Microfabrication activities at CERN

Update on work related to Microchannel Cooling Plates

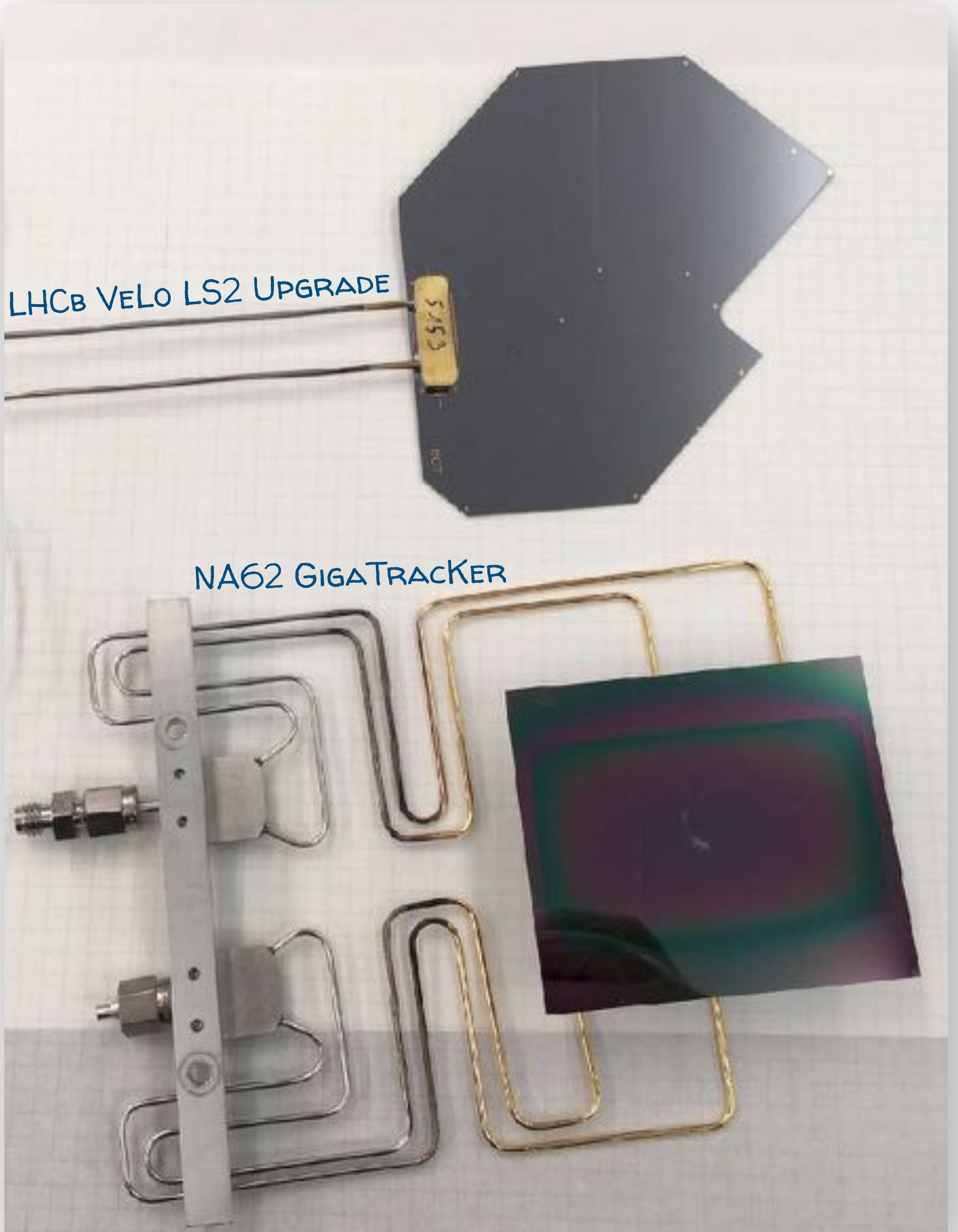
Alessandro Mapelli

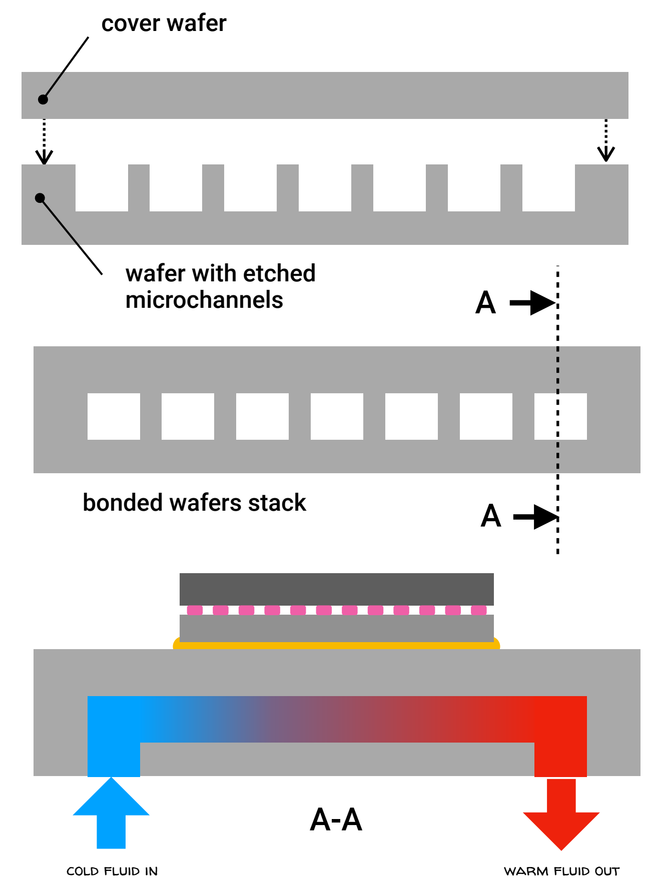
EP-DT
Detector Technologies

100 µm

	Introduction and status of the final deliverables *Seminar Room 11, St Anne's College*	*Paolo Petagna*	15:30 - 15:45
	Plans for testing microchannel cooling for the new MCM-boards of TPC electronics in Pisa *Seminar Room 11, St Anne's College*	*Filippo Bosi*	15:45 - 16:00
16:00	New measurements on CO2 boiling in mini- and micro- channels at CERN *Seminar Room 11, St Anne's College*	Paolo Petagna	16:00 - 16:15
	Status of the activities in Valencia *Seminar Room 11, St Anne's College*	*Guillem Vidal et al.*	16:15 - 16:30
	Microfabrication activities at CERN *Seminar Room 11, St Anne's College*	*Alessandro Mapelli*	16:30 - 16:45
	Coffee Break *[illegible]*		16:45 - 17:00
17:00	Embedding microfluidics into microelectronics *Seminar Room 11, St Anne's College*	*[illegible]*	17:00 - 17:15
	Silicon-based micro oscillating heat pipes for HEP and space applications *Seminar Room 11, St Anne's College*	*Timothee Frei*	17:15 - 17:30
	Silicon microchannel cooling frames for stave configurations *Seminar Room 11, St Anne's College*	*Massimo Angeletti*	17:30 - 17:45
	Status of the T9.3 activities in Oxford *Seminar Room 11, St Anne's College*	*Georg Viehhauser*	17:45 - 18:00
18:00	VISIT TO THE NEW OXFORD LAB *Seminar Room 11, St Anne's College*	*Georg Viehhauser*	18:00 - 19:00
19:00			

silicon microchannel cooling plates

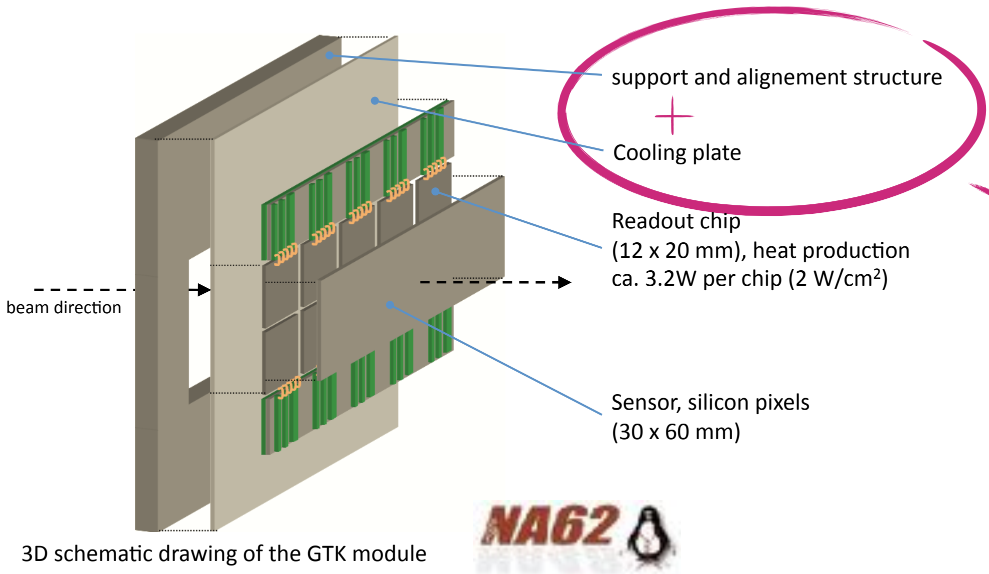




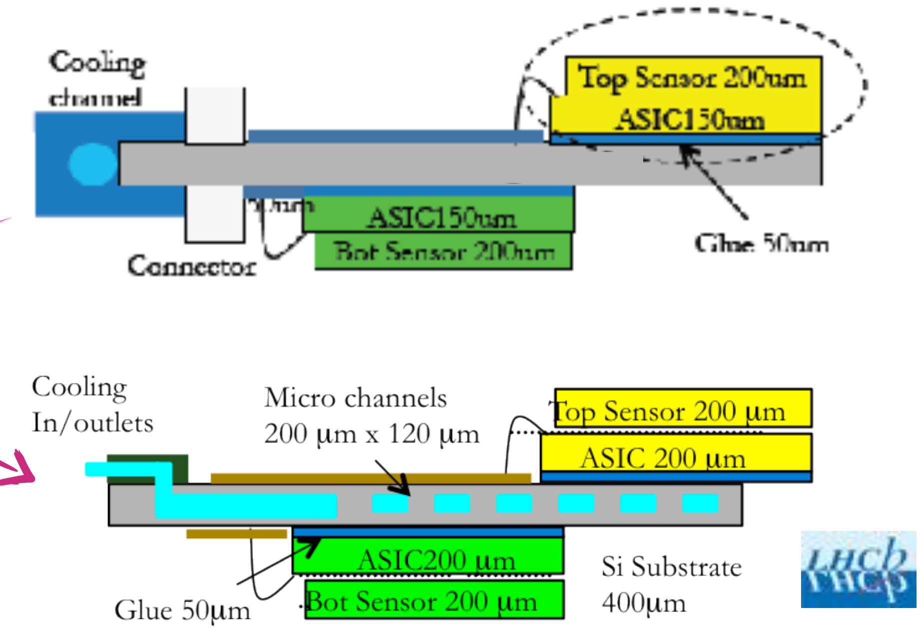
- No CTE mismatch
- Active and distributed cooling
  - Better temperature uniformity across sensor
- Low and uniform material budget
- Radiation resistance
- Great potential for integration
  - Same microfabrication techniques as sensors and microelectronics.
- Thermal Figure of Merit

$$TFM = \frac{T_{sensor} - T_{fluid}}{\text{power density}}$$

NA62 GTK and LHCb VELO Upgrade



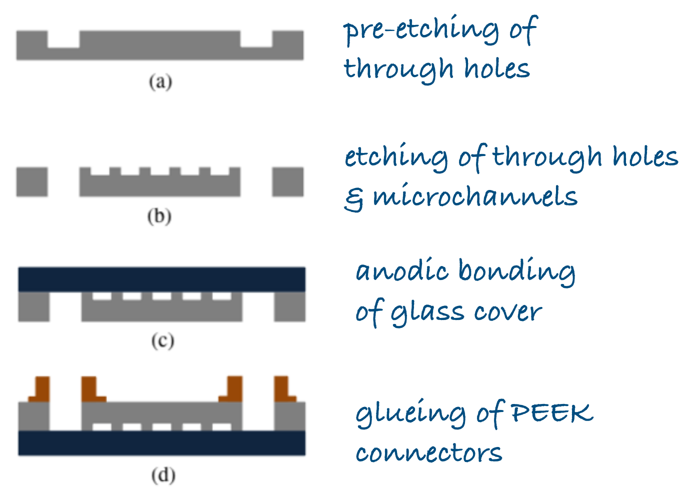
Silicon microchannel cooling plate



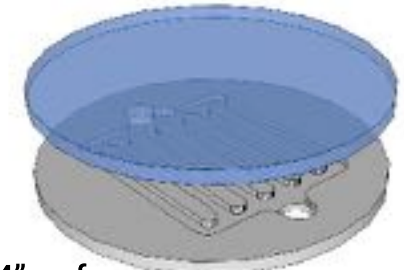
	NA62	LHCb
# of modules	3	52 (2x 26)
distance between modules	~10 m	2.5 cm
sensors	hybrid pixel	hybrid pixel
sensor size	60 x 38 mm	43 x 15 mm
sensors/module	1	4 (2 on each side of plate)
power dissipation (average)	~2 W/cm^2	~2 W/cm^2
coolant	liquid C_6F_{14}	evap. CO_2
cooling pate thickness	~200 µm	~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

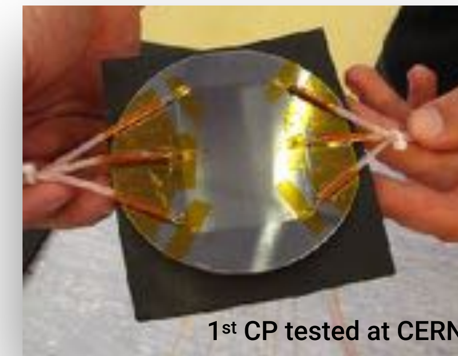
Process-flow developed at CERN for the first microchannel cooling plates

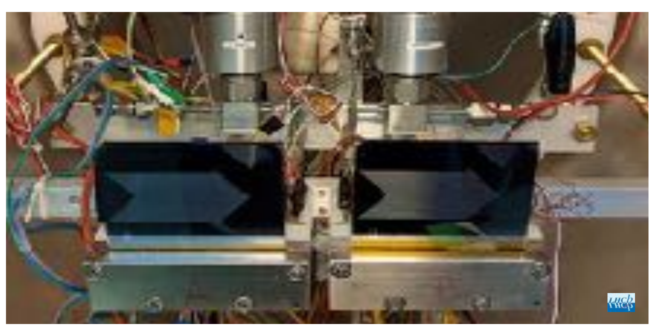


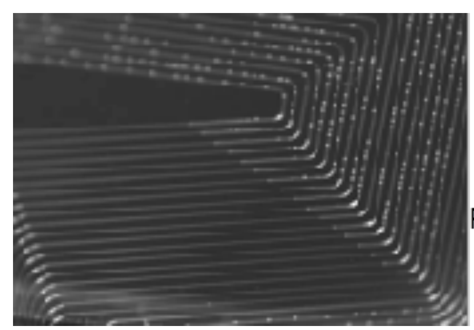
A. Mapelli et al. / Nuclear Physics B (Proc. Suppl.) 215 (2011) 349–352

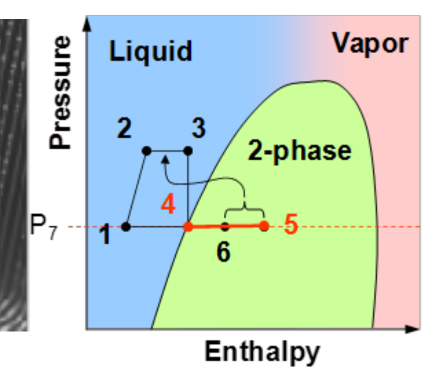


4” wafers

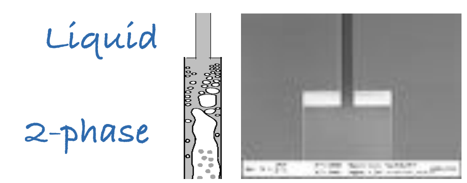


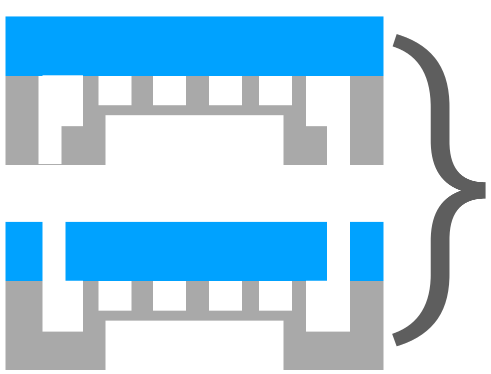


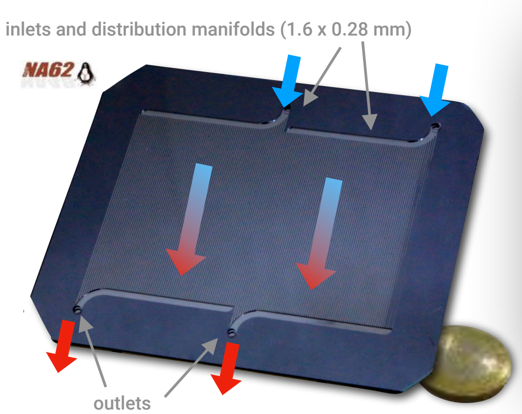




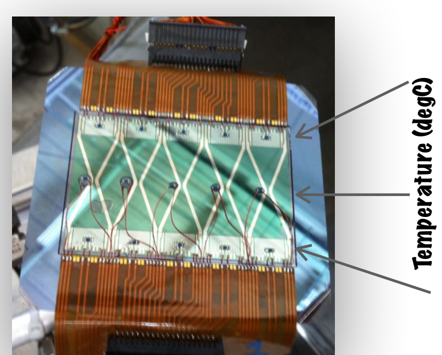
First demonstration of 2-phase CO_2 circulation in silicon microchannels.



