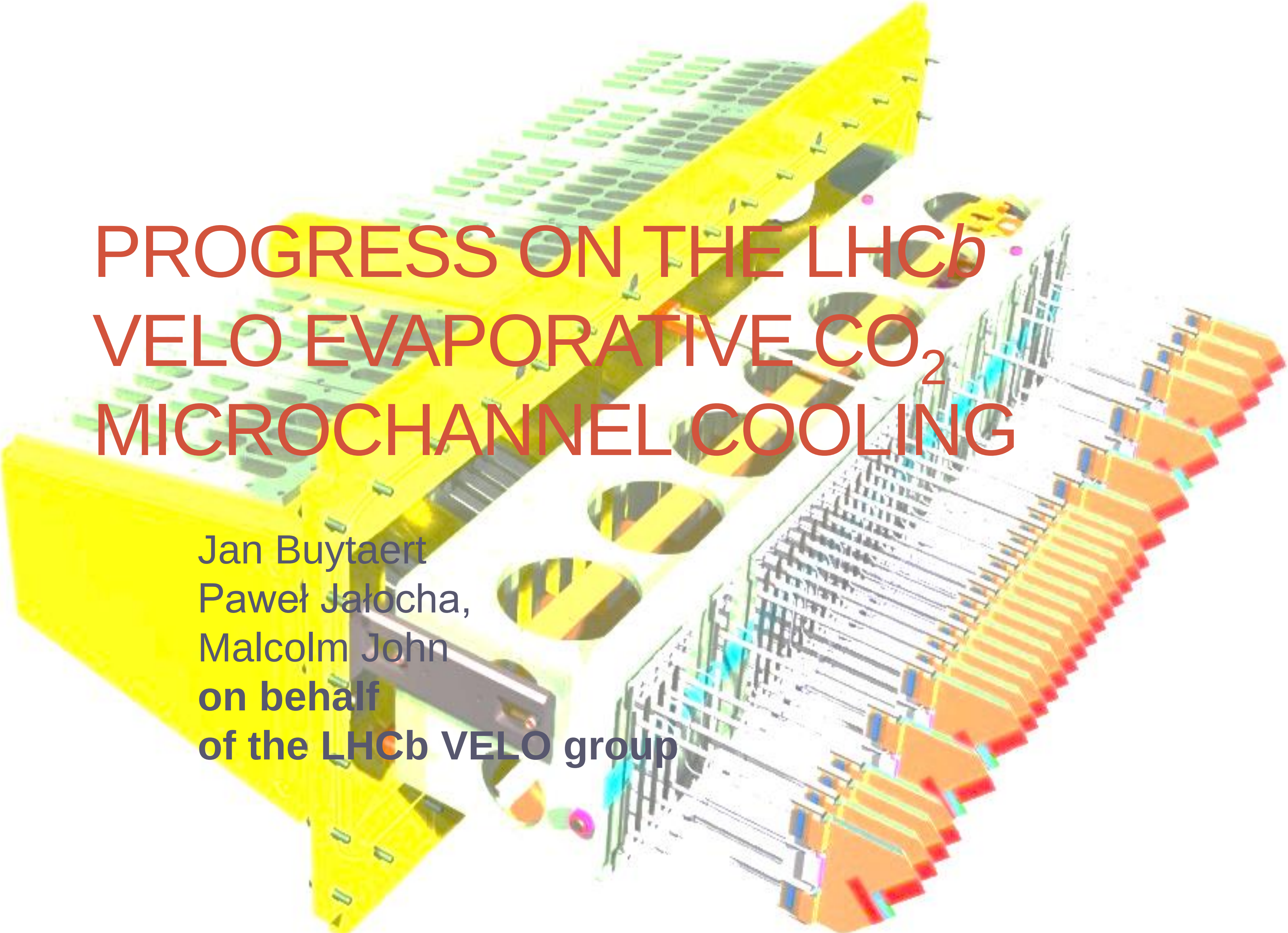
PROGRESS ON THE LHC*b* VELO EVAPORATIVE CO_2 MICROCHANNEL COOLING



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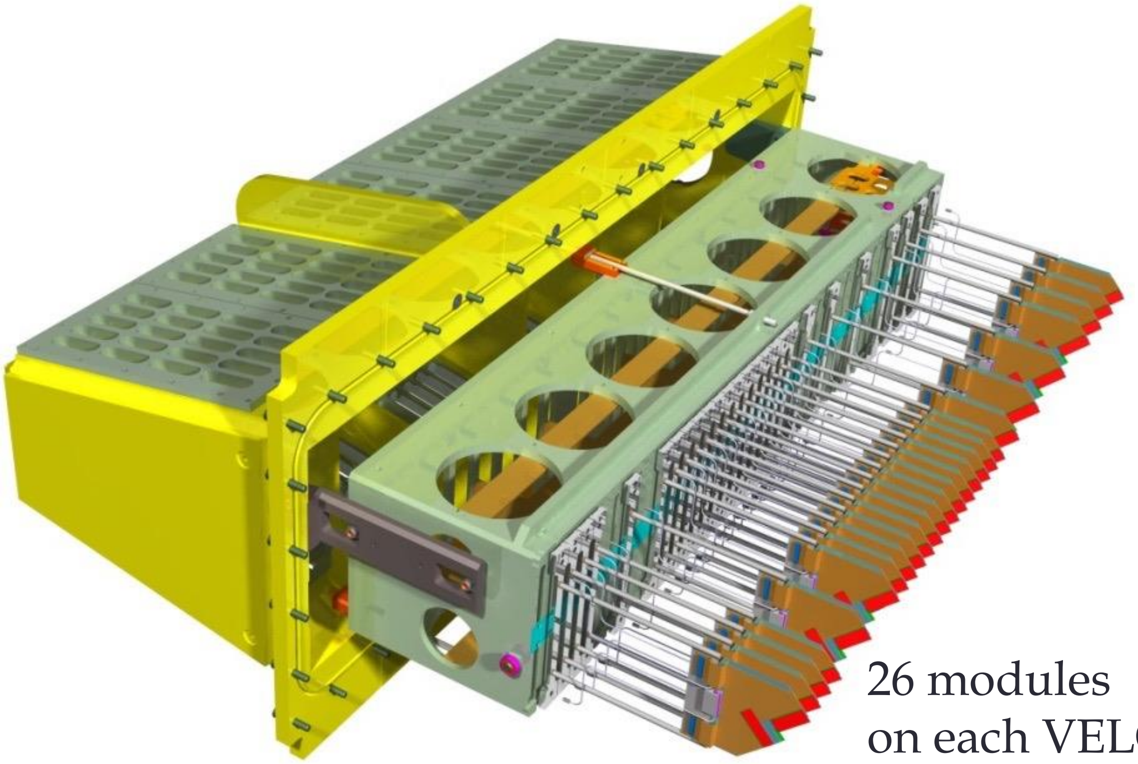
on behalf
of the LHCb VELO group

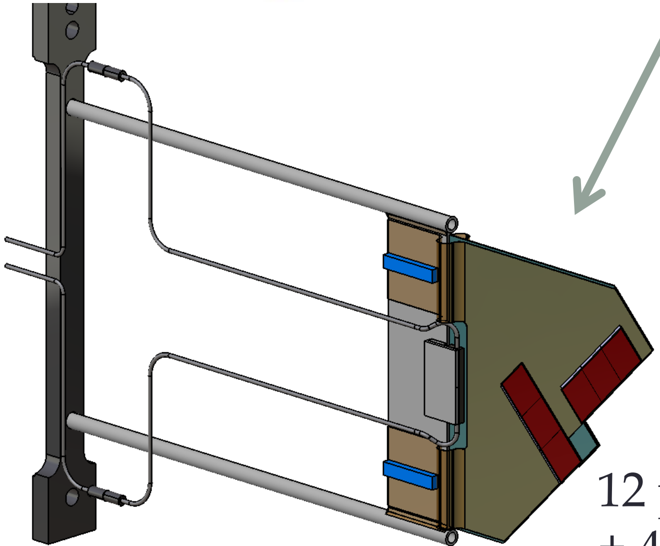
Topics

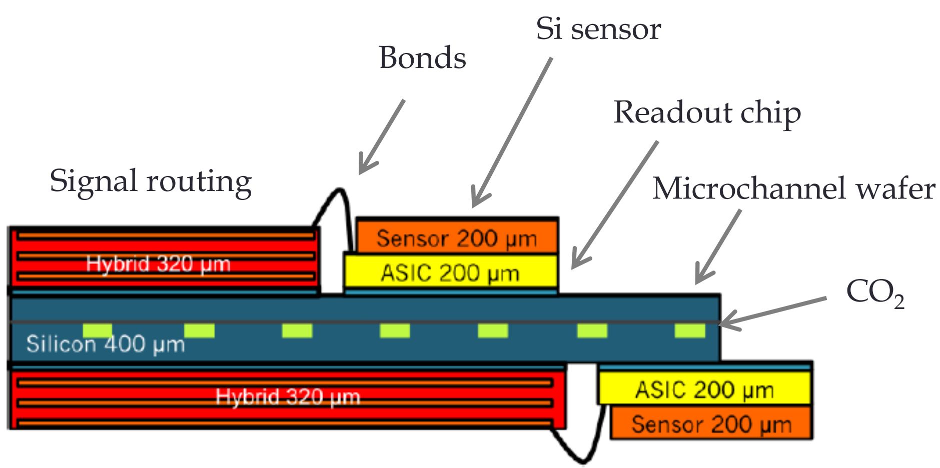
- Introduction
- Soldering
- Flow characteristics of the full size prototype
- Heat load characteristics
- Summary



2018 LHCb VELO upgrade:
52 pixel modules,
1.6 kW power dissipated,
so how do we cool that ?

26 modules
on each VELO side





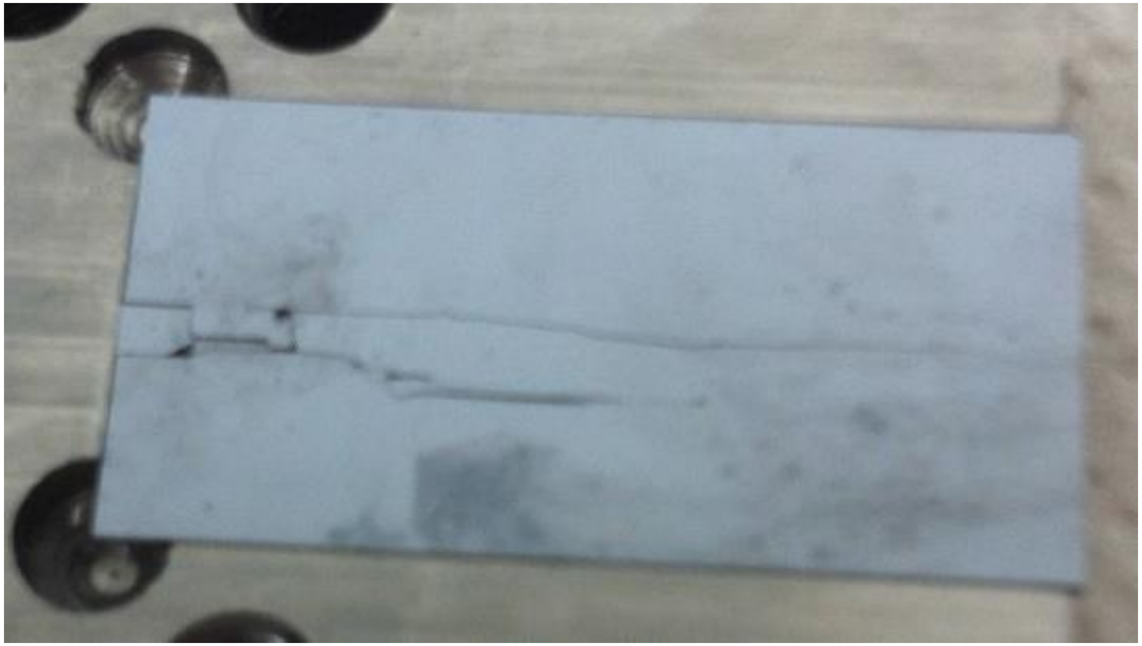
12 pixel ASIC's
+ 4 Si. pixel sensors = 30W

Challenges

- Make the silicon cooling wafer resist the CO_2 pressure of 65-70 bar – the Si-Si bond has to be strong enough
- Supply the wafer with CO_2 – how to join metal pipes to silicon ?
- Make this fluidic connection resist the high pressure, low temperature, irradiation and time
- What pressure and how much CO_2 do we need flow ?
- How much heat the wafer can take: what part of liquid CO_2 can be effectively evaporated ?

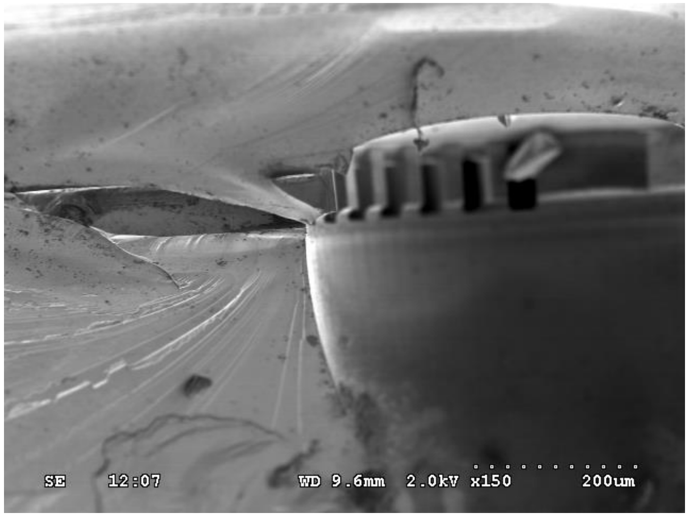
Wafer internal pressure resistance

- Was already measured for Si-Si direct bonded prototypes from Leti and if of no worry at this time
- Samples from University of Southampton has been tested and stand at least 250 bar. When they break, it appears to be related to the hole, not the microchannel.

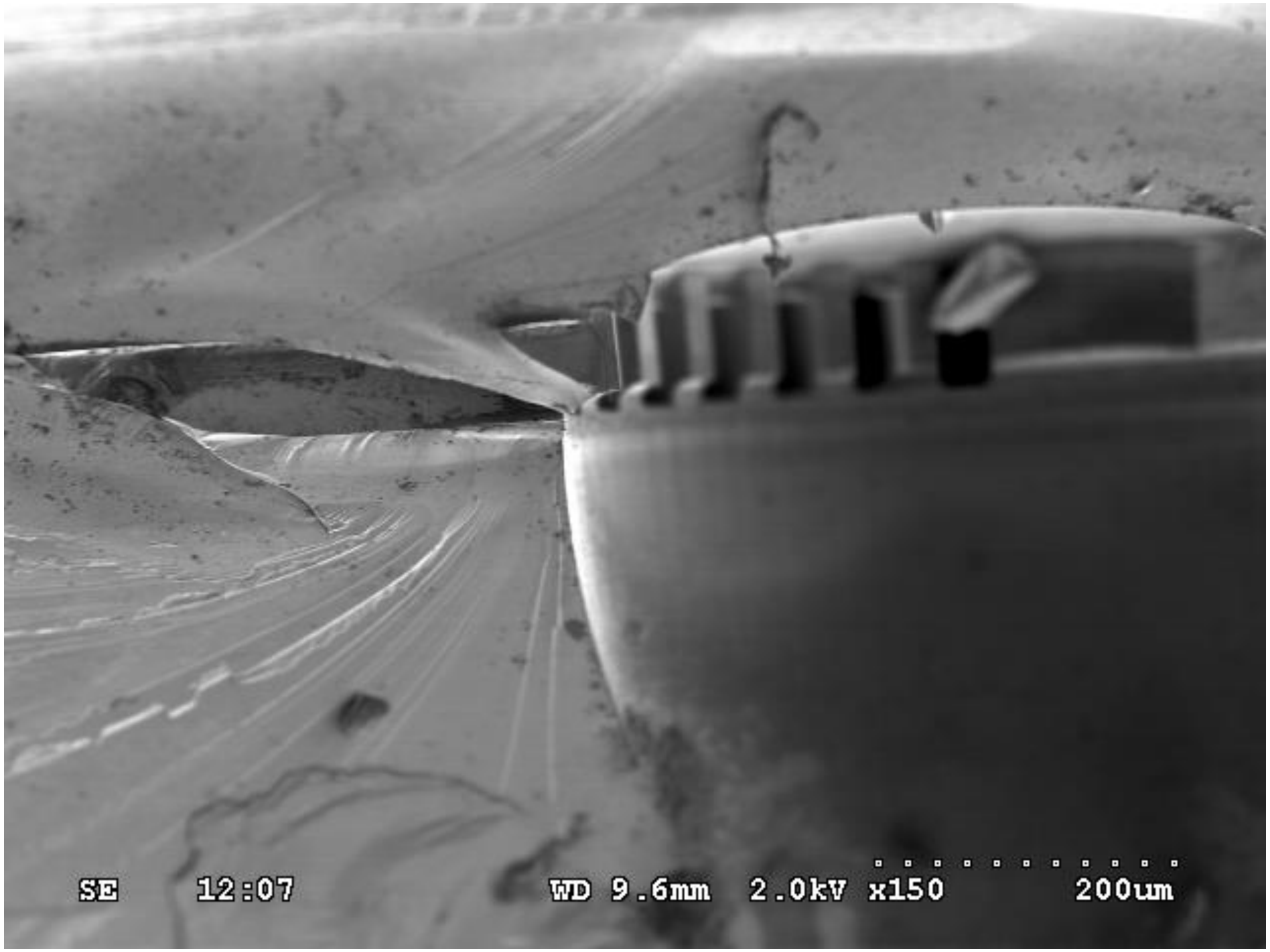


The breakage around the inlet hole, the crack propagates from near the bond layer, but not obviously from the bond layer.

