Micro-channel CO_2 cooling for the LHCb VELO upgrade.

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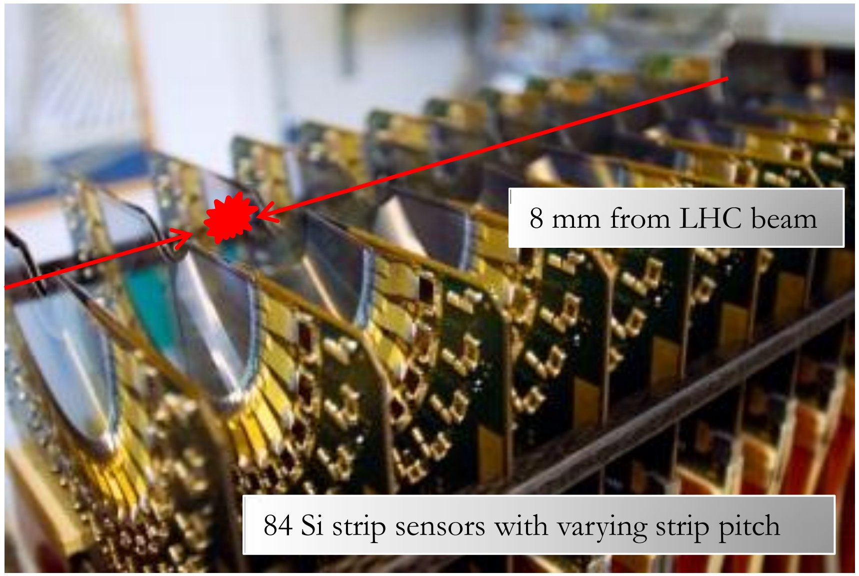
Outline

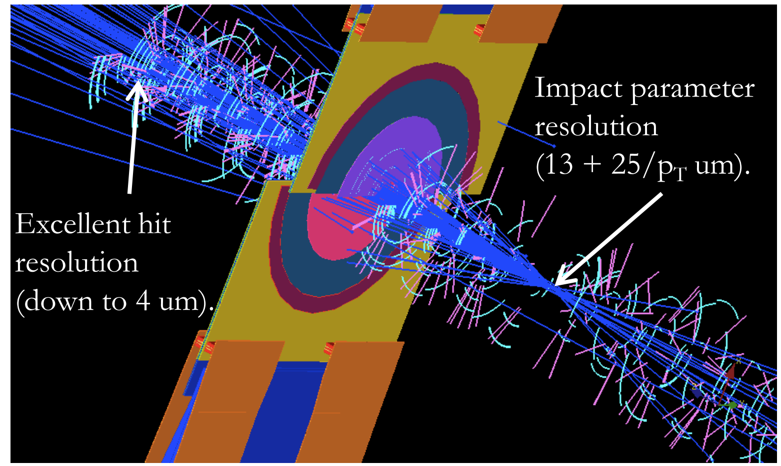
- The VELO detector.
- Key points of the LHCb Upgrade.
- VELO Cooling requirements.
- Micro-channel in Si technology.
- CO_2 cooling principle.
- First prototypes & results.
- Next prototypes.
- Other micro channel cooling projects.
- Summary.

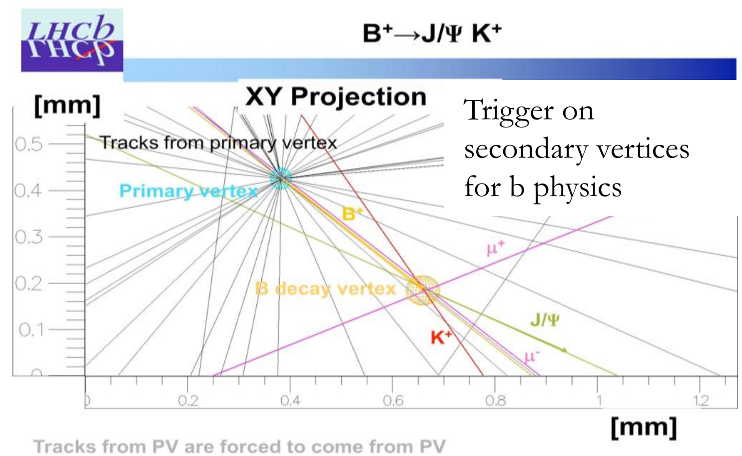
The VELO detector.

Vertex locator of the LHCb detector : select beauty and charm decays.