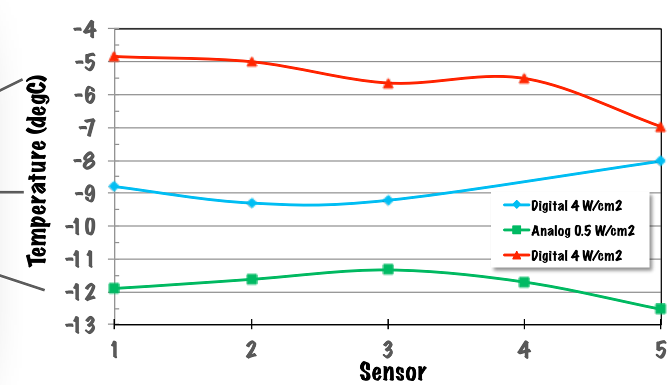




2 independent networks of 75 µchannels

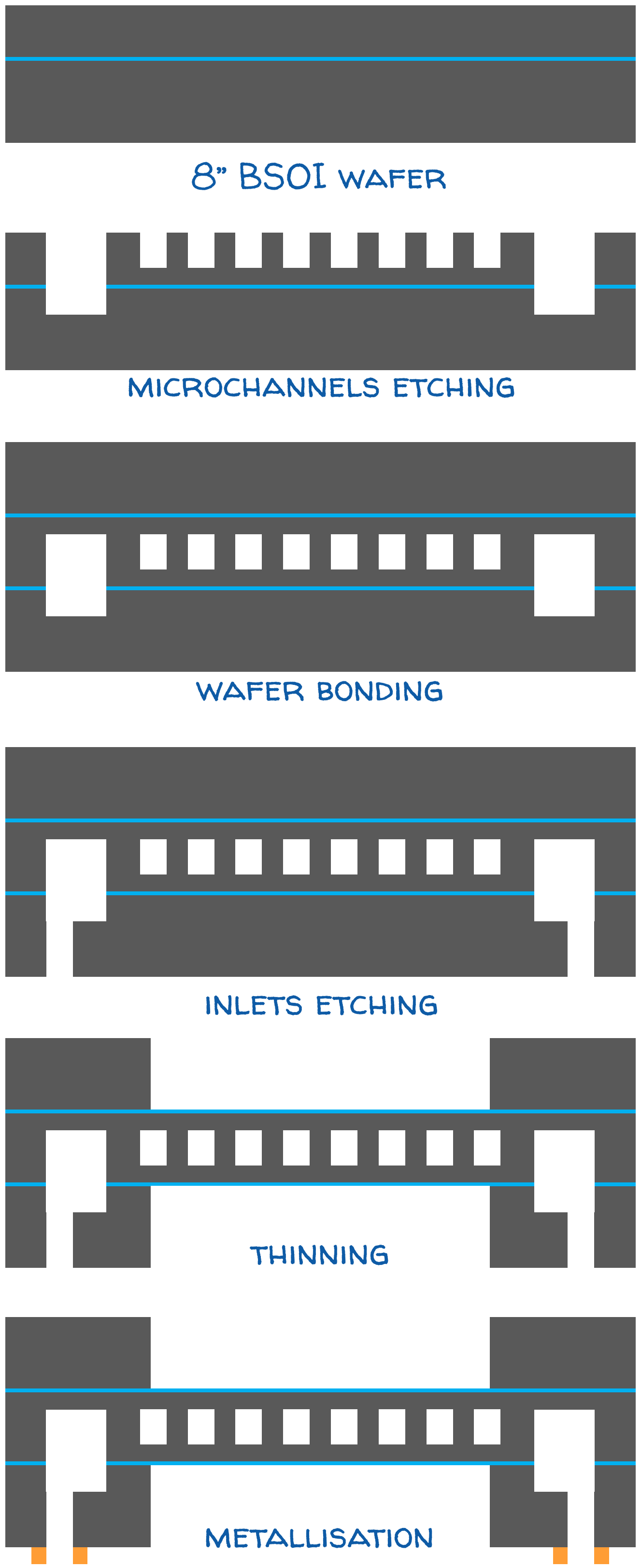


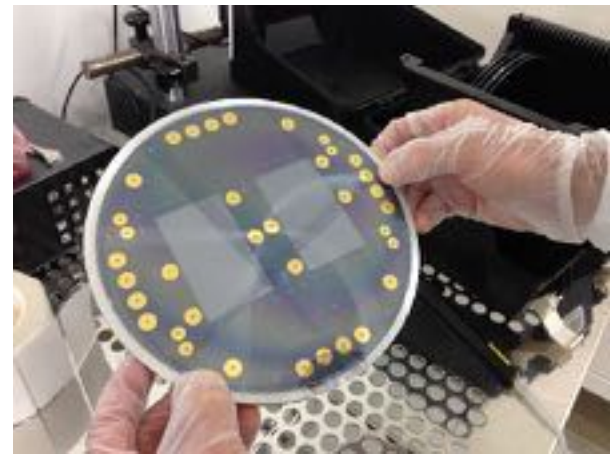
CP equipped with thermo-mechanical mockup of the hybrid detector

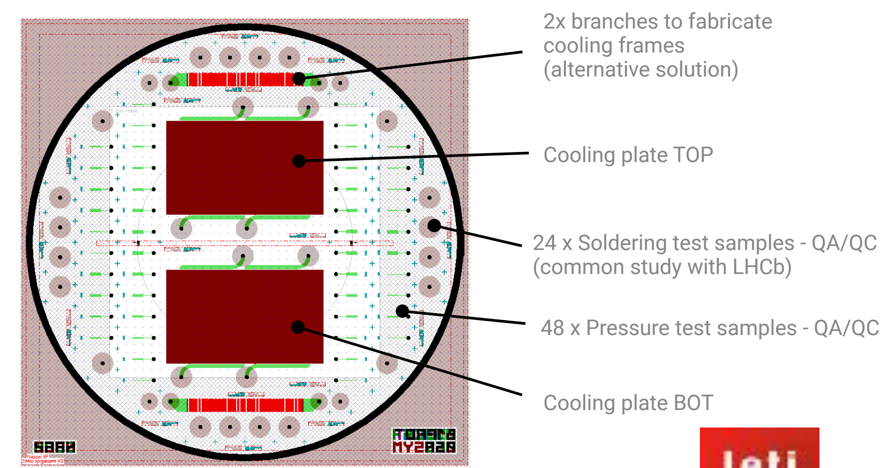


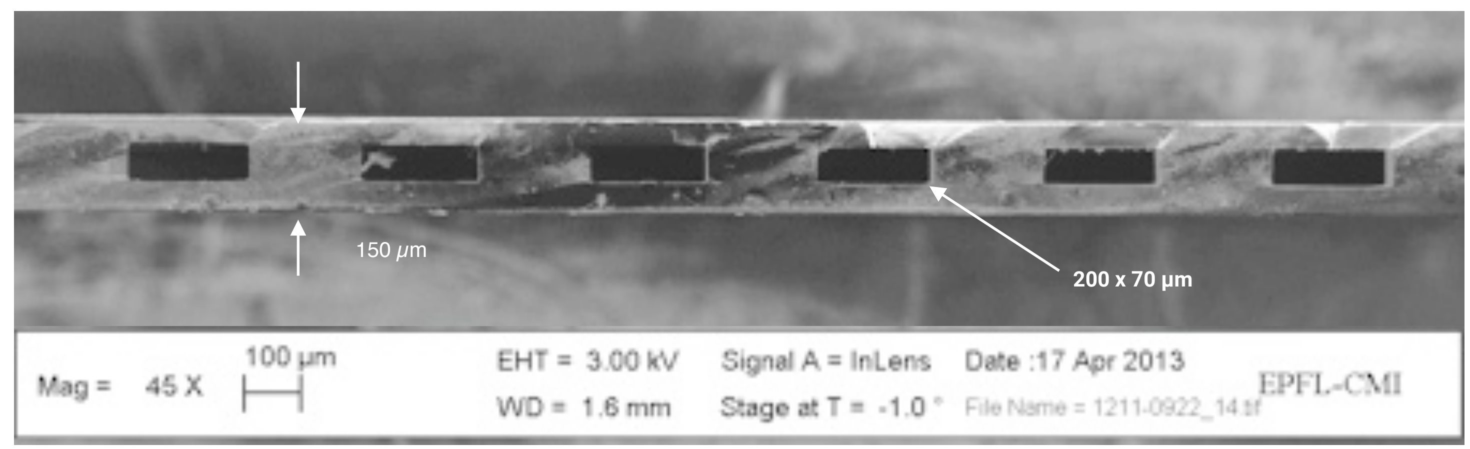
- Power dissipation
  - Digital Power 38 W
  - Analog Power 10 W
- Liquid C_6F_{14}
  - 7g/s
  - -19°C at inlet

microfabrication of the GTK cooling plates







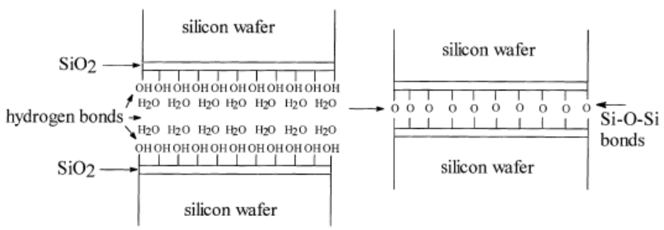


- Collaborative effort between CERN (ALICE, LHCb, NA62 and EP-DT) and external partners (CSEM, EPFL).
- Design by CERN EP-DT
- Prototypes fabricated by CERN EP-DT at EPFL-CMi on 4” wafers
- Pre-production series by IceMOS on 6” wafers
- Three batches fabricated at CEA-Leti on 8” wafers
- Fourth batch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

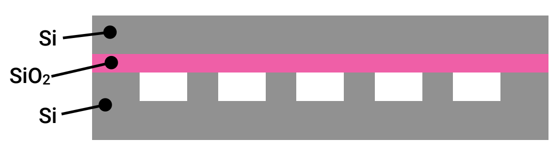
Silicon direct wafer bonding

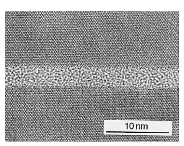
No intermediate layer such as eutectic metals or adhesives for the bonding

Hydrophilic bonding



A. Plößl, G. Kräuter/Materials Science and Engineering R25 (1999) 1-88

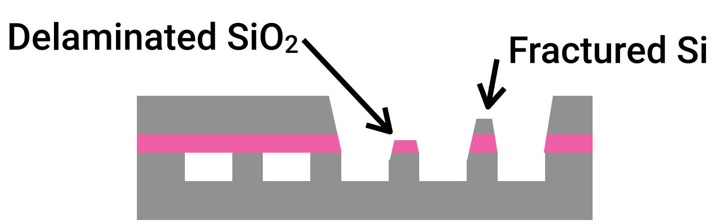


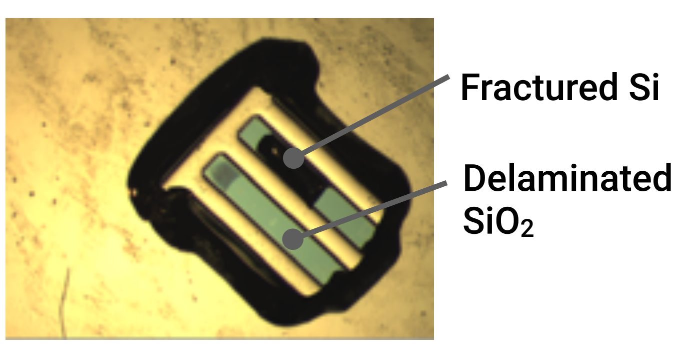


T_{anneal} = 1050°C

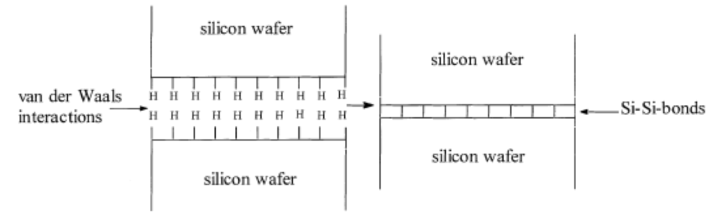
P_{max} ~400 bars

delamination + rupture

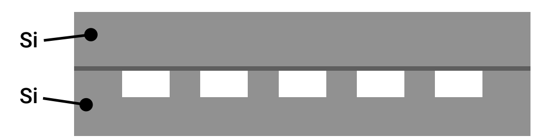


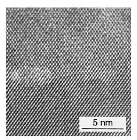


Hydrophobic bonding



A. Plößl, G. Kräuter/Materials Science and Engineering R25 (1999) 1-88

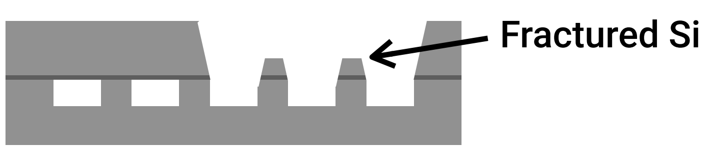


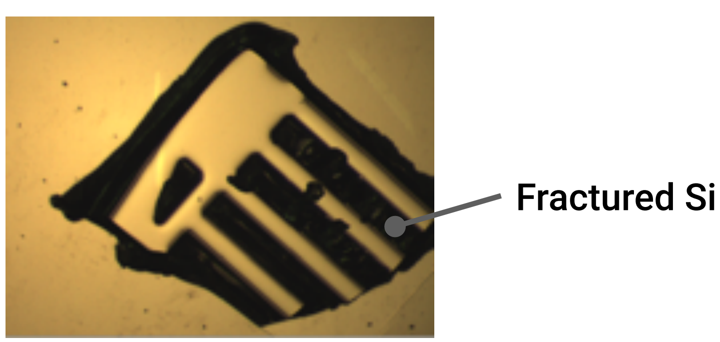


T_{anneal} = 1050°C

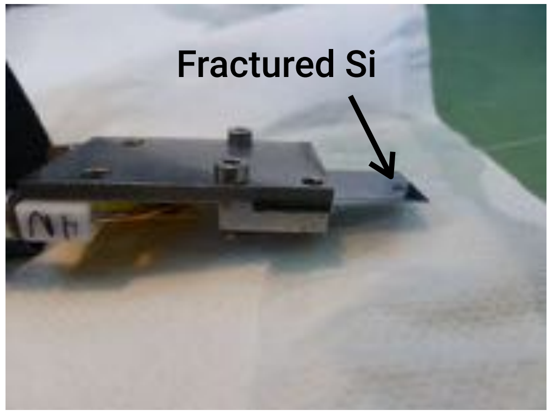
P_{max} ~700 bars

rupture without delamination



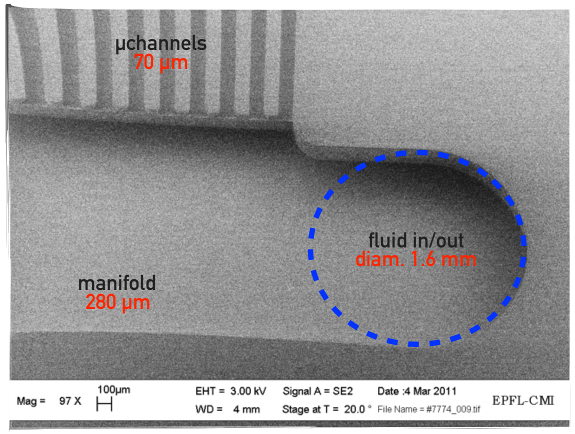


Scanning Acoustic Microscope image of bonded wafers with test structures.