Electron-scanning images of (broken) microchannels wafer

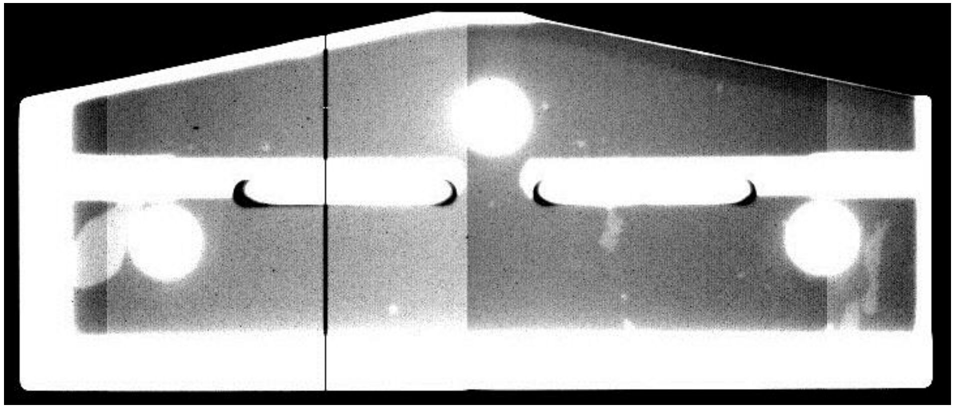


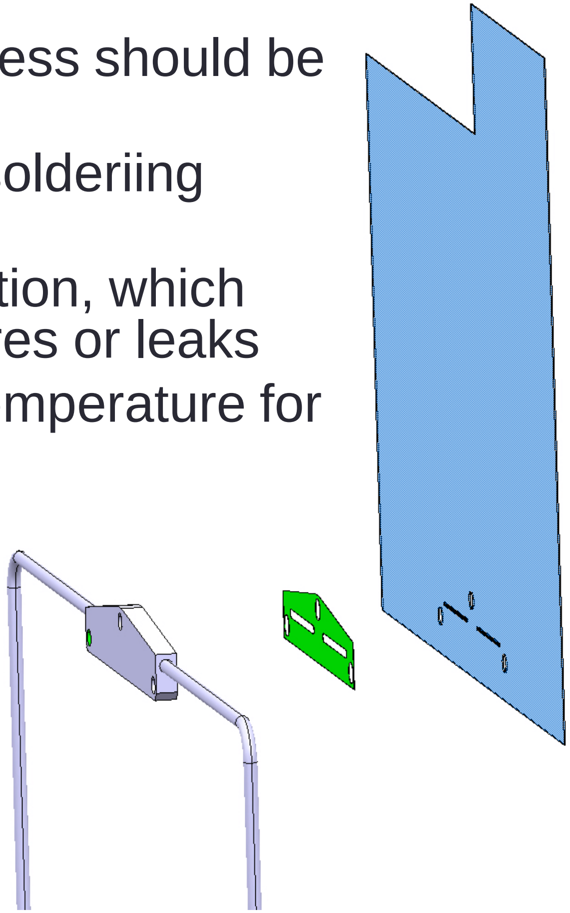
- a close-up of the end of the microchannel (away from the inlet hole) to look for evidence of the bond layer (a lateral feature a few 10’s of nm in thickness would be visible at this resolution)
- Image of the inlet hole and the entries to the microchannels


SE
12:07
WD 9.6mm
2.0kV
x150
200um

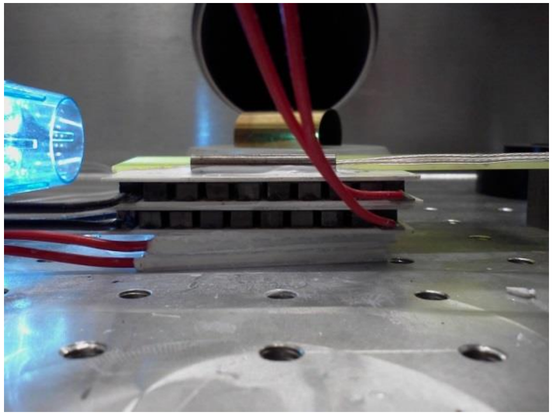
Soldering the fluidic connector

- Metal connector brings CO_2 supply to the microchannel wafer
- Silicon is metallized with Ti+Ni+Au and the connector soldered with a layer of PbSn solder.
- Liquid solder interracts with Ni layer thus the process should be quick and have controlled temperature profile
- Flux is believed to be bad for good lifetime, thus solderiing without it is preffered.
- Soldering on a large surface provokes void formation, which can weaken the joint and could be source of failures or leaks
- The joint must withstand high pressure and low temperature for the experiment lifetime

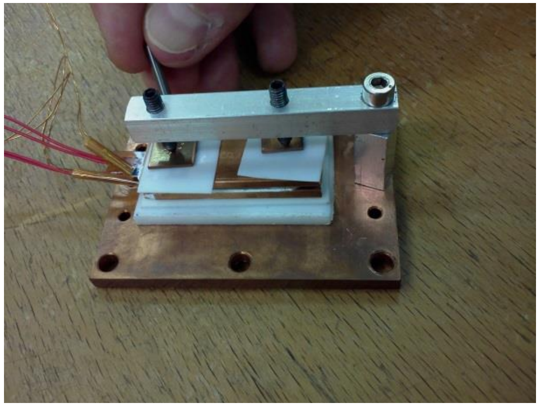




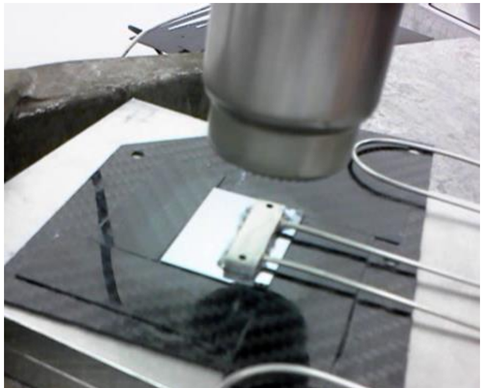
Soldering techniques

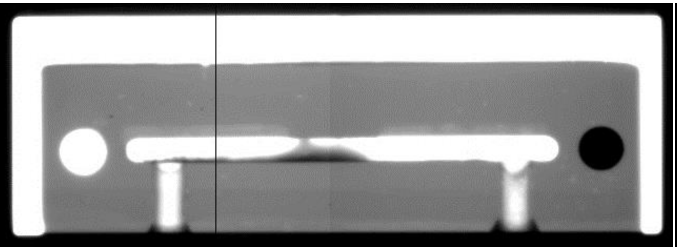


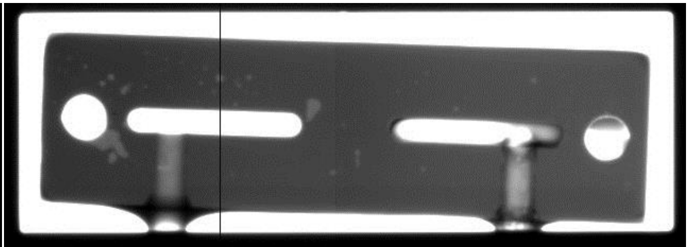
- In vacuum with Peltier stack and heater/cooler
- In vacuum with thin-film heaters, conductive cooling
- With hot-air (with organic, thus non-corrosive flux)
- Vapor phase



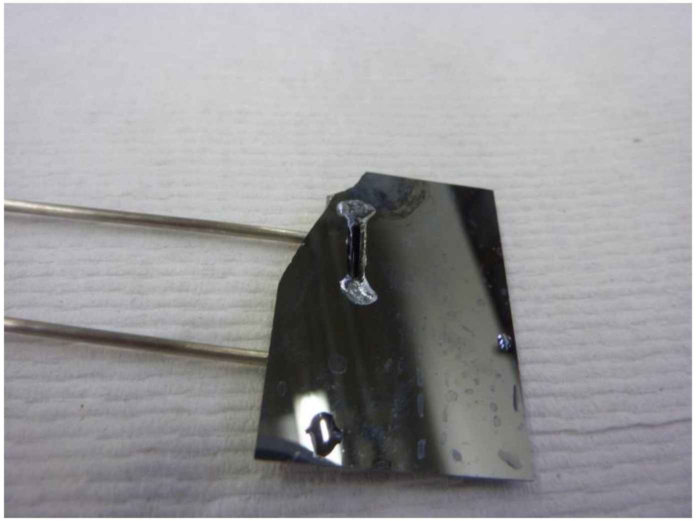
Varying results were obtained, in terms of void formation, however in terms of strength and resistance to pressure the soldering always stood up and weak point turned out to be the silicon.

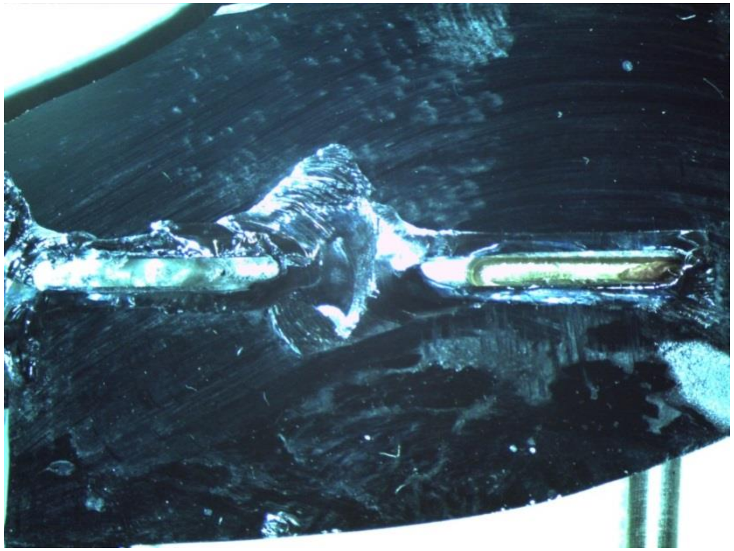






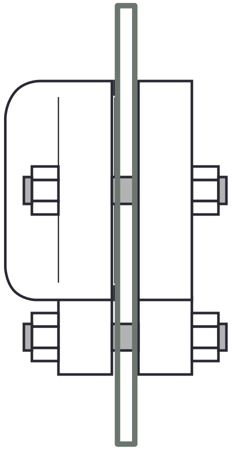
Fluidic connection pressure resistance





- Typical breaking pressure is 200bar and typical „breaking mode" is as on the above photo: silicon under the slit gives in to the pressure of the liquid
- This is bare silicon plate (no micro-channels) and thus thicker than final design
- Reinforcing the back should increase the breaking pressure by a significant factor

Reinforce the fluidic connection



- Support on the other side of the silicon wafer is needed
- or the wafer has to be thicker, at least where the connector is soldered

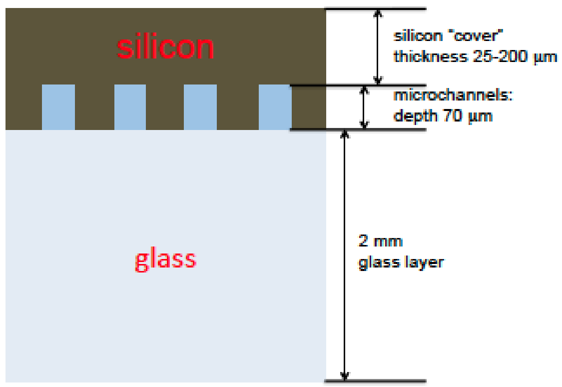
We now go for the solution to thicken the wafer under the connector and along the edge away from the ASIC’s and sensors.

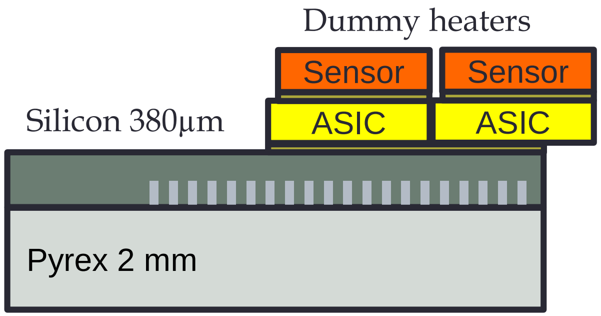
Holes appear to be a weak point too, thus we investigate scheme without any holes in the silicon.

Longer term creeping test is undergoing

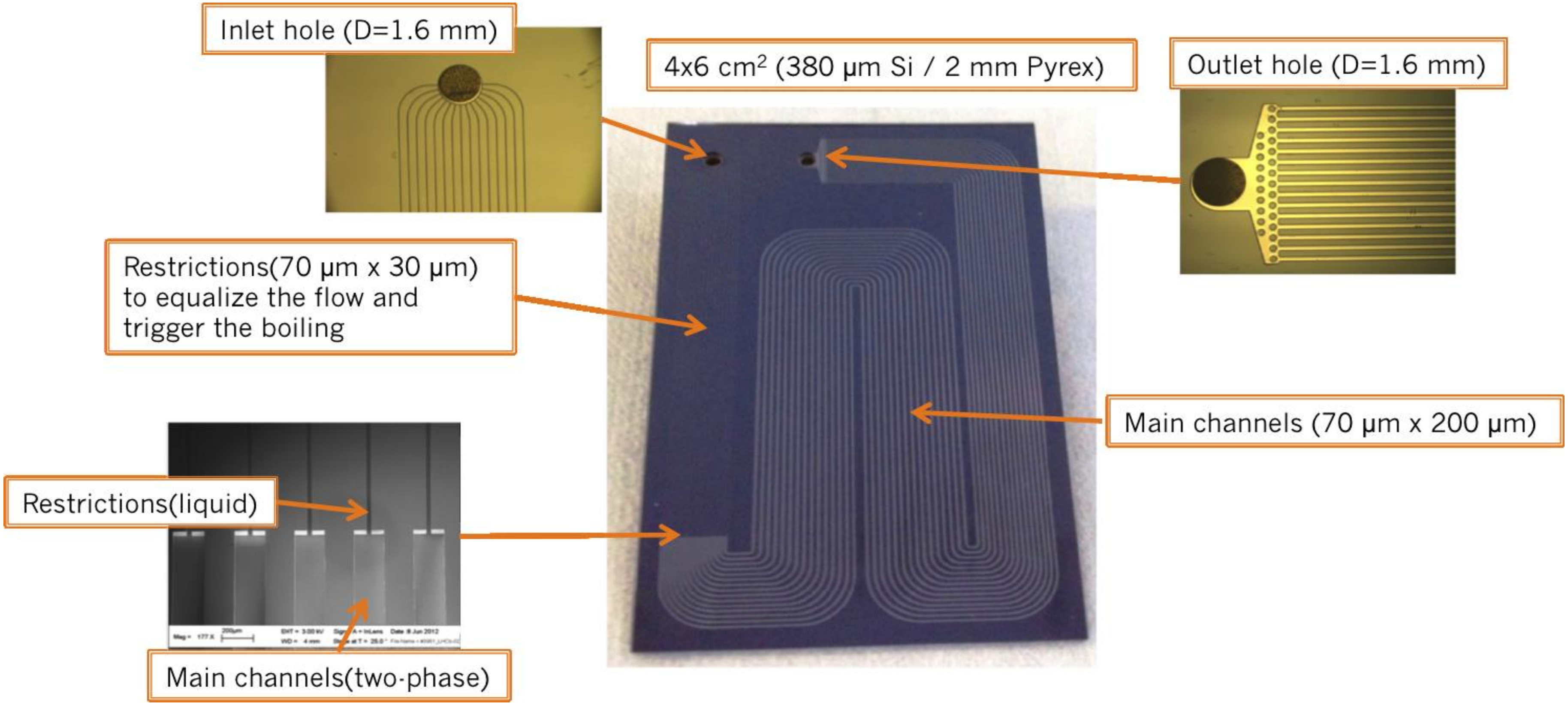
Microchannel prototypes

- Proof of concept
- Measure flow and heat characteristics
- Test microchannel geometry
- Silicon-to-glass (pyrex) anodic bonding technology is available in EPFL/Lausanne and suitable to produce prototypes
- One side is silicon, like the final design.
- The other side is much thicker pyrex (glass)
- Not ideal but close thermal expansion match: 2.3 vs 3.3 ppm/K
- Unfortunately not a good match for thermal conductivity: 130 vs 1 W/mK
- Heat load can only be applied on the silicon side
- Difficult to solder the fluidic connector: quick heating and cooling creates internal stresses.
- Glass makes it possible to visually inspect the CO_2 flow



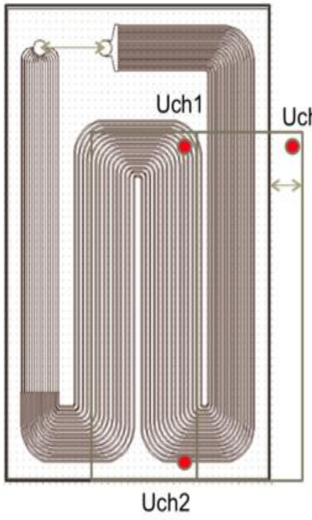


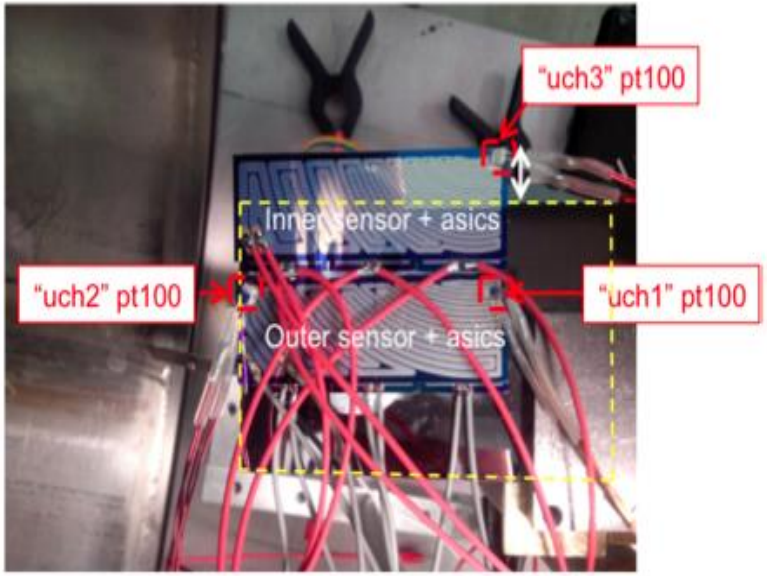
1st prototype: „Snake I”



