Cooling solutions for the pixel detectors of NA62 and LHCb

Alessandro MAPELLI

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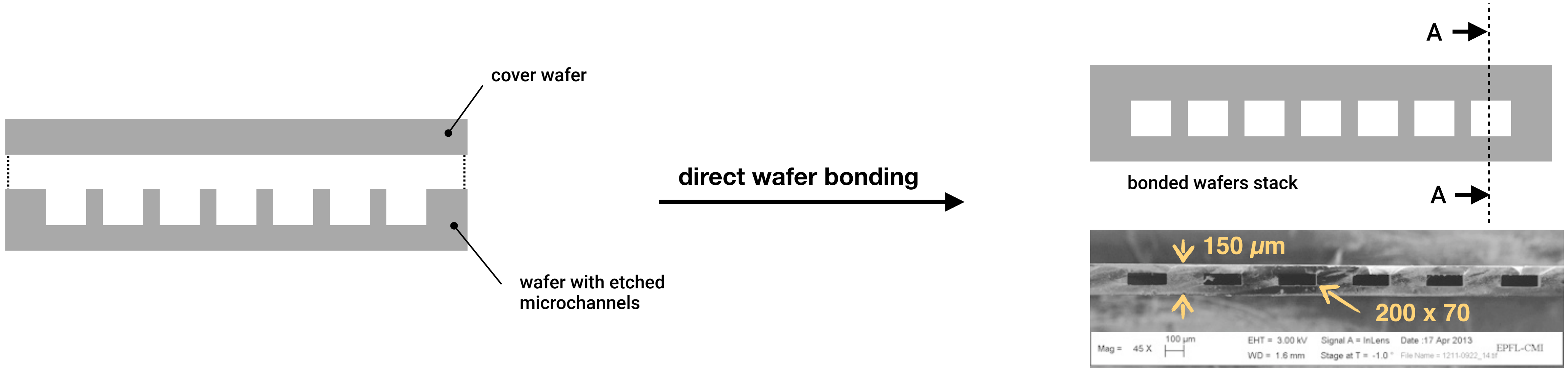
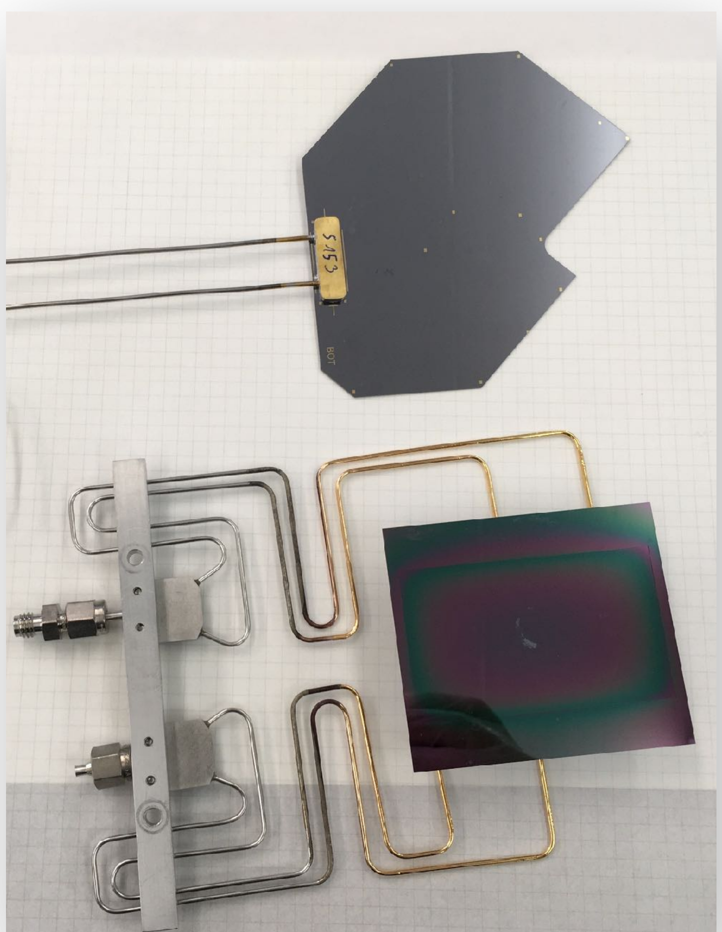
indico.cern.ch/event/838435

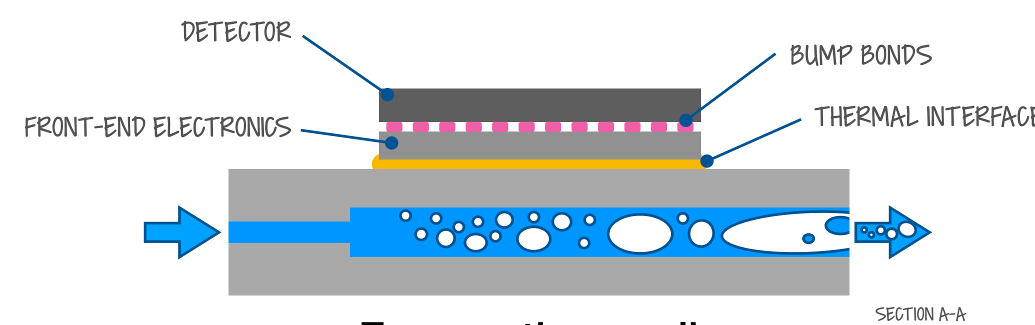
silicon microchannel cooling plates



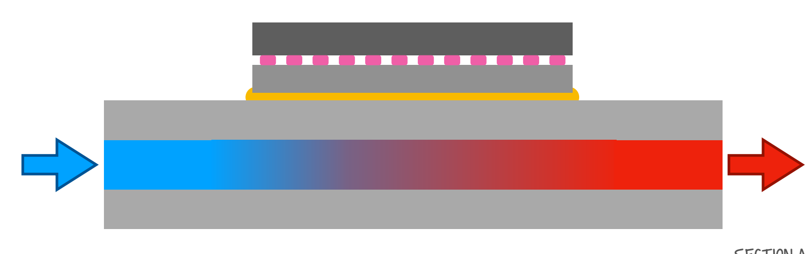


LHCb

NA62

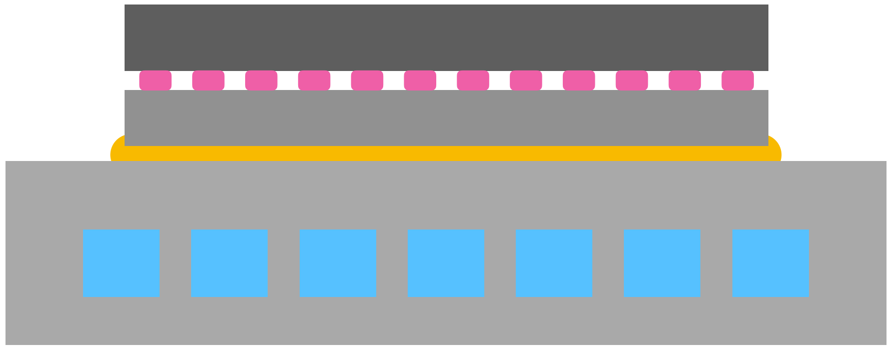


Evaporative cooling



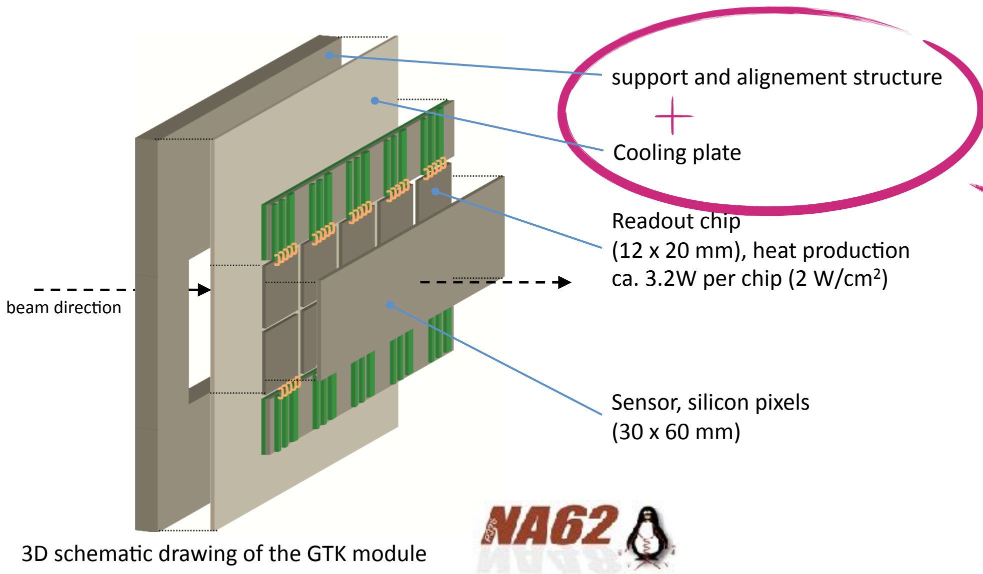
Liquid cooling

Silicon microchannel cooling plates



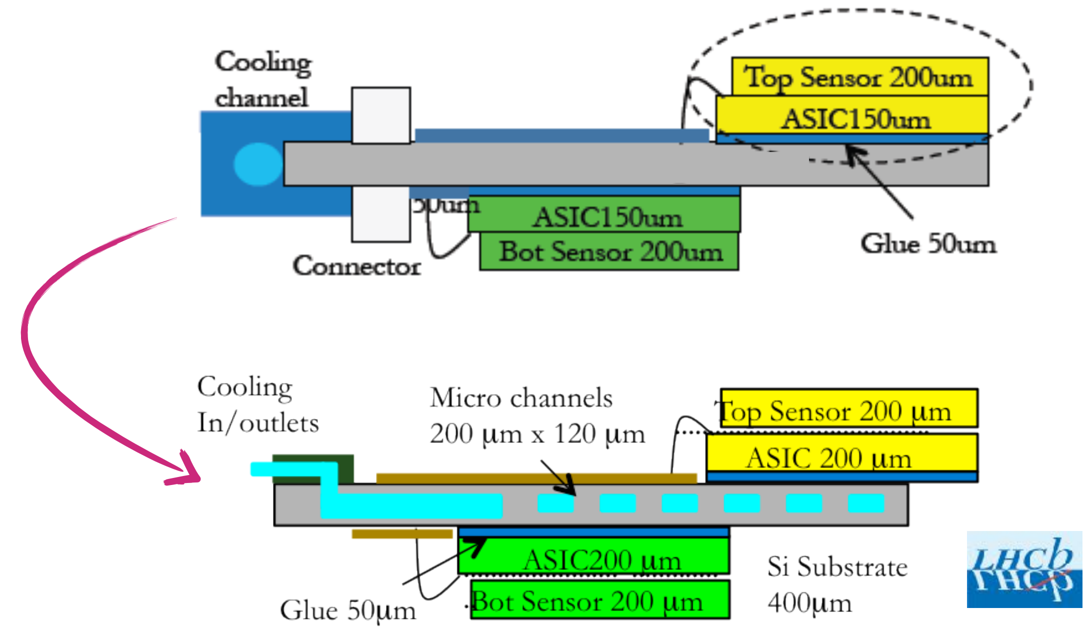
- No CTE mismatch
- Standard mcirofabrication processes
  - Microfliudics uses the same processes as microelectronics
- Active and distributed cooling
  - Better temperature uniformity across sensor
- Low and uniform material budget
- Radiation resistance
- Great potential for integration
  - Same microfabrication techniques as sensors and microelectronics.
- Thermal Figure of Merit

NA62 GTK and LHCb VELO Upgrade



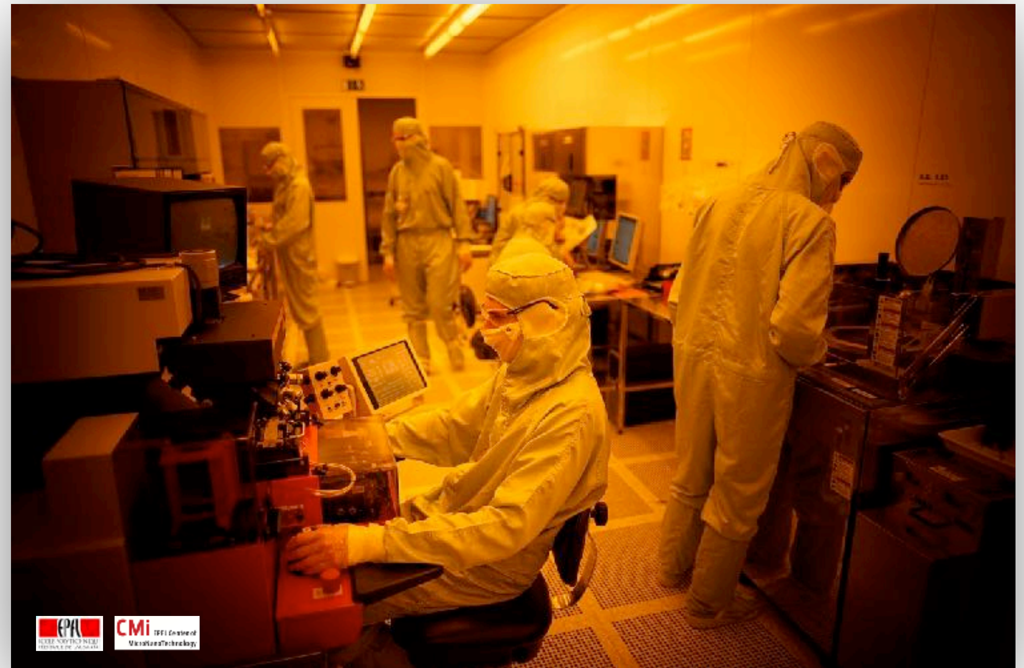
3D schematic drawing of the GTK module

Silicon microchannel cooling plate

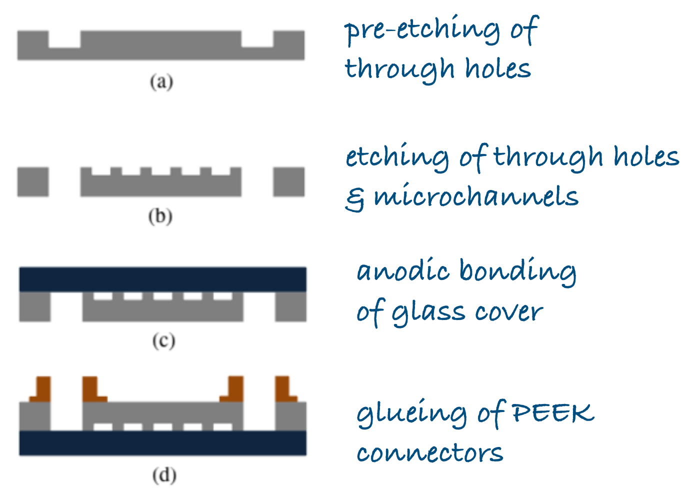


	NA62	LHCb
# of modules	3	52 (2x 26)
distance between modules	~10 m	2.5 cm
sensors	hybrid pixel	hybrid pixel
sensor size	60 x 38 mm	43 x 15 mm
sensors/module	1	4 (2 on each side of plate)
power dissipation (average)	~2 W/cm^2	~2 W/cm^2
coolant	liquid C_6F_{14}	evap. CO_2
cooling plate thickness	~200 µm	~500 µm
operating temp. on sensor	-10°C	> -20°C
max. operating pressure	~10 bars	~60 bars
safety pressure	~20 bars	~200 bars
operation in vacuum	primary vacuum of NA62	secondary vacuum of LHC
distance to beam	in the beam axis	5.1 mm

“in-house” microfabrication processes



Process-flow developed at CERN for the first microchannel cooling plates



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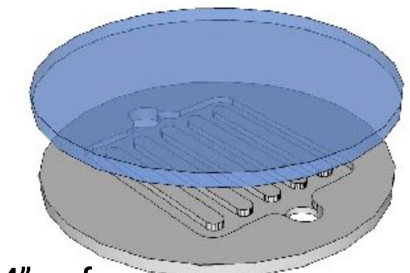
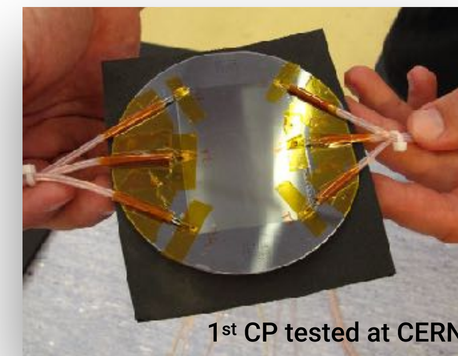
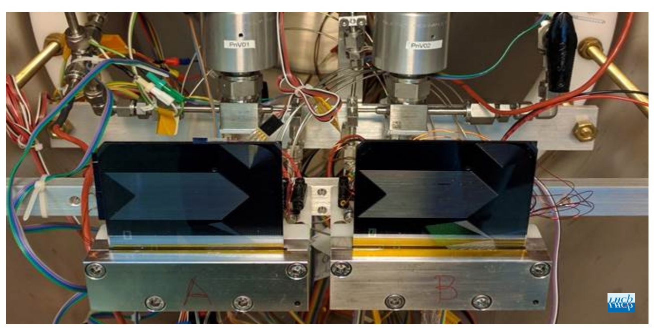
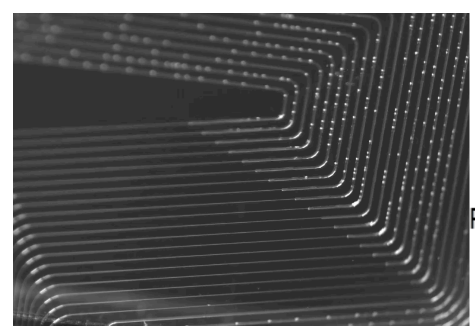
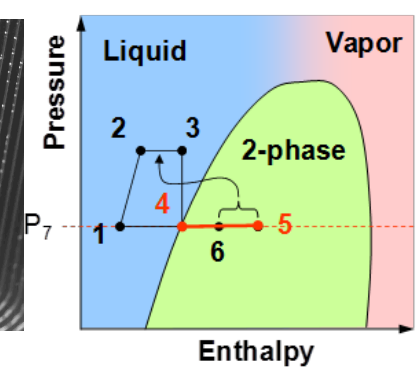


4” wafers

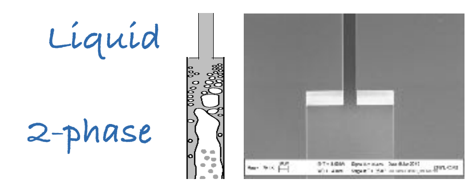


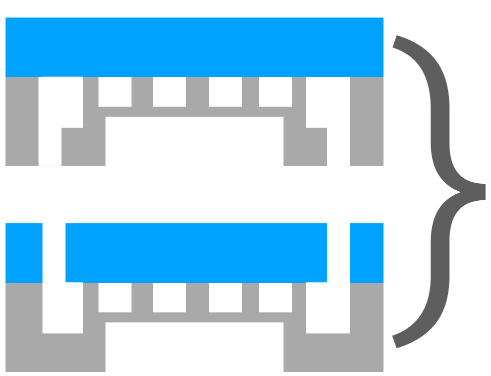


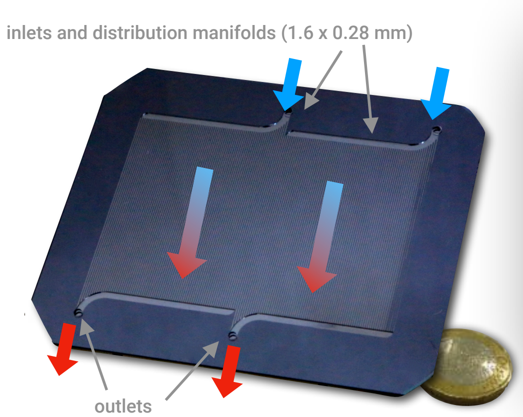




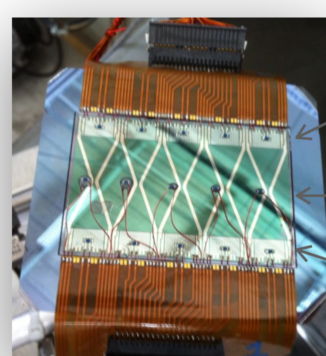
First demonstration of 2-phase CO_2 circulation in silicon microchannels.



