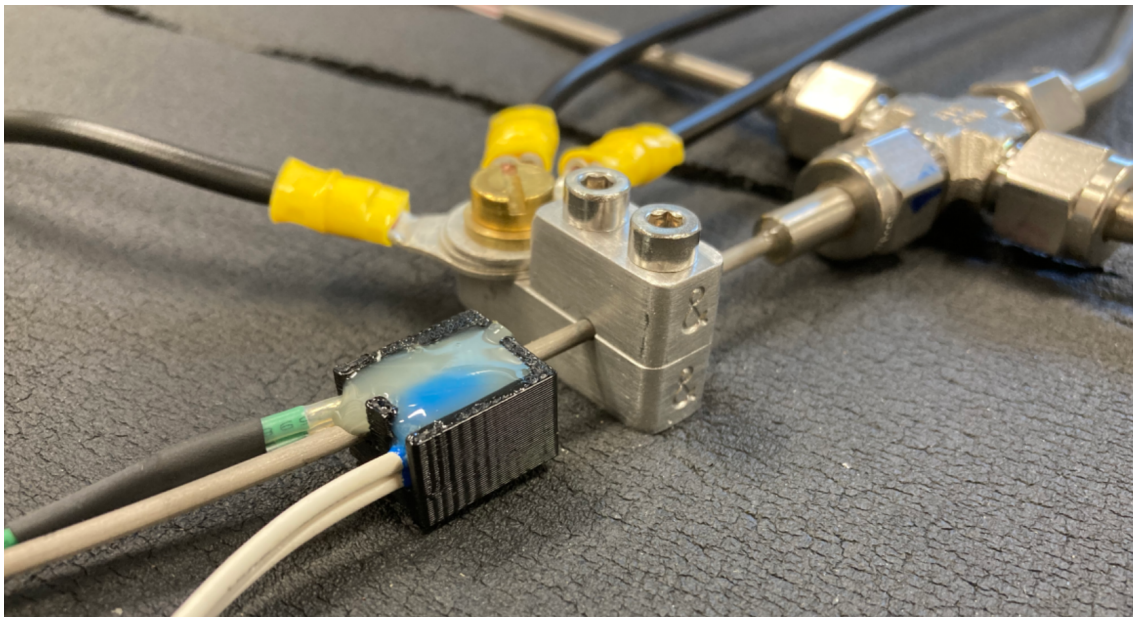


- 8 **temperature transmitters**, PT100 with 4 wires
- external sensors glued to the HRs:
  - sensors for **dry-out** and pipe temperature: 9 RTD PT100 ⌀ 2 mm
  - sensors for power-supplies **interlock**: 9 thermal switches T11A, 80 °C

Sensor gluing

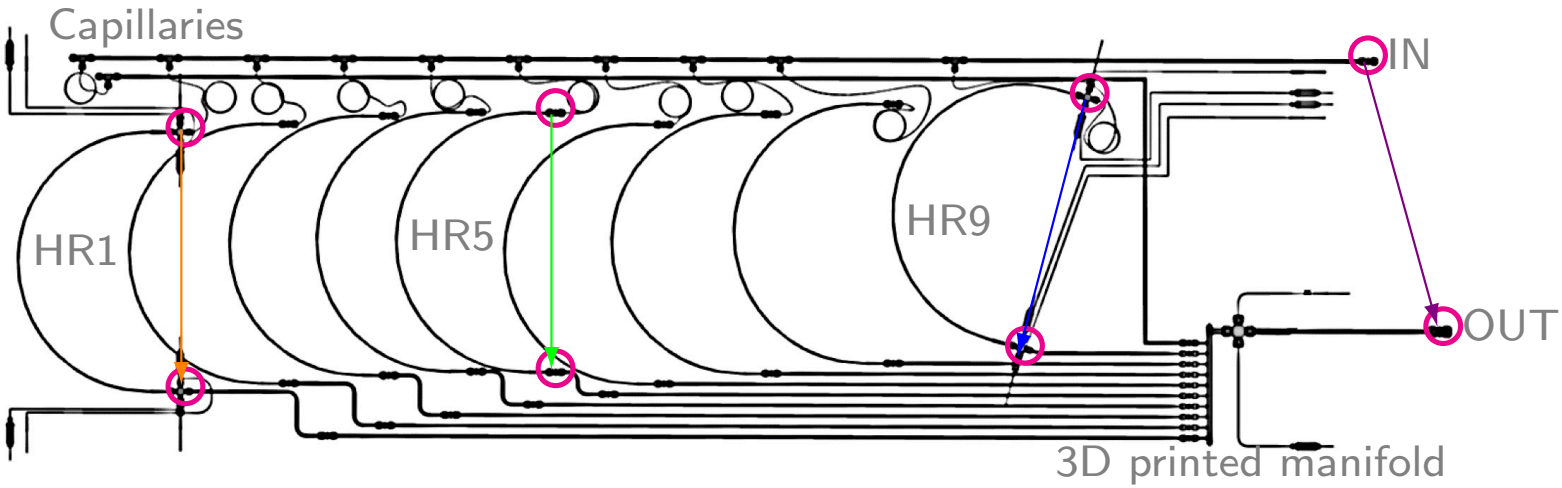
- Small support, 3D printed, to position the dry-out and interlock sensors around the pipe.
  - Helps the gluing procedure and protects from torsions that could detach the sensors from the pipes.
- First use Loctite 315, to glue the sensor to the pipe.
- Then fill the support with Araldite 2012.





ΔP and T plots

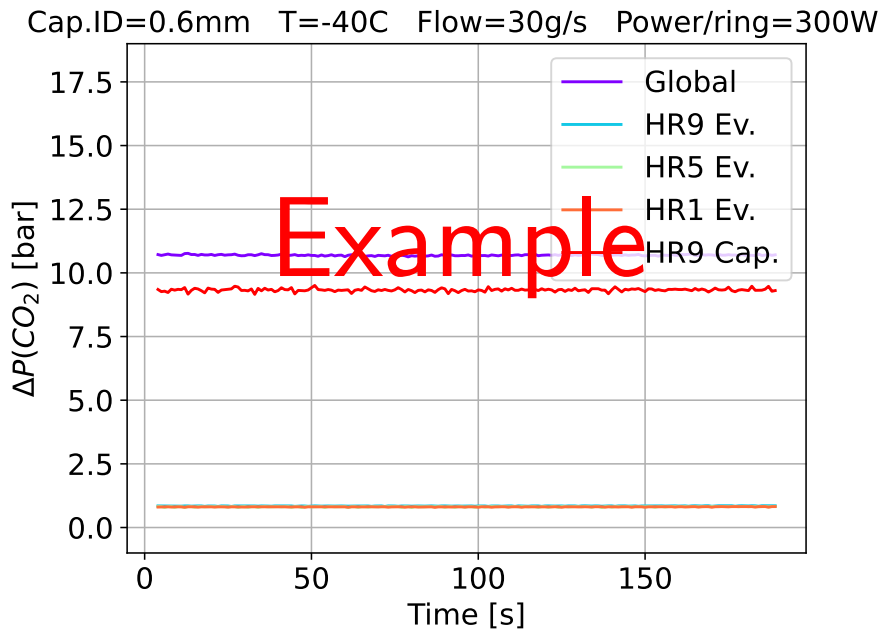
Pressure after sizing the capillaries



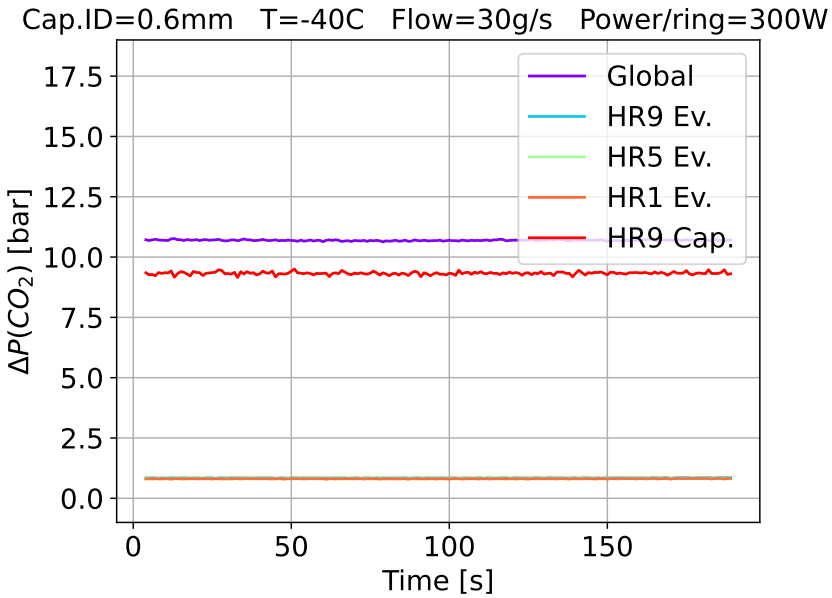
Shown in the following in-flow CO_2 ΔP as a function of time between:

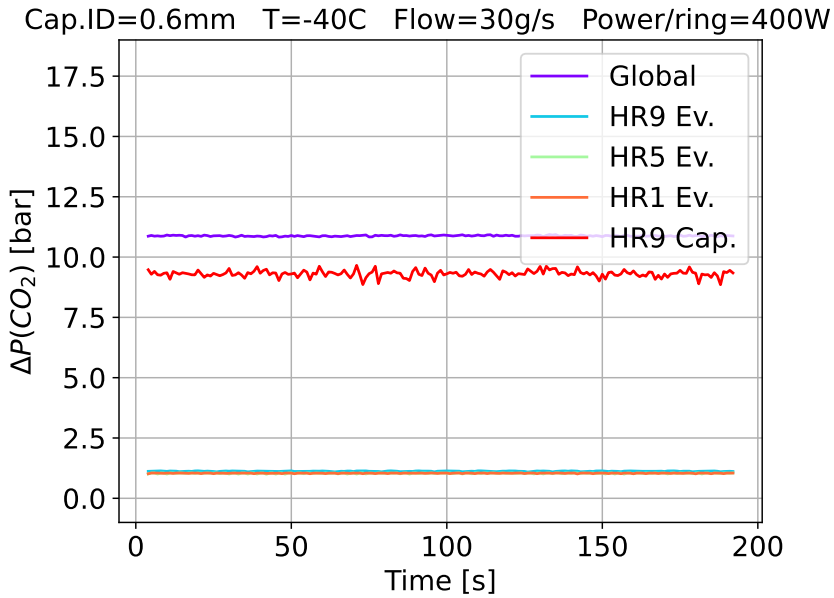
- Global IN and OUT,
- HR9, HR5 and HR1 IN and OUT
- HR9 capillary with DeltaBar

The plot title shows the capillary ID, the CO_2 temperature, the flow and the power.



