The University of Manchester

Microchannel CO_2 cooling for silicon detectors

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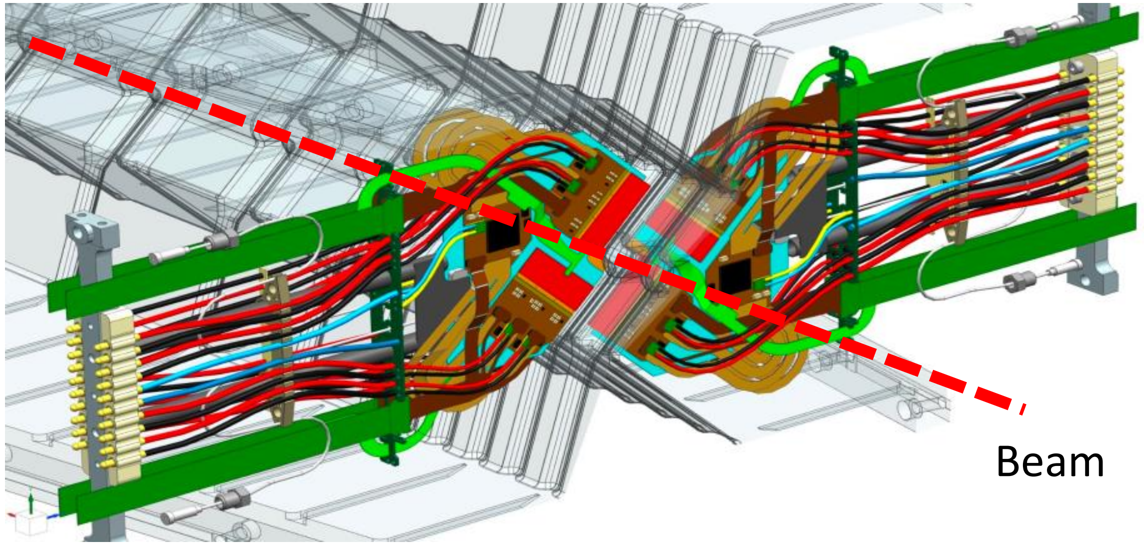
on behalf of the VELO and CERN EP-DT groups

Pisa Meeting May 22-28 2022

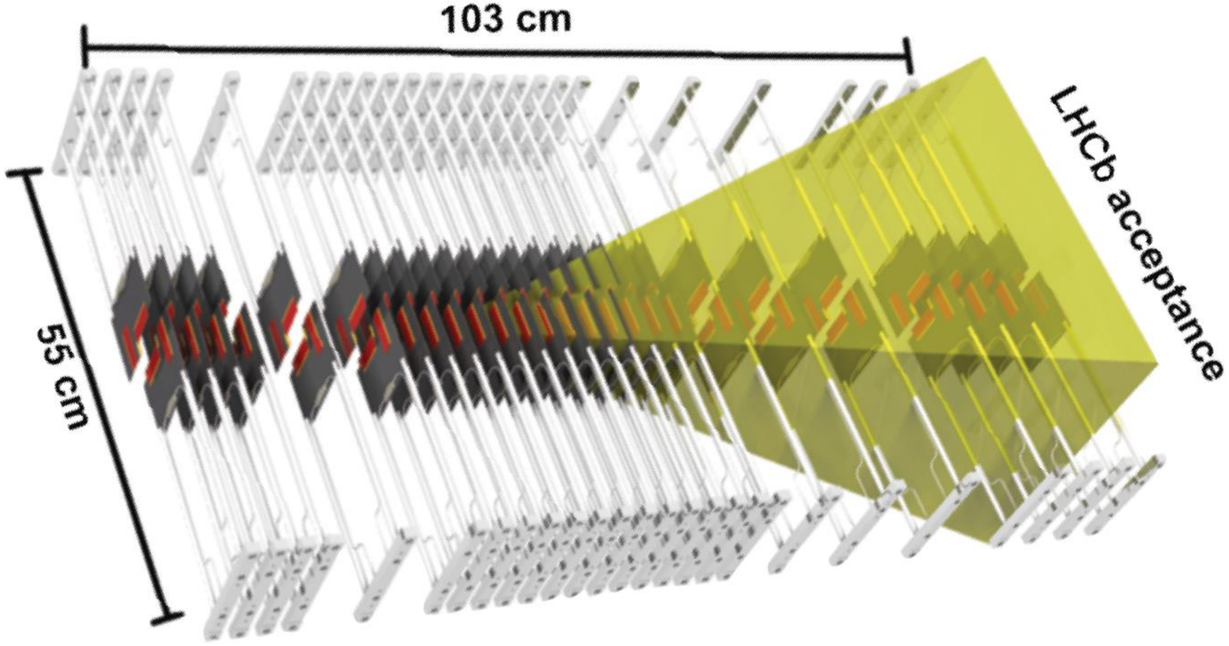
LHCb VELO Cooling Upgrade

Module key features:
The closest distance to LHC beam will be 5.1 mm (down from 8.2 mm)
Very high (8×10^{15} neq/cm^2) and non-uniform radiation (~r^{-2})
Detector active area 0.12 m^2

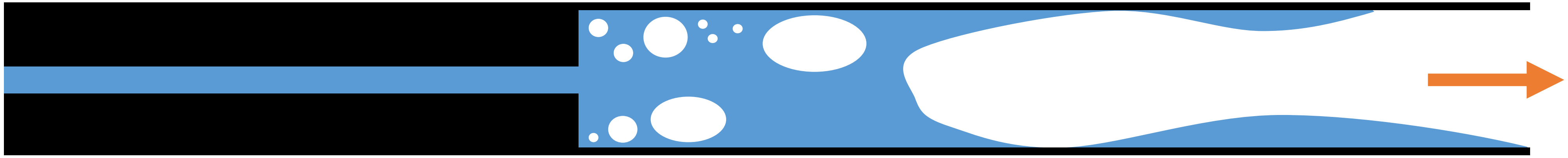
More information in VELO U1 poster, Gianluca



Module cooling requirements:
- Maximum detector temperature $-20°C$ to mitigate radiation damage
- Operates under vacuum
- Cooling retracted by 5 mm in the inner region to further reduce the material budget
- $\sim 30W$ power dissipation per module
  - Sensor area $\sim 1W/cm^2$



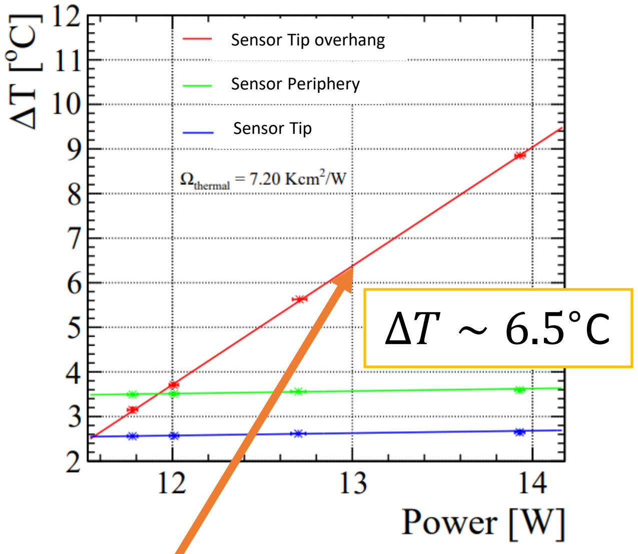
Microchannels evaporative cooling

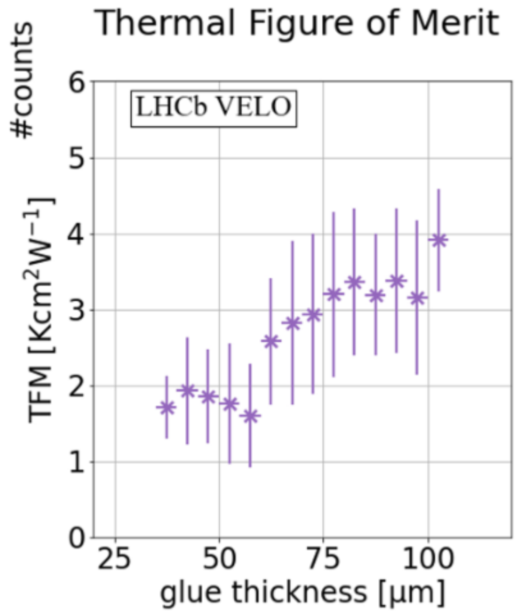


- Coolant in bi-phase regime (liquid/gas)
  - Heat produced by the electronics is absorbed by the liquid which turns into gas
  - Coolant decreases temperature from input to output
- CO_2 coolant:
  - High Latent heat, low viscosity and radiation hard
  - Lowest operational temperature defined by solidification
    - Stable operation at $-47^{\circ}\mathrm{C}$ at cooling plant (*Nucl. Instrum. Methods Phys. Res., A* 936 (2019) 648-649)
    - Solidification at $-56.6^{\circ}\mathrm{C}$
  - High pressure
    - Evaporator highest pressure during normal operation at ~20 bar ($-30^{\circ}\mathrm{C}$, LHCb VELO module)
    - At room temperature, the pressure is around 65 bar
    - Safety validation of evaporators up to 186 bar (safety factor on top of burst disks pressure)