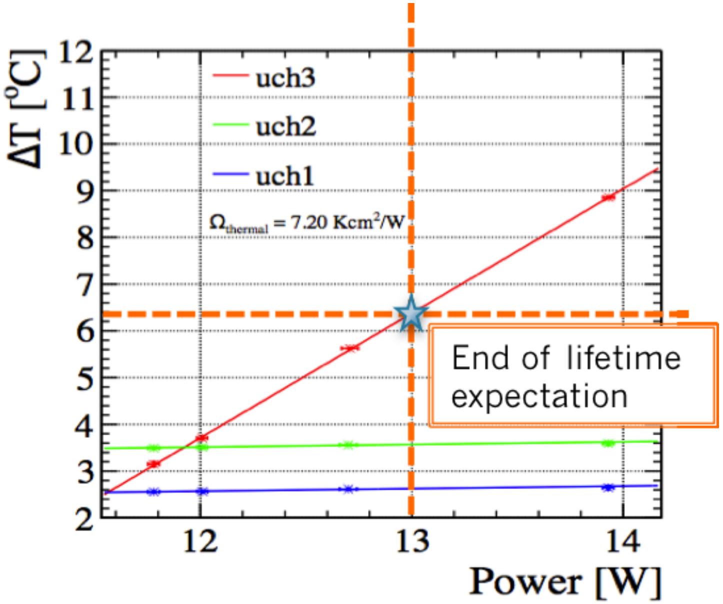
- Simple round holes as inlet and outlets for the liquid CO_2
- Very thin restrictions: turn out to be too thin.
- Microchannel geometry and active surface designed to represent half the thermal capacity of the VELO module

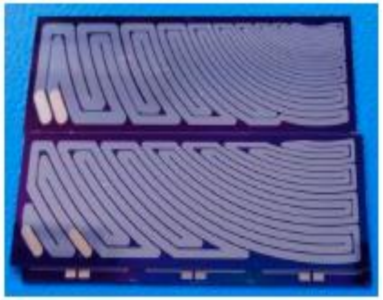
1st prototype: „Snake I" – first test in 2012





Glued surface: 11,34 cm2 CO2 connector



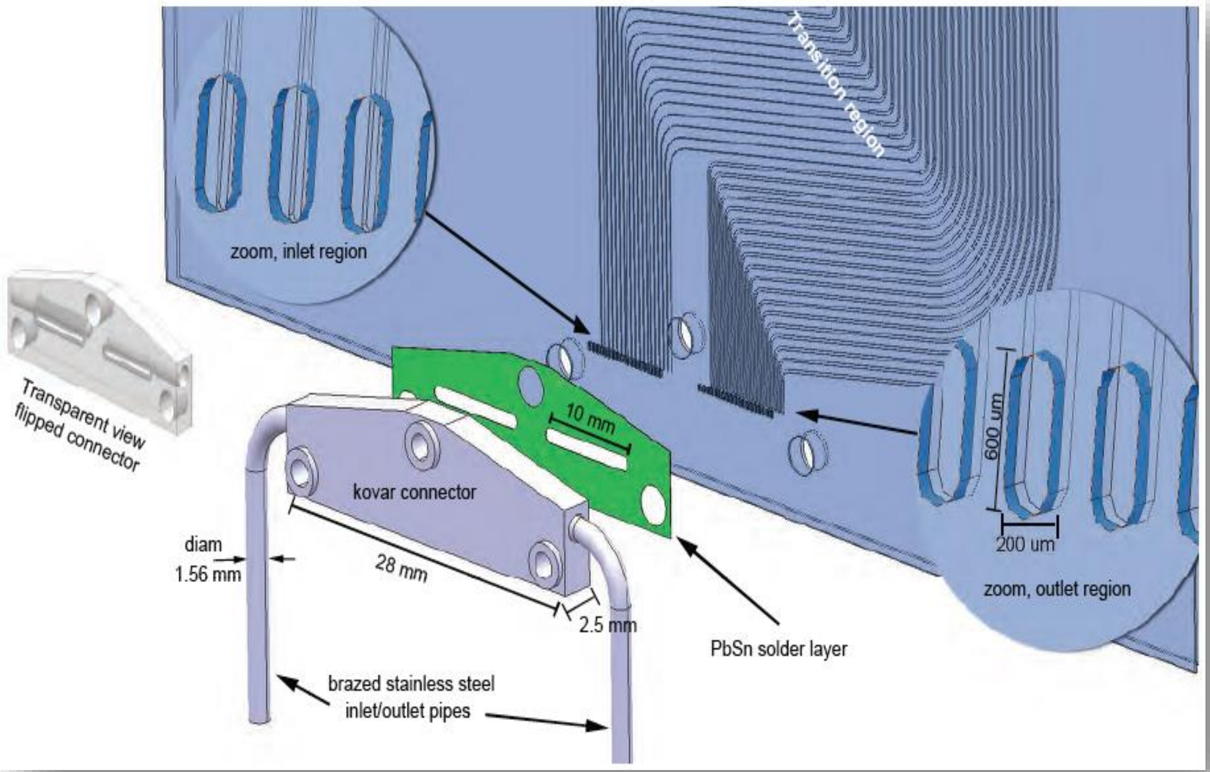


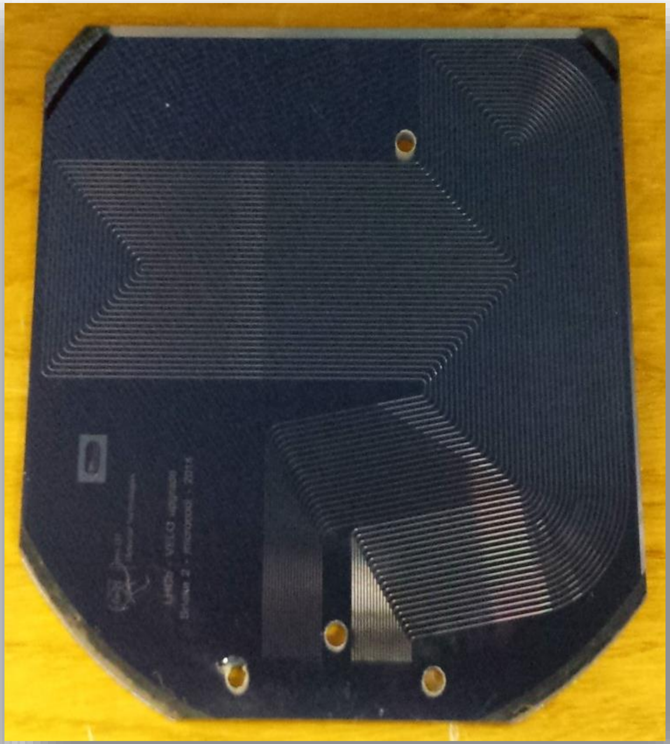
Sensor heaters

ASIC heaters

- Simple round holes as inlet and outlets for the liquid CO_2
- Microchannel geometry and surface designed to represent half the thermal capacity of the VELO module
- Thin-film heaters are used to generate heat load similar to the ASICs and irradiated sensors.
- Measurements show the tip of the sensor gets no higher than 7 °C above the flowing CO_2 temperature.

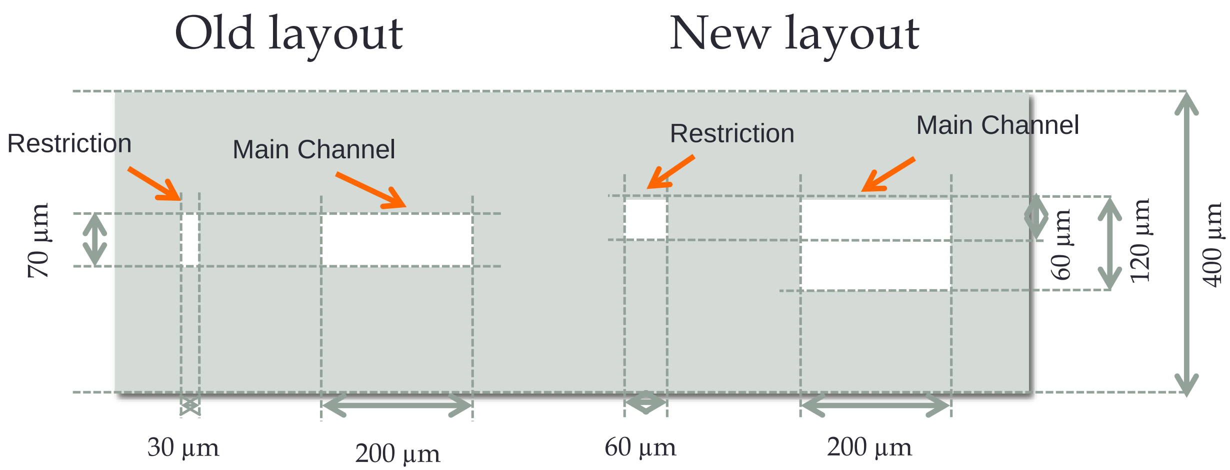
2nd prototype: Snake II





- New connector design, with holes for connector alignment during the soldering process
- Close-to-real layout of microchannels
- Designed to represent thermal capacity equal to a VELO module

Snake I vs II: channels dimensions



Designed to reduce fluidic resistance (by a factor ~4) while maintaining resistance to pressure:

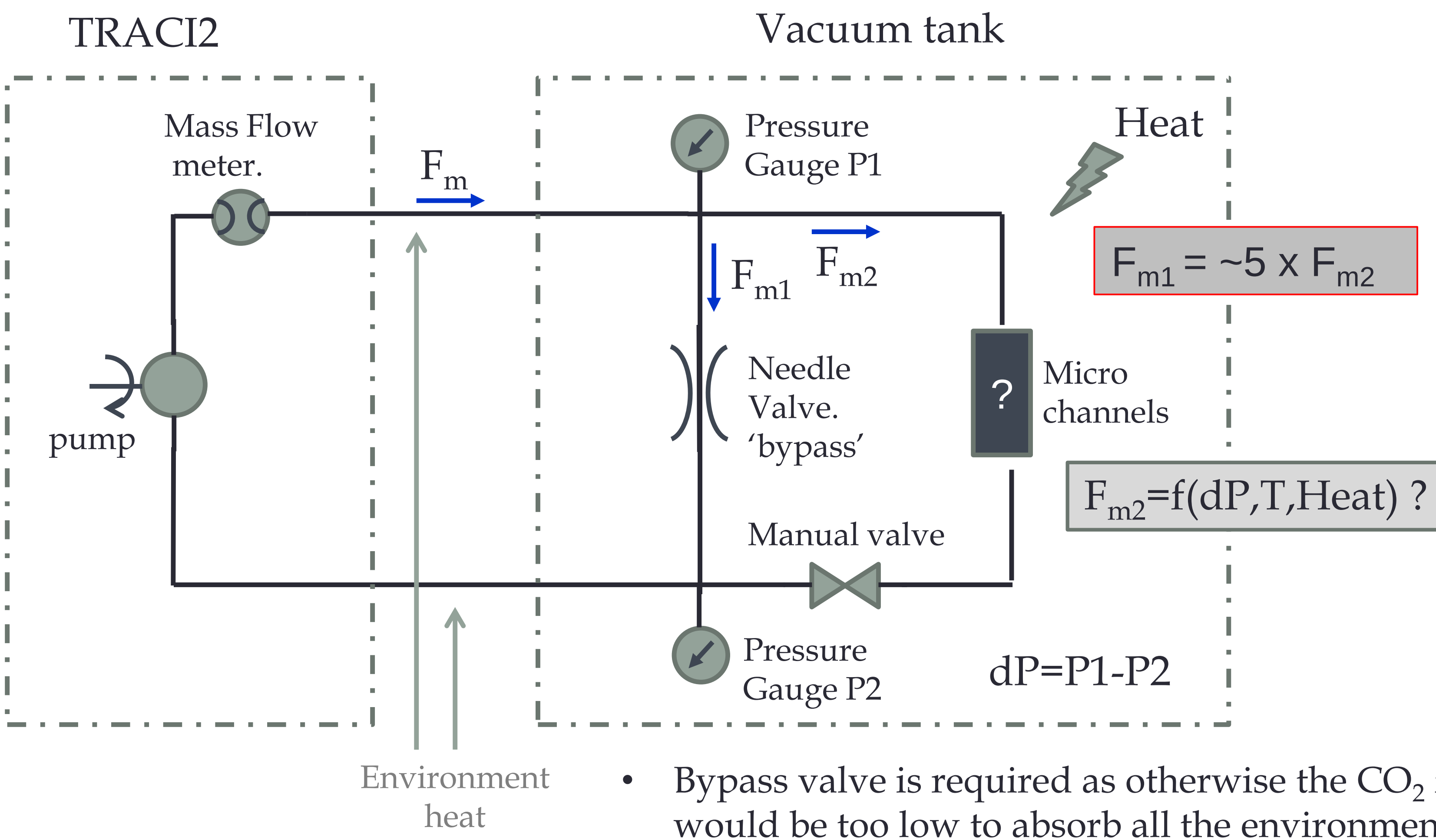
- Main channels have the same width (200 µm) but increased depth (120 µm)
- Restrictions made squared (60 µm x 60 µm) to avoid clogging

Considering the CO_2 is at -20˚C and assuming 30% vapor quality, we need a flow of 0.52g/s to dissipate 43 W/module. The pressure drop will be ~ 3 bar.

Fluidic characterisation

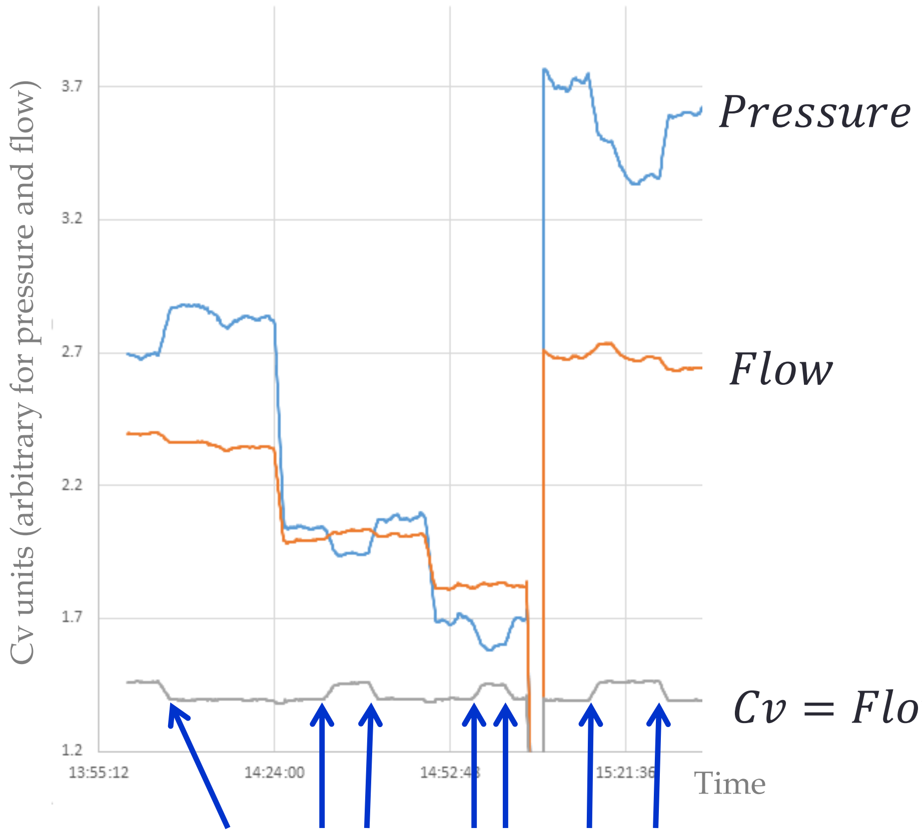
- Measure the CO_2 flow through the microchannel
- Measure fluidic „resistance" or dependency on the pressure
- Not a trivial task considering little flow levels: 0.05-0.5 g/s
- Important input for further geometry refinements and to the cooling factory design
- Needs the new TRACI with a strong pump (up to 8bar) to achieve full differential pressure range
- Connection to inlet/outlet is realized with clamps and o-rings.