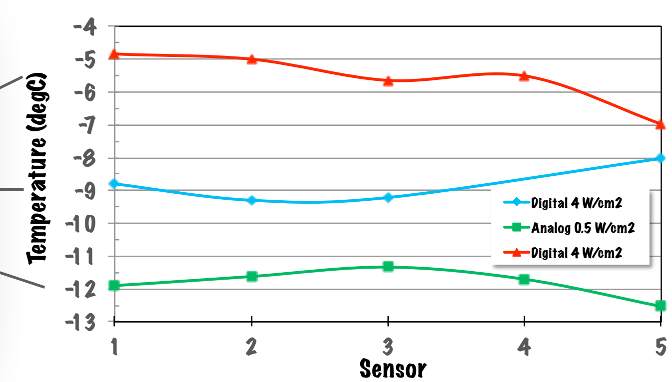




2 independent networks of 75 μchannels

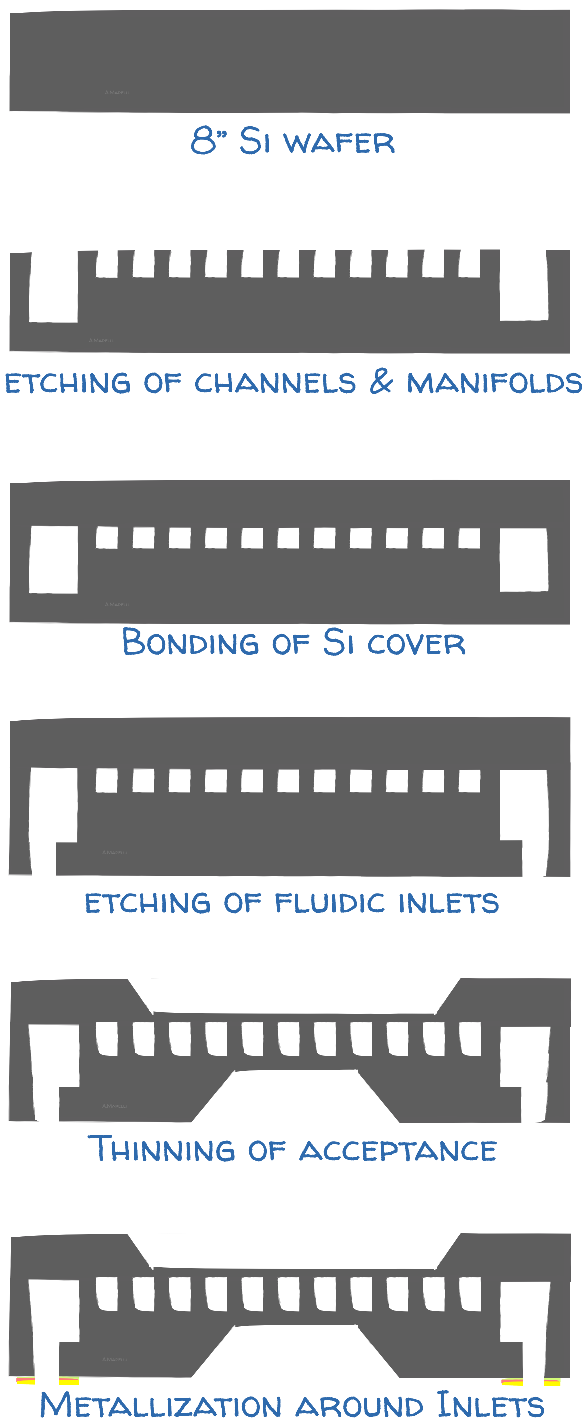


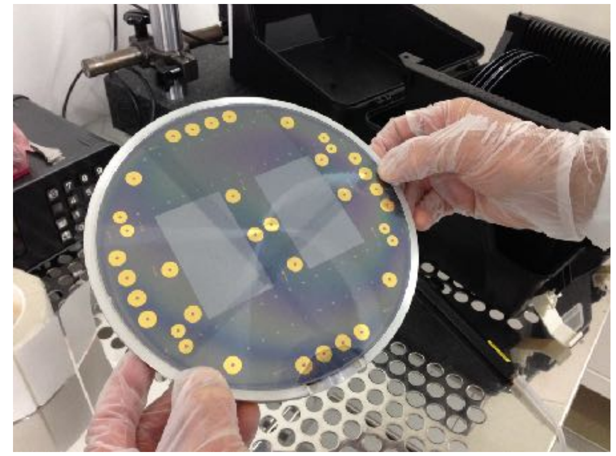
CP equipped with thermo-mechanical mockup of the hybrid detector

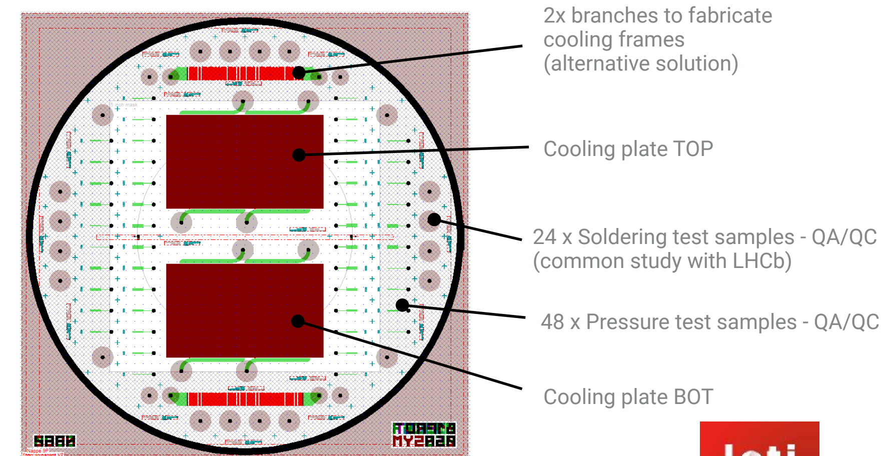


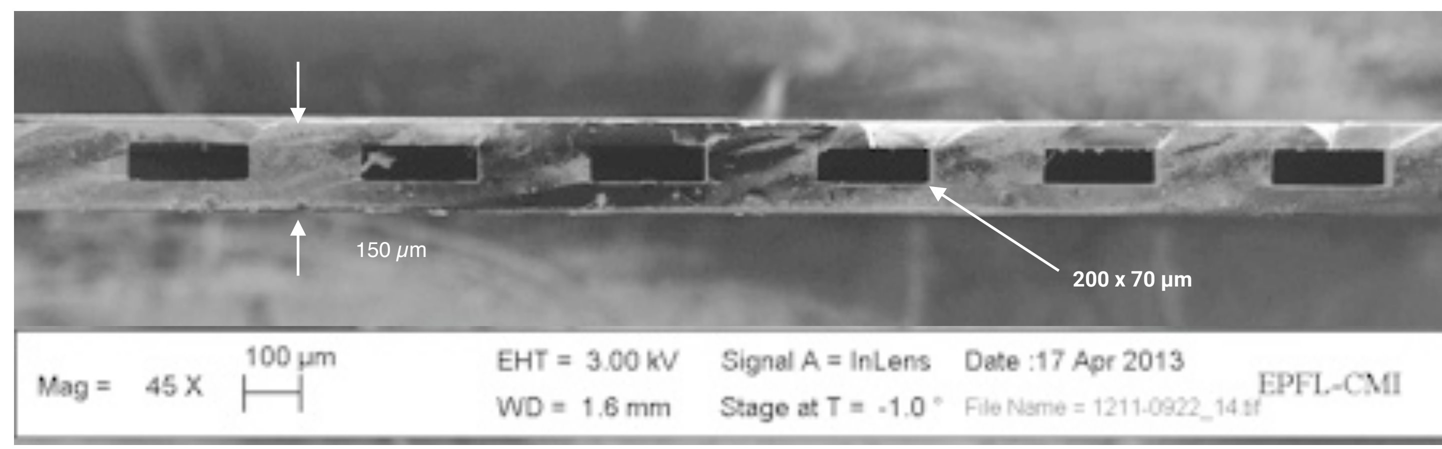
- Power dissipation
  - Digital Power 38 W
  - Analog Power 10 W
- Liquid C_6F_{14}
  - 7g/s
  - -19°C at inlet

microfabrication of the GTK cooling plates







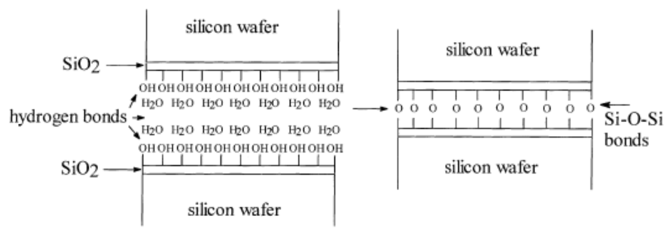


- Collaborative effort between CERN (ALICE, LHCb, NA62 and EP-DT) and external partners (CSEM, EPFL).
- Design by CERN EP-DT
- Prototypes fabricated by CERN EP-DT at EPFL-CMi on 4" wafers
- Pre-production series by IceMOS on 6" wafers
- Three batches fabricated at CEA-Leti on 8" wafers
- Fourth batch is under fabrication for the post-LS2 GTK modules.

Silicon direct wafer bonding

No intermediate layer such as eutectic metals or adhesives between the wafers

Hydrophilic bonding



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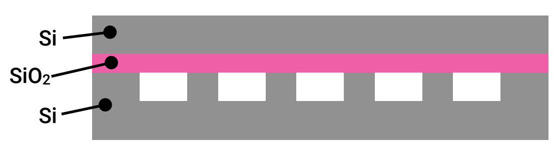
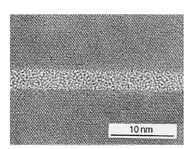
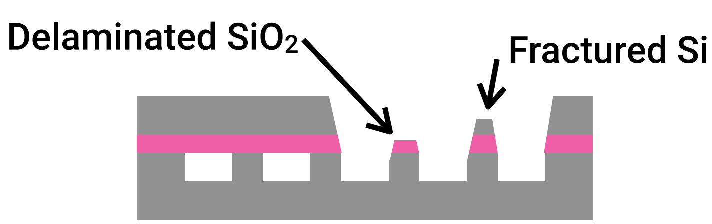


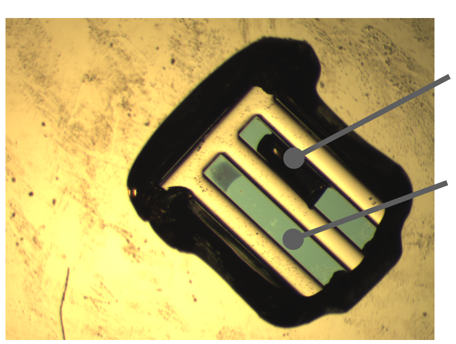


T_{anneal} = 1050°C

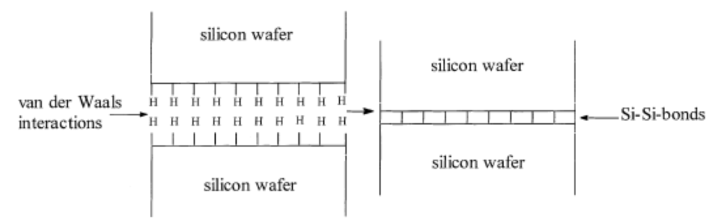
P_{max} ~400 bars

delamination + rupture





Hydrophobic bonding



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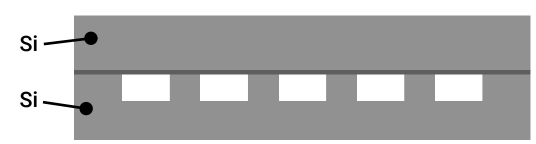
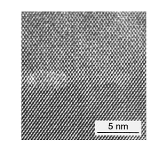
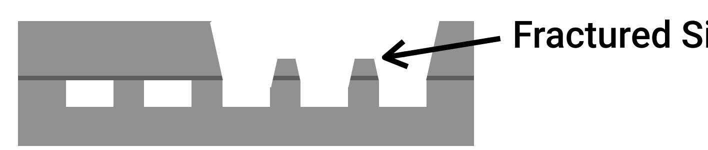


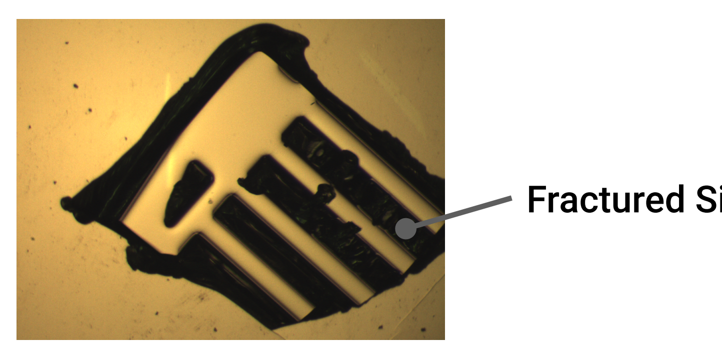


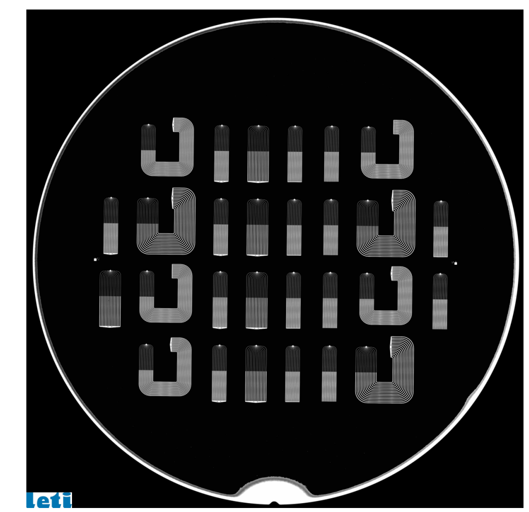
T_{anneal} = 1050°C

P_{max} ~700 bars

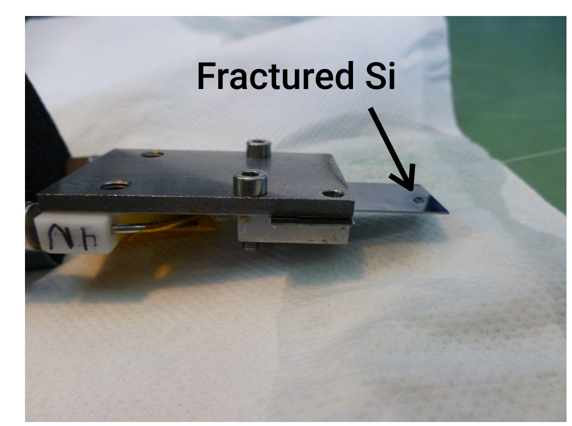
rupture without delamination



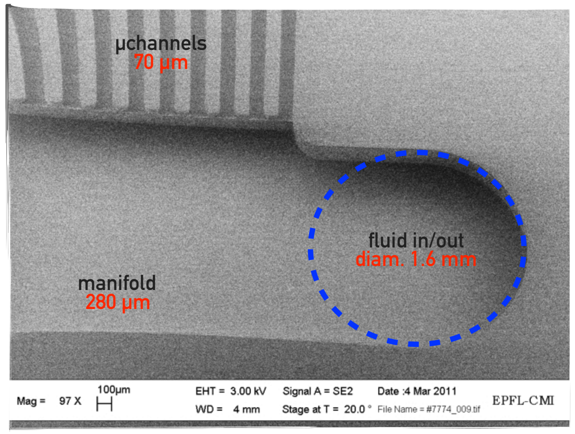




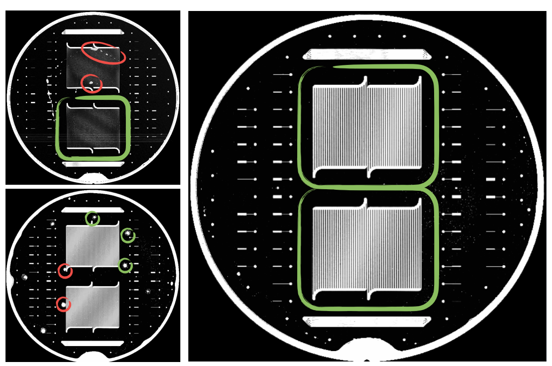
Scanning Acoustic Microscope image of bonded wafers with test structures.

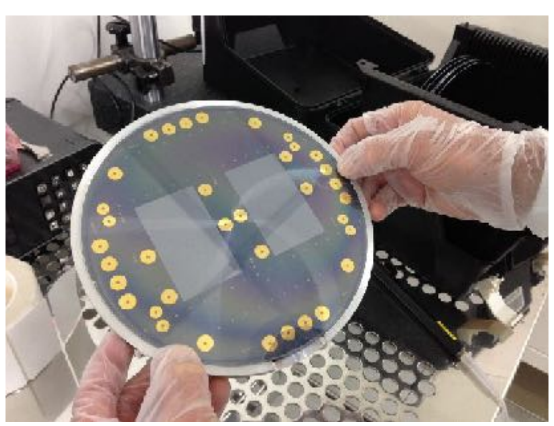


QA/QC of the cooling plates

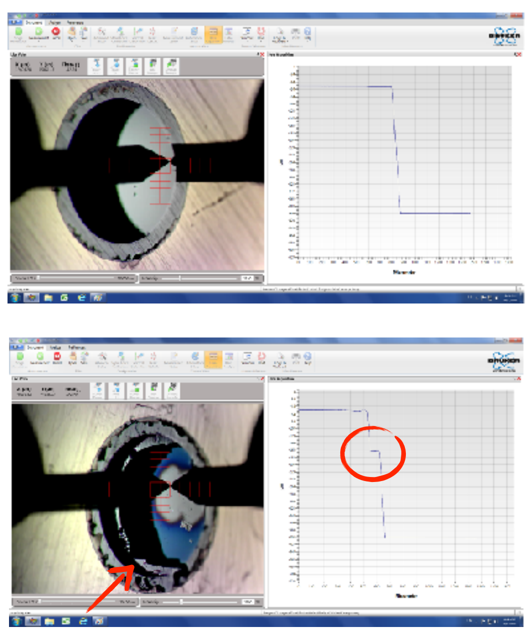


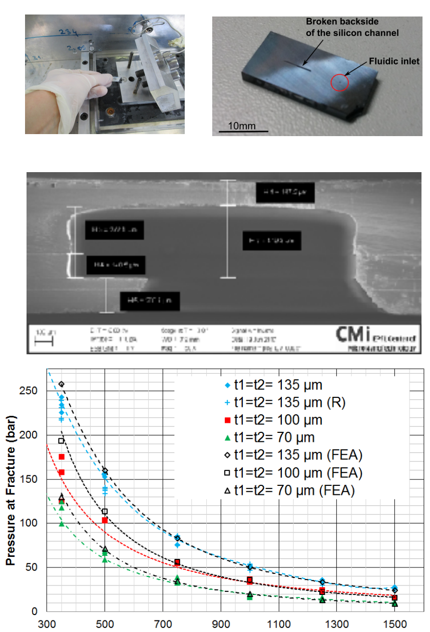
SEM of microchannels


SAM of bonded interface

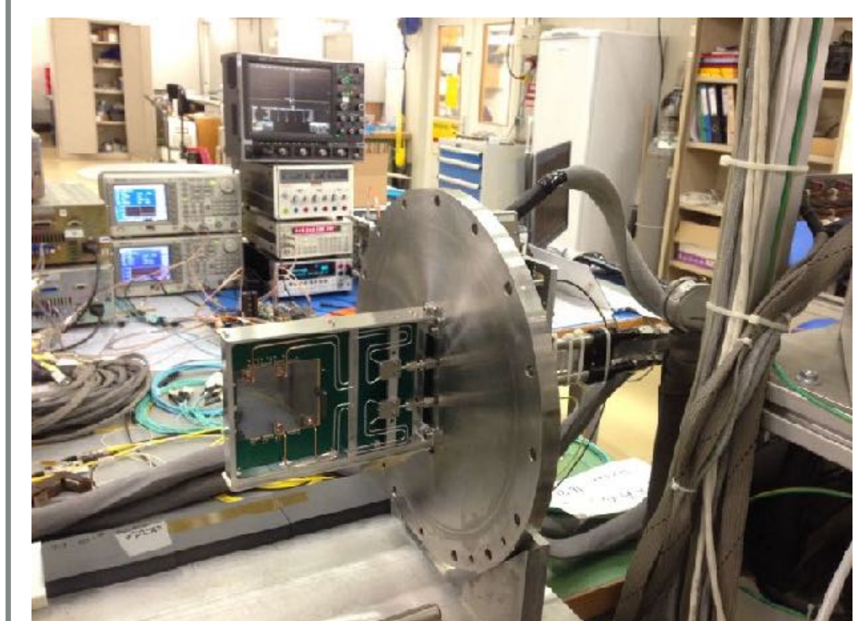

Visual inspection

- Etching profiles of the microchannels.
- Scanning Acoustic Microscopy of bonded wafers.
- Visual inspection during tape-out.
- Metrology of cooling plates (Inlets and pools).
- Pressure tests on dedicated samples
  - 1500 µm wide cavities (manifolds) > 25 bars
  - 200 µm wide cavities (microchannels) > 200 bars
  - Soldering pads > 200 bars
- Pressure and temperature cycles on soldered cooling plate.

