Microfabricated silicon substrates for pixel detectors assembly and thermal management

aka Silicon Microchannel Cooling Plates

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CERN | EP-DT
Detector Technologies

VCI
VIENNA CONFERENCE ON INSTRUMENTATION
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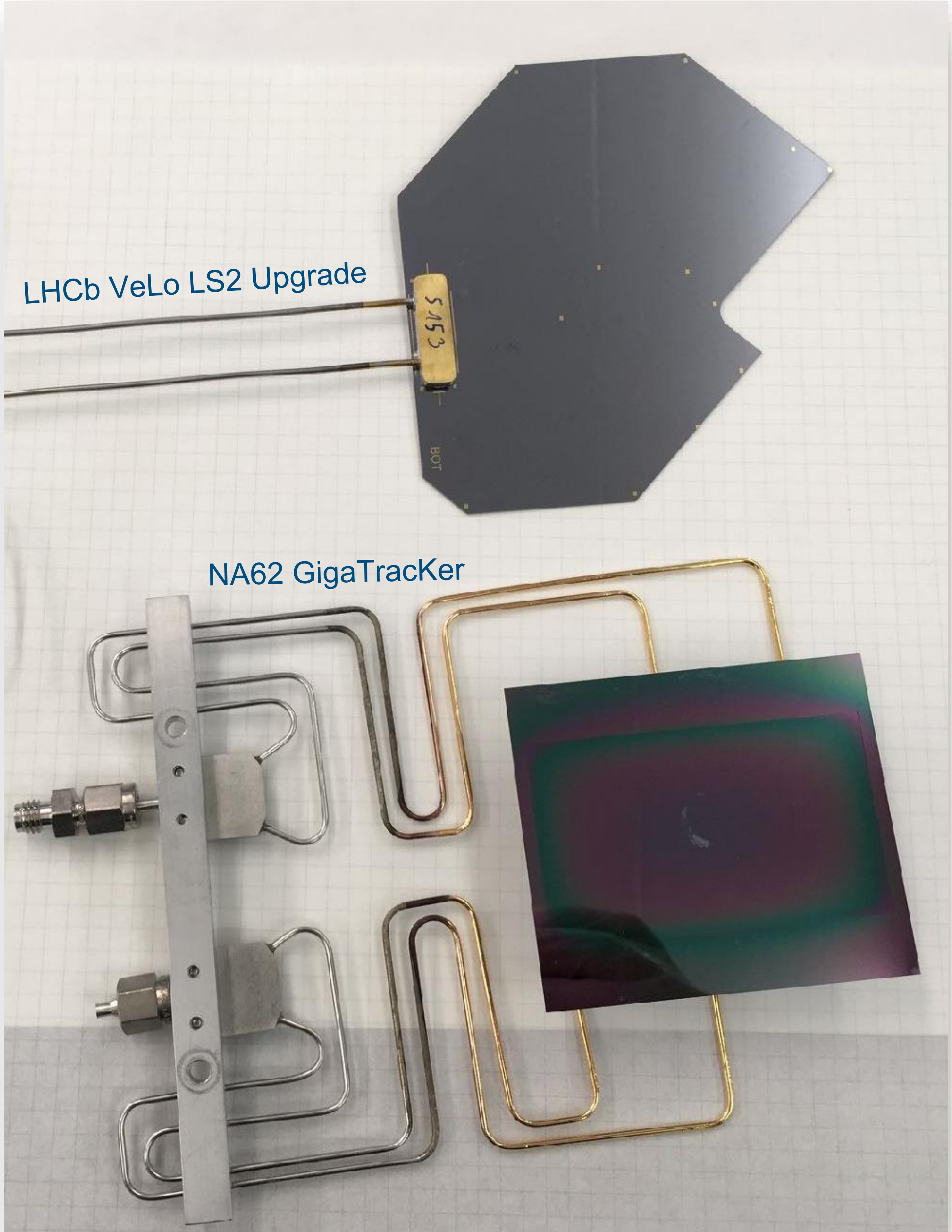
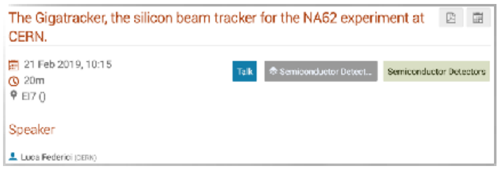
100 µm

Silicon Microchannel Cooling Plates



- NA62 GTK
- LHCb Velo LS2 Upgrade
- design, prototyping and characterisation
- microfabrication and QA/QC
- assembly of the modules
- further developments based on microfabrication

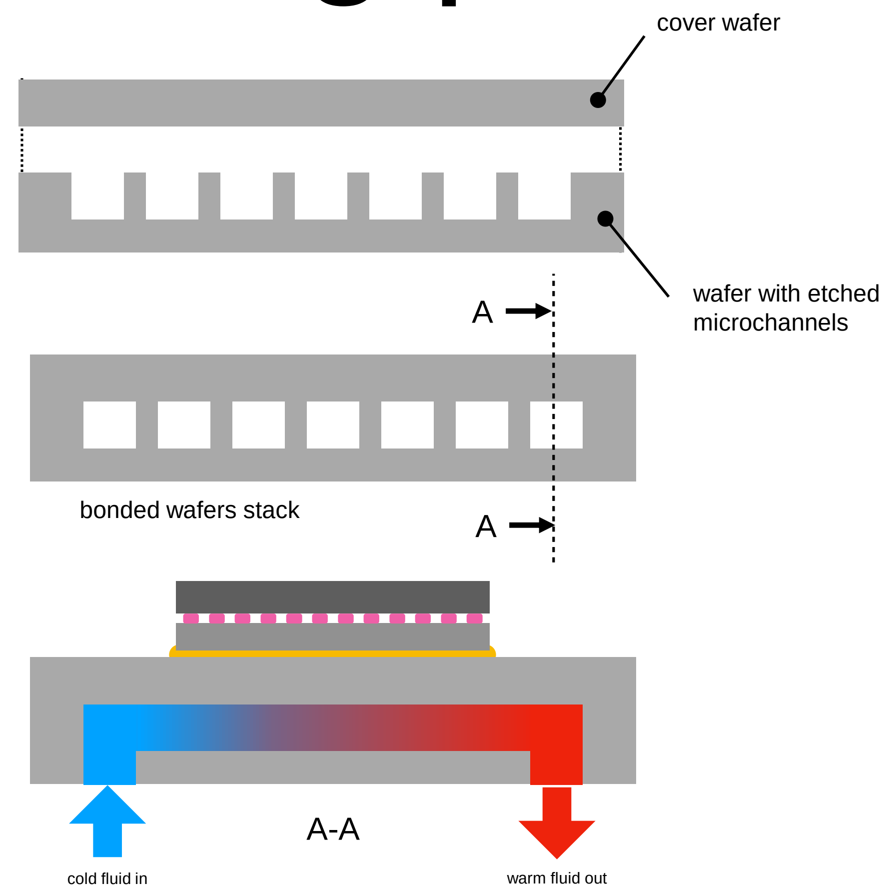
This talk will not cover the presentation of the LHCb and NA62 experiments nor the operation of the Velo and GTK detectors.

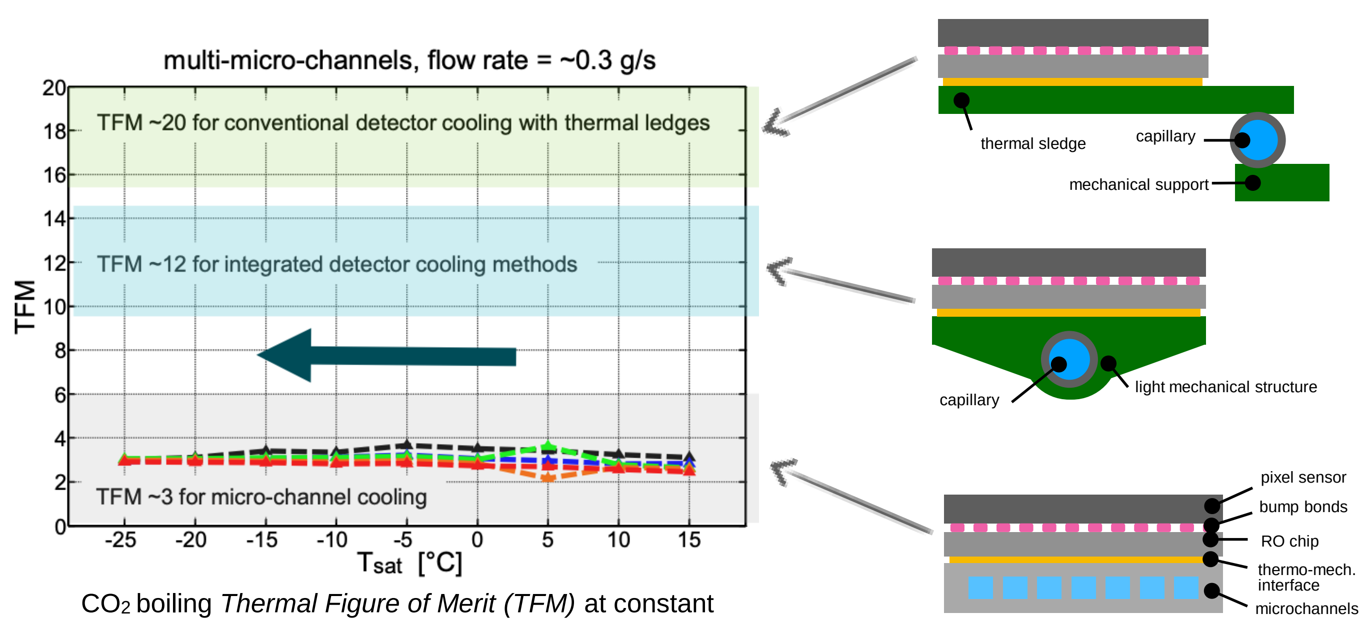


silicon microchannel cooling plates

- 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

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

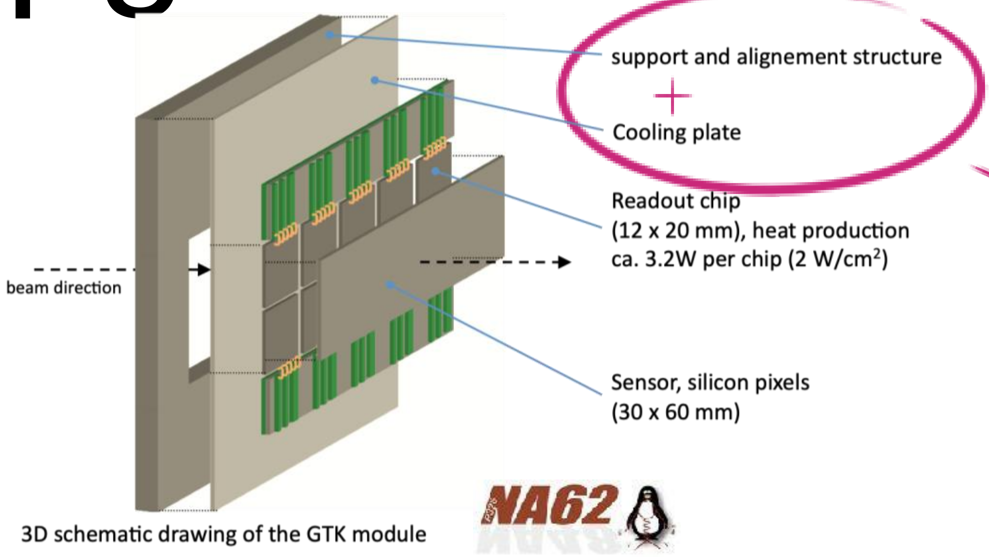




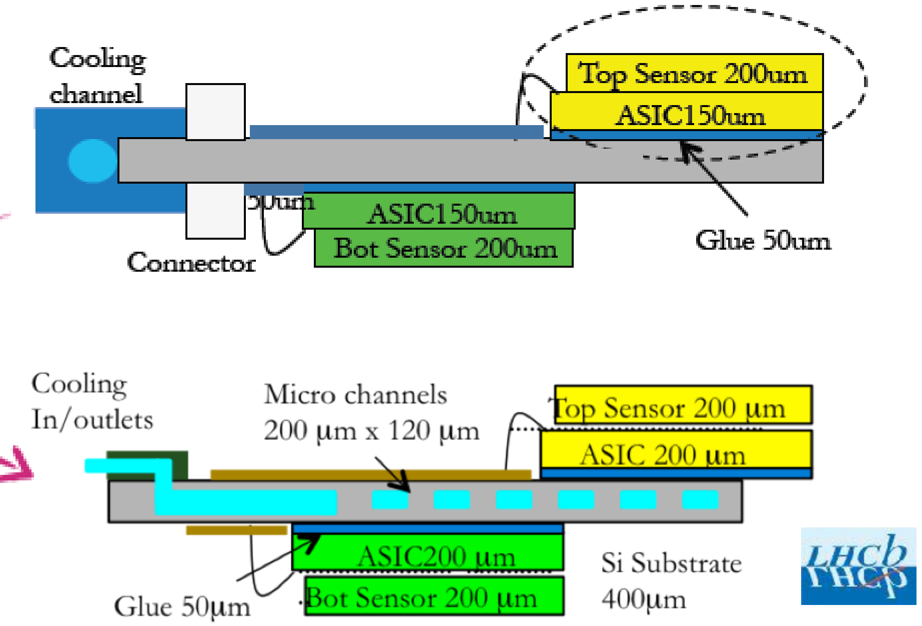
CO_2 boiling *Thermal Figure of Merit (TFM)* at constant flow rate 0.3 g/s and various Tsat

Désirée Hellenschmidt, Poster 78, VCI2019

NA62 GTK and LHCb VELO Upgrade

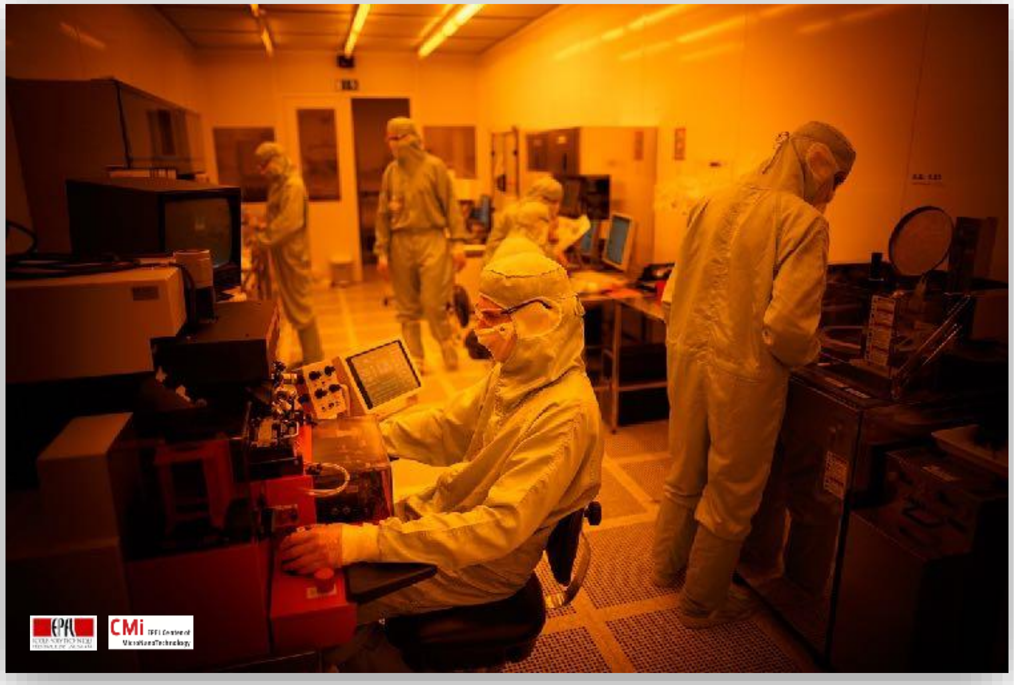


Silicon microchannel cooling plate

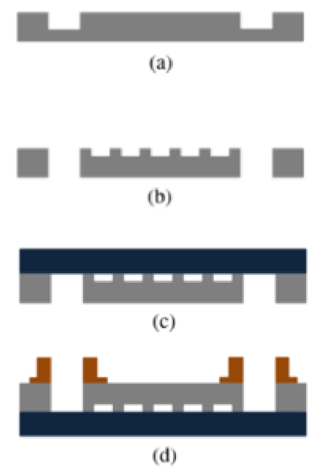


	NA62	LHCb
# of modules	3	52 (2x 26)
distance between modules	~10 m	2.5 cm
sensors	hybrid pixel	hybrid pixel
sensor size	60 x 38 mm	43 x 15 mm
sensors/module	1	4 (2 on each side of plate)
power dissipation (average)	~2 W/cm^2	~2 W/cm^2
coolant	liquid C_6F_{14}	evap. CO_2
cooling plate thickness	~200 µm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

"in-house" microfabrication processes



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



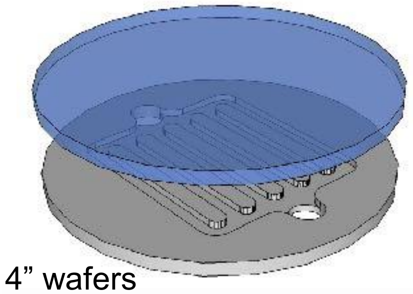
pre-etching of through holes

etching of through holes & microchannels

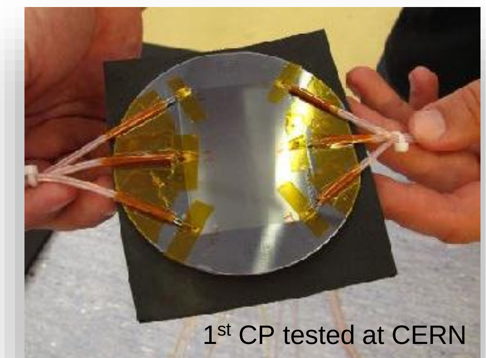
anodic bonding of glass cover

glueing of PEEK connectors

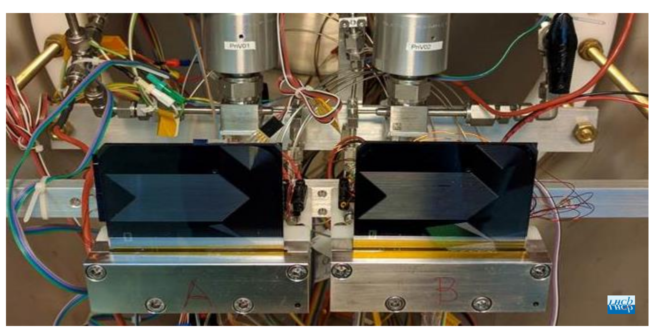
A. Mapelli et al. / Nuclear Physics B (Proc. Suppl.) 215 (2011) 349–352

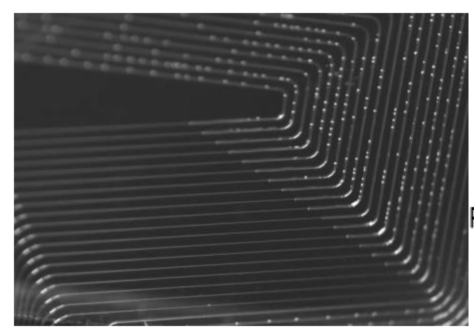


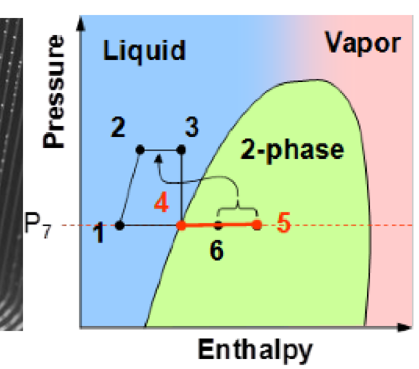
4" wafers



1st CP tested at CERN



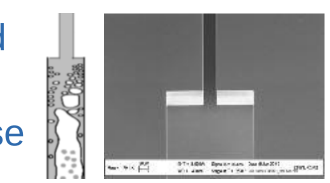


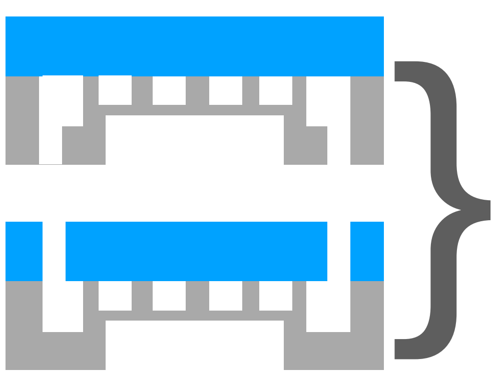


First demonstration of 2-phase CO_2 circulation in silicon microchannels.