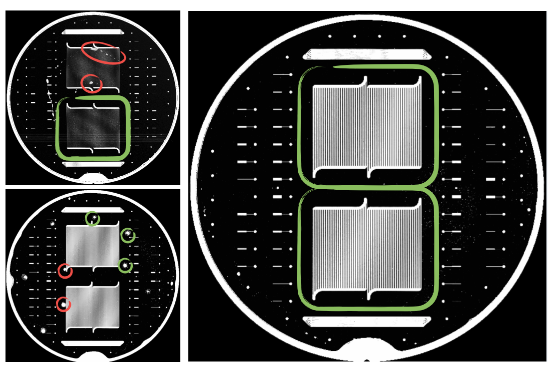


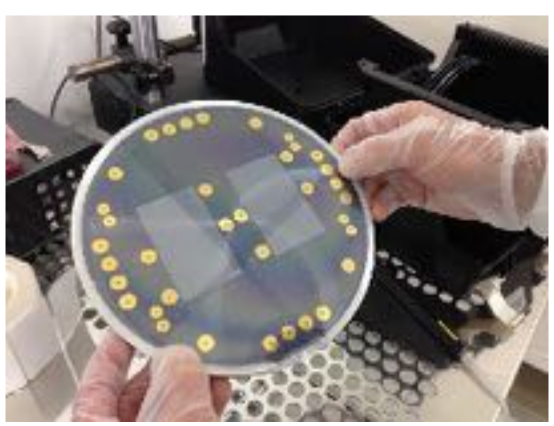
QA/QC of the cooling plates

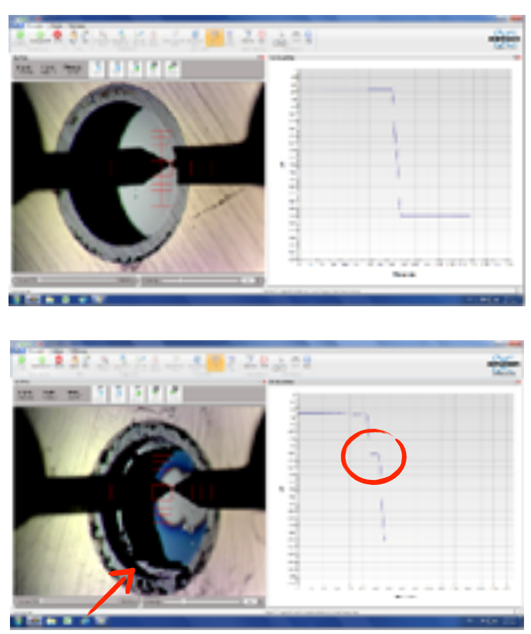
- Etching profiles of the microchannels.
- Scanning Acoustic Microscopy of bonded wafers.
- Visual inspection during tape-out.
- Metrology of cooling plates (Inlets and pools).
- Pressure tests on dedicated samples
  - 1500 µm wide cavities (manifolds) > 25 bars
  - 200 µm wide cavities (microchannels)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

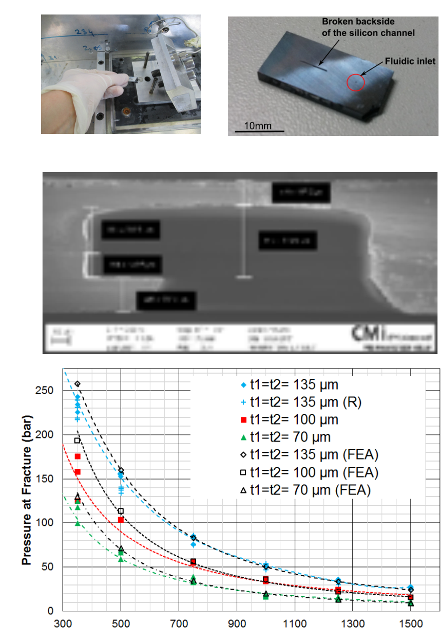


SEM of microchannels

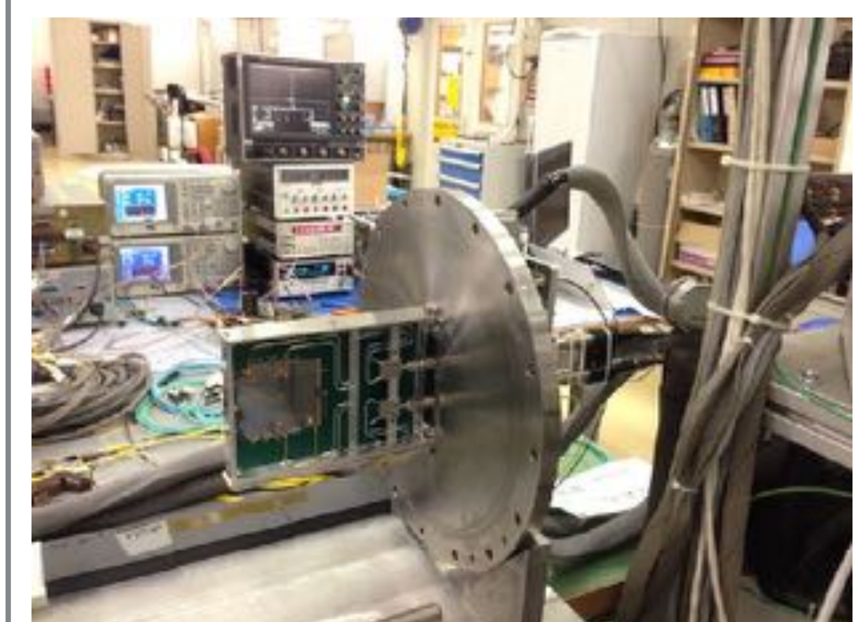

SAM of bonded interface


Visual inspection

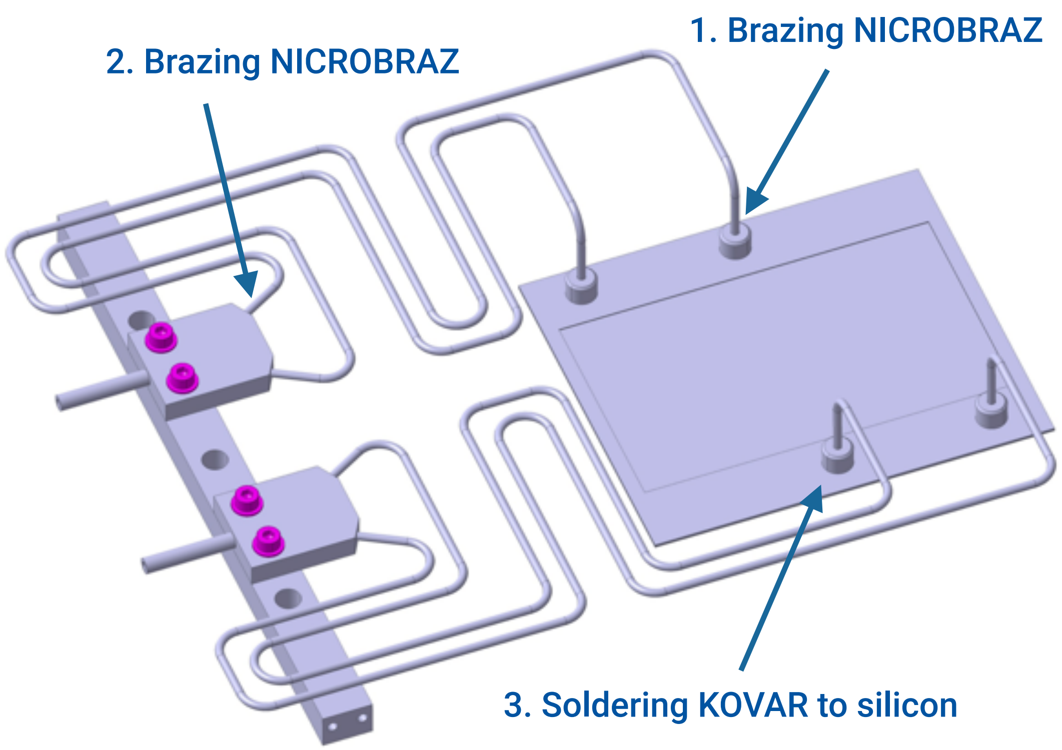

Metrology of fluidic inlet/outlet



Pressure testing of silicon microchannels


Cooling test setup at CERN

Microfluidic system integration

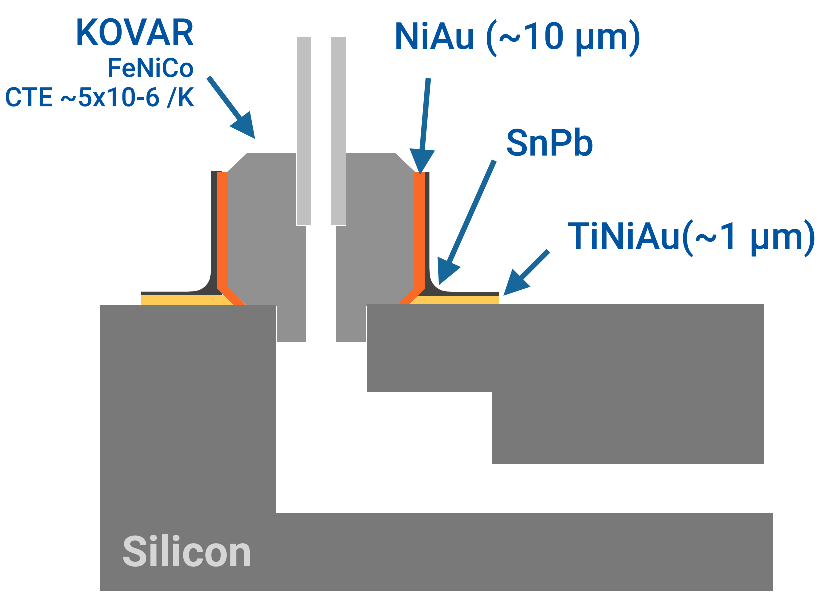


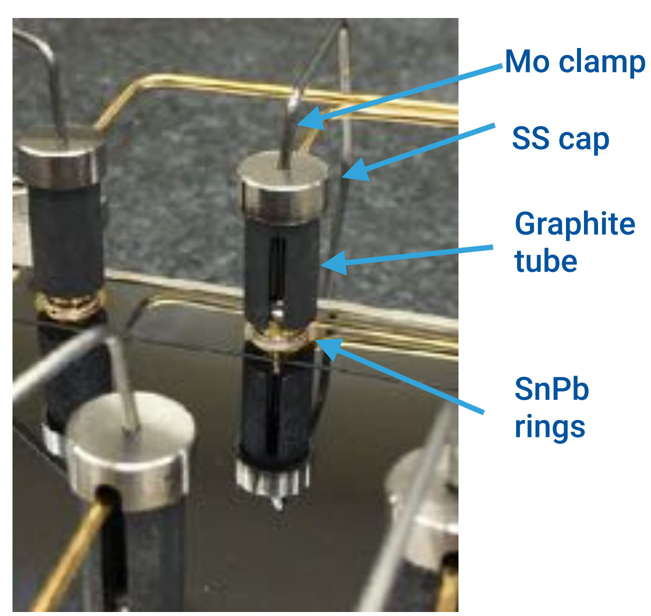
Assembly steps:

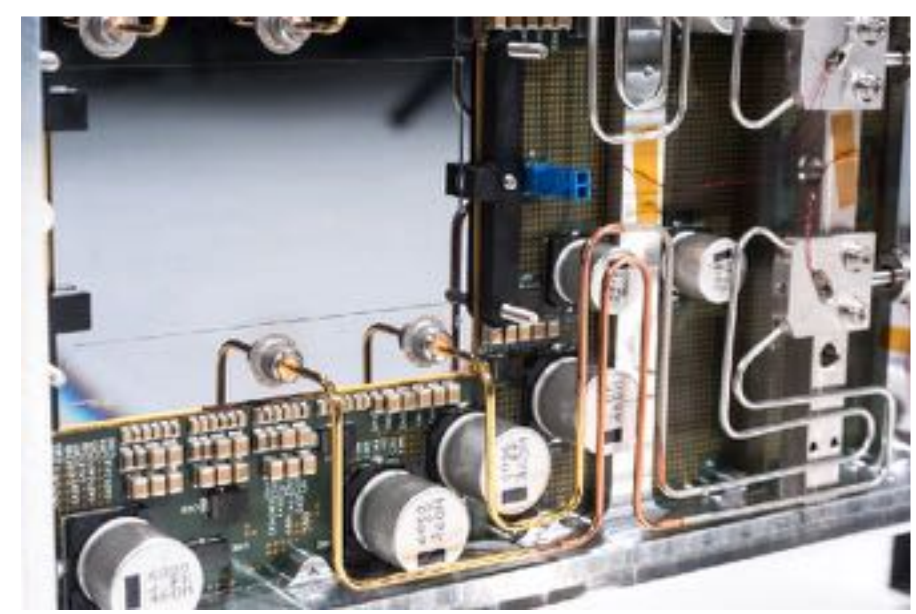
- Machining of KOVAR connectors;
- Brazing of connectors to capillaries (1);
- Bending of the capillaries;
- Brazing the other end of the capillaries to the manifolds (2);
- NiAu plating of the connectors;
- Soldering of the connectors to the silicon cooling plate (3);

QA/QC:

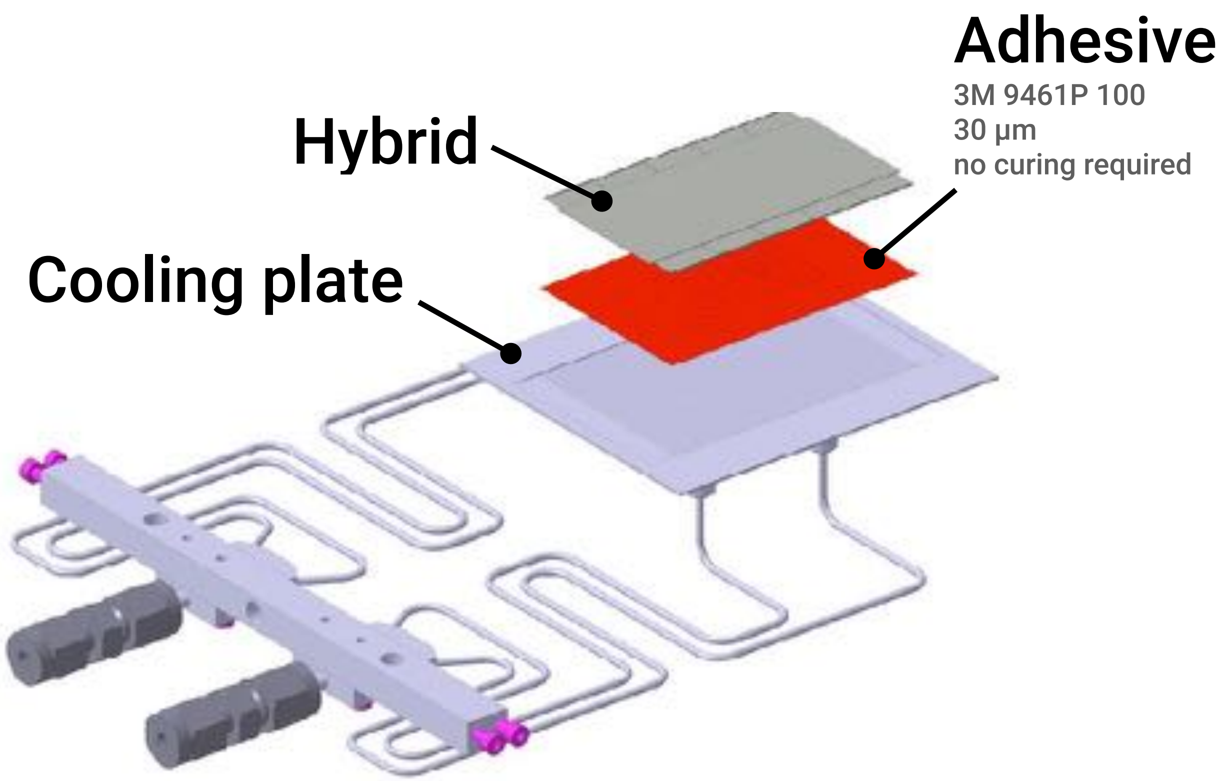
- After each joining step the He leak rate is measured. (Acceptance leak rate: 10_{-10} mbar l_{-1} s_{-1}).
- Pressure testing of the cooling plate at 1.43 x P_{op}