Microchannels embedded in Silicon

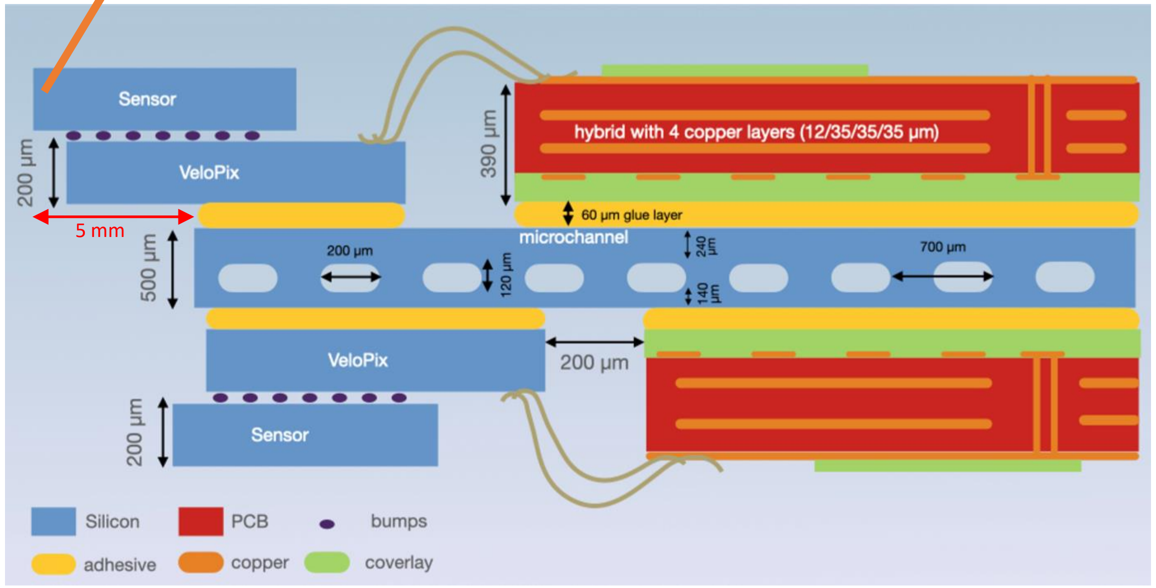
- Main advantages:
  - No CTE mismatch with respect to the silicon detector
  - Low and homogeneous material budget
  - Radiation hardness
  - Excellent cooling performance





- Thermal performance usually represented by the thermal figure of merit:

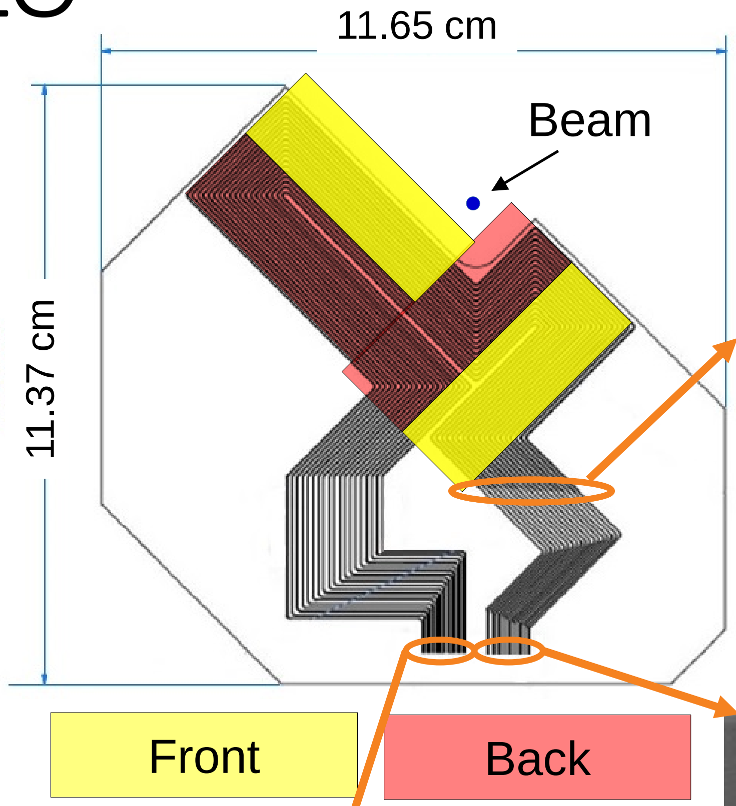
$$TFM = \frac{\Delta T(Sensor,\ \ coolant)}{Power/Area}$$

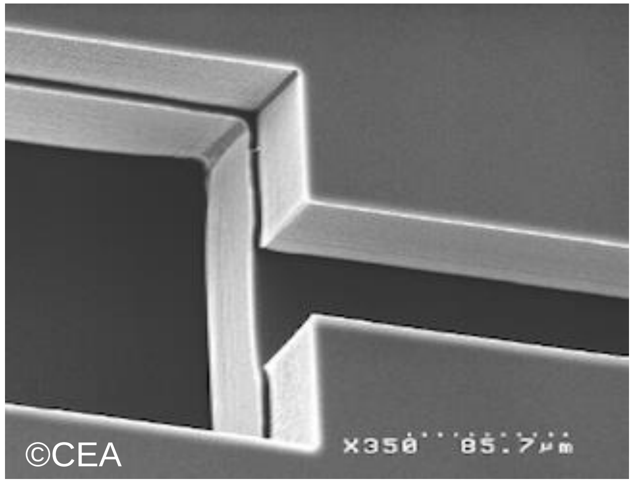


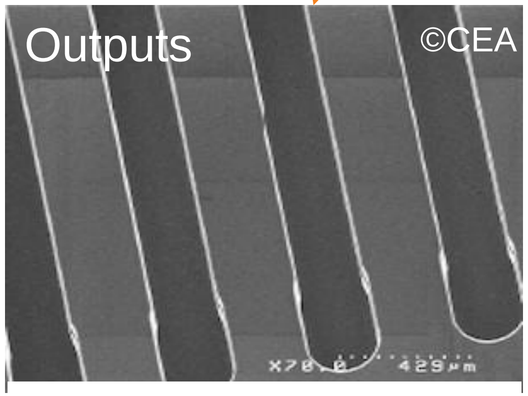
- Main challenges:
  - Production and cost ([1][2] and reusability [3])
  - Cooling integration
  - More fragile than conservative alternatives

Microchannels LHCb VELO

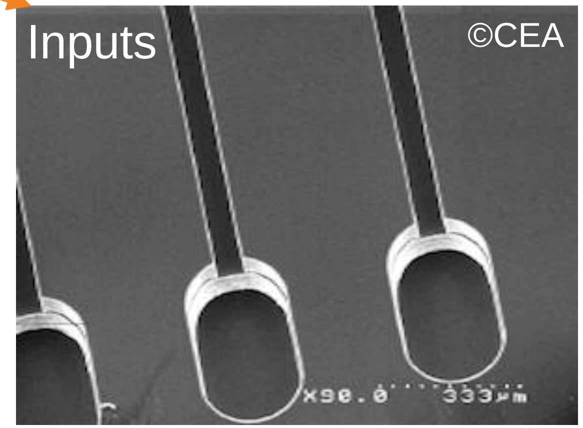
- Race-track like layout
  - 500 μm thick silicon cooler
- Restrictions to ensure even flow distribution and prevent instabilities (about 40 mm long)
- Power dissipation in the main channels which are around 260 mm long
- 19 channels with approximately the same length (~30 cm)
- Every channel has its own input/output







Main channel: 120 x 200 μm^2

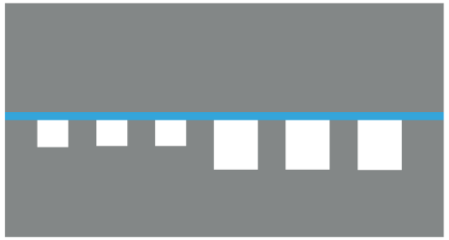


Restriction: 60 x 60 μm^2

Production process @ CEA LETI

Courtesy of CERN
EP-DT group

Etching 550 µm, double side polished Si
(60 µm ± 3 µm, 115 µm ± 6 µm)



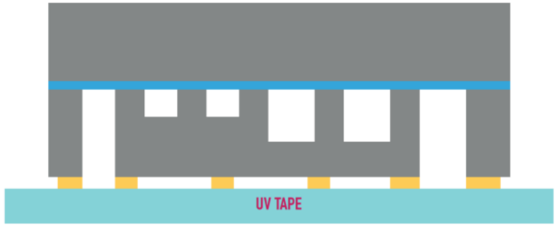
bonding of cap wafer with 400 nm at the bonding interface

thinning of cap wafer to 240 µm
(790 µm total thickness)

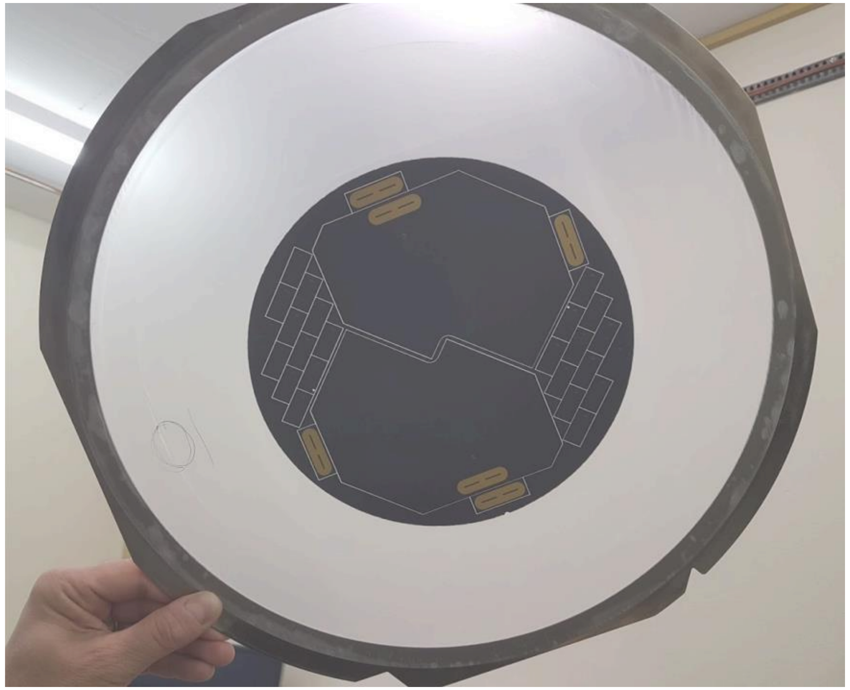
thinning of channels wafer to 260 µm
(500 µm total thickness)