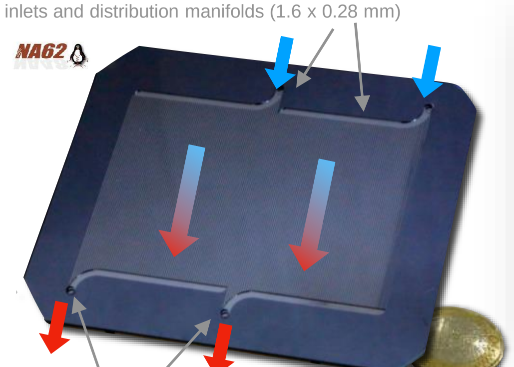
Liquid

2-phase



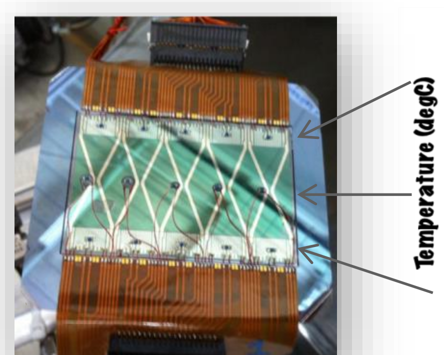


inlets and distribution manifolds (1.6 x 0.28 mm)

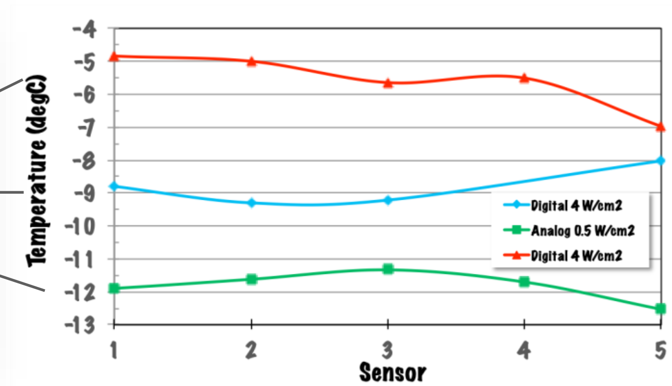


outlets

2 independent networks of 75 µchannels



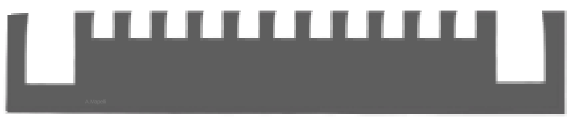
CP equipped with thermo-mechanical mockup of the hybrid detector



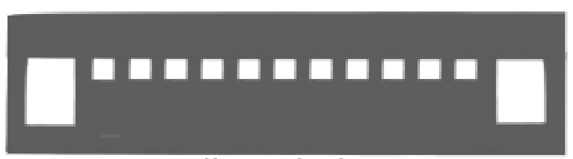
- Power dissipation
  - Digital Power 38 W
  - Analog Power 10 W
- Liquid C_6F_{14}
  - 7g/s
  - -19°C at inlet

microfabrication of the GTK cooling plates

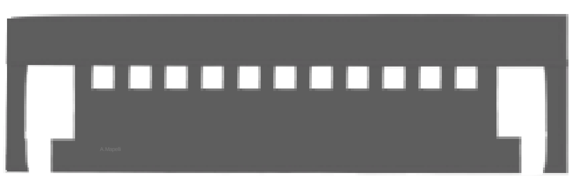
8” Si wafer



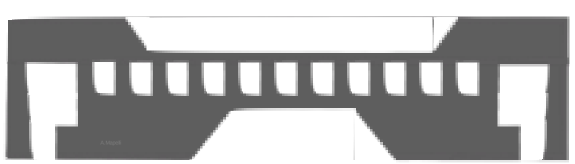
etching of channels & manifolds



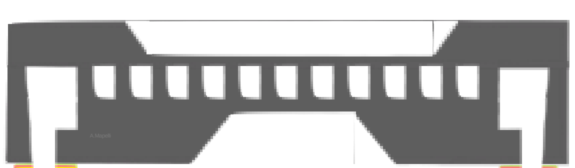
Bonding of Si cover



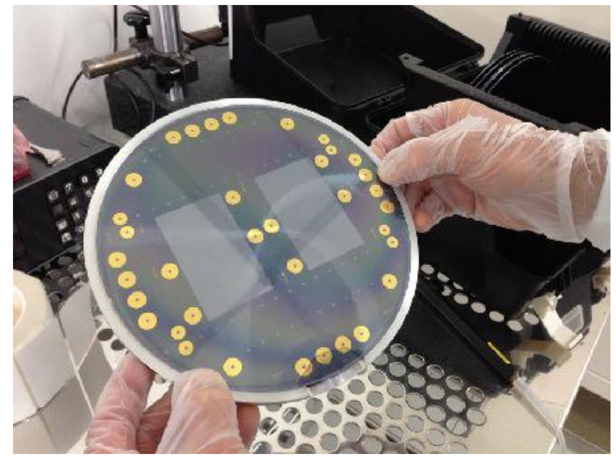
etching of fluidic inlets

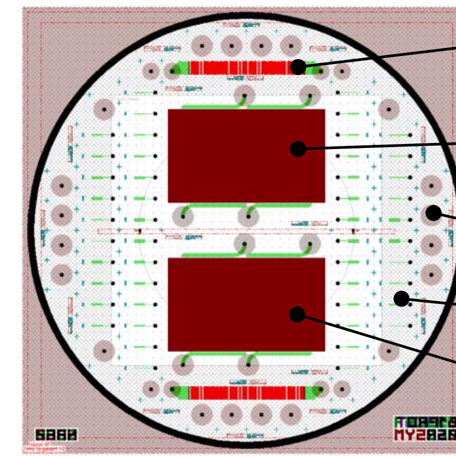


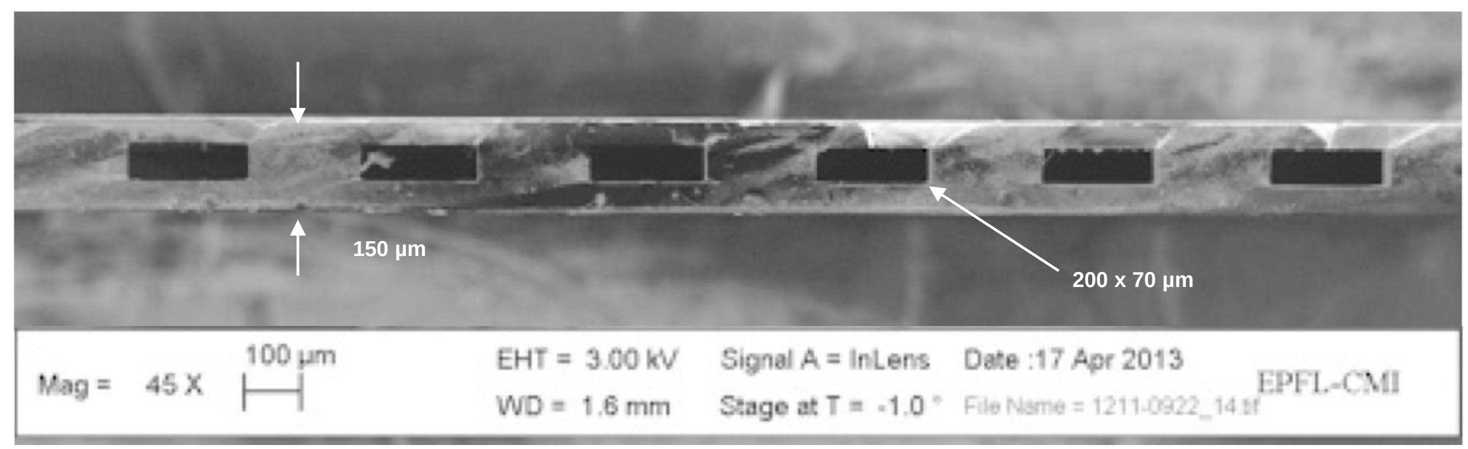
Thinning of acceptance



Metallization around Inlets





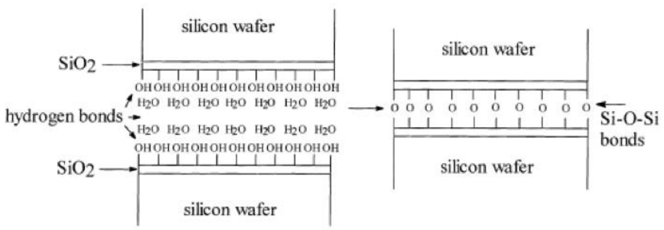


- Collaborative effort between CERN (ALICE, LHCb, NA62 and EP-DT) and external partners (CSEM, EPFL).
- Design by CERN EP-DT
- Prototypes fabricated by CERN EP-DT at EPFL-CMi on 4” wafers
- Pre-production series by IceMOS on 6” wafers
- Three batches fabricated at CEA-Leti on 8” wafers
- Fourth batch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

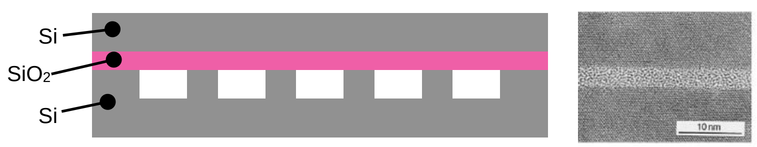
Silicon direct wafer bonding

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

Hydrophilic bonding



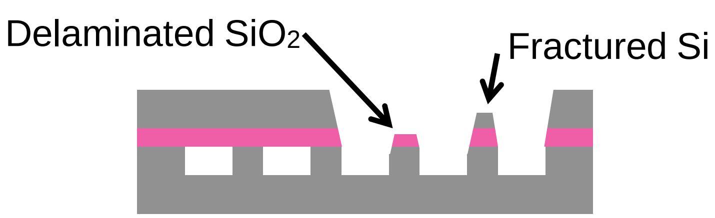
A. Plößl, G. Kräuter/Materials Science and Engineering R25 (1999) 1-88

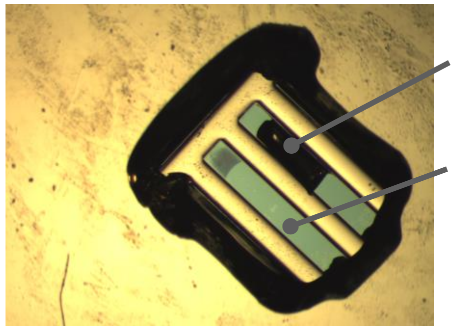


T_{anneal} = 1050ºC

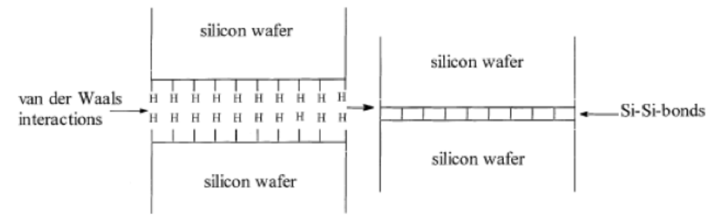
P_{max} ~400 bars

delamination + rupture





Hydrophobic bonding



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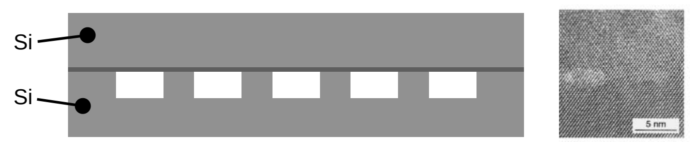
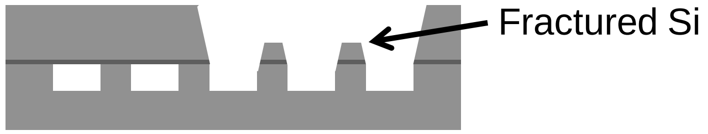
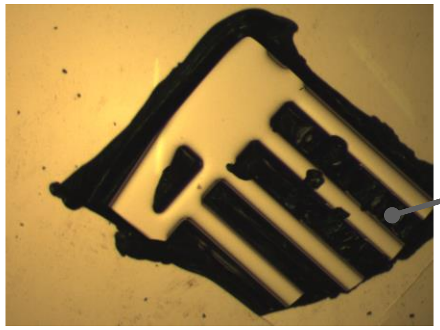


T_{anneal} = 1050ºC

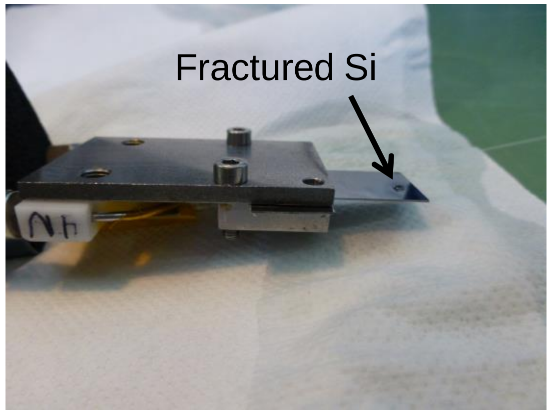
P_{max} ~700 bars

rupture without delamination

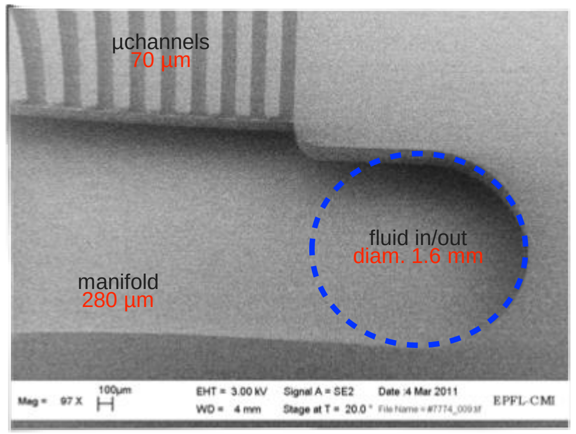




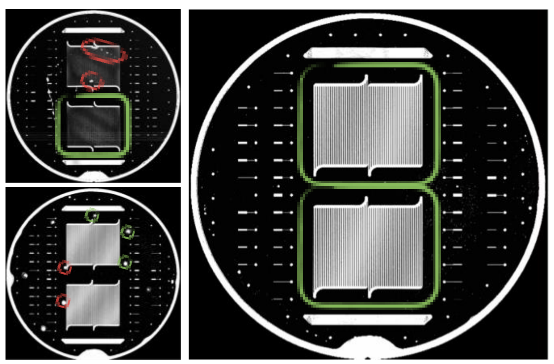
Scanning Acoustic Microscope image of bonded wafers with test structures.