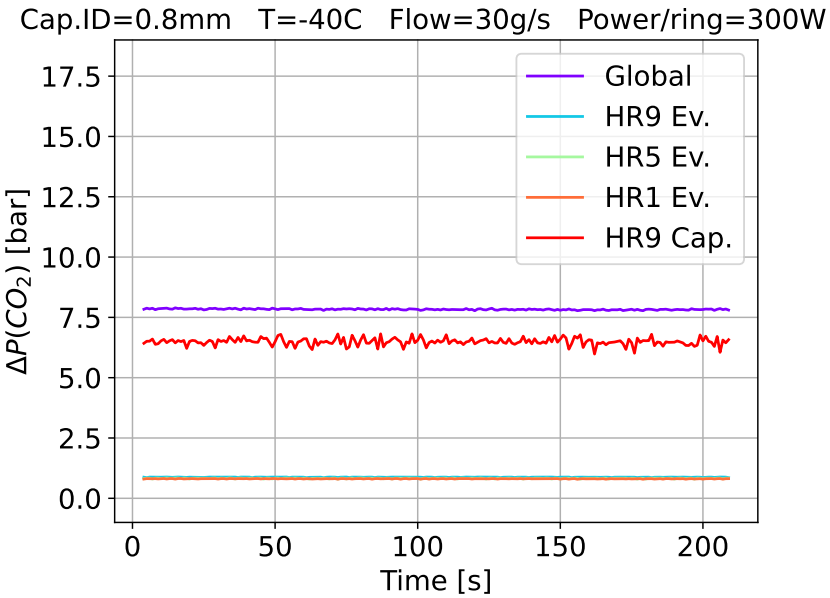
After sizing the capillaries - ID 0.6 mm

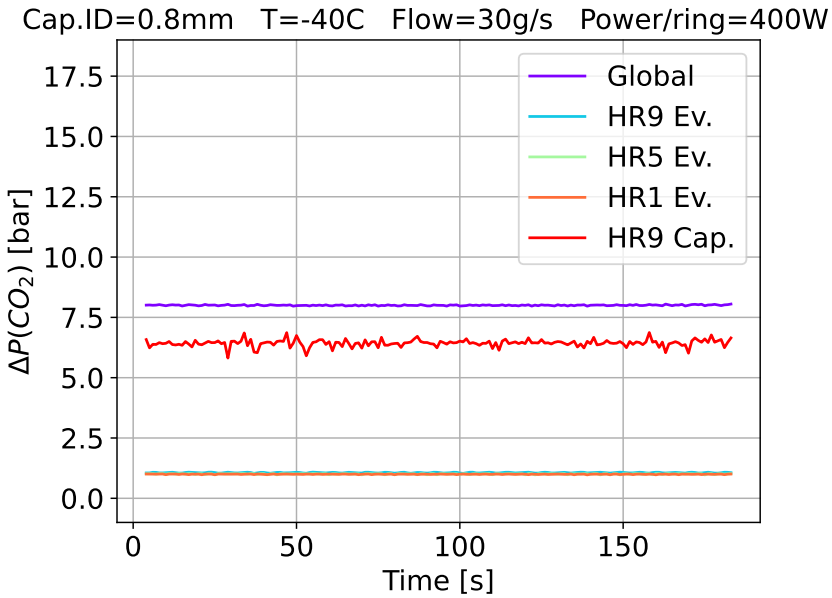




- Plots for $T_{ev} = -40\,°C$ and 30 g/s, using 300 W and 400 W.
- ΔP around 9.5 bar over capillary with ID 0.6 mm and length of 0.225 m.
  - Final ID 0.6 mm lenght should be around 20 cm.
- ΔP for HR1, HR5 and HR9 is the same, despite different capillary shapes (due to space).

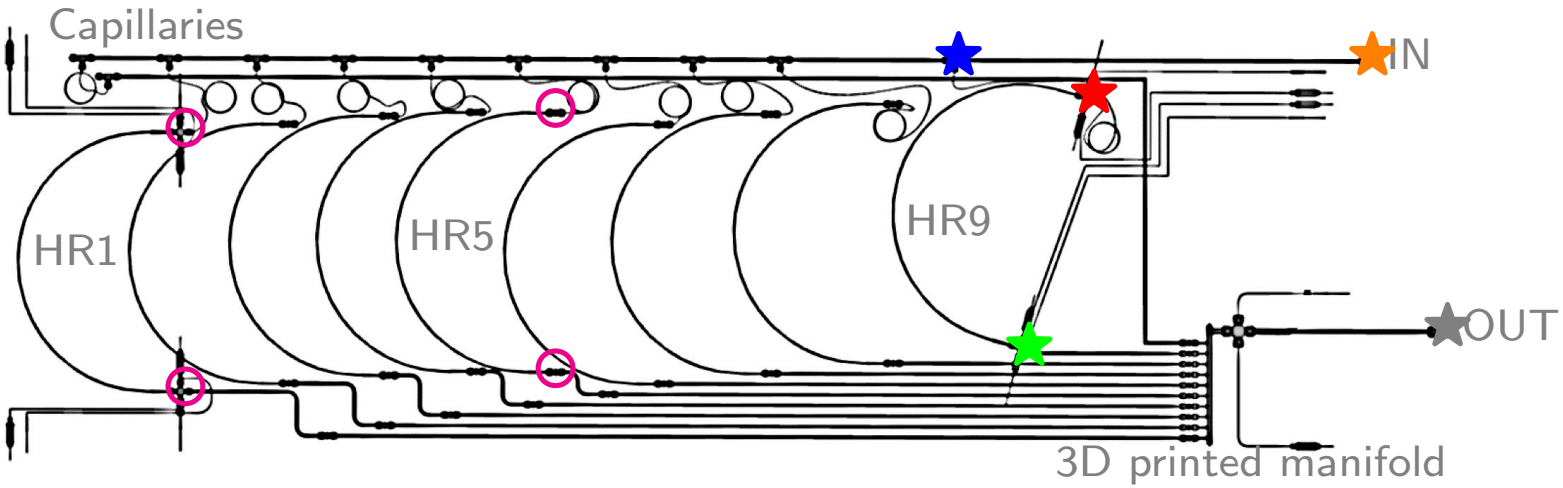
After sizing the capillaries - ID 0.8 mm





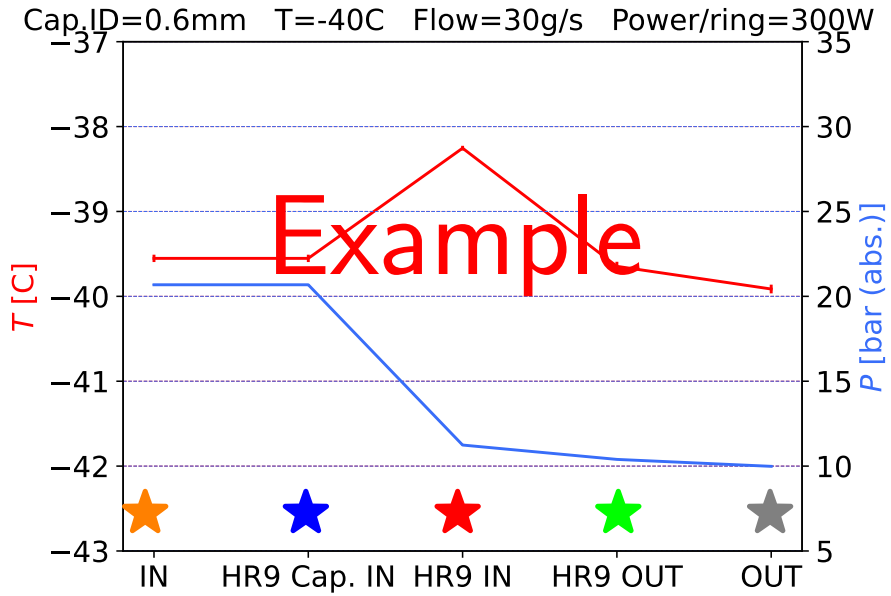
- Plots for $T_{ev} = -40\,°C$ and 30 g/s, using 300 W and 400 W.
- ΔP around 6.5 bar over capillary with ID 0.8 mm and length of 0.9 m.
  - Final ID 0.8 mm lenght should be slightly more than 90 cm.
- ΔP for HR1, HR5 and HR9 is the same, despite different capillary shapes (due to space).