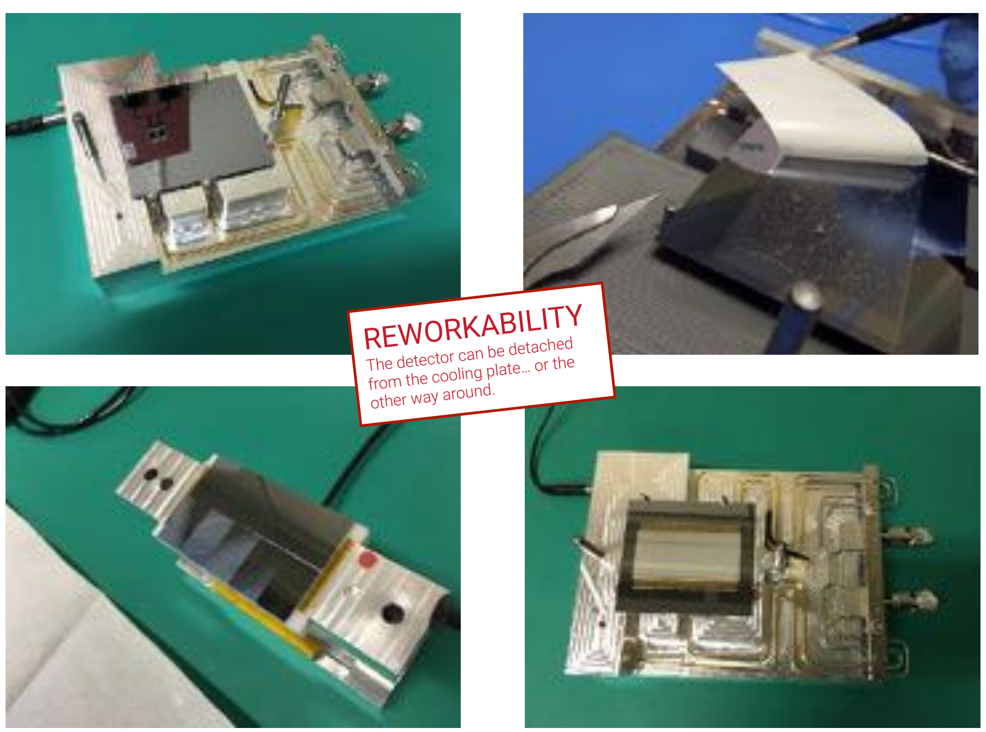




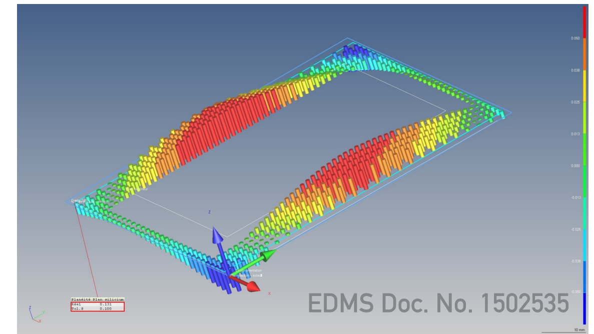


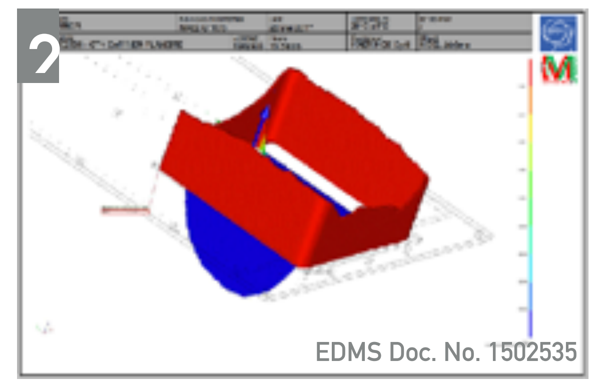
Glueing the hybrid on the cooling plate

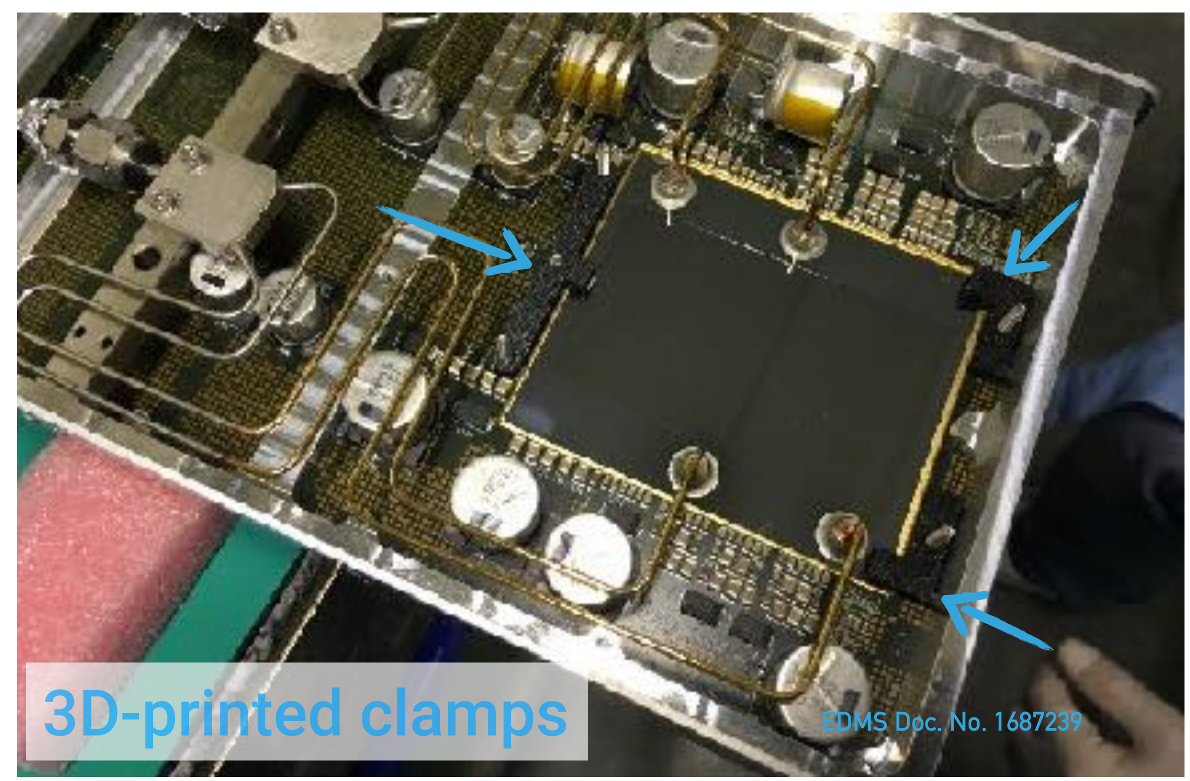




Clamping the cooling plate to the PCB

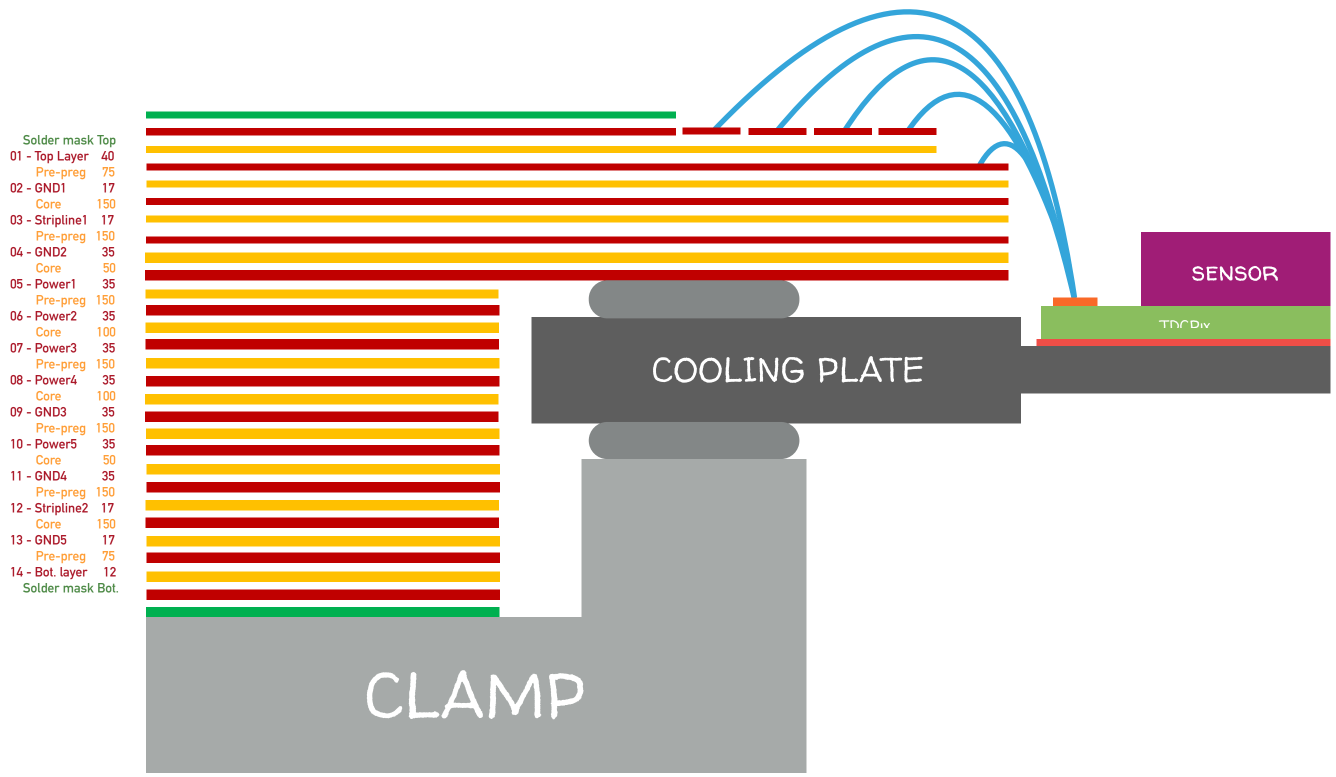


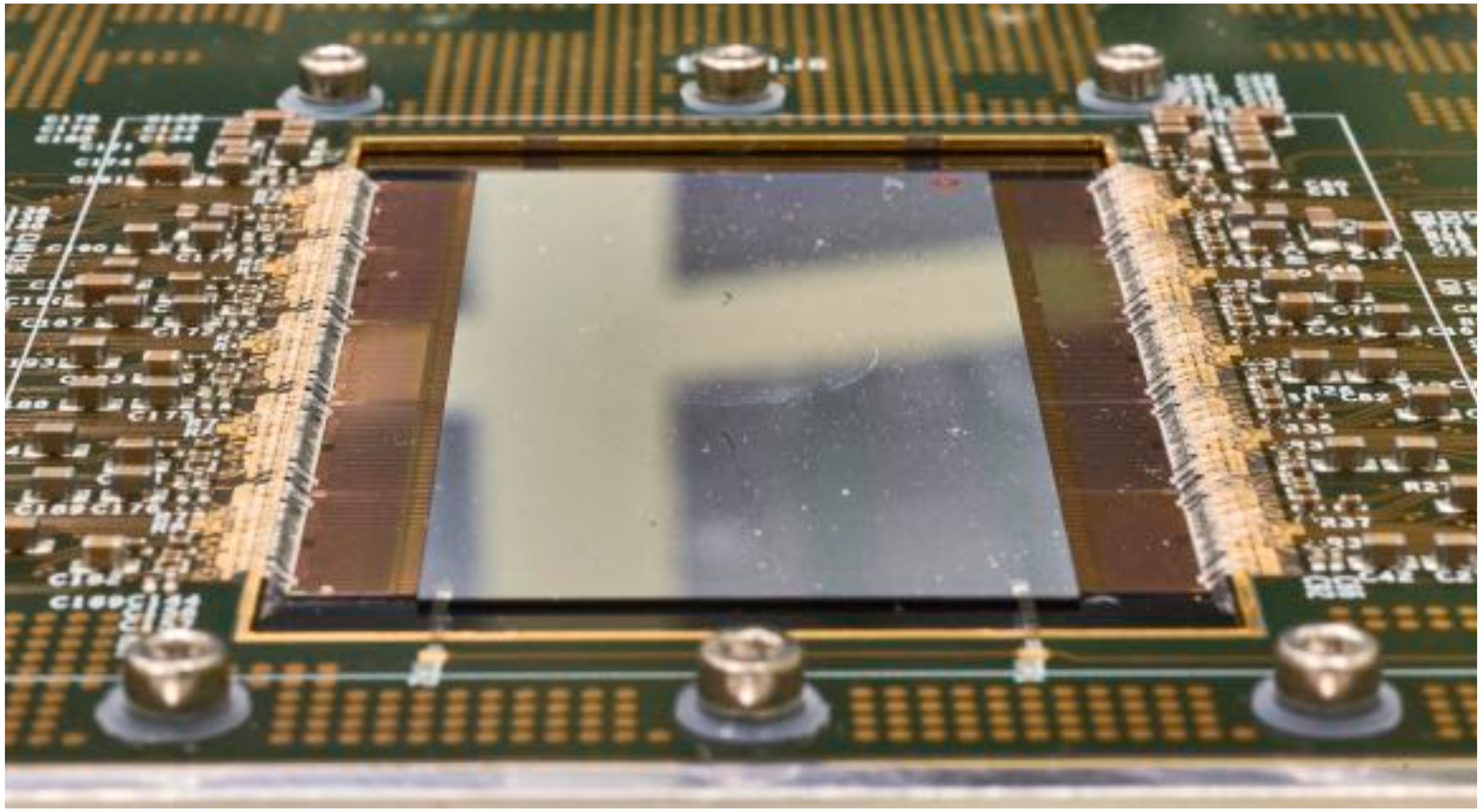


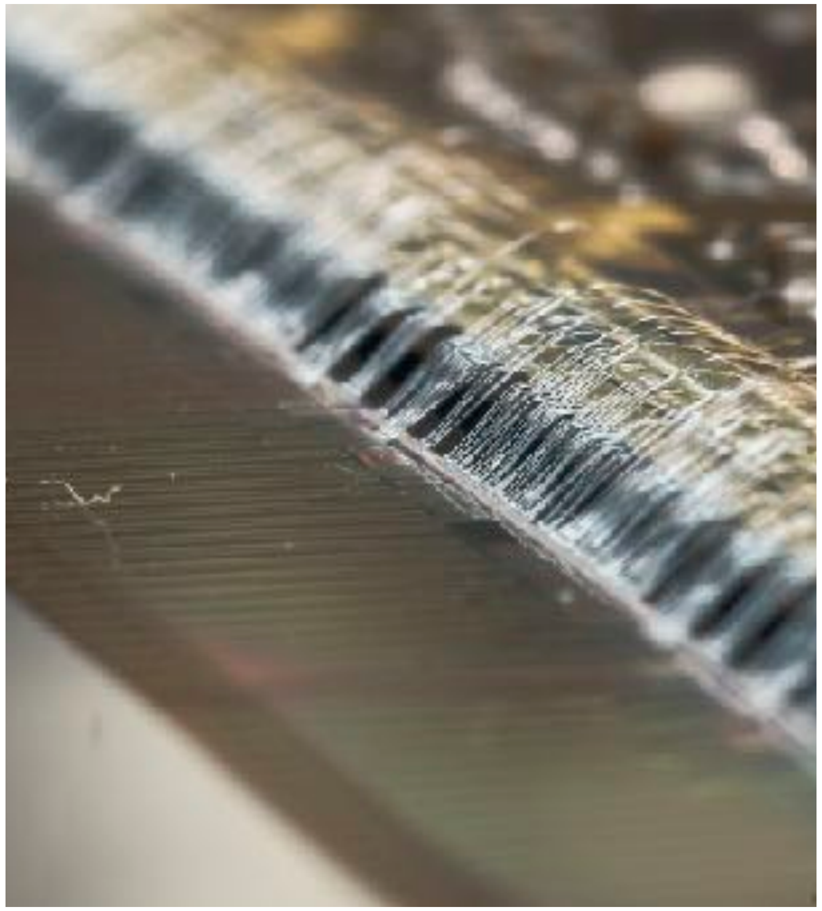


Wire-bonding

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

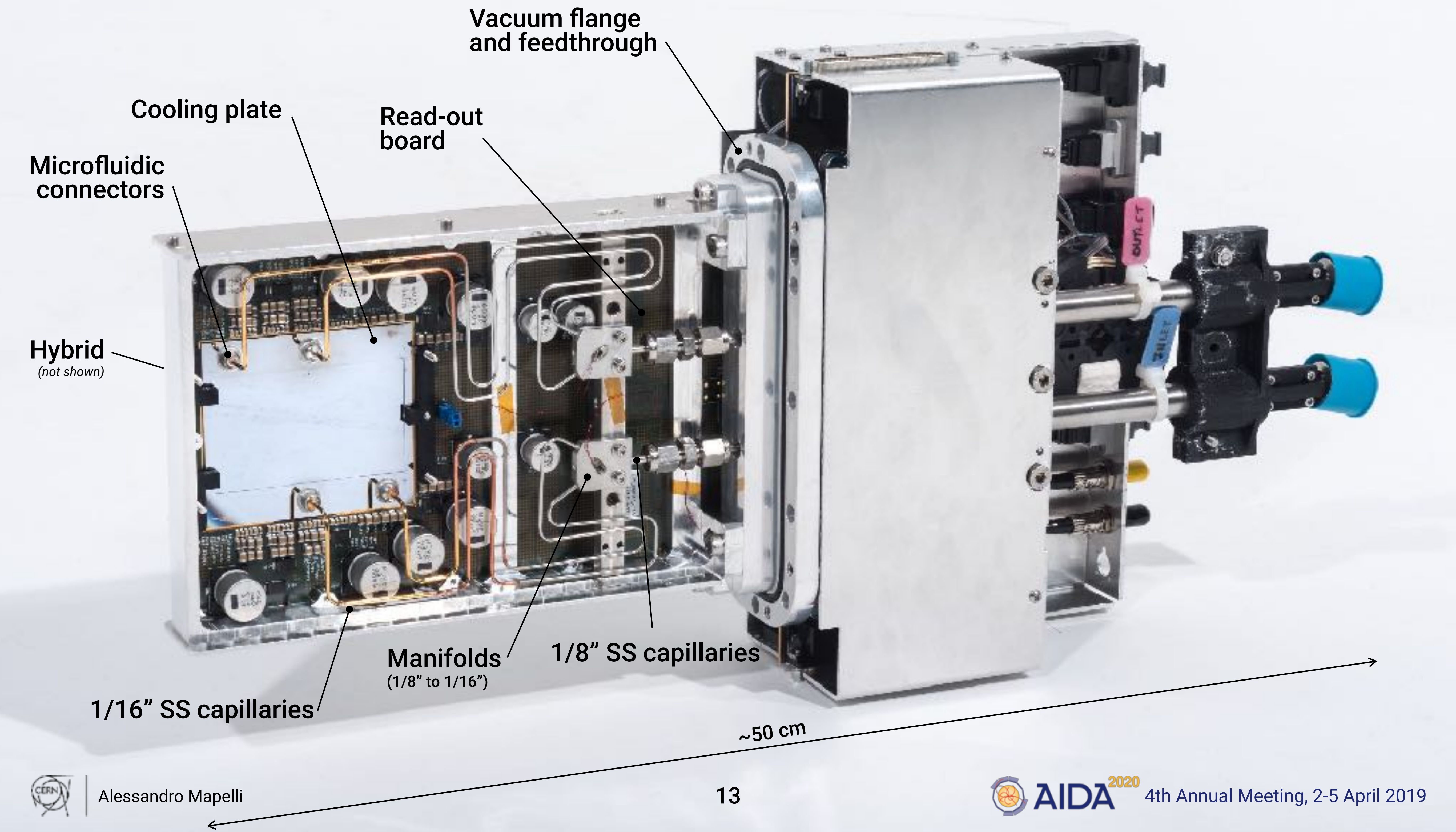






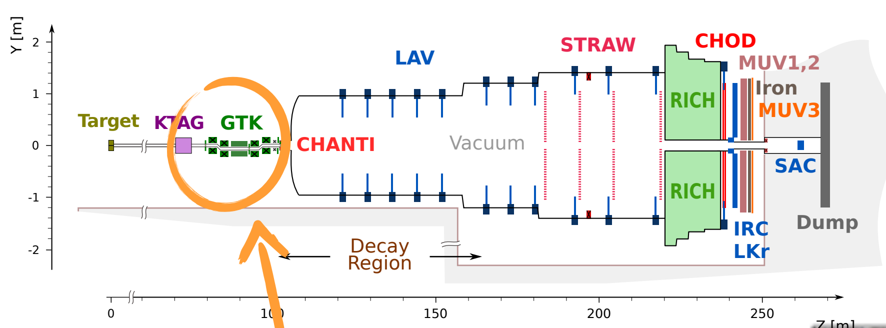

J1

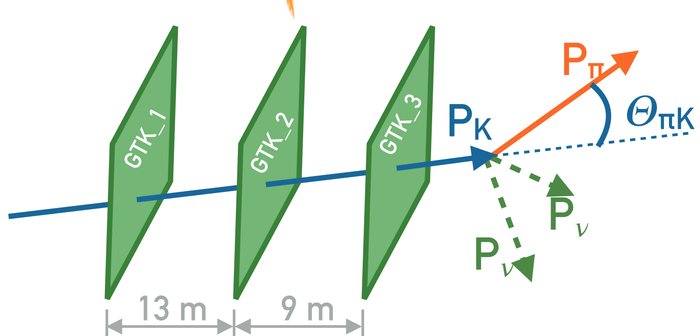
NA62 GigaTracKer

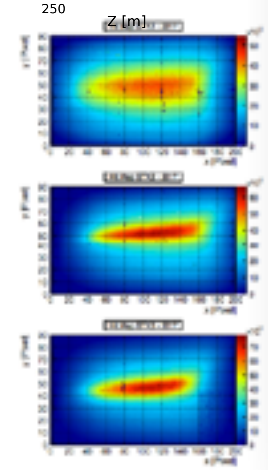


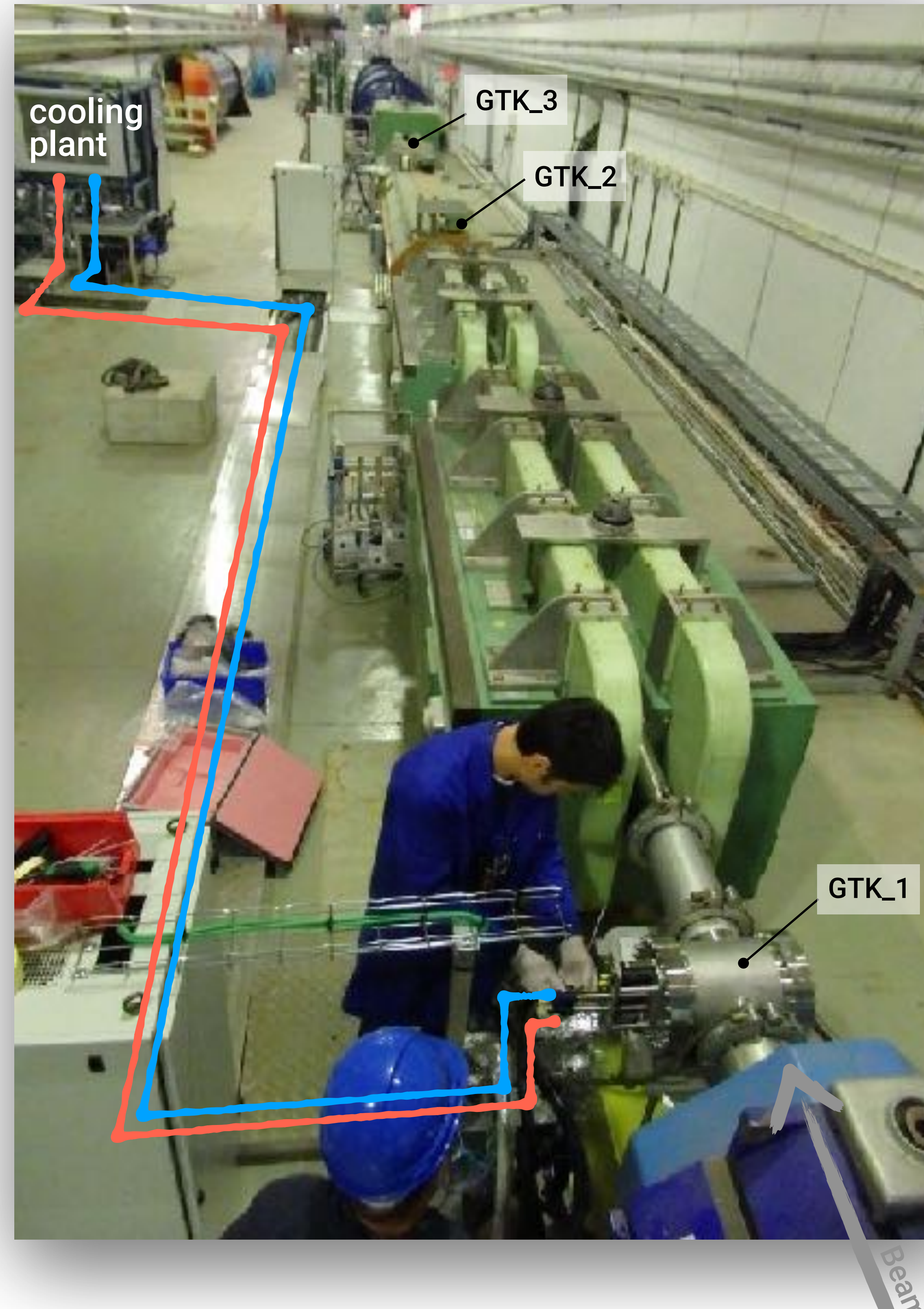
The GTK in the NA62 experiment

- **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 $4 \times 10^{14}\ n_{eq}/cm^2$ in one year (200 days) of data taking.