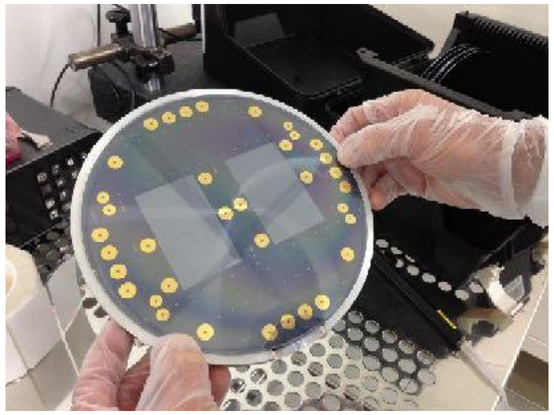
QA/QC of the cooling plates



SEM of microchannels

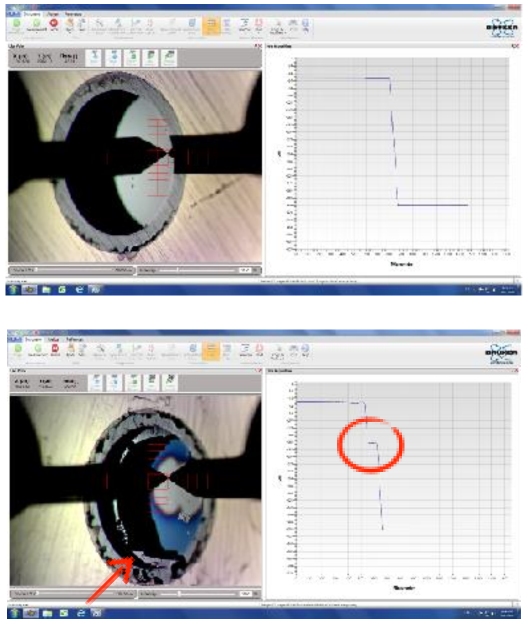


SAM of bonded interface

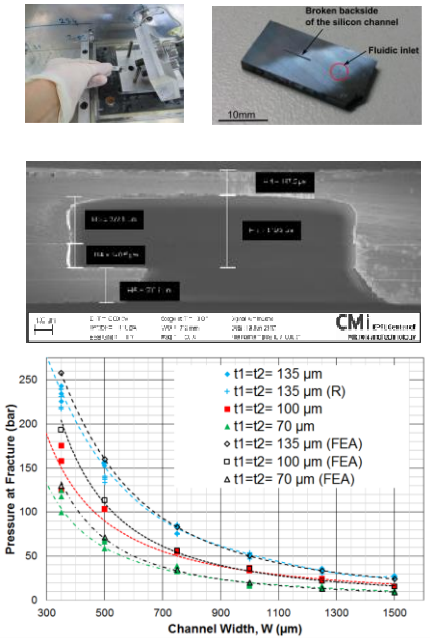


Visual inspection

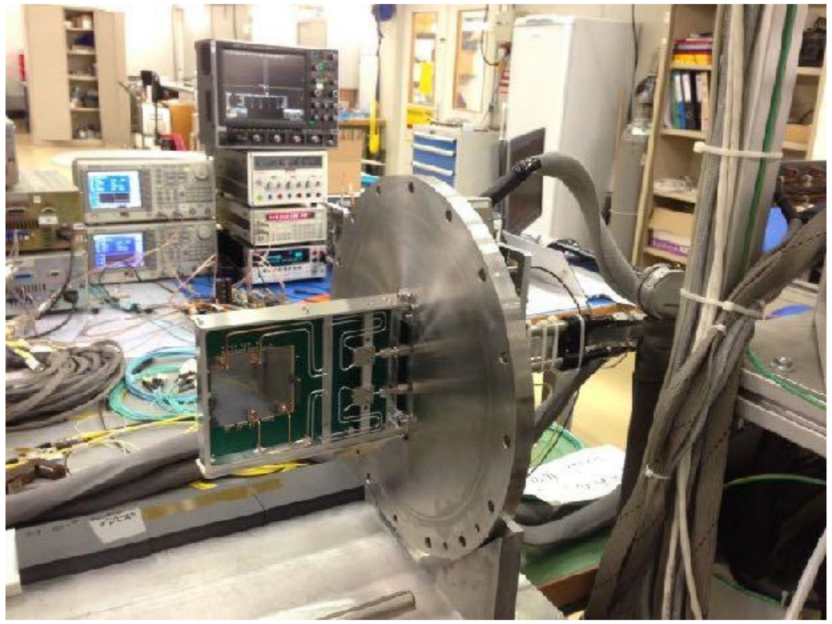
- Etching profiles of the microchannels.
- Scanning Acoustic Microscopy of bonded wafers.
- Visual inspection during tape-out.
- Metrology of cooling plates (Inlets and pools).
- Pressure tests on dedicated samples
  - 1500 µm wide cavities (manifolds) > 25 bars
  - 200 µm wide cavities (microchannels)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



Metrology of fluidic inlet/outlet

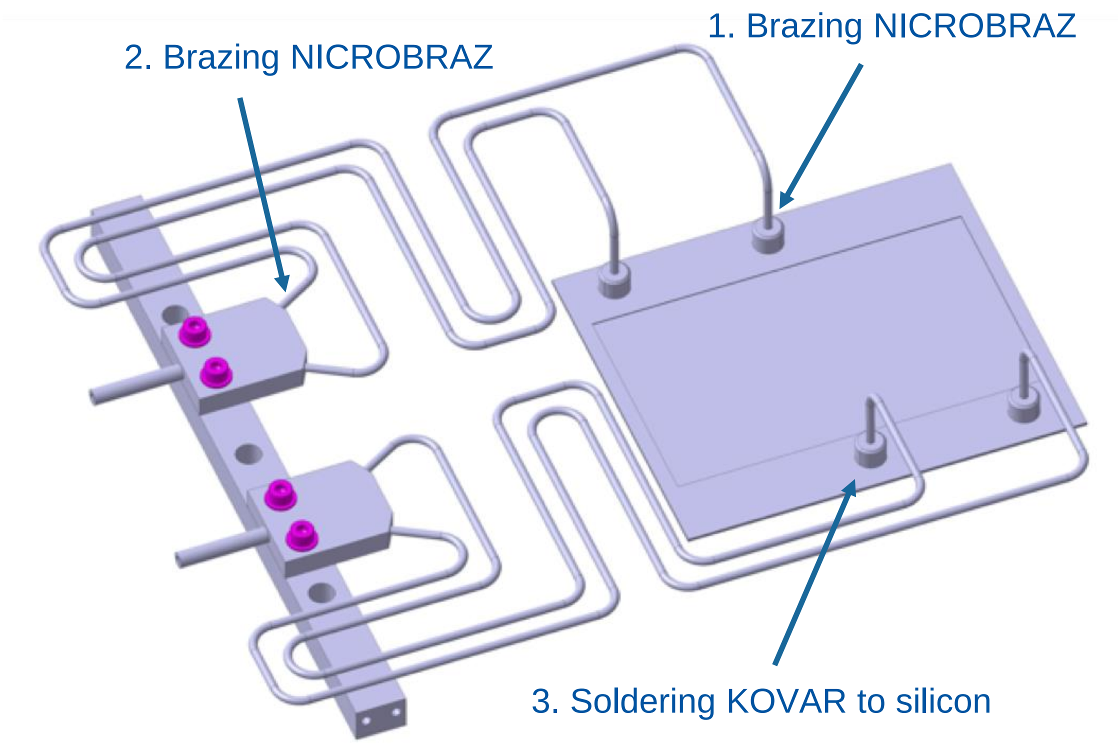


Pressure testing of silicon microchannels



Cooling test setup at CERN

Microfluidic system integration

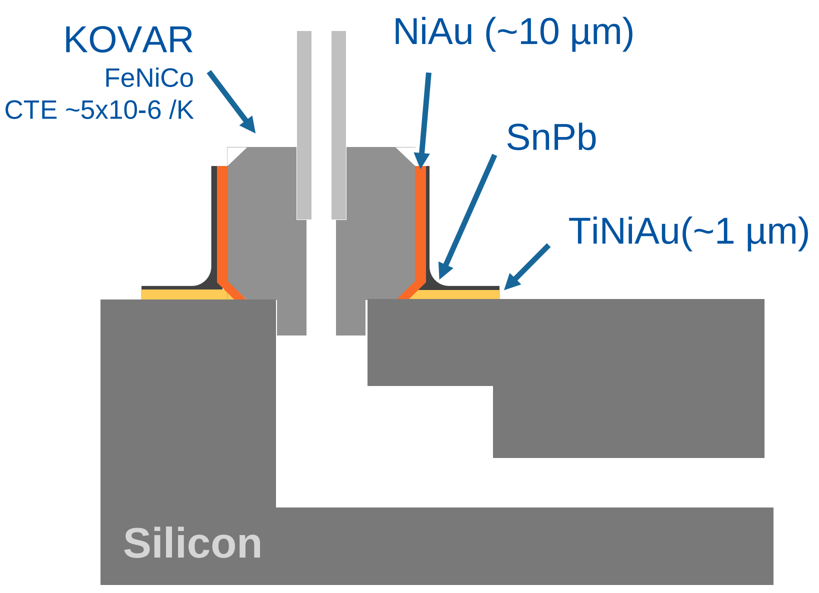


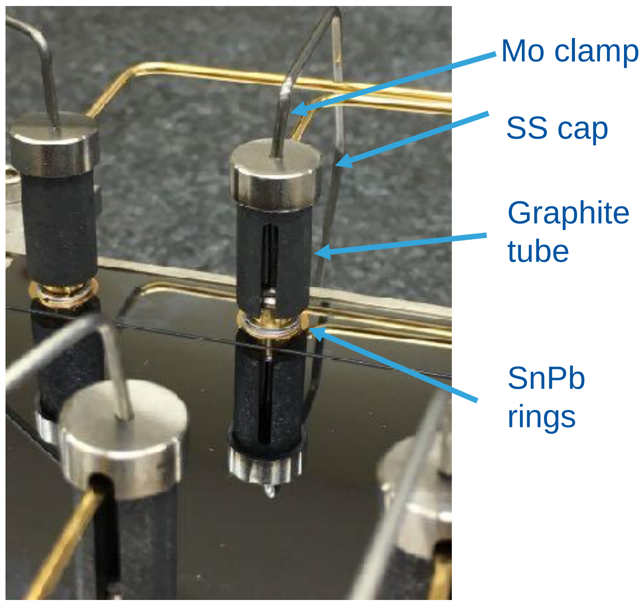
Assembly steps:

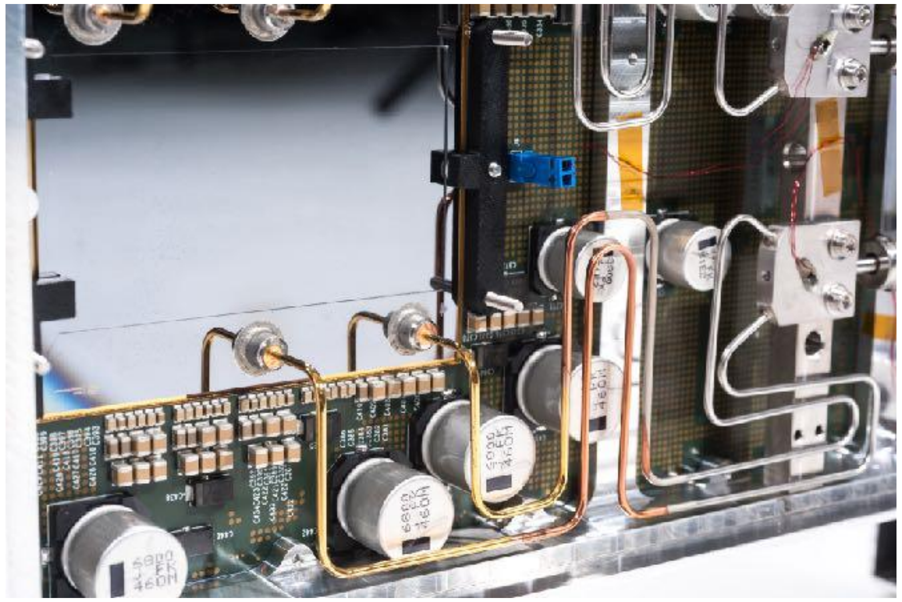
- Machining of KOVAR connectors;
- Brazing of connectors to capillaries (1);
- Bending of the capillaries;
- Brazing the other end of the capillaries to the manifolds (2);
- NiAu plating of the connectors;
- Soldering of the connectors to the silicon cooling plate (3);

QA/QC:

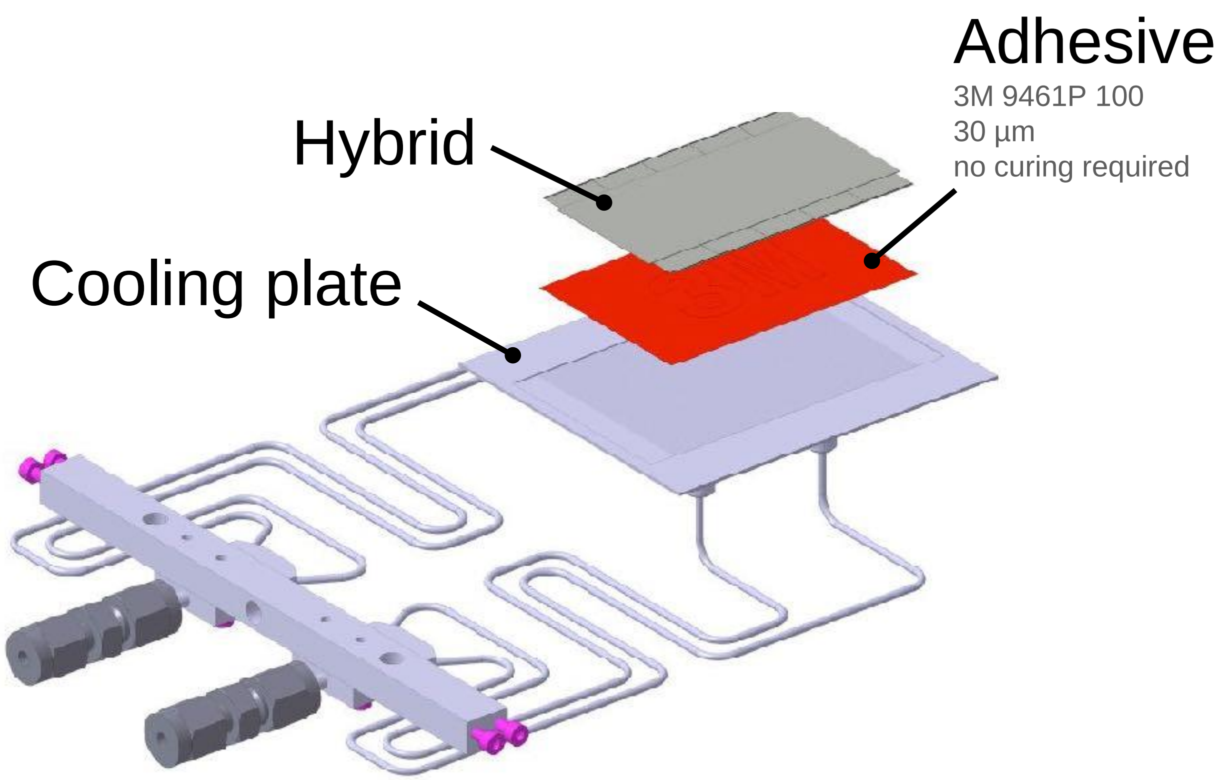
- After each joining step the He leak rate is measured. (Acceptance leak rate: 10_{-10} mbar l_{-1} s_{-1}).
- Pressure testing of the cooling plate at 1.43 x P_{op}

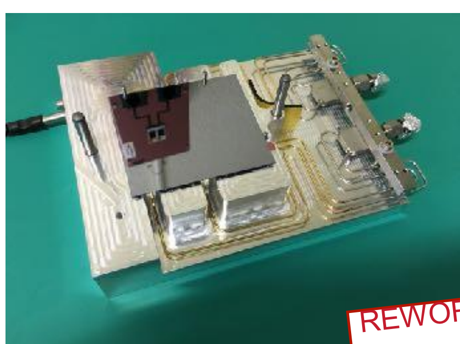




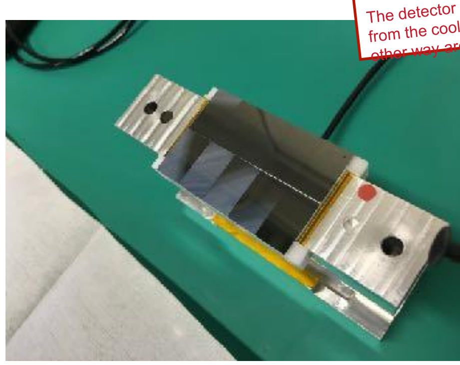


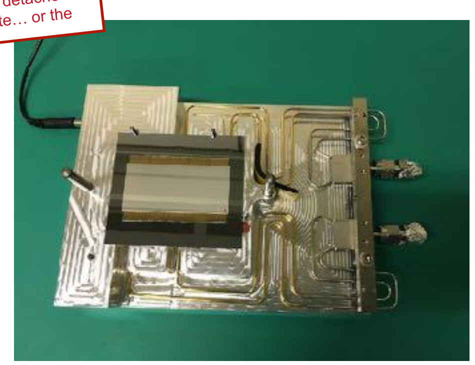
Glueing the hybrid on the cooling plate



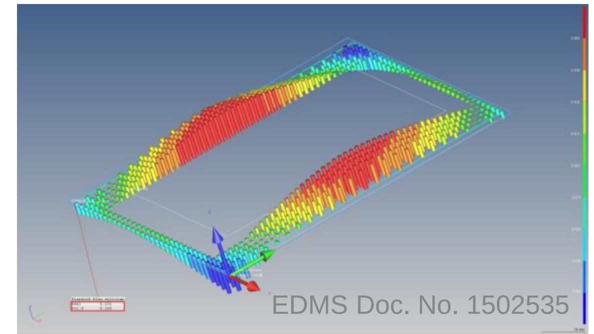


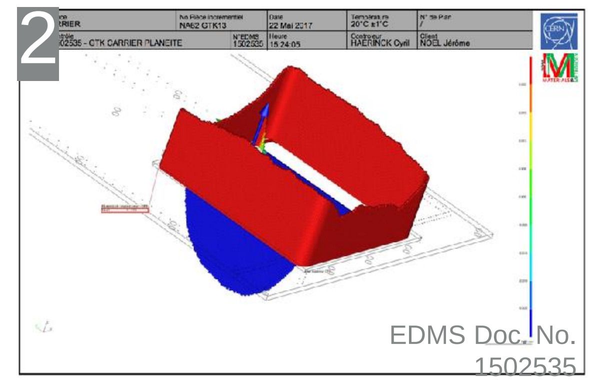
REWORKABILITY
The detector can be detached from the cooling plate… or the other way around.