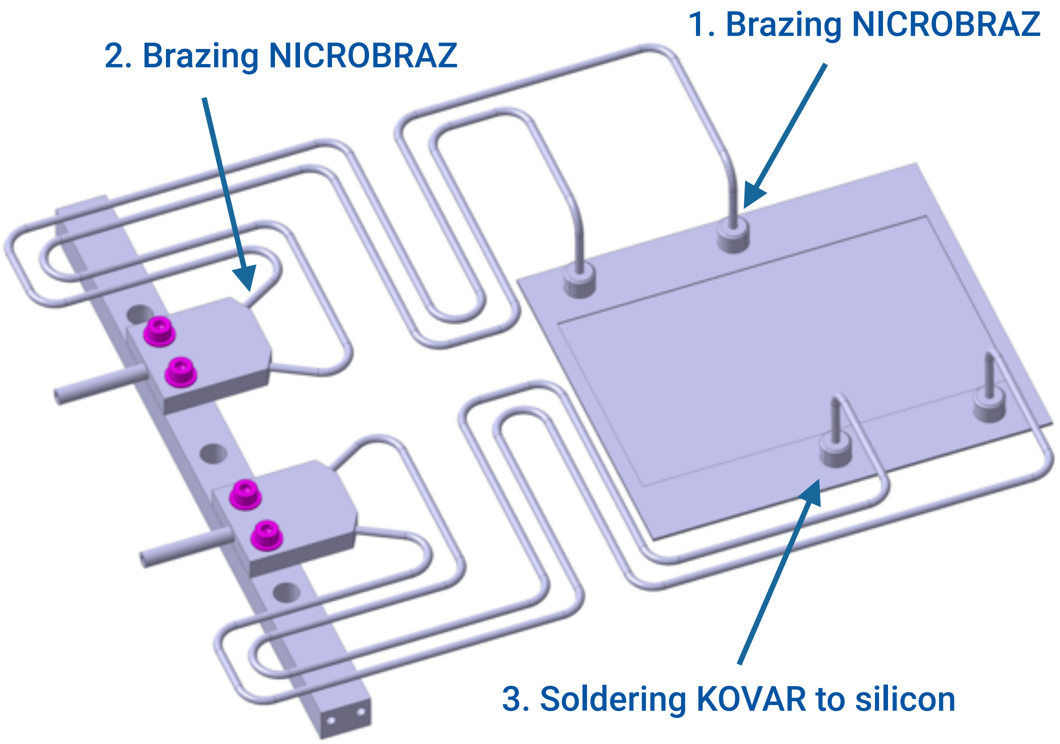

Metrology of fluidic inlet/outlet



Pressure testing of silicon microchannels


Cooling test setup at CERN

Microfluidic system integration

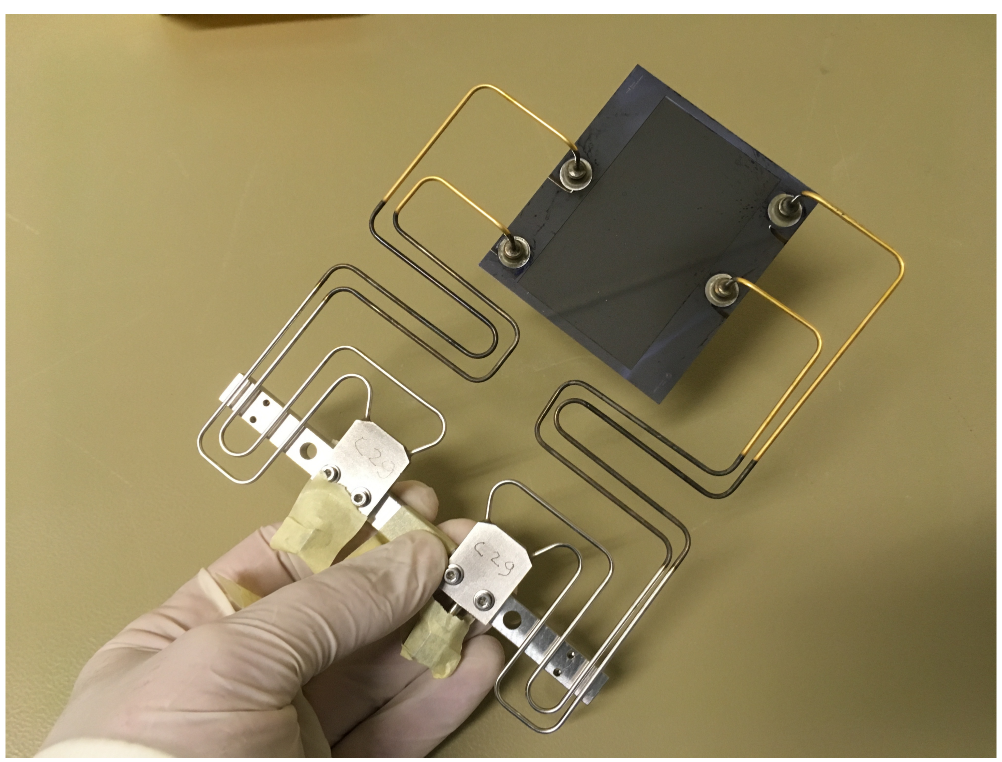


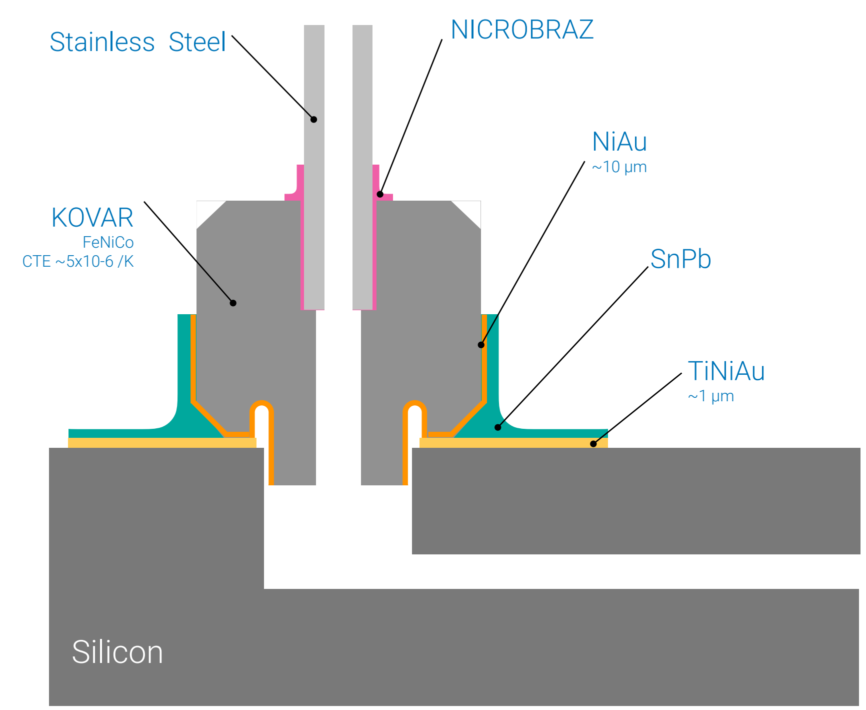
Assembly steps:

- Machining of KOVAR connectors;
- Brazing of connectors to capillaries (1);
- Bending of the capillaries;
- Brazing the other end of the capillaries to the manifolds (2);
- NiAu plating of the connectors;
- Soldering of the connectors to the silicon cooling plate (3);

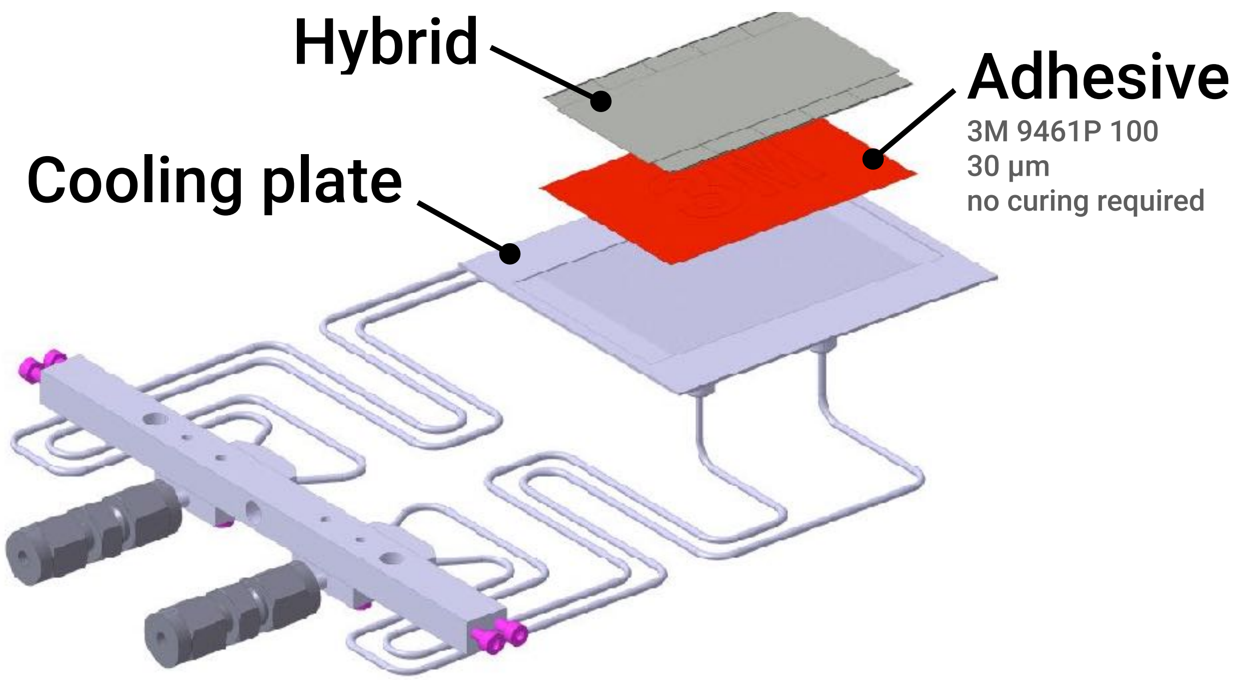
QA/QC:

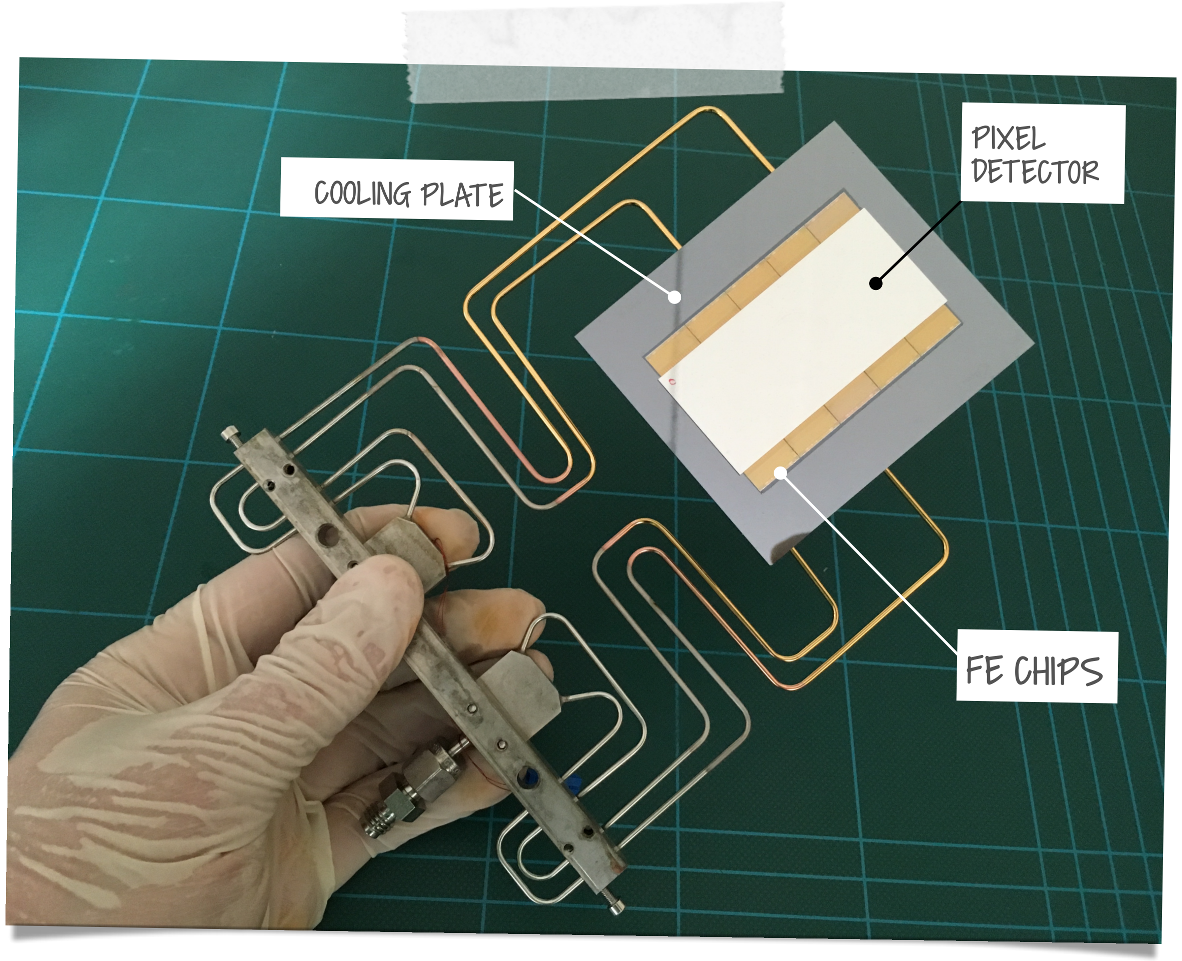
- After each joining step the He leak rate is measured. (Acceptance leak rate: 10^{-10} mbar $l^{-1}s^{-1}$).
- Pressure testing of the cooling plate at 1.43 x P_{op}



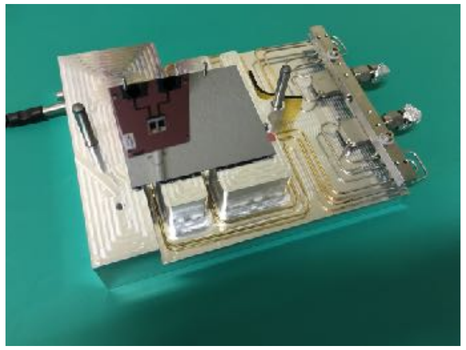


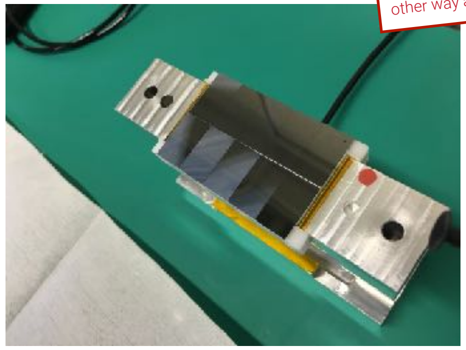
Glueing the detector on the cooling plate

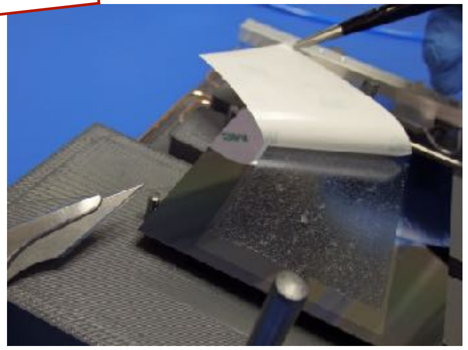


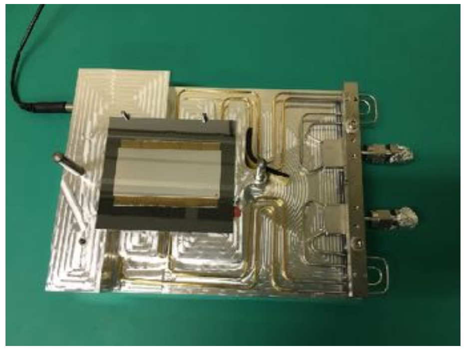


REWORKABILITY
The detector can be detached from the cooling plate... or the other way around.