  - In order to minimise radiation-induced damages, the detectors are operated at approximately -15ºC in vacuum (~10^{-6} mbar).
  - Detectors have to be replaced every 100 days.
  - GTK **designed to be replaced rapidly** (<0.5 day intervention).





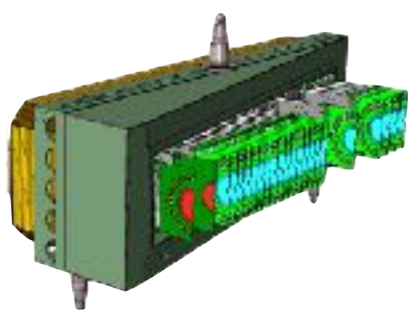


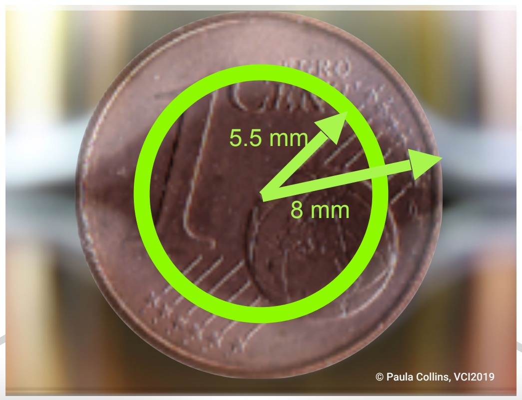


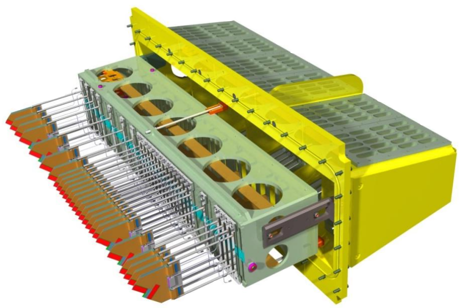
LHCb VELO Upgrade

- LHCb will pioneer the use of evaporative CO_2 in silicon microchannels.
- The future upgrade of the LHCb's Vertex Locator (VELO) will combine in 2021 multiple silicon plates with embedded microchannels with an evaporative CO_2 system to cool 52 pixel modules dissipating a total of about 1.5 kW.

	current	LS2 Upgrade
modules	52	52
sensors	strip	pixel
distance to LHC beam	8 mm	5.5 mm
cooling	evap. CO_2	evap. CO_2
evaporator	metal blocks	silicon microchannels
module power dissipation	~ 16.5 W	~ 30 W