Fluidic characterisation: system setup



- Bypass valve is required as otherwise the CO_2 flow would be too low to absorb all the environment heat and for the TRACI to stabilize.
- About 80% flow is through the bypass

Fluidic characterisation: Snake I

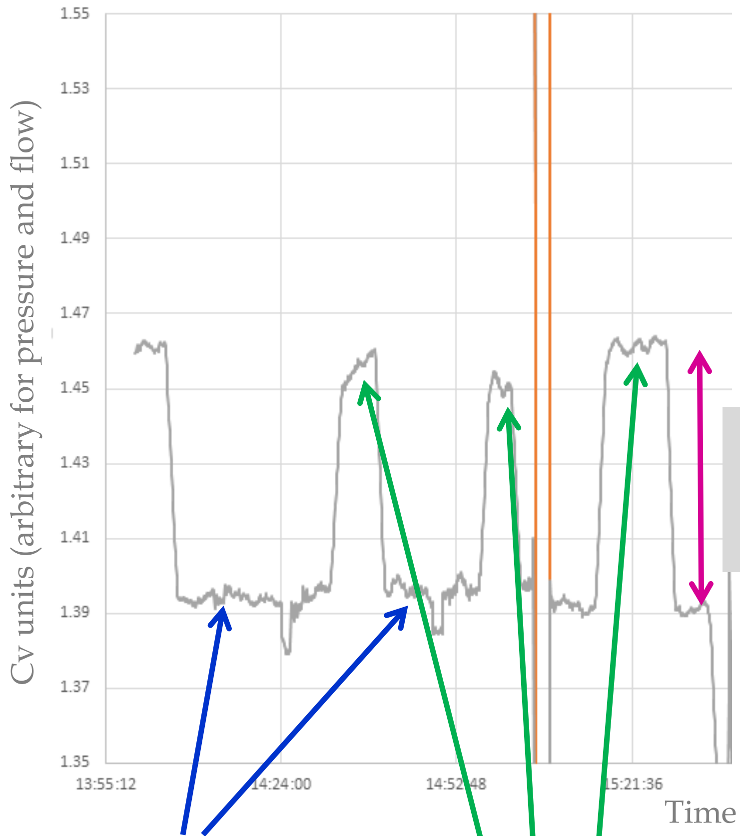


$$Cv = Flow/\sqrt{Pressure}$$

uChannel turned on/off
(manual valve)

- Flow vs pressure characteristic fits very well the „orifice" model, where the flow is proportional to the square root of the pressure (as oposed to the „resistance" model where flow is proportional directly to the pressure).
- Once a good model is established, it simplifies the measurements as the bypass valve and the microchannels can be characterized by a single number: the flow coefficient Cv
- There is still certain dependency on the temperature as the specific density of the fluid changes (we measure mass-flow not volume-flow coefficient)

Fluidic characterisation: Snake I



$$Cv = 0.065 \frac{\frac{g}{s}}{\sqrt{bar}}$$

$Cv\ [valve]$

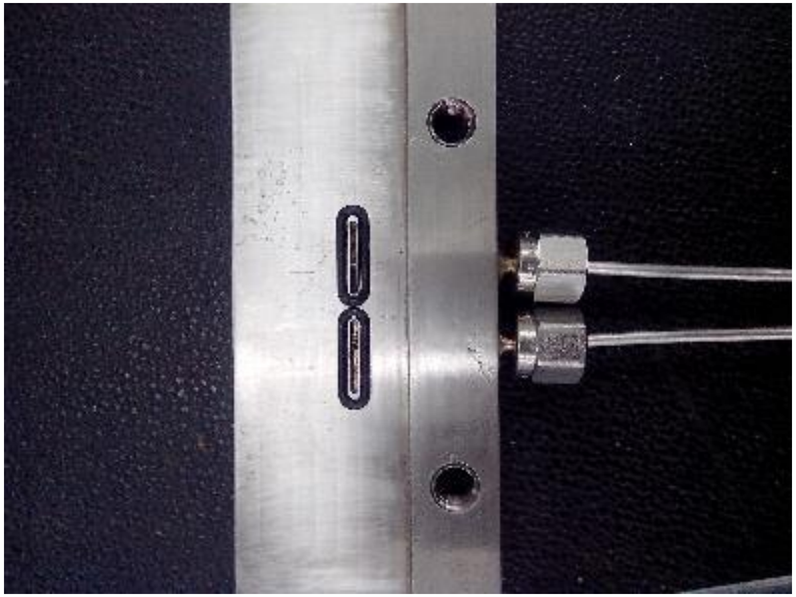
$Cv\ [valve + microchannel]$

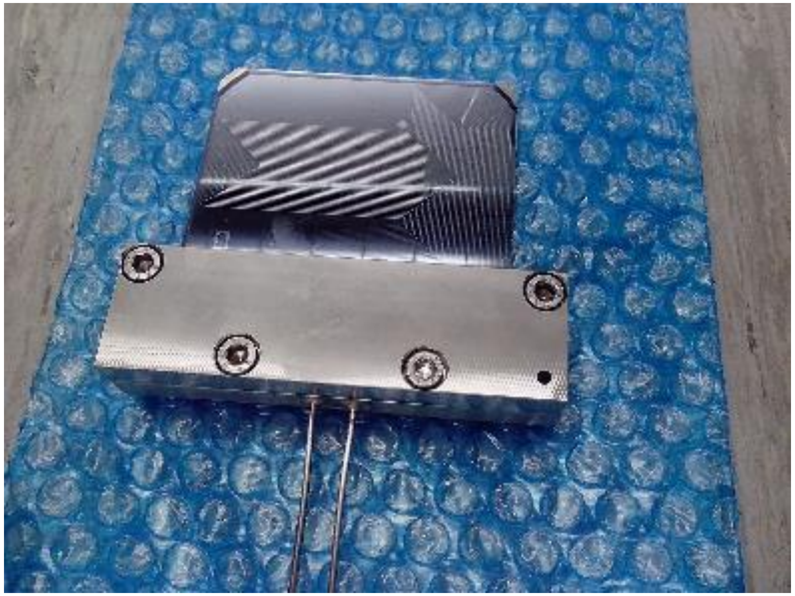
Flow coefficient of the Snake I prototype was measured, thus knowing the differential pressure the flow can be easily calculated. E.g. at 4 bars the flow is 0.13 g/s

Flow coefficient measurement is now trivial: turn on and off the bypass valve and that's it !

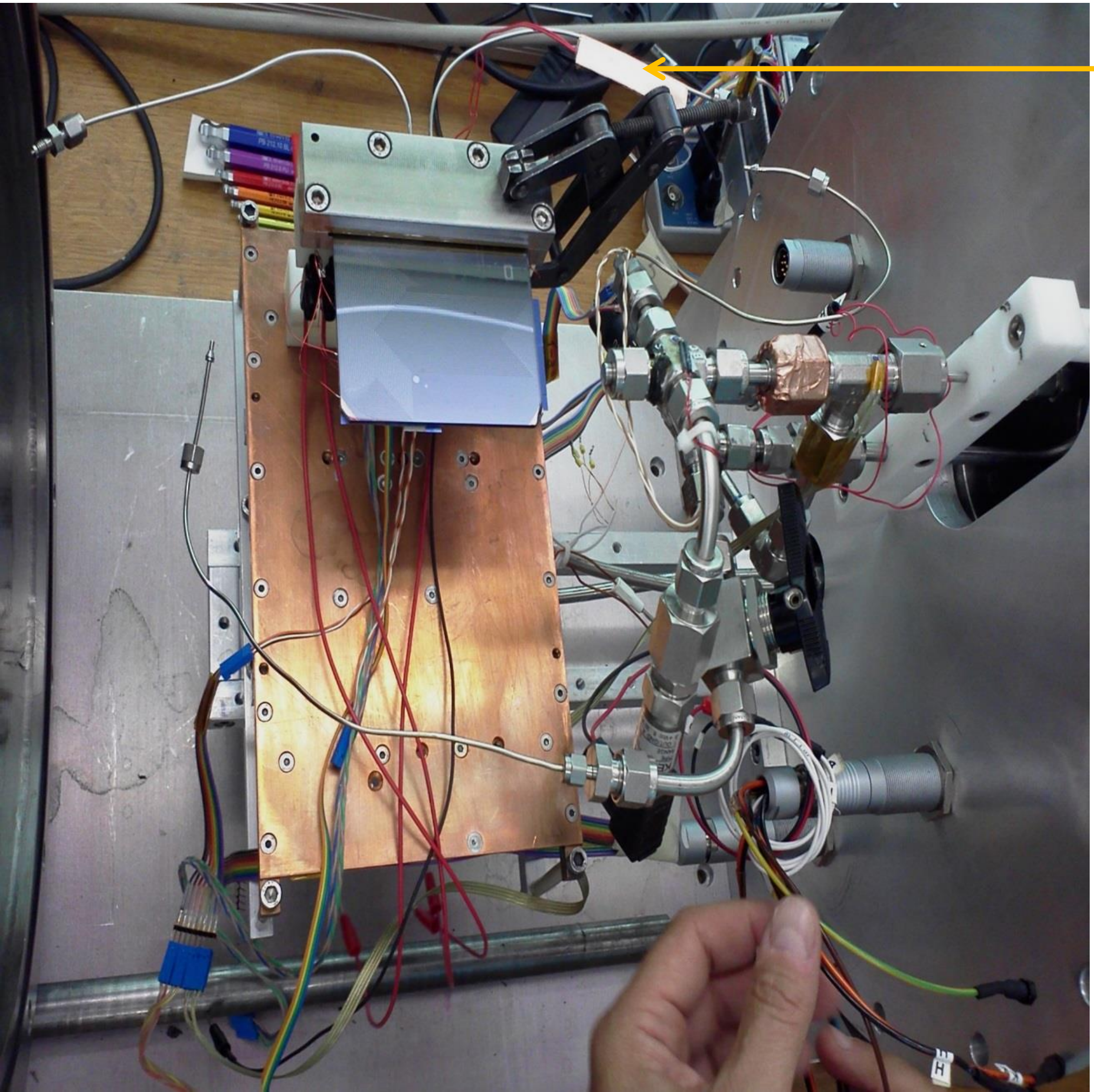
Fluidic „clamp" connector for Snake II

- Metallic clamp with O-rings.
- Sample is in contact with the metal block only on the pyrex side (good heat isolator) and not on the Si side.
- The cooling tubes are in contact with the metal block.





Snake II in the TRACI cooling system



Pre-heater on the CO_2 inlet tube: 5-10W

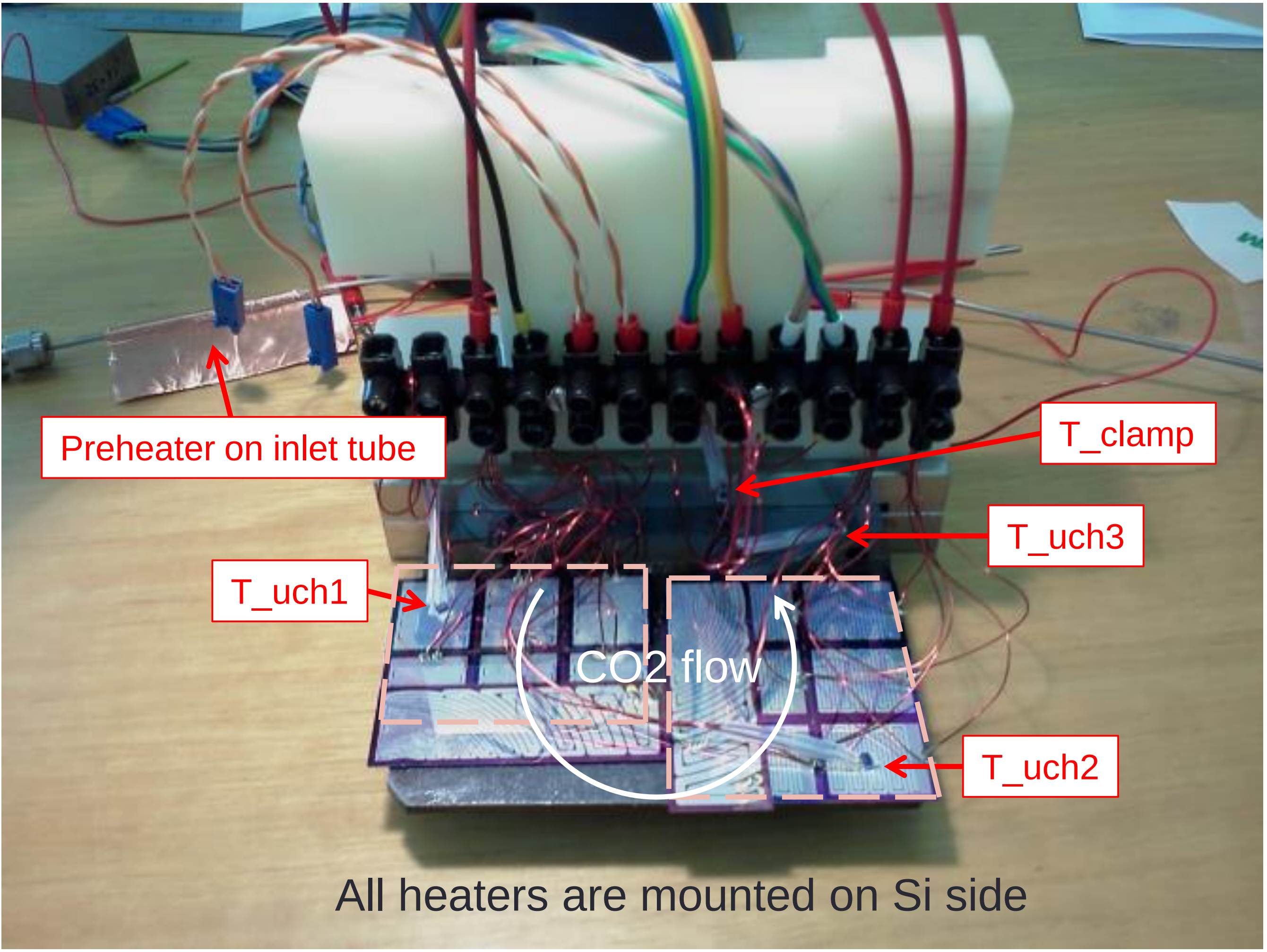
Snake II flow coeff. is three time the Snake I – designed factor was 4, thus a good match.

Prototype measured	Cv $[\frac{g/s}{\sqrt{bar}}]$
Snake I	0.065
Snake II	2.10

Heat load tests

- Prototype wafer is heated on the silicon side
- Heaters are made of silicon (like ASICs and sensor) with a thin film deposit working as the actuall electric heater.
- Temperature is recorded at two different points on the heaters and at the wafer close to the outlet.
- Heating power is applied in steps
- As larger and larger part of CO_2 evaporates, eventually there is no cooling power left and the outlet temperature shoots up.
- We don’t go beyond this point

Heat load tests of Snake II – fitting the heaters



- Heaters attached on the silicon side to cover completely the surface above microchannels
- 3M tape used for the attachment
- ASIC heaters wired in parallel and split into two groups.
- Four temperature probes strategically placed:
  1. on a heater closest to the inlet
  2. on a heater half-way
  3. on silicon close to the outlet
  4. on the mounting block
- Note the pre-heater on the inlet tube

Snake II heat load test at -15 ºC

Differential pressure in the system [bar]:
Red = measured
White = averaged

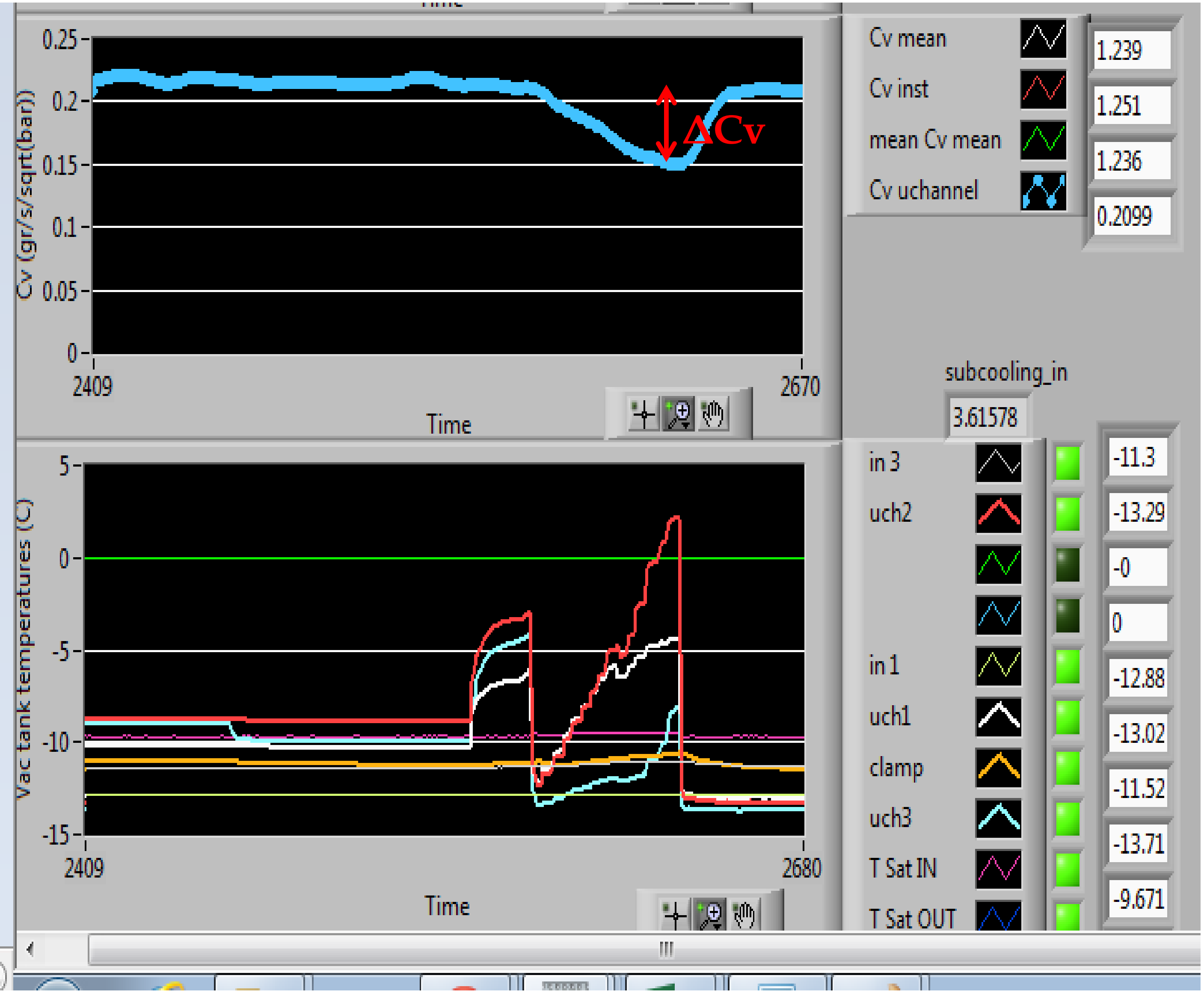
Flow through the system [g/s]:
Red = measured
White = averaged

Microchannel flow coefficient calculated after subtracting the bypass valve contribution to the total flow $[\frac{g}{s}/\sqrt{bar}]$

Temperatures measured at various points:

1. White = heater close to inlet
2. Red = heater half-way
3. Cyan = silicon near the outlet
4. Orange = clamping block

Snake II heat load test at -15 ºC – cont.