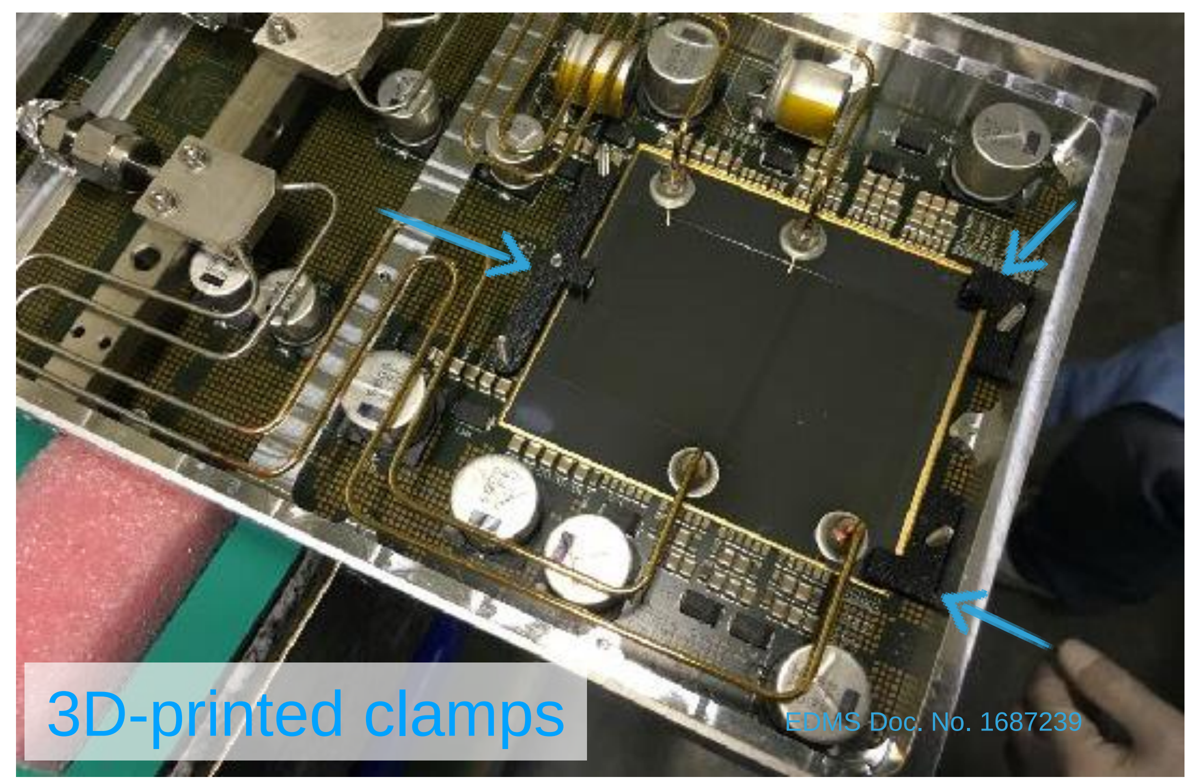




Clamping the cooling plate to the PCB

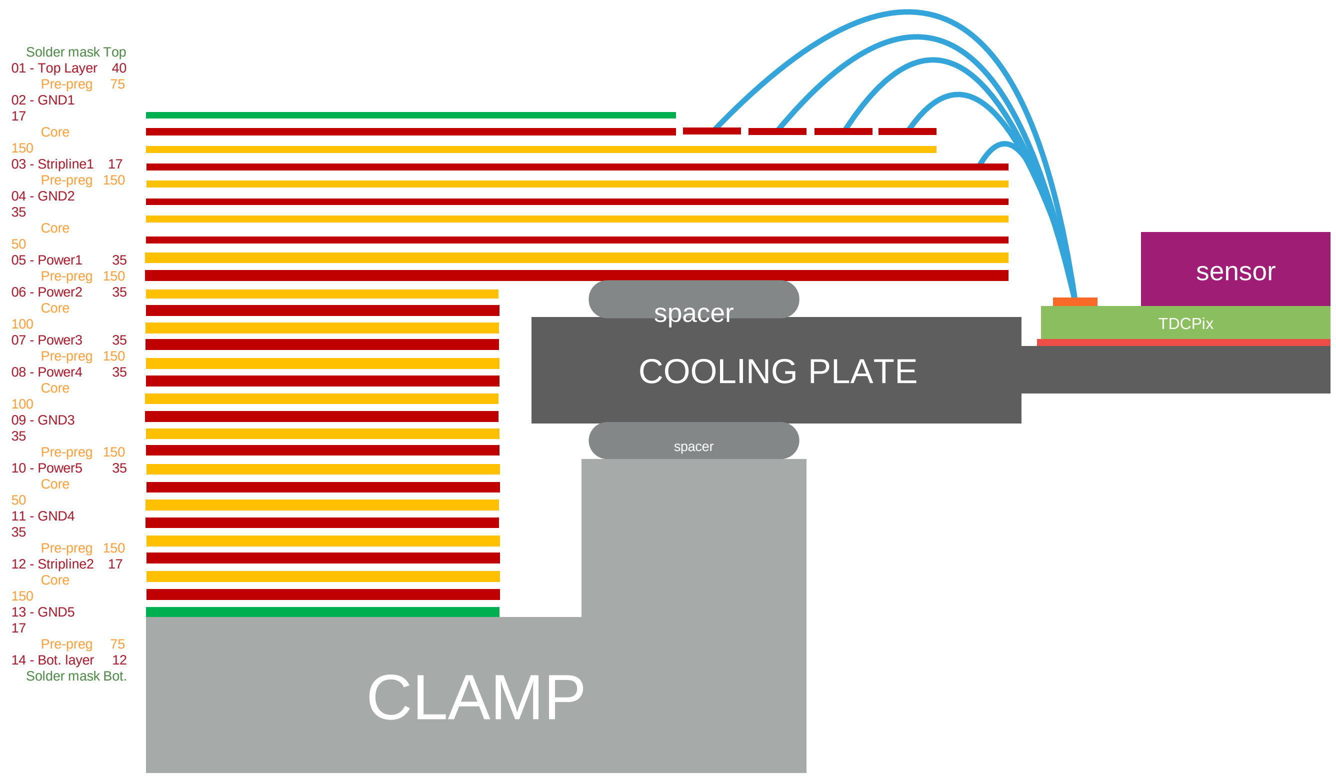


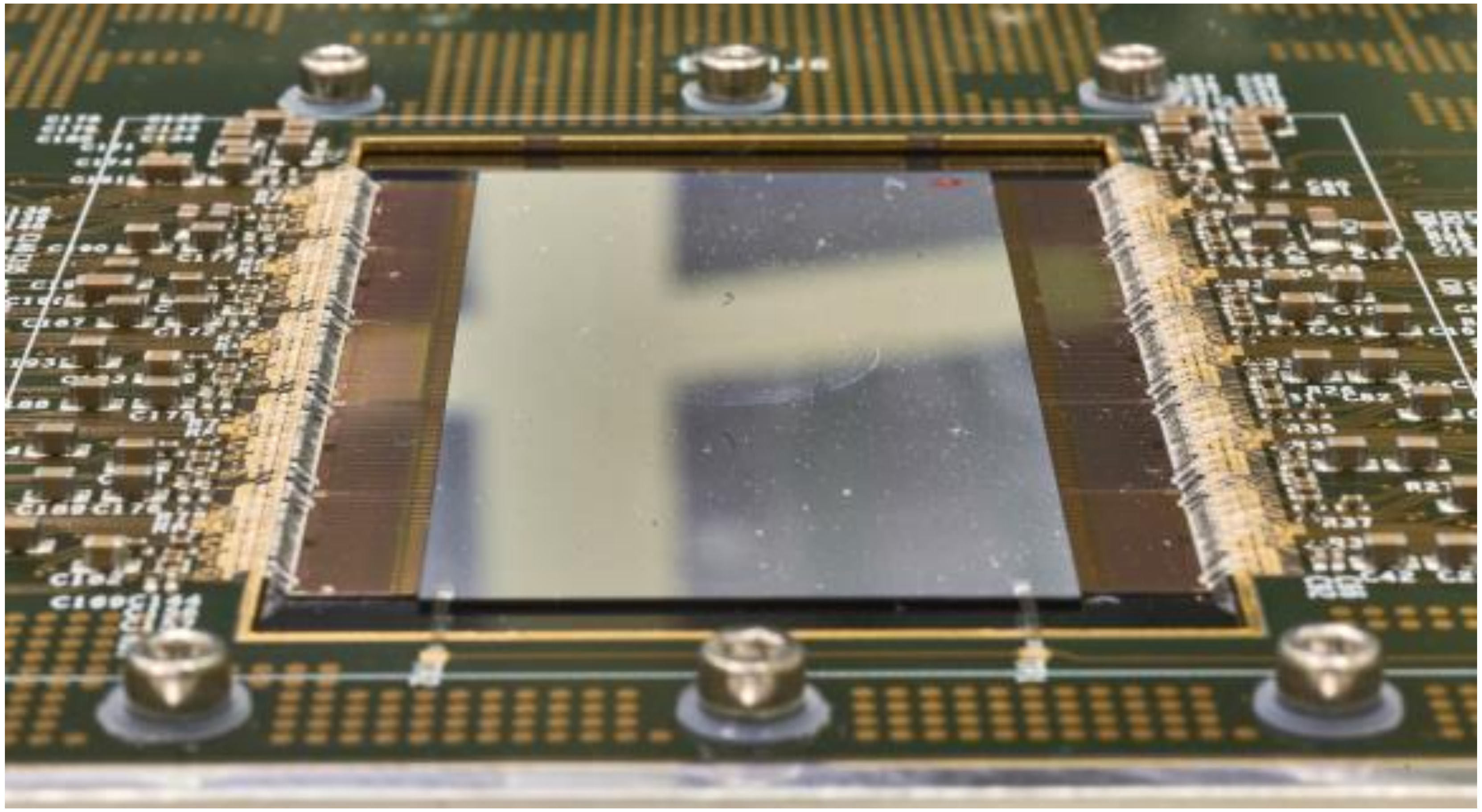


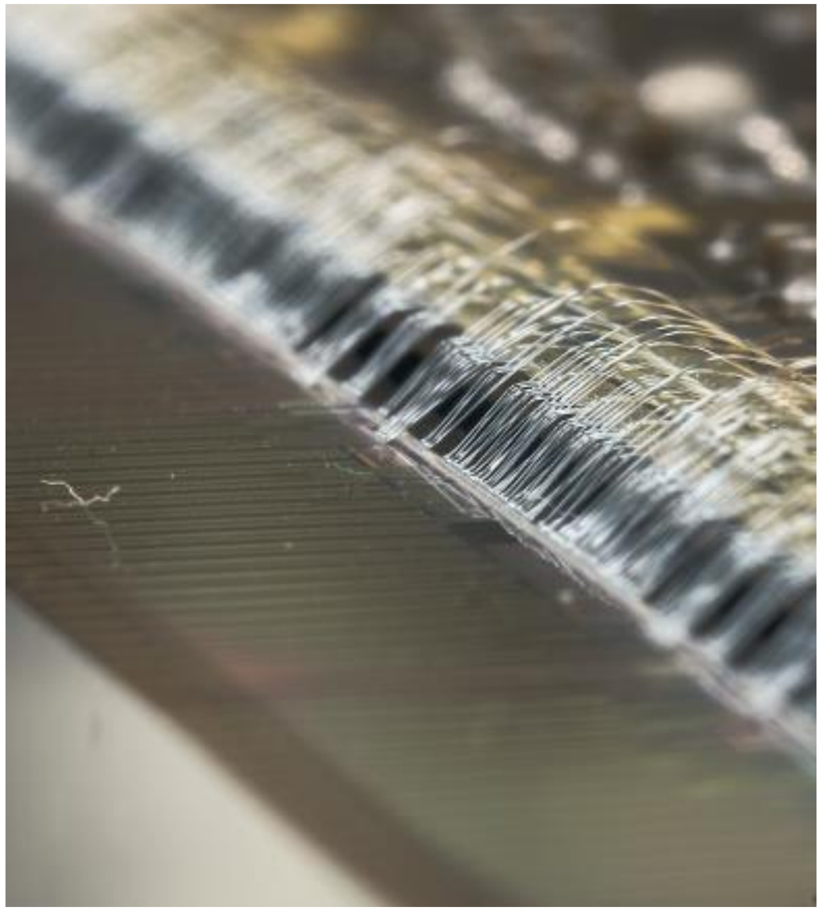


Wire-bonding

- 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.

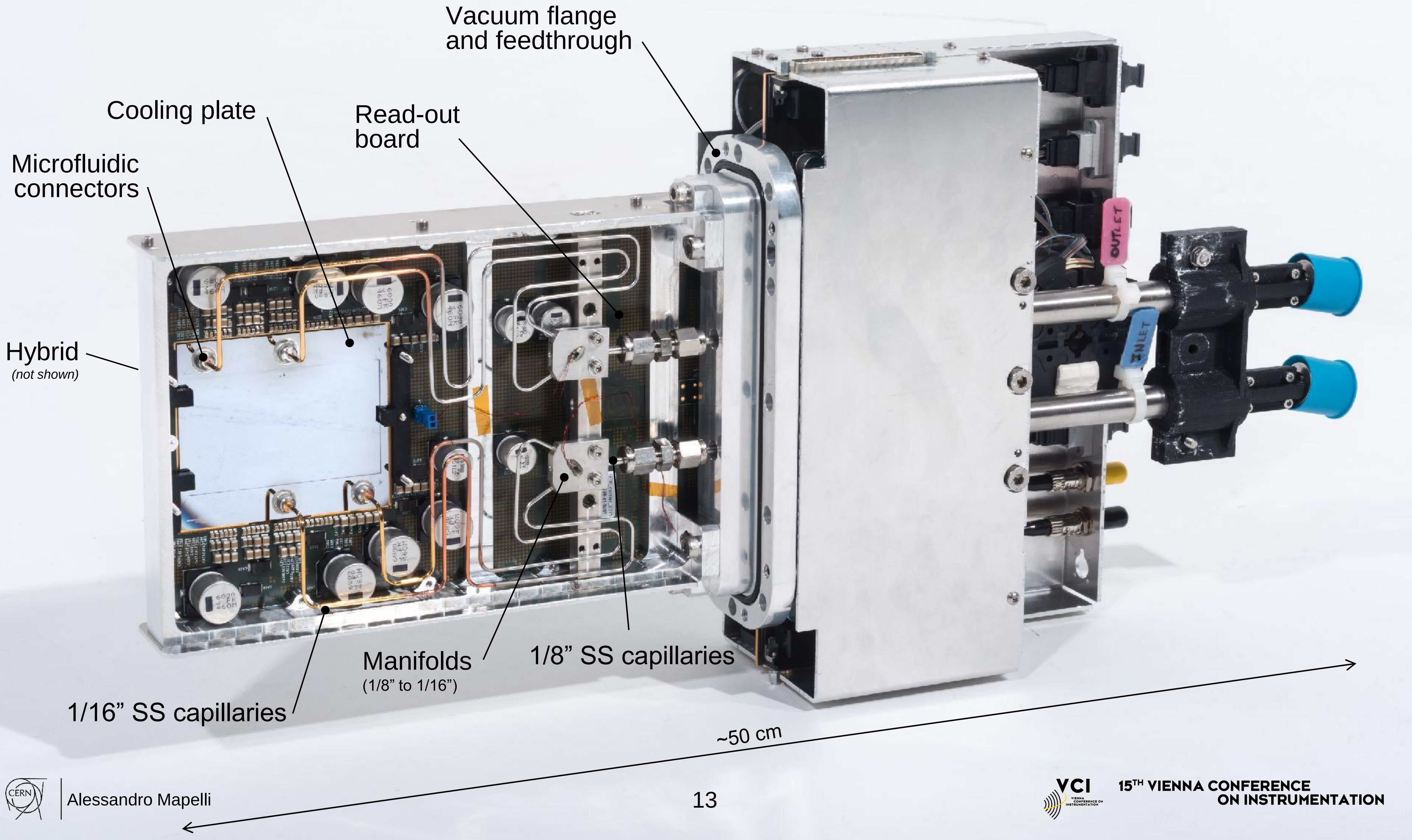


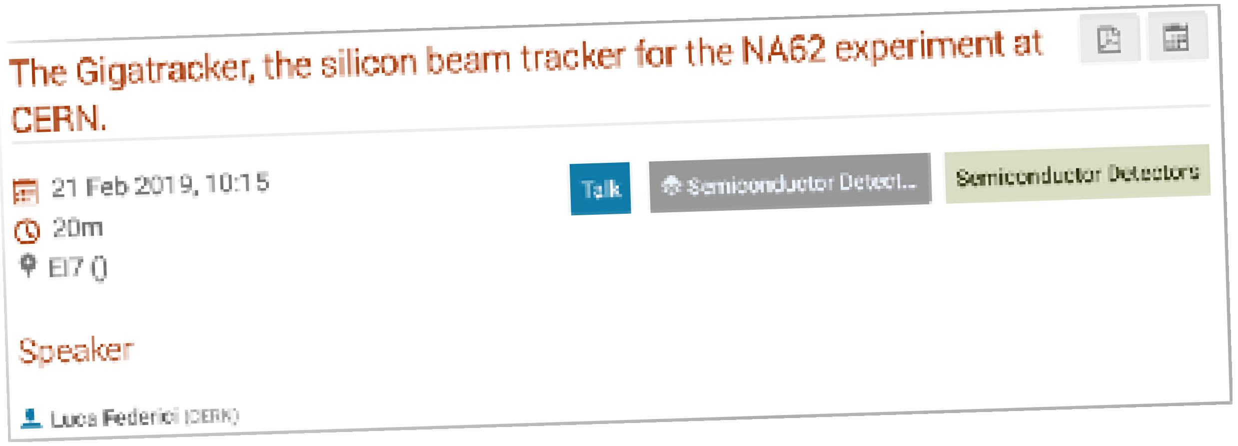





J1

NA62 GigaTracKer




The Gigatracker, the silicon beam tracker for the NA62 experiment at CERN.

