Microchannel cooling techniques for the LHCb VELO Upgrade

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LHCb VELO Upgrade and CERN PH-DT groups

CERN

26th International Workshop on Vertex Detectors

Las Caldas, Asturias, Spain

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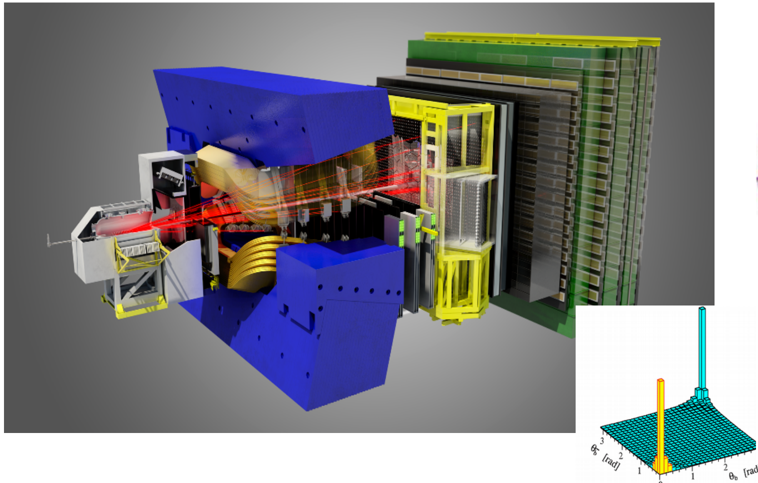
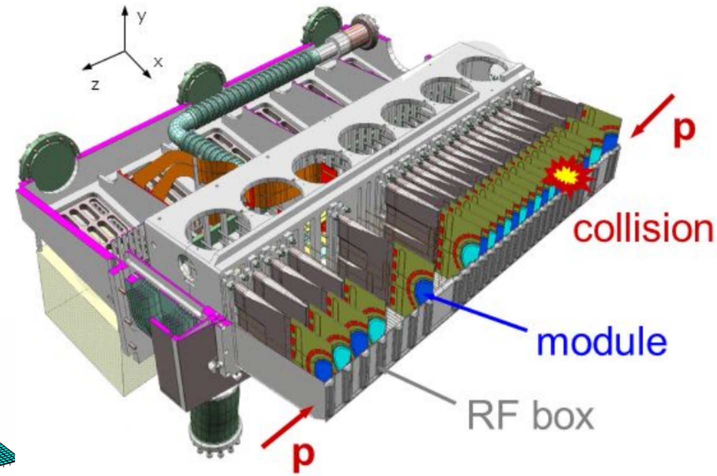
Summary

- Introduction
- Microchannels
  - Design
  - Cooling performance
  - Attachment of the fluidic connector
  - Reliability tests of the attachment
  - Fluidic characterization
- Back-up alternatives
  - Tubes embedded in ceramics
  - Titanium 3D printing
- Conclusion

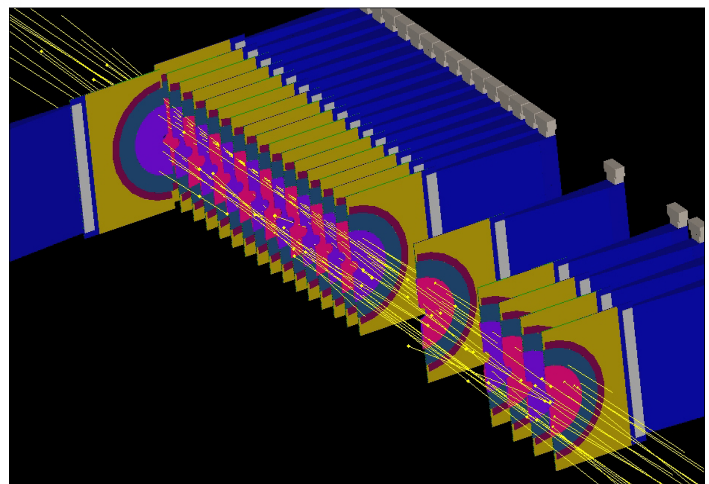
LHCb experiment

[Performance of the LHCb Vertex Locator - arXiv:1405.7808]





LHCb experiment:
- One of the 4 major experiments at LHC
- Forward spectrometer designed to measure CP violation, study rare decays of c and b hadrons and search for new physics.

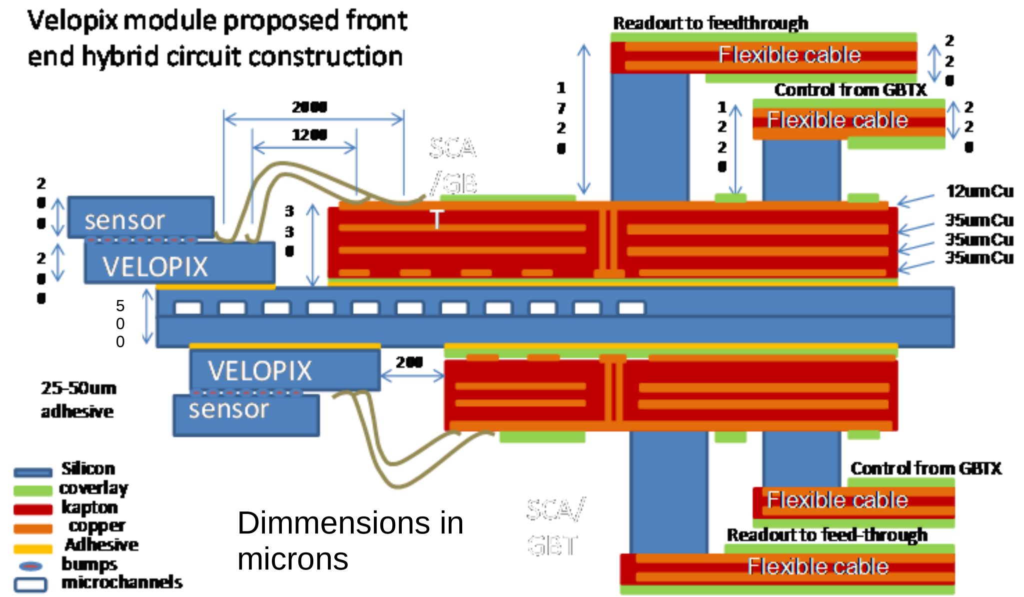


Current VELO
- Subdetector located around the p-p collisions
- Responsible for vertex and track reconstruction
- 88 Si-strip sensors surrounding the interaction point
- Modules are moved away during the beam injection
- Excellent impact parameter resolution (down to 11.6 μm)
- Excellent single hit resolution ~4 μm
- Total power dissipated is ~16.5W/module

More details at Emma's and Edgar's talks

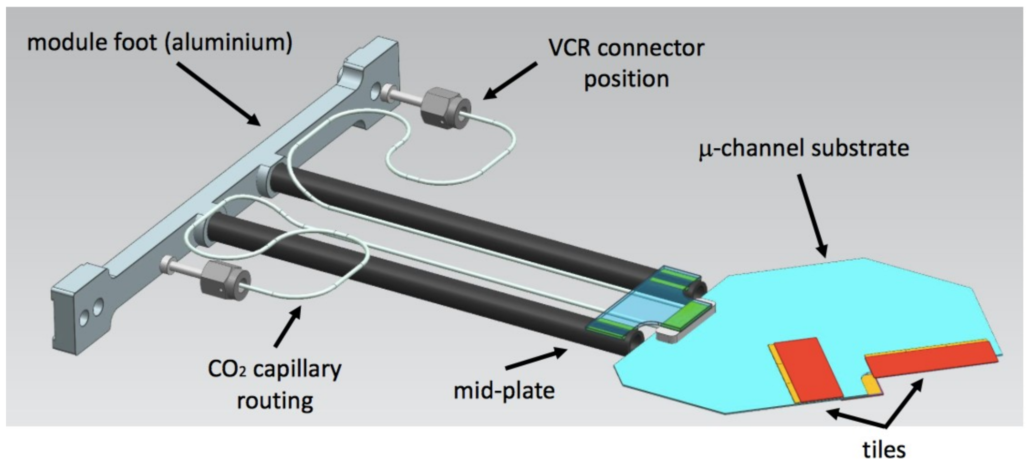
Key features for the upgrade

- The closest distance to LHC beam will be 5.1 mm (down from 8.2 mm)
- Very high ($8x10^{15}$ MeV n_{eq}/cm^2 for 50 fb^{-1}) & non-uniform radiation ($\sim r^{-2}$)
- Huge data bandwidth: up to ~15 Gbit/s for central ASICs and 2.9 Tbit/s in total

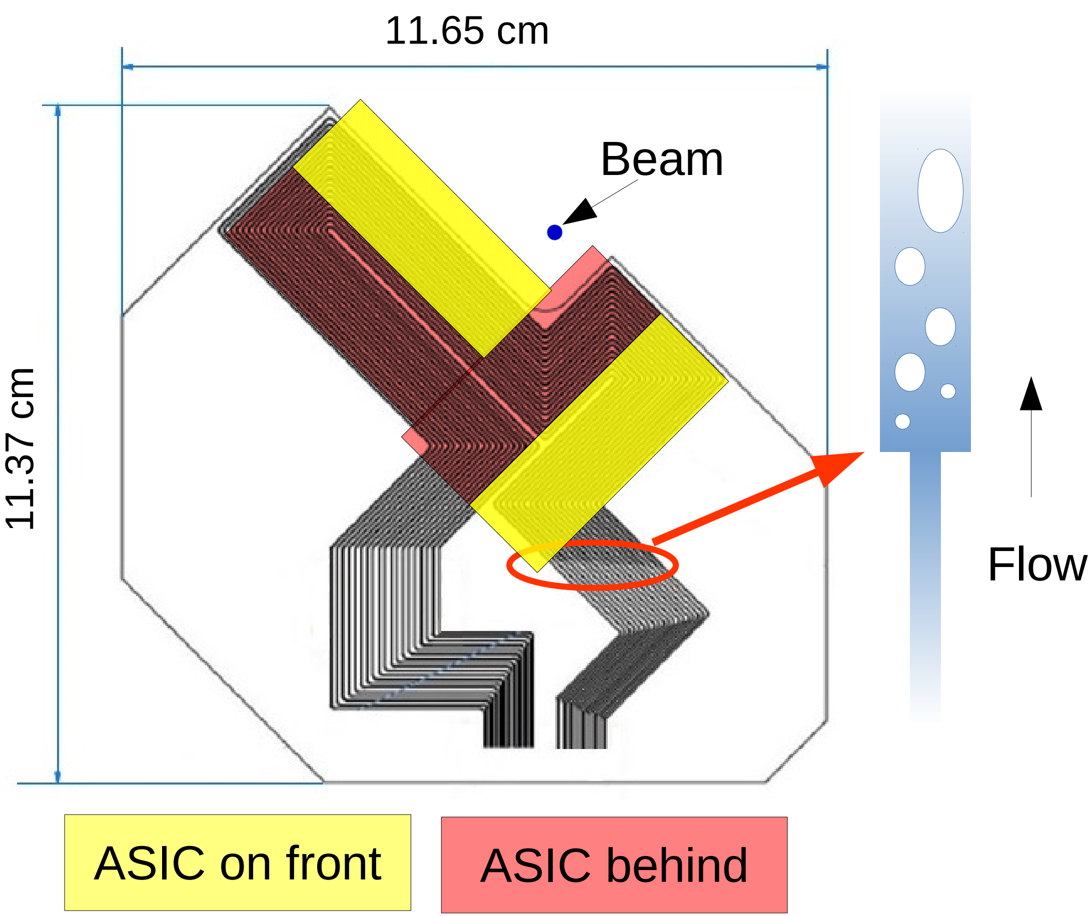


Cooling requirements:

- Sensor temperature < -20 °C (CO_2 @ -35°C)
- Operates under vacuum (Secondary vacuum)
- Total maximum power dissipation per module ~30 W
- Minimum material: cooling substrate is retracted by 5 mm at the inner region