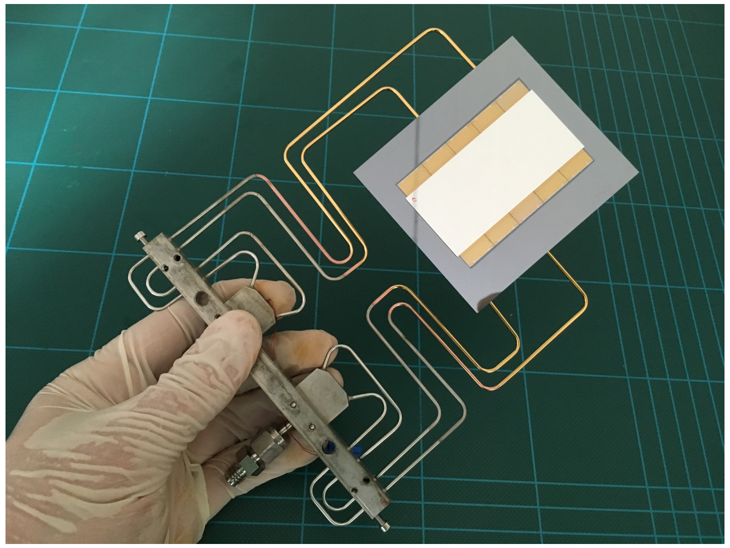


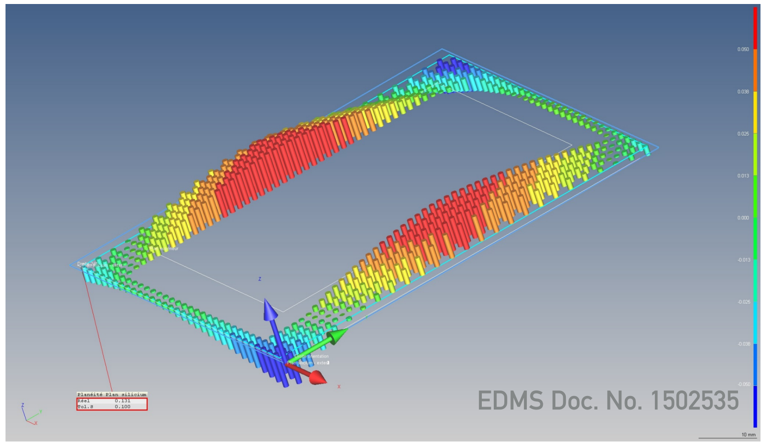


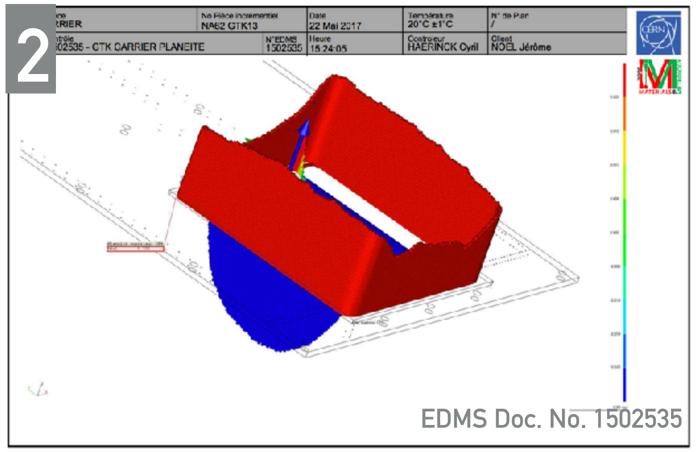


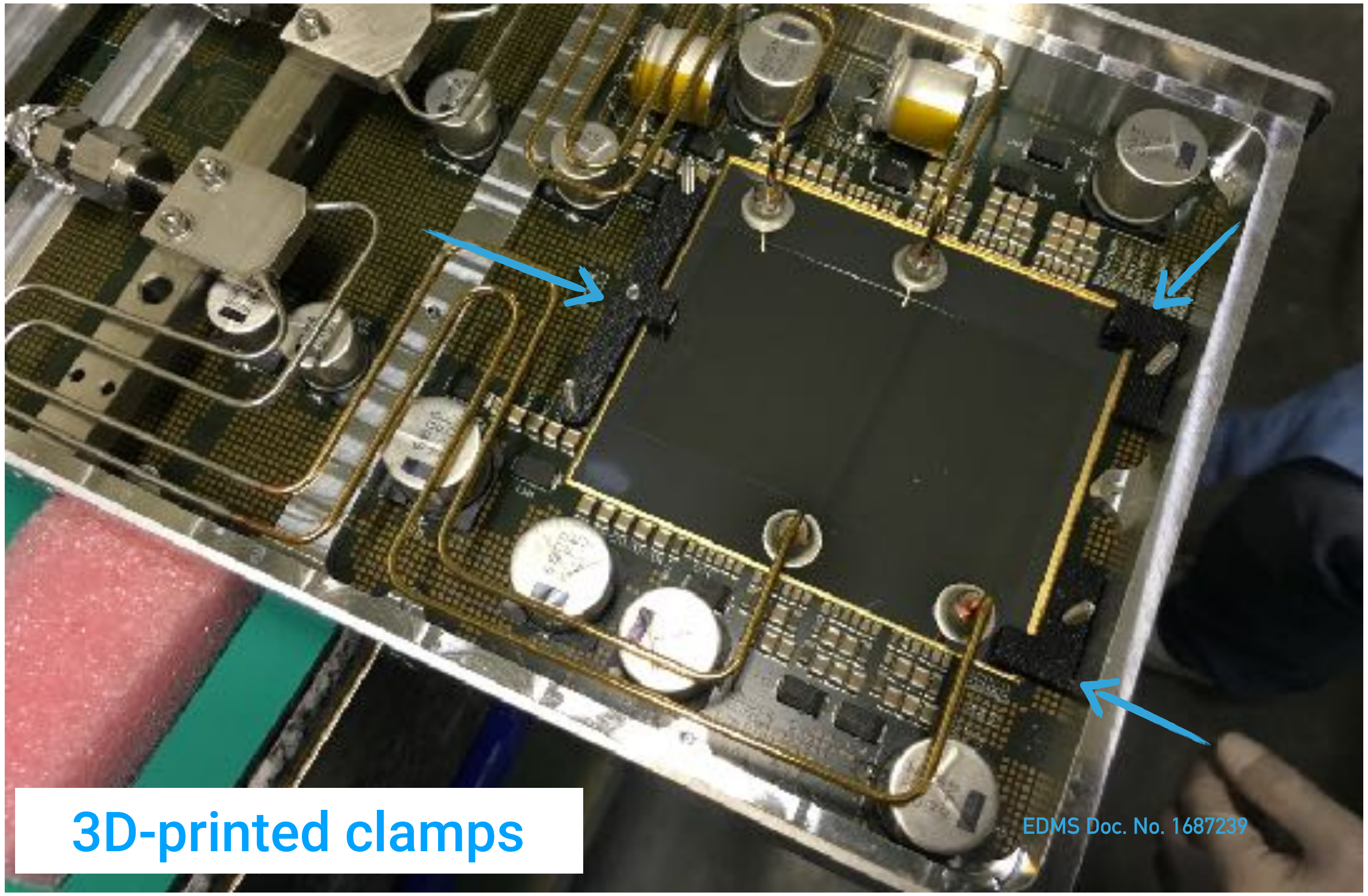


Clamping the cooling plate to the PCB



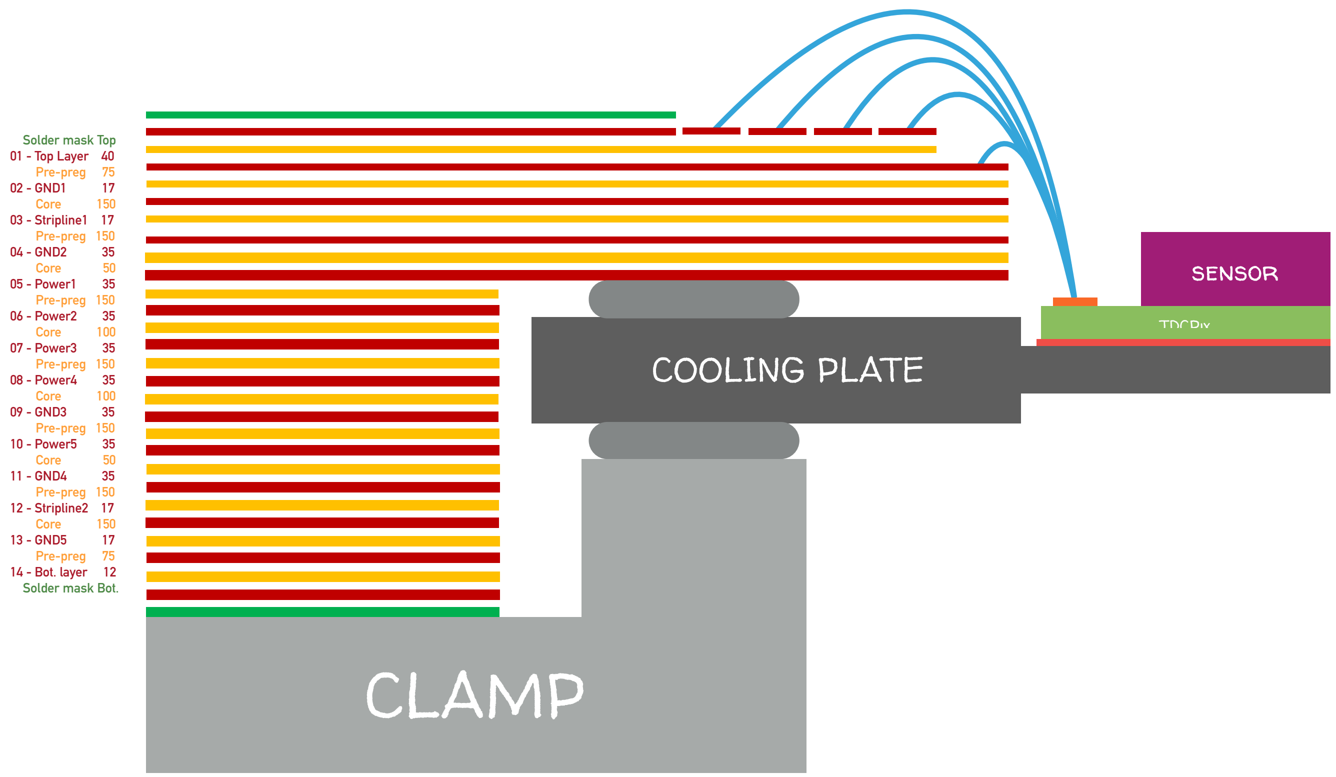


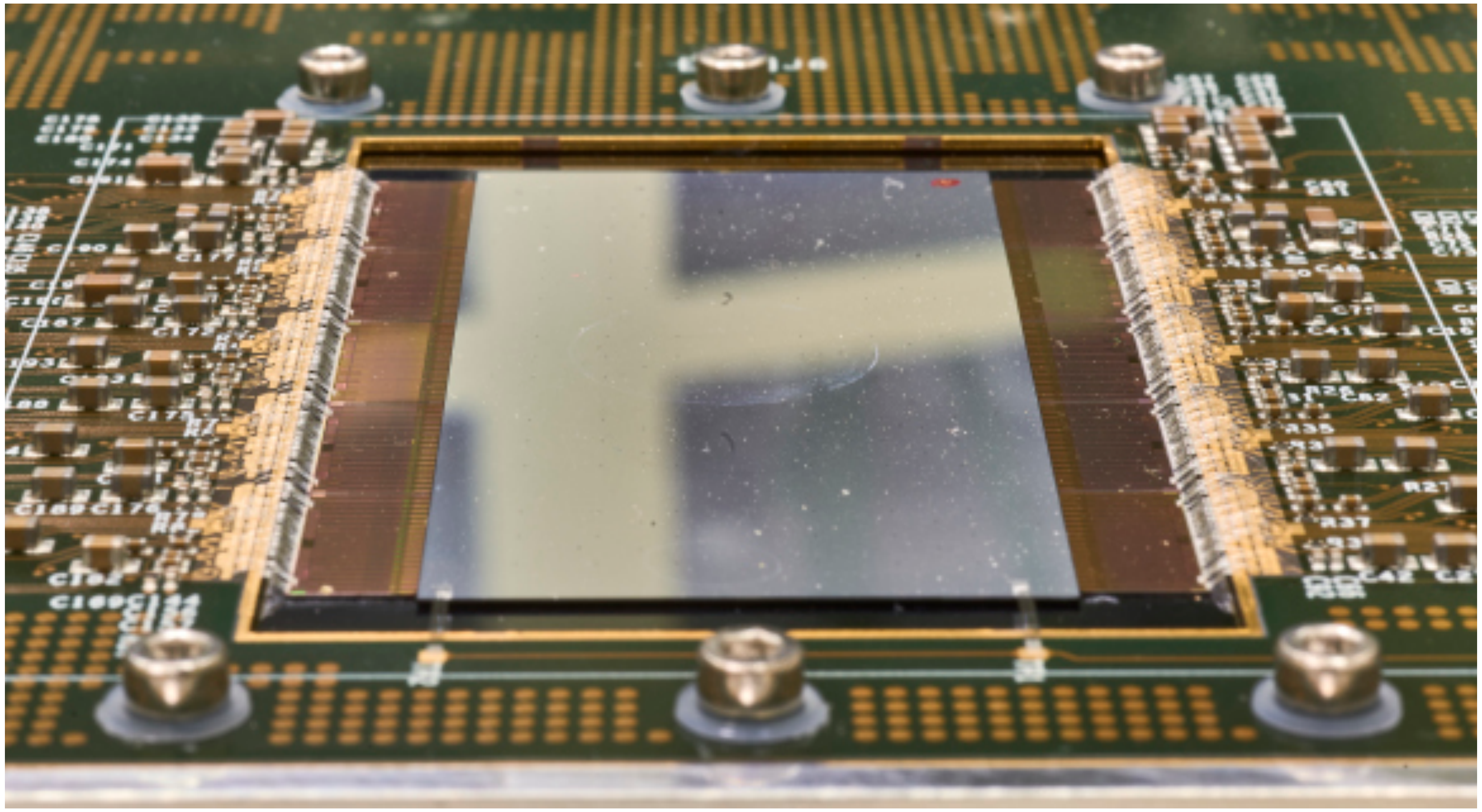


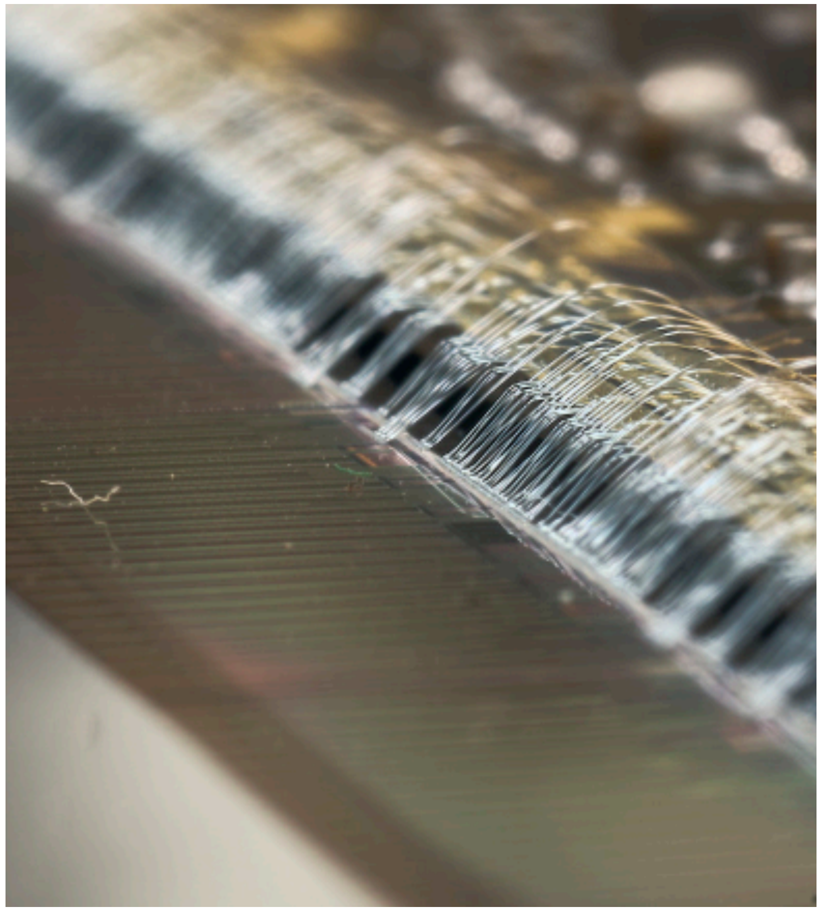


Wire-bonding

- Performed at CERN (http://bondlab-qa.web.cern.ch/)
- 18000 wire bonds per module with a pitch of 73 μm
- Height difference between PCB pads and TDCPix pads.

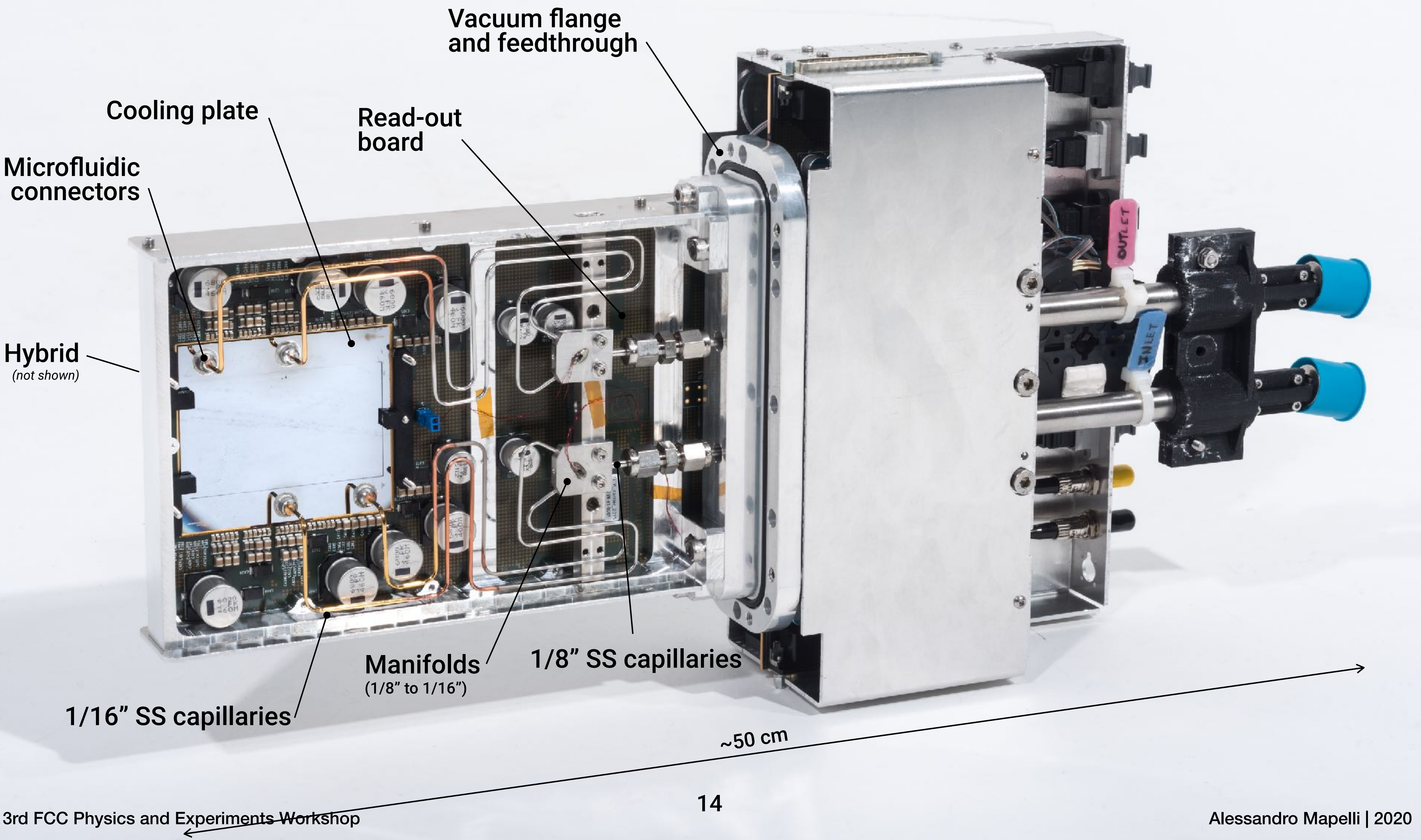







J1

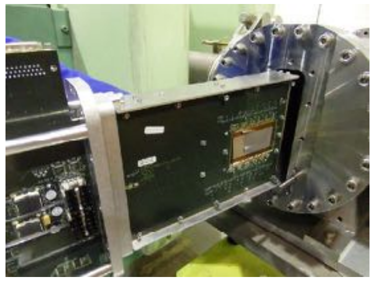
NA62 GigaTracKer

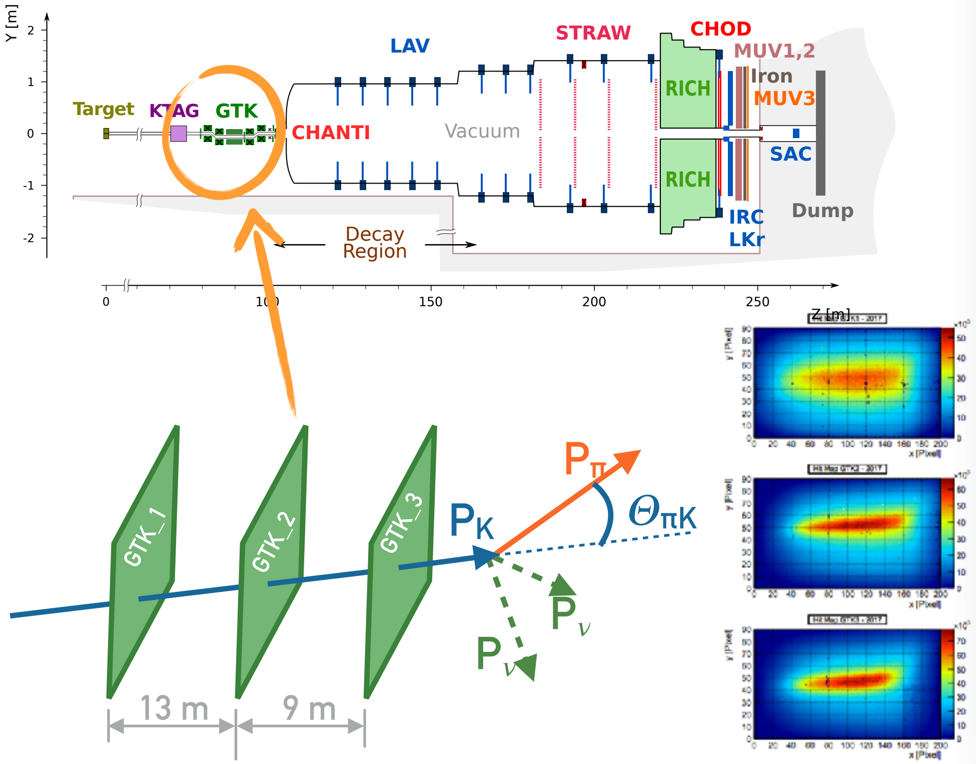


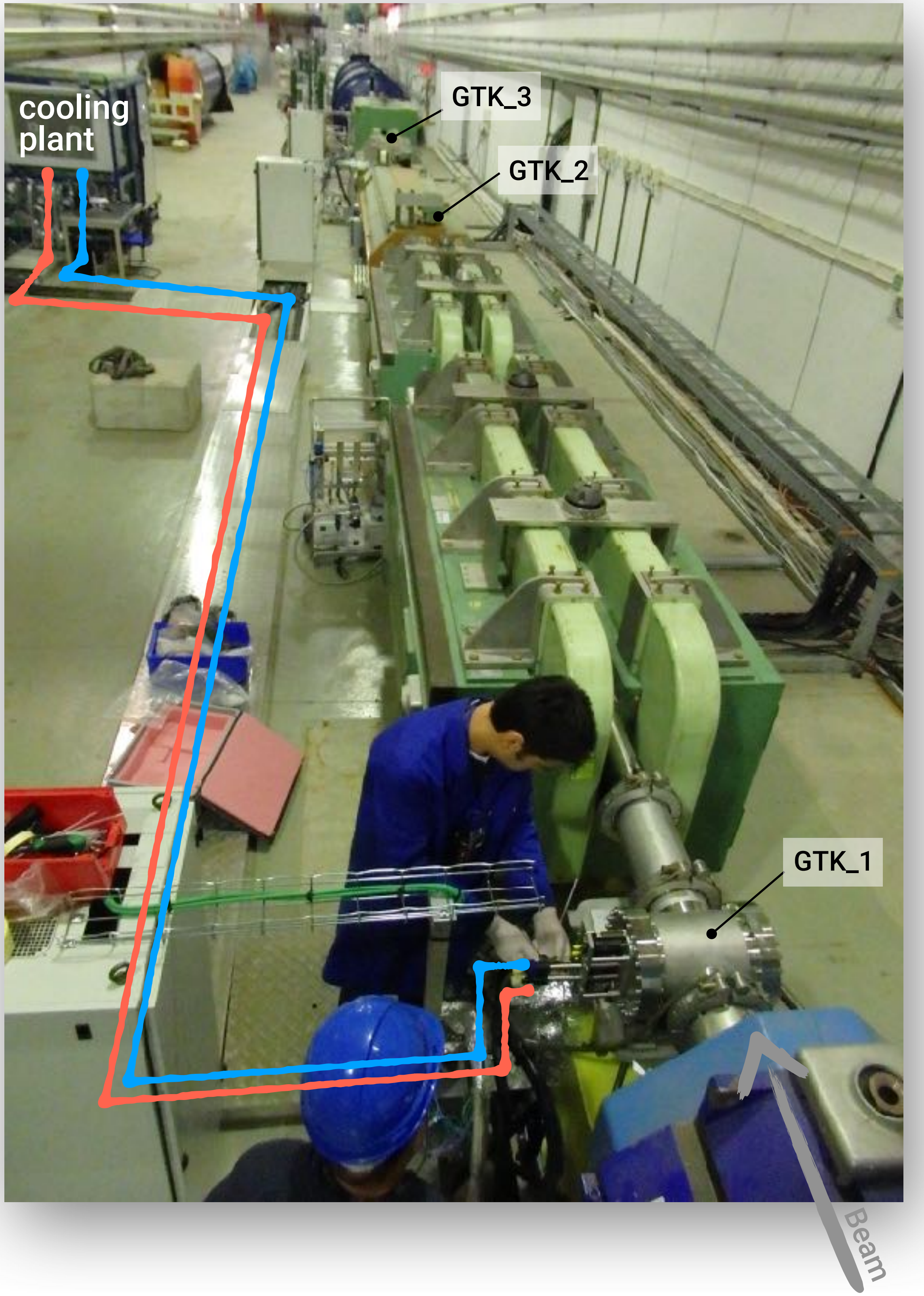
The GTK in the NA62 experiment

- **2014** - Installation of the first GTK.
- **2016-2018** - Physics runs with 3 GTK detectors.
- **2019-2020** - (LS2) construction of the GTKs for 2021-2022.

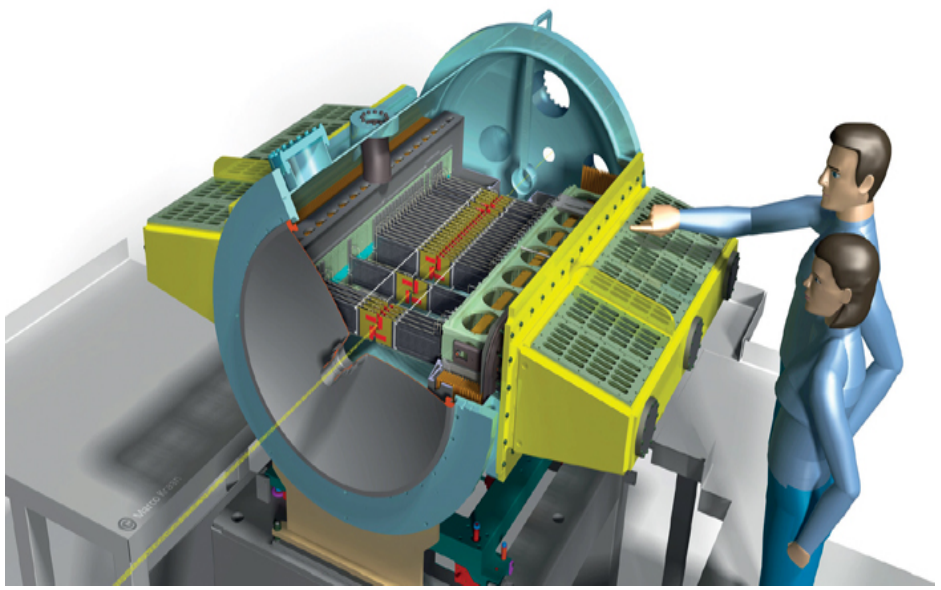
  - At nominal beam intensity the detectors are exposed to a fluence corresponding to 4×10^{14} neq /cm^2 in one year (200 days) of data taking.
  - In order to minimise radiation-induced damages, the detectors are operated at approximately -15°C in vacuum (~10^{-6} mbar).
  - Detectors have to be replaced every 100 days.
  - GTK **designed to be replaced rapidly** (<0.5 day intervention).