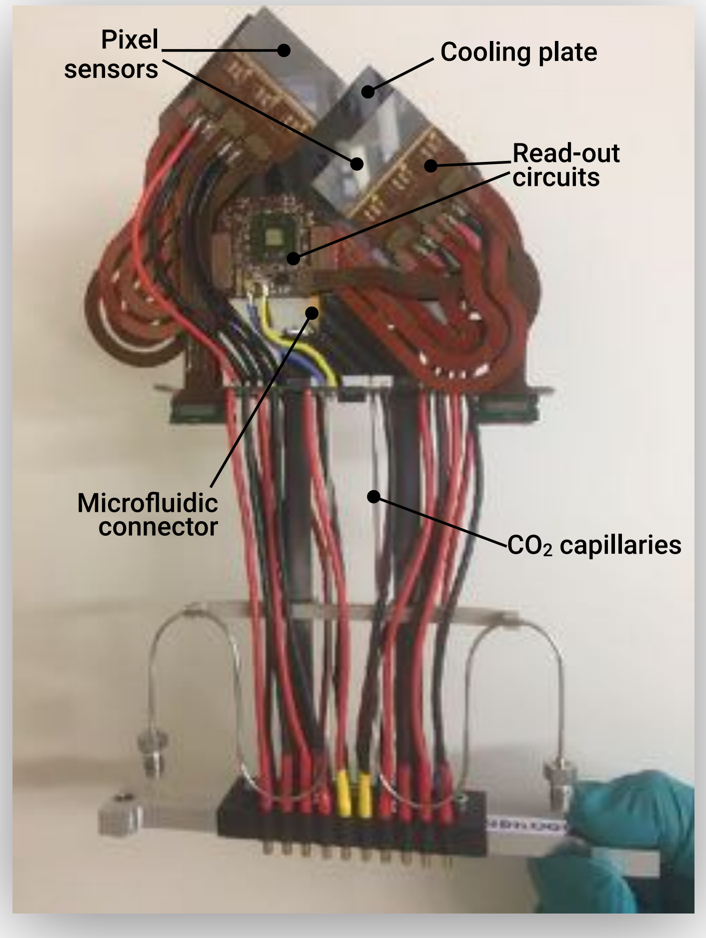


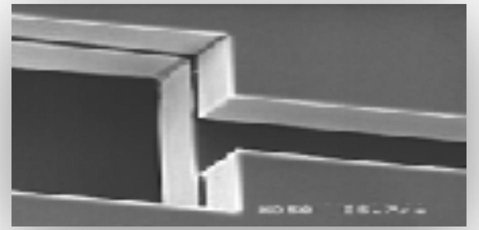




current VeLo module

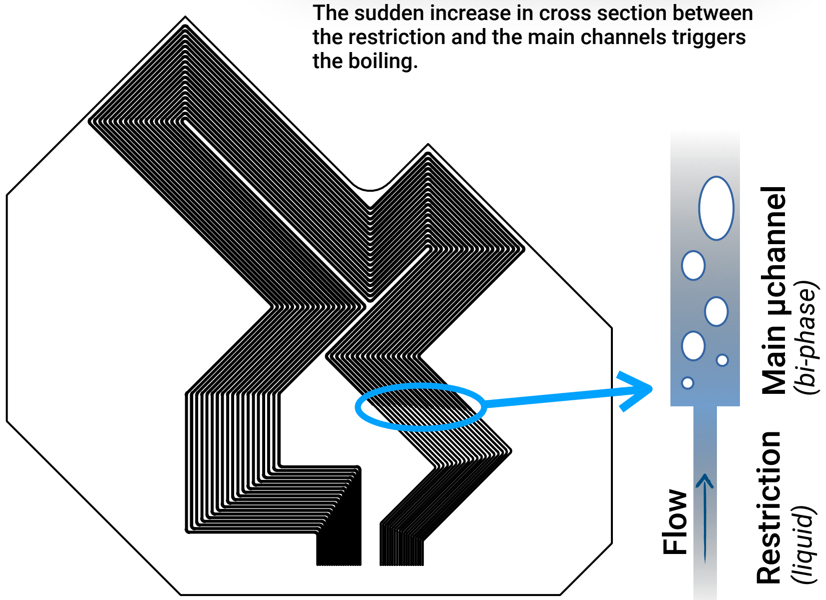
LS2 upgrade module





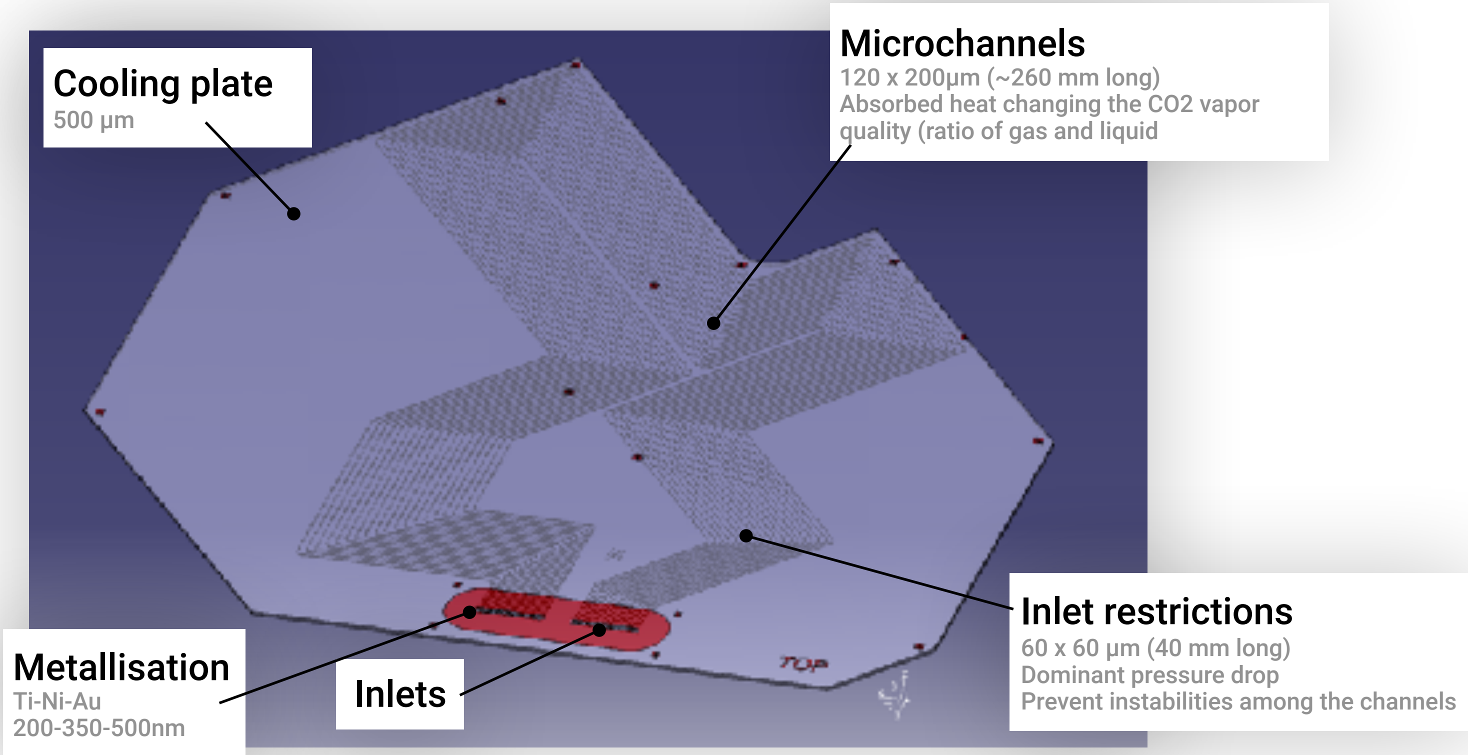
microchannel etched at different depths

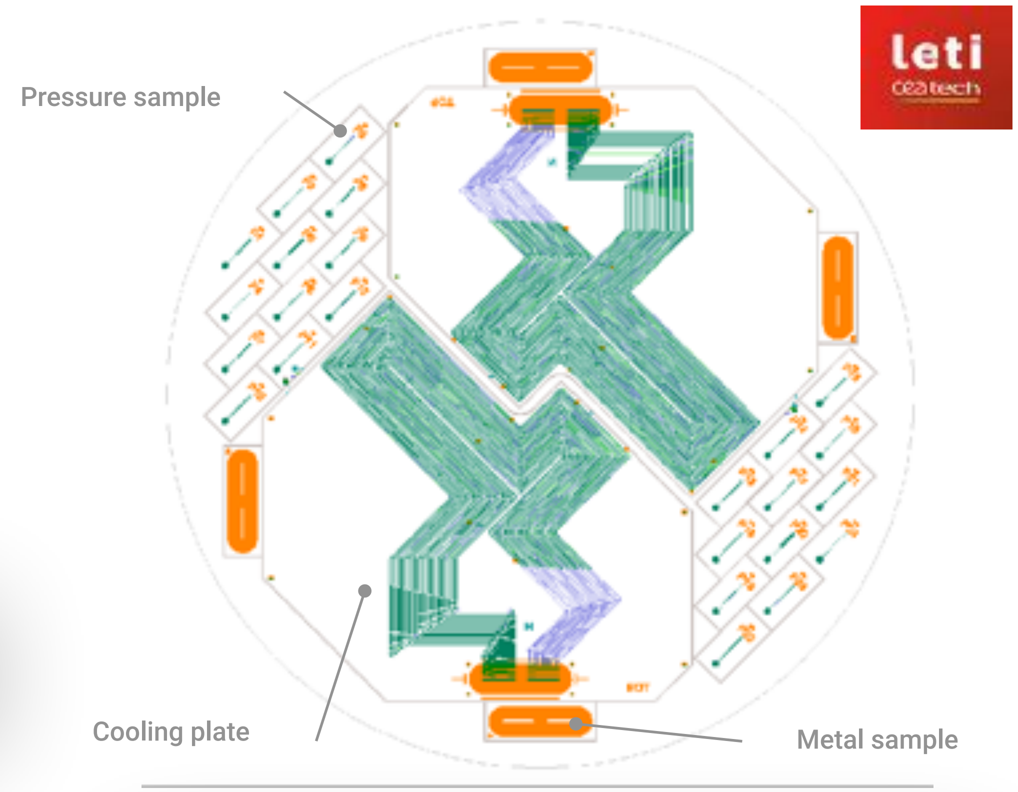
The sudden increase in cross section between the restriction and the main channels triggers the boiling.

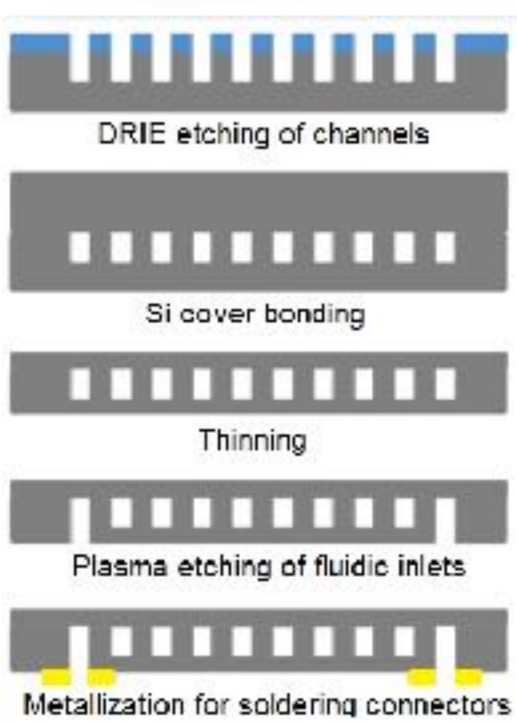


Microchannels designed to bring the coolant under the heat sources.

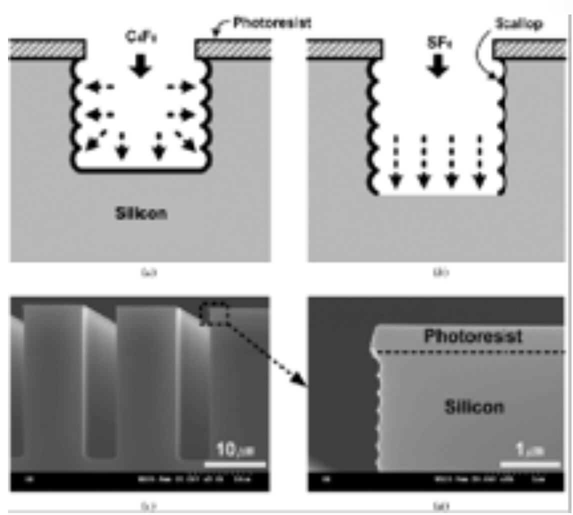
microfabrication of the VeLo cooling plates



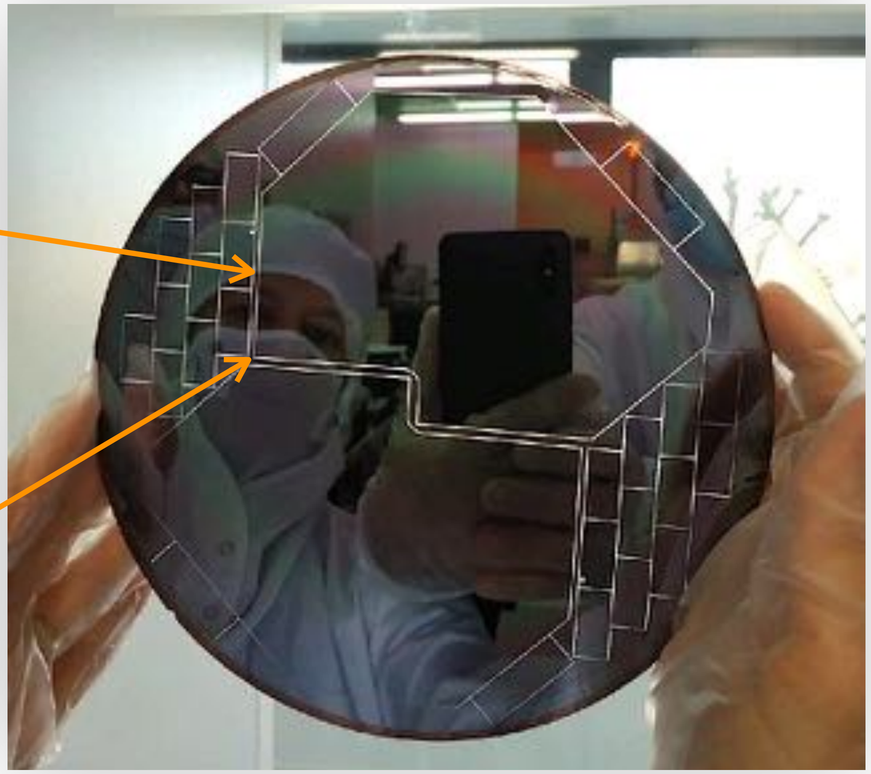




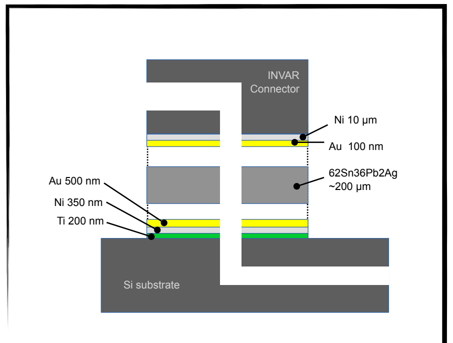
Plasma dicing by DRIE
Deep Reactive Ion Etching



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

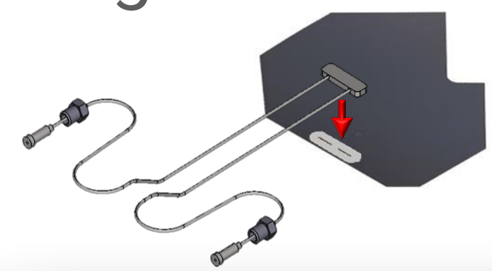


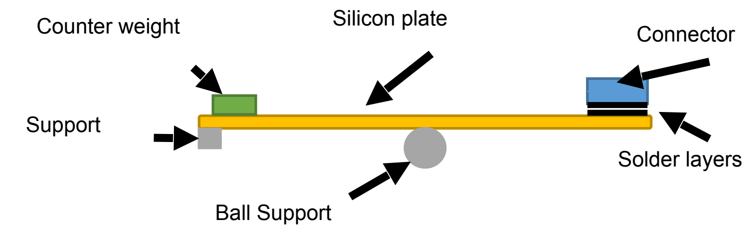
soldering of metallic connectors



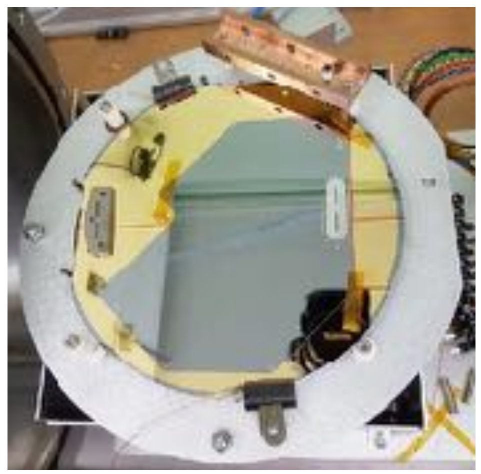
62Sn36Ag2Pb preform for pre-tinning of cooling plate and connector

3. Alignment of connector to cooling plate

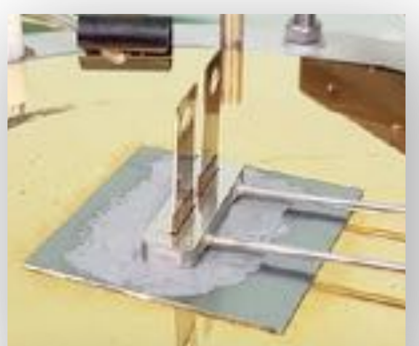




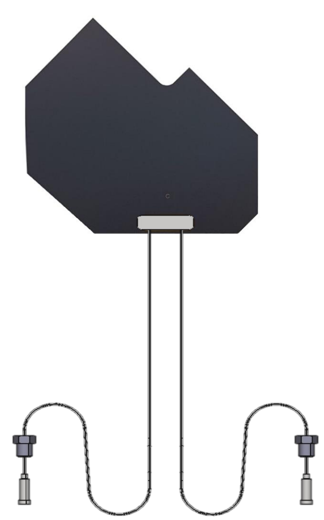
1. Pre-tinning of cooling plate

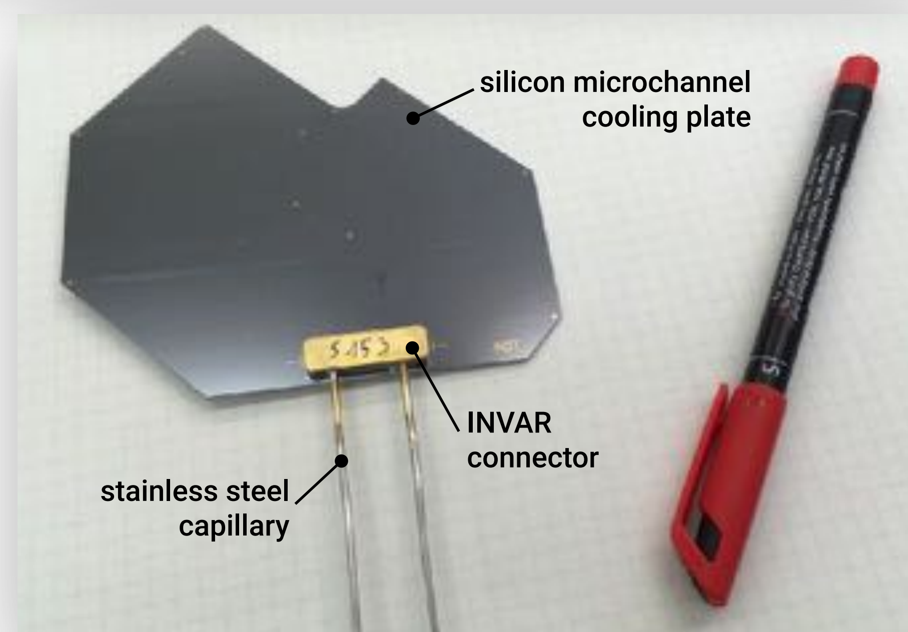


2. Pre-tinning of connector



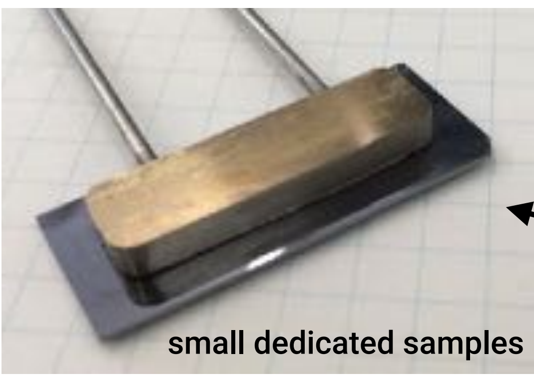
4. Soldering

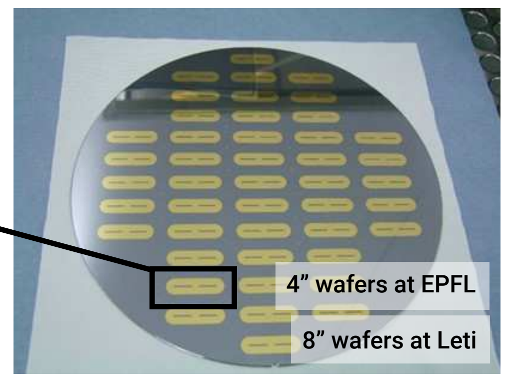


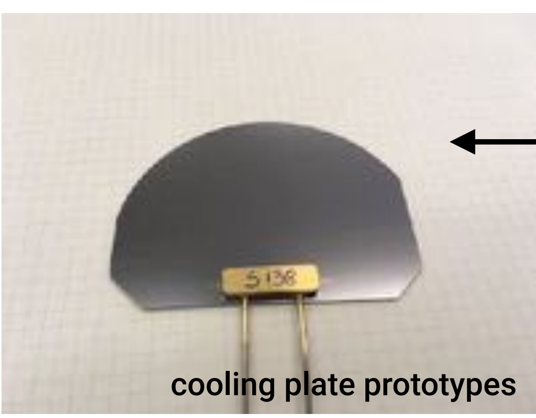


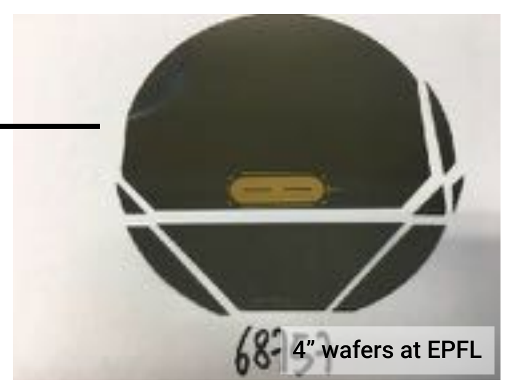
voidless and fluxless soldering of metal to silicon