Microchannels etched in silicon

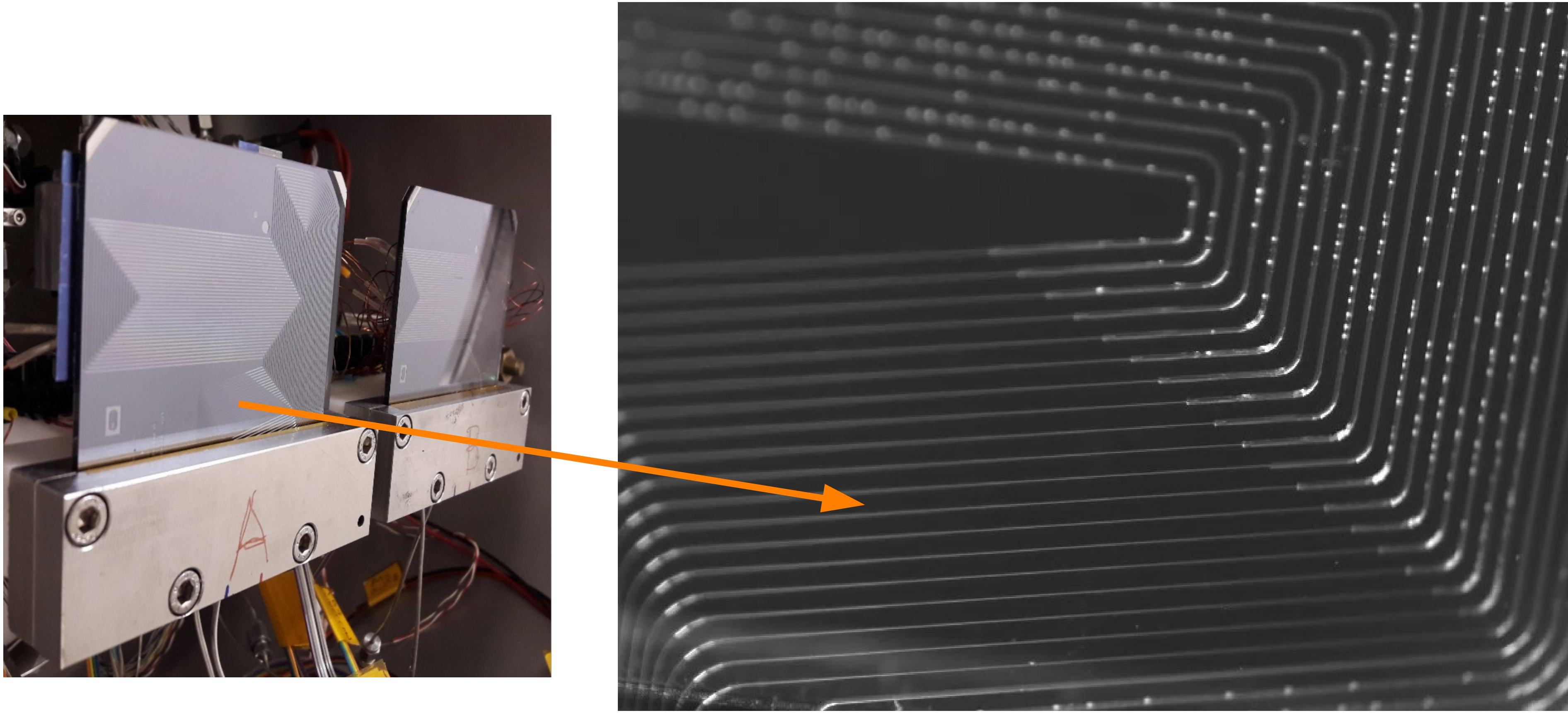


- Narrow restrictions at the entrance
  - 60 µm x 60 µm (40 mm long)
  - Dominant pressure drop
  - Prevents instabilities among the channels

- Main channels
  - 120 µm x 200 µm (~260 mm in average)
  - Heat provided by electronics is absorbed by the CO_2 changing the ratio of gas/liquid

- The sudden increase in cross section between the restriction and the main channels triggers the boiling

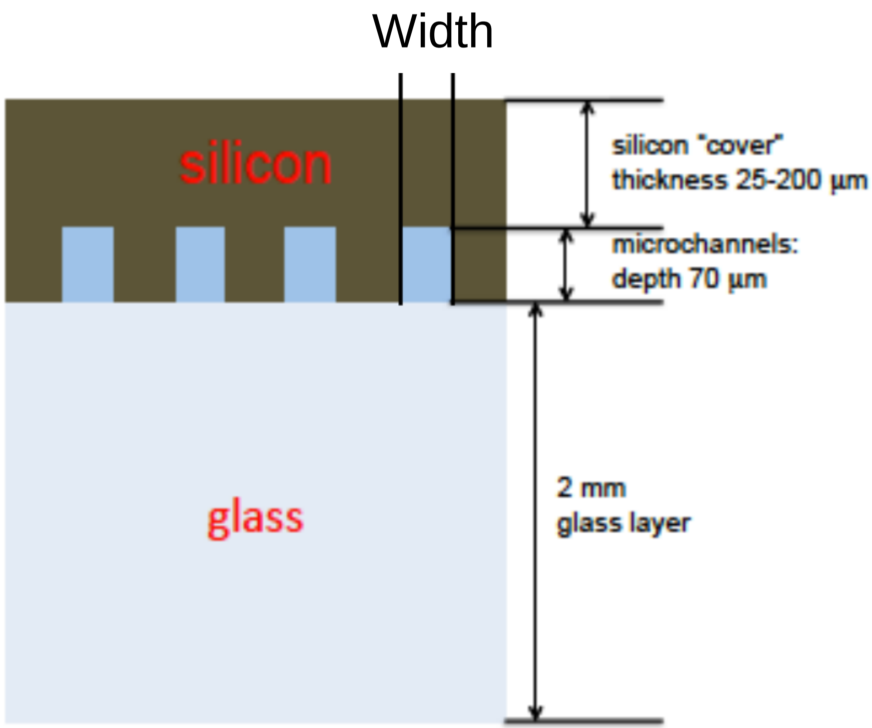
CO_2 boiling inside micro-channels

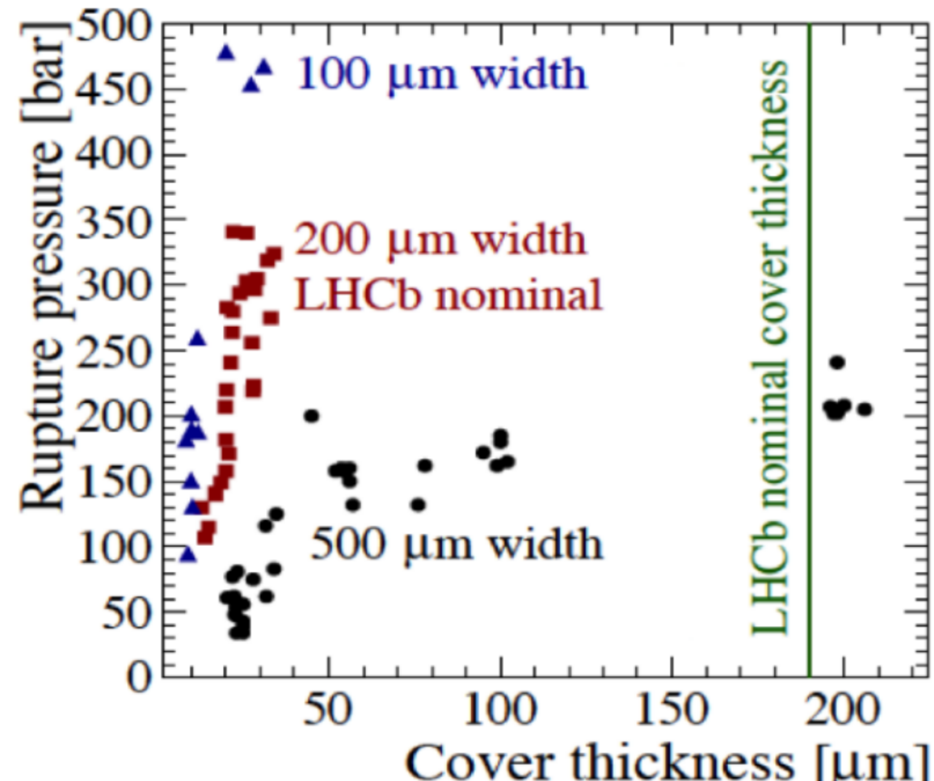


Nice video in the following link!

Resistance to high pressure

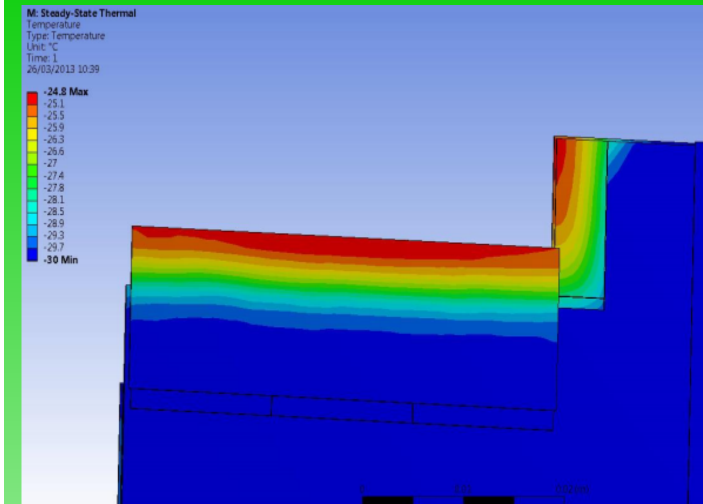
At room temperature, the saturation pressure of the CO_2 is around 65 bar.
For safety reasons, the system is validated to 186 bar.





Cooling performance

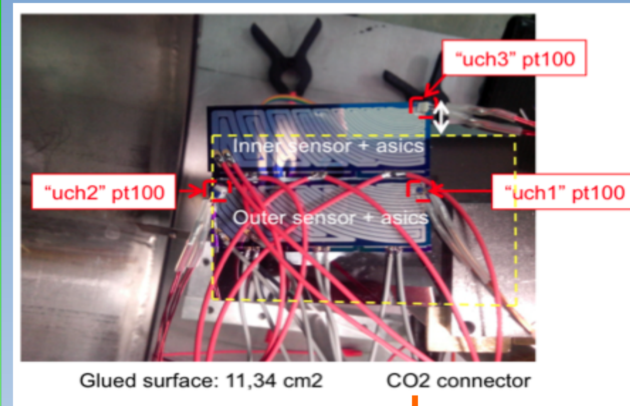
Simulation

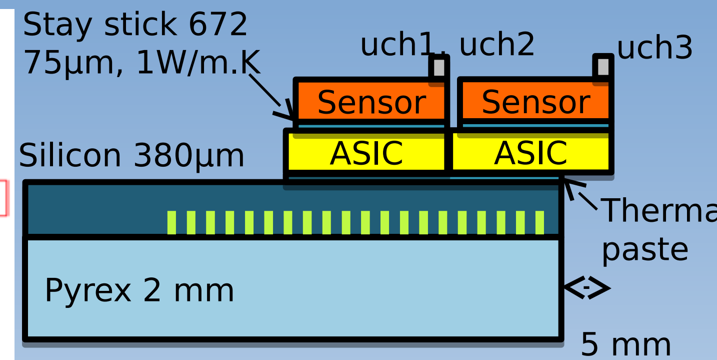


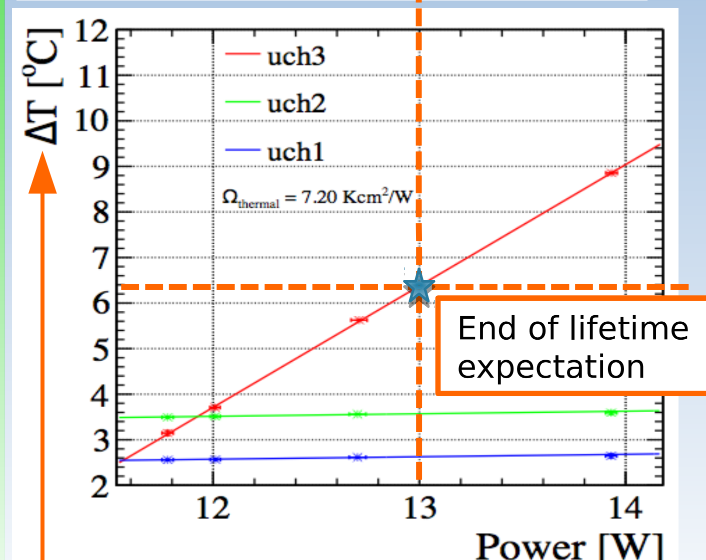
ANSYS simulation:

- 3W/ASIC (36W/module)
- No power consumption on the sensors
- CO_2 at -30˚C
- 100 µm stycast® 8550 FT + catalyst 9 (1.25W/mK)
- ΔT ~ 5˚C (Due to the 5 mm overhang)