21 Feb 2019, 10:15

20m

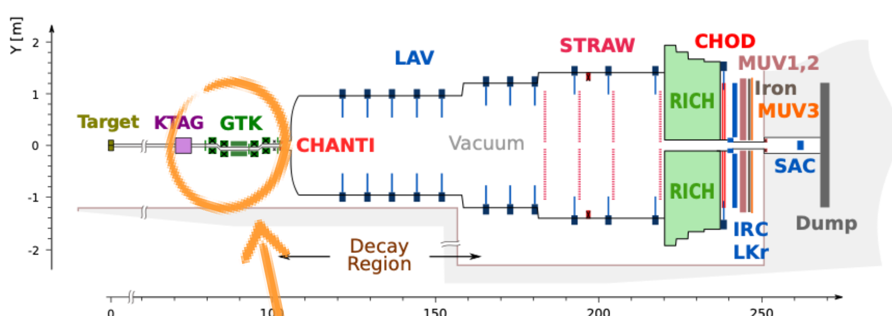
EI7 ()

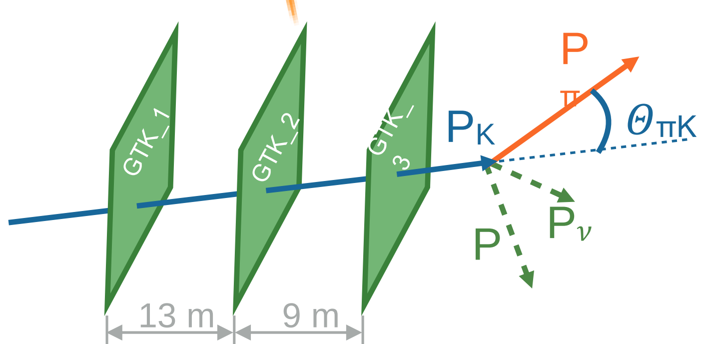
Talk | Semiconductor Detect... | Semiconductor Detectors

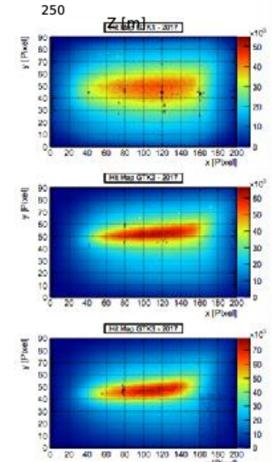
Speaker

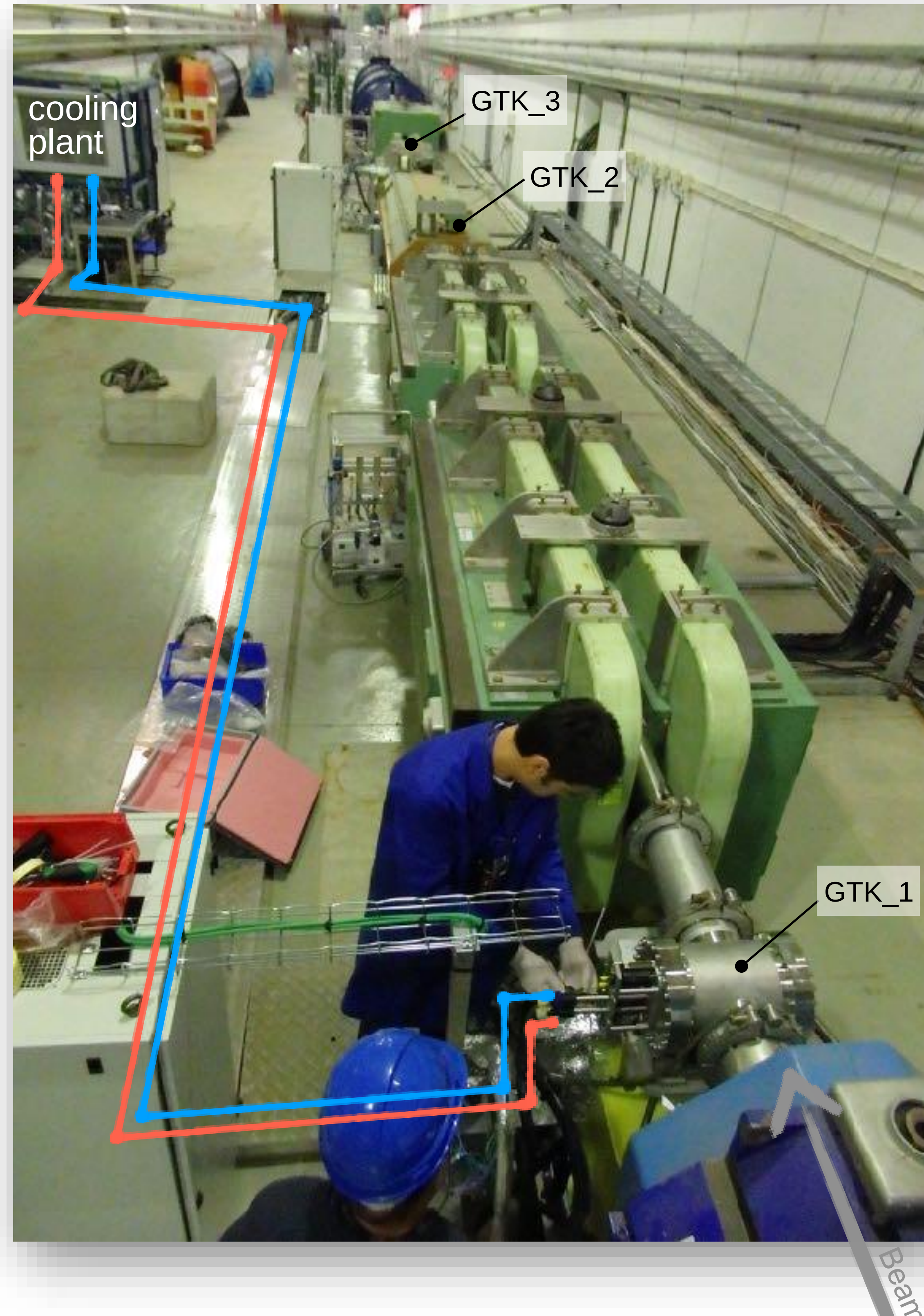
Luca Federici (CERN)

- **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 $4x10^{14}$ neq /cm^2 in one year (200 days) of data taking.
  - In order to minimise radiation-induced damages, the detectors are operated at approximately -15ºC in vacuum (~10^{-6} mbar).
  - Detectors have to be replaced every 100 days.
  - GTK **designed to be replaced rapidly** (<0.5 day intervention).





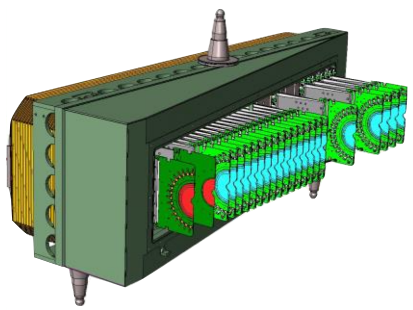




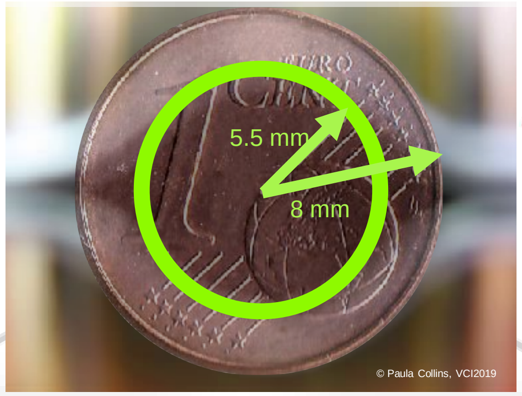
LHCb VELO Upgrade

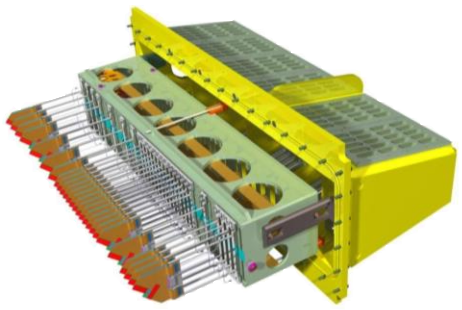
- LHCb will pioneer the use of evaporative CO_2 in silicon microchannels.
- The future upgrade of the LHCb's Vertex Locator (VELO) will combine in 2021 multiple silicon plates with embedded microchannels with an evaporative CO_2 system to cool 52 pixel modules dissipating a total of about 1.5 kW.

	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

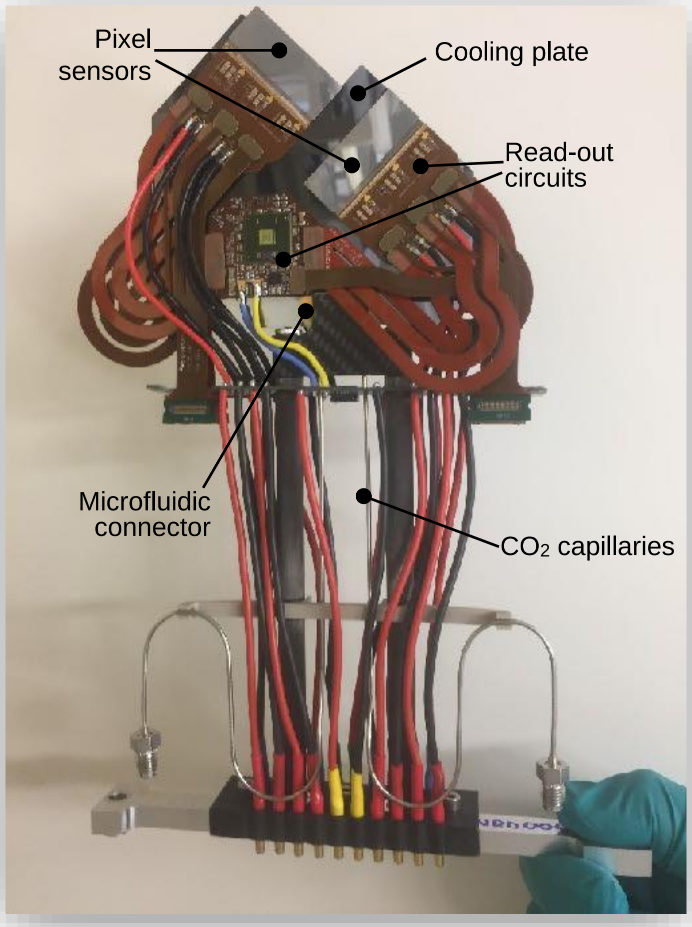


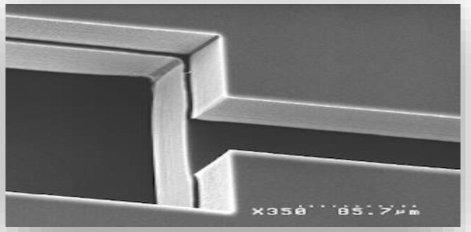
current VeLo module





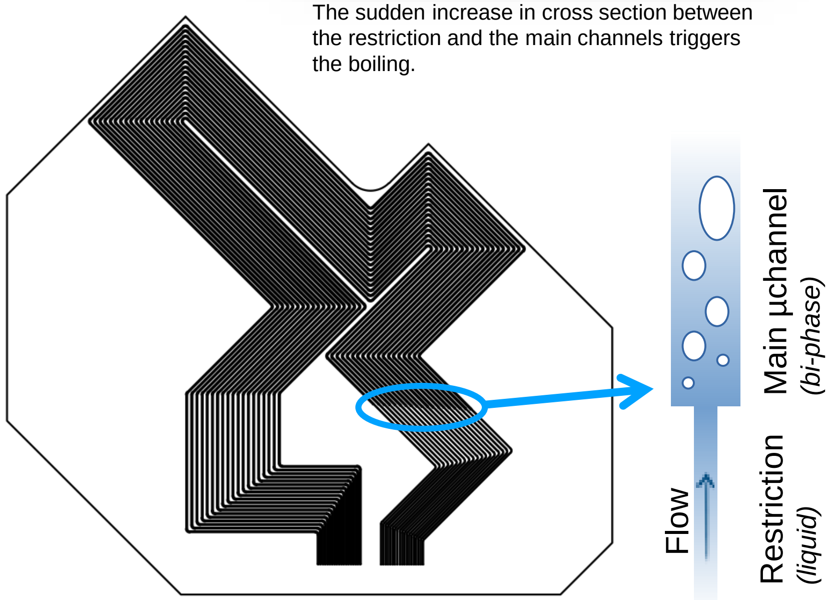
LS2 upgrade module





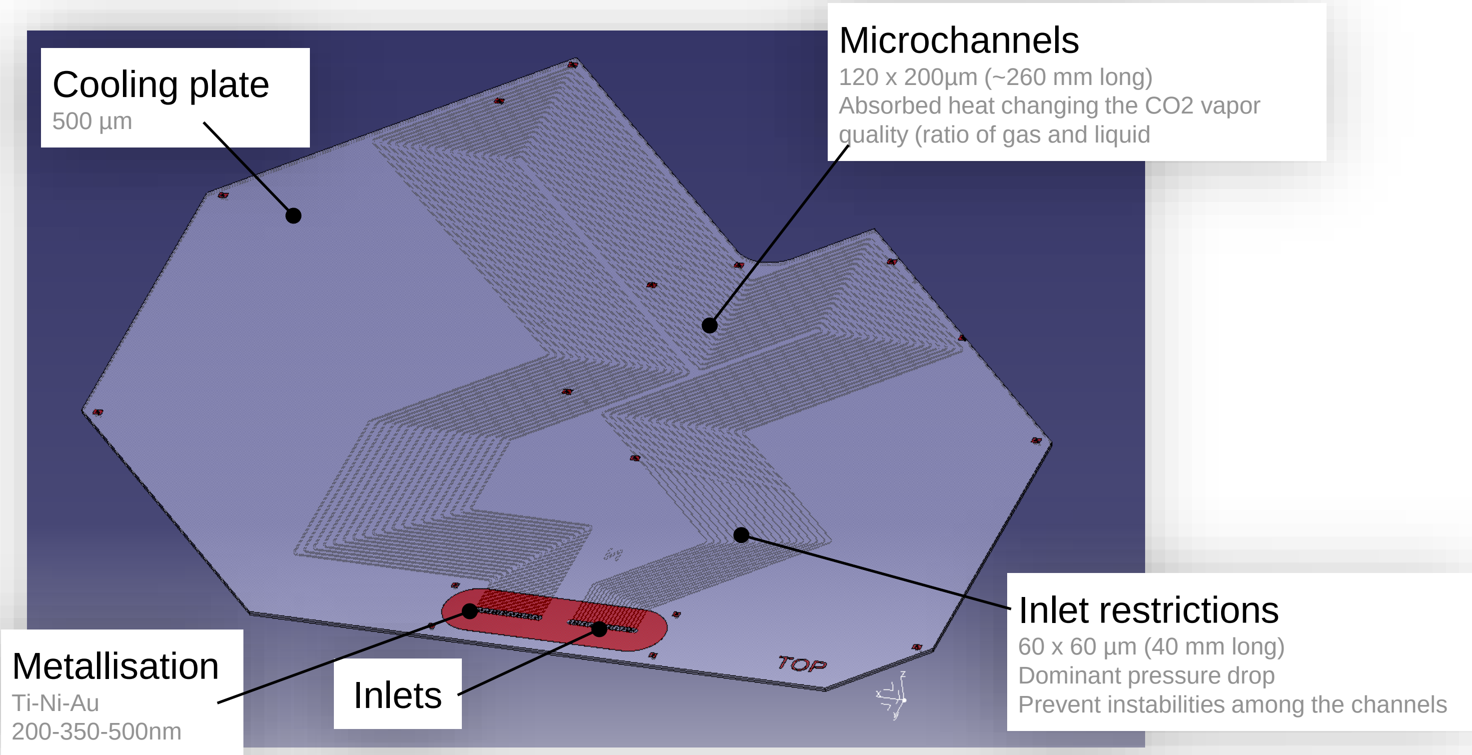
microchannel etched at different depths

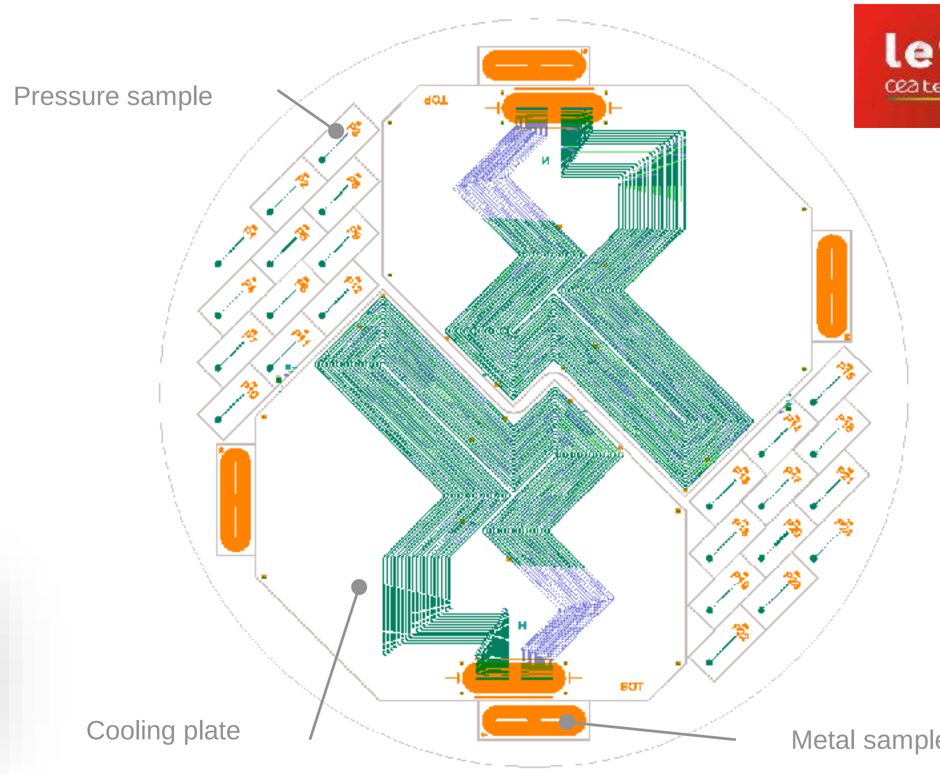
The sudden increase in cross section between the restriction and the main channels triggers the boiling.

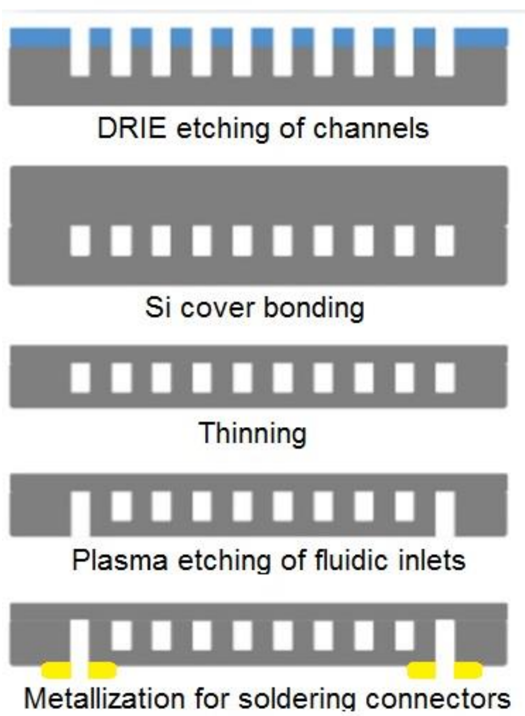


Microchannels designed to bring the coolant under the heat sources.