See talk of K. Akiba, Session 2





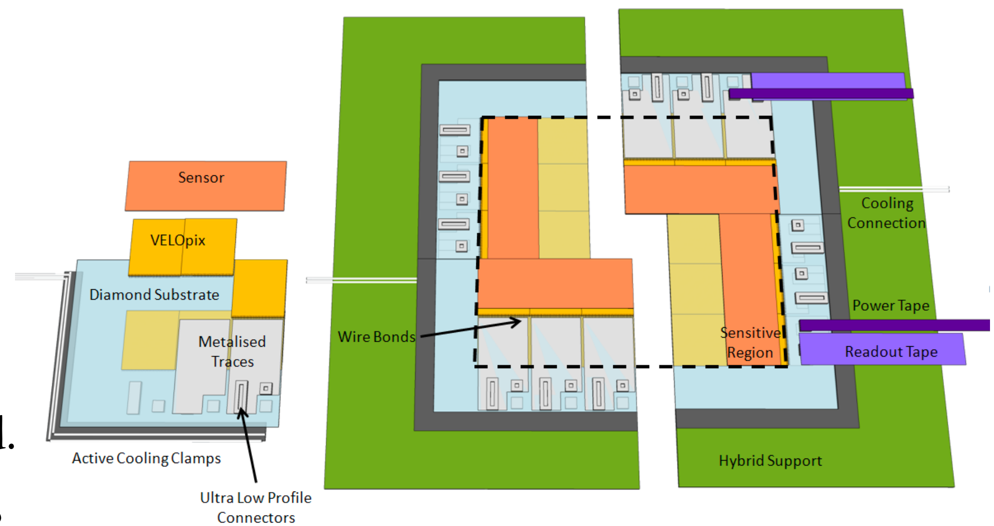


- Cooling:
  - Module power dissipation ~16W
  - Operates in vacuum.
  - Pioneering use of evaporative CO_2 cooling.

Upgrade of the LHCb detector.

- Key points:
  - 5-fold increase in luminosity:
    - $2 \times 10^{33} cm^{-2} s^{-1}$
  - 40 MHz event readout.
  - Installation during Long shutdown 2 in ~ 2018.
- New VELO modules & asics :
  - Pixel option is most advanced.
  - Also a new strip module is pursued.
- More details were given in talks by M. Van Beuzekom "VeloPix" in session 5)

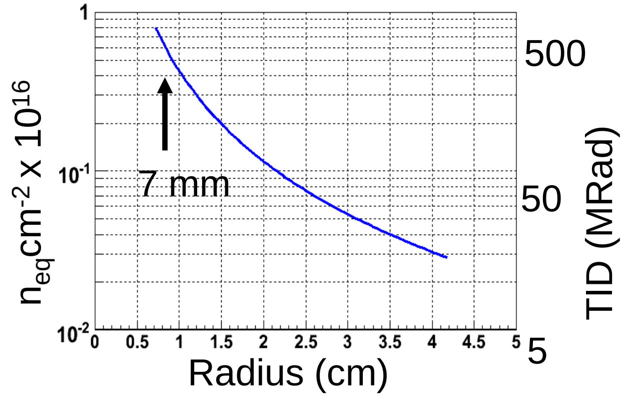
Conceptual view of pixel modules.



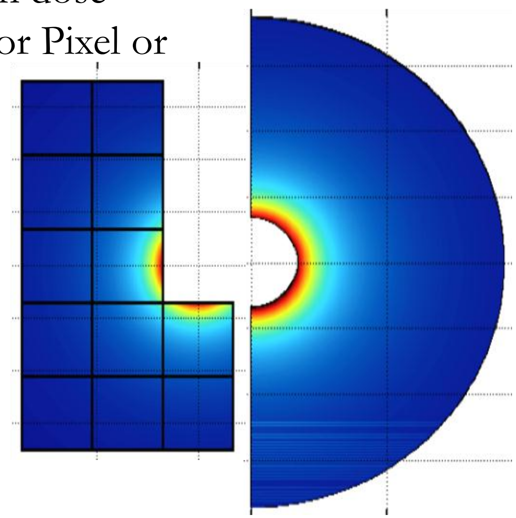
The cooling requirements

- 12 ASICS: ~ 36W max.
- Sensor heat dissipation:
  - Extreme radiation environment After 100 fb^{-1} sensors accumulate 370 MRad or 8 x 10^{15} n_{eq}/cm^2 at 7 mm from beam.
  - High sensor leakage current & power dissipation : ~ $1Wcm^{-2}$!
  - The sensor temperature at 7mm must stay below -15 C to avoid thermal run-away.
- The maximal total dissipated power density is ~40 W/24 cm^2 ~ 2 $W.cm^{-2}$
- This requires a very efficient cooling solution with minimal material impact !