Experimental Test





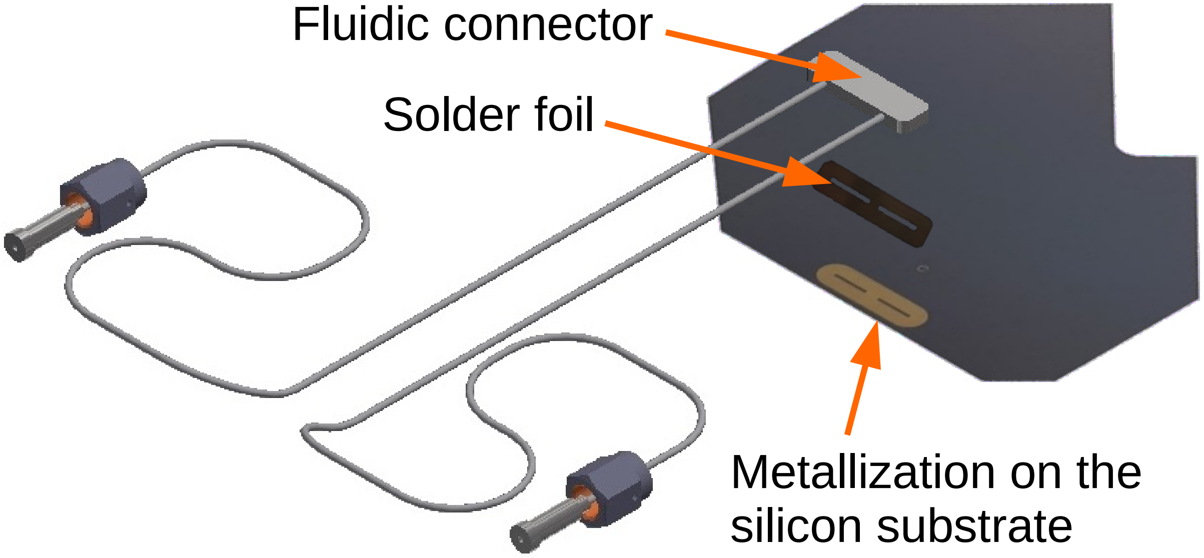


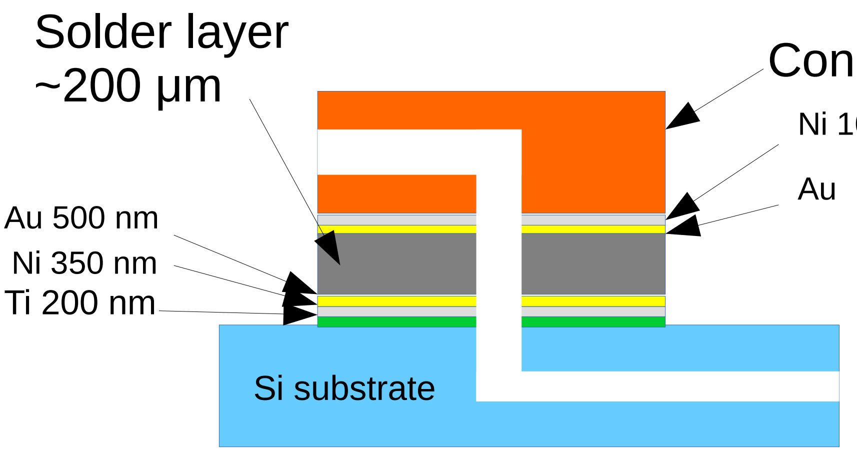
The power dissipation of half of a module was simulated:
→ ~ 11.5 W on the 6 ASIC mockups
→ 1.5 W on the innermost sensor mockup

Max ΔT ~ 6.5 ºC for the end of lifetime expectation

ΔT with respect to the output CO_2 temperature

Attachment of the fluidic connector

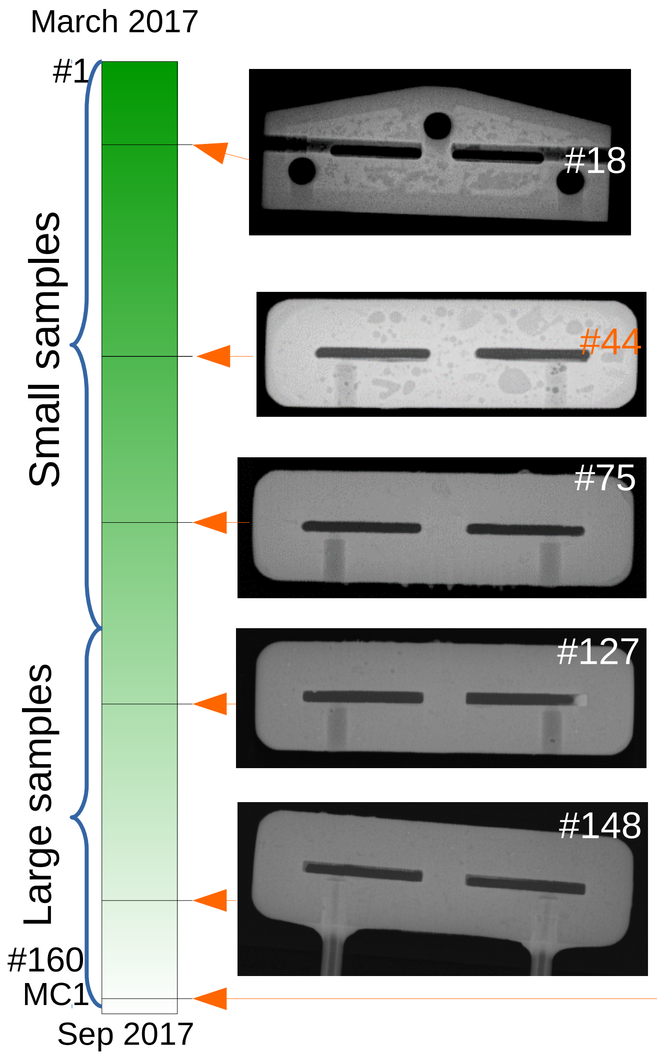




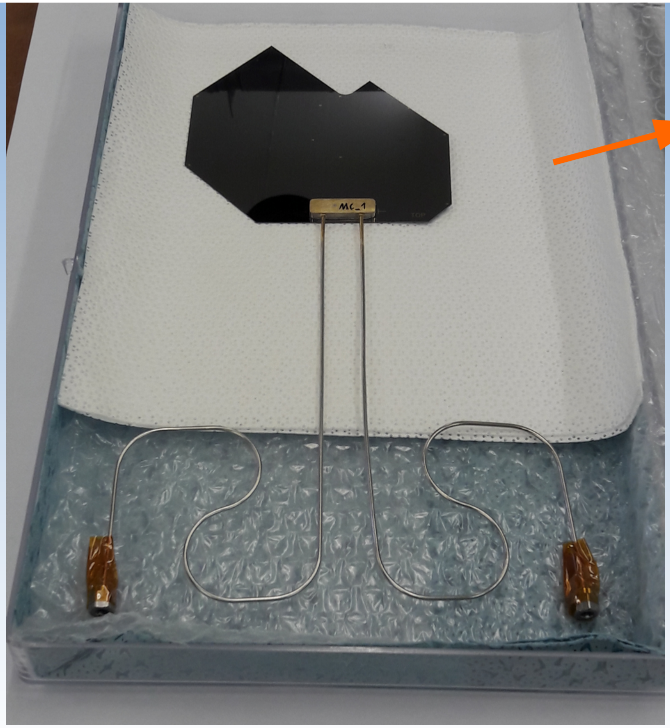
Challenges involved:

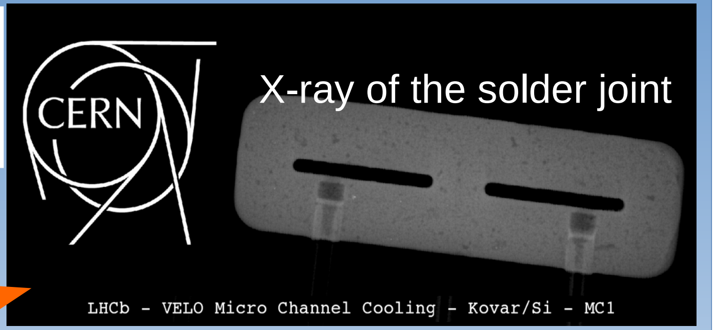
- Leak tight (modules are in the secondary vacuum)
- Planarity
- Voids on the solder layer
- No flux
- High pressure (up to 186 bar)

Attachment of the fluidic connector

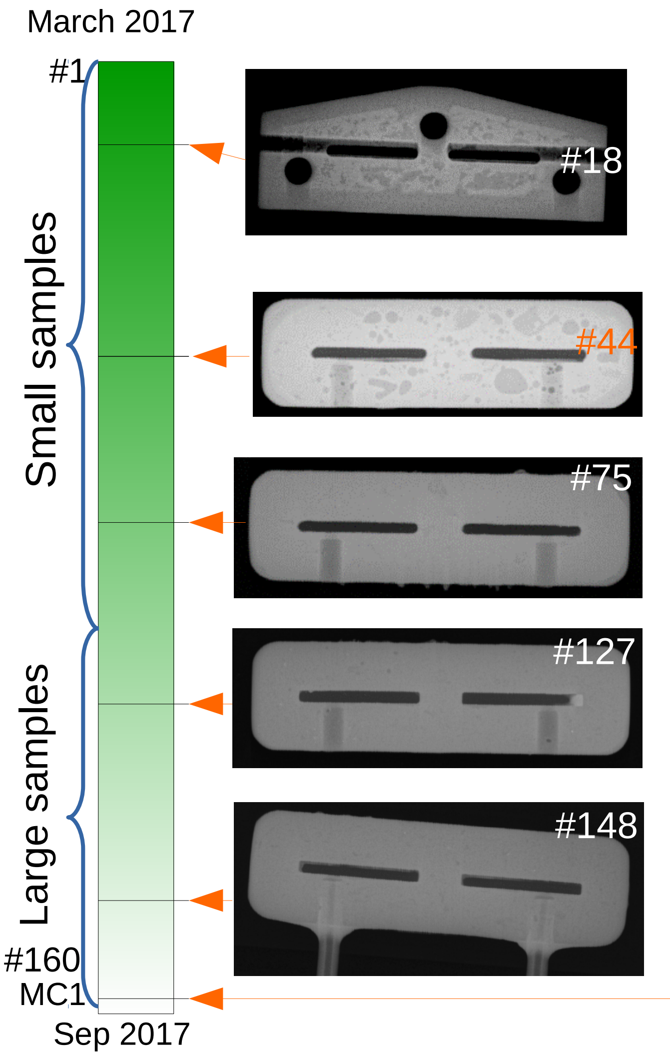


First microchannels soldered on September 1st 2017





Attachment of the fluidic connector



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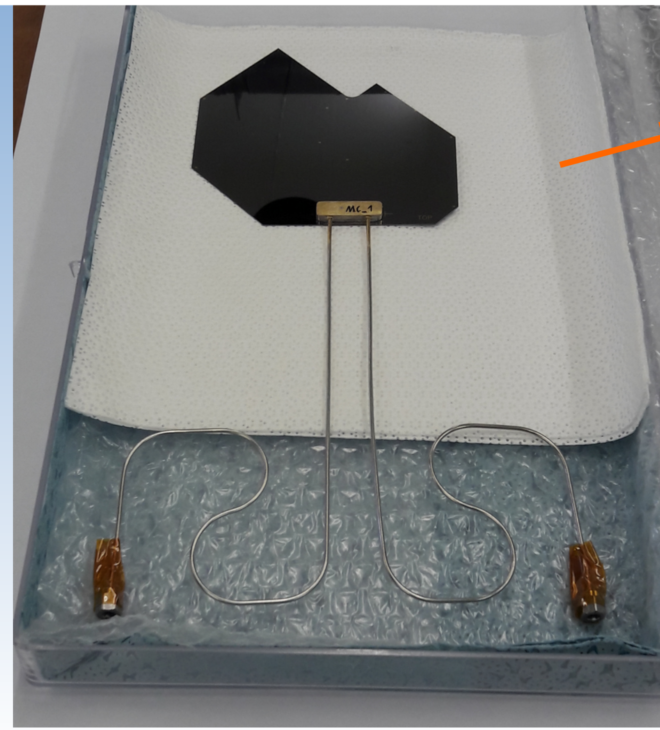
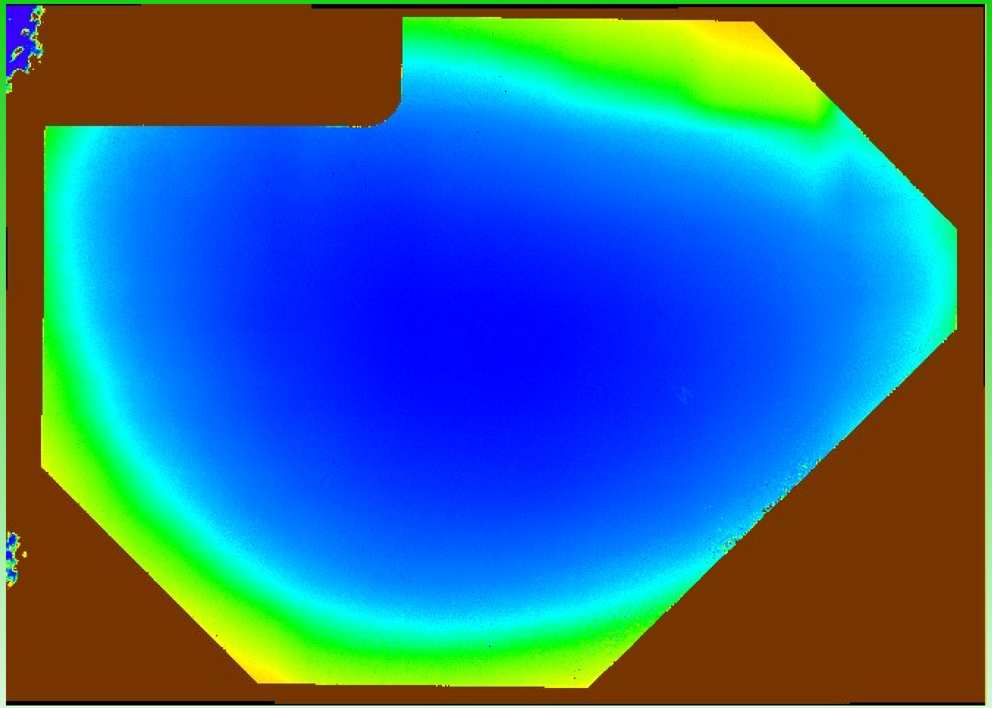