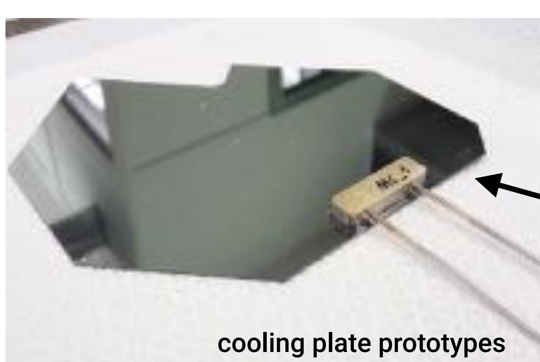
validation of soldering procedure with thermo-mechanical mockups

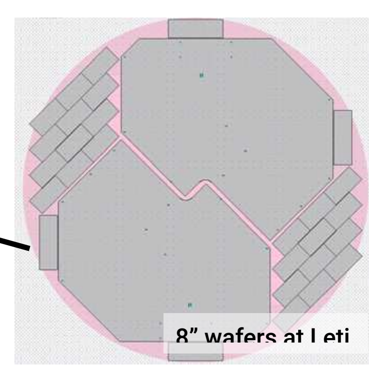




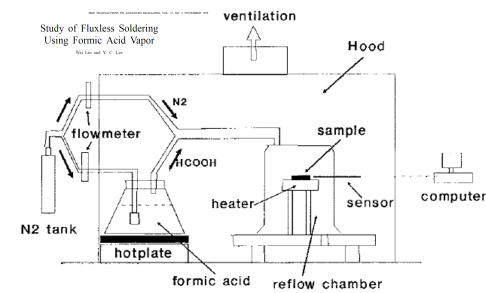


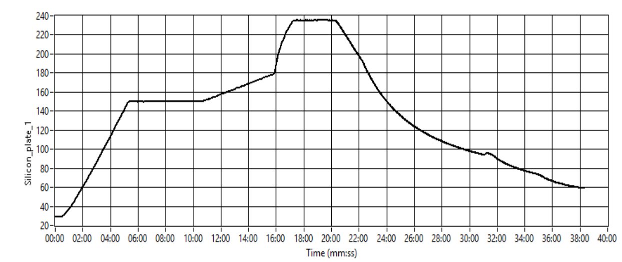


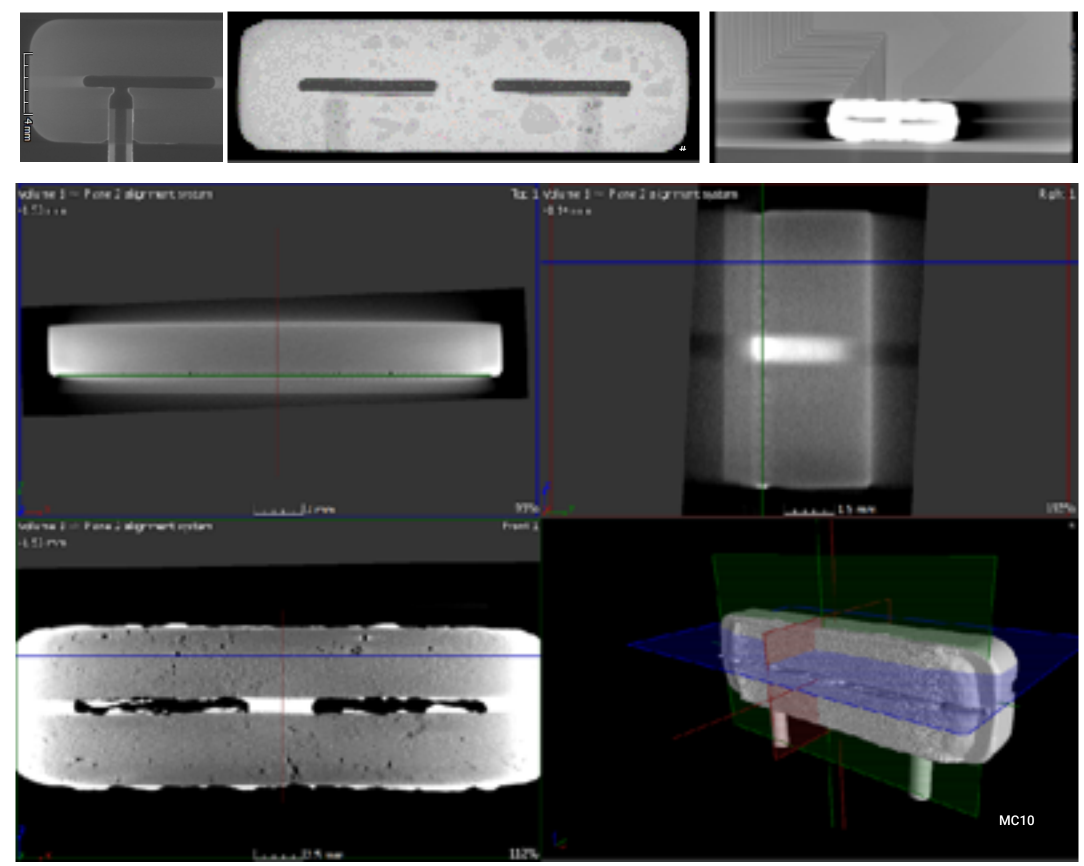




soldering in reducing atmosphere using Formic Acid

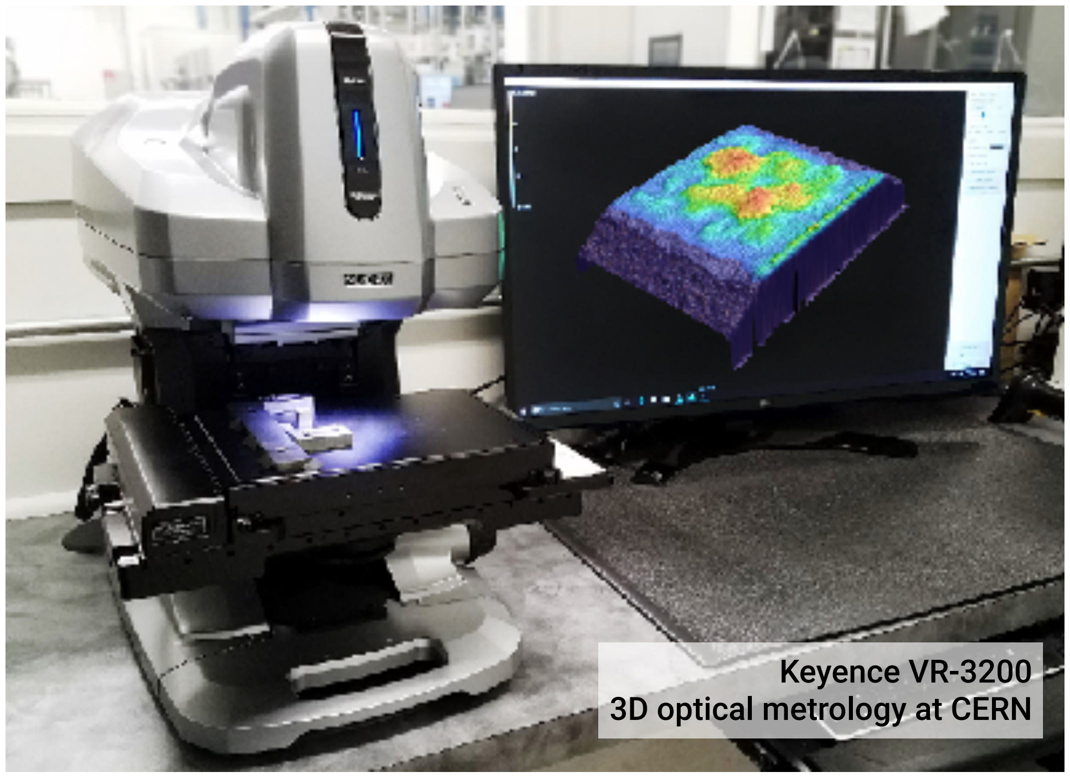


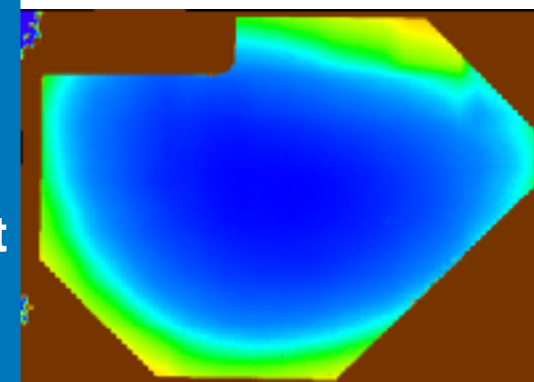
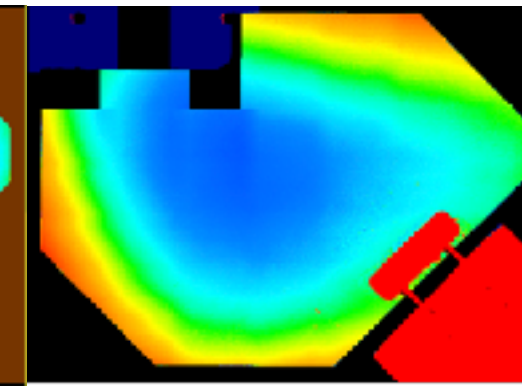


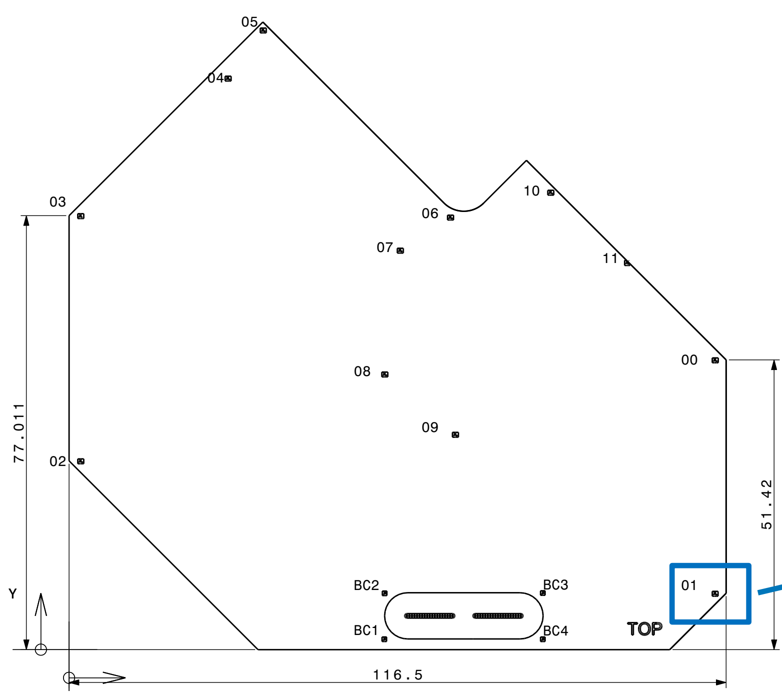


3D Xray µ-CT at CERN

cooling plates planarity

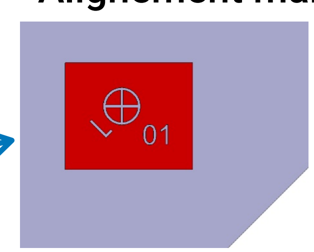


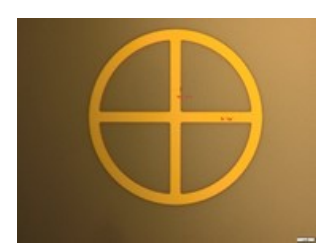
	before soldering	after soldering
planarity measurement		
min.	-60 μm	-50 μm
max.	+26 μm	+25 μm
variation	86 μm	75 μm



- 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

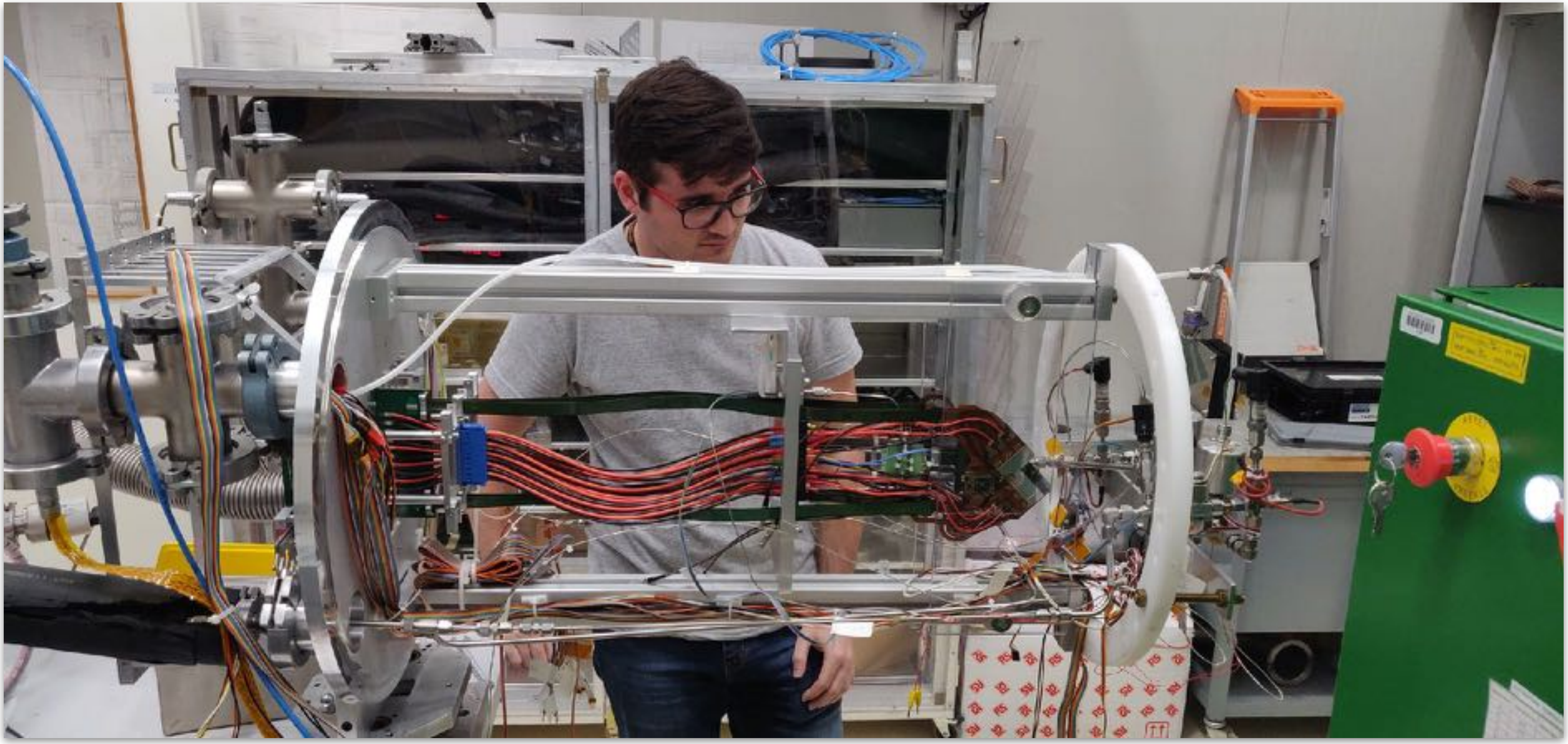




patterned on metal

etched in silicon

Slide from the talk **The LHCb Upgrade and the VELO** by Paula Collins at VCI2019