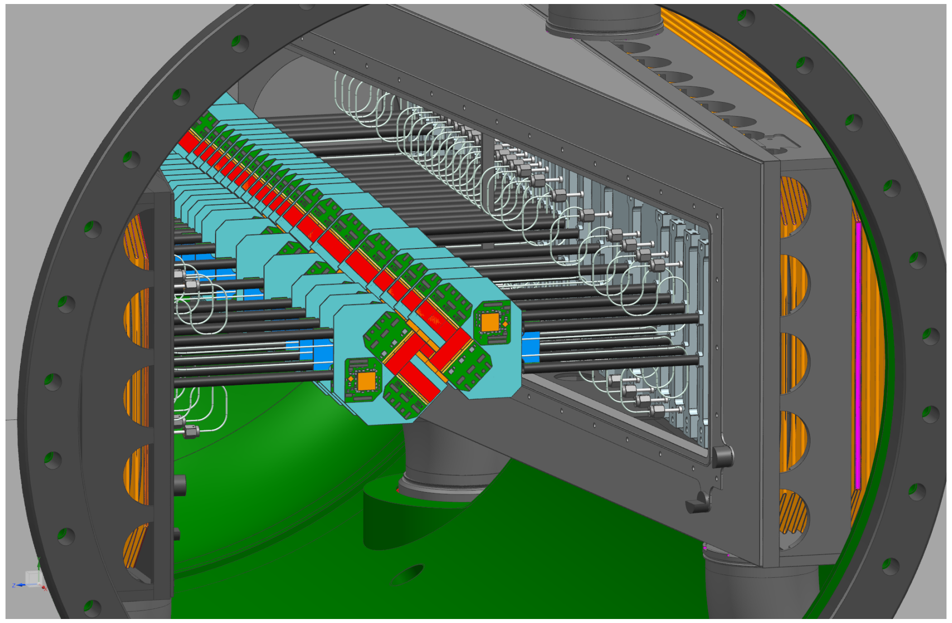




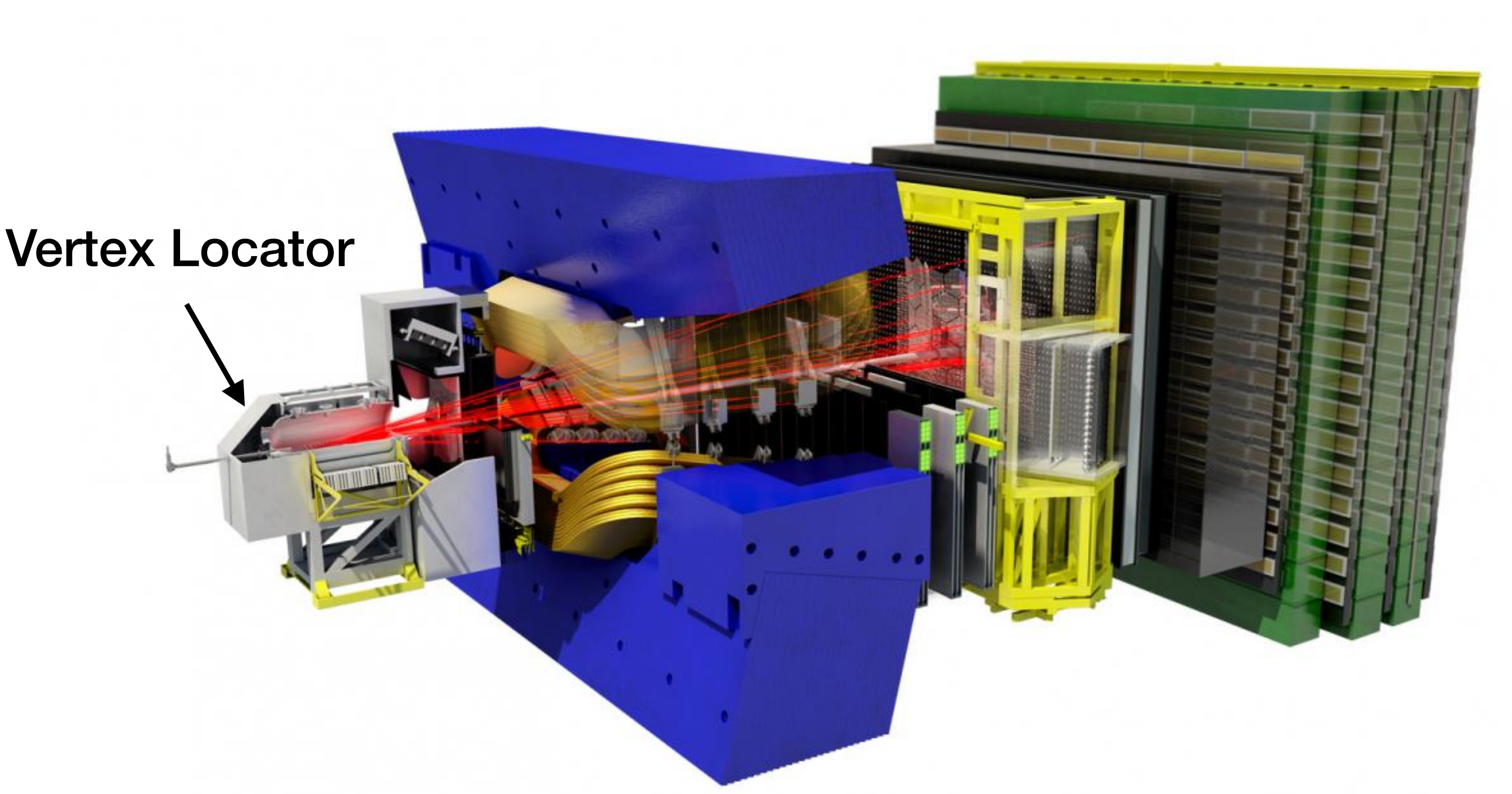
LHCb VELO Upgrade



- Distance of closest pixel to LHC beam is 5.1 mm.
- Particle rate up to 600MHz/cm^2.
- Very high radiation dose
  - 4x10^{14} neq /cm^2 for 50 fb^{-1},
  - and non-uniform radiation.
- Very high data rates
  - up to ~15 Gbit/s for central ASICs and 2.9 Tbit/s in total.
- Sensor temperature < -20°C (CO_2 @ -30°C).
- Total maximum power dissipation per module is ~30 W. Nearly 1W/cm^2.
- Inside vacuum vessel.

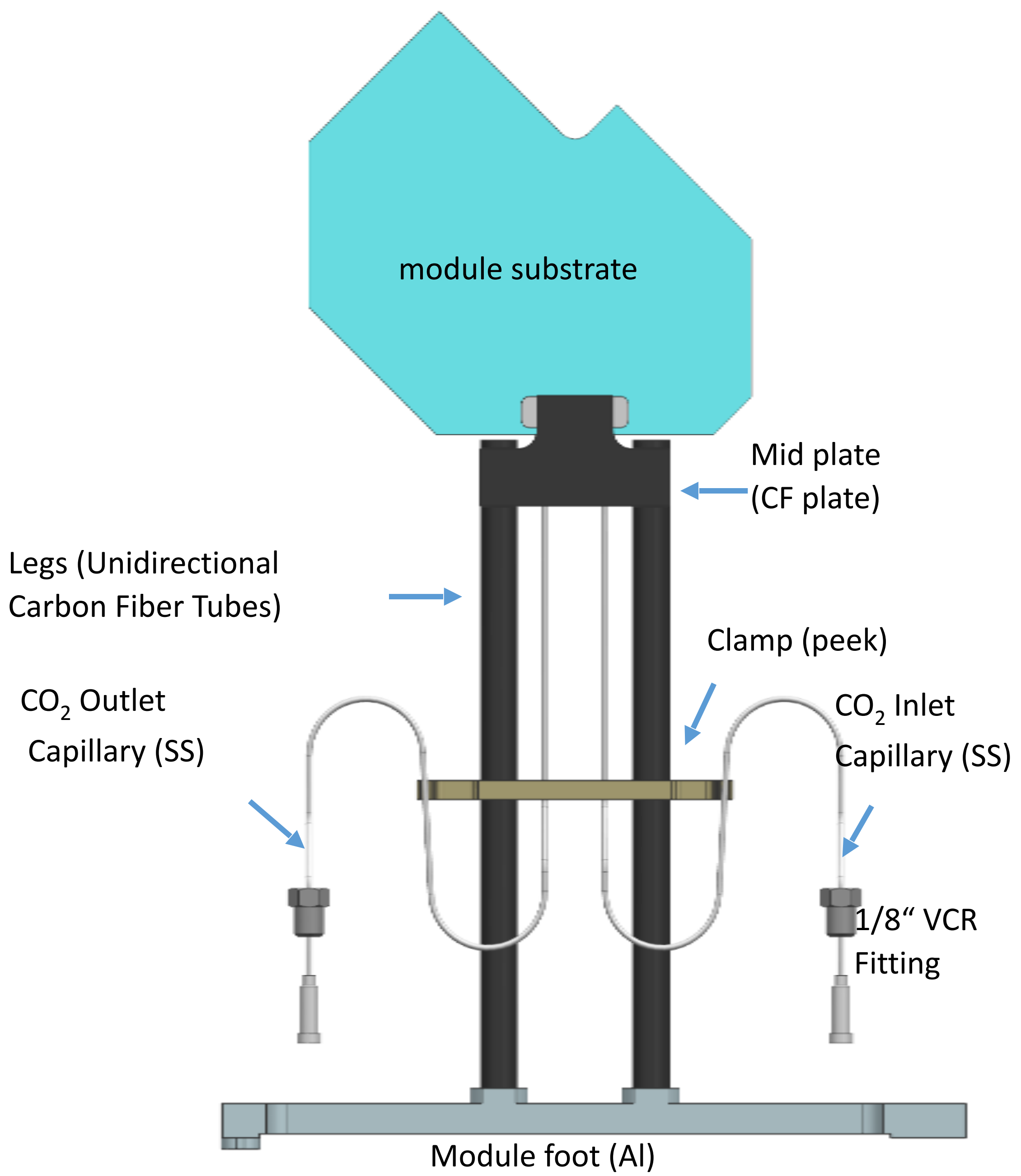


52 modules (26 per side)

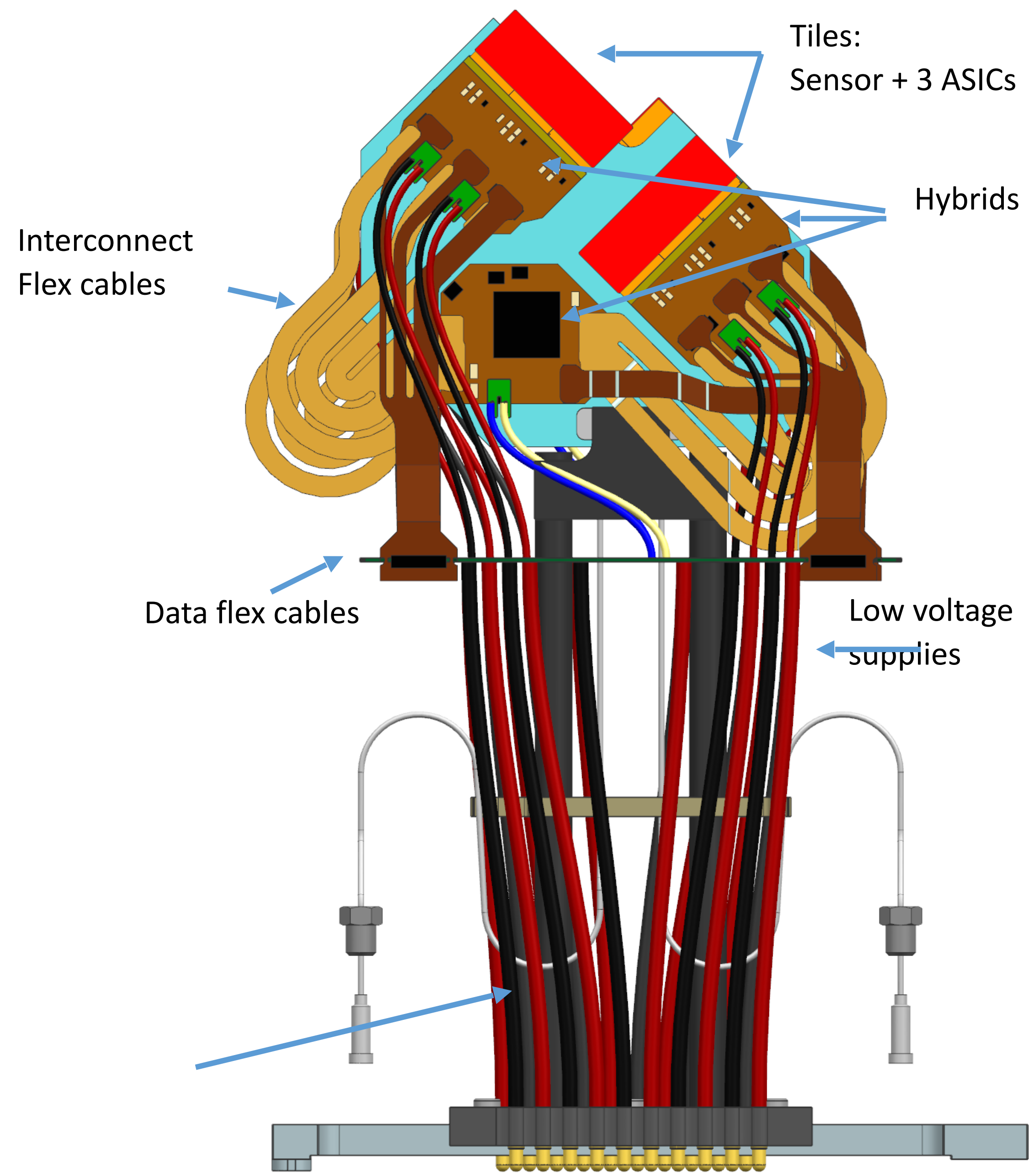


Module Design

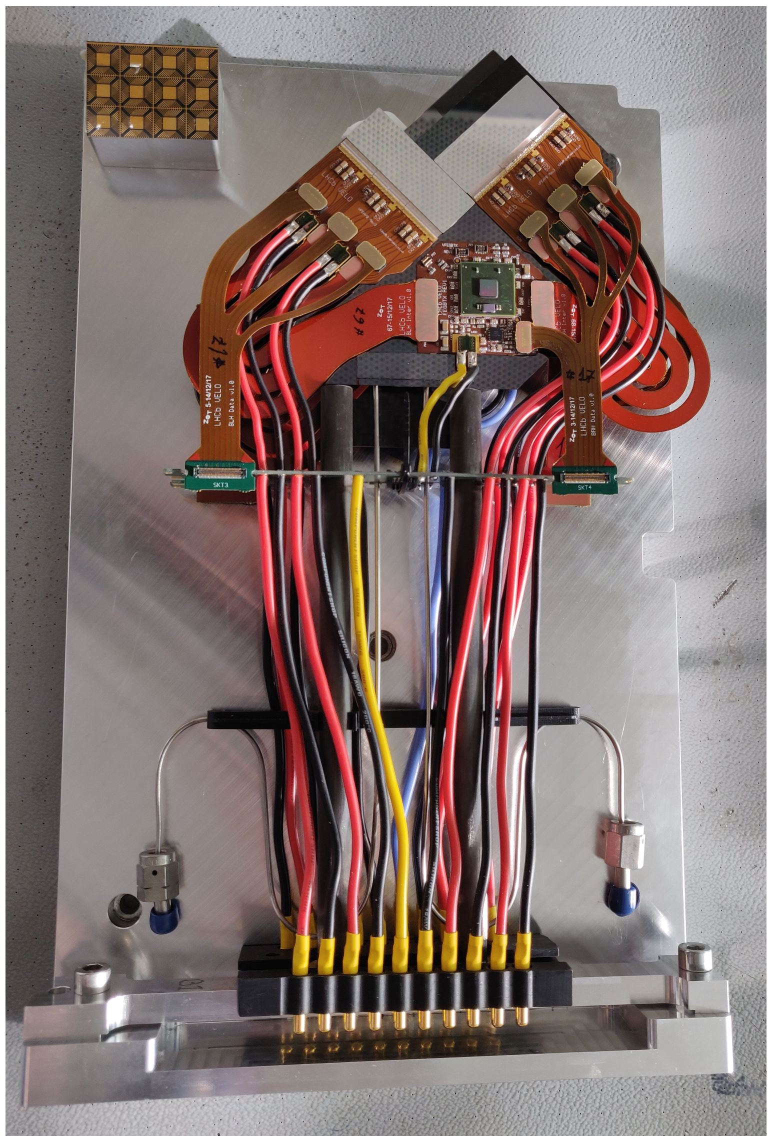
“Bare” Module

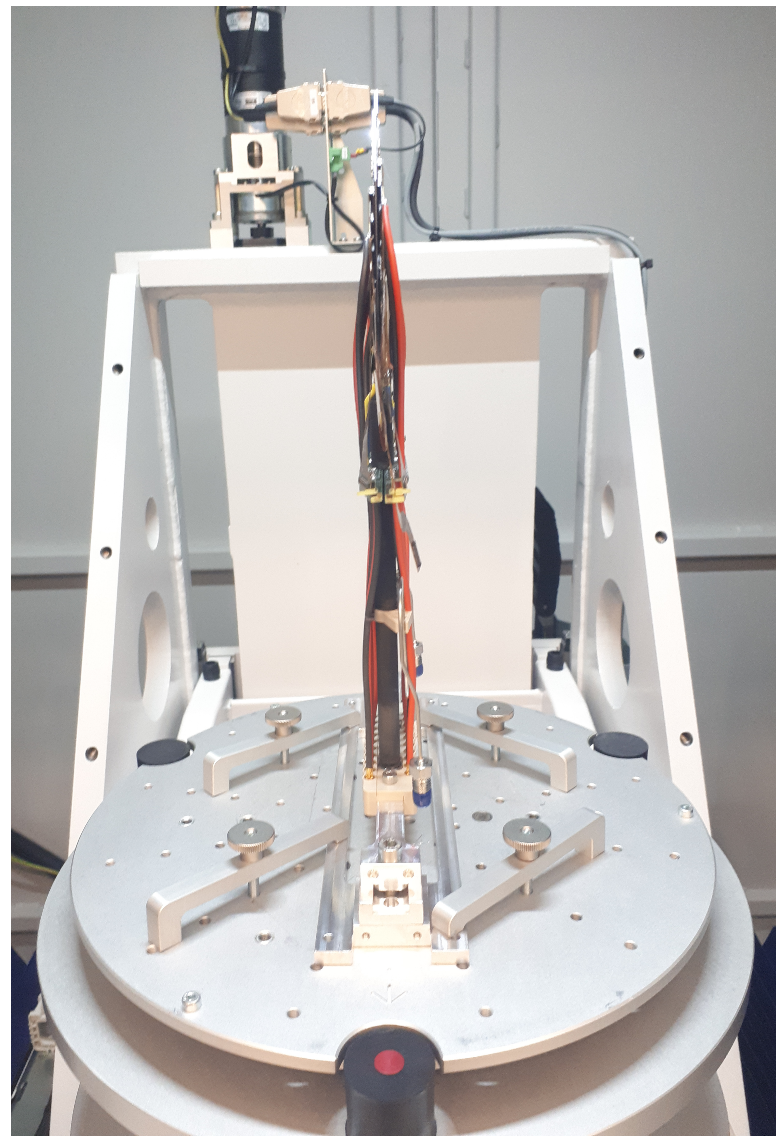


“Full” Module

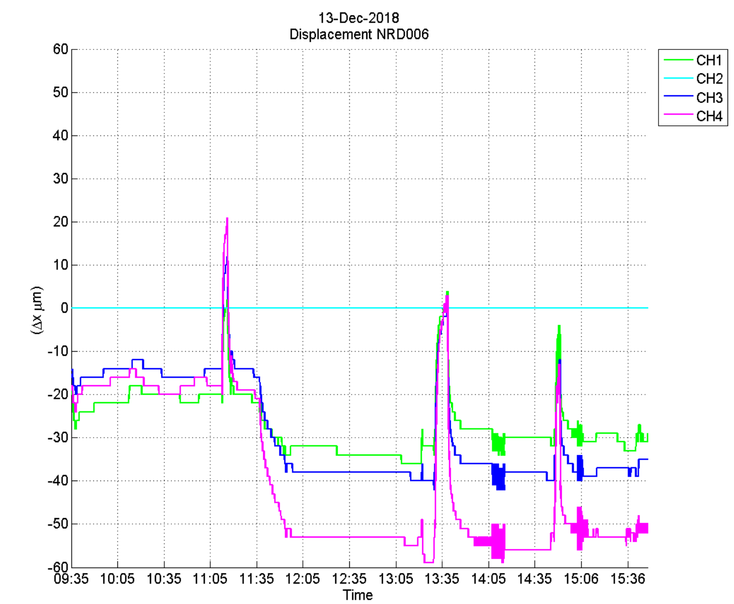


VELO Module

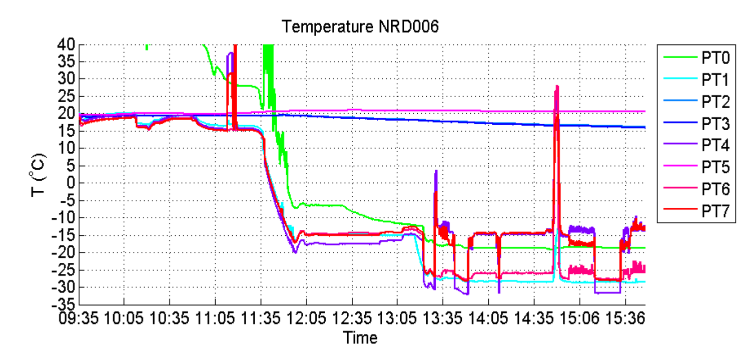




The tip of the module is displaced by less than 40 µm when cooling from room temperature +20ºC to -30ºC