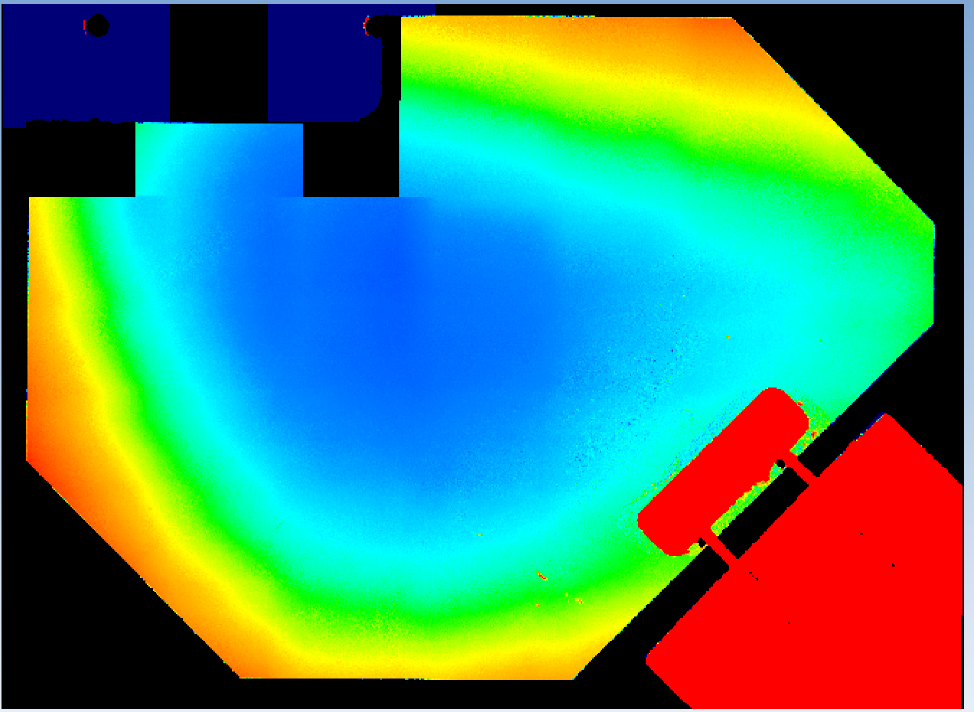
Planarity before soldering

Before soldering



Max deviation: +26 μm
Min deviation: -60 μm
Total variation: 86 μm

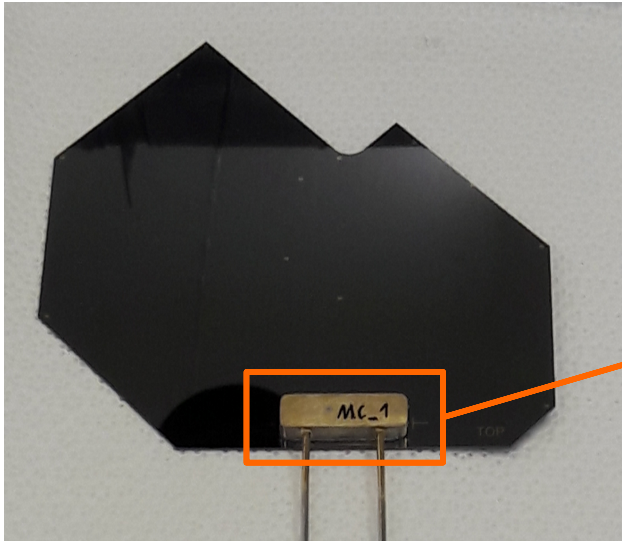
After soldering

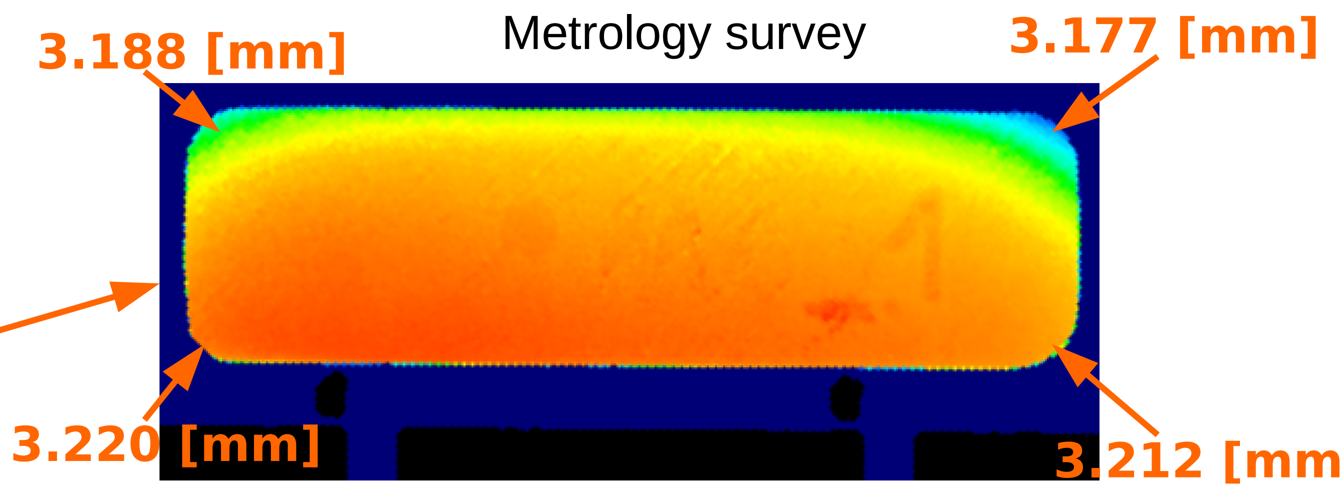


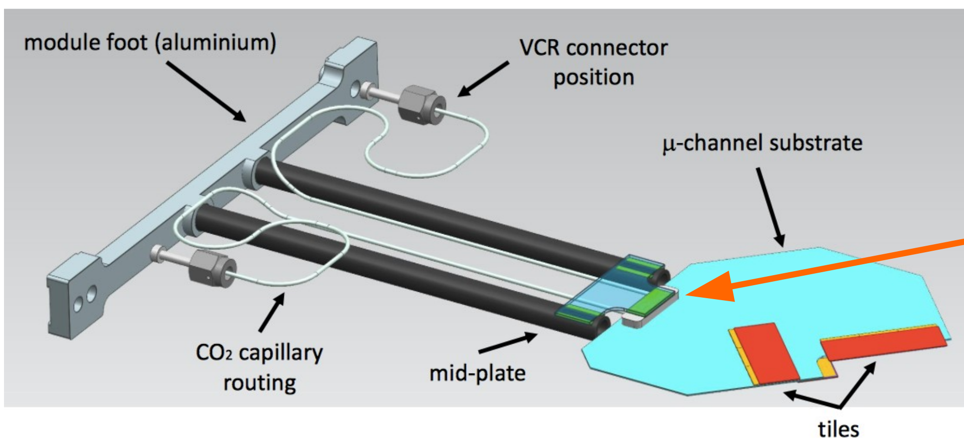
Max deviation: +25 μm
Min deviation: -50 μm
Total variation: 75 μm

No significant change on the planarity of the silicon plate.
Therefore, no significant stress generated by the soldering procedure.

Connector/Silicon planarity





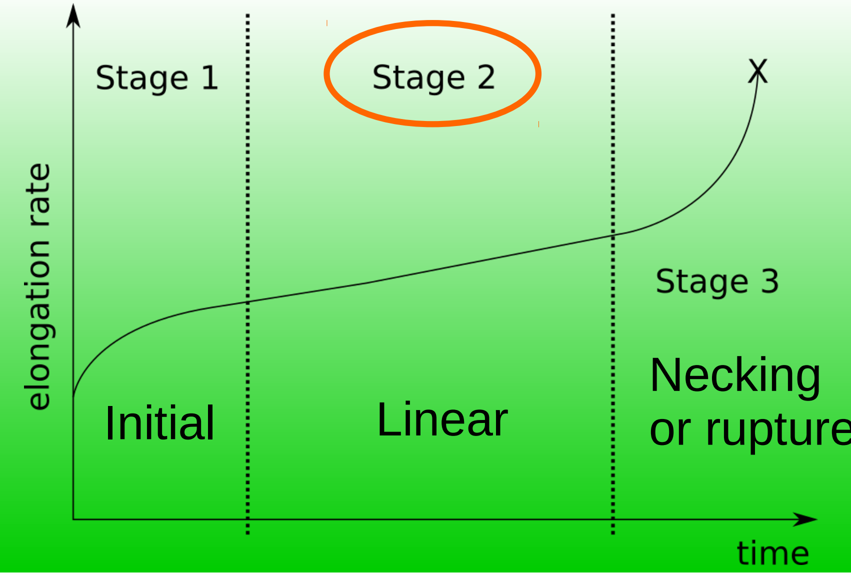


The variation of 43 μm can be easily absorbed by the glue layer between the connector and the midplate

Reliability tests of the solder joint

1 - “Creep is the plastic deformation of a material at very low mechanical stress levels”

- ***Very temperature and load dependent***
- ***Relevant when the temperature > 50 % of melting temperature of the material***
- ***Typically, it is a very slow fenomena (might take years or more)***

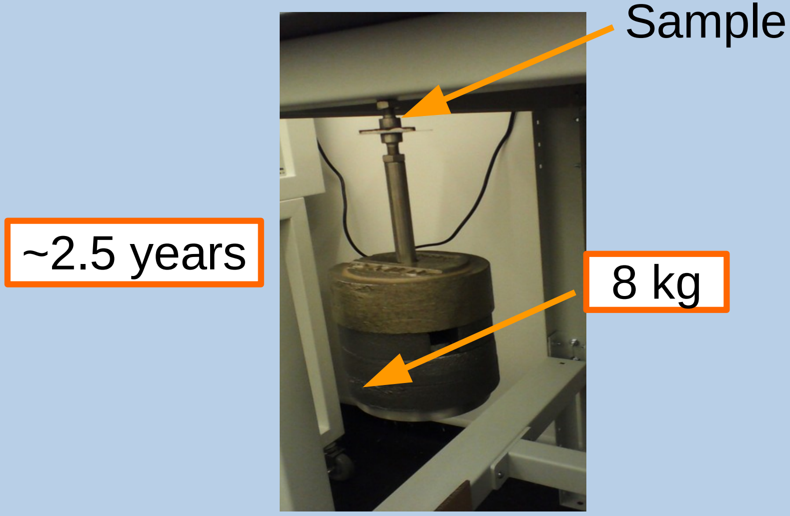


2 - “Fatigue is the weakening of the material due to repeatedly applied load.”