Pressure and temperature along the loops

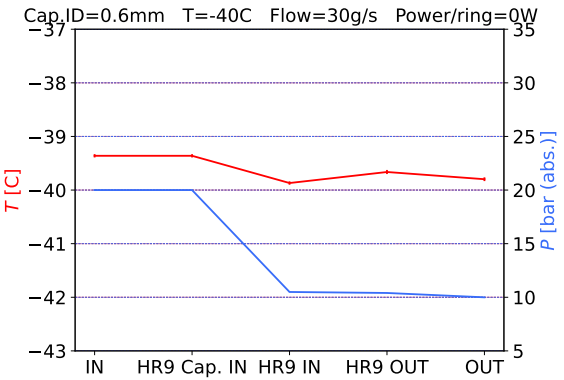


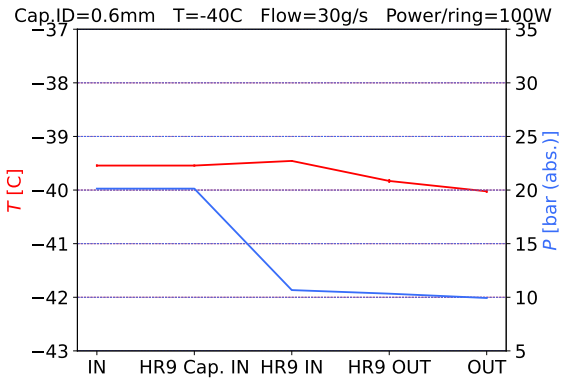
Shown in the following in-flow CO_2 P and T as a function of the position along the mockup:

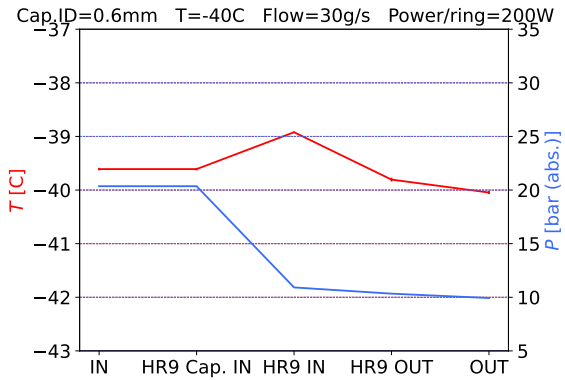
- T, following the scale on the y-axis on the left,
- P, following the scale on the y-axis on the right.

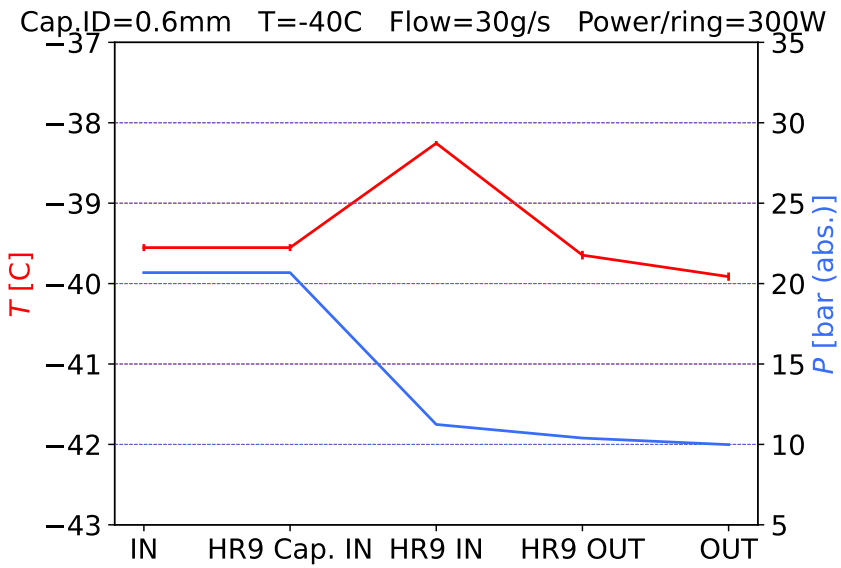


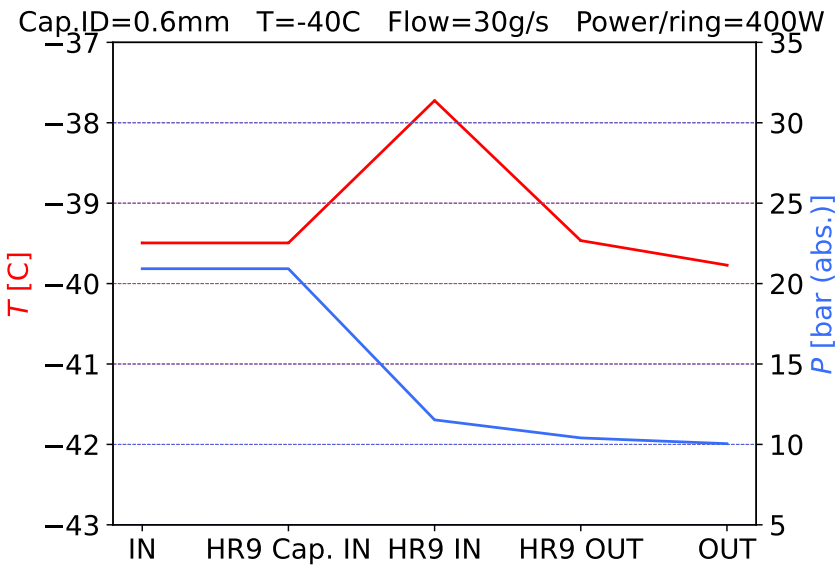
Pressure and temperature - ID 0.6 mm





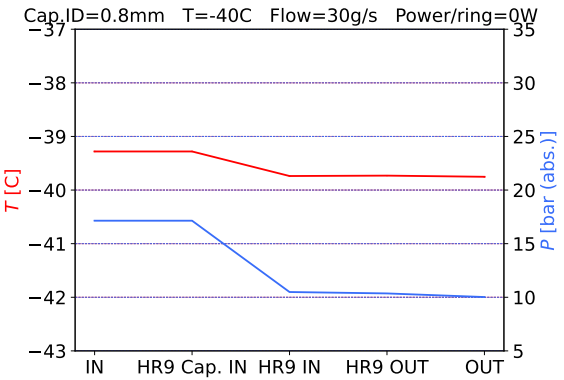


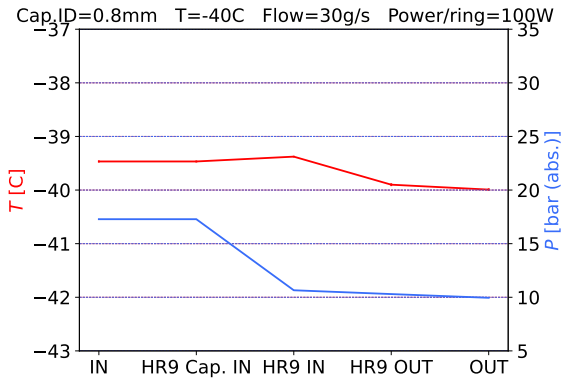


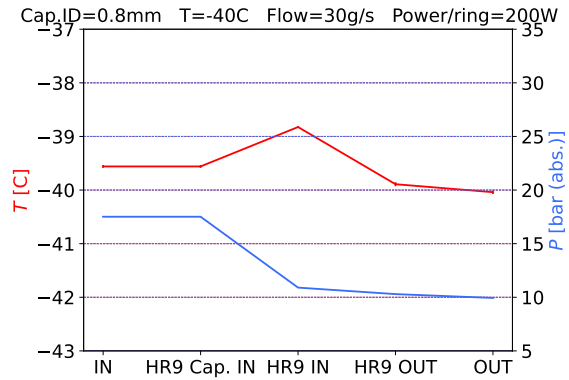


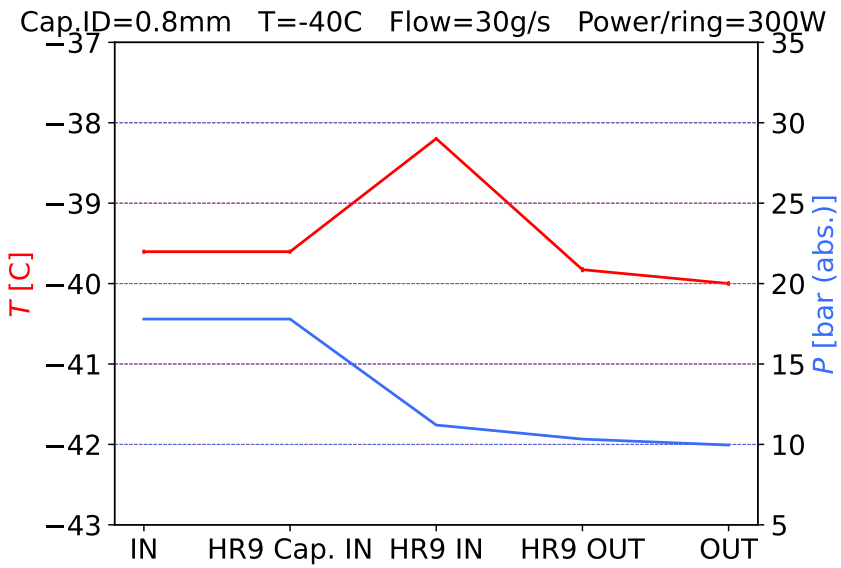
Note: data points are obtained as the average of the measurements over time. The uncertainty is present and it's computed as the standard deviation of the measurements.