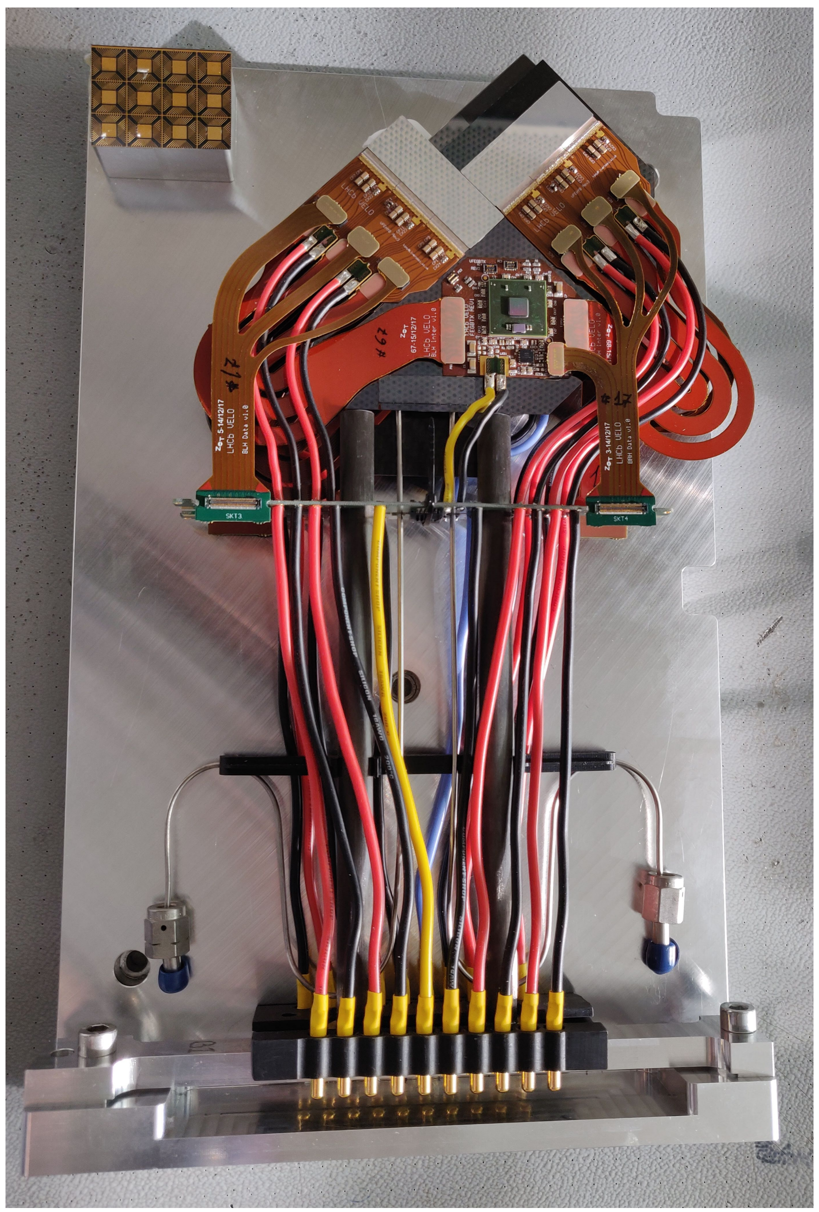


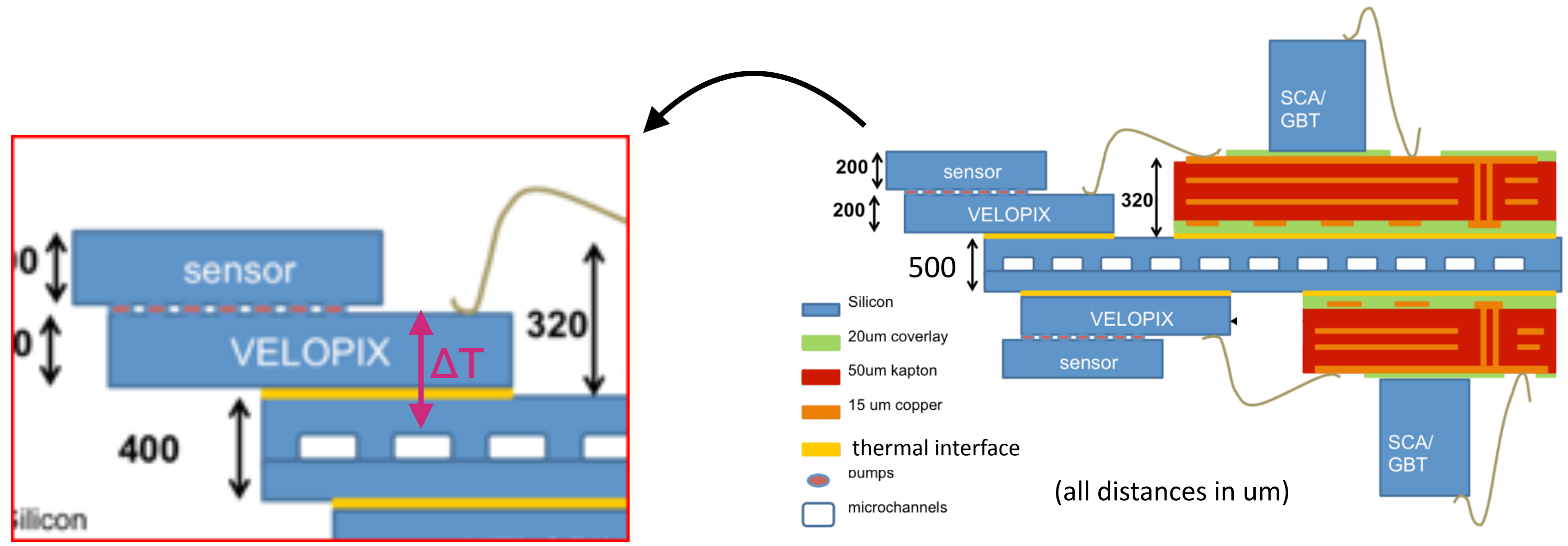
Δx ~40 µm



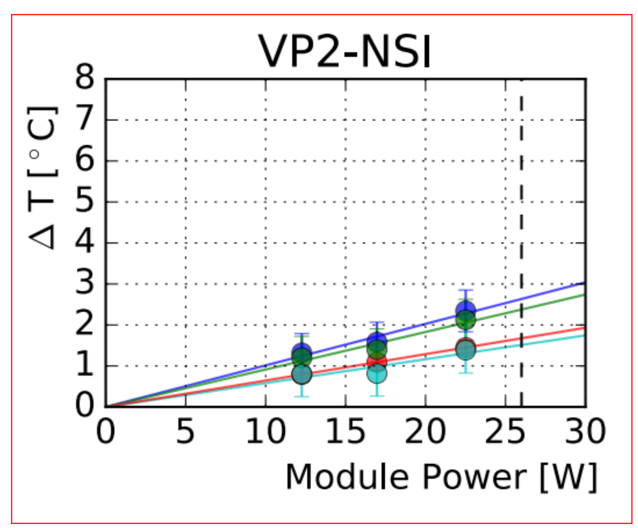
ΔT 50ºC

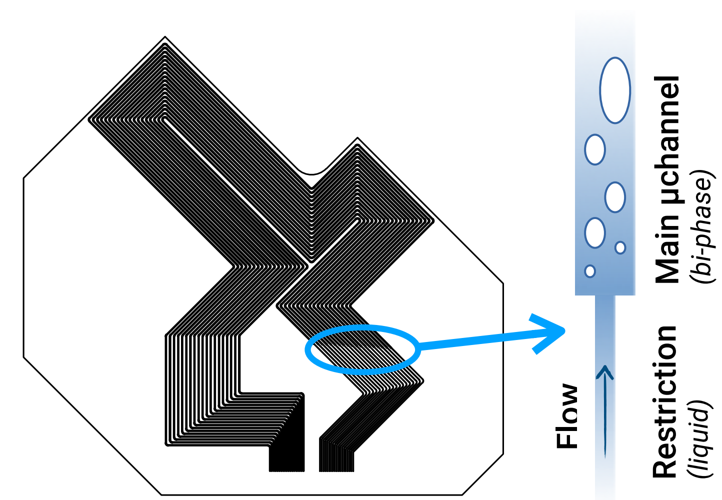
VELO Module





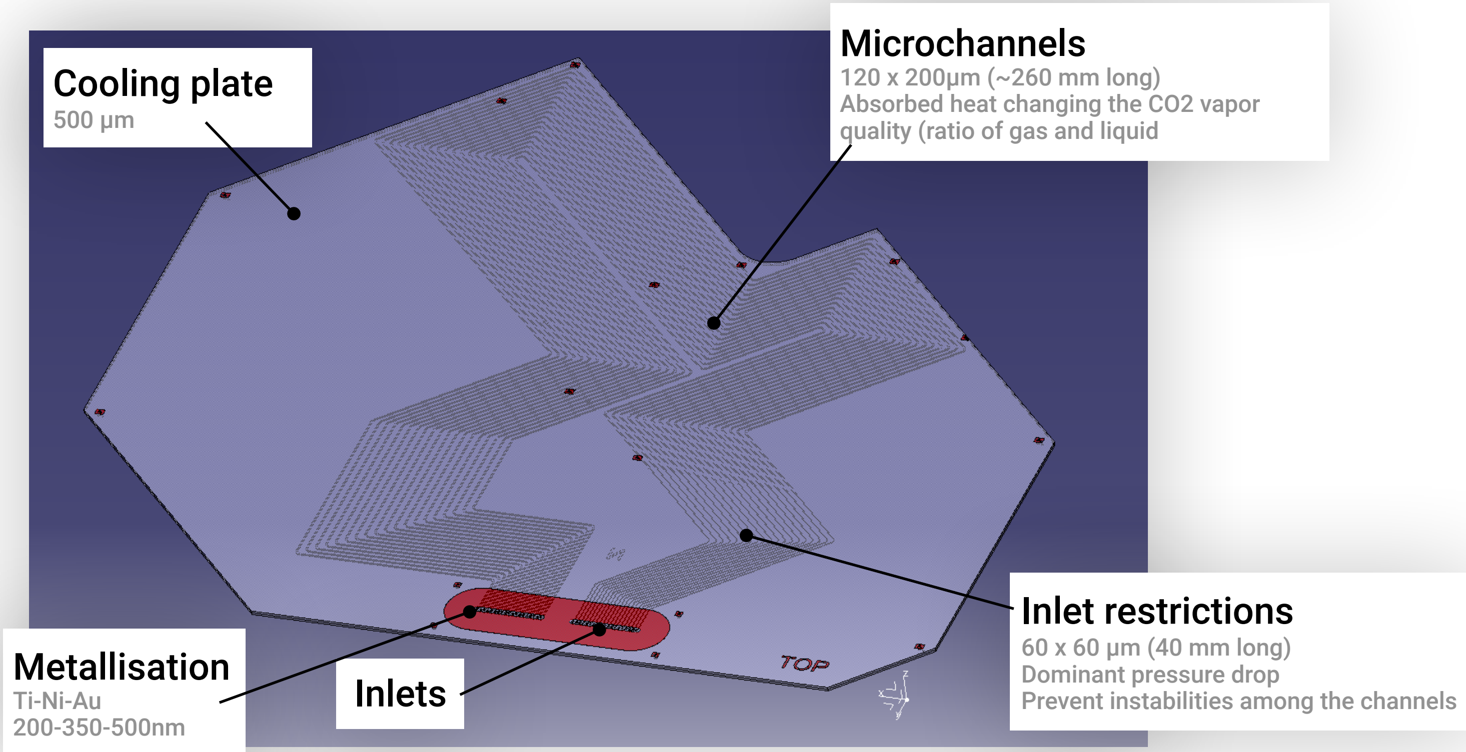
For 22W dissipated in the module
the ASIC temperature is < 3C above
CO_2 cooling liquid temperature.
(Stycast glue layer thickness < 100 um)

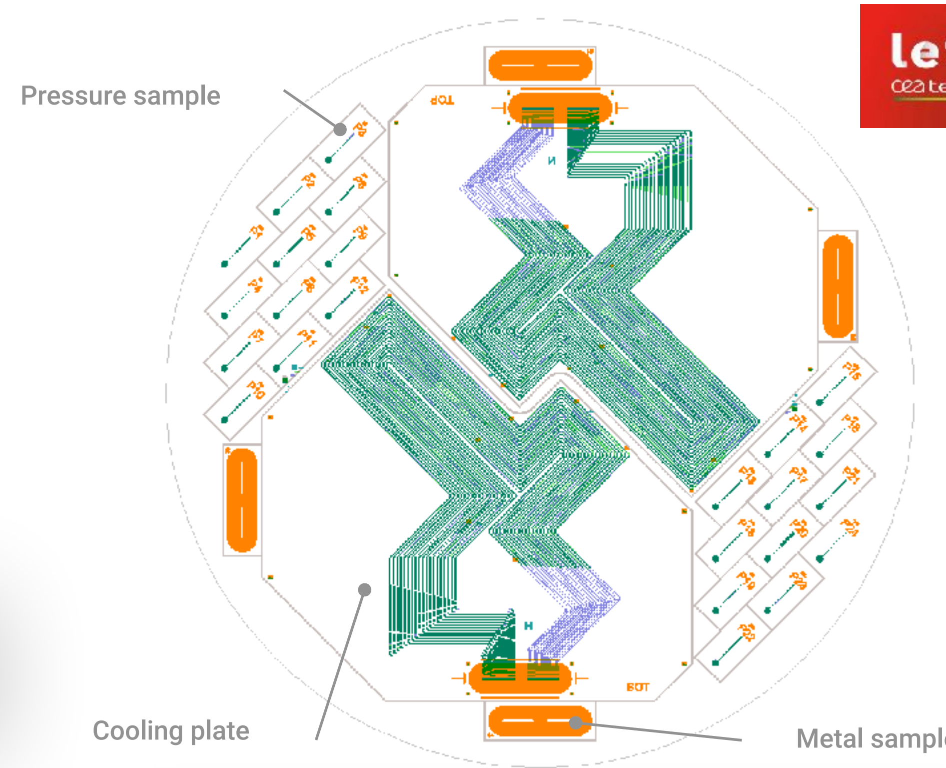


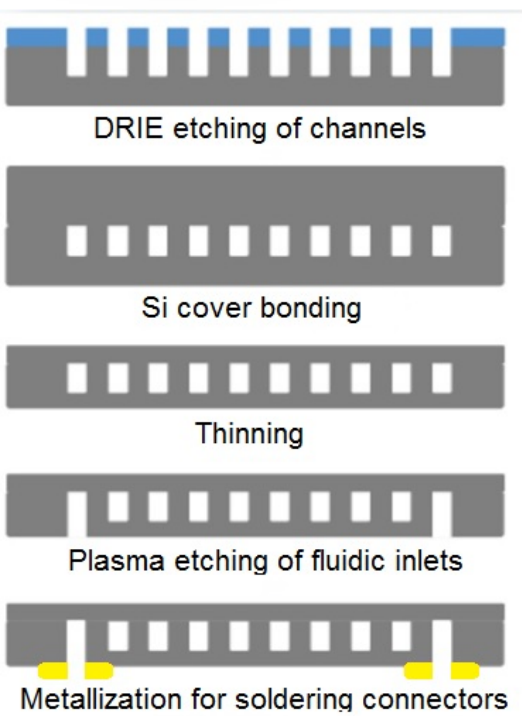


Microchannels designed to bring the coolant under the heat sources.

microfabrication of the VELO cooling plates

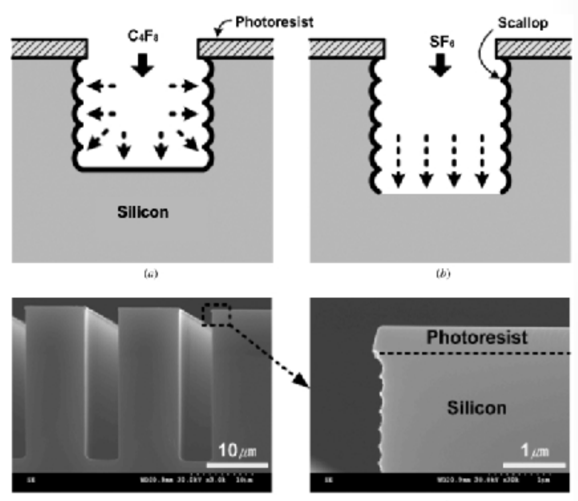




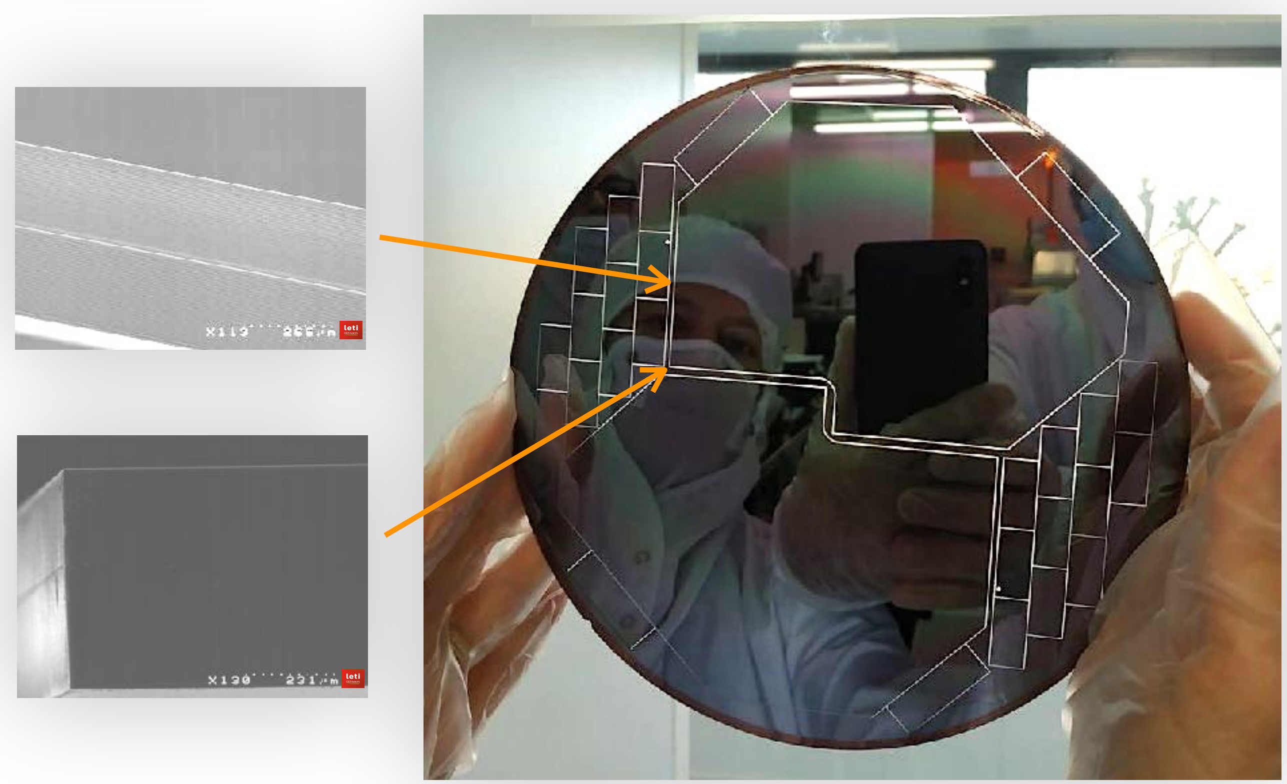


Plasma dicing by DRIE

Deep Reactive Ion Etching

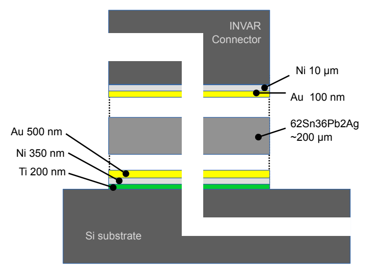


Chang Kun Kang *et al* 2008 *J. Micromech. Microeng.* **18** 075007



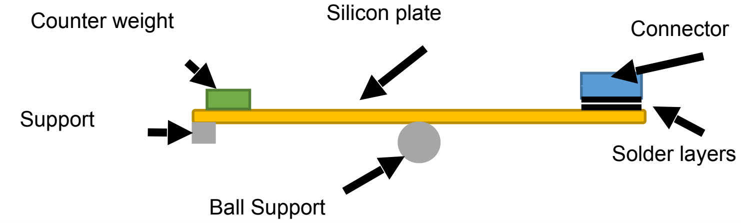
Leti-3S received in December 2019 an LHCb Industry Award to acknowledge their outstanding contribution for the successful manufacturing of the microchannel cooling plates for the LHCb VELO LS2 Upgrade.