Metalization: Ti(200nm), Ni(350nm), Au(500nm)

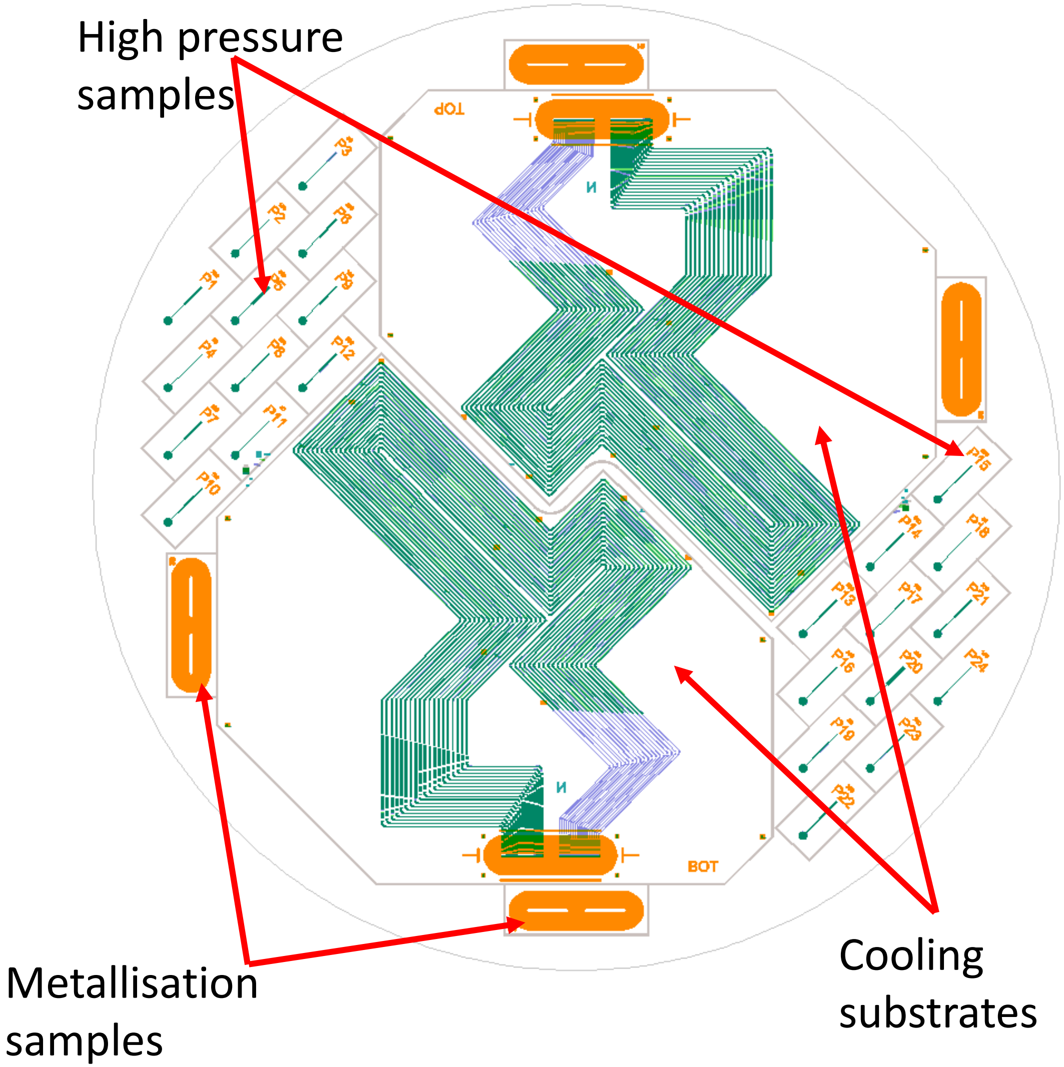
Etching of inlets and outlets

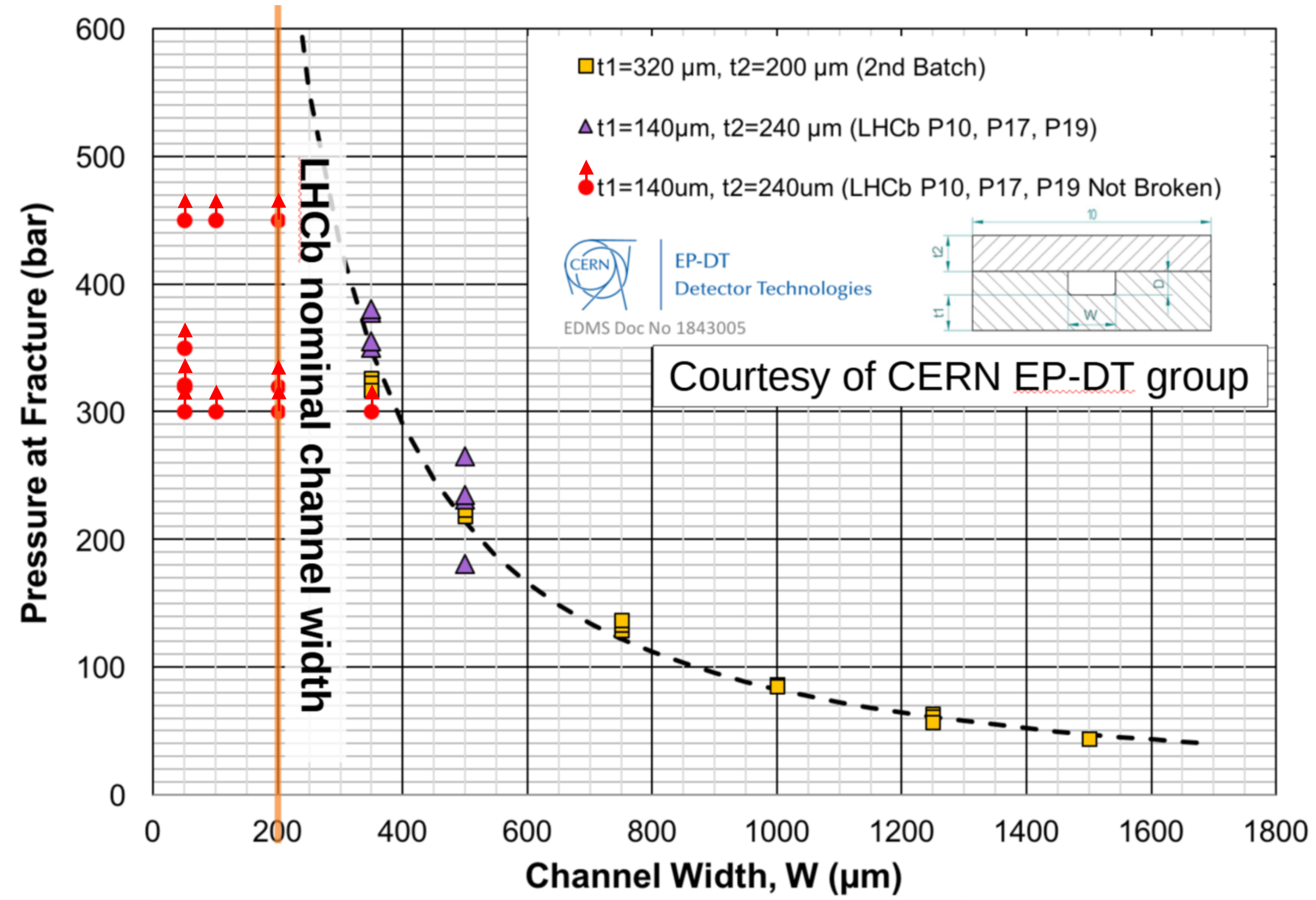


Dicing by plasma etching



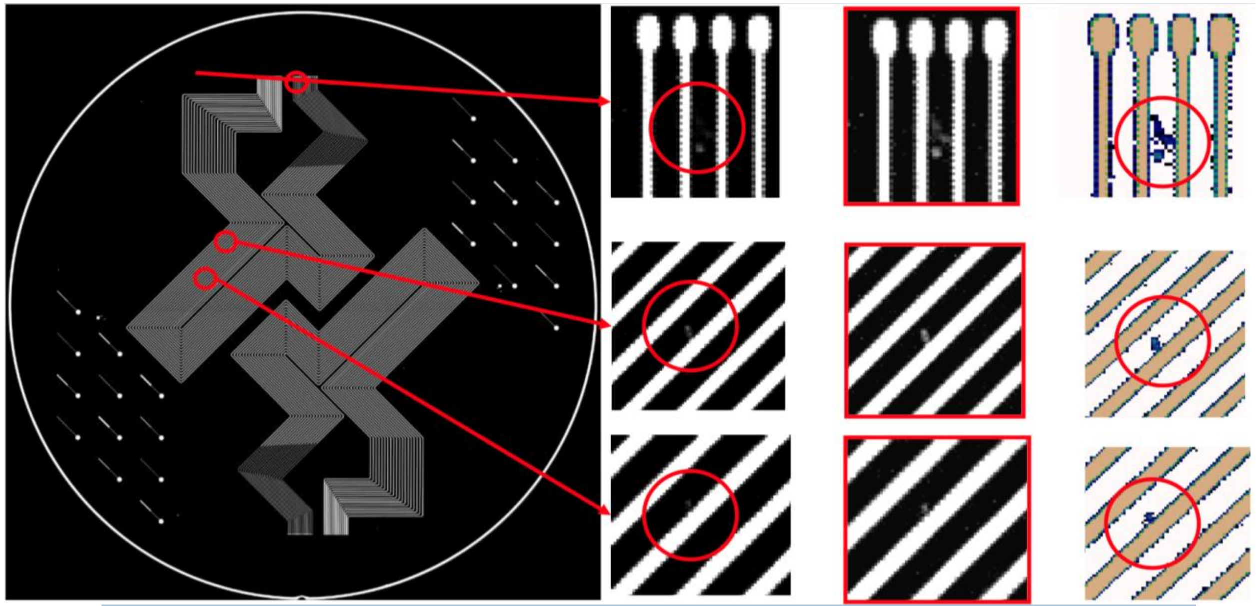
High pressure resistance

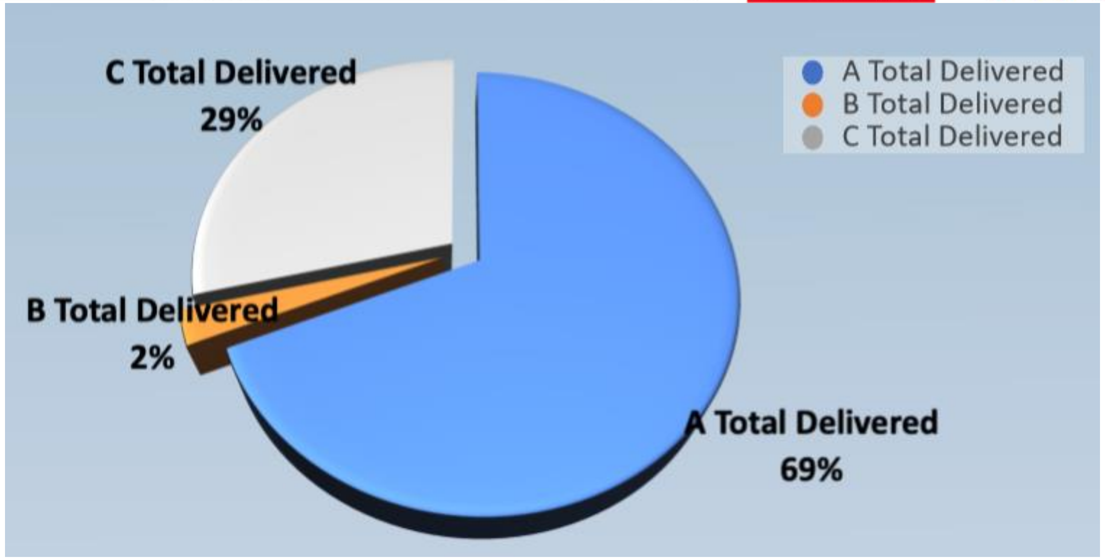




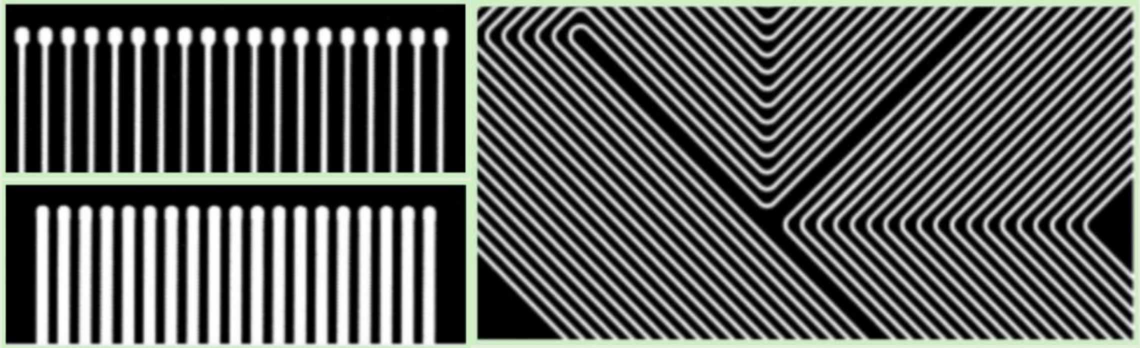
Bonding Q&A [1]

Scanning Acoustic Microscope Images features enhanced

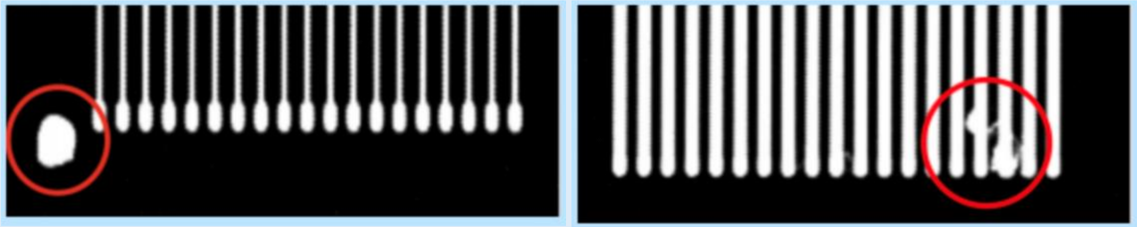