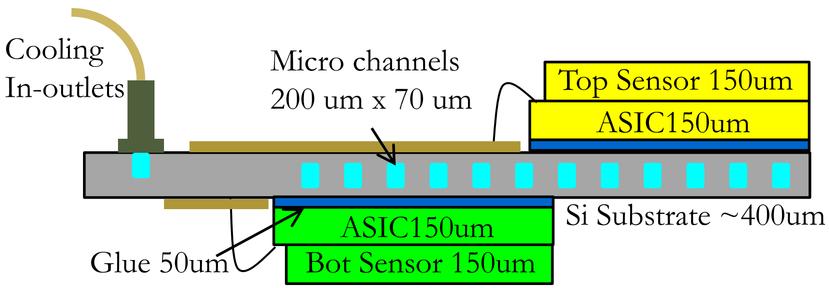
Dose after 100 fb^{-1}

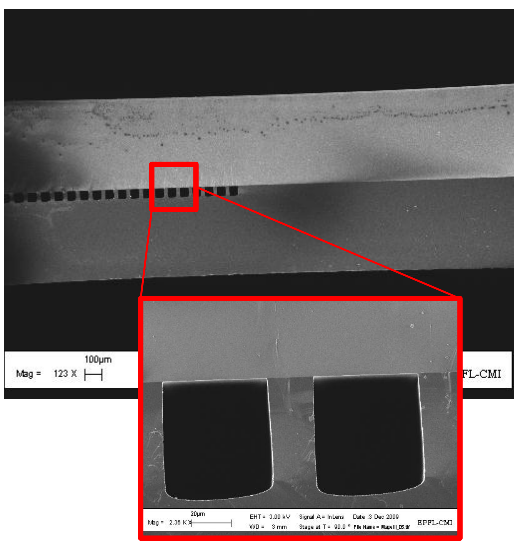


Radiation dose profile for Pixel or Strips



Micro-channels in Si.



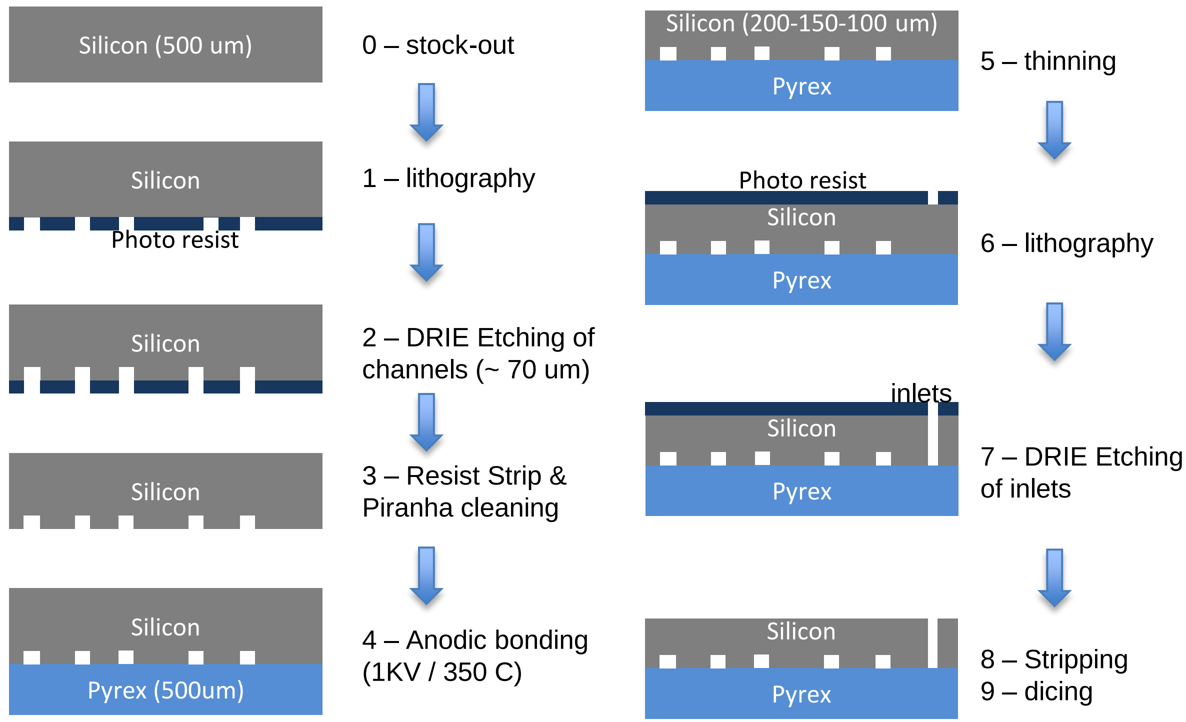


Advantages:

- Cooling tube is integrated in the substrate:
  - Can customize the routing of channels to run exactly under the heat sources.
- Many parallel channels:
  - large liquid-to-substrate heat exchange surface.
- Low mass :
  - No extra 'bulky' thermal interface required between cooling channel and substrate.
- No heat flows in the substrate plane:
  - Small thermal gradients across the module.
- All material is silicon :
  - No mechanical stress due to CTE mismatch.

μ channel fabrication.

- Process used for first prototypes by CERN/PH-DT at CMI at EPFL, Lausanne.



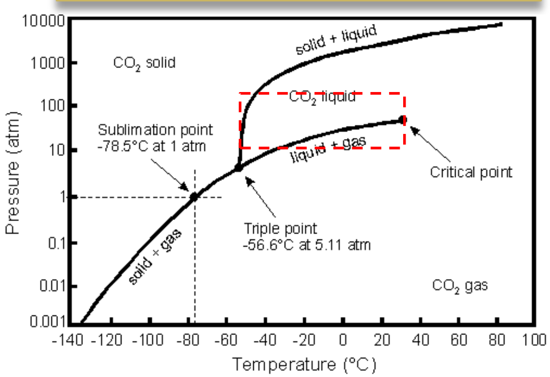
Evaporative CO2 cooling.