microfabrication of the VeLo cooling plates

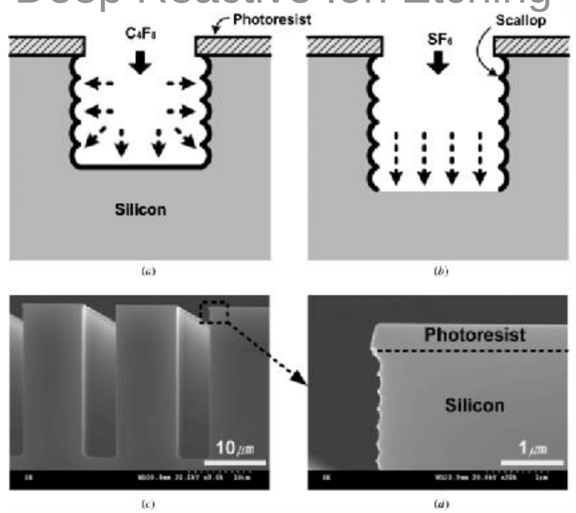




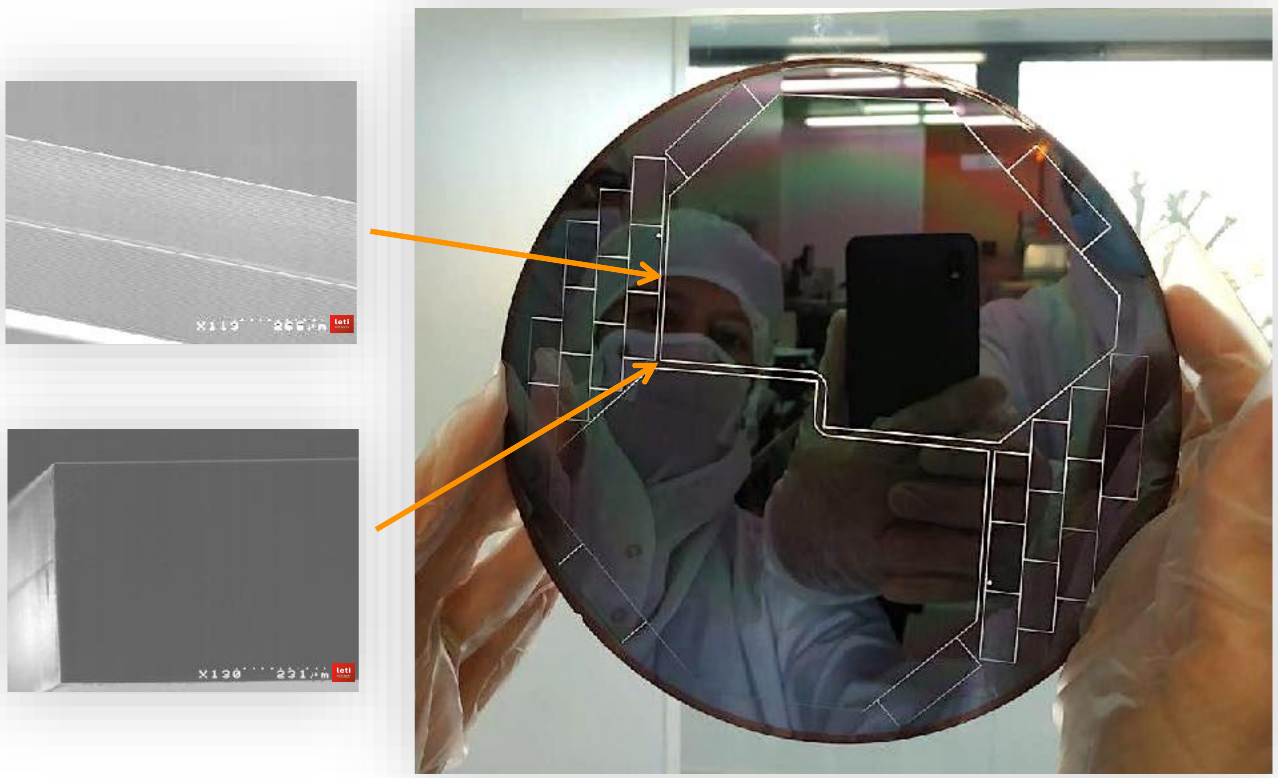


Plasma dicing by DRIE

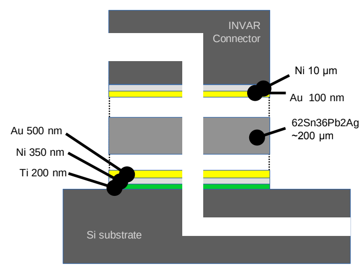
Deep Reactive Ion Etching



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

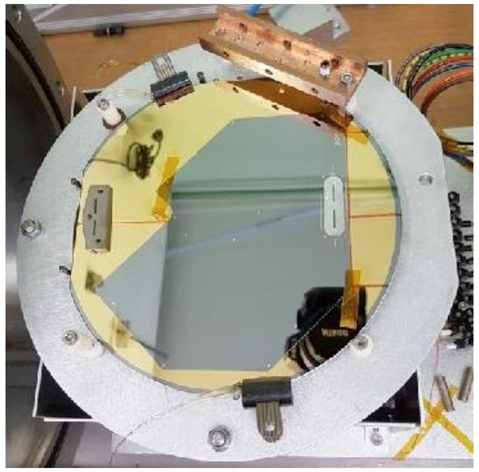


soldering of metallic connectors

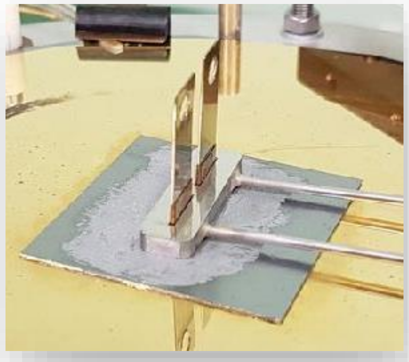


62Sn36Ag2Pb preform for pre-tinning of cooling plate and connector

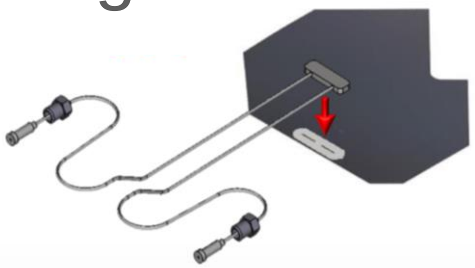
1. Pre-tinning of cooling plate

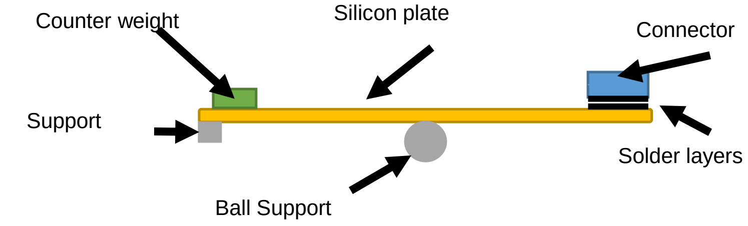


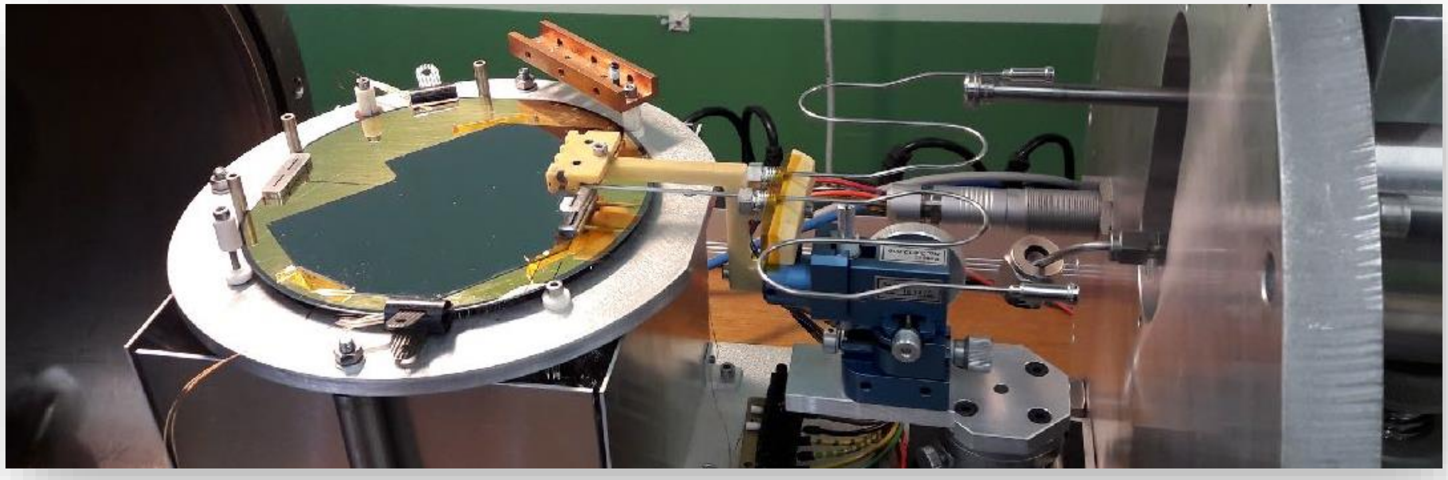
2. Pre-tinning of connector



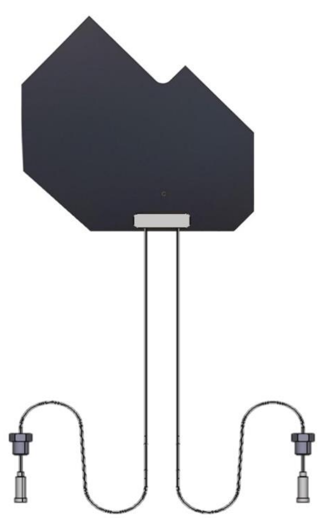
3. Alignment of connector to cooling plate

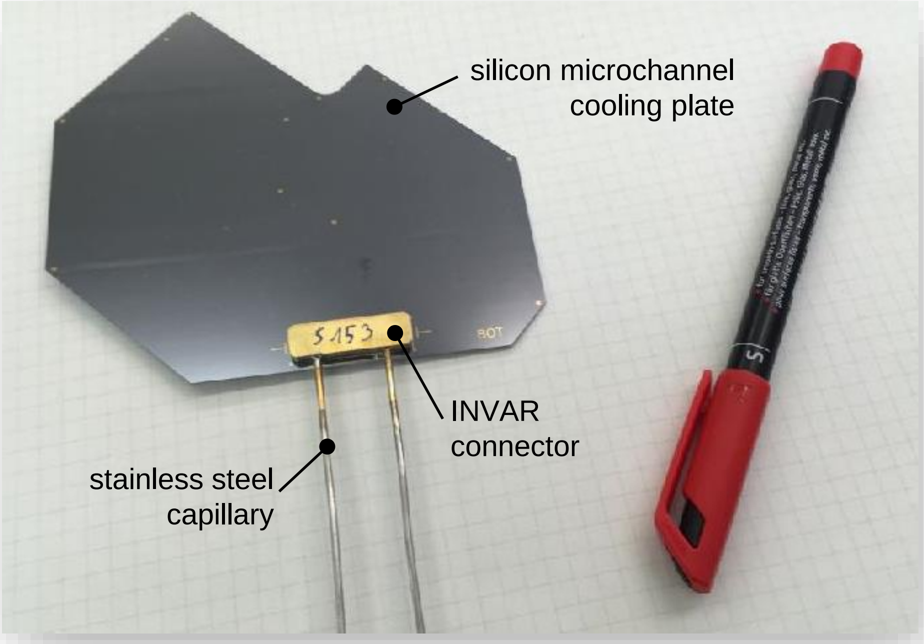






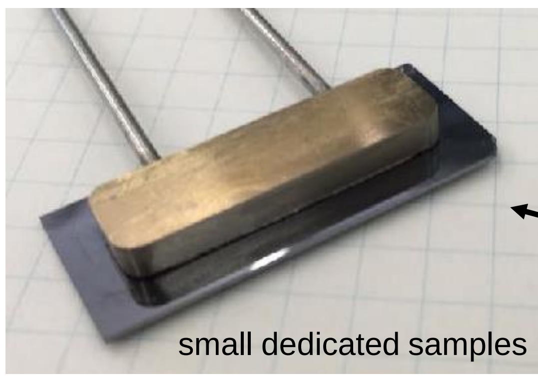
4. Soldering

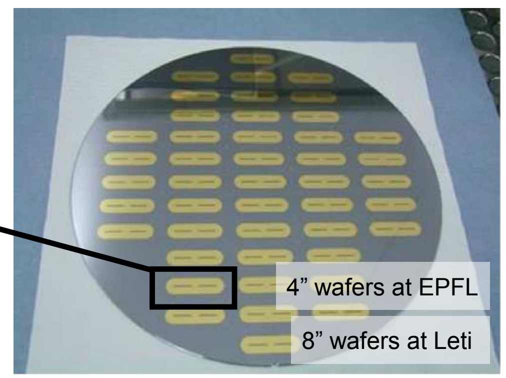


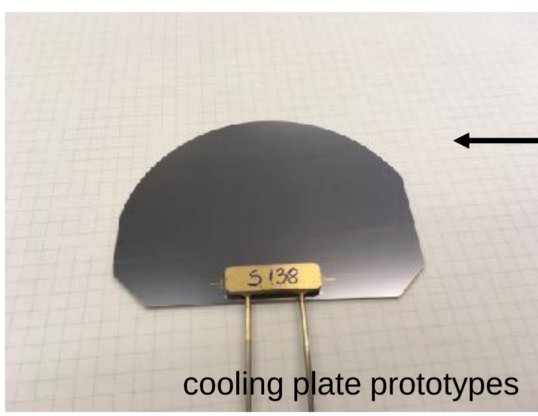


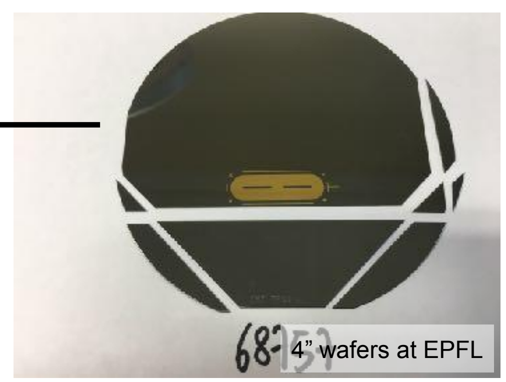
voidless and fluxless soldering of metal to silicon

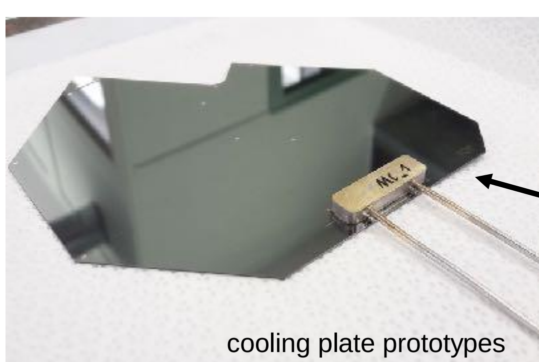
validation of soldering procedure with thermo-mechanical mockups