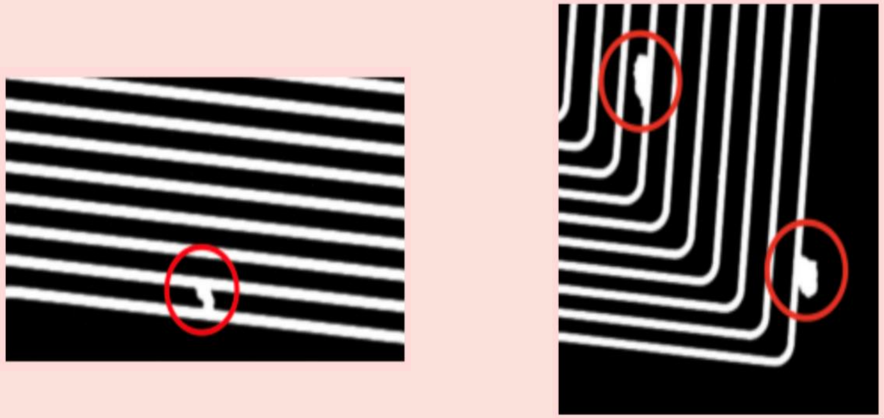
Grade-A: no imperfections



Grade-B: imperfections in the input/output region



Grade-C: imperfections in the input/output region

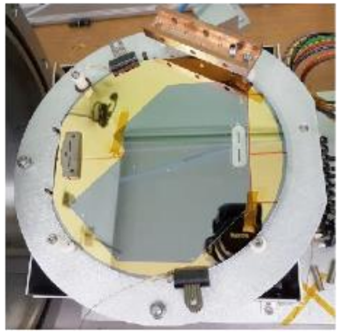


Connectorization

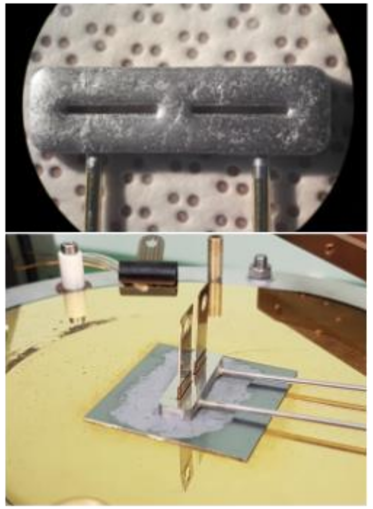
More information [1][2]

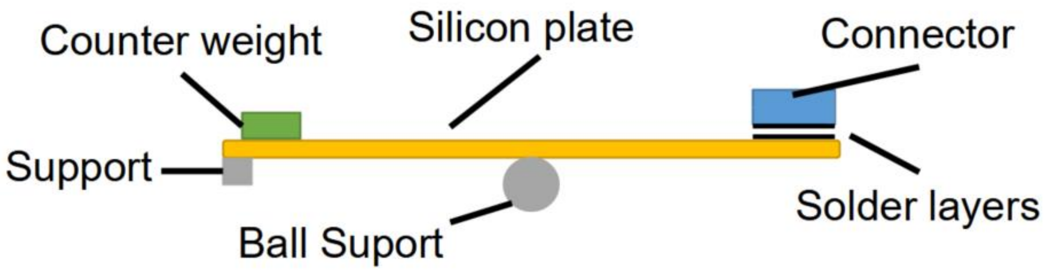
Fluxless process to avoid long term corrosive effects in the cooling system