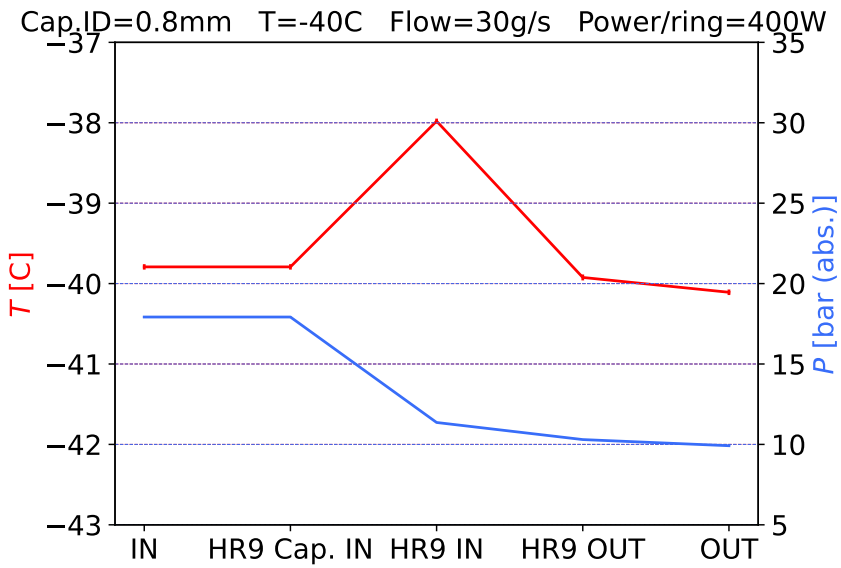
Pressure and temperature - ID 0.8 mm







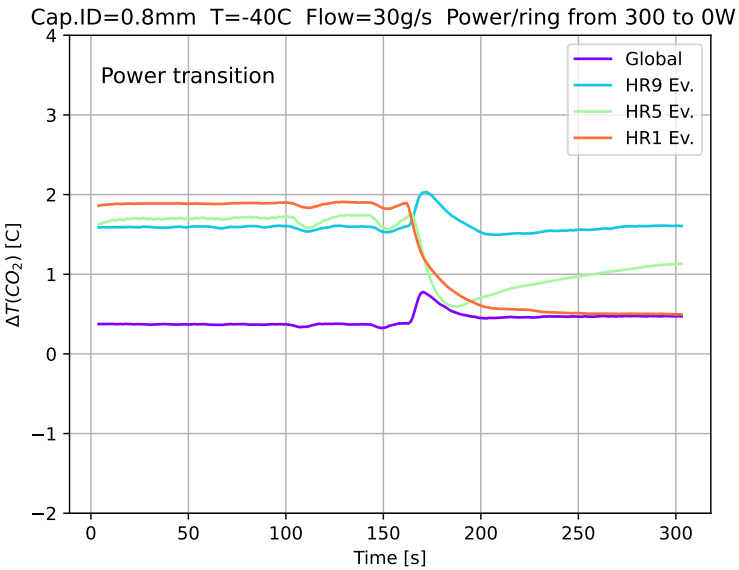


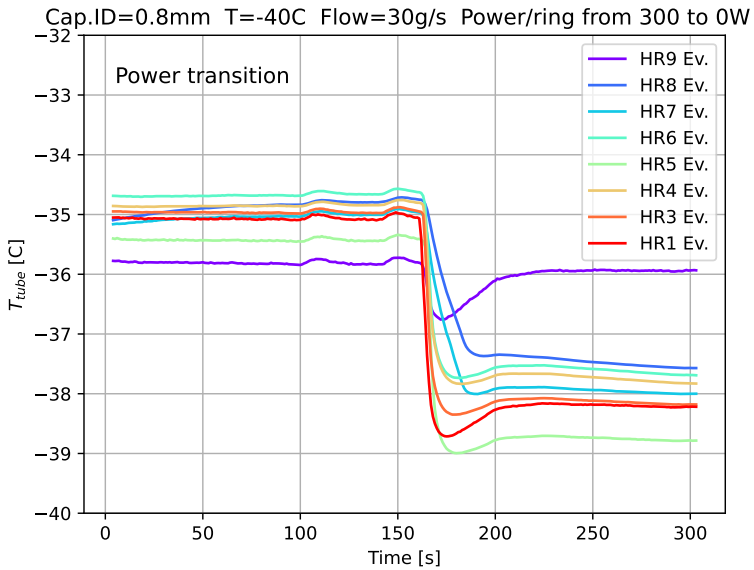


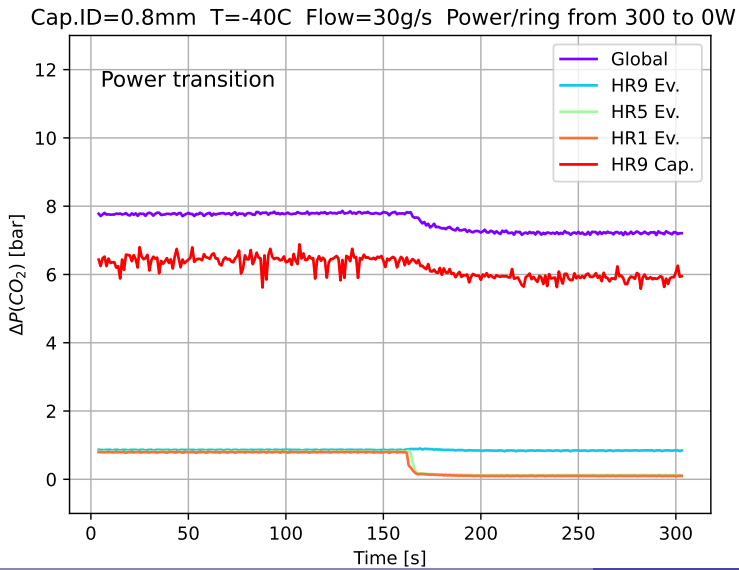
Note: data points are obtained as the average of the measurements over time. The uncertainty is present and it's computed as the standard deviation of the measurements.

Power transitions - Capillaries ID 0.8 mm

Power transition from 300 W to 0 W - ID 0.8 mm

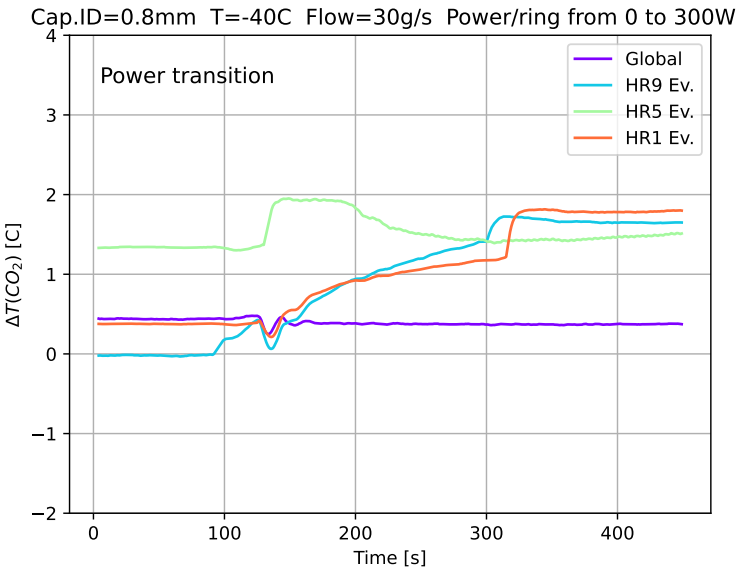


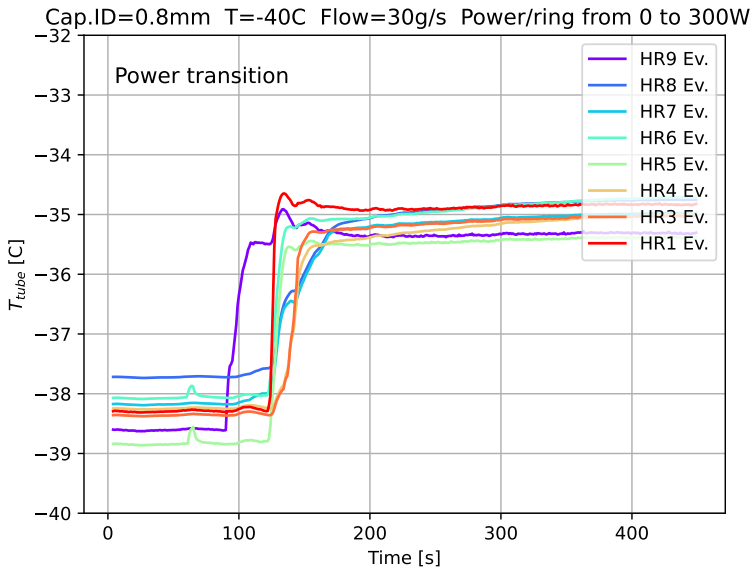


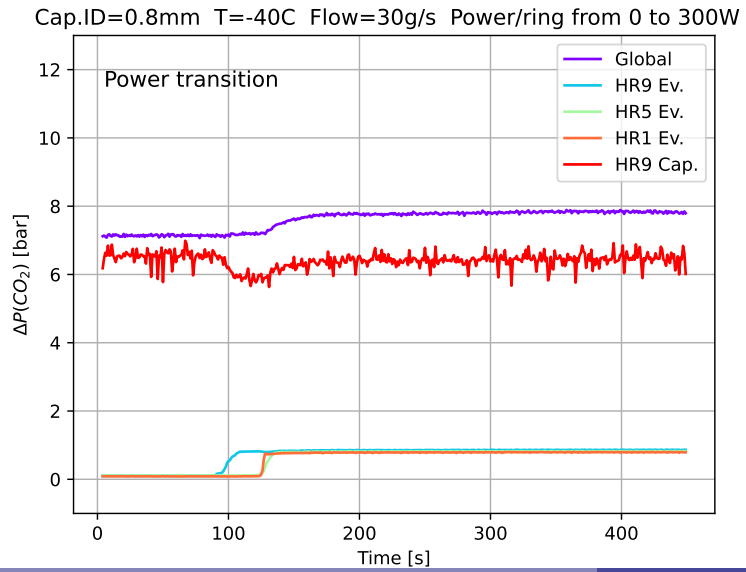


- T_{PP1} −40 °C and flow 30 g/s
- Transitioning from 300 W to 0 W for all evaporators
- ΔT variation within 2 °C
- ΔP variation within 1 bar