Notice the flow coefficient drop (by about 0.06) when power is applied. This drop is relatively small at room temperature but becomes significant below zero, most likely due to rising viscosity. CO_2 viscosity has strong dependence on temperature

Notice how white and red follow each other for certain time and then white and red start to separate: this is when the 2nd part is not getting same quality cooling as the 1st part due to CO_2 dry out

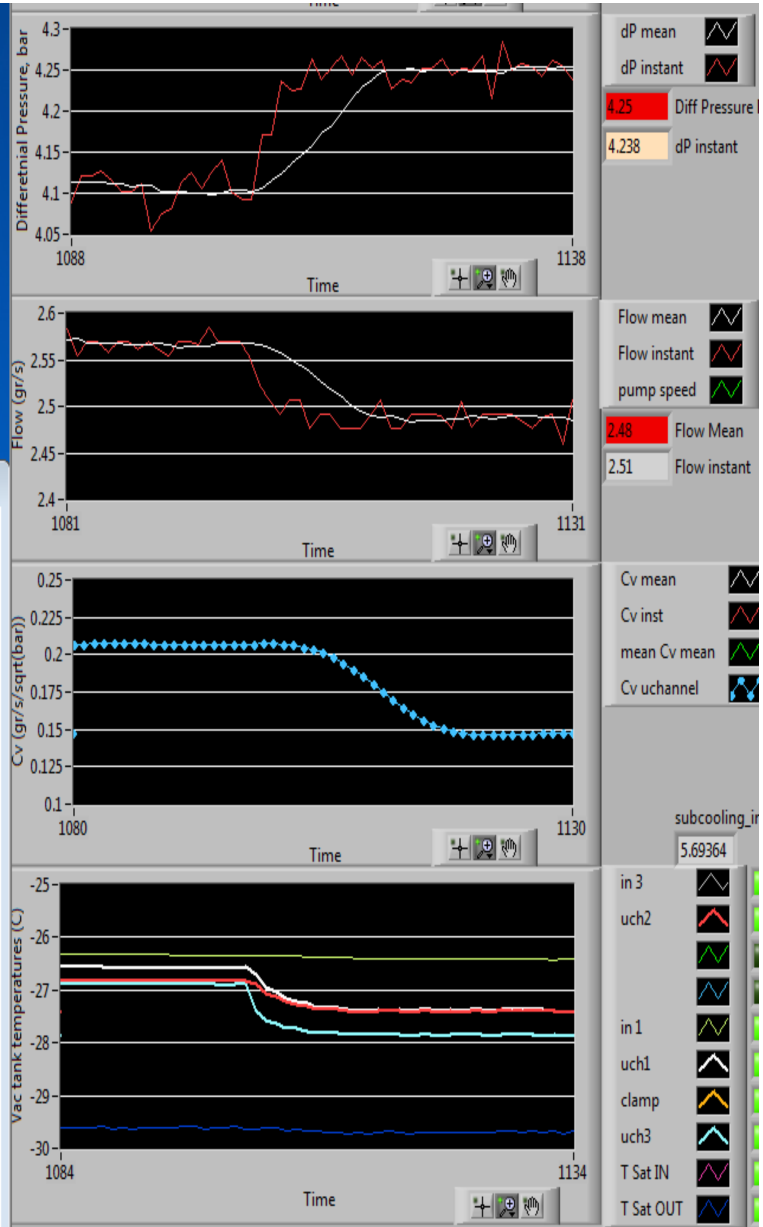
At power close to the capacity the silicon temperature at the outlet (cyan) begins to rise: liquid and gas are no longer at equilibrium.

Heat load test summary

Temp [ºC]	Cv @ no heat load	Cv @ max. Heat load	ΔCv	Pmax. [W]
-25	0.206	0.13	0.076	60
-15	0.210	0.15	0.060	66
-5	0.216	0.16	0.056	66
+5	0.212	0.17	0.042	58
+15	0.189	0.16	0.029	57

- Data recorded at 4 bar diff. pressure
- Well over max. expected heat load (40W/module) can be achieved
- Vapor quality ~75÷80% - thus good part of CO_2 is actively absorbing the heat.
- At low temperatures the flow coeff. drops significantly when boiling starts: by as much as 1/3
- At chosen diff. pressure the max. power does not depend very much on temperature. But we have seen with Snake I this is not true for all operating points.

Flow coeff. changes just becasue the CO_2 begins to boil



Pressure: rises when the CO_2 starts to boil. It is only triggered by the pre-heater – there is no other thermal load applied here

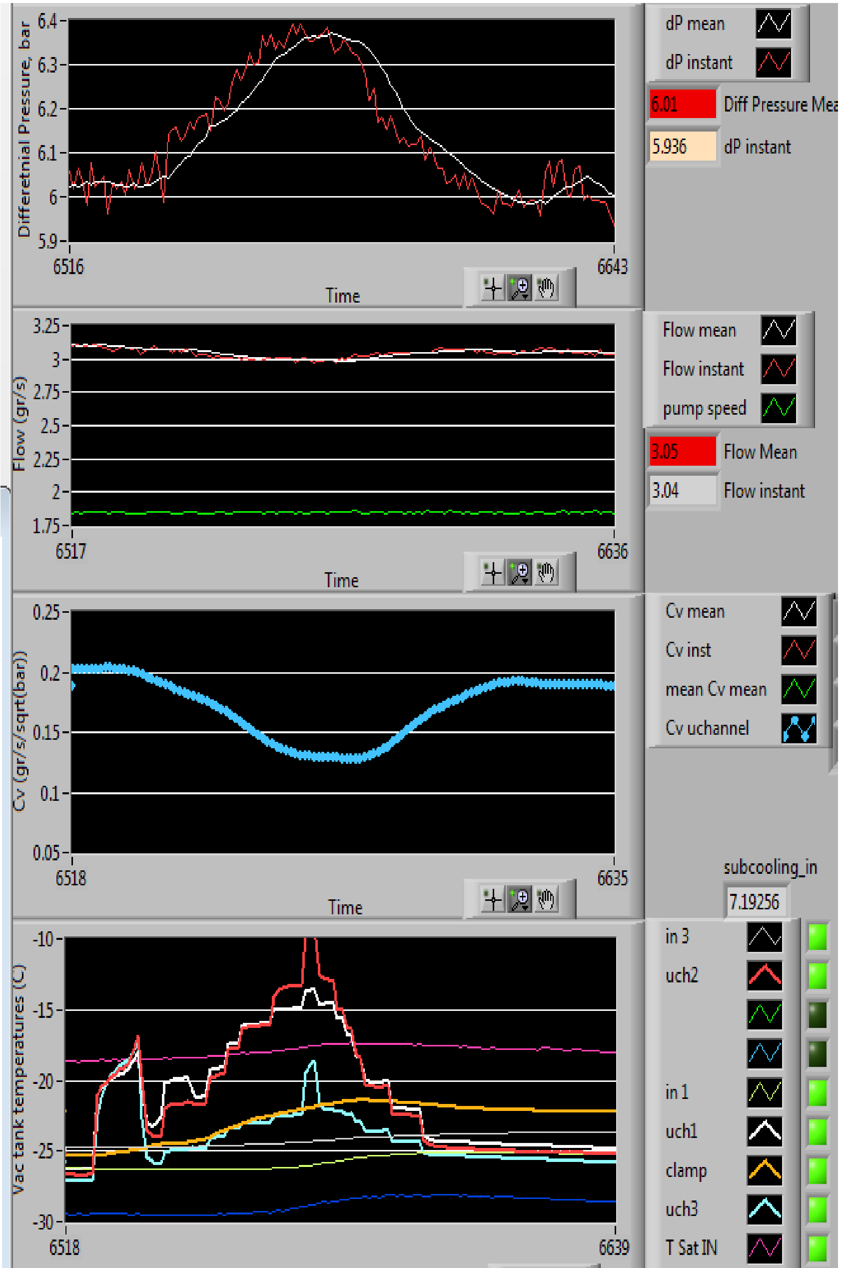
- Red = measured diff. pressure
- White = averaged diff. pressure

Flow through the system: drops when boiling starts
Red = measured flow (bypass + microchannel)
White = averaged flow

Microchannel flow coeff. drops by 0.06 when boiling starts.

Temperatues: drop, when CO_2 exits super-heated state, begins to boil and cools down

Heating test at -30 ºC and 6 bar diff. pressure

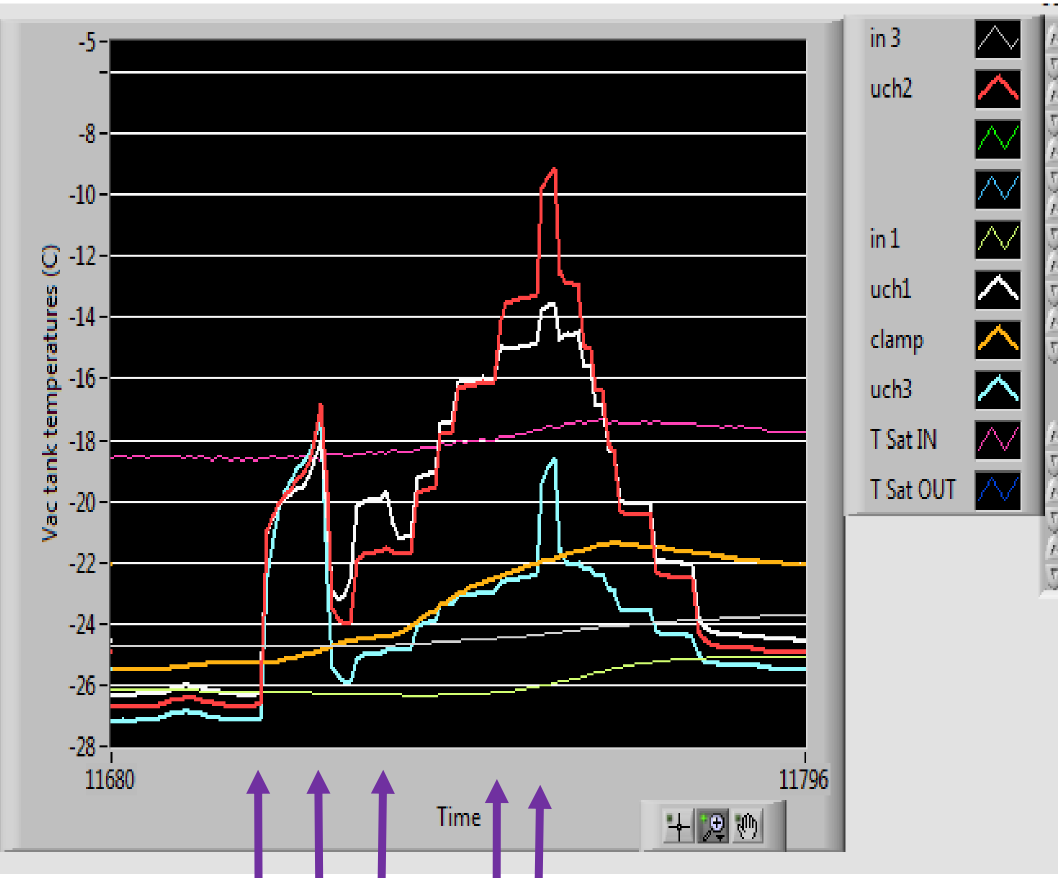


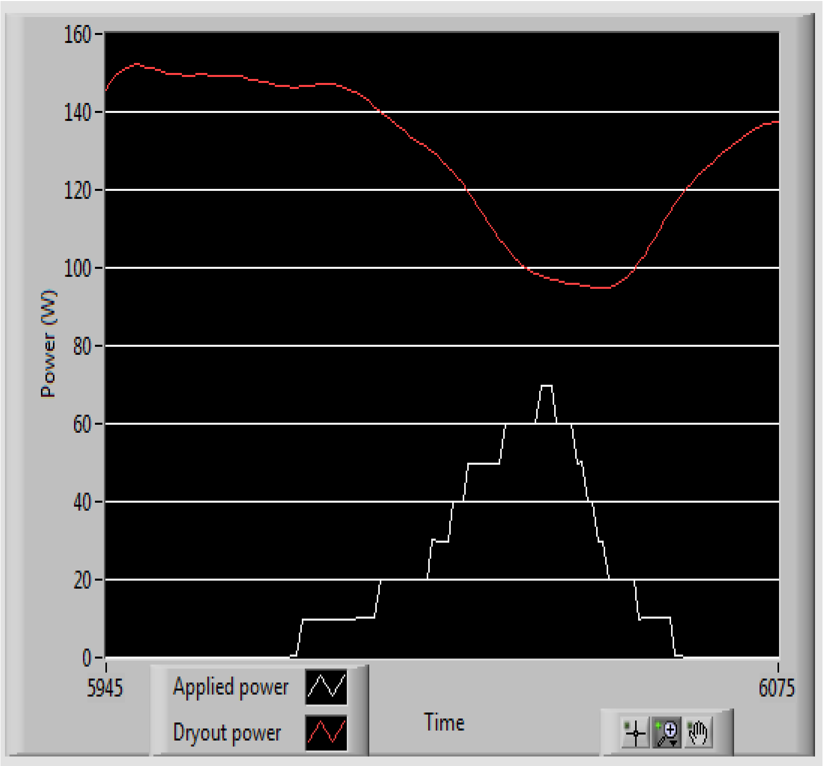
Diff. pressure rises by 0.3 bar as the flow coeff. drops.

Flow coeff. of the microchannel drops by 1/3 as the boiling starts.

After the first 10W of load is applied all three temp. sensors go up in exact same pattern: CO_2 is superheated and does not want to boil. Pre-heater has to go into action.

Heating test at -30 ºC and 6 bar diff. pressure





At 70W the outlet temperature jumps up – we stop here

At 60W white and red start to separate

Pre-heater applied again and sustained, as some channels stop to boil

Pre-heater applied to trigger the boiling

10W applied but all temperatures go up and follow each other

Applied power (white) and max. theoretical power (red) derived from CO_2 flow and latent heat. Note that the red curve is delayed as it is based on averaged CO_2 flow coeff.

Summary

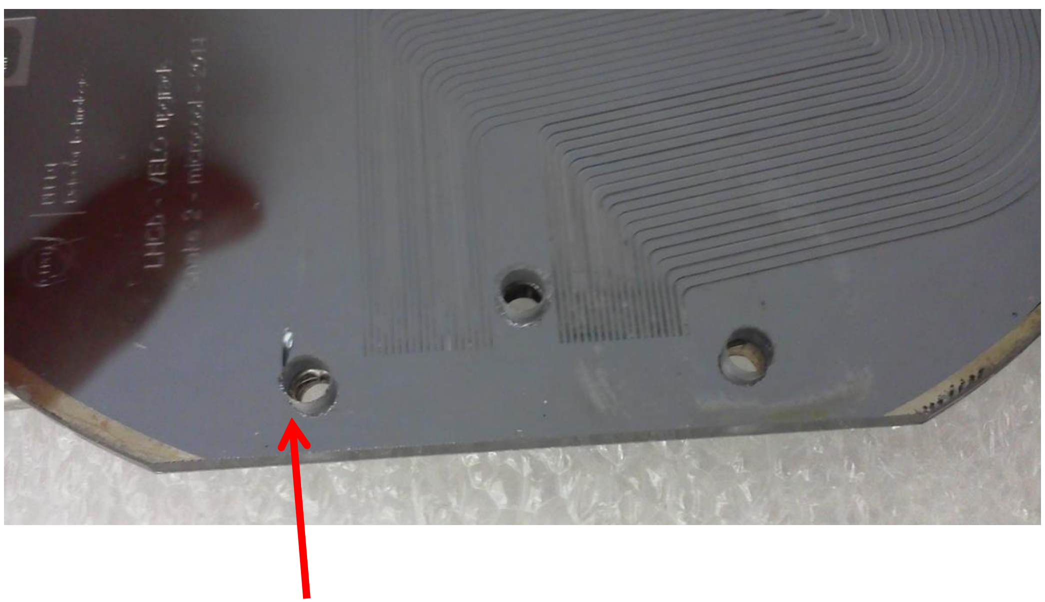
- Snake II prototype has been measured in terms of flow and cooling performance
- Nominal performance is easily achieved with 4 bar of diff. pressure and 0.4 g/s CO_2 flow per module
- Super-heated effects can be observed and controlled with pre-heating the liquid on the inlet.
- Work on the soldering and obtaining good strength progresses.

Credits

- Snake I and II prototype are produced at CMI in EPFL Lausanne.
- TRACI's are assembled at CERN, piping done in Sheffield
- Clamp for the SNAKE II prototype was built in Oxford
- Soldering/pressure tests were done at CERN and in Oxford
- Flow and thermal load tests were conducted at CERN.