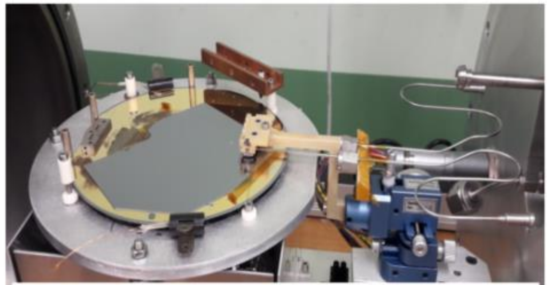
Silicon pretinning



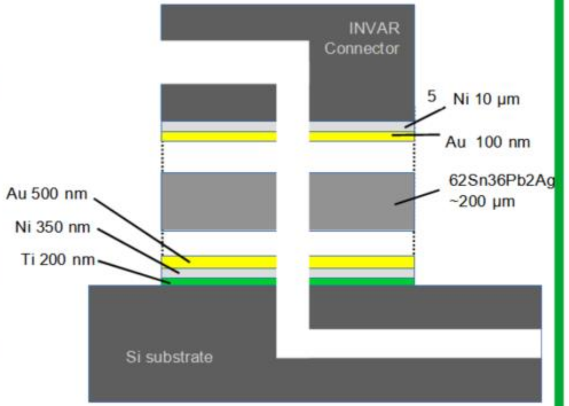
Connector pretinning

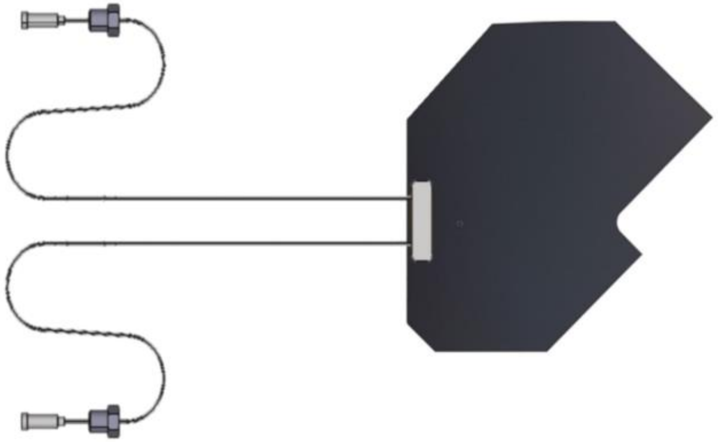






Light heating plate – ~27 [g], 8”, metallized silicon wafer





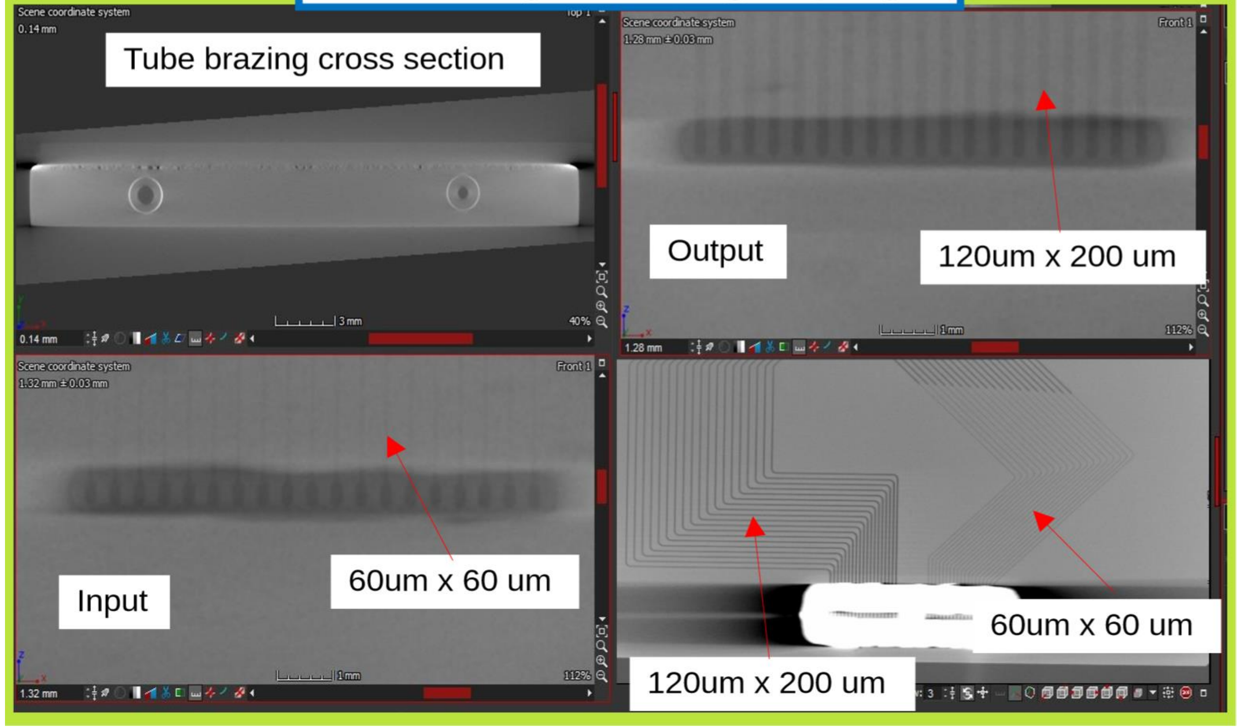
Substrates Q&A

High pressure test up to 186 bar

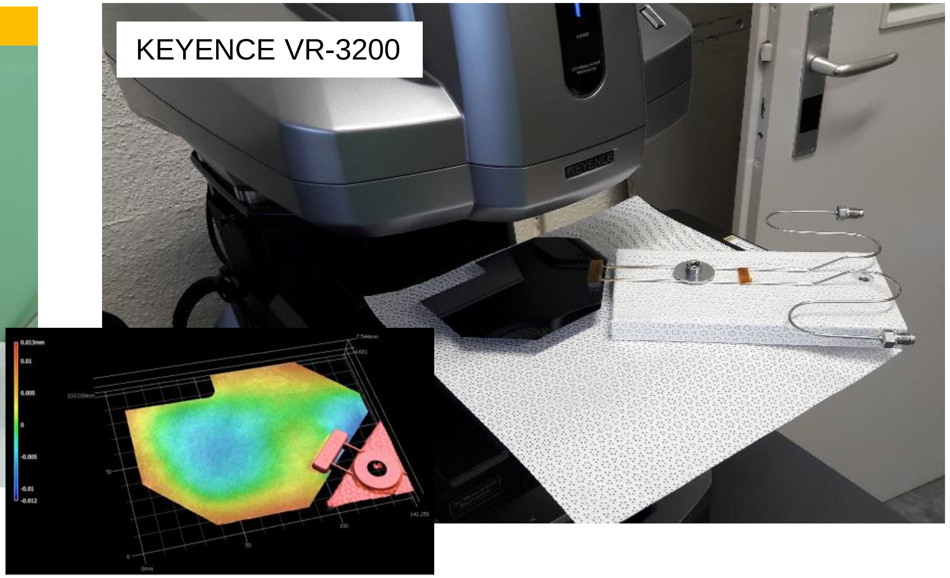
Helium leak test (vacuum inside)

Adixen ASM 142

3D X-ray tomography



High pressure helium leak test (60 bar)



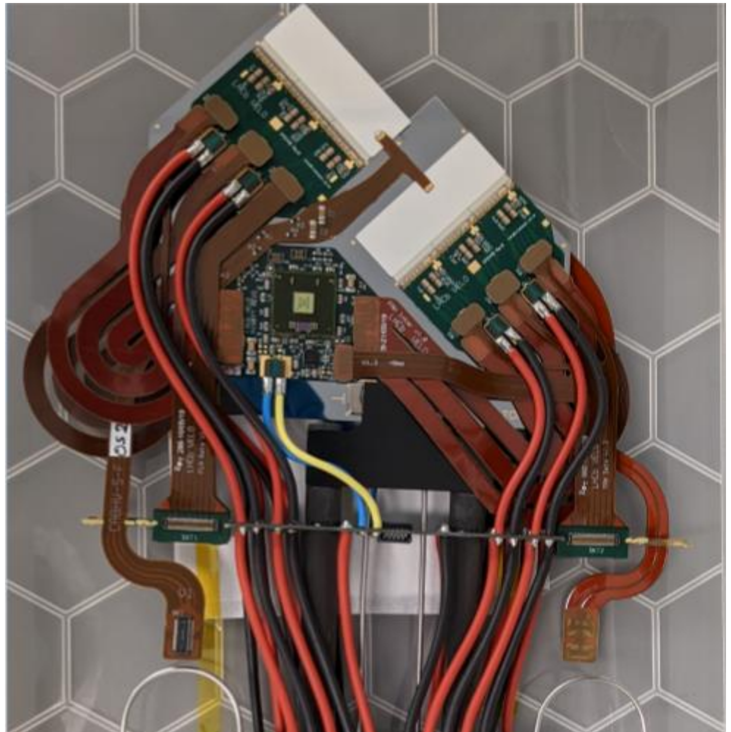
Module assembly

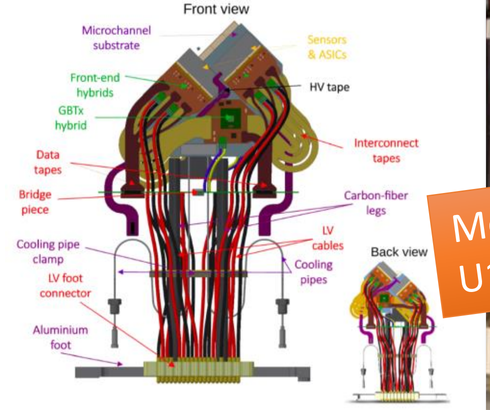
Transport by personnel through plane or car