What happens inside a cooling tube ?

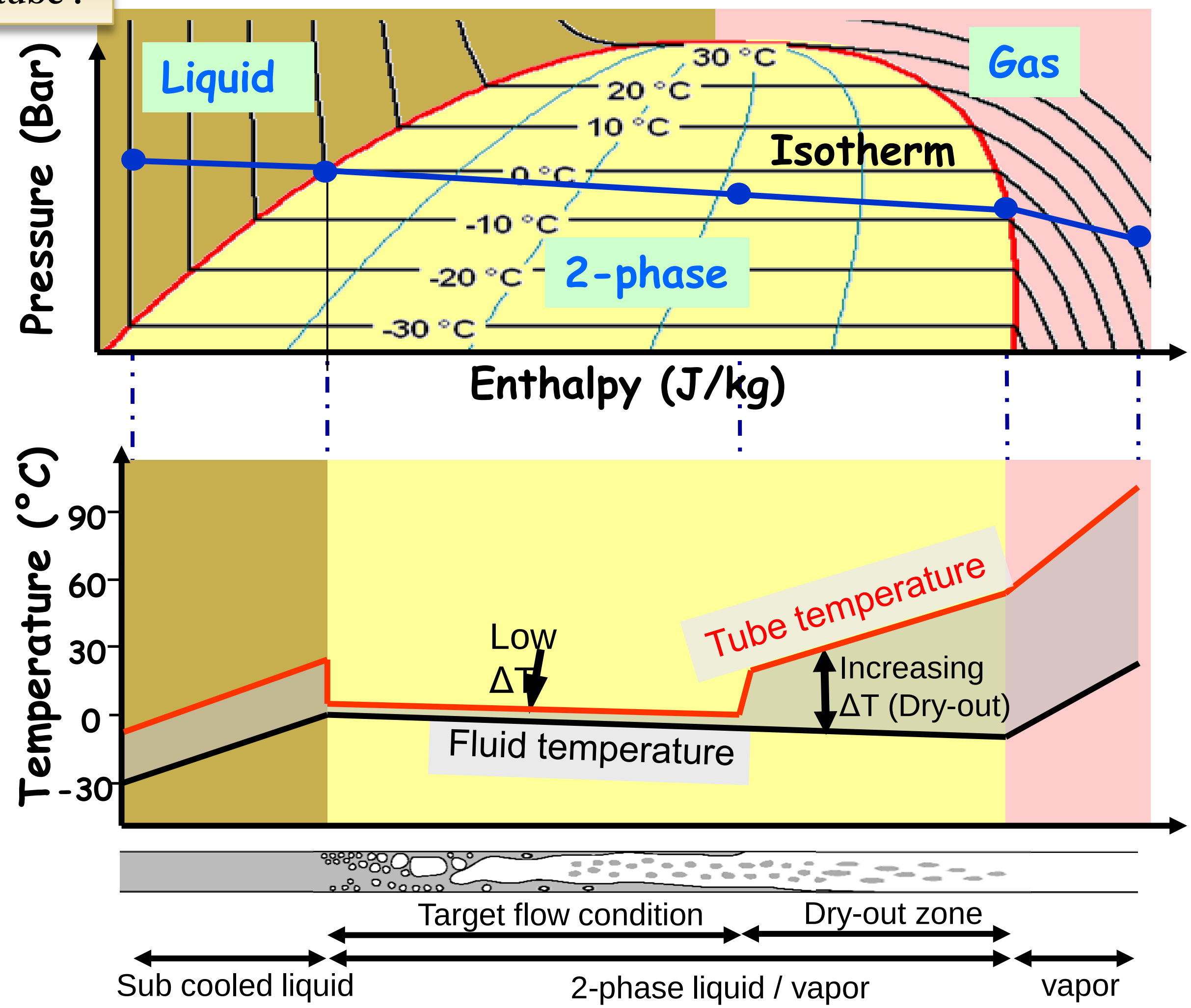
CO_2 is boiling

- CO_2 absorbs heat from environment to raise its enthalpy (internal energy).
- this happens at nearly constant temperature.

Temperature is defined by pressure.
-56 C < T < +31 C
5 bar< P < 73 bar



Pressure-Temperature phase diagram for CO_2.



Modeling & channel dimension.