The cracks found in the asphalt after temperature and pressure cycles are a good example

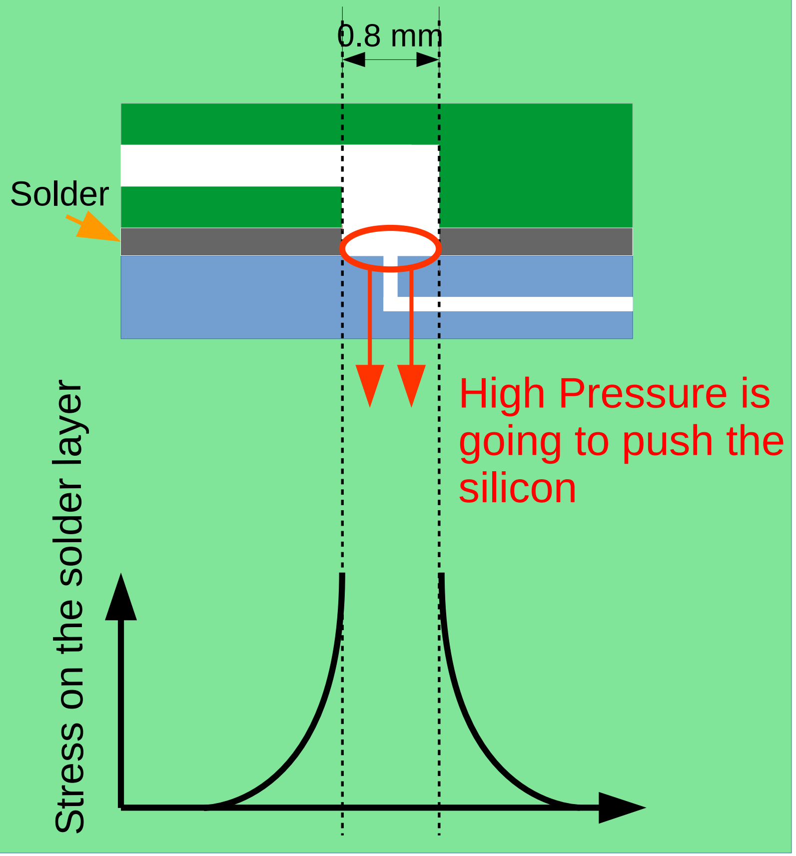
Creep testing of the solder joint

Simple creep test is done with weight at room temperature



At nominal conditions, the pressure of the CO_2 will be around 20 bar. This corresponds to a force of ~ 28 N pushing the silicon away.

Realistic case

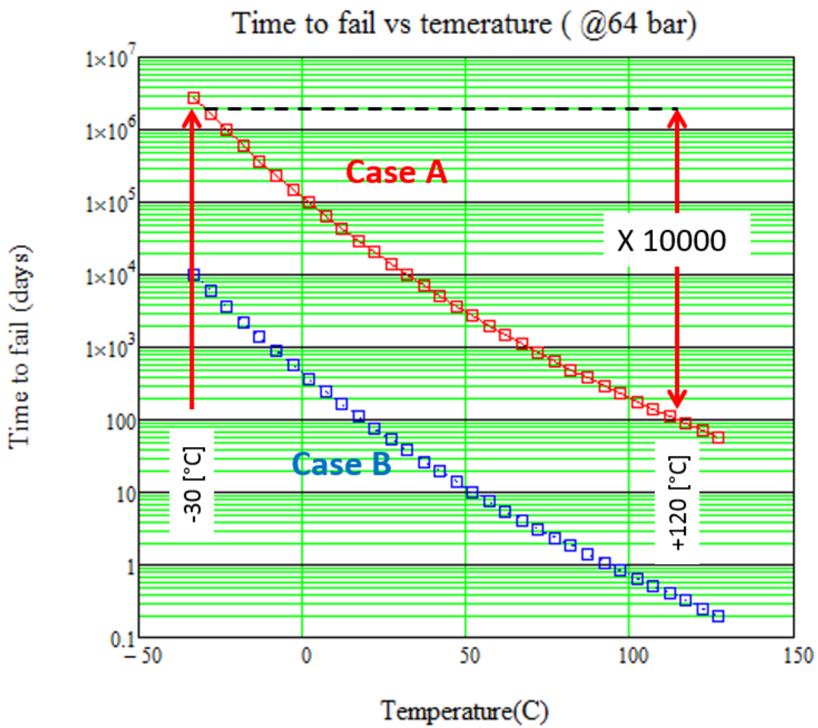


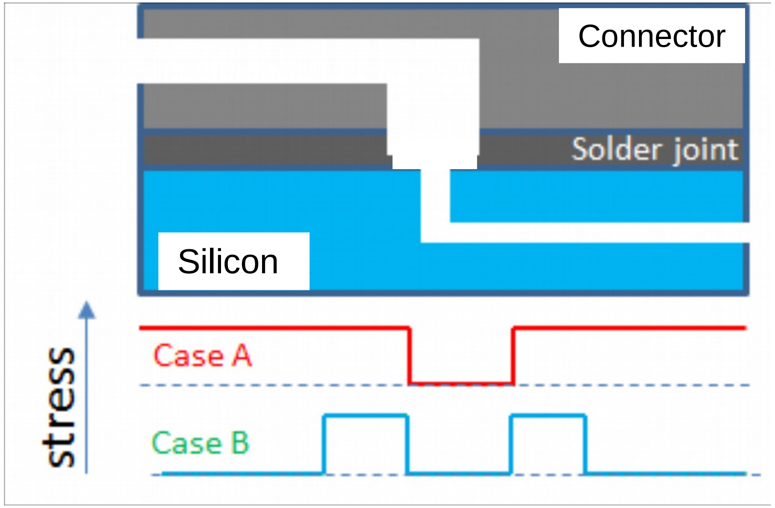
Accelerated creep modelling

The model based on [1] can only predict the behaviour at the linear stage.

Based on this model, we want to estimate the acceleration factor using higher temperatures and loads.

The failure is defined as 1% (arbitrary) of elongation





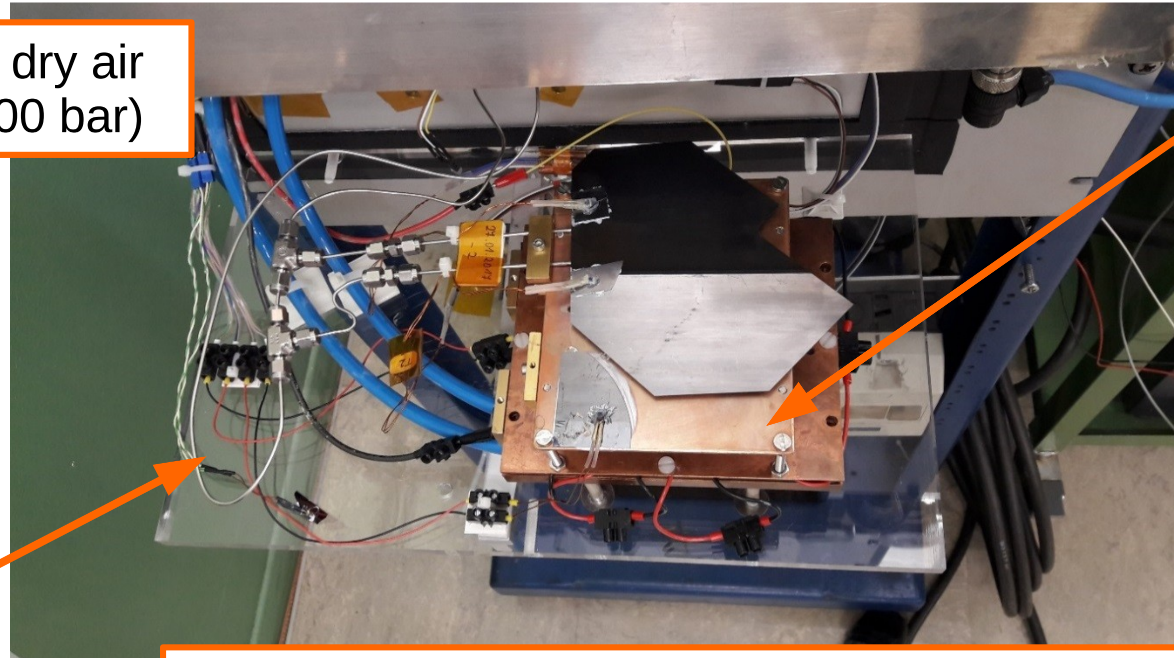
Two load cases:
case A – The stress is uniformly distributed over the solder layer
case B – The stress is concentrated in the region close to the input/output

Changing the temperature from nominal (-30°C) to +120°C, the time to fail decreases by a factor 10000 (1h → ~ 1 year)

[1] - "**A new creep constitutive model for euthetic solder alloy**". Shi, Wang, Zhou, Pang, Yang. Transactions of the ASME page 84, Vol124, June 2002.

Creep test

High pressure dry air bottle (up to 200 bar)

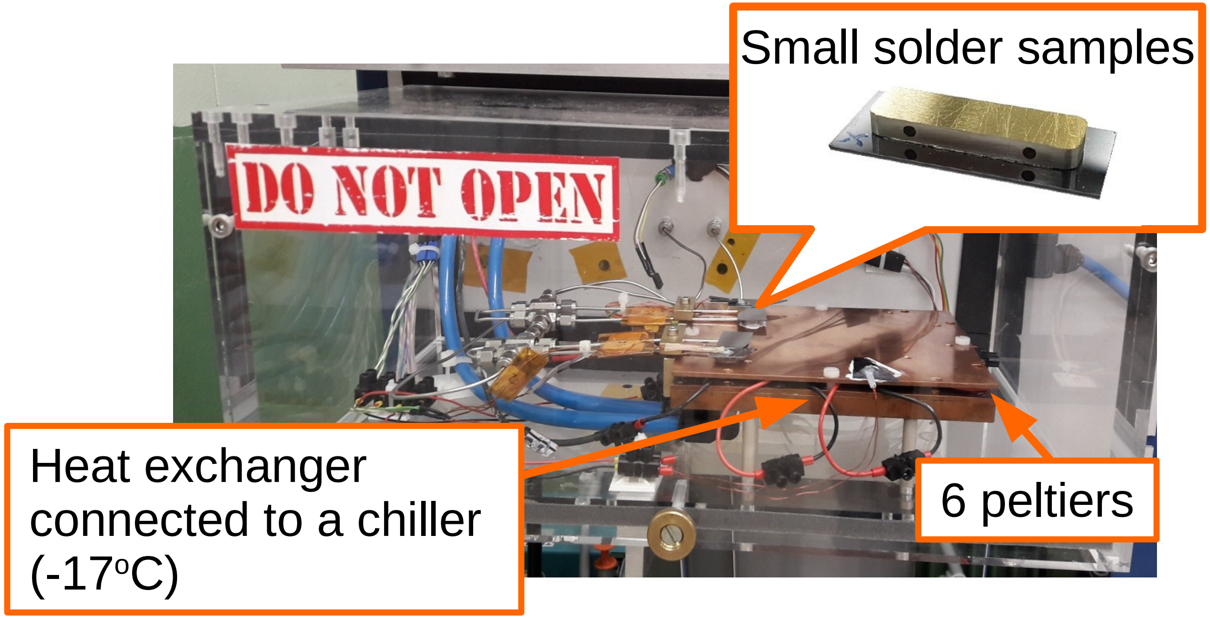


2 heaters of 50 W under the plate

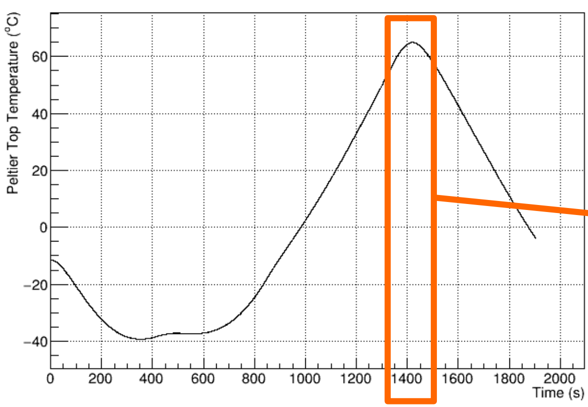
Typically, this test was run at 60 bar and 120 ºC

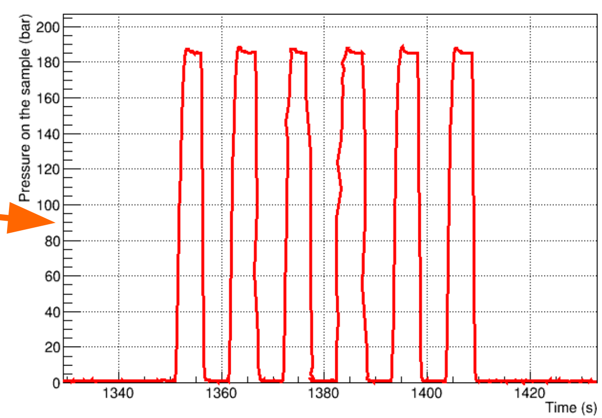
Summary of the test campaing:
Total number of samples: 18
Total number of hours: 2630 hours
Total number of hours: ~ 110 days