No transport casualties

Transport by plane or consolidated truck

Final module built in the assembly sites

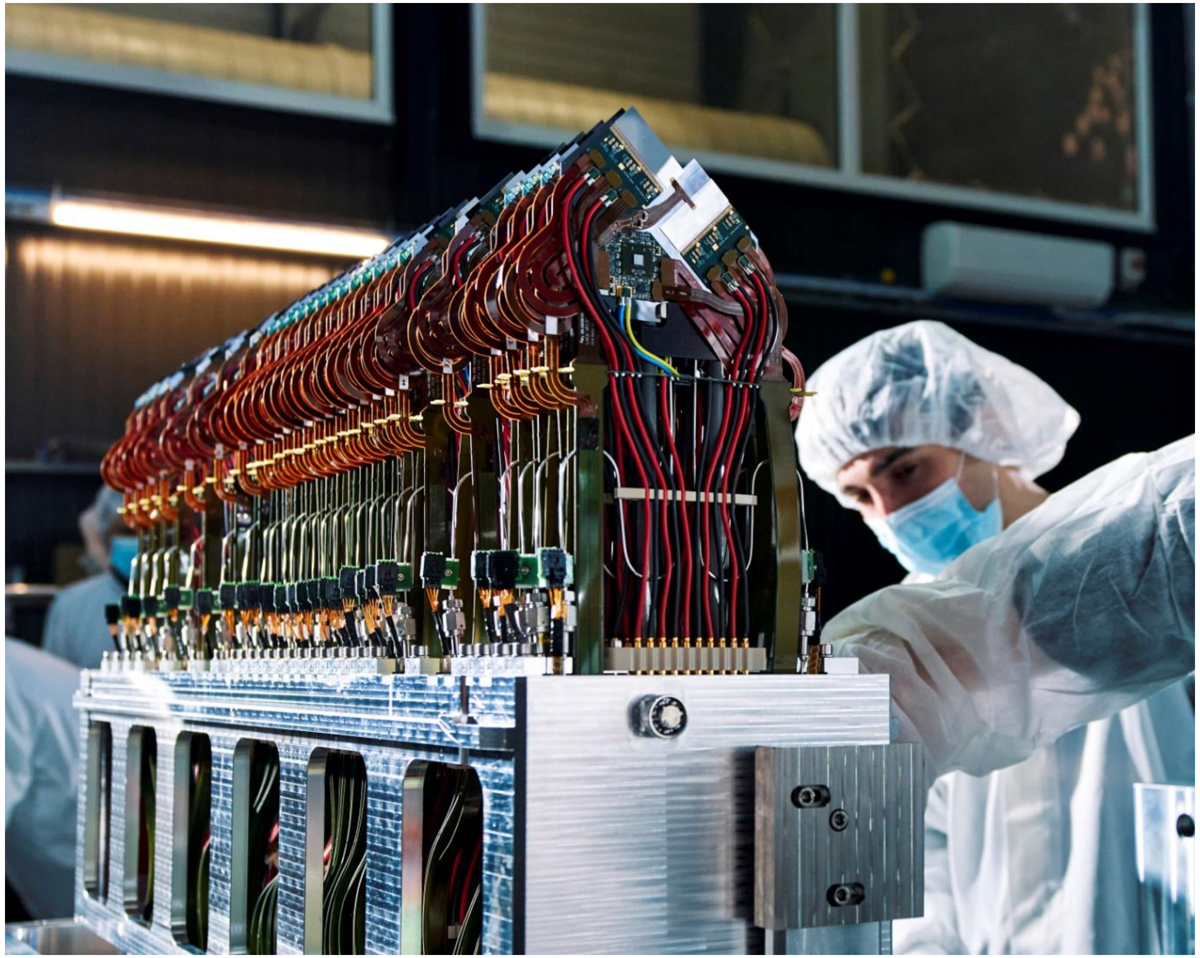




More information in VELO U1 poster, Gianluca

81/52 Grade A/B substrates produced with 87% yield and additional lower grade substrates

LHCb VELO Upgrade installation

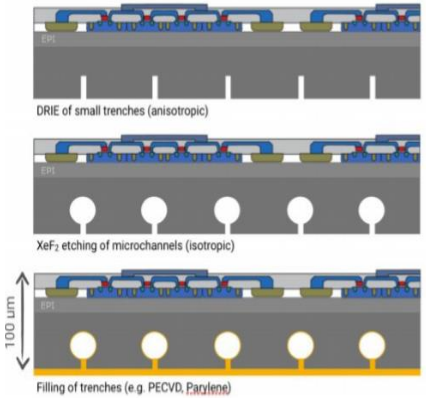


Both detectors halves installed and being commissioned

Additional techniques

Alternative bonding techniques (anodic bonding, …)
Smaller cooling substrates
R&D on new connectorization techniques

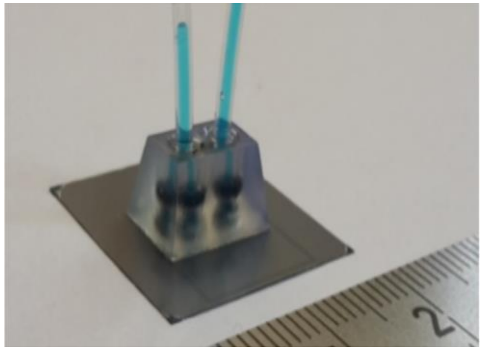
More info in VELO U2 talk, Efren Rodriguez



AIDA-2020-NOTE

CMOS compatible process potential
post processing step holds 110 bars

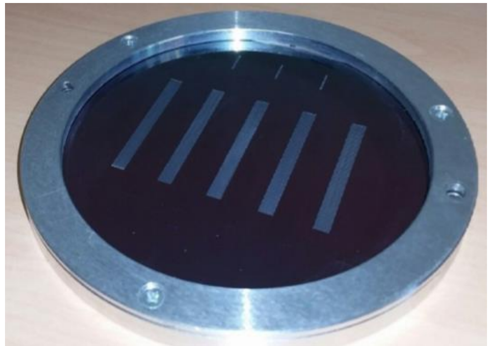
Most ambitious approach: bring the cooling to the sensors

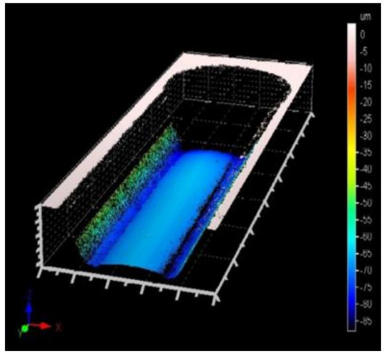


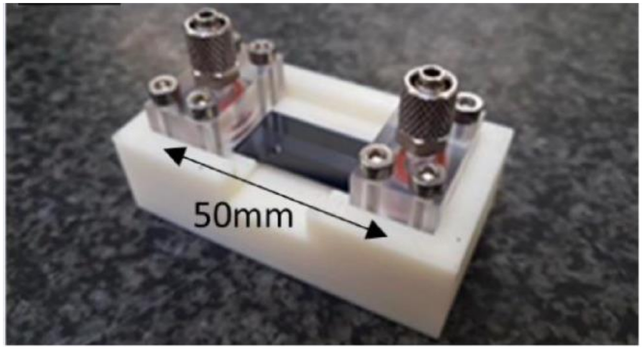
Build the connector with a mold already attached to the cooling substrate

Marcel Vos, Forum on tracking detector mechanics, 2019

R&D @ CPPM
Laser etching and anodic bonding
5 x 10 cm channels per wafer
200 um x 70 um x 4.5 cm per channel
Next step: connector with anodic bonding



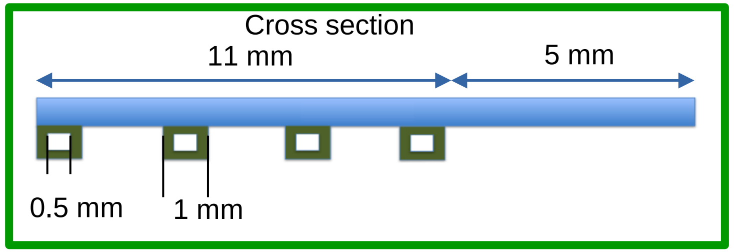


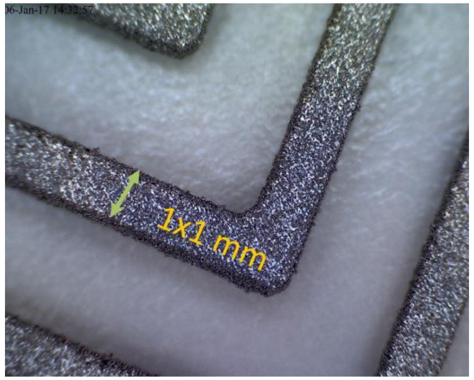


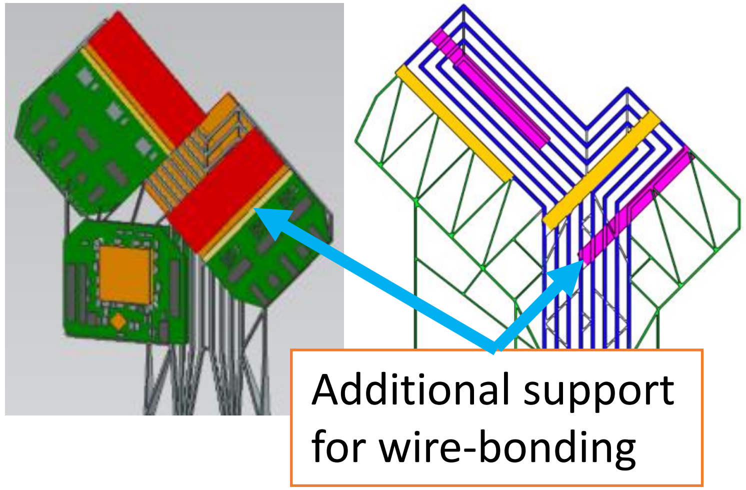
Short-pulse Laser-Assisted Fabrication of a Si-SiO2 Microcooling Device, A. Mouskeftaras et al

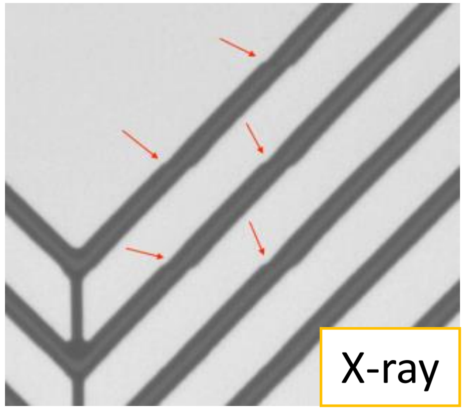
3D printing

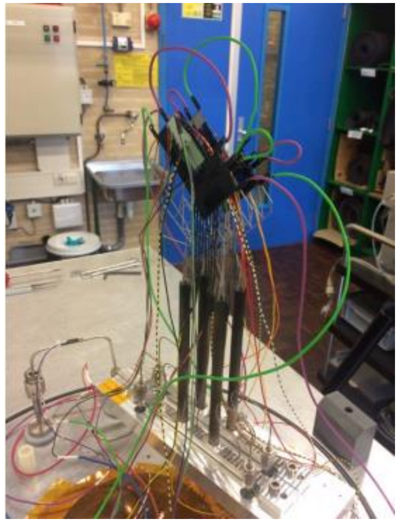
- Several options of materials: Ti, SiC, Alumina,…
- Ti key features:
  - Low material budget overall
  - Easier to handle (compared to Si)
  - Restrictions can be integrated in the inlet
  - (0.35 mm x 0.35 mm x 40 mm)
  - Easier to integrate with the cooling plant
  - High pressure test (up to 250 bar)
  - Leak tight (at least 250 µm wall)
  - Deflection due to temperature variations (< 100 µm)
- Production:
  - Relatively cheap (<500 EUR/module, including welding capillaries)
  - Fast turnaround for design changes (weeks)
  - Fast production: 25/batch, 1 batch/ few days
- Main challenges:
  - Glue layer, thermal performance, production irregularities and flatness

