PROGRESS ON THE LHCb VELO EVAPORATIVE CO₂ MICROCHANNEL COOLING

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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
Soldering the fluidic connector

- Metal connector brings CO₂ supply to the microchannel wafer
- Silicon is metallized with Ti+Ni+Au and the connector soldered with a layer of PbSn solder.
- Liquid solder interacts with Ni layer thus the process should be quick and have controlled temperature profile
- Flux is believed to be bad for good lifetime, thus soldering without it is preferred.
- 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 CO₂
- 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

- Simple round holes as inlet and outlets for the liquid CO₂
- 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 CO₂ 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 CO₂ 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\textsubscript{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

Mass Flow meter.

Manual valve, Needle Valve, ‘bypass’

Vacuum tank

Pressure Gauge P1

Pressure Gauge P2

Vacuum tank

Heat

TRACI2

Environment heat

dP = P1 - P2

- 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

$F_{m1} = 5 \times F_{m2}$
Fluidic characterisation: Snake I

• 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 \( C_v \)
• There is still certain dependency on the temperature as the specific density of the fluid changes (we measure mass-flow not volume-flow coefficient)

\[ C_v = \frac{\text{Flow}}{\sqrt{\text{Pressure}}} \]
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 CO₂ inlet tube: 5-10W

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

<table>
<thead>
<tr>
<th>Prototype measured</th>
<th>Cv [\frac{g}{s/\sqrt{bar}}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snake I</td>
<td>0.065</td>
</tr>
<tr>
<td>Snake II</td>
<td>2.10</td>
</tr>
</tbody>
</table>
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 actual 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

All heaters are mounted on Si side
Snake II heat load test at -15 °C

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
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. \( \text{CO}_2 \) 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 2\textsuperscript{nd} part is not getting same quality cooling as the 1\textsuperscript{st} part due to \( \text{CO}_2 \) 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

<table>
<thead>
<tr>
<th>Temp [°C]</th>
<th>Cv @ no heat load</th>
<th>Cv @ max. heat load</th>
<th>ΔCv</th>
<th>Pmax [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25</td>
<td>0.206</td>
<td>0.13</td>
<td>0.076</td>
<td>60</td>
</tr>
<tr>
<td>-15</td>
<td>0.210</td>
<td>0.15</td>
<td>0.060</td>
<td>66</td>
</tr>
<tr>
<td>-5</td>
<td>0.216</td>
<td>0.16</td>
<td>0.056</td>
<td>66</td>
</tr>
<tr>
<td>+5</td>
<td>0.212</td>
<td>0.17</td>
<td>0.042</td>
<td>58</td>
</tr>
<tr>
<td>+15</td>
<td>0.189</td>
<td>0.16</td>
<td>0.029</td>
<td>57</td>
</tr>
</tbody>
</table>

- 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 CO₂ 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 because the CO₂ begins to boil

Pressure: rises when the CO₂ 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.

Temperatures: drop, when CO₂ exits super-heated state, begins to boil and cools down
Heating test at -30 °C 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: CO₂ is superheated and does not want to boil. Pre-heater has to go into action.
Heating test at -30 °C and 6 bar diff. pressure

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

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

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

Applied power (white) and max. theoretical power (red) derived from CO2 flow and latent heat. Note that the red curve is delayed as it is based on averaged CO2 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 CO₂ 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 develop around the holes and seem to follow the connector shape
- Not tested (yet) with liquid CO₂
- This far all measurements of flow and thermal performance done on the clamped Snake II prototype.
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 $+5 \, ^\circ C$
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.
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.

Thermal mockups made of 300 µm Si metallized to simulate the heat density.
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 $\Delta T < 7^\circ C$ 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!
Increasing power levels applied

Temperatures at various points

Cv (Valve+uChannel)

Cv drop due to heavy boiling

Runaway, when too much heat applied

Cooling power scan example