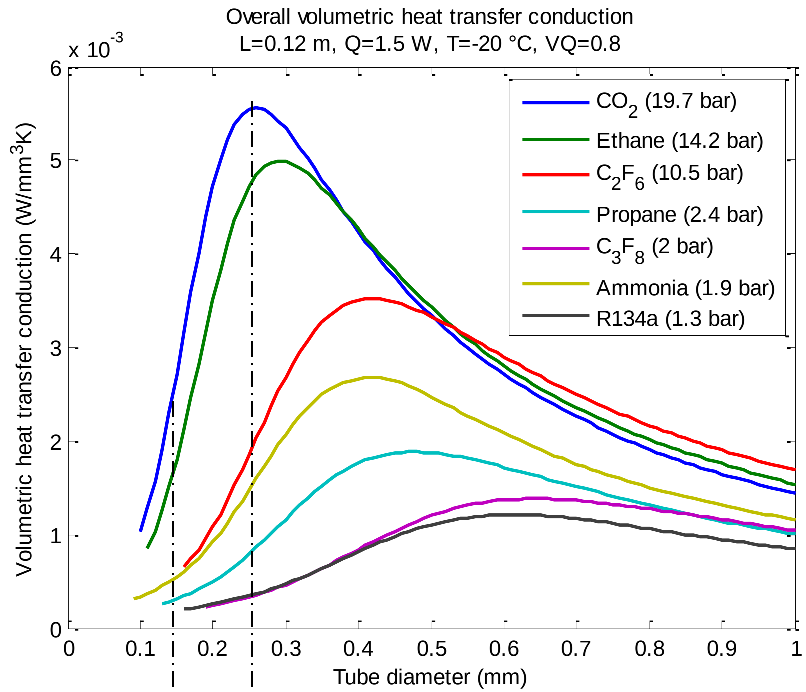
- Model simulation ("CoBra")
  - with channel parameters:
    - length =120 mm,
    - absorbed heat = 1.5W,
    - Temperature at inlet = -20 C
    - Vapor quality at exit =0.8
  - This model does not include :
    - coupling between parallel channels
    - Square tubes.
- CO_2 is optimal for small channels !
- Also CO_2 has a low viscosity and high latent heat, which contributes to less pressure drop and smaller mass flow, leading to smaller channels and lower total mass.

Volumetric heat transfer conduction = $\frac{Q}{V.dT}$

with Q = absorbed heat

V = volume of tube

dT= T(tube) – T(liquid).



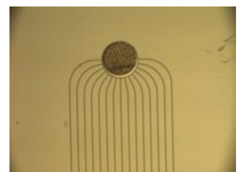
Optimal Ø (round tube) ~ 250 um

Square tube 70x200 um2 ~ 133 um Ø (round tube)

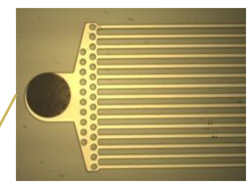
First prototypes

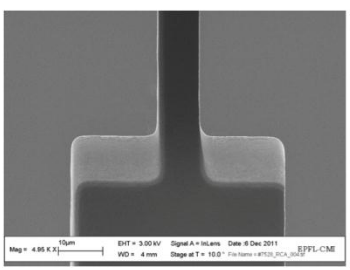
- The aim is to:
  - Demonstrate CO2 circulation in micro channels.
  - Measure
    - the cooling performance
    - the pressure resistance.

Input restrictions (30 um width) to equalize the flow across all channels

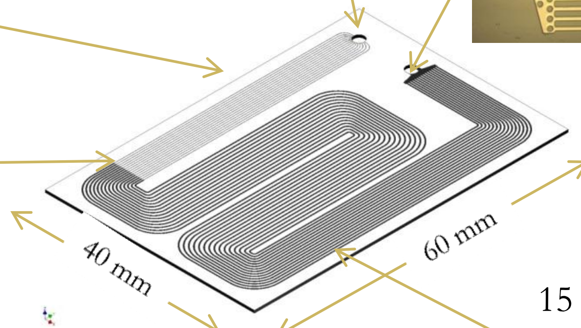


In- & outlet holes (Ø 2mm)





transition of restriction to channel



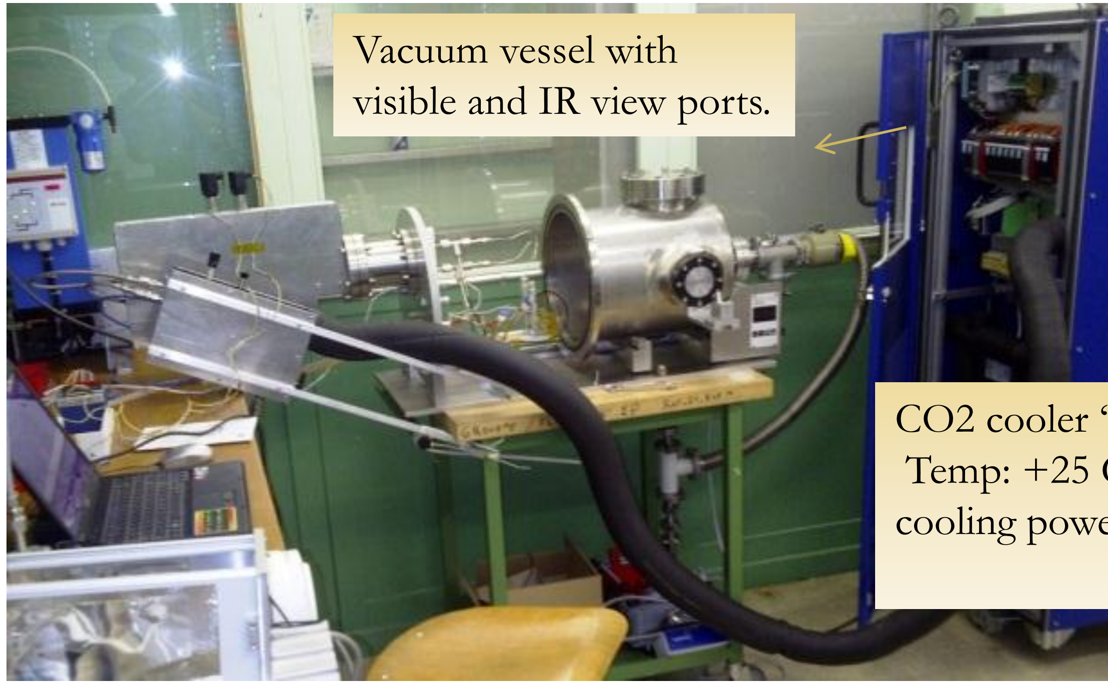
15 cooling channels (200 um width)