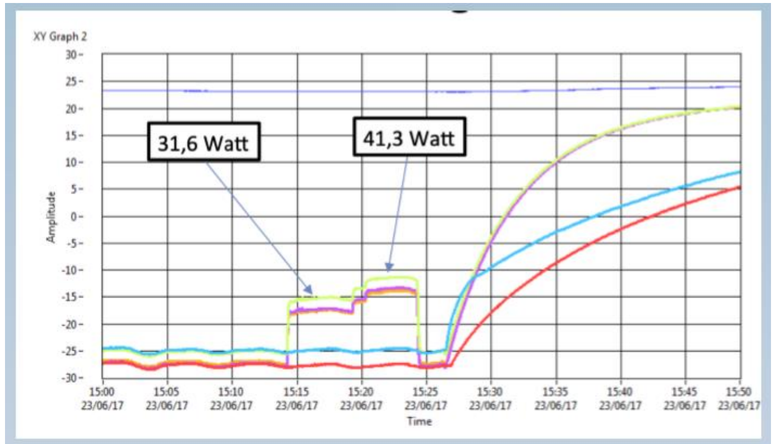






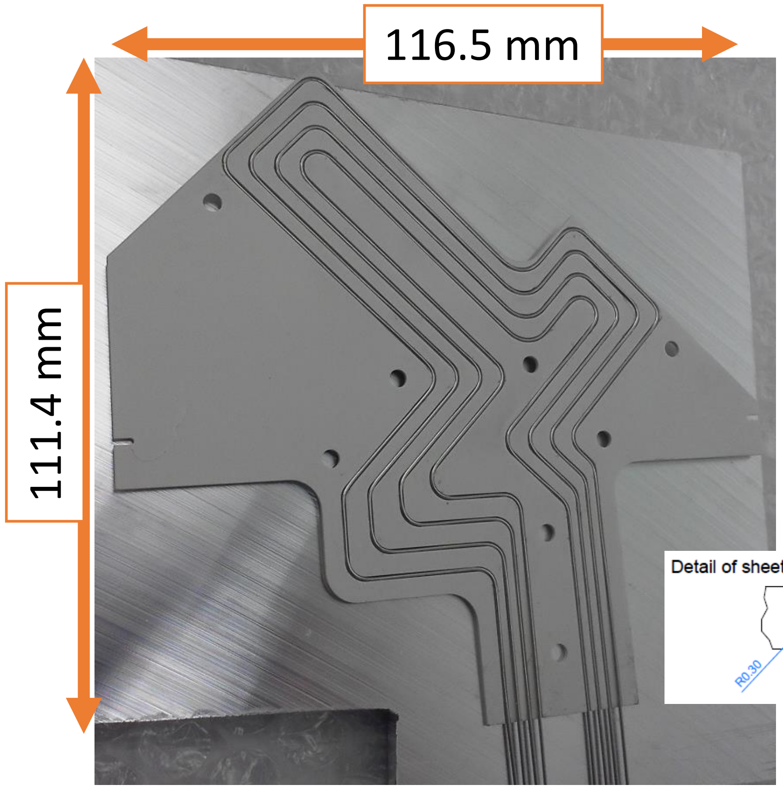


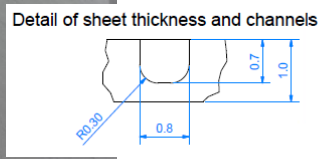


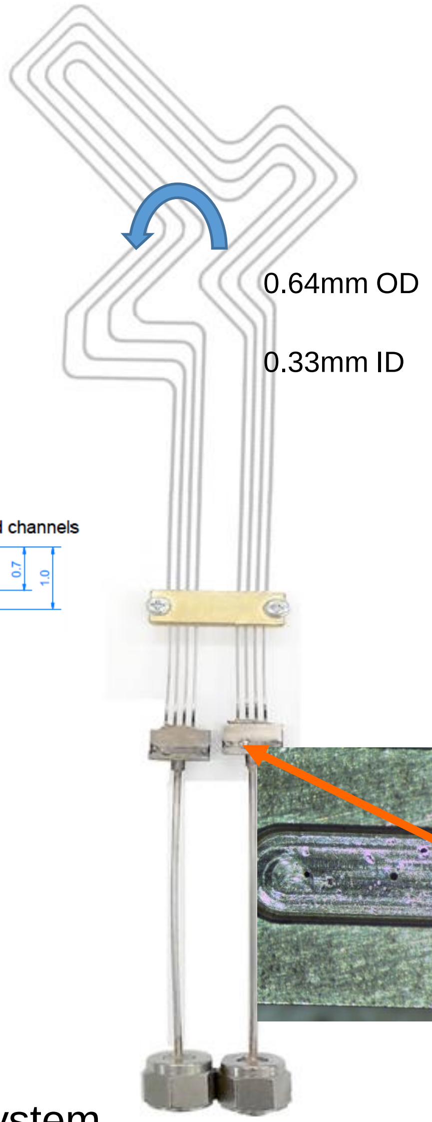


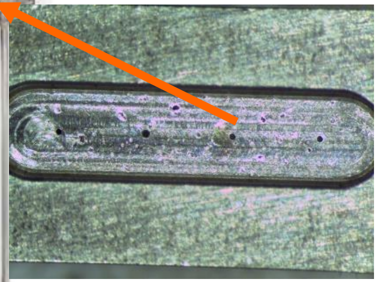
successful cooling test (ΔT~13°C)

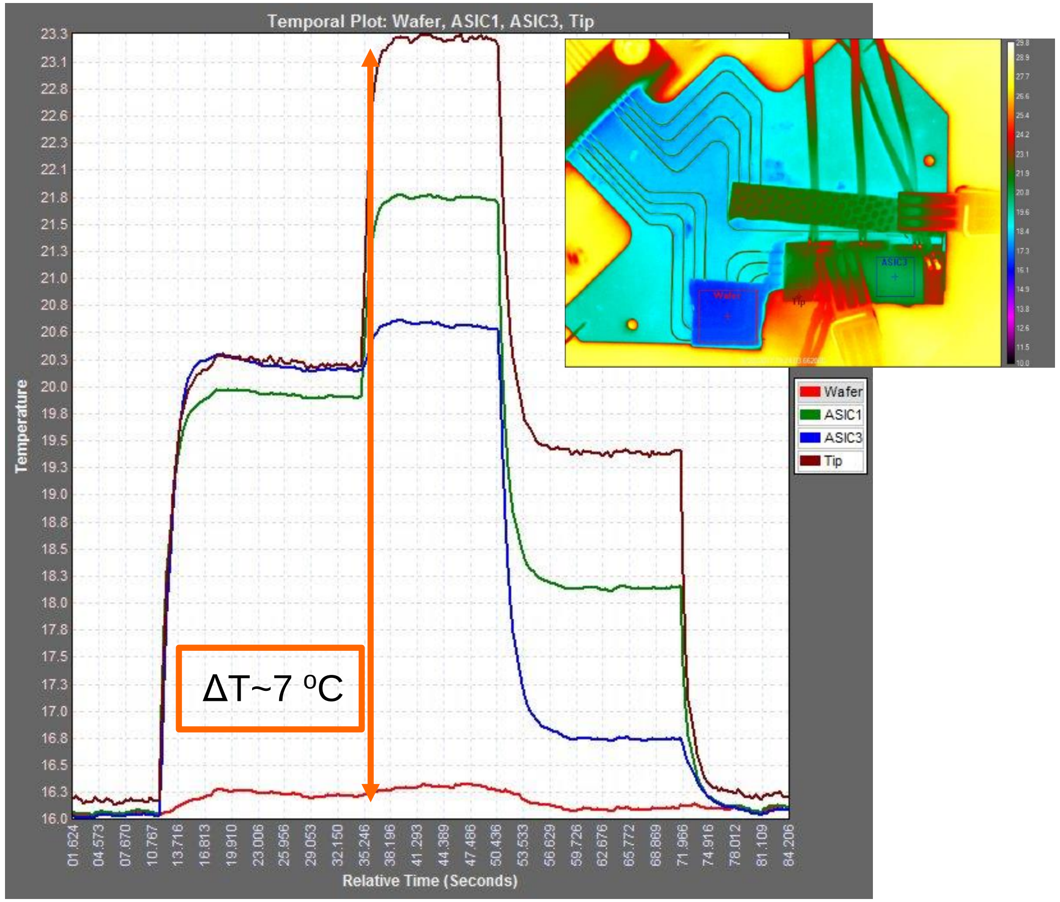
Tubes embedded in ceramics











Aluminum Nitride (Shapal):

- Machinable ceramic
- Thermal expansion coefficient: 4.8 x 10^{-6} /K
- Thermal conductivity: 92 W/m°C
- Tubes glued to the trenches
  - Creative Materials 122-39 (SD)
- Thermal deflections < 100 um with constraint system

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

Conclusion

- The evaporative cooling through microchannels embedded in silicon has several advantages such as minimal material budget, no CTE mismatch with respect to the silicon sensor and great cooling performance
- The main challenge for the LHCb VELO U1 was the development of the fluidic connector attachment technique
- Alternative techniques are being developed to reduce the cost of microchannels in silicon and look for alternative connectorizations procedures
- In addition, other techniques as additive manufacturing are being considered for the VELO Upgrade 2 (2030) due to its robustness and more flexible 3D design
- Very exciting R&D ahead of us for the VELO Upgrade 2

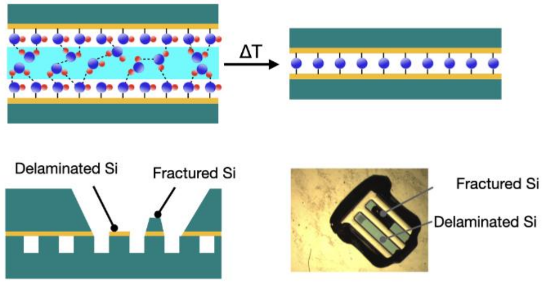
Thank you very much for your attention!