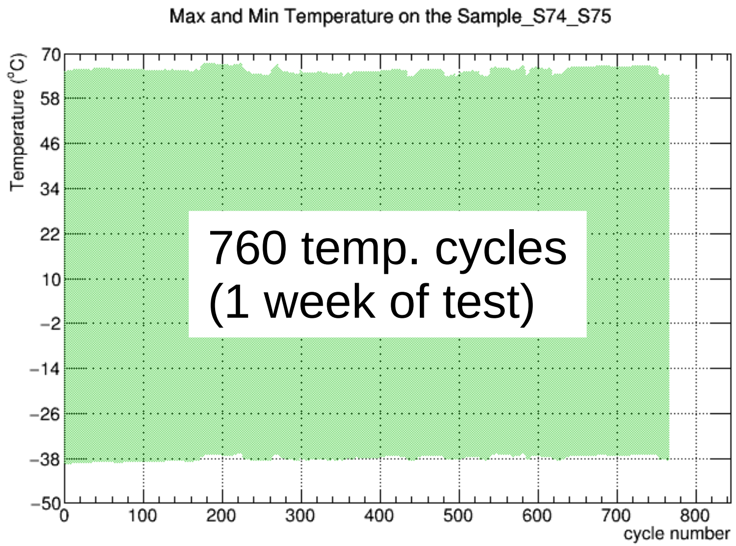
Fatigue test of the solder joint



Simultaneous temperature cycles and pressure cycles

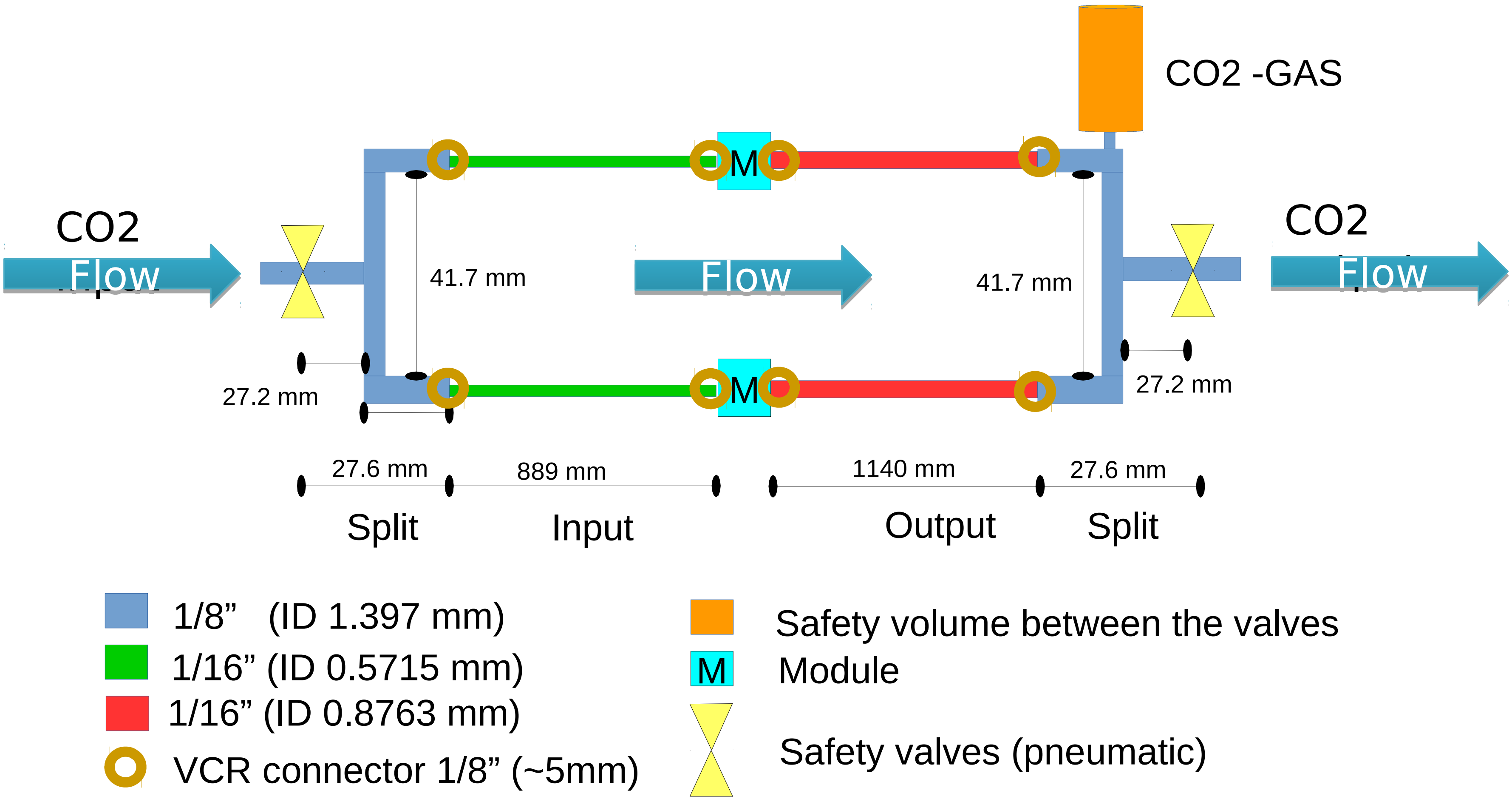




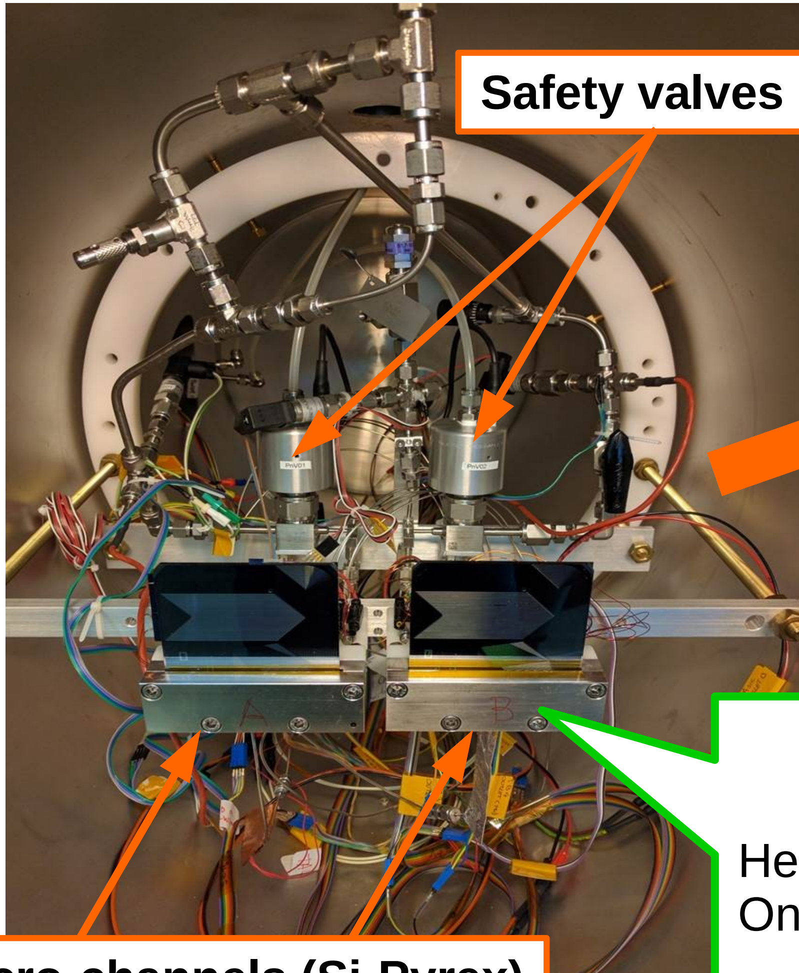


Summary of tests:
Samples: 9
Total number of temp. cycles: 5232

Plan-A: Fluidic characterization at -25C



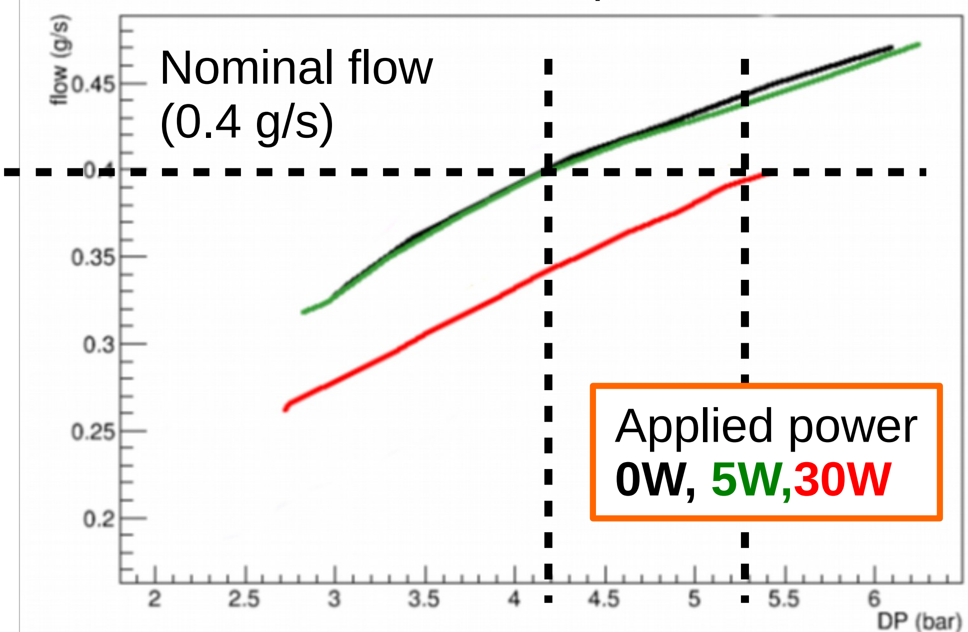
Plan-A: Fluidic characterization at -25C



Safety valves

Micro-channels (Si-Pyrex)

Characterization per module

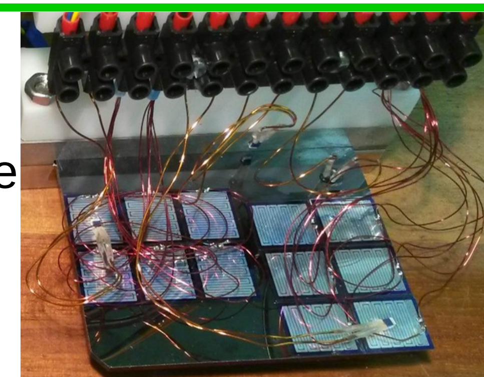


Nominal flow
(0.4 g/s)

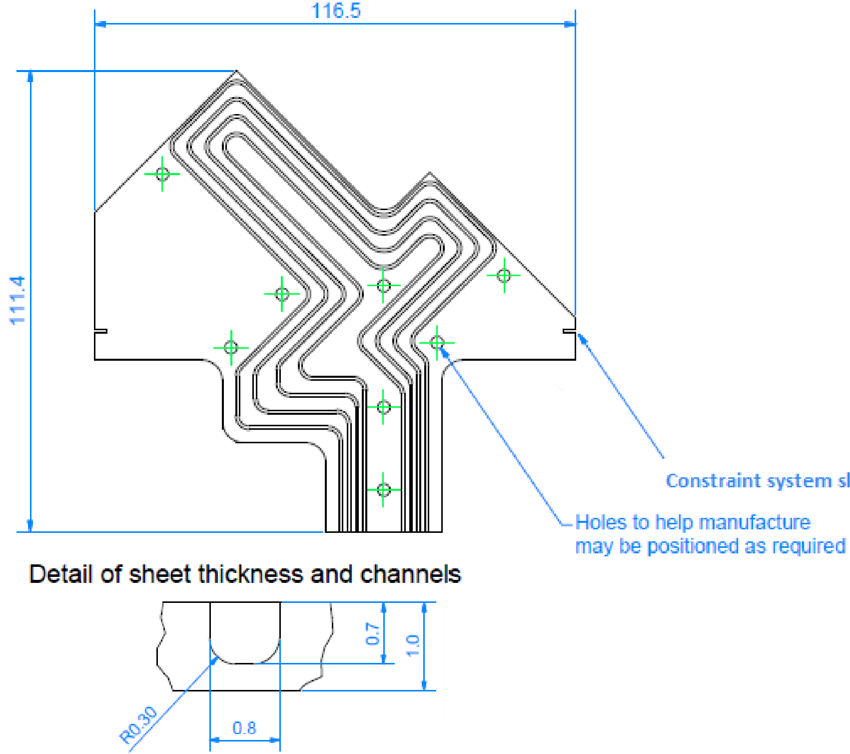
Applied power
0W, 5W,30W

The pressure difference is between 4.2-5.4 bar

Heaters on the other side
On the silicon side

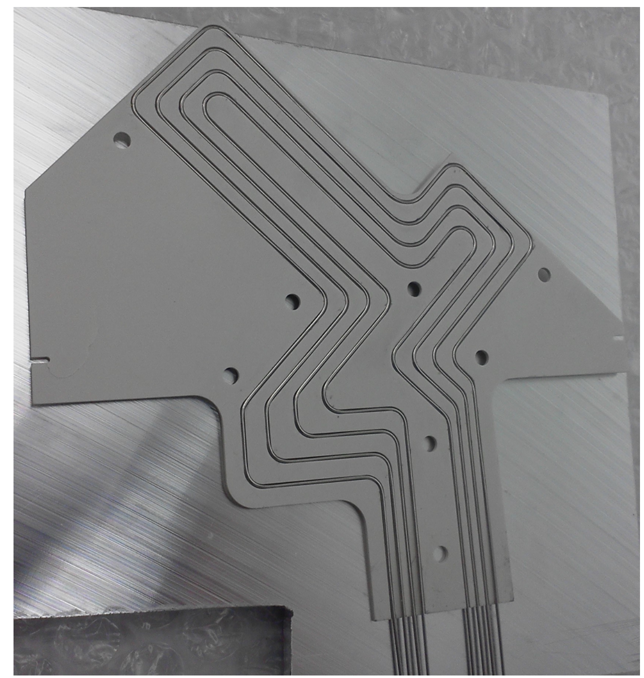


Tubes embedded in ceramics

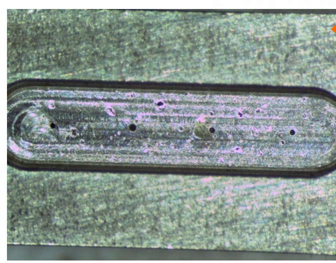


0.64mm OD
0.33mm ID

Tubes are fixed in the trenches on the ceramic with glue previously applied by robot (122-39 (SD) – 3.5 W/mK)