"Snake" layout

Test stand

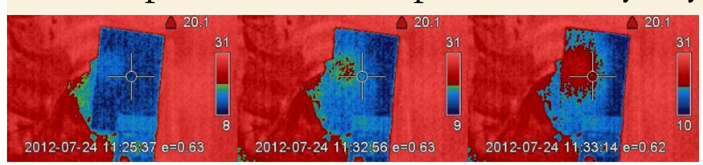
Test sample equipped with cooling tubes, heater and pt100 probes

Vacuum vessel with visible and IR view ports.



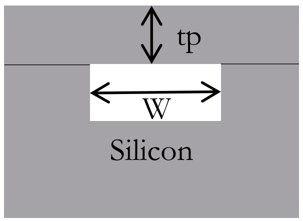
CO2 cooler “Traci”:
Temp: +25 C to -40 C
cooling power: 400W

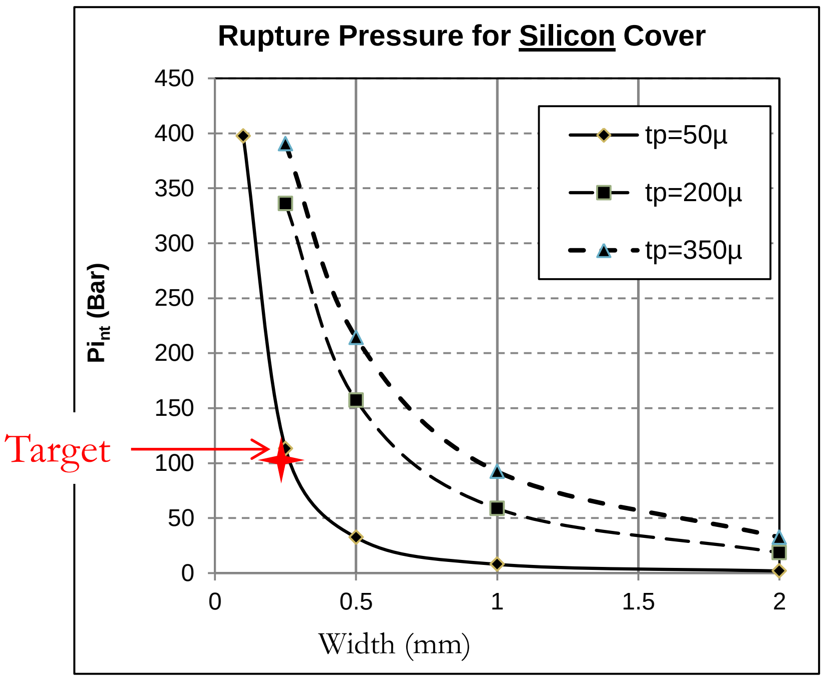
Infrared camera pictures taken through IR windows
Development of a hotspot caused by dry-out of CO2



Pressure resistance.

Structural analysis with ANSYS 2D.





First unsuccessful trials with Si-Si bonding : (failure due to contamination in apparatus).