Backup slides

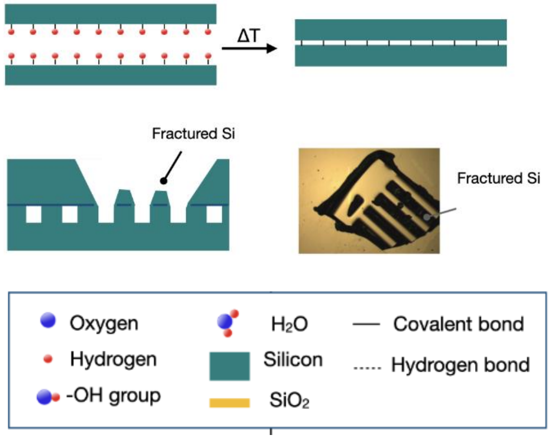
High pressure resistance

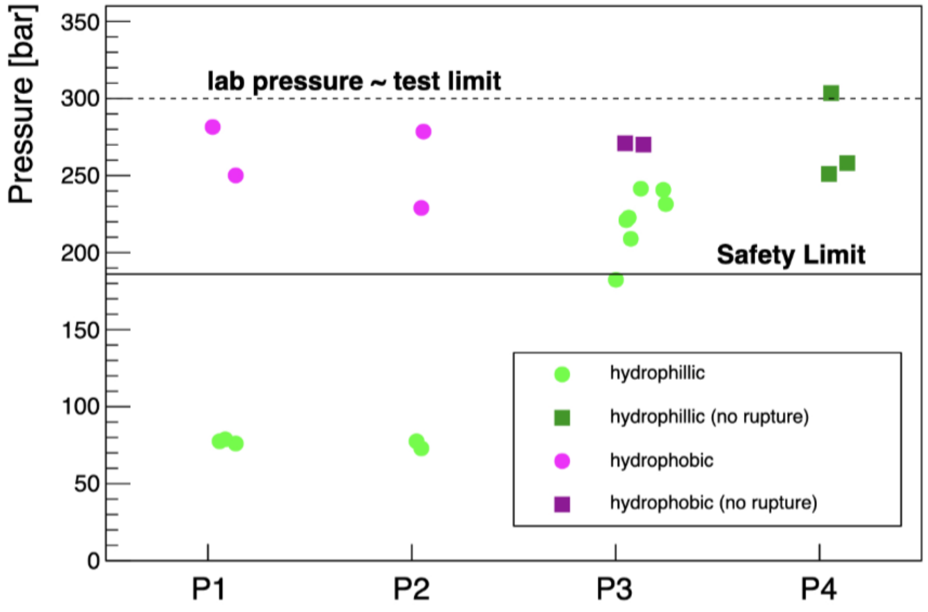
Manifold and bonding

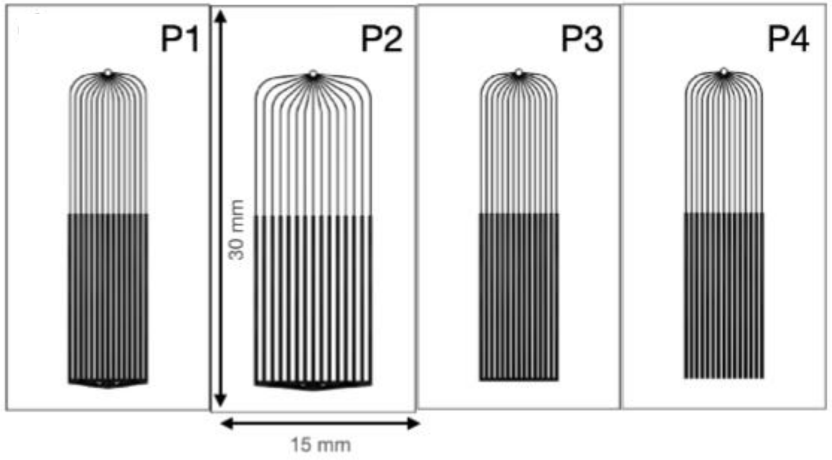
Hydrophilic bonding



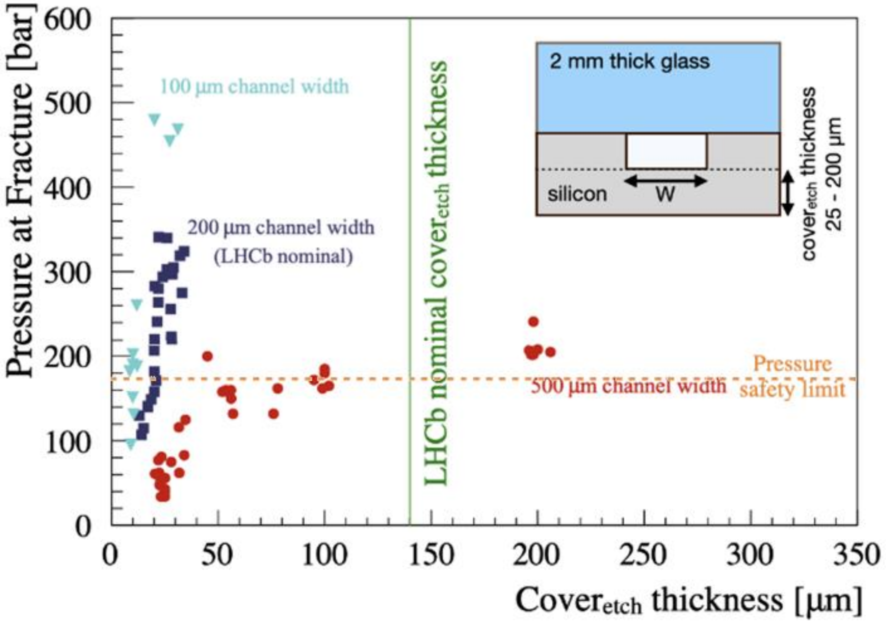
Hydrophobic bonding



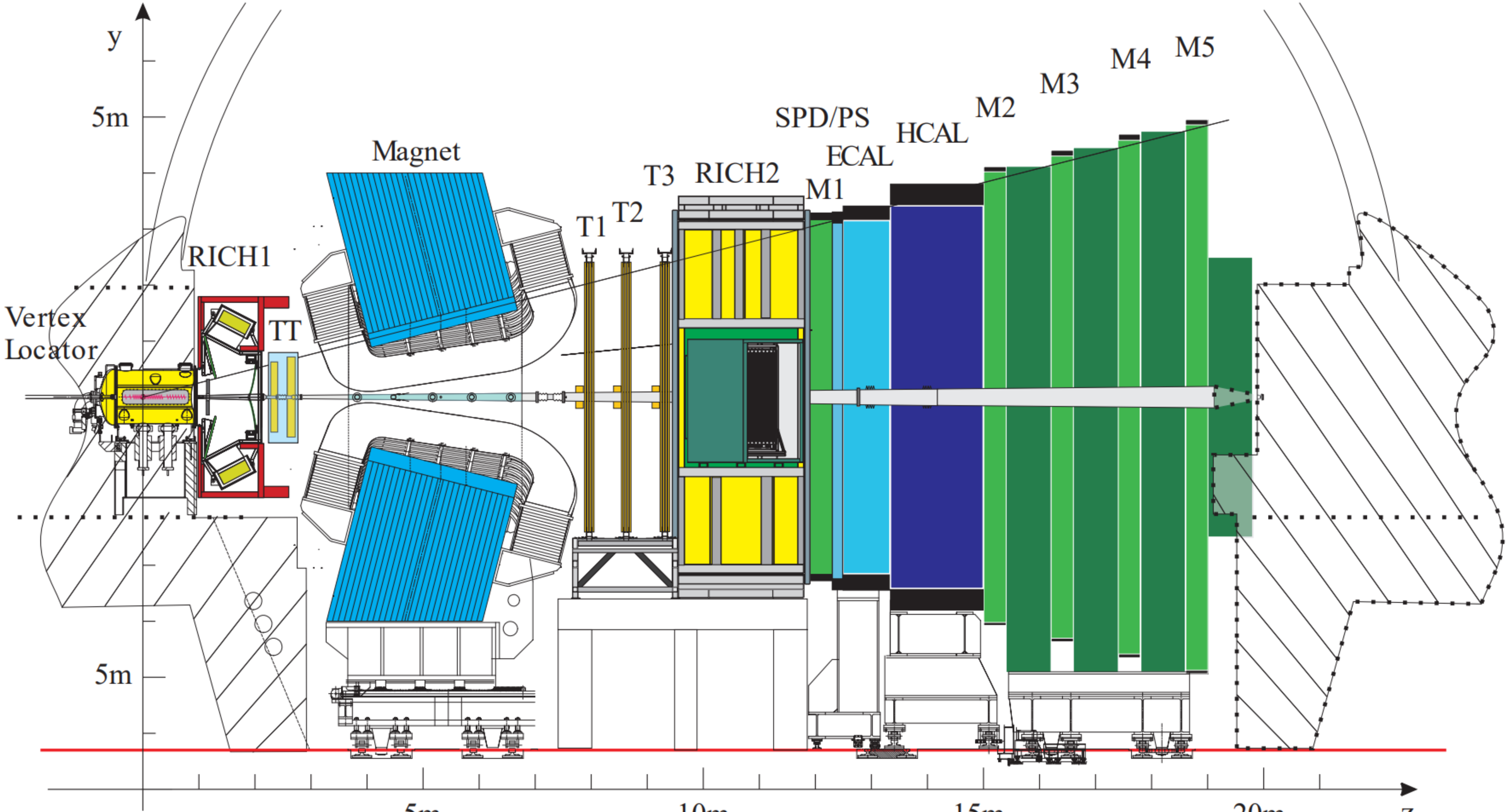




Silicon cover thickness



Material budget



LHCb Dectector Upgrade