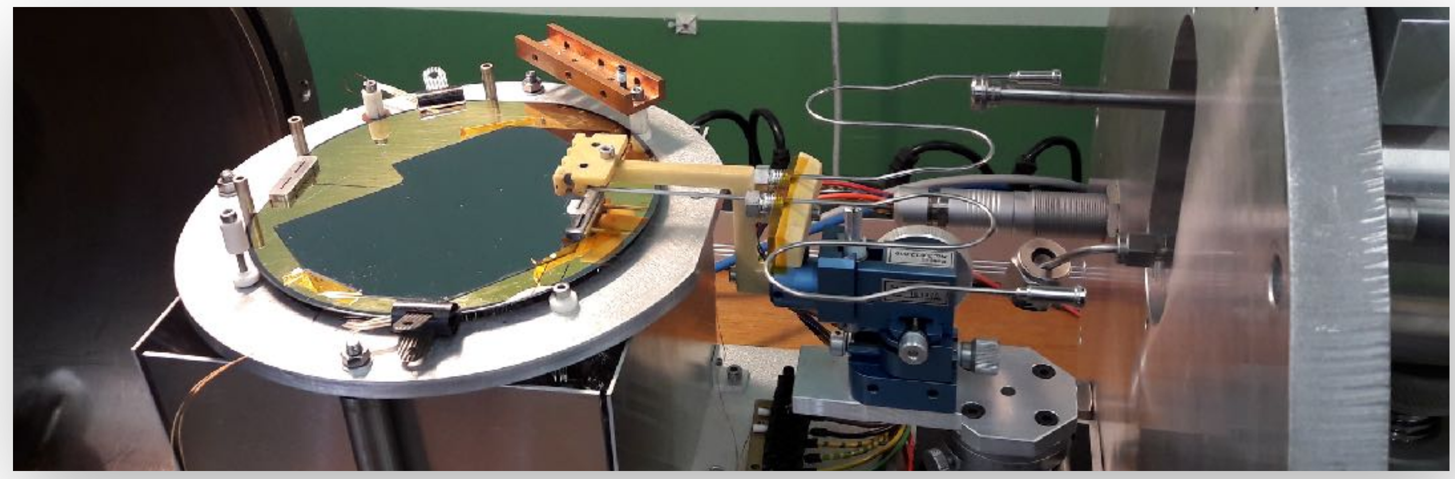
soldering of metallic connectors



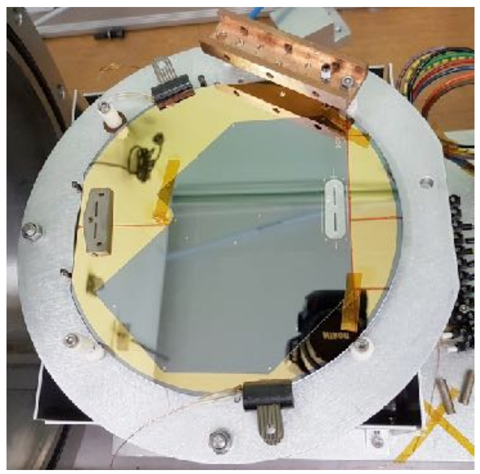
62Sn36Ag2Pb preform for pre-tinning of cooling plate and connector

3. Alignment of connector to cooling plate

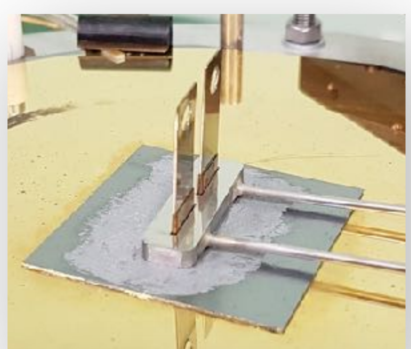




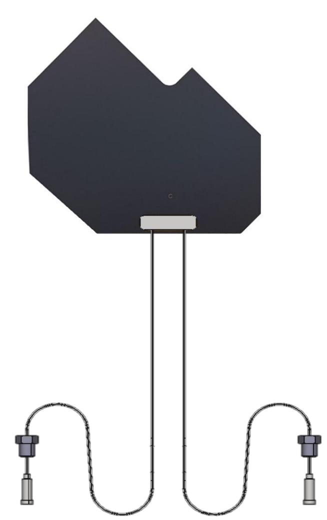
1. Pre-tinning of cooling plate

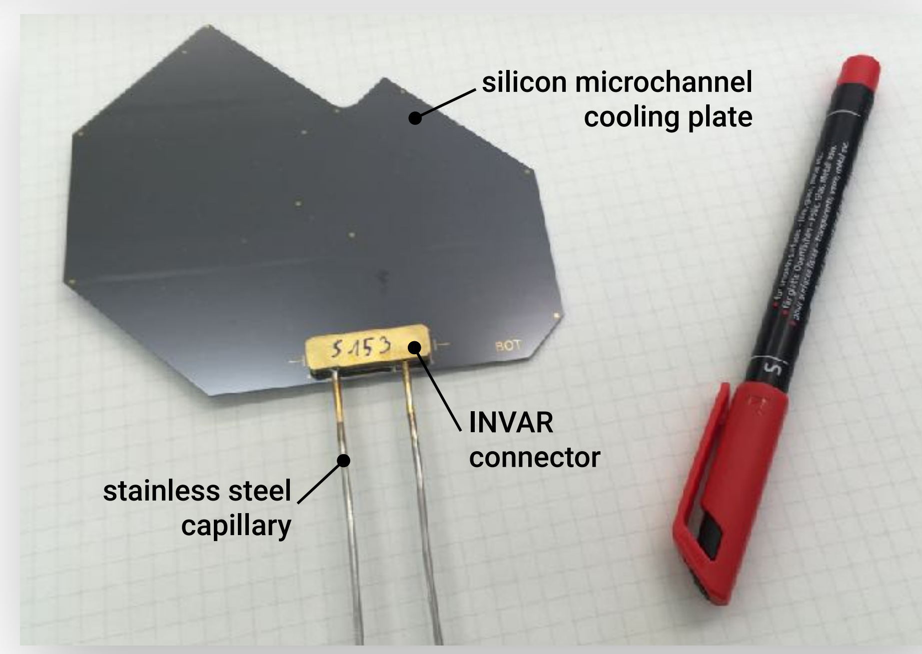


2. Pre-tinning of connector

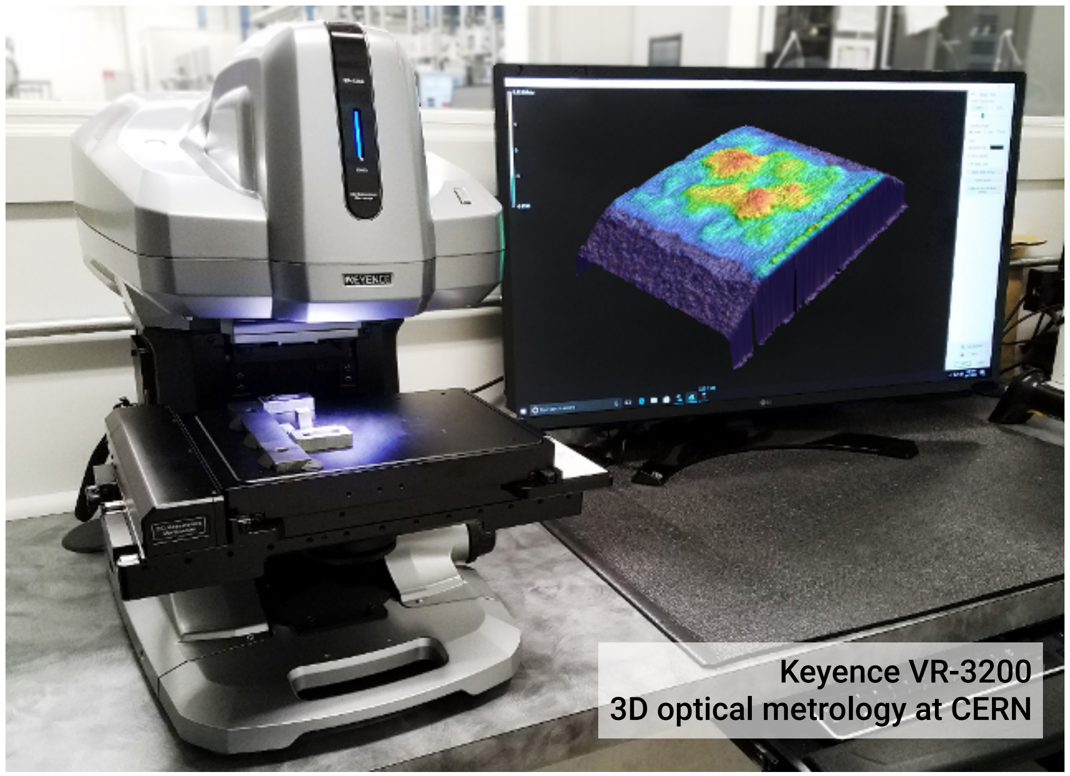


4. Soldering

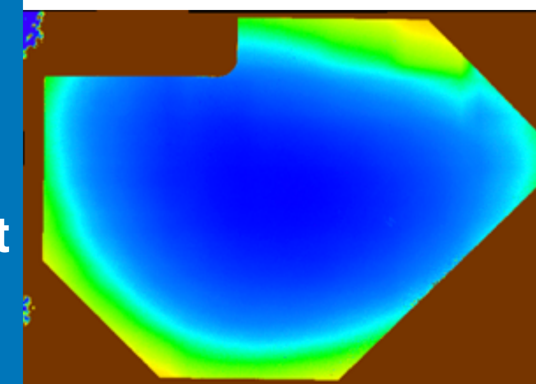
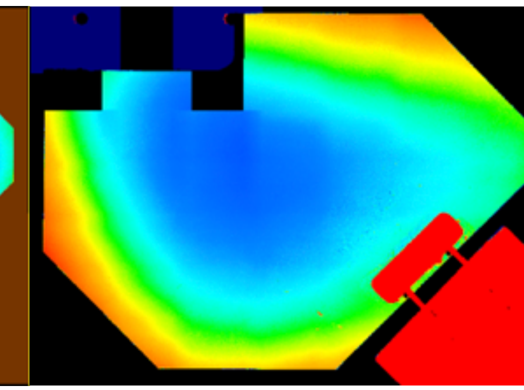


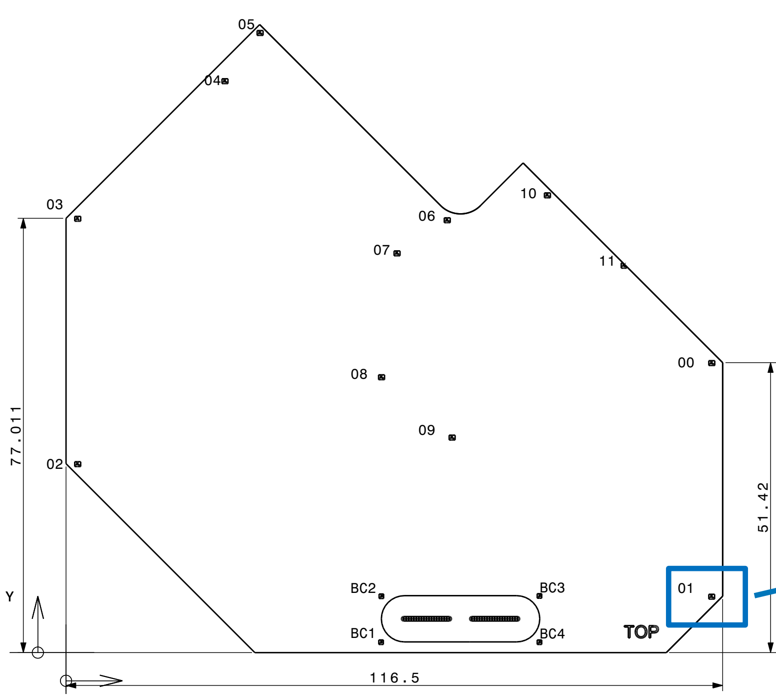


cooling plates planarity



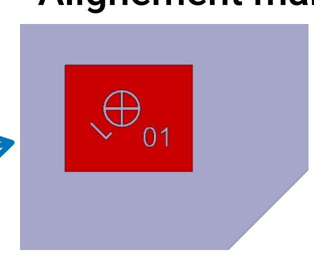
Keyence VR-3200
3D optical metrology at CERN

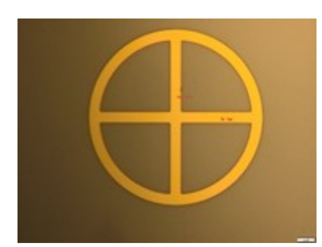
	before soldering	after soldering
planarity measurement		
min.	-60 µm	-50 µm
max.	+26 µm	+25 µm
variation	86 µm	75 µm



- Slight change on the planarity of the cooling plates.
- No significant stress generated by the soldering.
- The cooling plate is the backbone of the mechanical assembly of the VELO module.

Alignement marks for module assembly

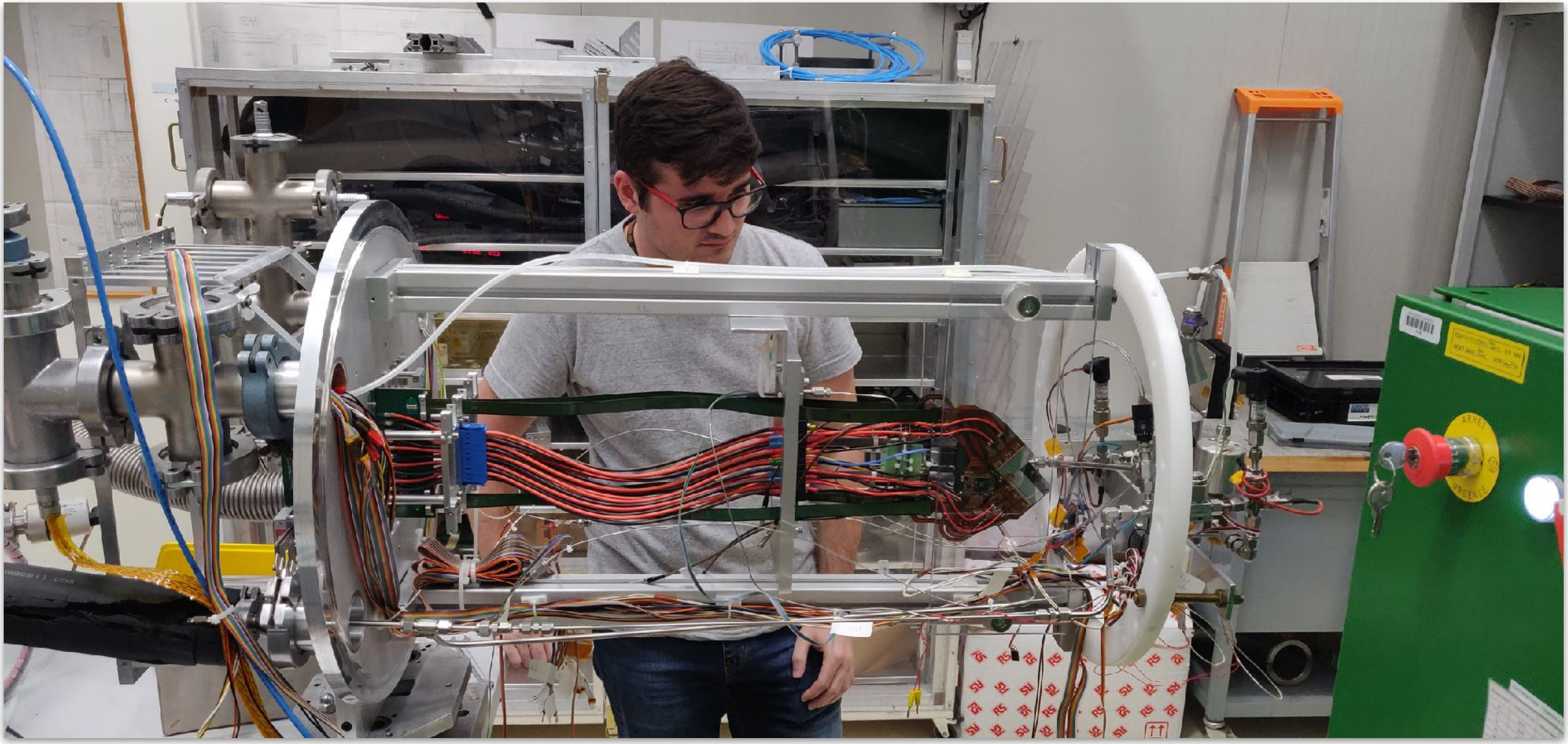




patterned on metal

etched in silicon

VELO module under test



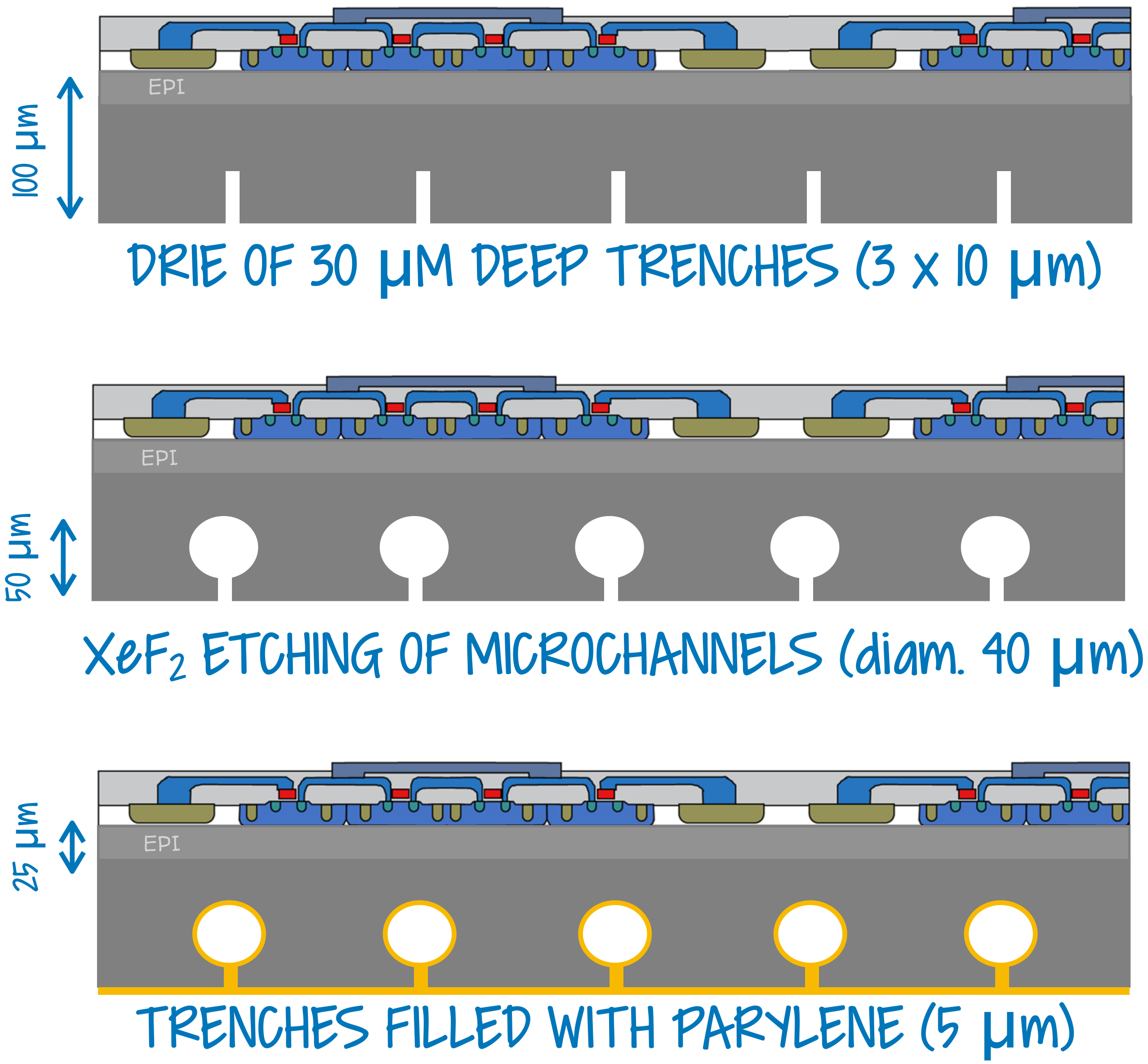
© Oscar Augusto de Aguiar Francisco, CERN, Feb. 2019

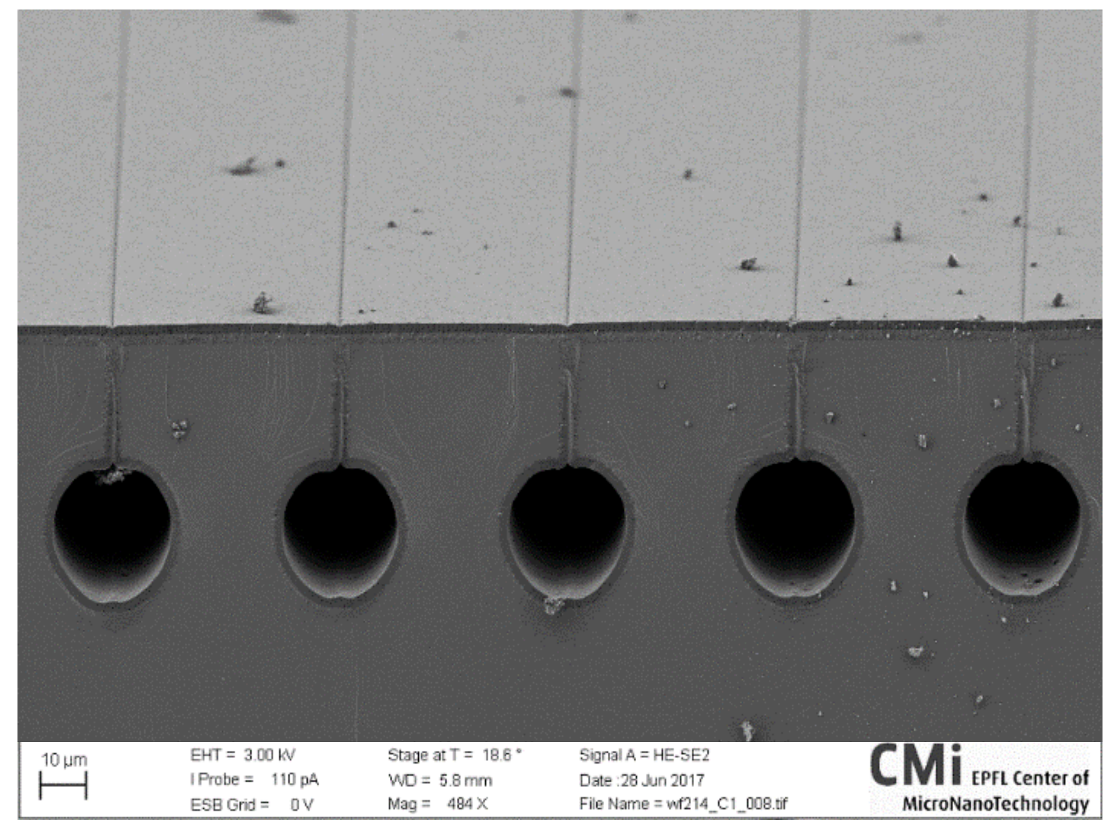
Next steps..