Power transition, from 0 W to 300 W - ID 0.8 mm

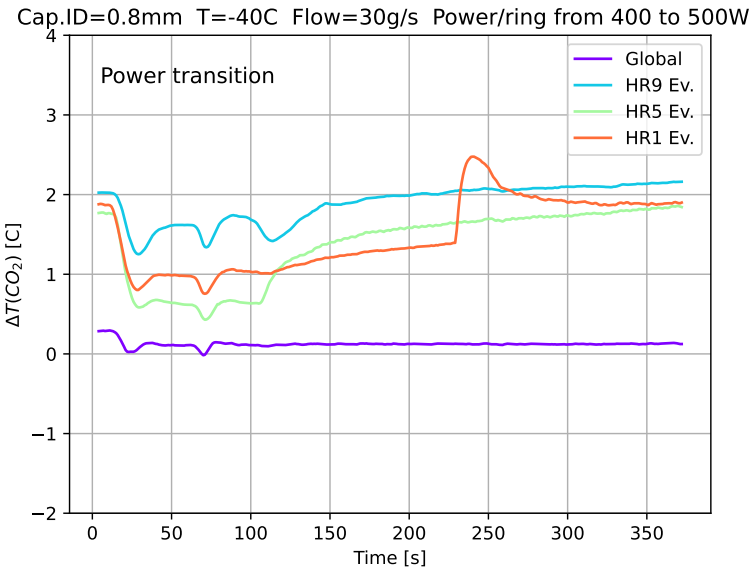


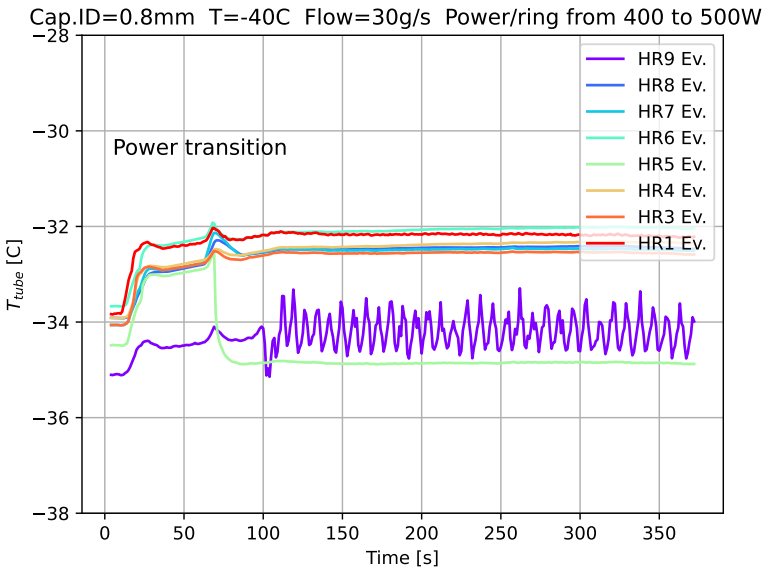


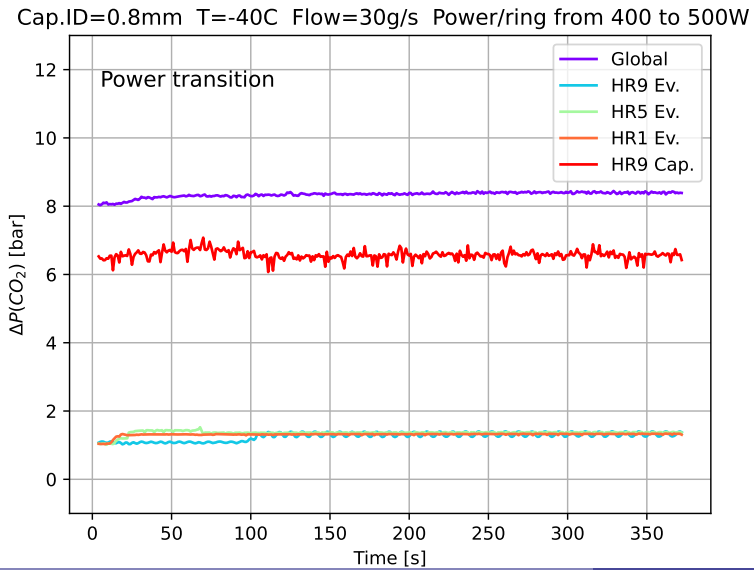


- T_{PP1} −40 °C and flow 30 g/s
- Transitioning from 0 W to 300 W
- ΔT variation within 2 °C
- ΔP variation within 1 bar

Power transition, from 400 W to 500 W - ID 0.8 mm

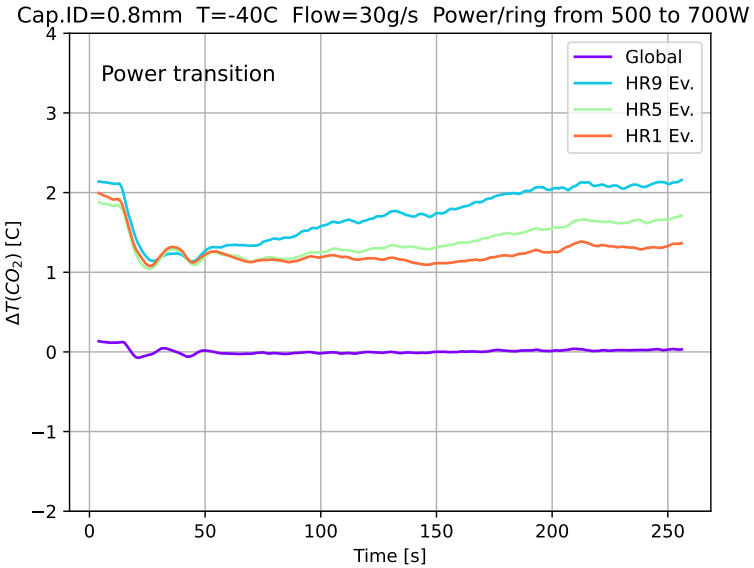


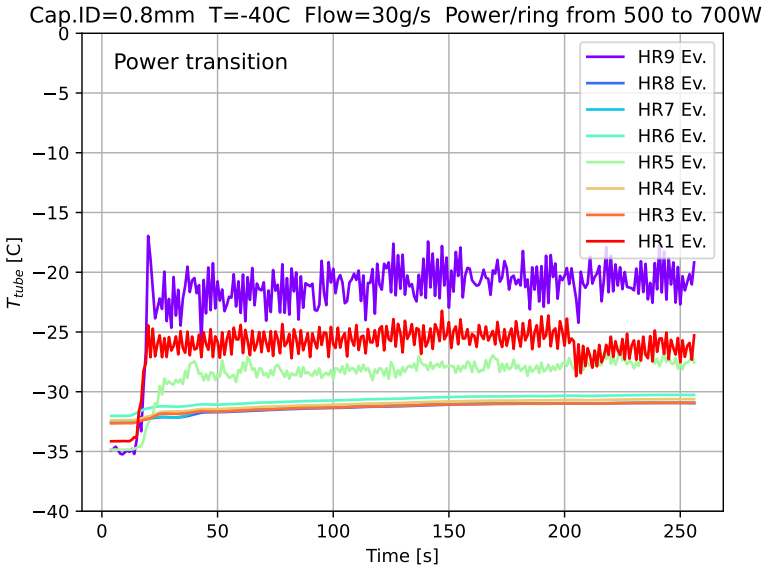


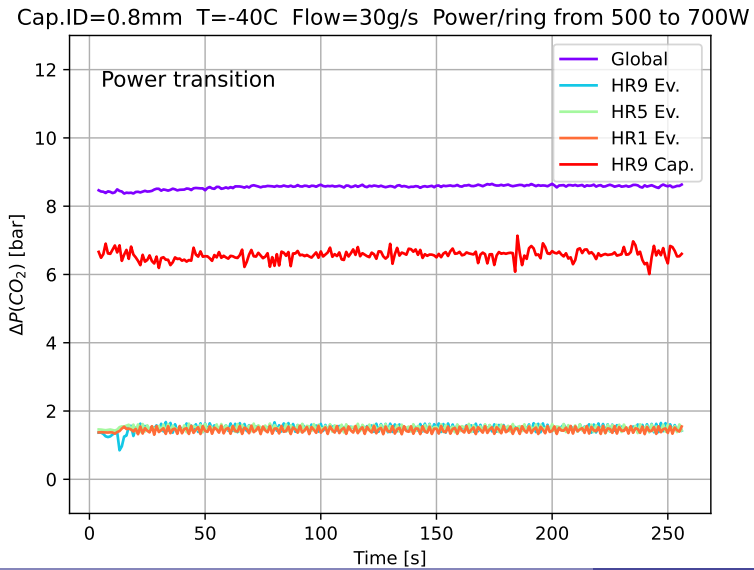


- T_{PP1} −40 °C and flow 30 g/s
- Transitioning from 400 W to 500 W
- ΔT variation within 2 °C
- ΔP variation within 1 bar