Orifices (125 +/- 5 µm) in the input trigger the boiling of the CO_2 and prevent instabilities among the channels

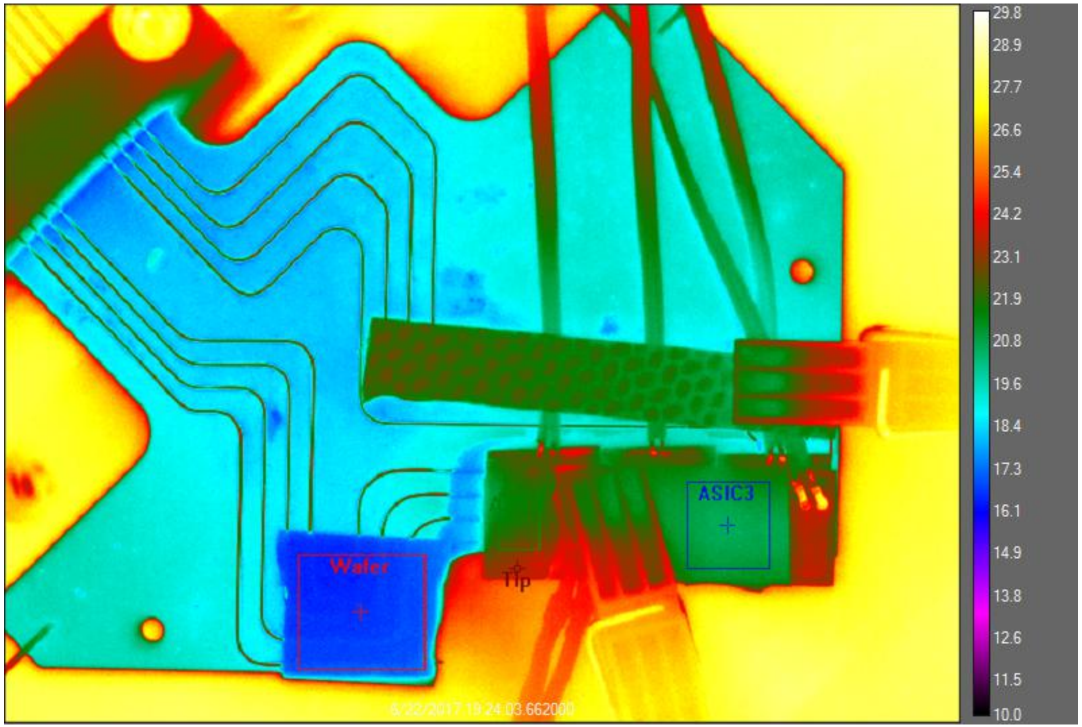


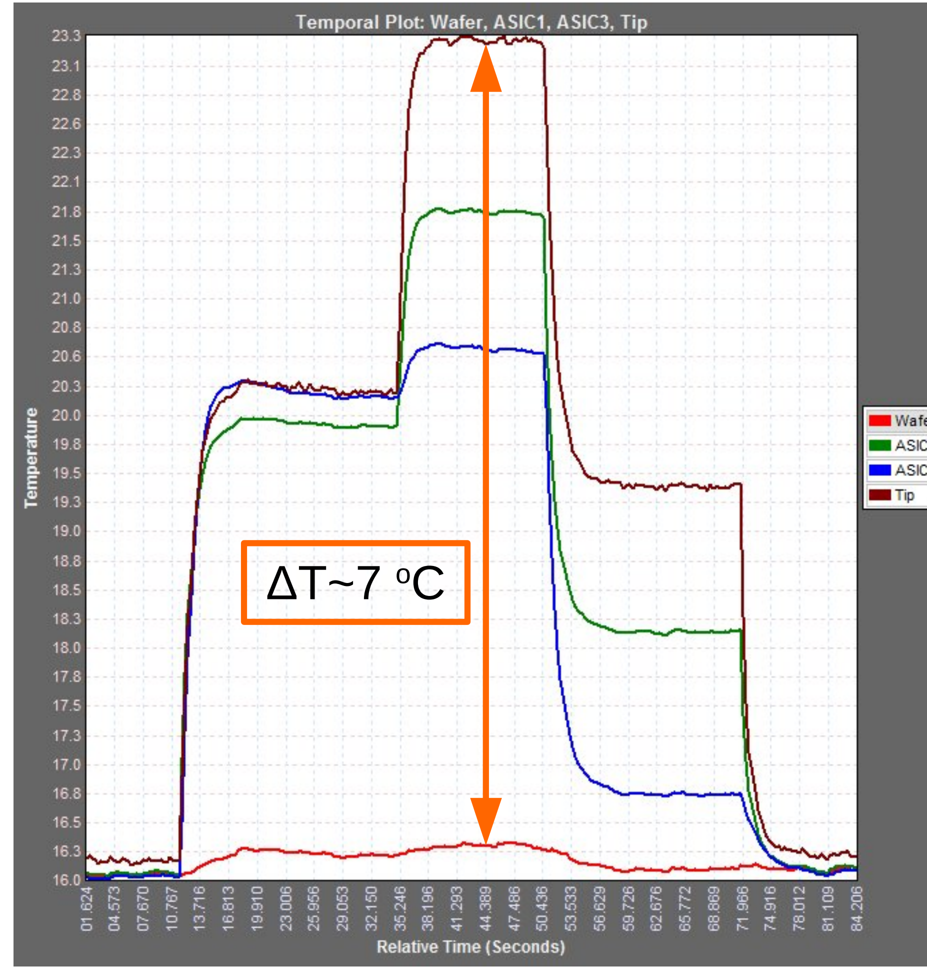
Aluminum Nitride (Shapal):

- Machinable ceramic
- Thermal expansion coeficient: 4.8×10^{-6}
- Thermal conductivity: 92 W/m°C

Cooling performance

Cooling performance was evaluated with ¼ of the system glued with Stycast: 3 ASICS mockups + 1 sensor mockup (3 x 2W + 1W)

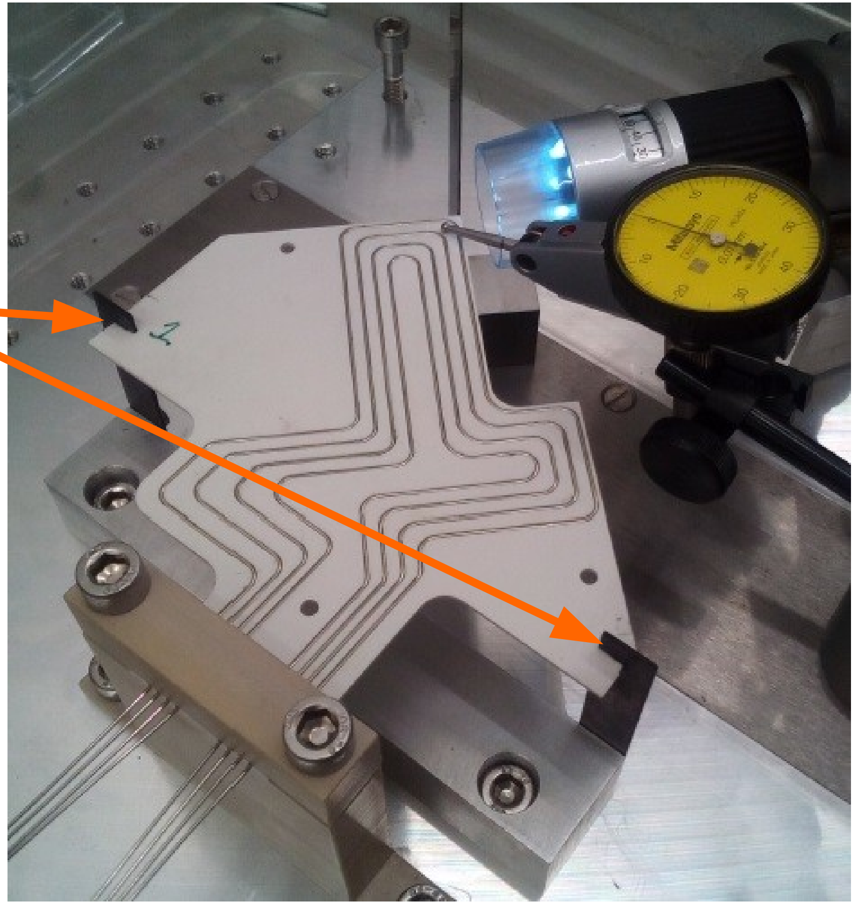




The temperature of the output CO_2 was 15 ºC. Therefore, the max DT is around ~8 ºC.