Embedding channels in detectors
Getting rid of the fluidic connectors

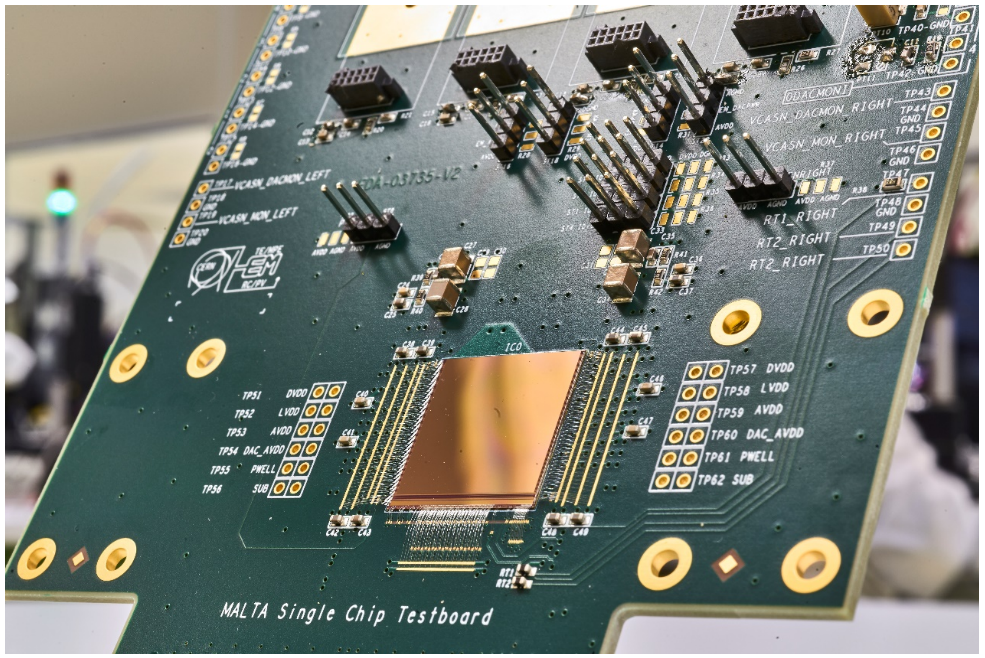
BCTs on the backside of monolithic detectors

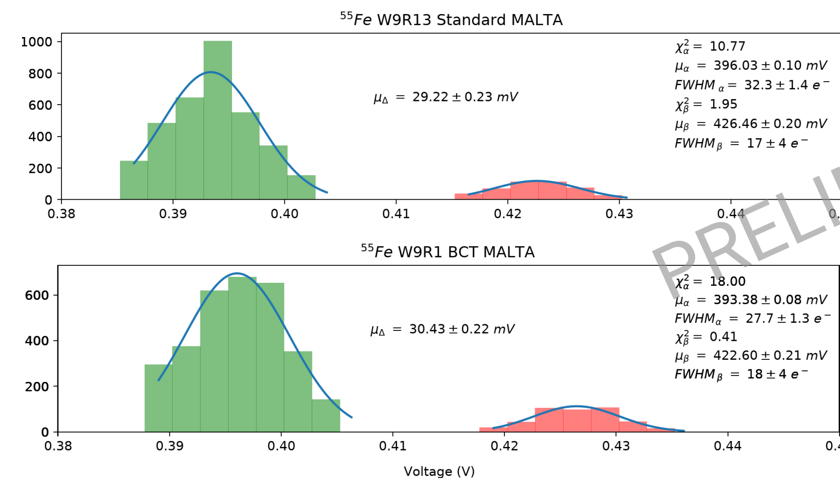
CMOS-compatible post-processing of single dies.



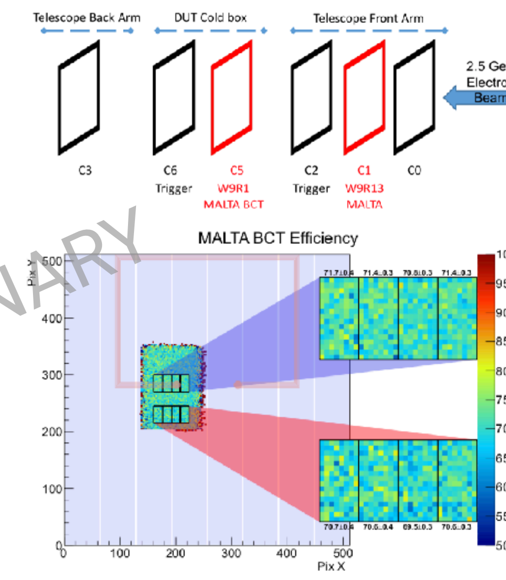


Performance of MALTA with BCTs

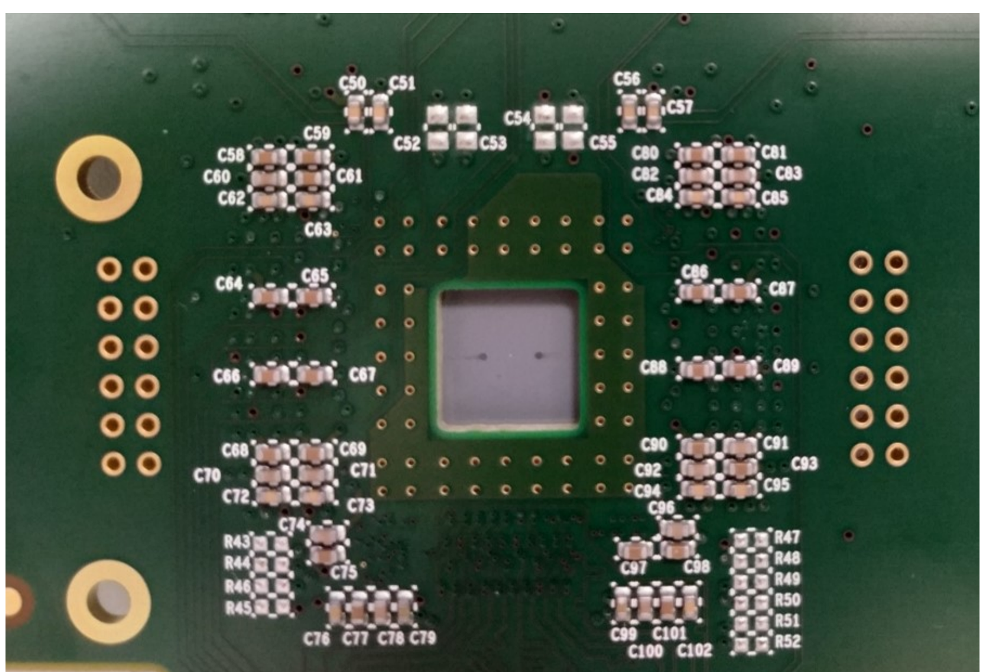




^{55}Fe source scan



test beam



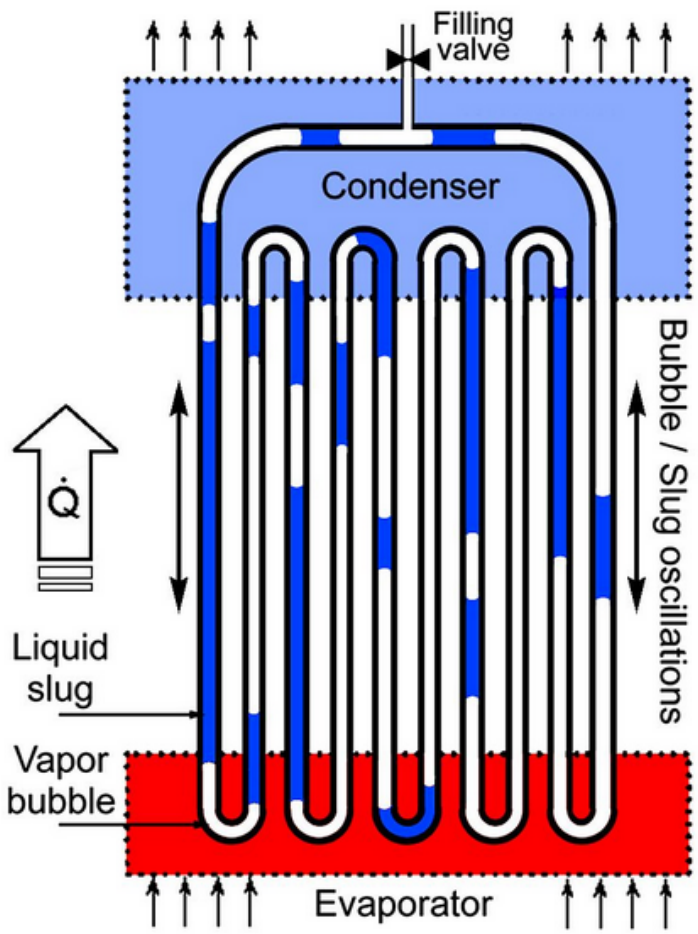
^{55}Fe source scan

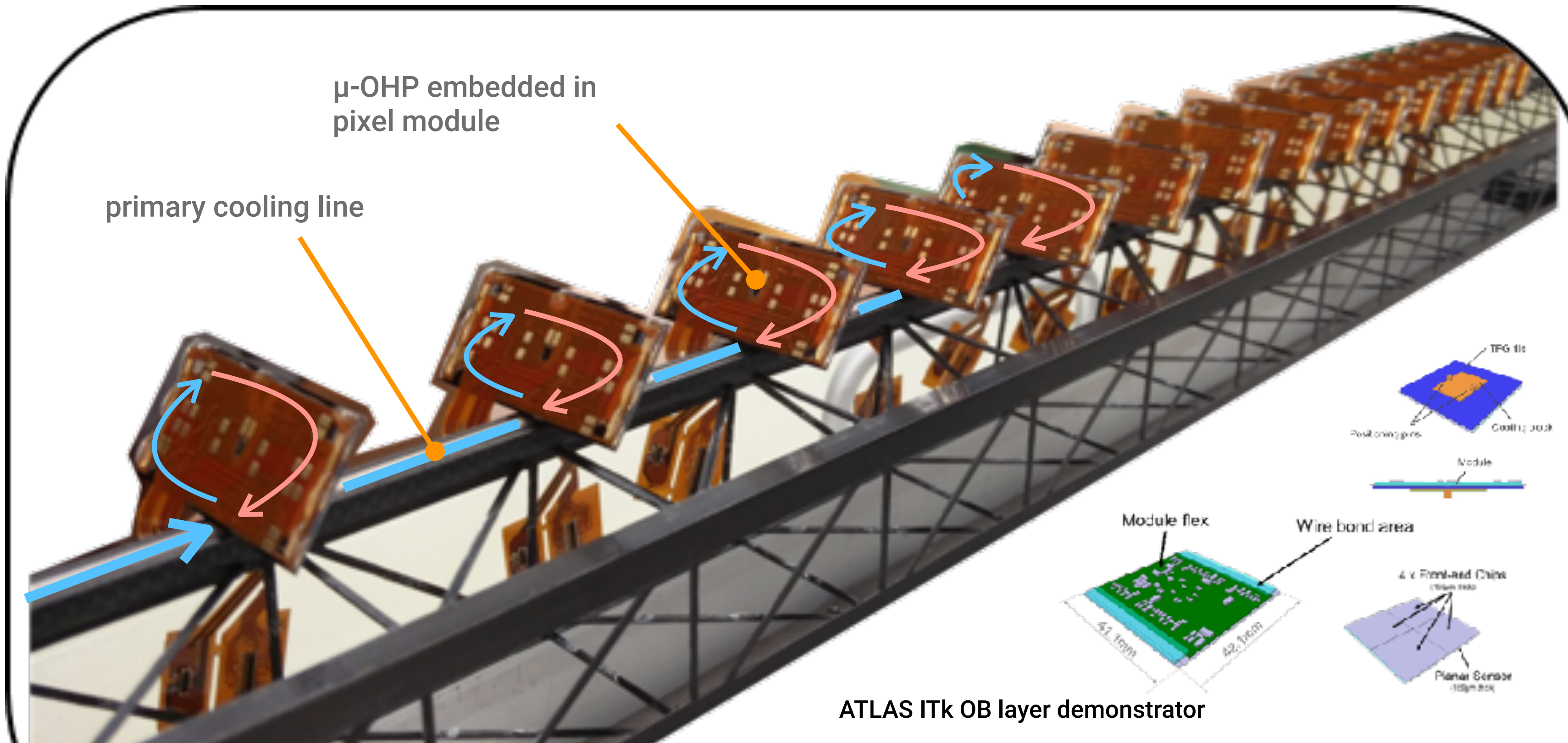
- Peaks fit comparable
- Distance of the peaks within the gain dispersion of MALTA

Collection Efficiency

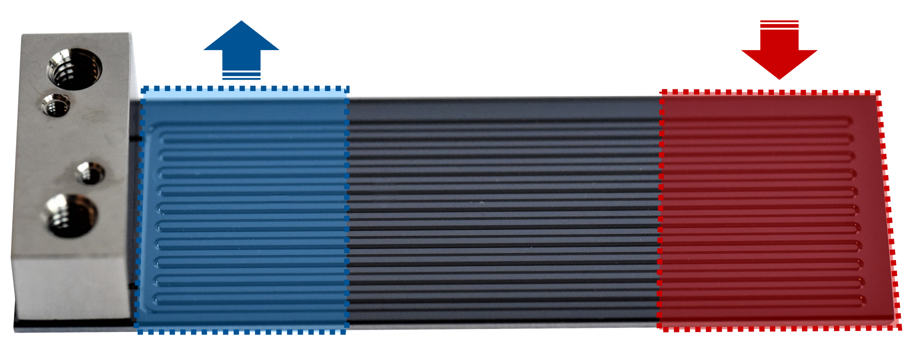
- Readout issue reduced the efficiency of ALL detectors to ~70%
- Comparable efficiency for the different ROIs

Micro-oscillating heat pipes

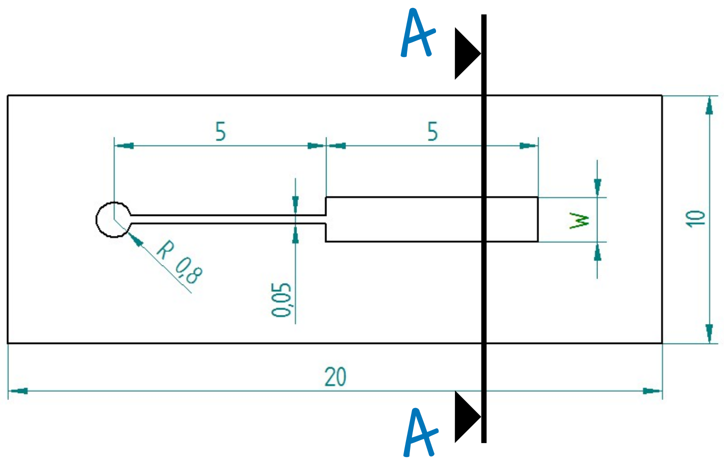




Studies with ATLAS ITk OB specifications to evaluate the thermal performance and reworkability of a cooling block based on μ-OHP in a stave configuration.

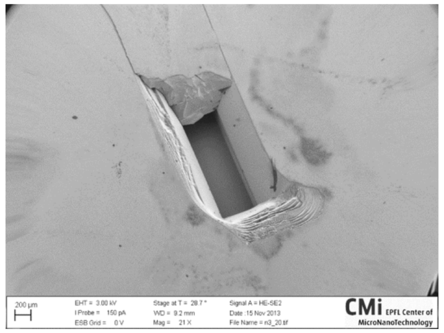


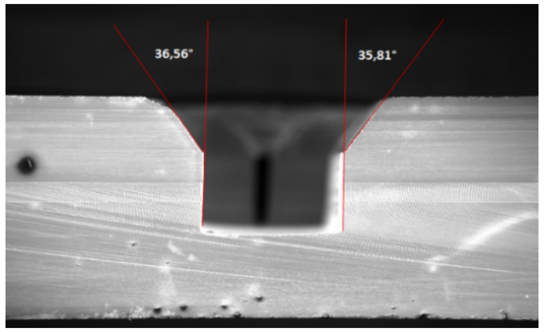
Pressure Resistance



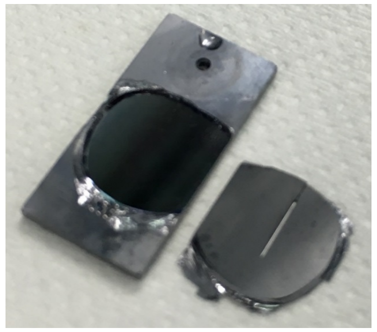
EDMS doc no CERN-0000191313

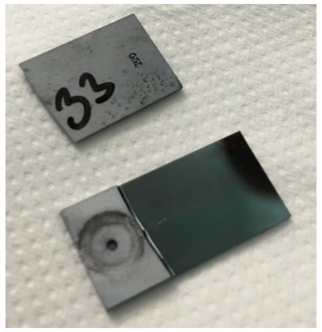
- **Standard samples** used for the **QA/QC** of the LHCb and NA62 cooling plates as well as for the investigation of **new fabrication techniques** (bonded wafers, buried channels, 3D-printed devices in plastics, ceramics,…).



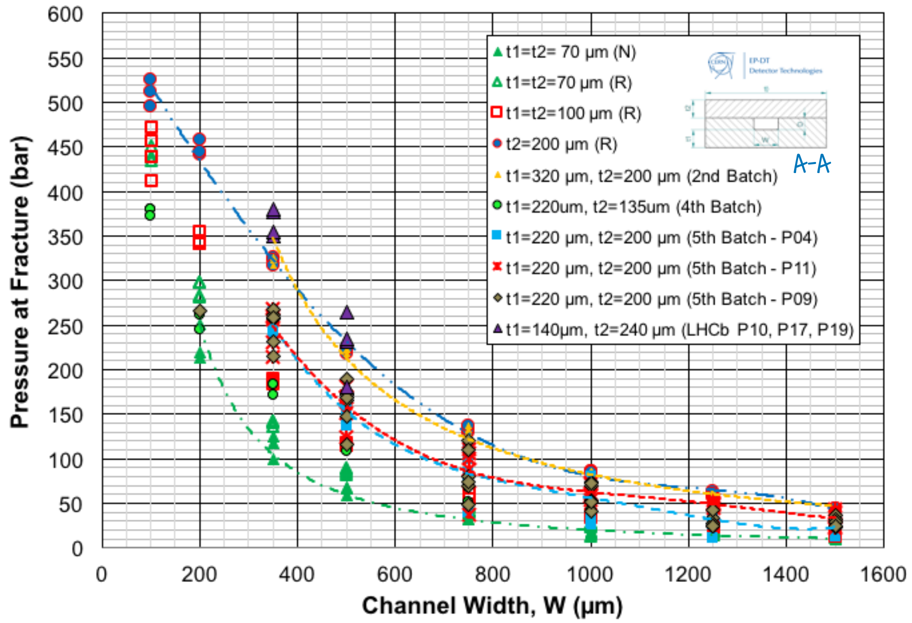


FRACTURE OF BONDED WAFERS

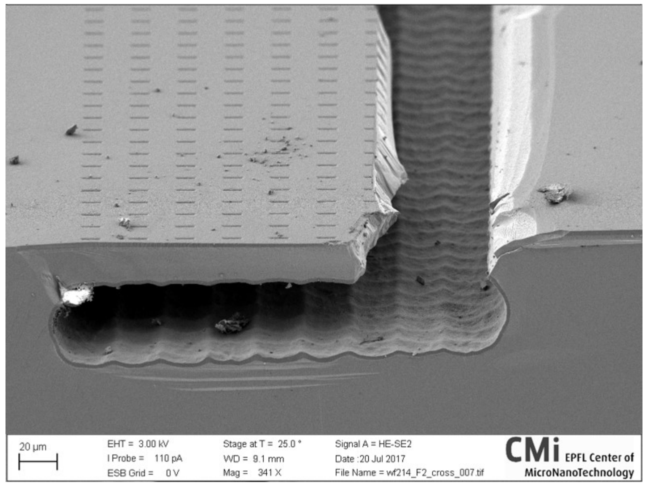




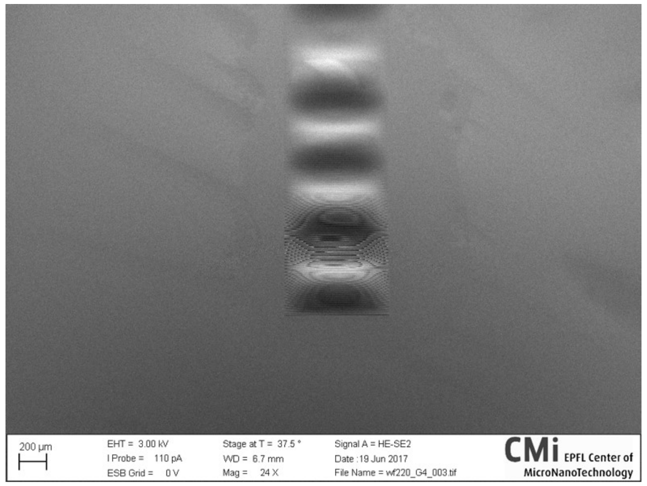
DELAMINATION OF BONDED WAFERS



BURIED CHANNELS



FRACTURE



DEFORMATION

summary

- The NA62 experiment has pioneered the use of silicon microchannel cooling plates with **liquid C_6F_{14}** for the thermal management of the **GTK pixel detectors**.
- The LHCb experiment will pioneer the use of **evaporative CO_2** in silicon microchannels for the **LS2 Upgrade of the VELO**.
- Current developments are aiming at eliminating connectors with **stand-alone microfluidic circuits** such as heat pipes and **embedding the microchannels into monolithic** pixel detectors with **CMOS-compatible microfabrication** processes.