Power transition, from 500 W to 700 W - ID 0.8 mm

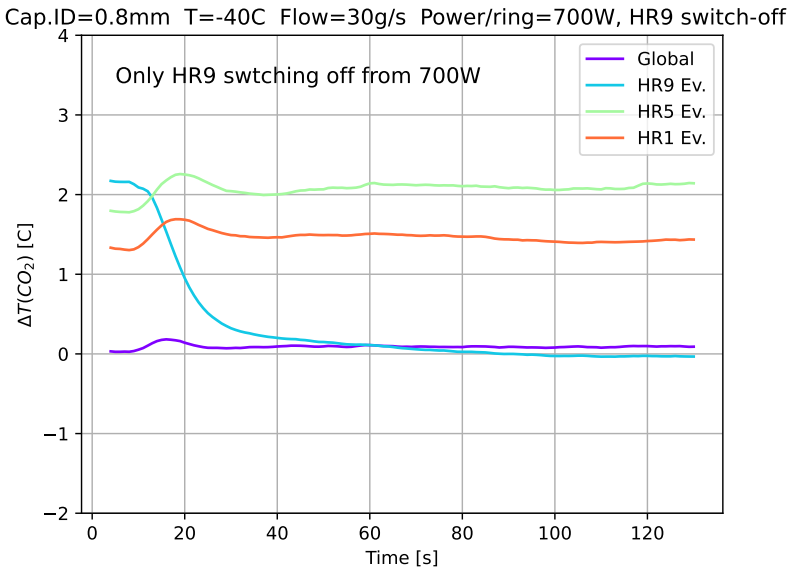


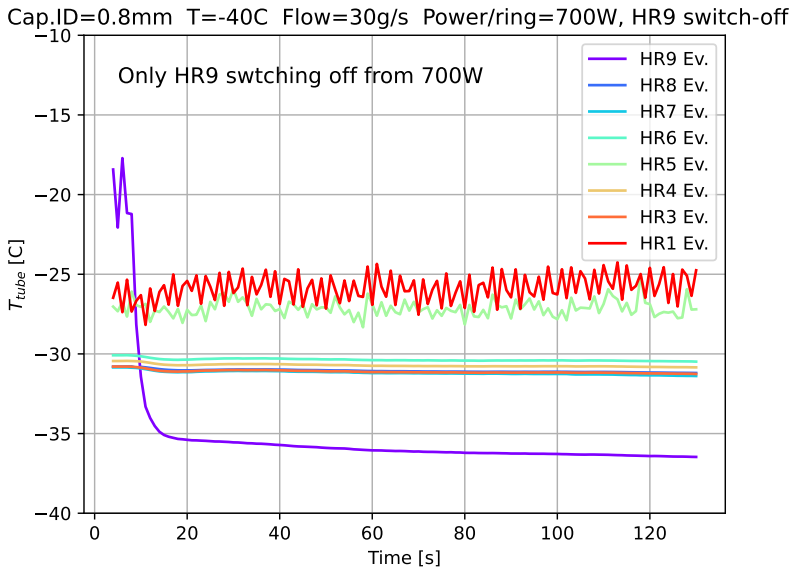


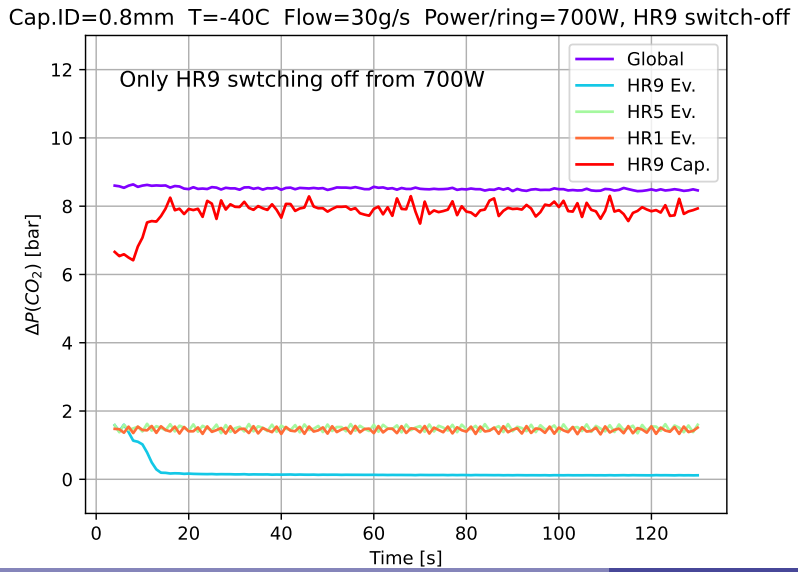


- T_{PP1} −40 °C and flow 30 g/s
- Transitioning from 500 W to 700 W
- ΔT variation within 1.5 °C
- ΔP variation within 1 bar

Power transition for HR9 only - ID 0.8 mm



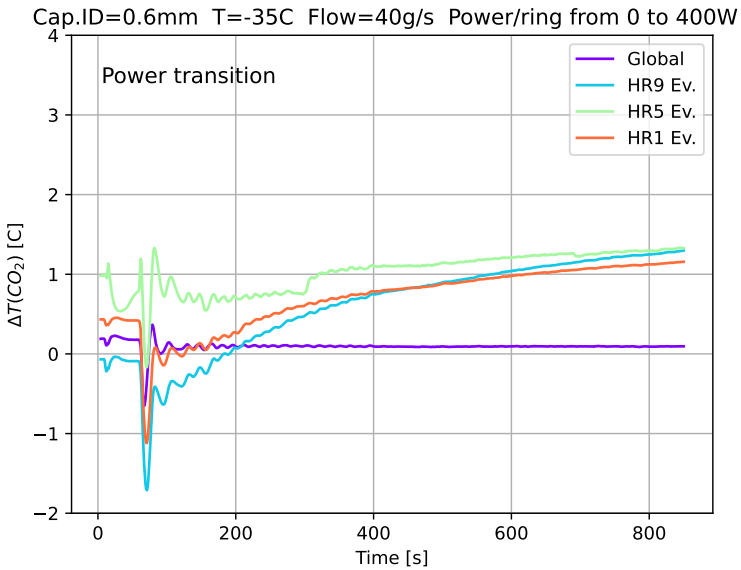


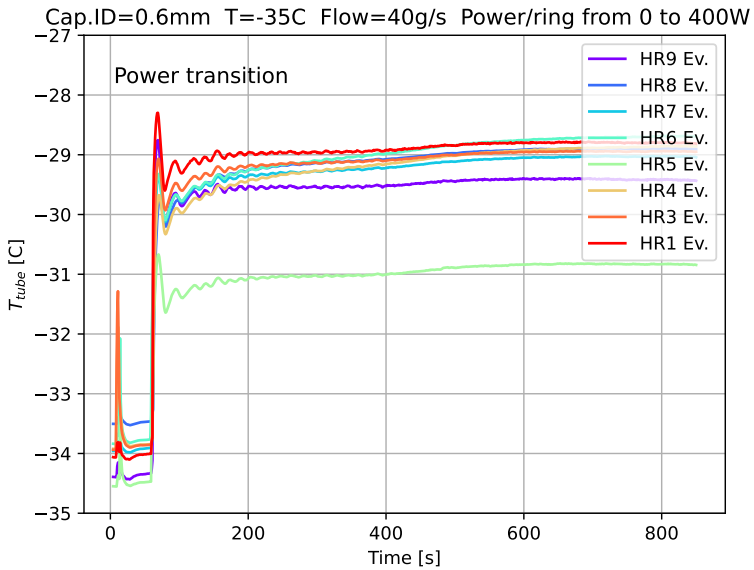


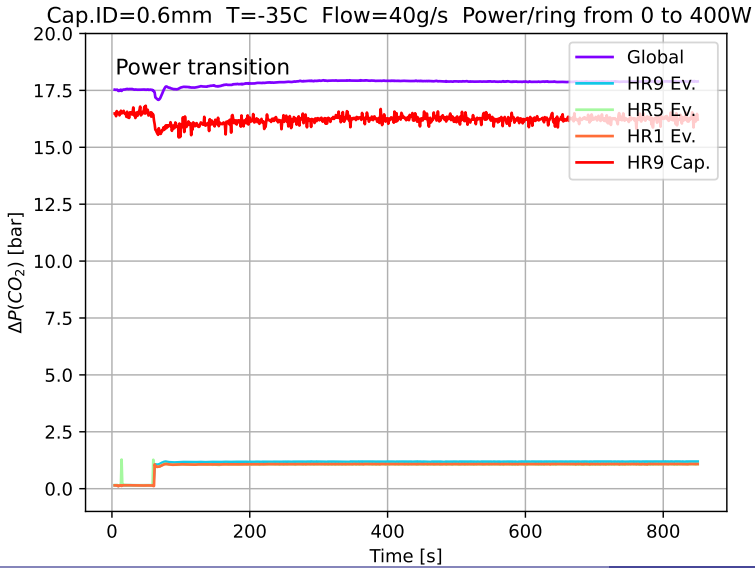
- T_{PP1} −40 °C and flow 30 g/s
- Transitioning from 700 W to 0 W for HR9 only, other evaporators at 700 W
- ΔT variation within 2.5 °C
- ΔP variation within 2 bar