Embedding microfluidics into microelectronics	*Riccardo Callegari*
Seminar Room 11, St Anne's College	17:00 - 17:15
Silicon-based micro oscillating heat pipes for HEP and space applications	*Timothee Frei*
Seminar Room 11, St Anne's College	17:15 - 17:30
Silicon microchannel cooling frames for stave configurations	*Massimo Angeletti*
Seminar Room 11, St Anne's College	17:30 - 17:45

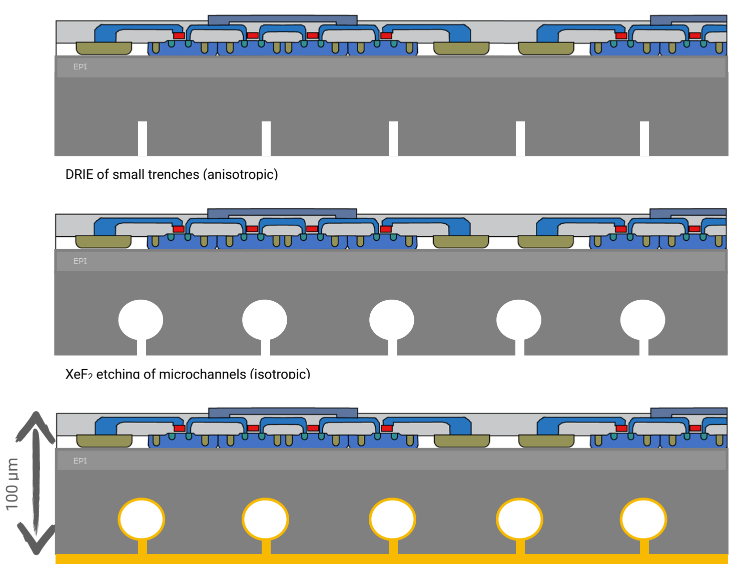
Junior Fellow: *Riccardo Callegari*
PhD Candidate: *Roberto Cardella*

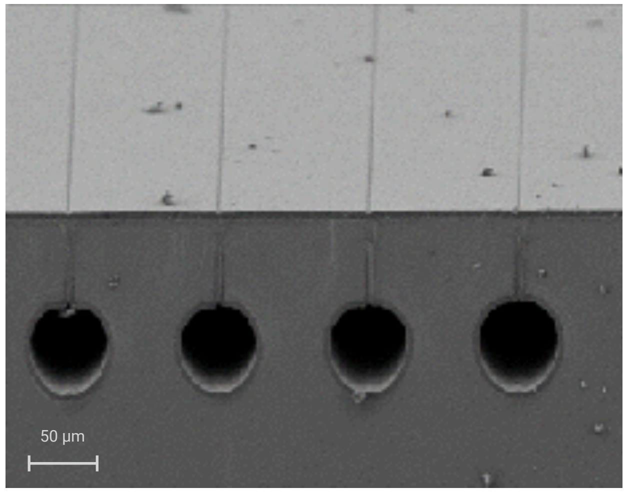
- CMOS-compatible process developed at CERN.
- Microchannels etched on the backside of monolithic pixel detectors.
- **The michrochannels are sealed without wafer bonding**
- A demonstrator is currently being produced by post-processing functional MALTA* chips in the class 100 (ISO5) MEMS cleanrooms of EPFL.

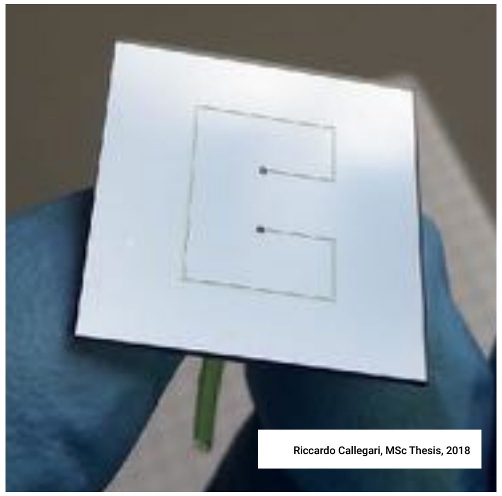
*MALTA: an asynchronous readout CMOS monolithic pixel detector for the ATLAS High-Luminosity upgrade. R. Cardella et al., PIXEL2018

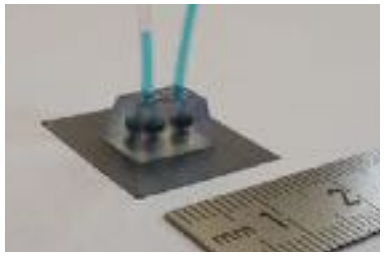
Getting rid of wafer bonding

M.J. de Boer et al./J. Microelectromechanical Systems 9 (1) (2000) 94-103
M. Boscardin et al./Nuclear Instruments and Methods in Physics Research A 718 (2013) 297-298
C. Lipp, EPFL MSc Thesis, 2017
R. Callegari, Università di Genova, MSc Thesis, 2018







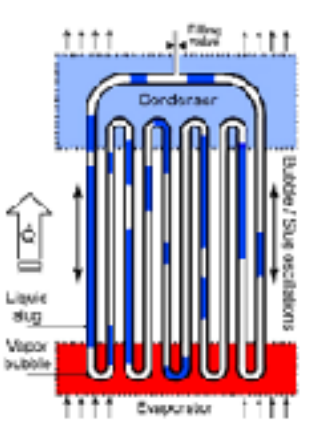


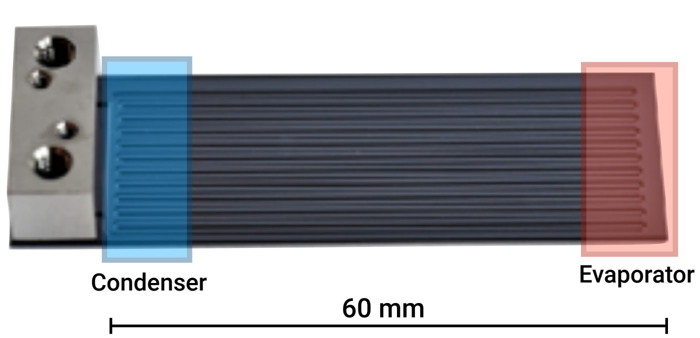
Embedding microfluidics into microelectronics	*Riccardo Callegari*
Seminar Room 11, St Anne's College	17:00 - 17:15
Silicon-based micro oscillating heat pipes for HEP and space applications	***Timothee Frei***
Seminar Room 11, St Anne's College	**17:15 - 17:30**
Silicon microchannel cooling frames for stave configurations	*Massimo Angeletti*
Seminar Room 11, St Anne's College	17:30 - 17:45

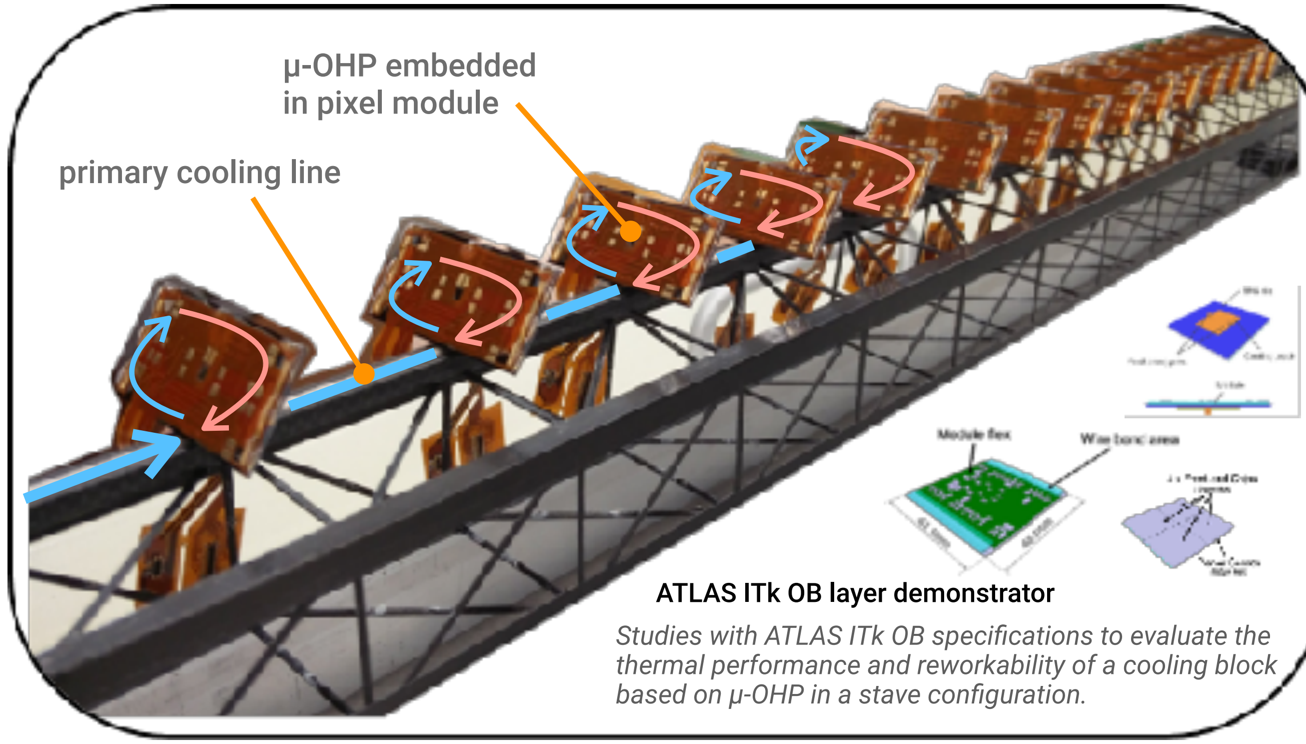
PhD candidate: *Timothée Frei*

Getting rid of the connectors

- Miniaturised closed loop device operated in stand-alone mode.
- Self-contained and self-actuated.
- Eliminate connectors
- MEMS Heat Pipes Review (EDMS Doc No 1852809).







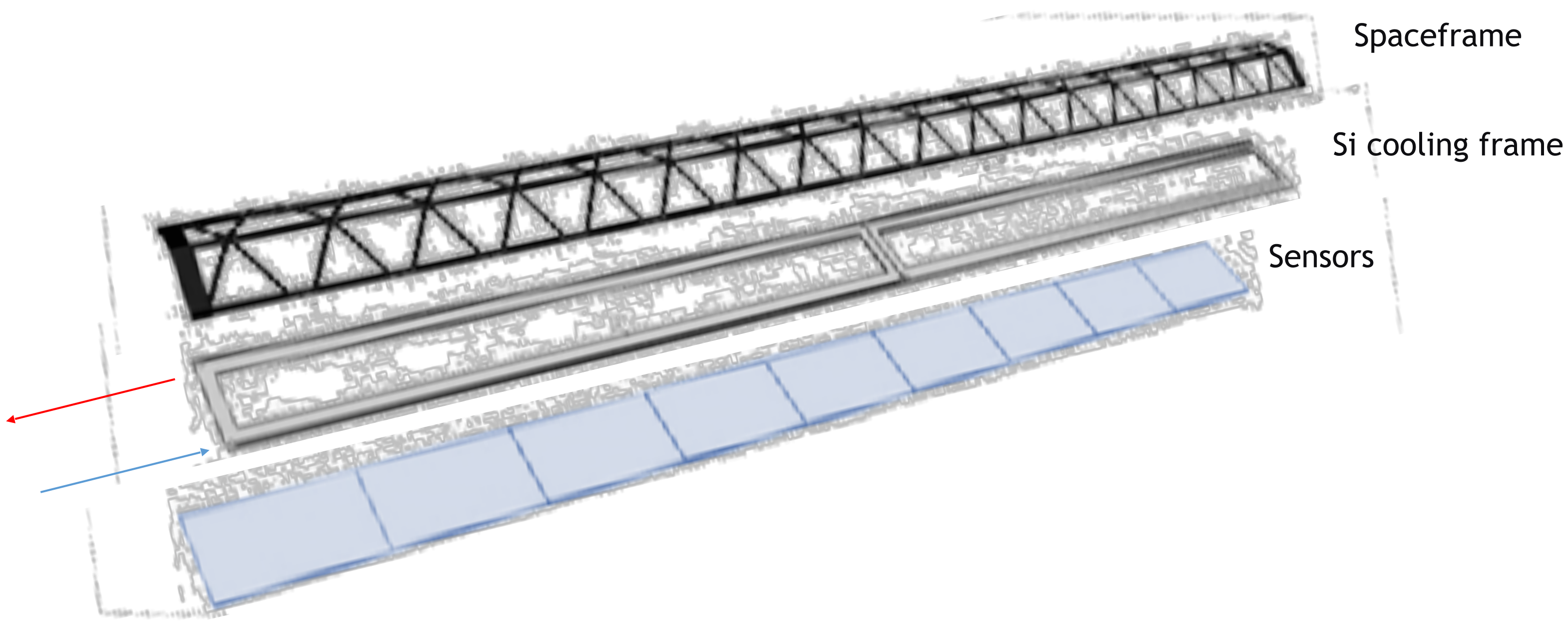
ATLAS ITk OB layer demonstrator

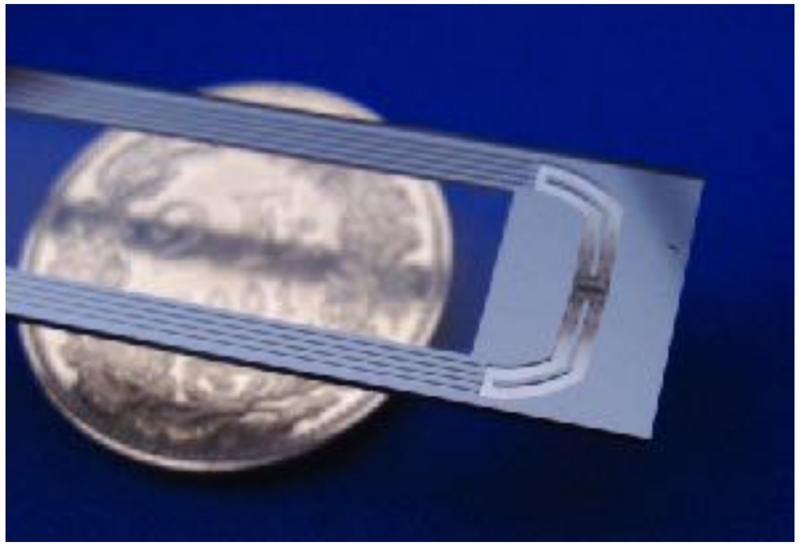
Studies with ATLAS ITk OB specifications to evaluate the thermal performance and reworkability of a cooling block based on μ-OHP in a stave configuration.

Embedding microfluidics into microelectronics	*Riccardo Callegari*
Seminar Room 11, St Anne's College	17:00 - 17:15
Silicon-based micro oscillating heat pipes for HEP and space applications	*Timothee Frei*
Seminar Room 11, St Anne's College	17:15 - 17:30
Silicon microchannel cooling frames for stave configurations	*Massimo Angeletti*
Seminar Room 11, St Anne's College	17:30 - 17:45

PhD candidate: *Massimo Angeletti*

Getting rid of the plate





conclusions and outlook

- 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 at CERN are aiming at:
  - eliminating connectors with **stand-alone microfluidic circuits** such as heat pipes;
  - **embedding the microchannels into monolithic** pixel detectors with **CMOS-compatible microfabrication** processes;
  - **reducing the material budget with frames** instead of cooling plates;
  - developing **interconnection solutions to cover larger areas** such as staves.

100 µm