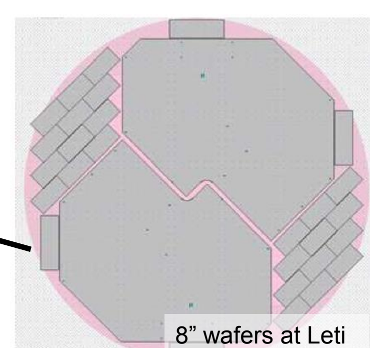




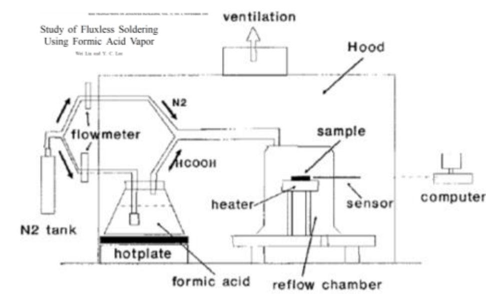


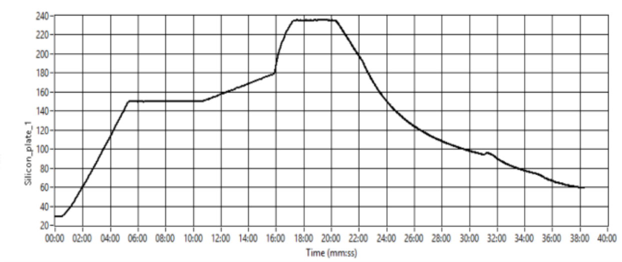


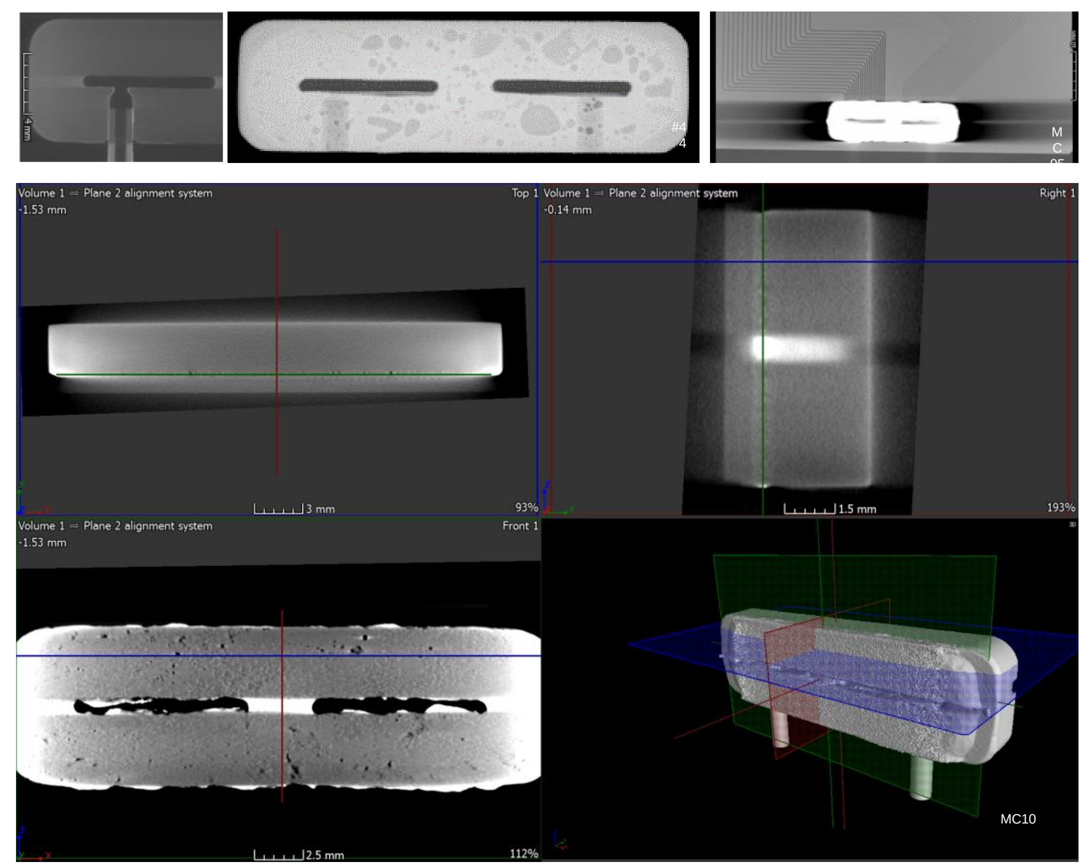




soldering in reducing atmosphere using Formic Acid

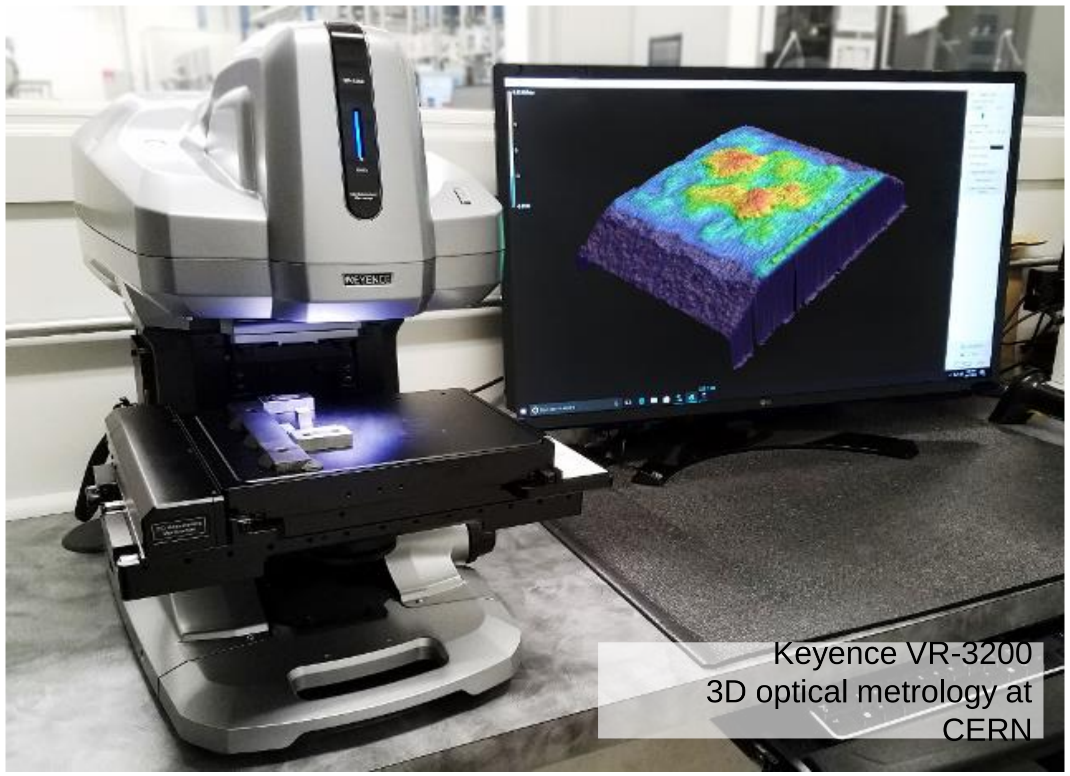




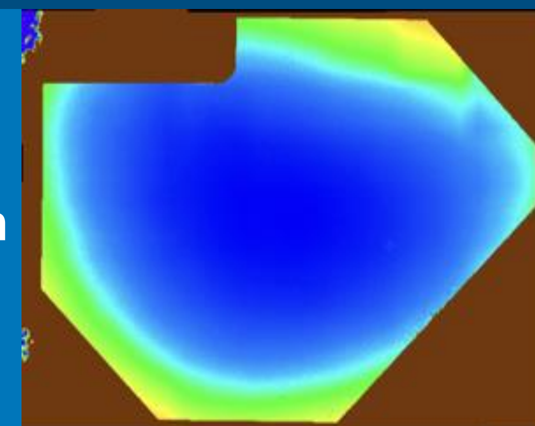
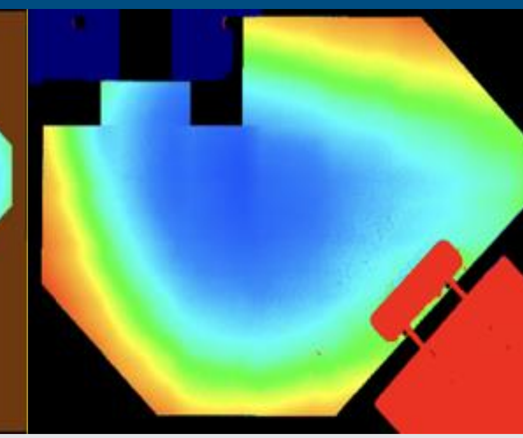


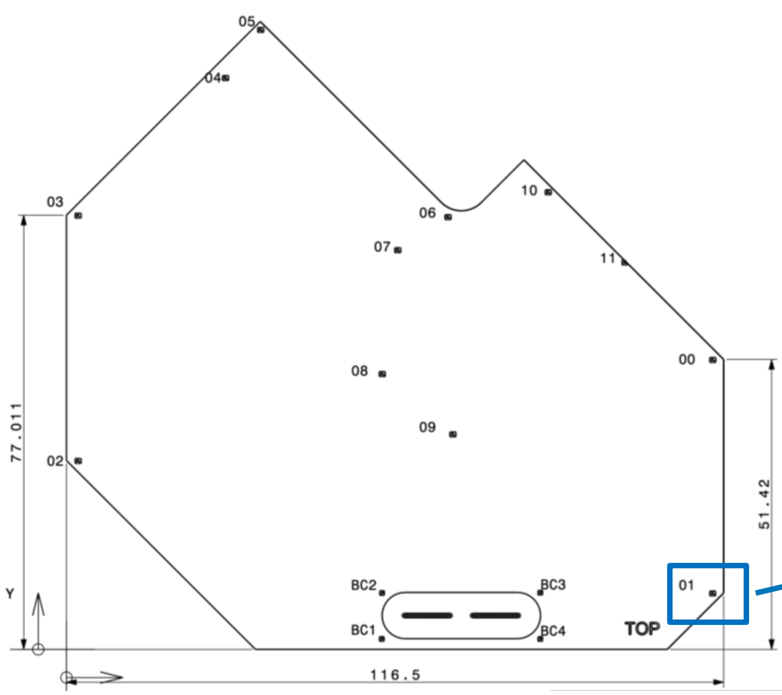
3D Xray µ-CT at CERN

cooling plates planarity



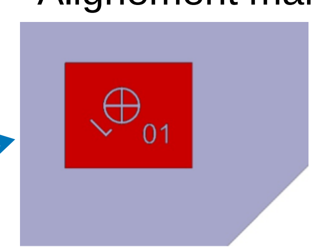
Keyence VR-3200
3D optical metrology at CERN

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



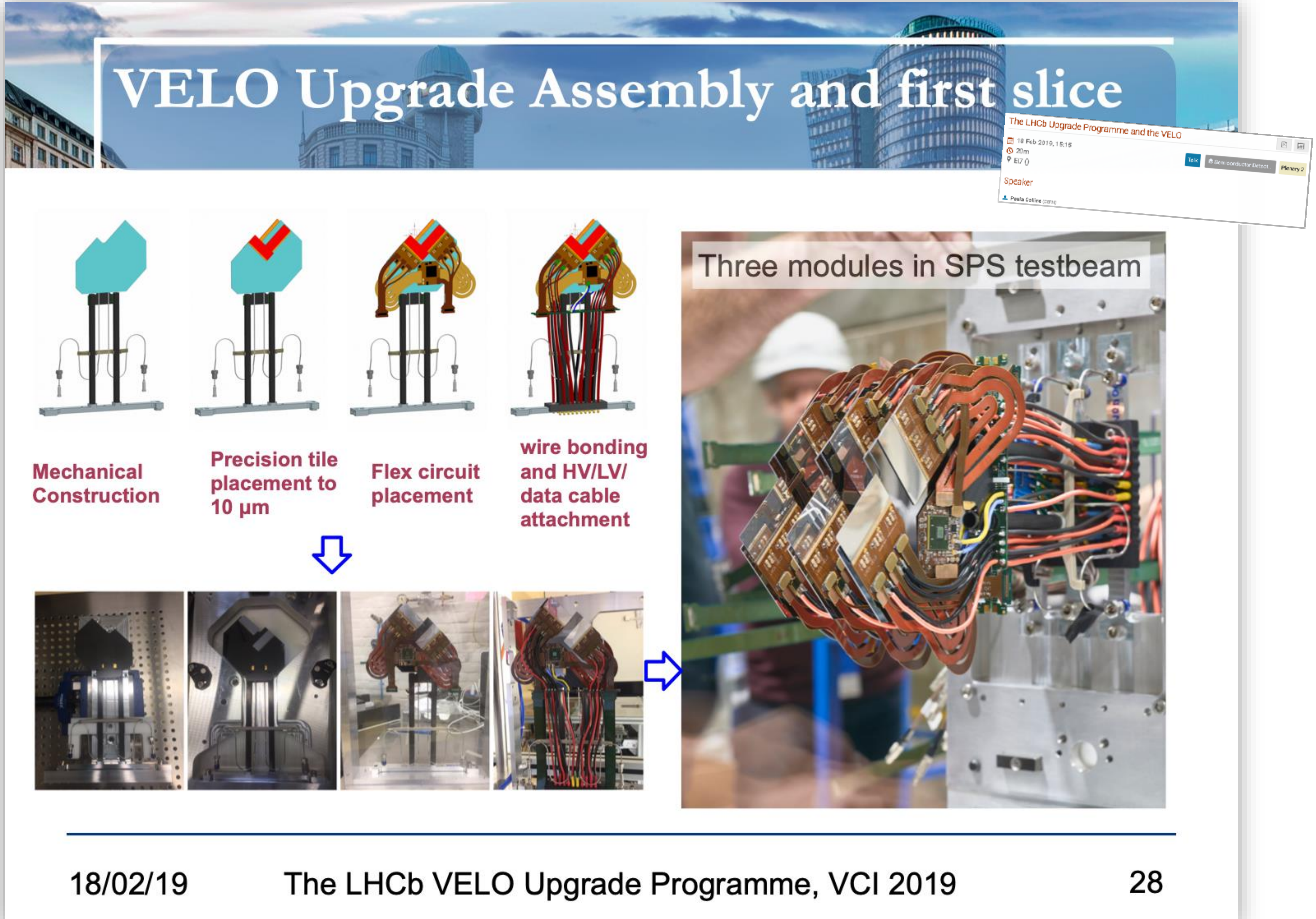
- Slight change on the planarity of the cooling plates.
- No significant stress generated by the soldering.
- The cooling plate is the backbone of the mechanical assembly of the VELO module.

Alignement marks for module assembly

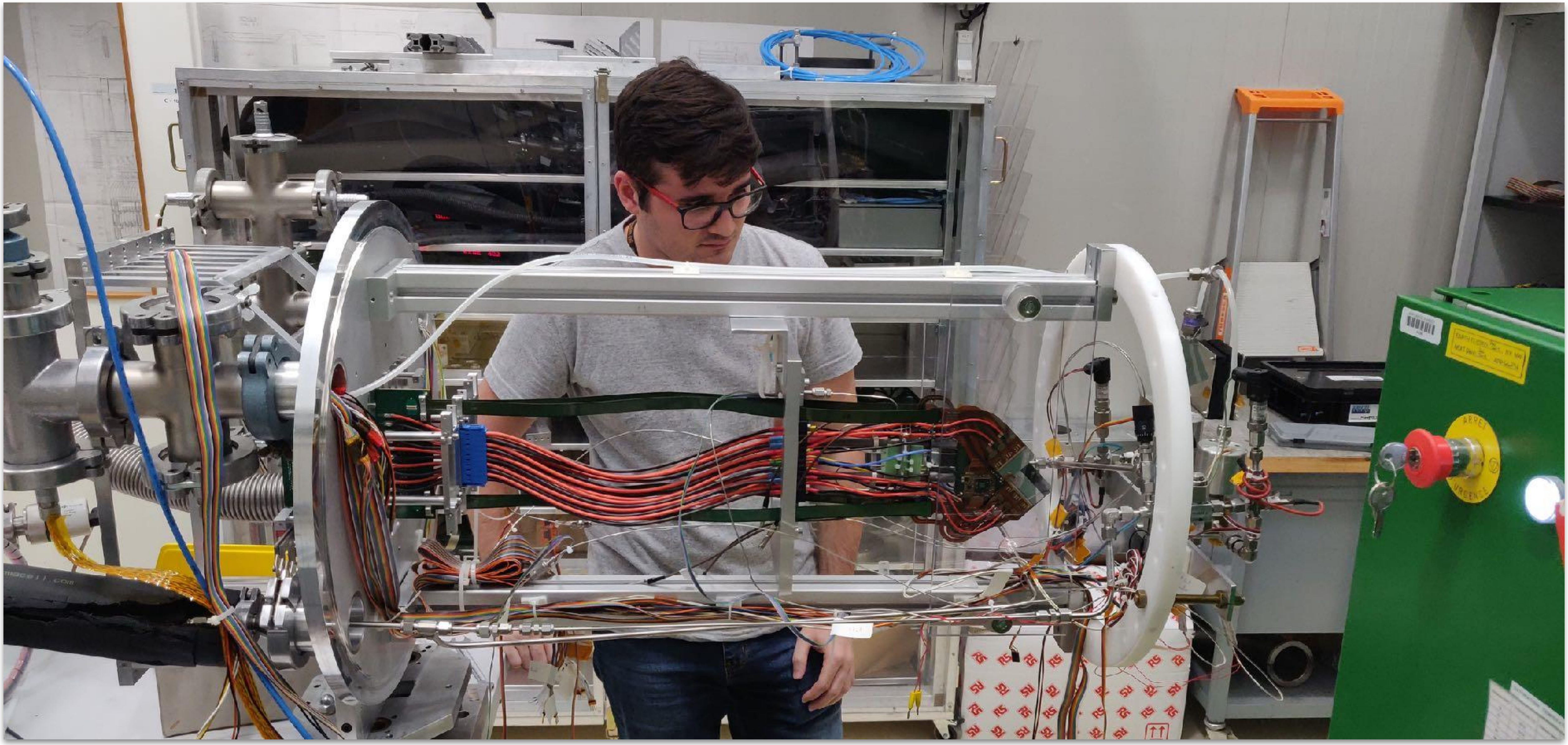


patterned on metal

etched in silicon



Slide from the talk **The LHCb Upgrade and the VELO** by Paula Collins on Monday

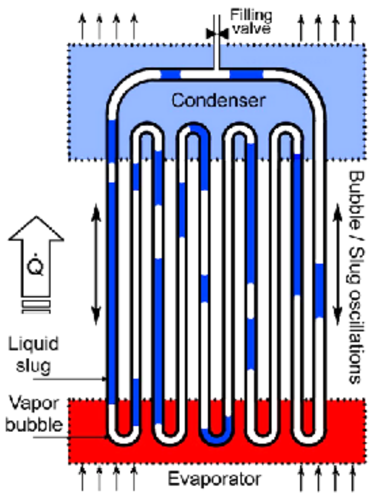


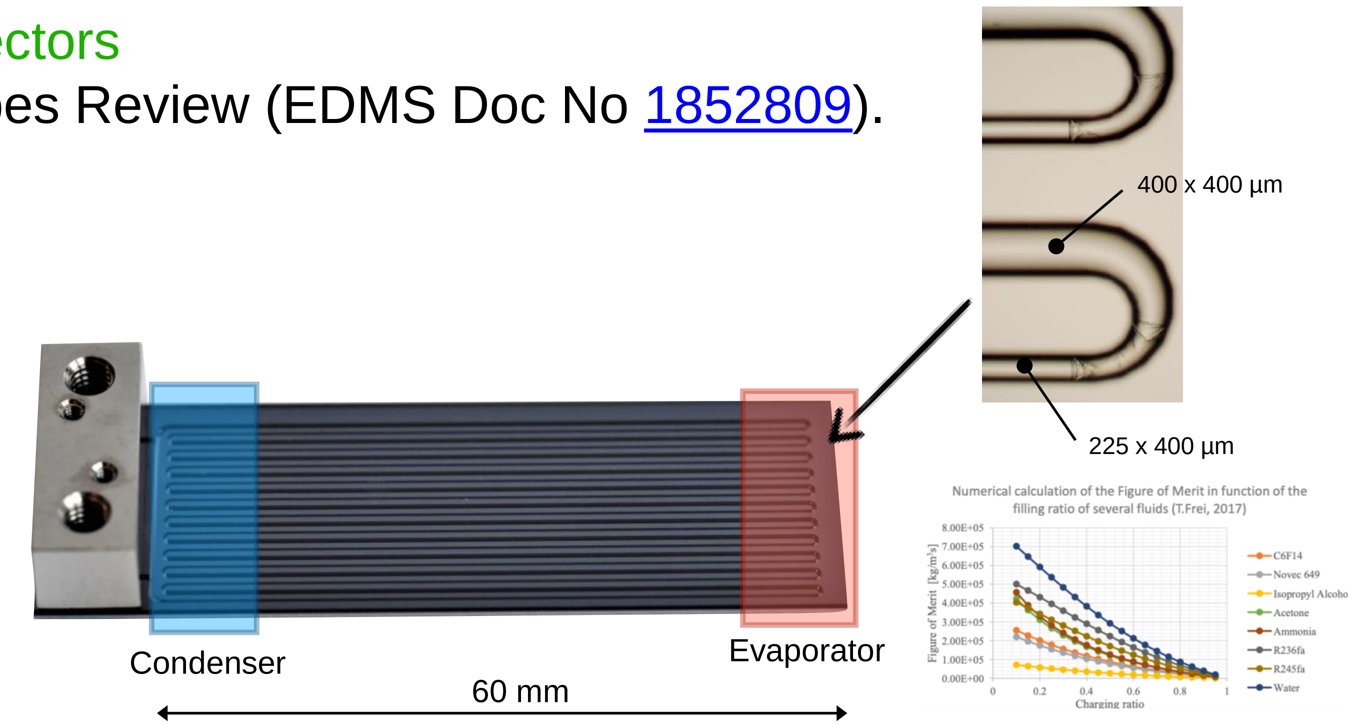
© Oscar Augusto de Aguiar Francisco, CERN, Feb. 2019