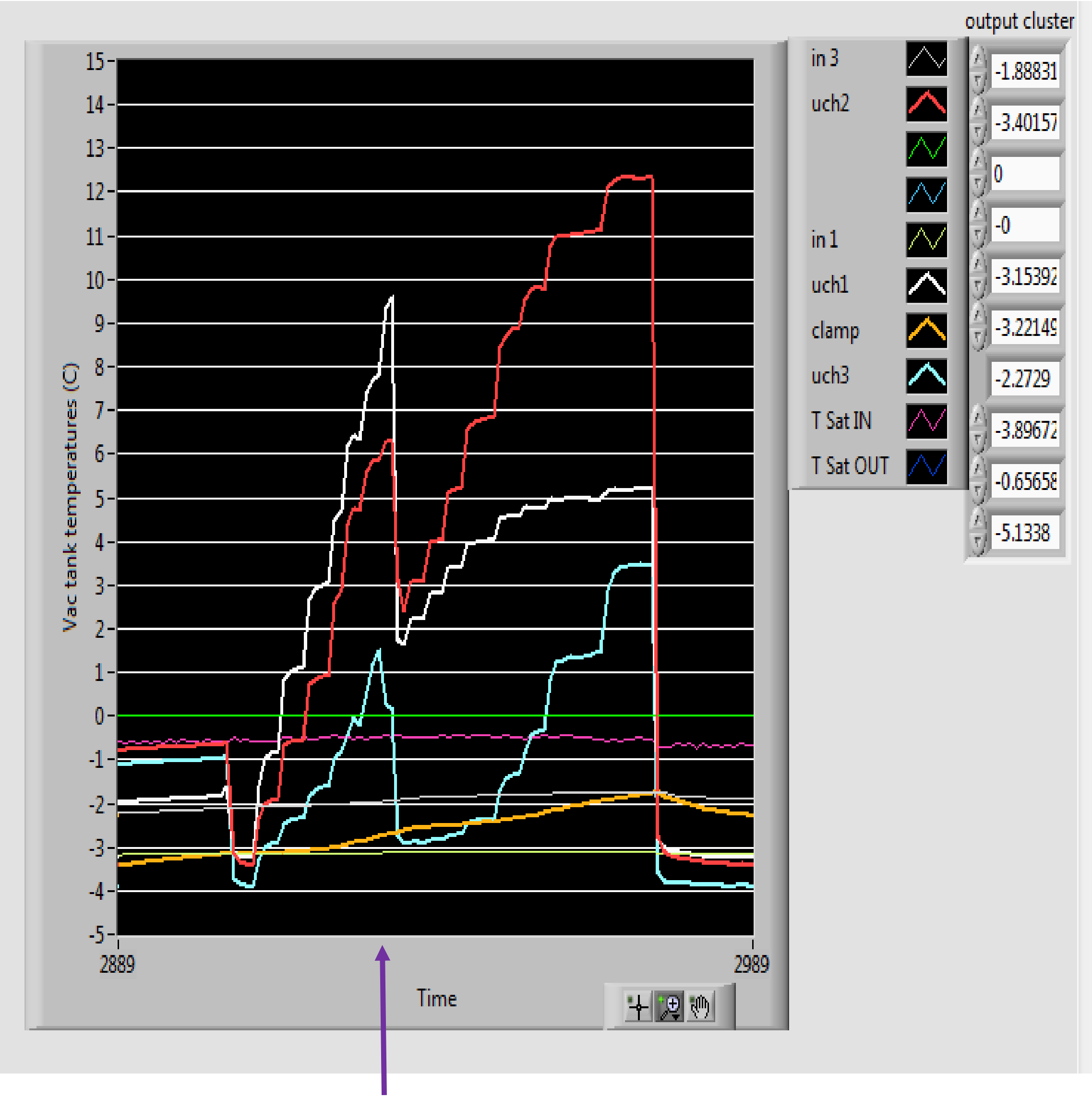
BACKUP SLIDES

Soldered fluidic connector for Snake II



- Flows water and withstands at least 90 bar of pressure (not tested higher)
- Cracks in pyrex develope around the holes and seem to follow the connector shape
- Not tested (yet) with liquid CO_2
- This far all measurements of flow and thermal performance done on the clamped Snake II prototype.

Super-heated states: heating test at -5 ºC

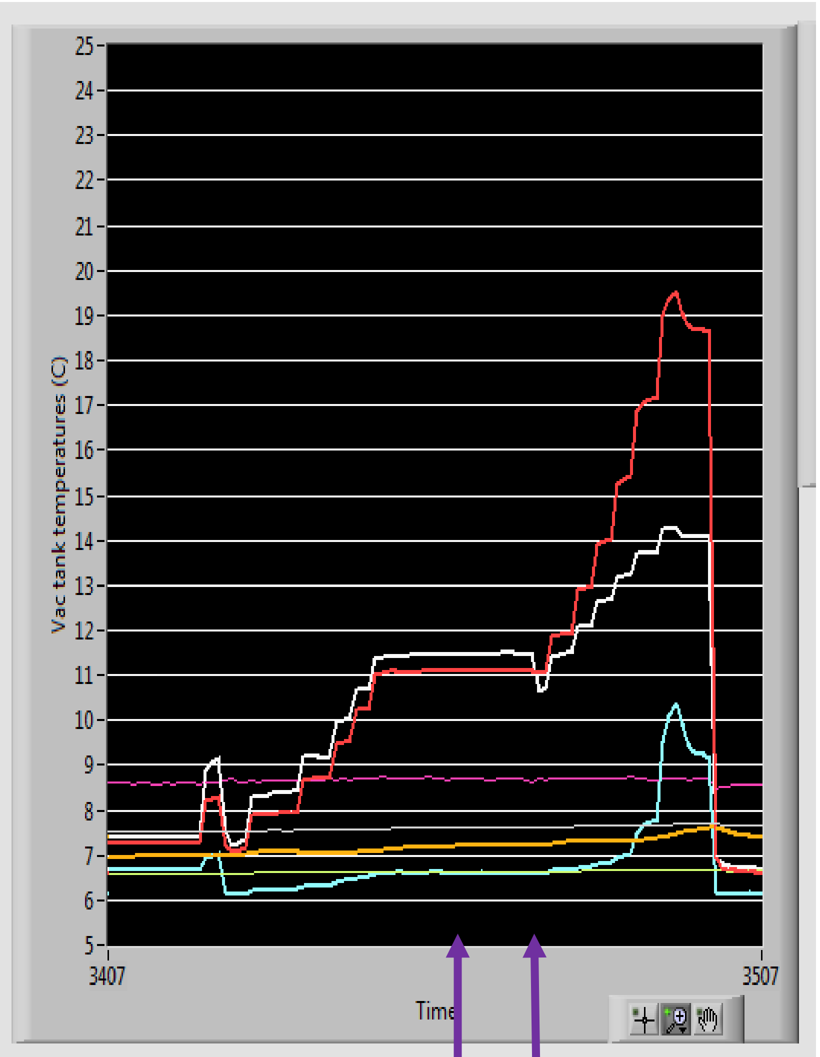


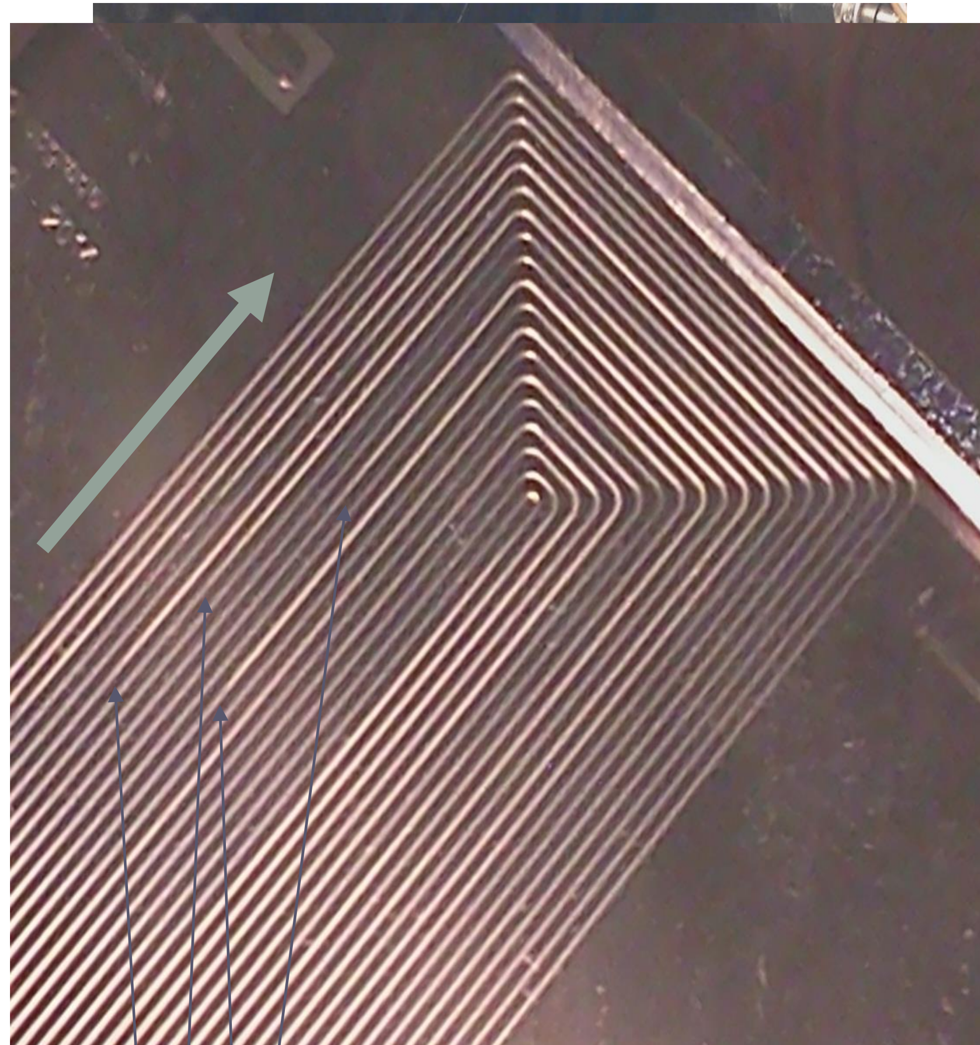
Pre-heater power (6W) applied.
Heating power was already 35W.

Notice how the temperatures were rising quickly in the first part of the test. Some channels were not boiling. When pre-heater power was applied, all channels began to boil, cooling became more efficient and the temperatures fell by more than half.

It was observed that CO_2 enters the super-heated state very easily and triggering it to boil is not trivial. Heater on the inlet pipe is best method found this far.

Super-heated states: heating test at +5 ºC



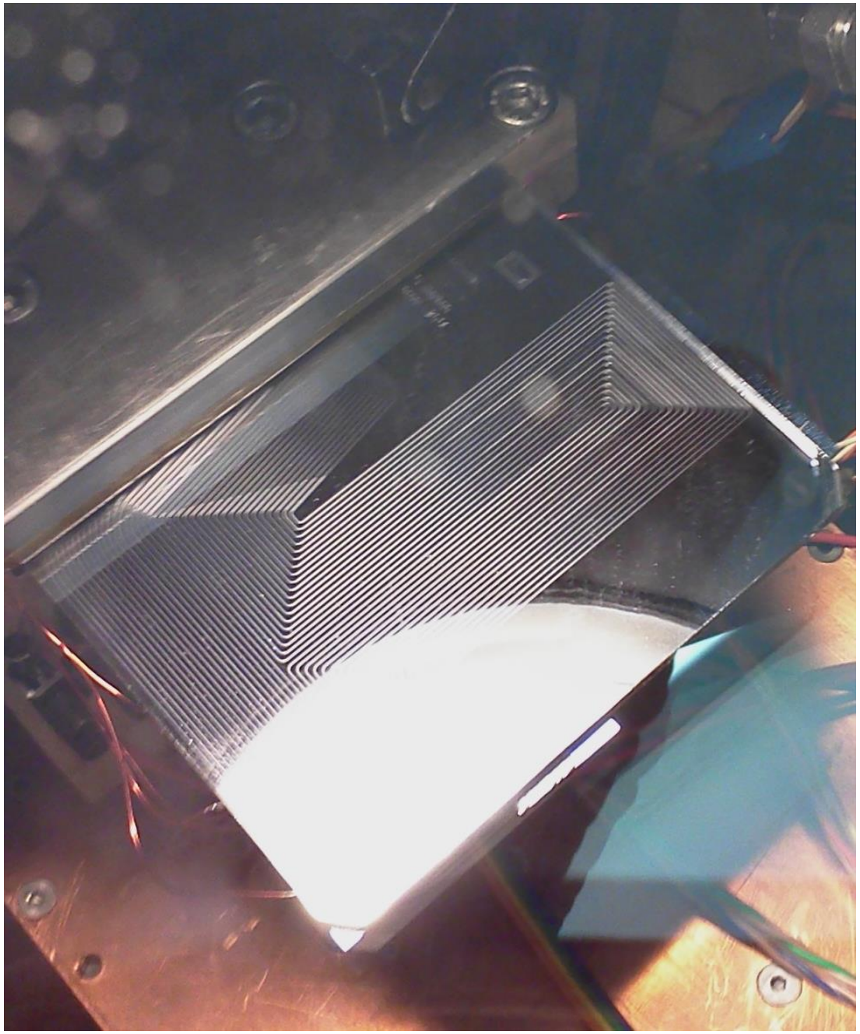


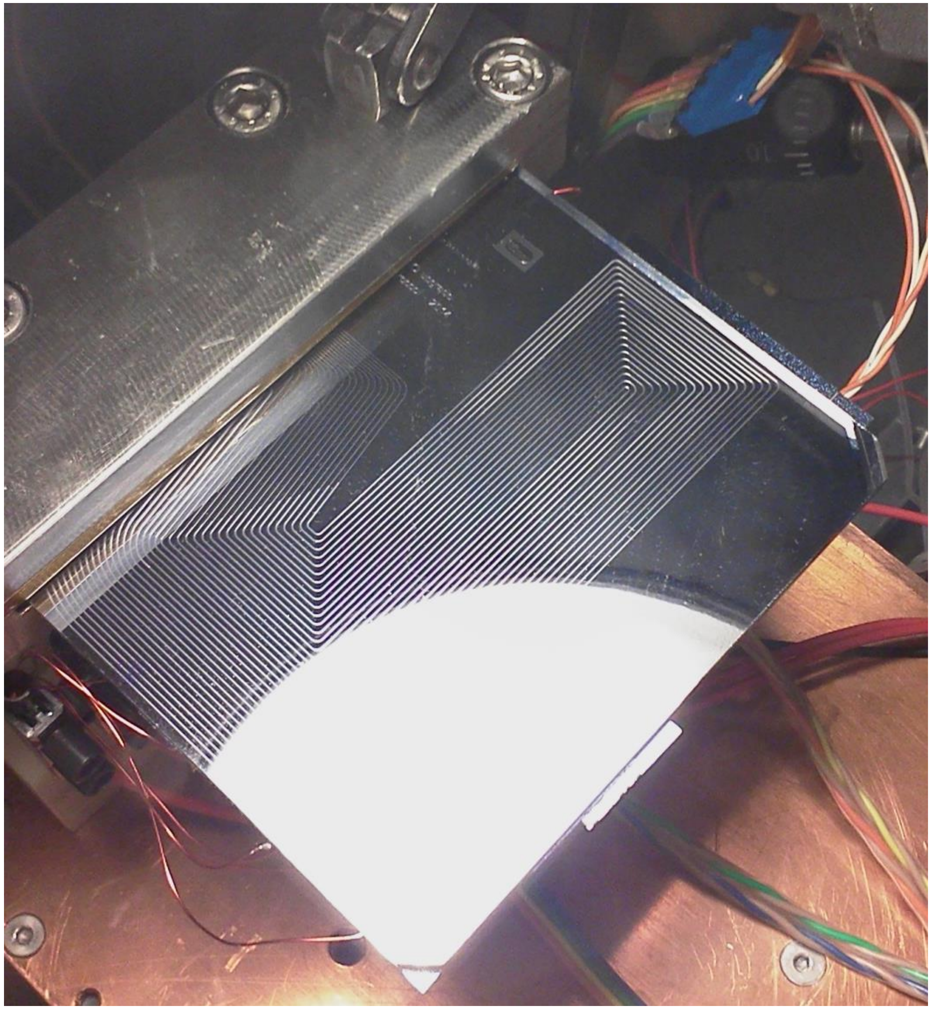
Pre-heater power applied

Channel picture (on the right)

Do different channels start boiling at different points ?

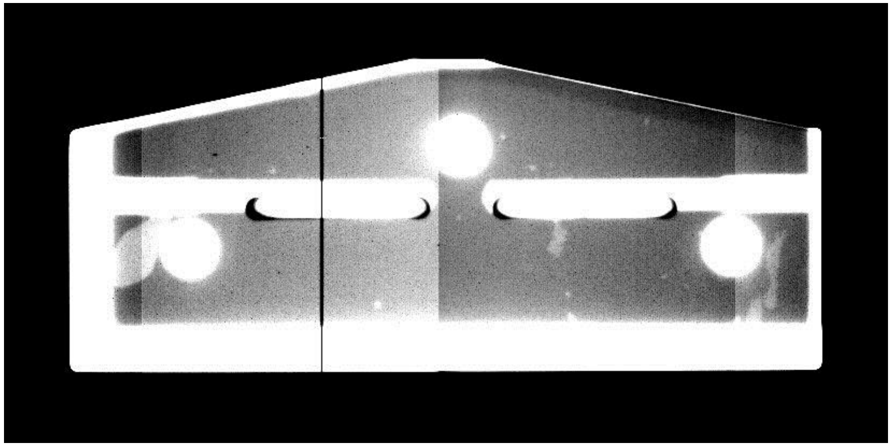
Partial boiling states

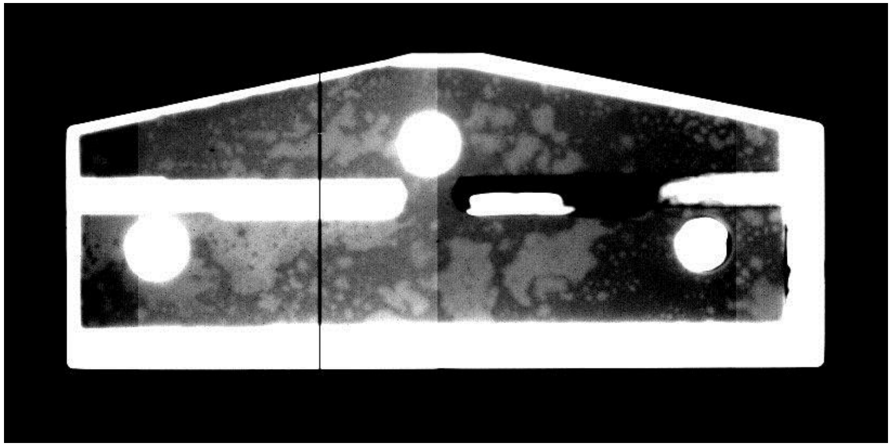




X-ray imaging of soldering samples

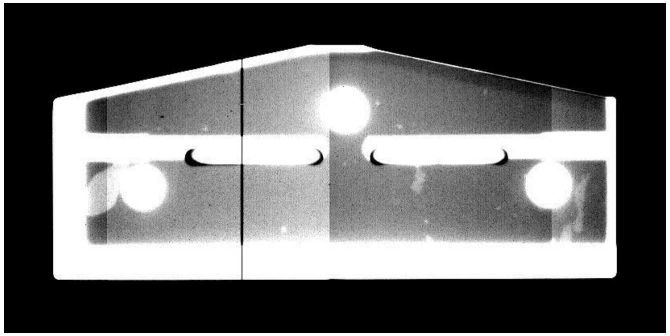
- Access to a local lab with an x-ray tube up to 160kV and a flat-panel imaging detector
- Setup almost ready to test production wafers
- Sample pictures (good and bad):