Power transitions - Capillaries ID 0.6 mm

Power transition from 0 W to 400 W - ID 0.6 mm

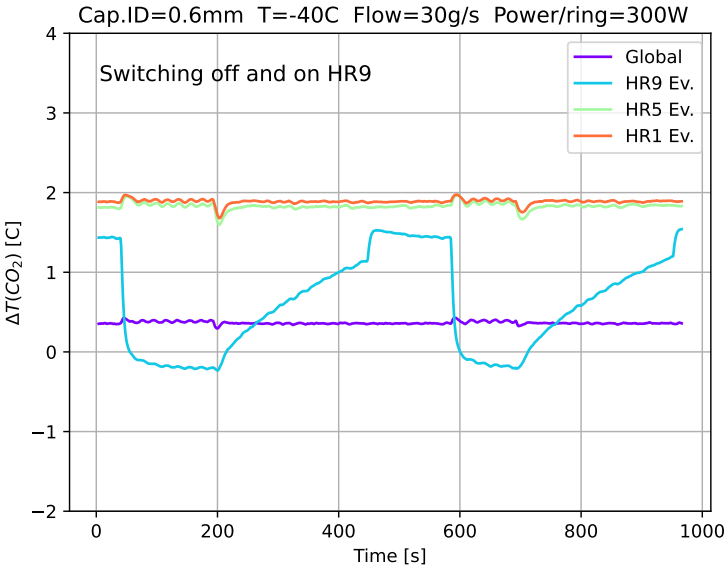


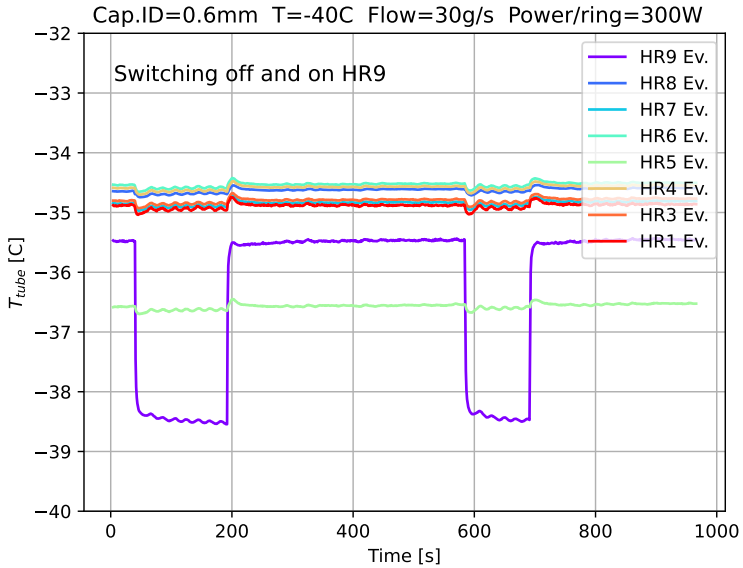


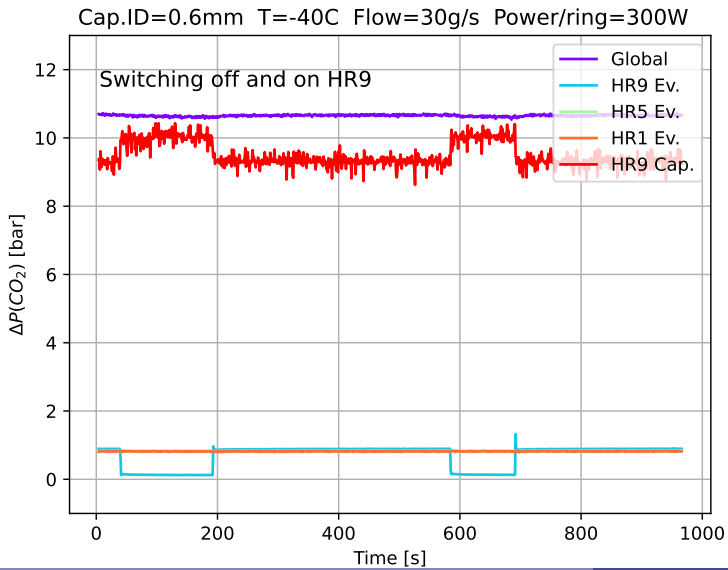


- T_{PP1} −35 °C and flow 40 g/s
- Transitioning from 0 W to 400 W
- ΔT variation within 2.5 °C
- ΔP variation within 1 bar

Power switch on HR9 only - ID 0.6 mm

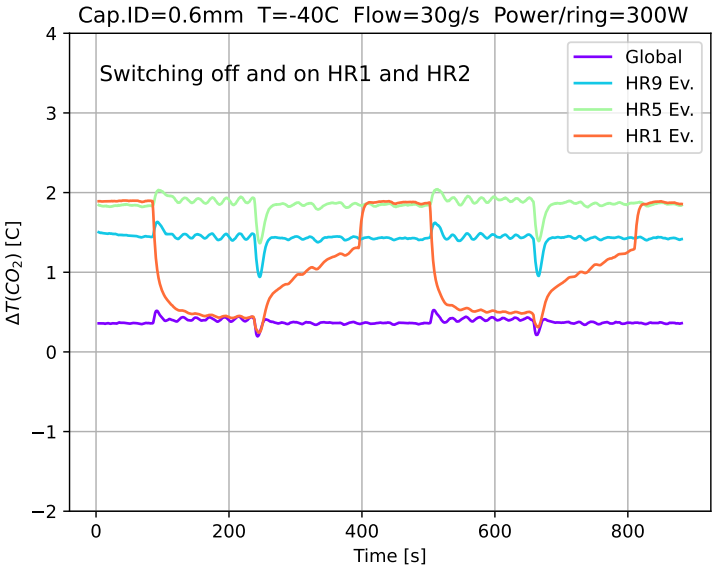


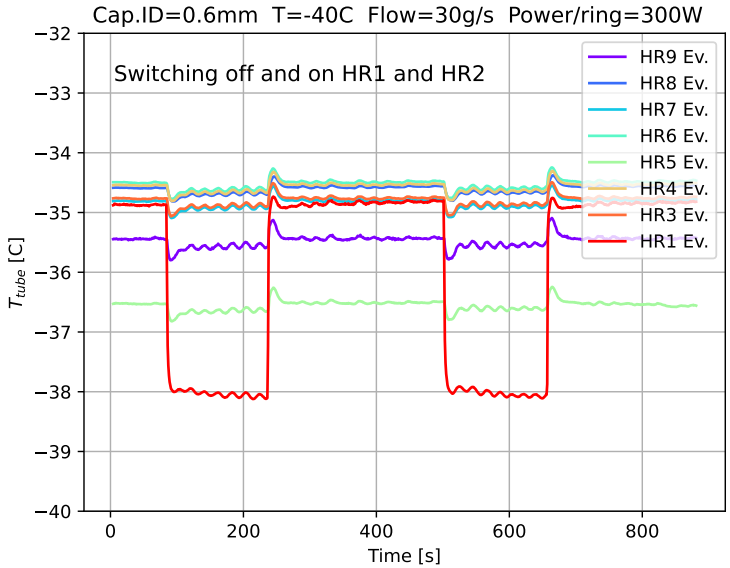


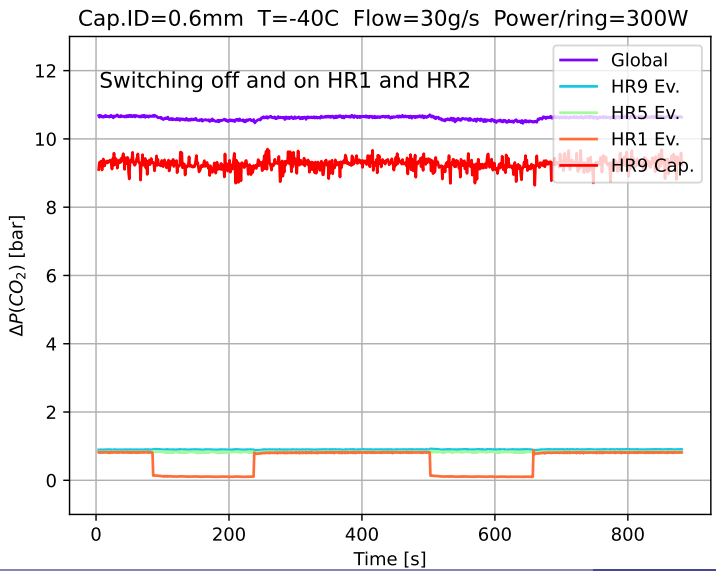


- T_{PP1} −40 °C and flow 30 g/s
- Switching off and on HR9 only, while other evaporators are at 300 W
- ΔT variation within 2 °C
- ΔP variation within 1 bar

Power switch on HR1 and HR2 - ID 0.6 mm







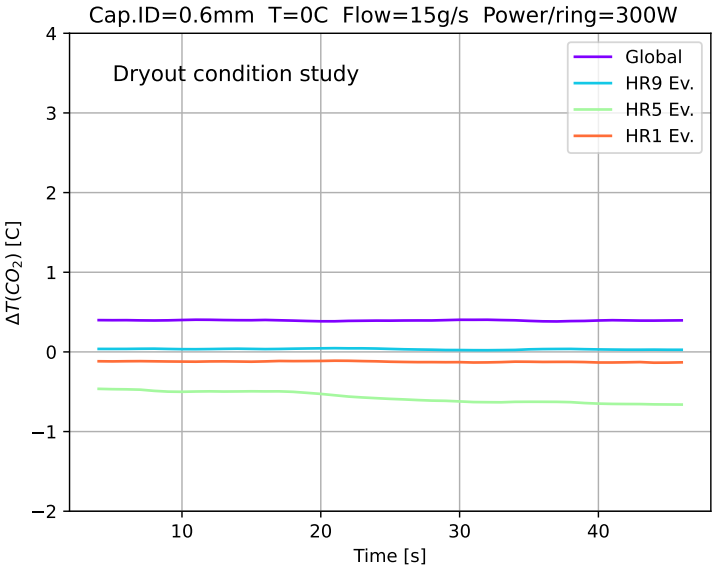
- T_{PP1} −40 °C and flow 30 g/s
- Switching off and on HR1 and HR2 only, while other evaporators are at 300 W
- T_{tube} for HR2 not available
- ΔT variation within 2 °C
- ΔP variation within 1 bar

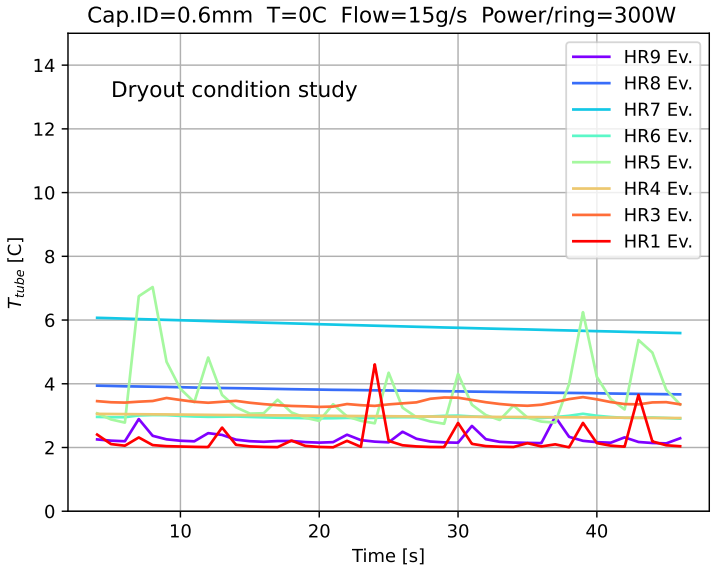
Dry-out studies - Capillaries ID 0.6 mm

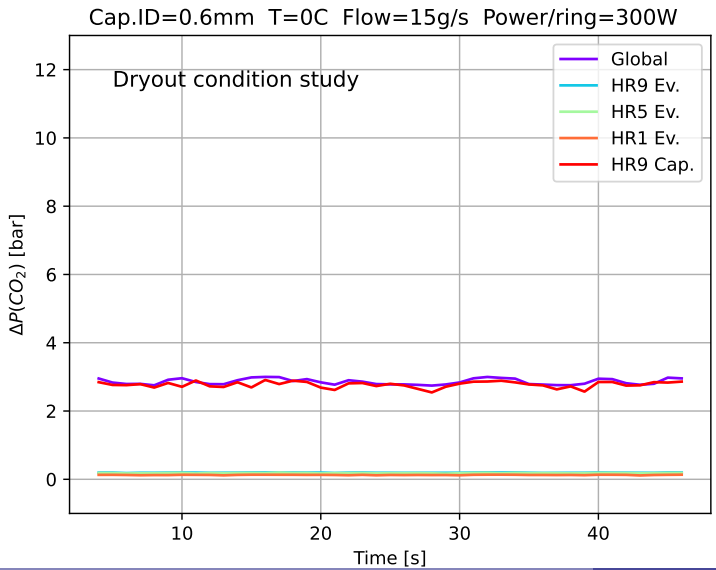
Dry-out studies

- Measurements decreasing the flow to detect dry-out conditions
- Using nominal power, 300W/HR
- PP1 temperature of 0 °C, –20 °C and –40 °C.
- Flow transition from 30 g/s to 15 g/s (10 g/s in one case), which was found to be the value that triggers the dry-out in this condition
- Plots for ΔP, ΔT and T_{tube} at the 15 g/s (or 10 g/s) condition are reported, for each temperature