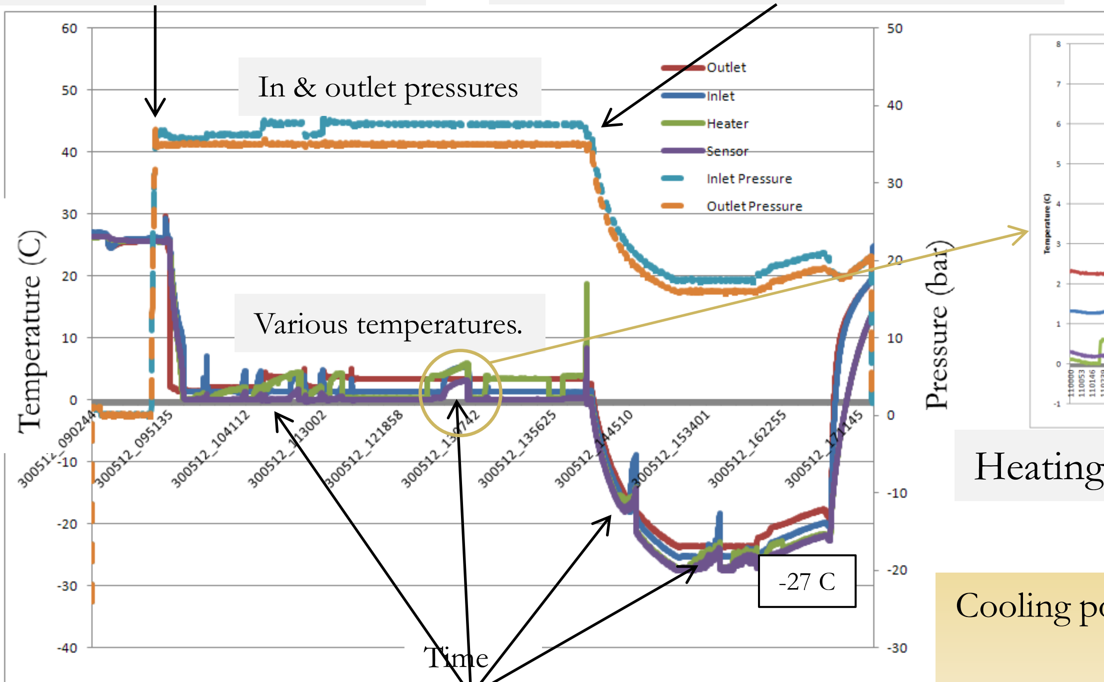
- Then successfully used Si-Pyrex instead (more robust & faster).
  - with Pyrex thickness of 500um : pressure tested OK up to 30 bar.
  - with Pyrex of 2 mm: OK up to 69 bar. (=P_{CO2} @ 25 C).

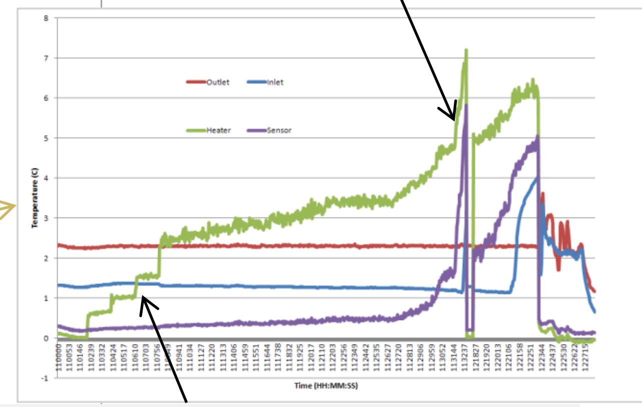
Cooling power test.

1. CO_2 enters micro channels. Sample cools down to 0 C

3. CO_2 pressure is lowered. Temperature decreases to -26 C.

CO_2 can no longer evacuate heat : “dry-out”





Heating power is increased stepwise

2. Heater is switched on/off.

Cooling power achieved:

$1.9 W/cm^2$ at T= 0 C,

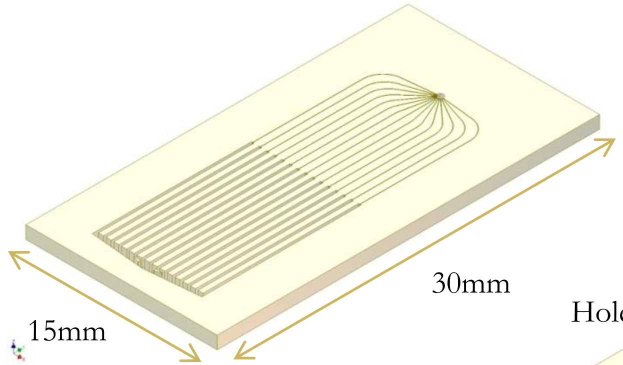
$0.5 W/cm^2$ at T=-27 C

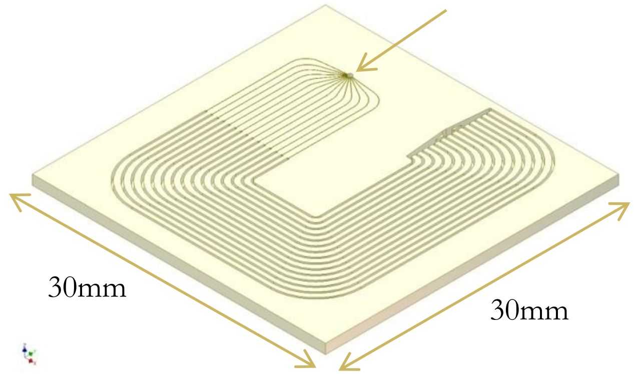
Limited by achievable mass flow (pump limit)

Expect much higher with improved pump !