Testing the soldering joint under constant load

Connector soldered to silicon: two screws glued on both sides

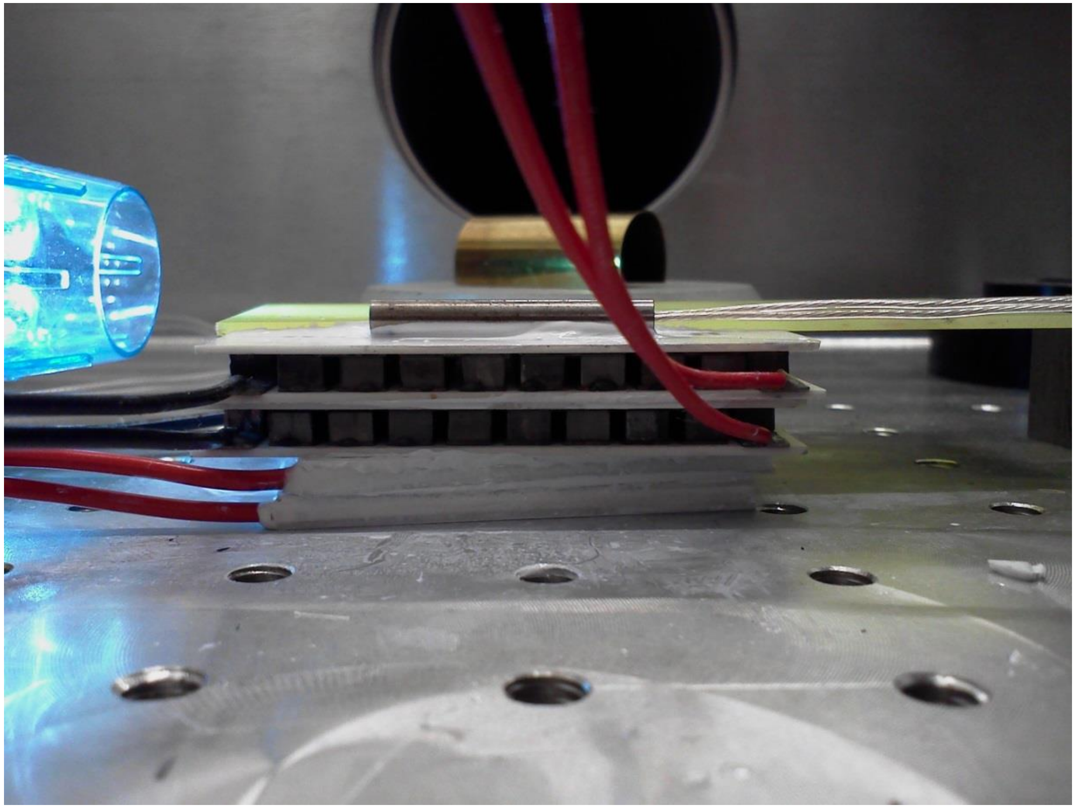


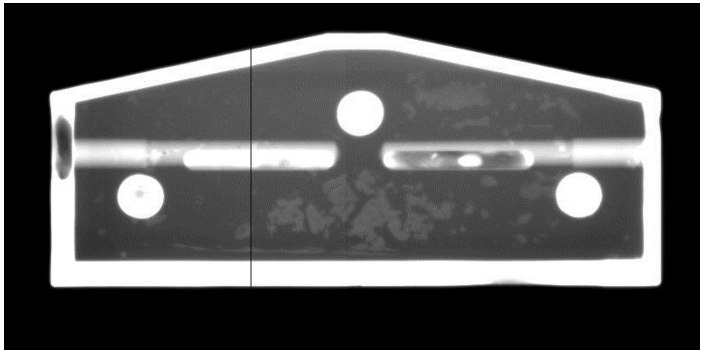
6÷12 kG weight

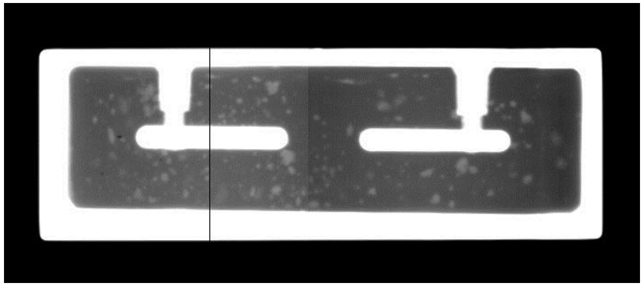
Soldering in vacuum

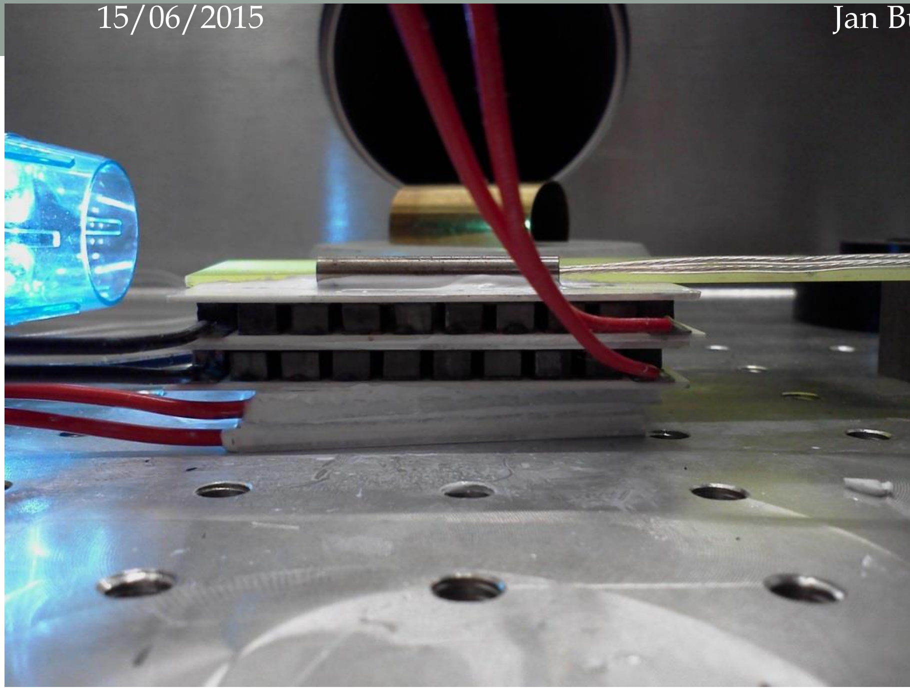
Peltier stack as heater and cooler

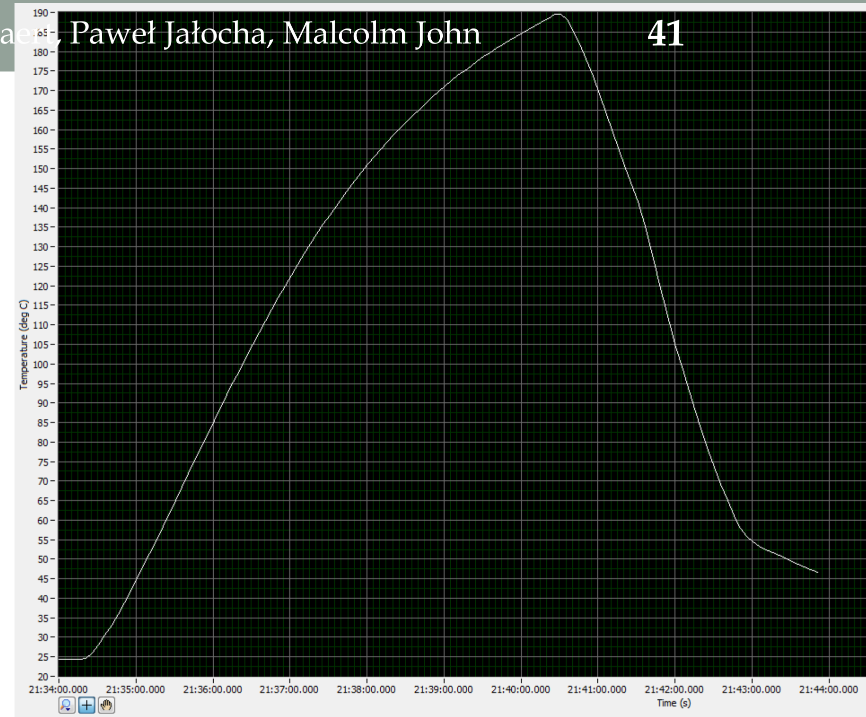
- 4 Peltier units can both warm up and actively cool down.
- Can go to 180 degrees in few minutes, even quicker come back.
- USB microscope for visual check of the soldering process
- Works well to warm or pre-warm the wafer
- Separate IR heater (halogen bulb) heats the connector.










Temperature (deg C)
190
180
175
170
165
160
155
150
145
140
135
130
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
21:34:00.000
21:35:00.000
21:36:00.000
21:37:00.000
21:38:00.000
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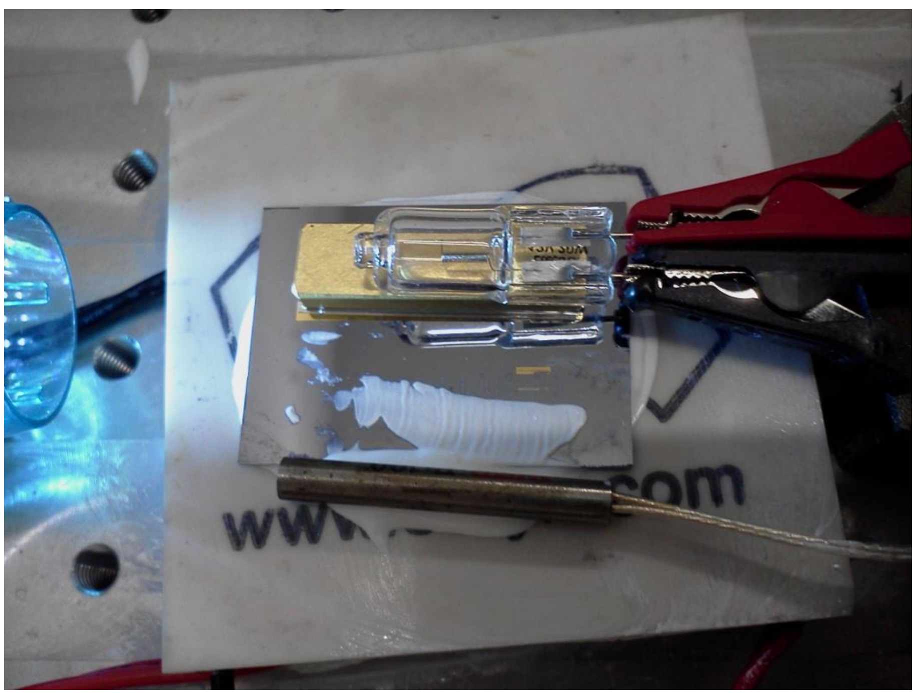
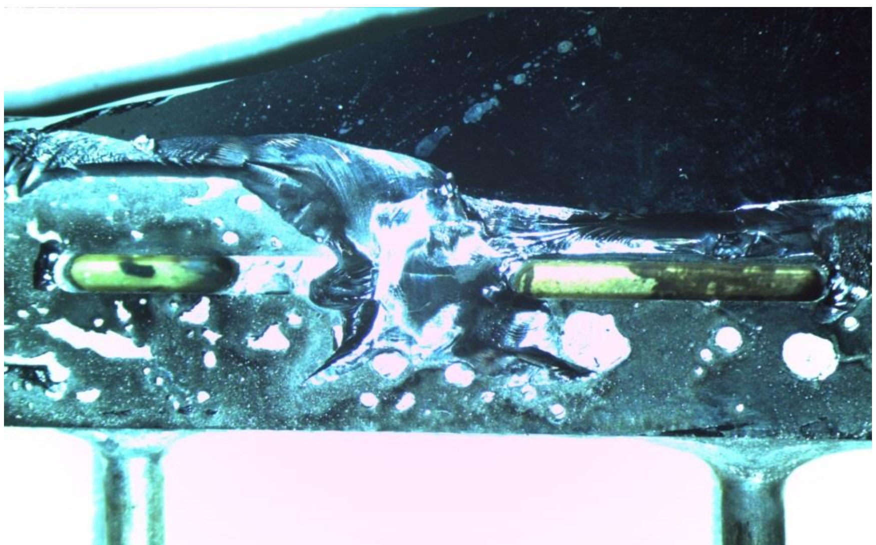
21:40:00.000
21:41:00.000
21:42:00.000
21:43:00.000
21:44:00.000
Time (s)

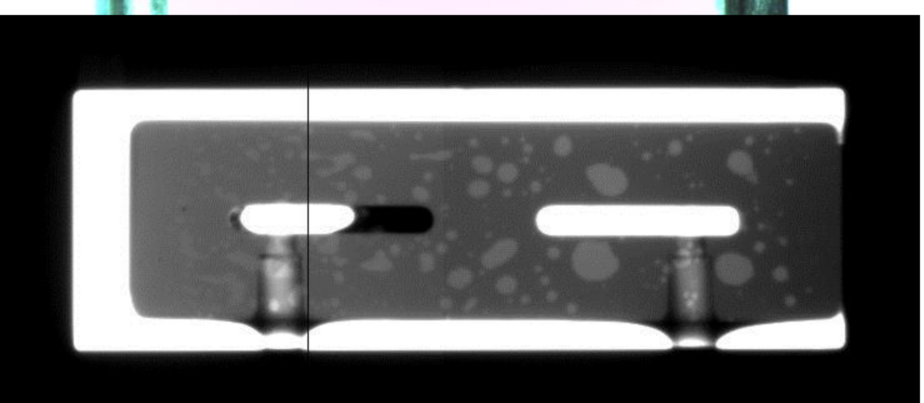


Pressure tests

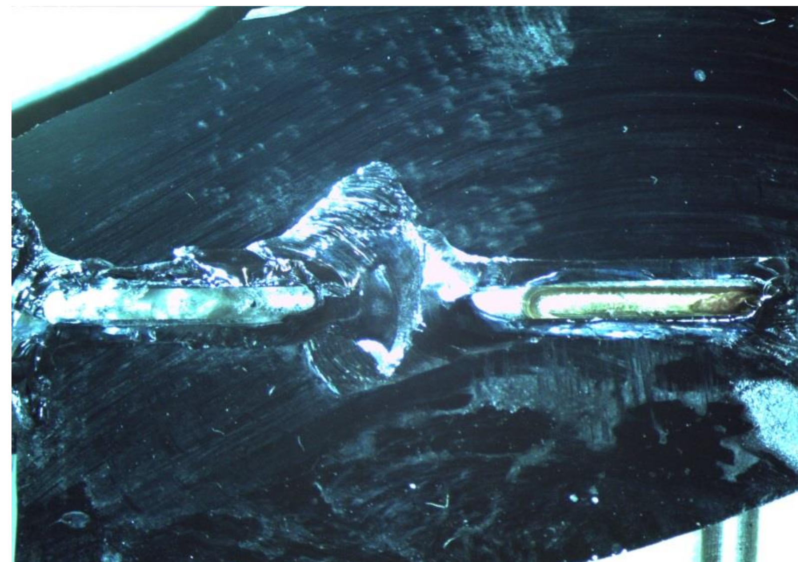
Brass connectors, soldered with organic flux

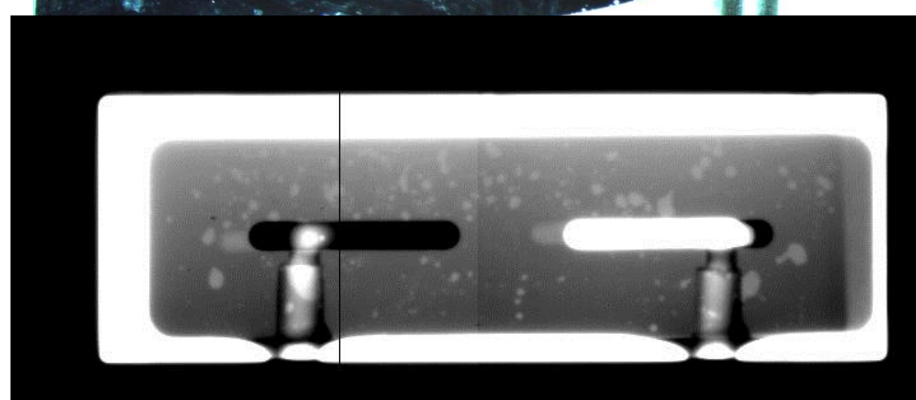
- Delamination ?
- <20bar, 150bar





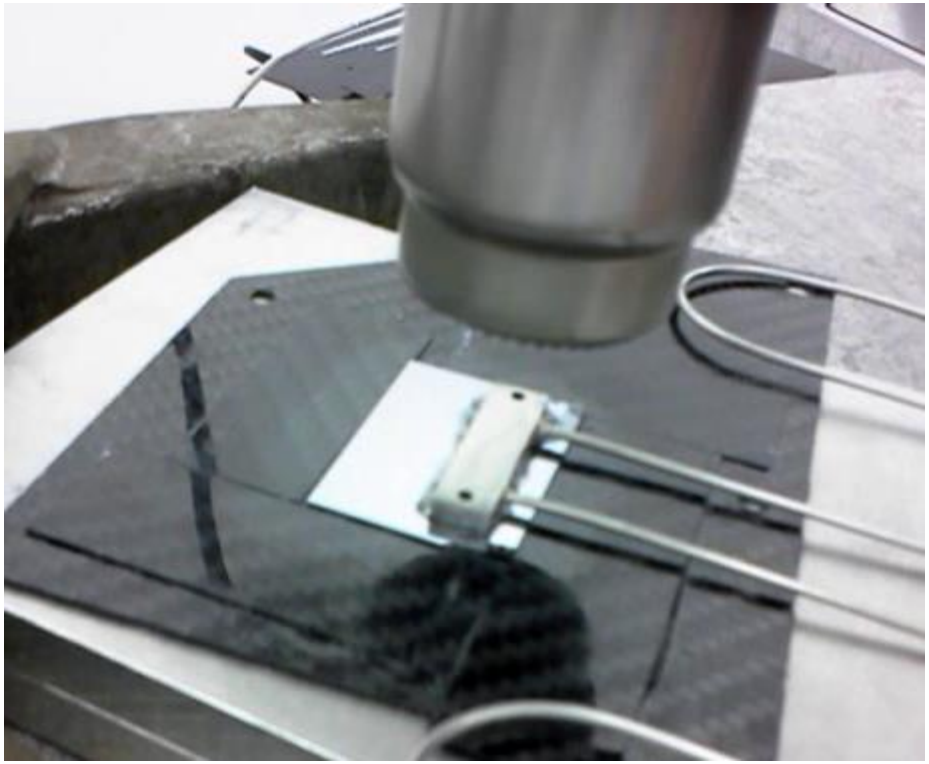
- Cracked silicon
- 180bar, 200bar





Soldering with the hot air gun

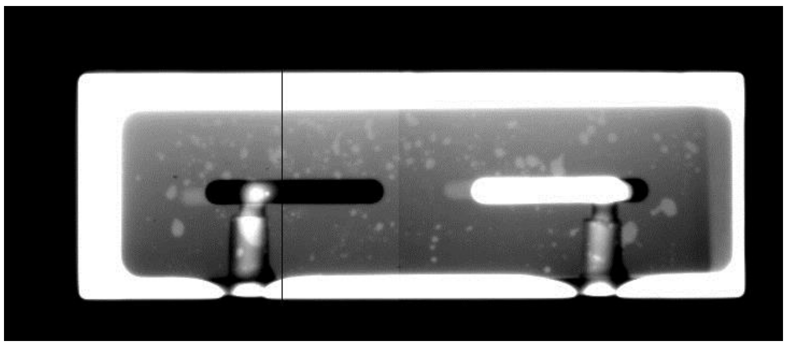
- Use hot air to warm up the connector and the wafer
- Quick method under visual control.
- Organic flux seems to work well.
- Air could possibly be replaced with nitrogen.