Deflection measurement

Carbon fiber
constraint system



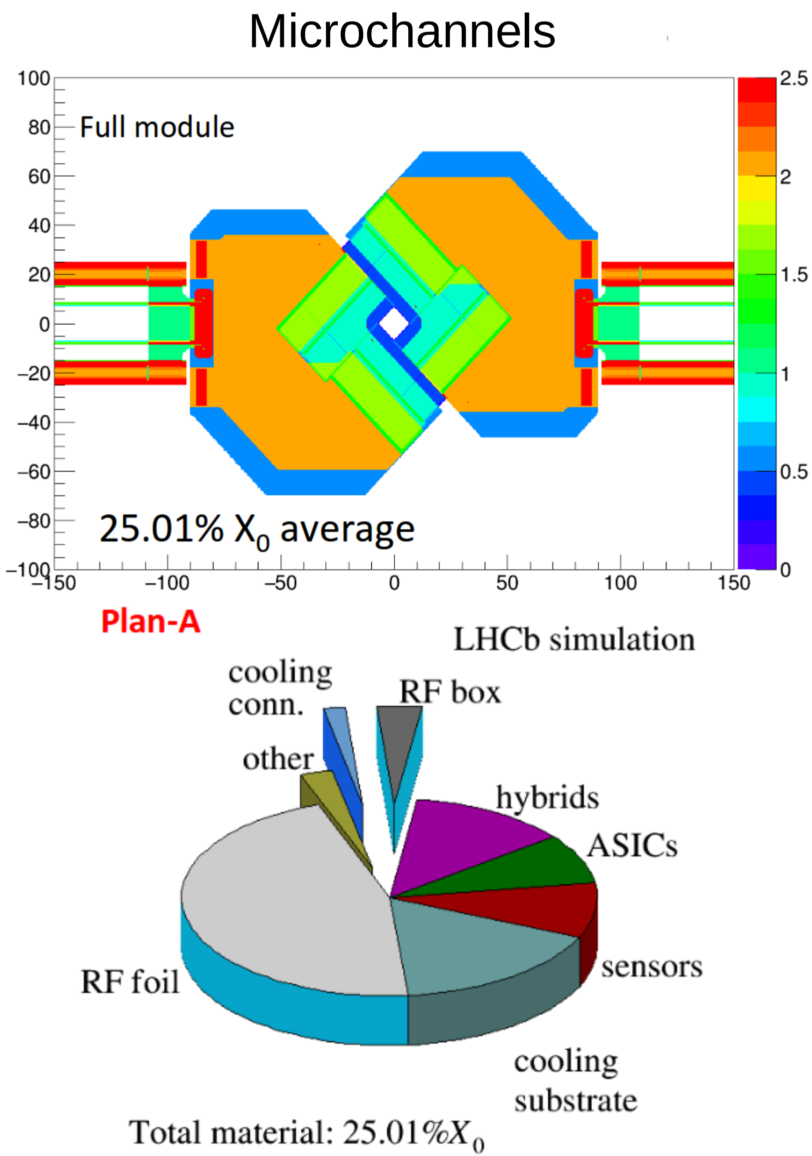
Thermal expansion coefficients

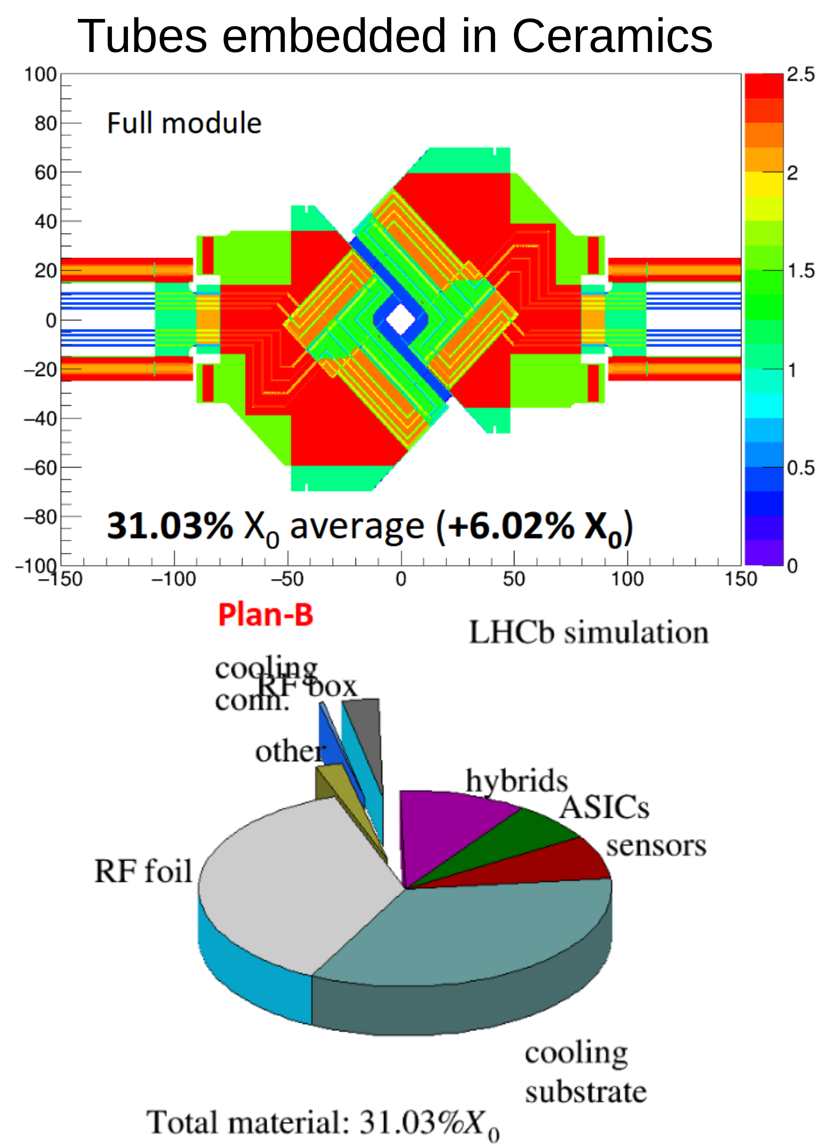
Shapal - 4.8 x 10^{-6}/K

Stainless steel - 16 x 10^{-6}/K

Deflections are < 100 μm due to the variations of temperature

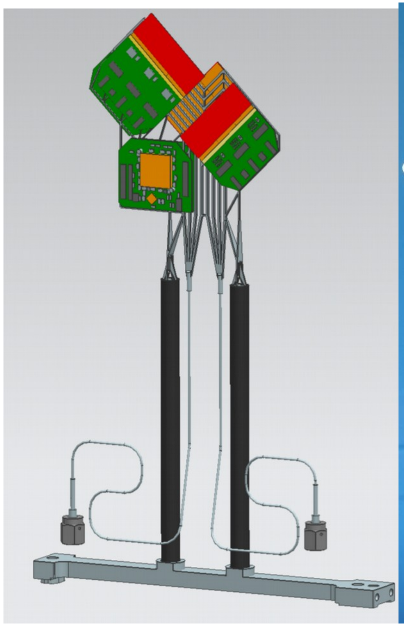
Comparison of the material budget

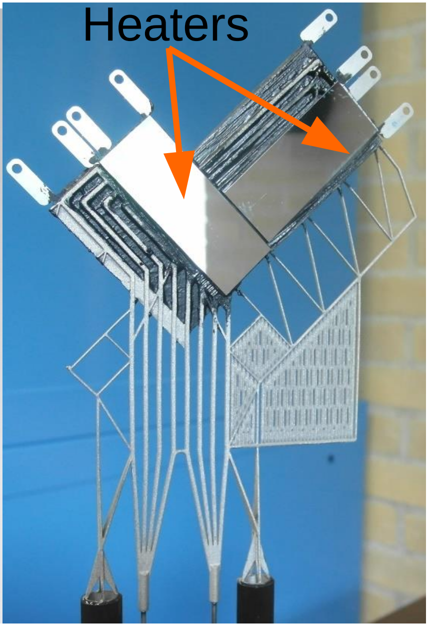




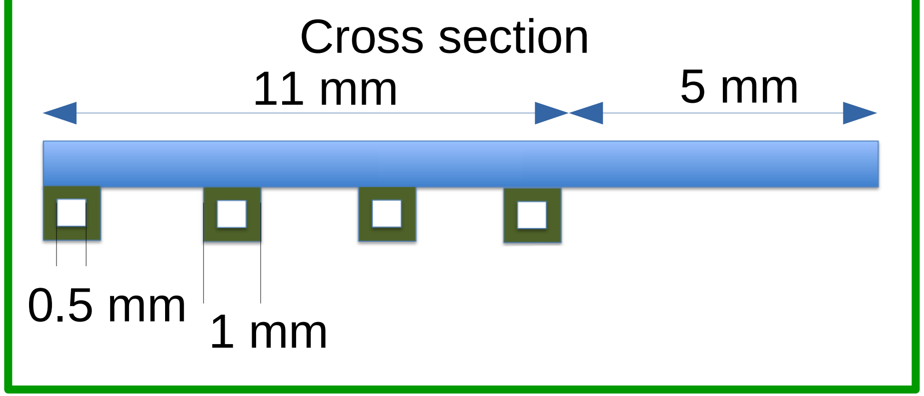
Ti 3D printing

Key features:
Material: grade 2 Ti
Easier to handle (compared to Si)
Easy to weld
Cheap (~250 EUR excluding welding)
Fast turnaround for design changes (few weeks)
Fast production: 25/batch, 1 batch/ few days
Restrictions can be integrated in the inlet
(0.35 mm x 0.35 mm x 40 mm)





Disadvantages:
Low thermal conductivity (16 W/m K)
CTE mismatch (6 ppm/K)



- High pressure test (up to 250 bar)
- Leak thight (at least 250 μm wall)
- Deflection due to temperature variations (< 100 μm)

Work on going:
Glue layer
Thermal simulation
Cooling performance
Flatness
Reproducibility

Conclusion

1) Micro-channels
   - Better physics performance due to less material
   - No CTE mismatch between the substrate and electronics
   - No fatigue or accumulated stress effects were observed by doing cyclic tests
   - First micro-channel successfully soldered

2) Back-ups are designed to match the micro-channels fluidic characteristics and easier to handle
   - Tubes embedded in ceramics:
     - Good cooling performance
   - Ti 3D printing
     - Fast prototyping and cheaper

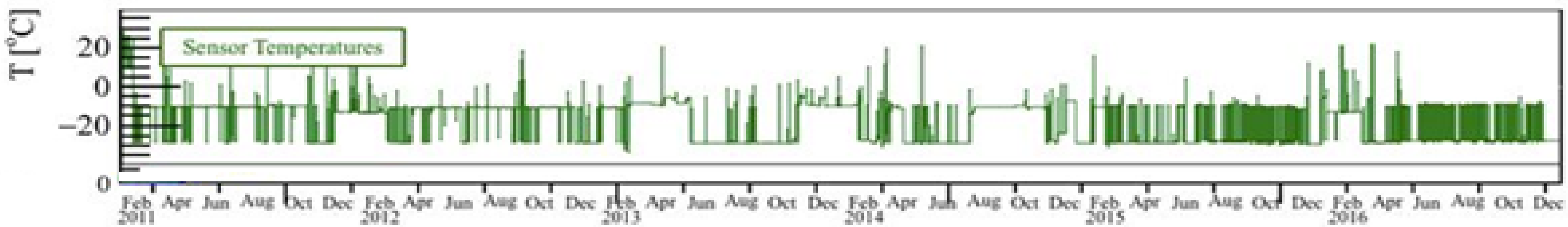
These technologies will be reviewed on September 28th and the decision will be taken shortly after

Thank you for your attention! :)

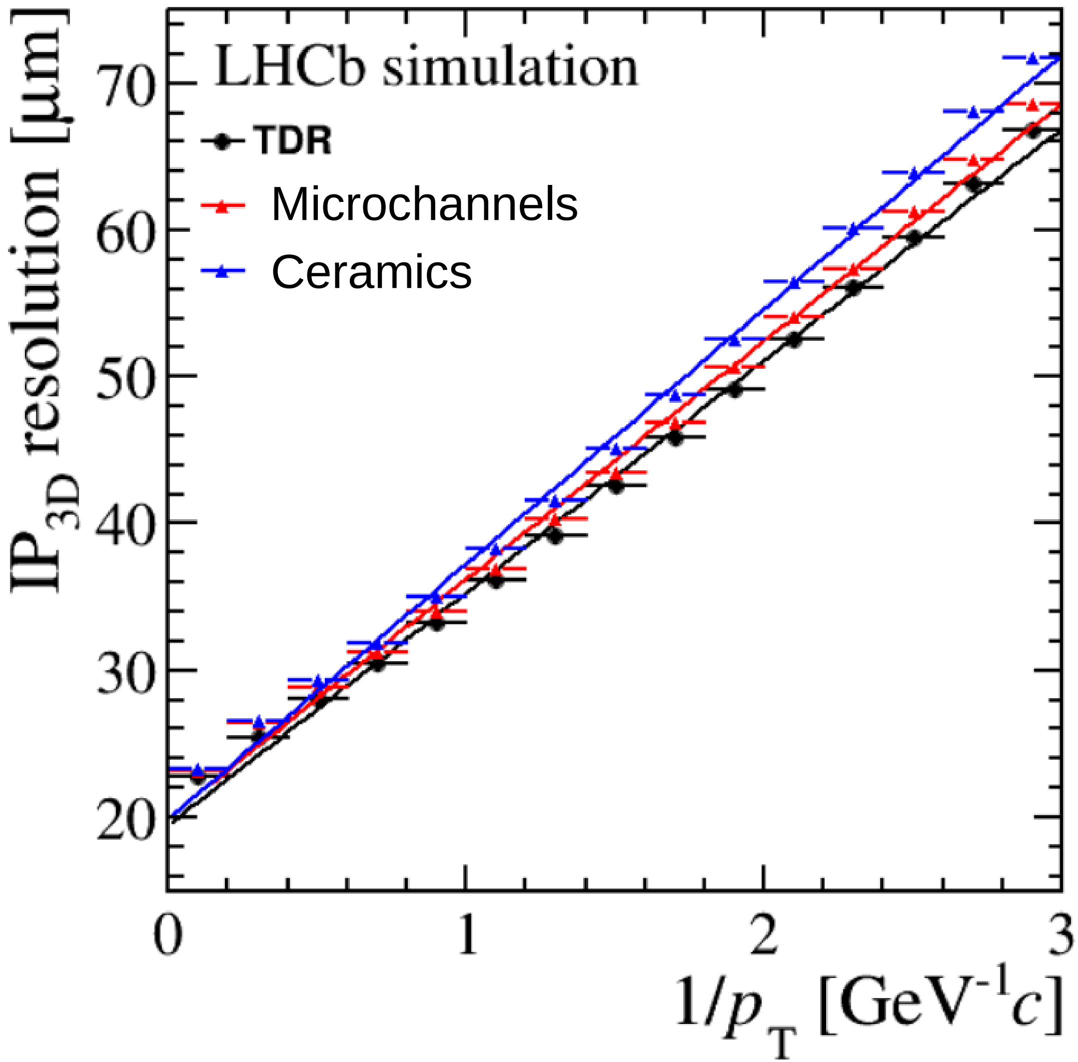
Backup slides

Fatigue of the solder joint

the current VELO endured 200-300 temperature and pressure cycles between 2011 until the end of 2016



Comparison of the impact parameter resolution



Microchannels manufacturing