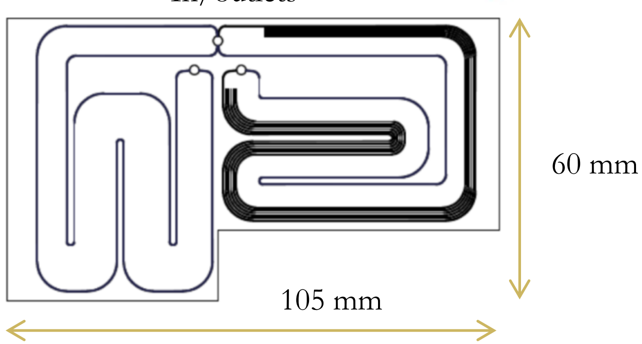
Next prototypes.

- Aim to prove pressure resistance
  - Beyond 100 bar
  - on large number of small size samples (~100).
- Experiment with
  - The variation of the channel pitch.
  - The geometry of the outlet manifold
- Must use Si-Si fusion bonding.
- Select a commercial supplier : LETI, Grenoble. (8"wafers)
- Quality assurance.
  - Scanning acoustic microscope
  - Knife edge tests, etc…
  - Thermal cycling





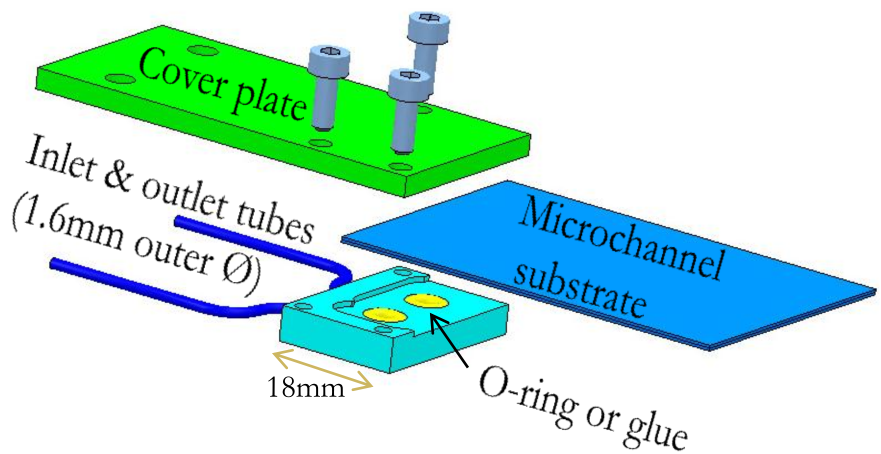
Towards a "double snake" for a full module



Custom fluidic connector.

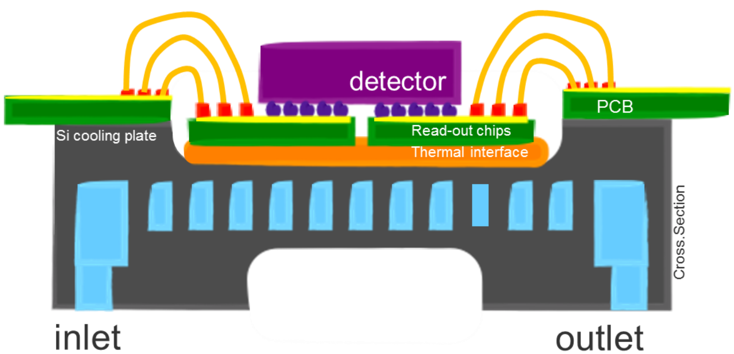
- NanoPort connectors (Upchurch Sientific,UK) are
  - guaranteed up to 103 bar,
  - but bonded to surface with adhesive polymer rings : radiation hardness, long term performance are unknown.

- We started a design of a more rugged connector at CERN.
  - Micro-channel substrate is clamped between two metallic pieces, tightened with screws.
  - Tubes are welded in bottom piece.
  - O-rings or glue seal gas tightness.
  - Not yet optimized for lowest mass



Other micro channel projects.

NA62 Gigatracker



- Cooling requirements
  - minimize material below detector
  - detector area: 60 x 27 mm
  - T on Si detector: -20ºC ÷ 5ºC
  - ΔT over detector: 6ºC
  - Heat dissipation by read-out chips:
    - 4 W/cm^2 in the periphery (Digital)
    - 0.5 W/cm^2 in the center (Analog)
    - total 48 W
  - thin silicon plate (130 µm)
  - C_6F_{14} liquid (8bar)

ALICE upgrade pixels

- cooling µ-channels only under asics.
- no material under sensor
- Total heat dissipation 21W.
- T sensor ~ +20C
- Evaporative C_4F_{10}
- Pressure 2 bar

Summary.

- The upgraded VELO modules require a very efficient thermal management: low temperature, high power density & low mass.
- The innovative combination of CO2 evaporative cooling and micro channels in Si is a promising solution.
- We are addressing the main outstanding issues of high pressure resistance & connectivity under vacuum conditions.
- Micro channel cooling is rapidly gaining popularity in new pixel detector projects.

Arigato !