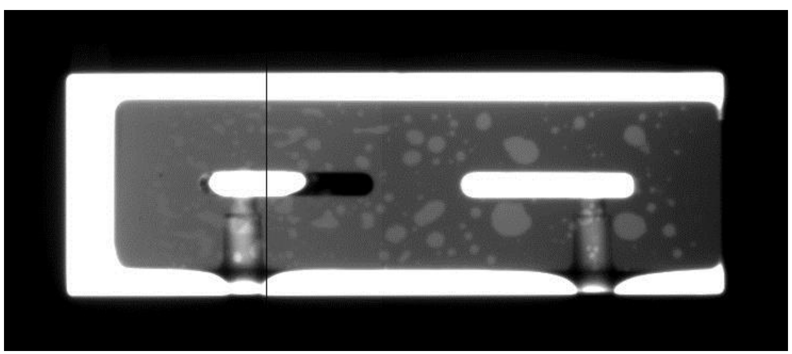


(Organic) flux hot air soldering

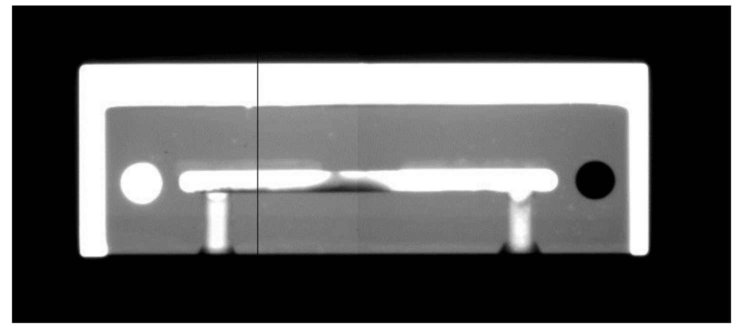
Why would covar connectors produce fewer voids ?

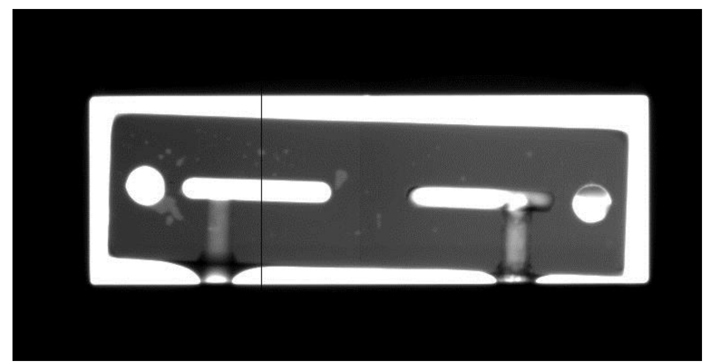
- Brass connectors

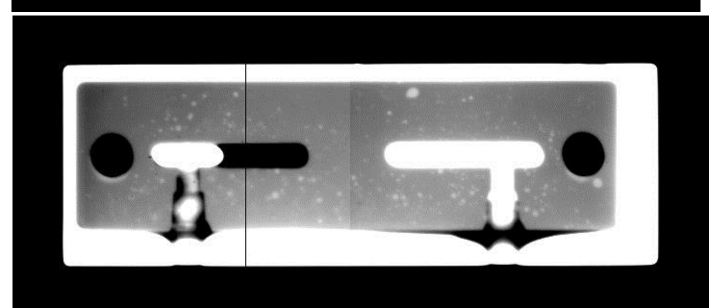




- Covar connectors

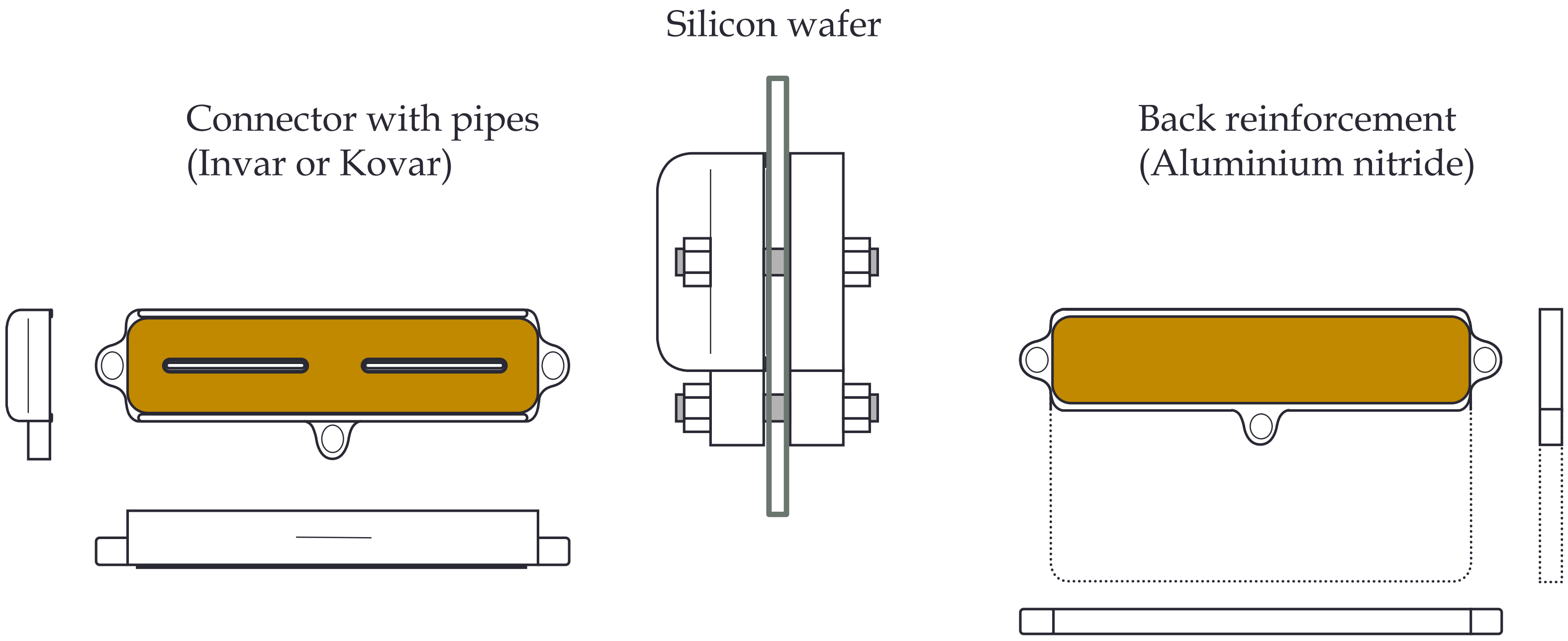






Soldering the connector

- New concept after pressure tests: reinforce the back by a piece of ceramic.

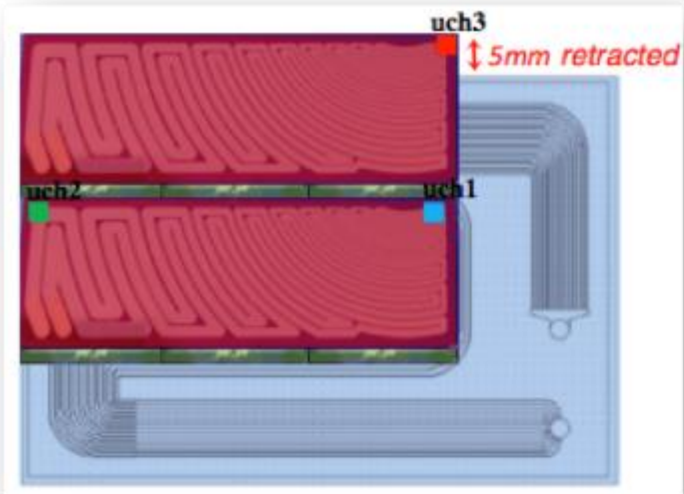


Cooling test using dummy heaters.

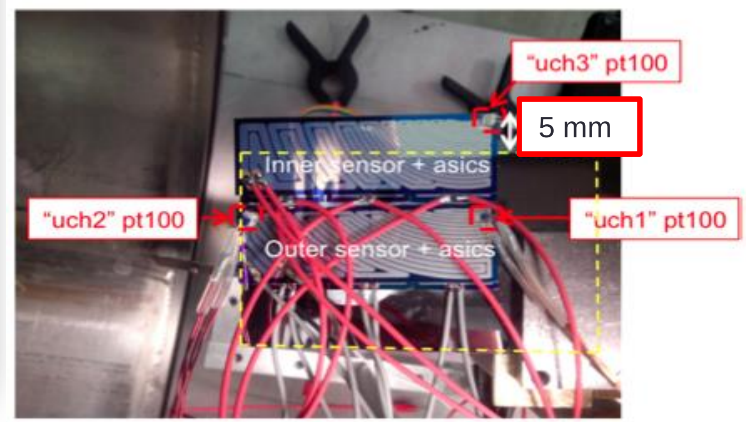
Sensor heaters

ASIC heaters

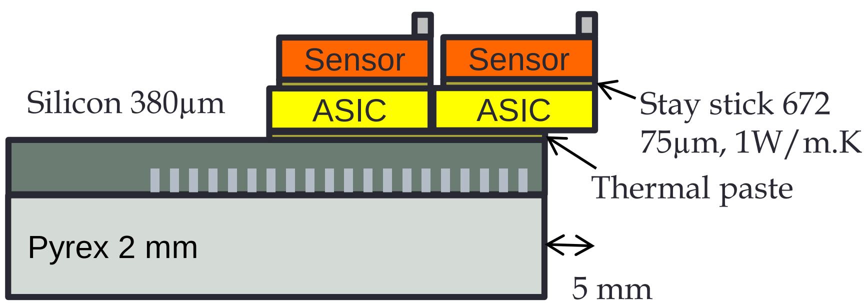
Thermal mockups made of 300 µm Si metallized to simulate the heat density



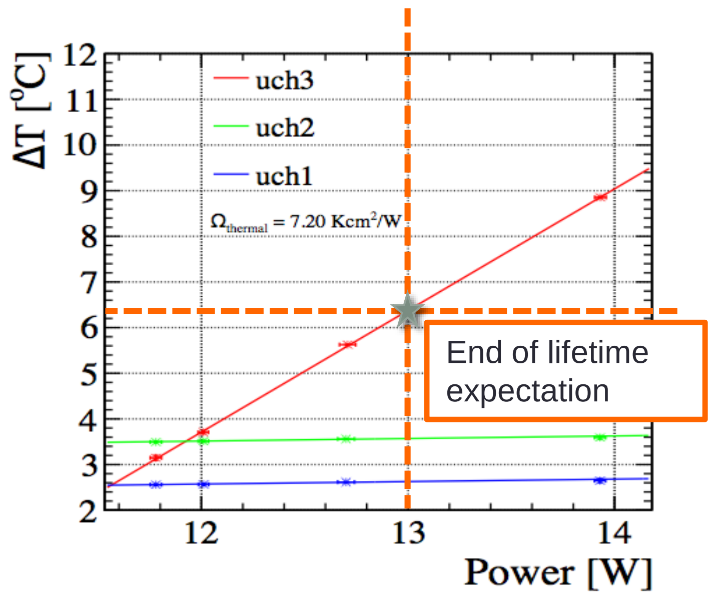
uch1, uch2 uch3

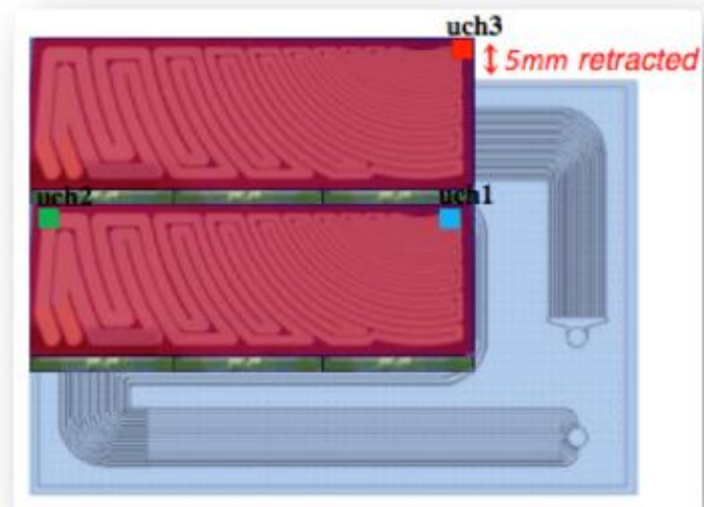


Glued surface: 11,34 cm2 CO2 connector



Cooling performance.

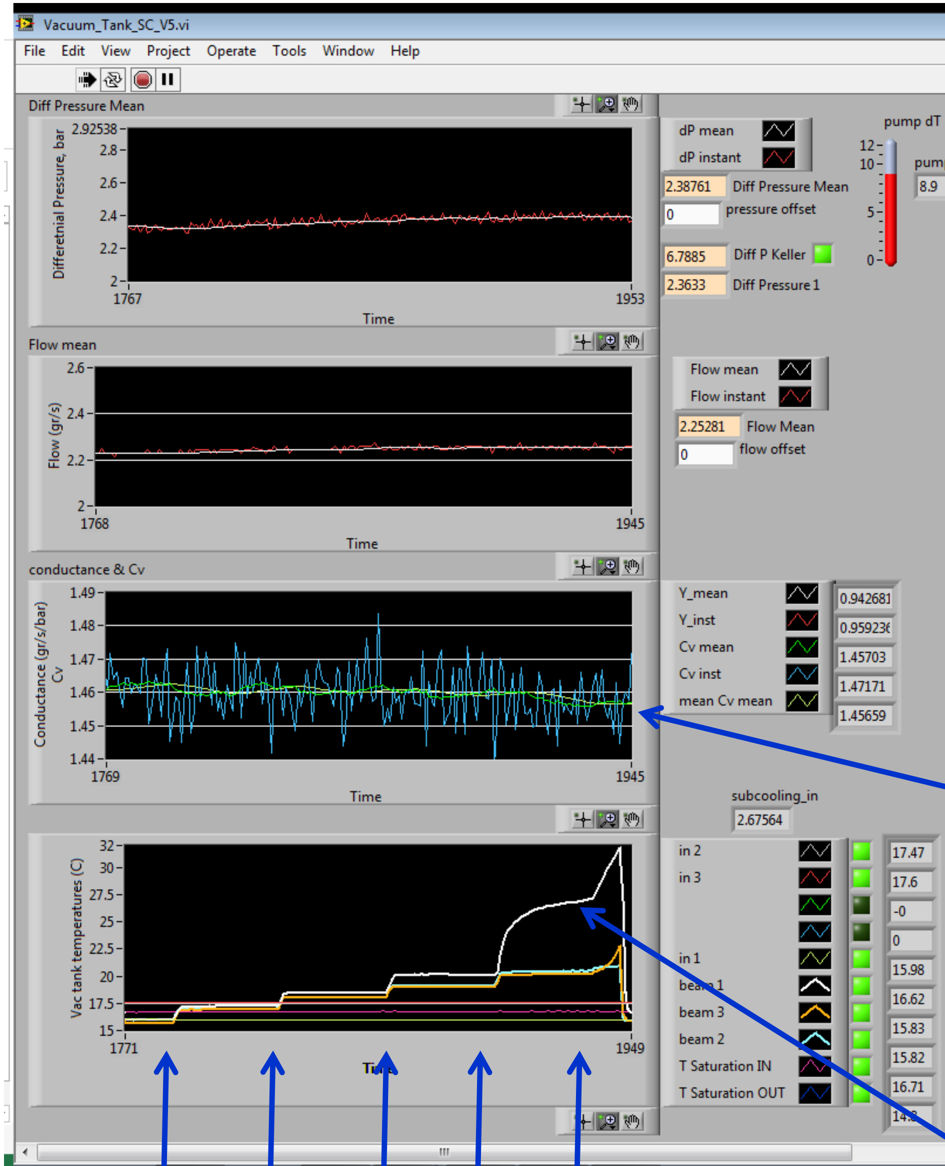




The end of lifetime expectation for half of a module corresponds to ~13W (12W ASIC and 1W on inner sensor) and in this condition the ΔT < 7˚C across the module.
{It was not possible to test up to maximum power of 21.5W because of the insufficient CO_2 flow}

Proof of principle. Not exhaustive !

Cooling power scan example



Cv (Valve+uChannel)

Cv drop due to heavy boiling

Temperatures
at various points

Runaway, when too much
heat applied

Increasing power levels applied