Dry-out condition at 0 °C - ID 0.6 mm

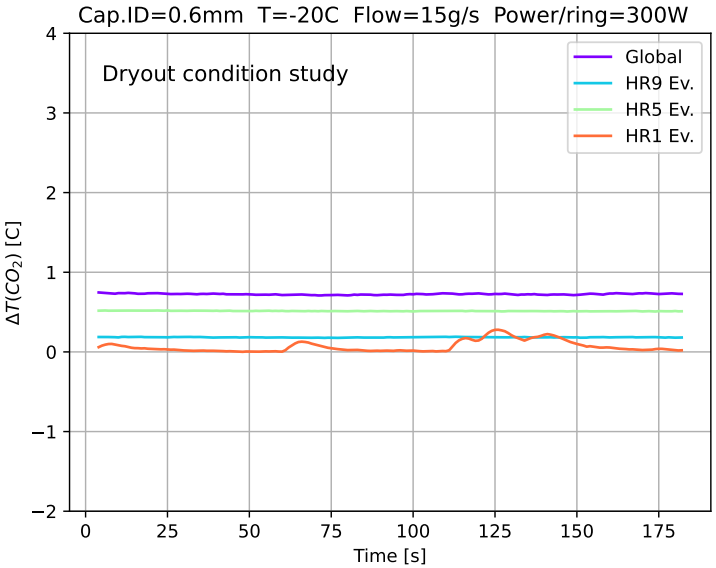


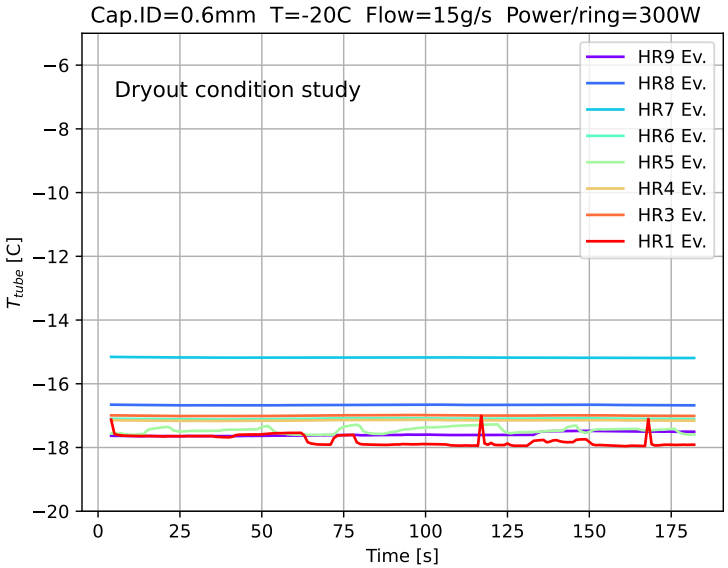


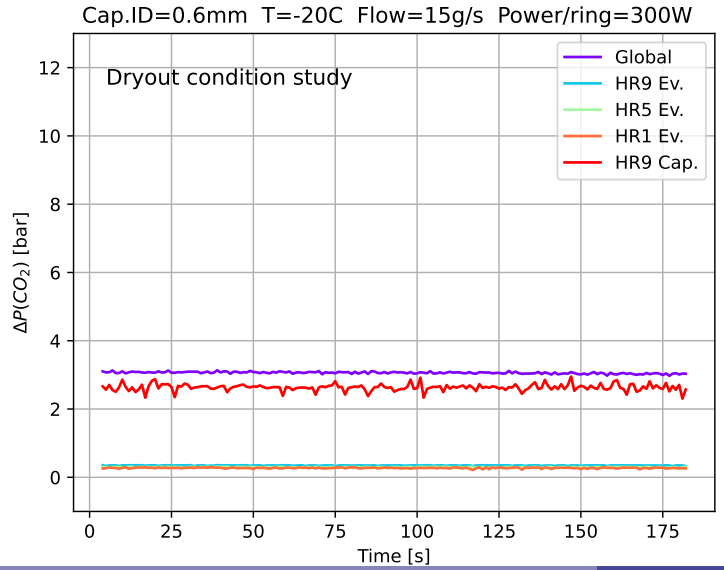


- T_{PP1} 0 °C and 300 W power applied to each evaporator
- Dry-out reached around 15 g/s

Dry-out condition at −20 °C - ID 0.6 mm

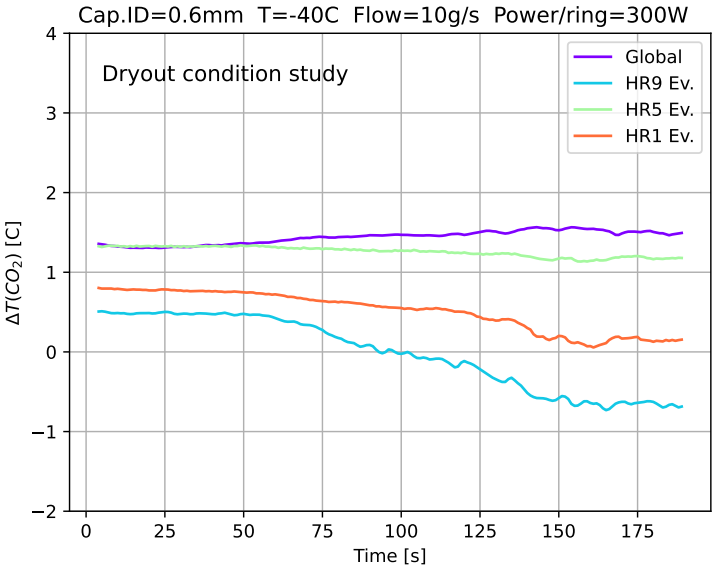


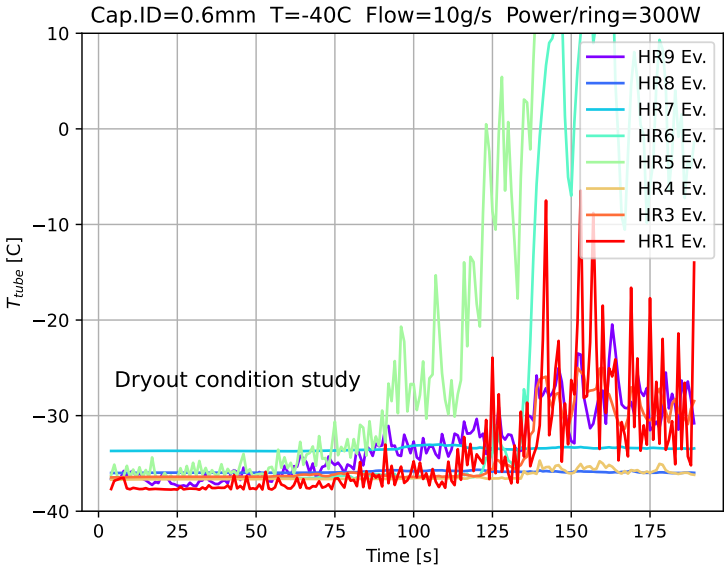


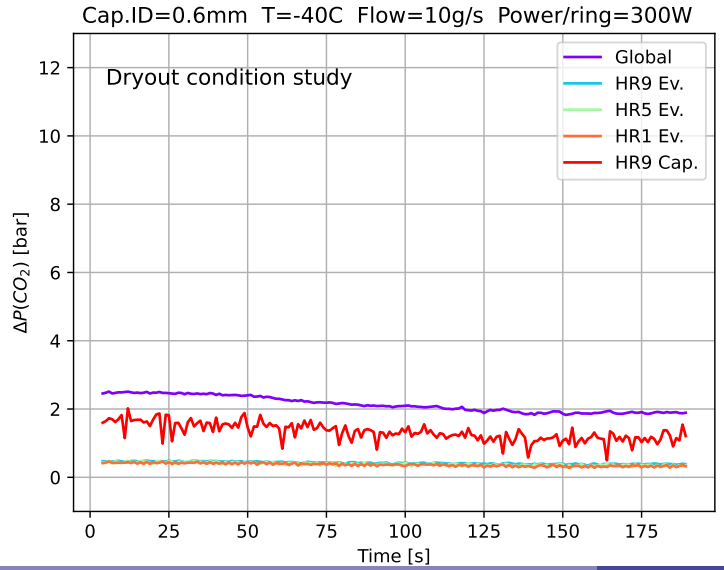


- T_{PP1} −20 °C and 300 W power applied to each evaporator
- Dry-out reached around 15 g/s

Dry-out condition at −40 °C - ID 0.6 mm







- T_{PP1} −40 °C and 300 W power applied to each evaporator
- Dry-out starting around 19 g/s for few HR (HR5 and HR9), decreasing flow until 10 g/s