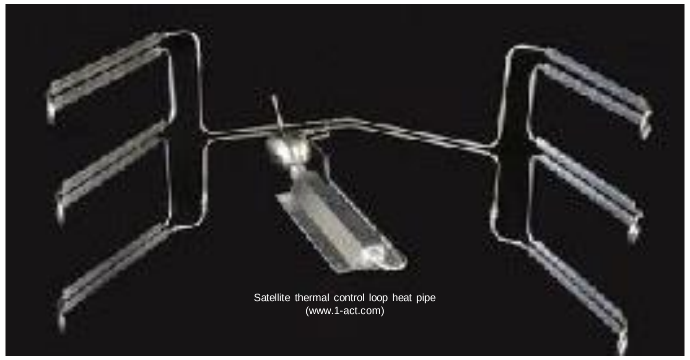
μ oscillating heat pipes

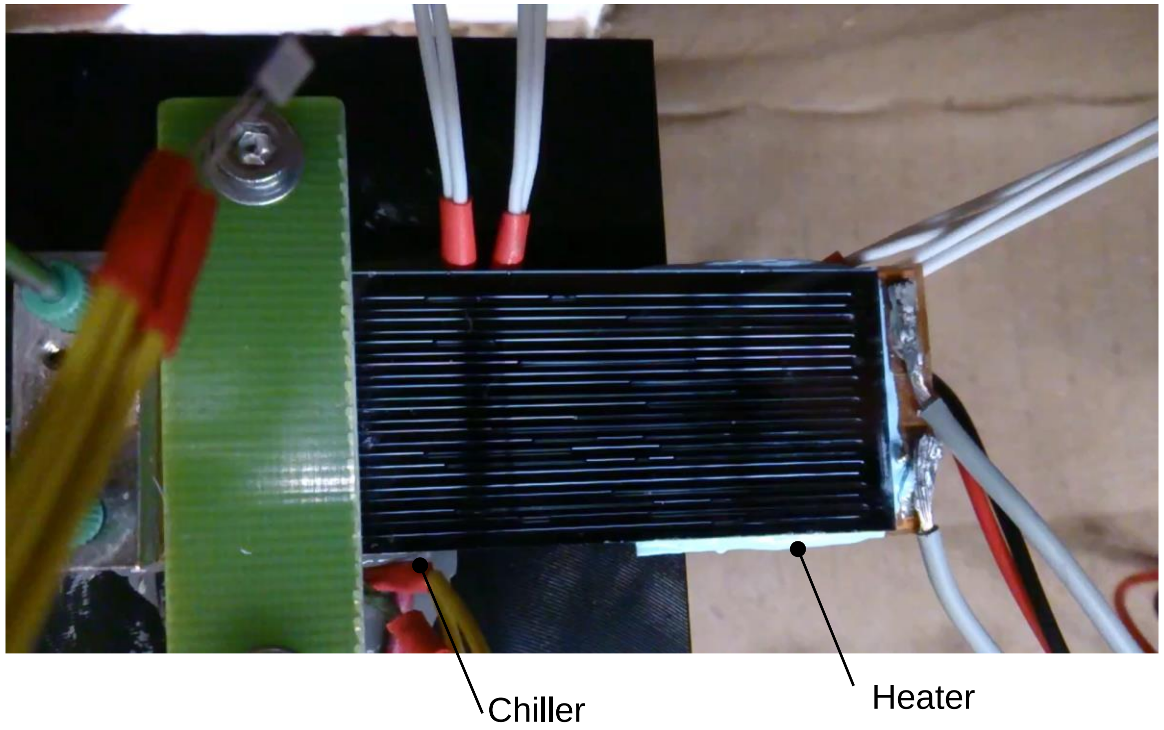
PhD candidate: Timothée Frei

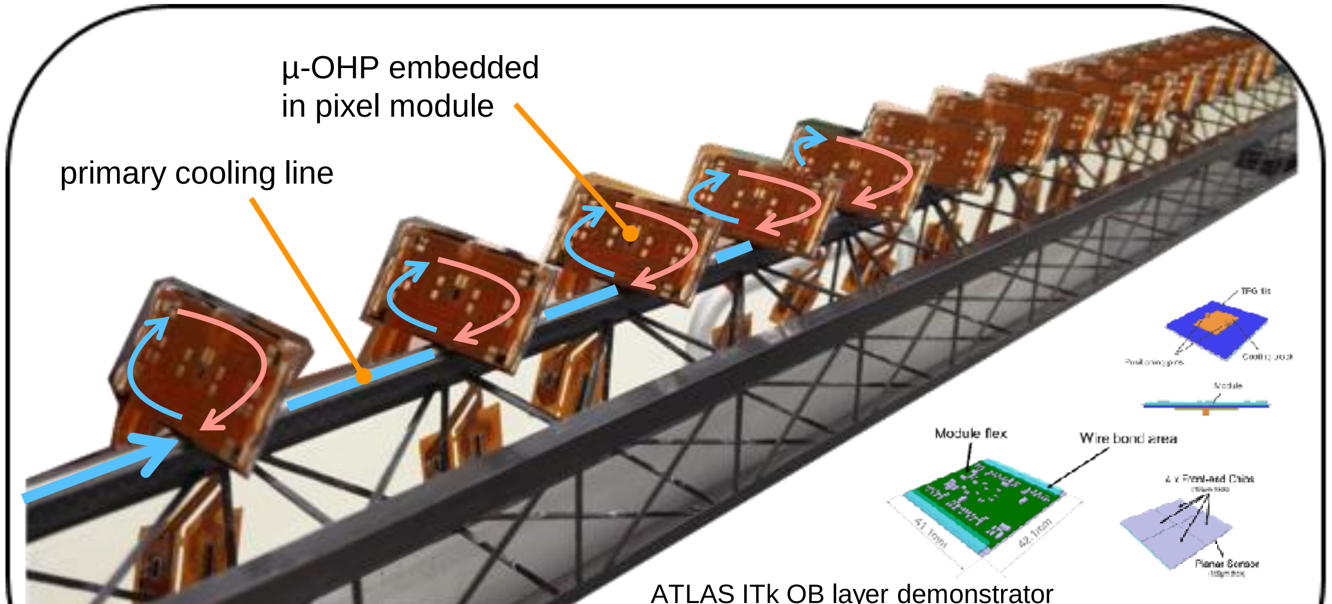
- Miniaturised closed loop device operated in stand-alone mode.
- Self-contained and self-actuated.
- Eliminate connectors
- MEMS Heat Pipes Review (EDMS Doc No [1852809](1852809)).









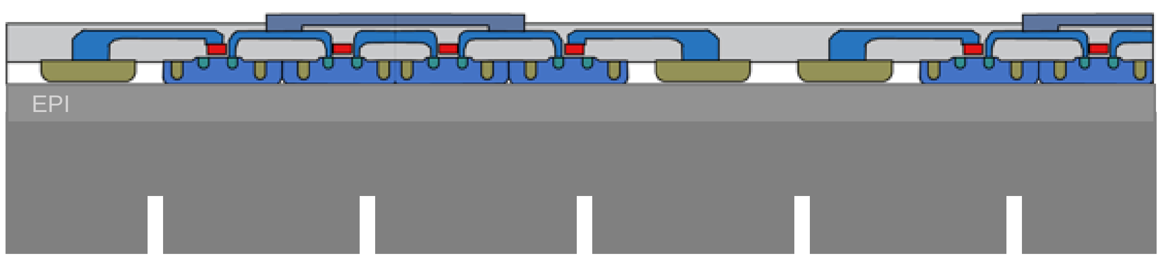


Studies with ATLAS ITk OB specifications to evaluate the thermal performance and reworkability of a cooling block based on µ-OHP in a stave configuration.

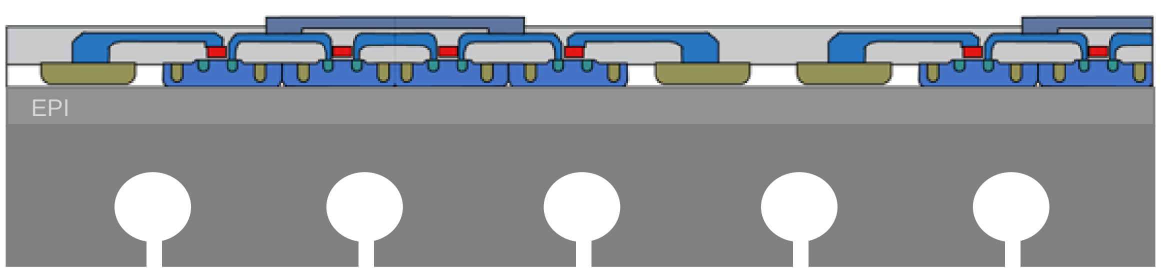
Embedding Microfluidics into Microelectronics

- CMOS-compatible process developed at CERN.
- Microchannels etched on the backside of monolithic pixel detectors.
- A demonstrator is currently being produced by post-processing functional MALTA* chips in the class 100 (ISO5) MEMS cleanrooms of EPFL.

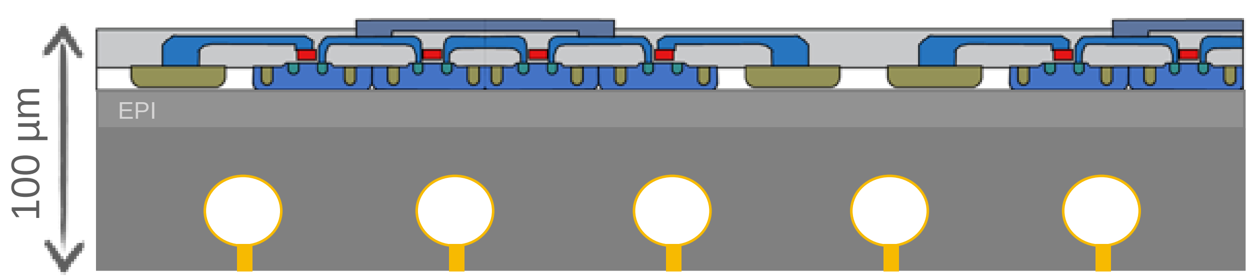
***MALTA**: an asynchronous readout CMOS monolithic pixel detector for the ATLAS High-Luminosity upgrade. R. Cardella et al., PIXEL2018



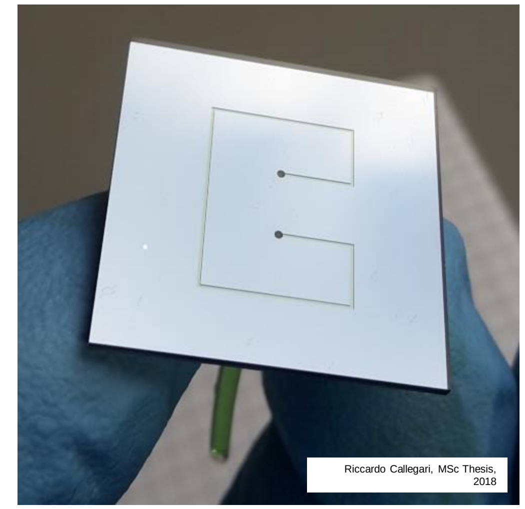
DRIE of small trenches (anisotropic)

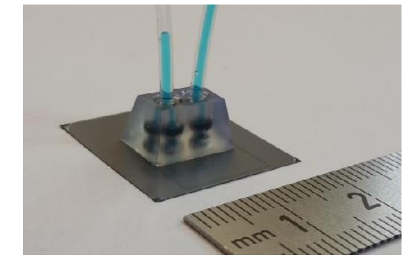


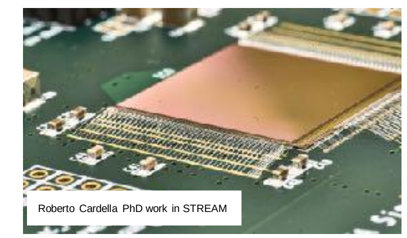
XeF_2 etching of microchannels (isotropic)

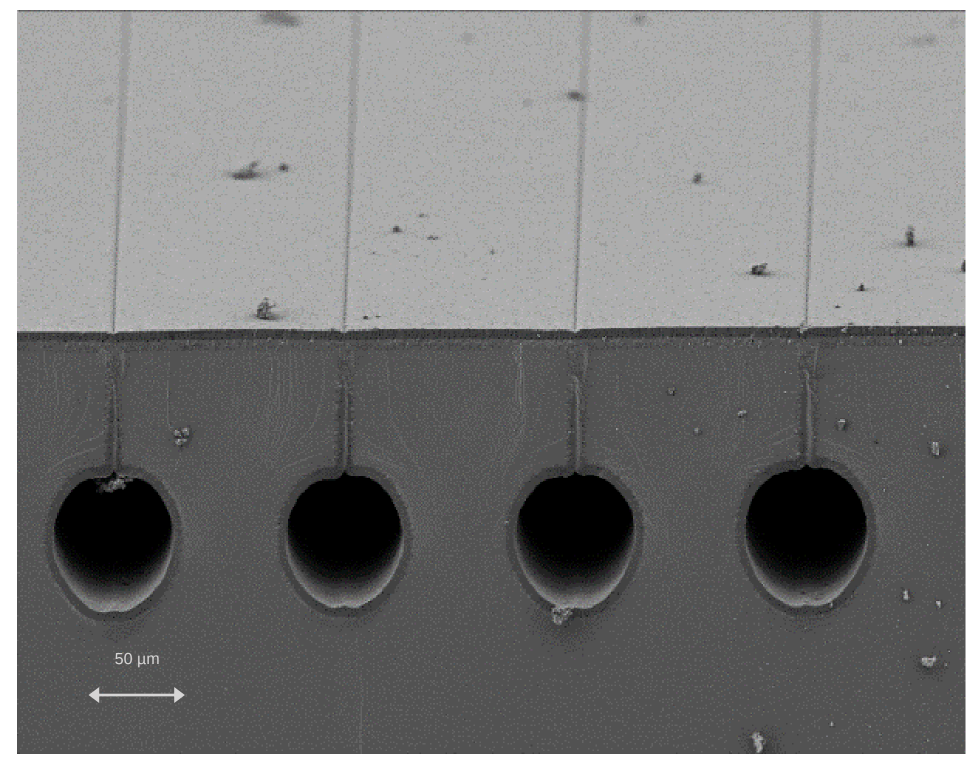


Filling of trenches (e.g. PECVD, Parylene)









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

conclusions and outlook

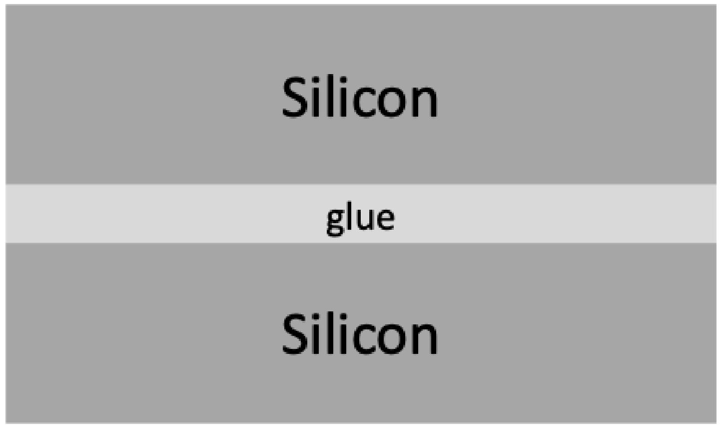
- CERN is leading the development of **silicon microchannel cooling plates** in close collaboration with LHC and non-LHC experiments and with external partners.
- The NA62 experiment has pioneered the use of silicon microchannel cooling plates with **liquid C_6F_{14}** for the thermal management of the **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.

100 µm

backup

Silicon samples

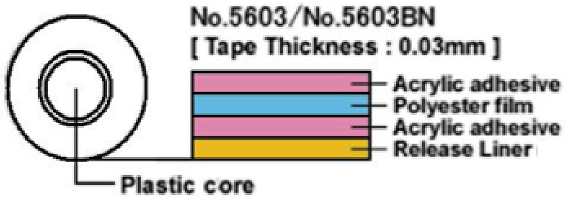
Silicon samples 10 x 10 mm with wafers 525 µm thick



Shear tests with four different adhesive types:

Adhesive tape

NITTO DENKO 30 µm thick



- Polyester film double coated by acrylic adhesive
- Polyester = 0.13-0.15 W/m K
  Acrilyc = 0.2 W/m K

- Surface cleaning with acetone
- **1 Kg** for 65 hours

Adhesive tape

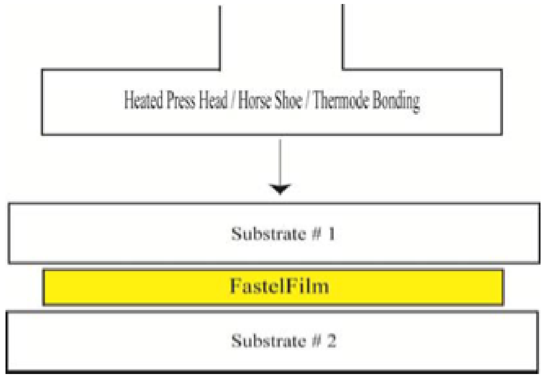
3M 9461P – 30 µm thick

- 3M Adhesive 100 (Acrylic adhesive)
- 3M Adhesive 100 = 0.178 W/m K

- Surface cleaning with acetone
- **1 Kg** for 65 hours

Adhesive film

FastelFilm 30 µm thick



- EVA (Ethylene - vinyl Acetate) adhesive film
- EVA = 0.34 W/m K

- Surface cleaning with acetone
- 1 Kg for 3 minutes
- 80 °C in the oven (weight and plate already hot)

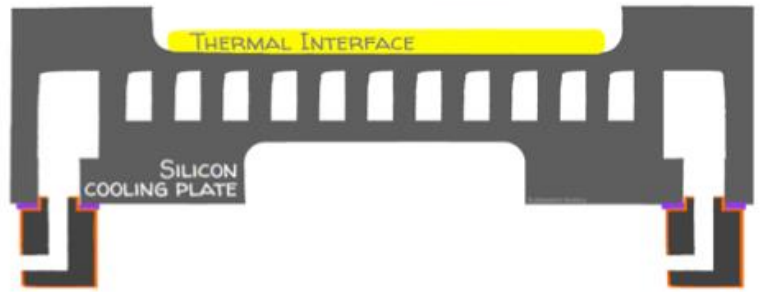
Liquid glue

Araldite 2020

- Two components epoxy liquid glue
- Epoxy = 0.188 W/m K

- Surface cleaning with acetone
- Vacuum outgassing after mixing the component
- Dispensing with a slice

2- TAPE 3M - 9461P Adhesive 100



Tape thickness: 30 µm
Bond Build-up: The bond strength of 3M™ Adhesive 100 increases as a function of time and temperature.
Humidity Resistance: High humidity has a minimal effect on adhesive performance. Bond strengths are generally higher after exposure for 7 days at 90°F (32°C) and 90% relative humidity.
U.V. Resistance: When properly applied, nameplates and decorative trim parts are not adversely affected by outdoor exposure.
Water Resistance: Immersion in water has no appreciable effect on the bond strength. After 100 hours in room temperature, the bond actually shows an increase in strength.
Temperature Cycling Bond strength generally increases after cycling four times (4 hours at 158°F (70°C) 4 hours at -20°F (-29°C) 16 hours at room temperature)
Chemical Resistance: When properly applied, nameplate and decorative trim parts will hold securely after exposure to numerous chemicals including gasoline, oil, Freon™ TF, sodium chloride solution, mild acids and alkalis.
Heat Resistance: The 3M adhesive 100 is usable for short periods (minutes, hours) at temperatures up to 450°F (232°C) and for longer periods (days, weeks) up to 300°F (149°C).
Low Temperature -40°F (-40°C). Parts should be tested for low temperature

Thermal Conductivity (ASTM C518)
- 0.103 BTU-ft/ft2-hr-°F (@105°F)
- 0.106 BTU-ft/ft2-hr-°F (@160°F)
- 0.108 BTU-ft/ft2-hr-°F (@214°F)
- 0.178 Watt/m-K (@41°C)
- 0.183 Watt/m-K (@71°C)
- 0.187 Watt/m-K (@101°C)

Coefficient of Thermal Expansion (ASTM-D696)
First heat (125-175°C) 19.9 x 10-5 m/m/°C
Second heat (25-175°C) 58.4 x 10-5 m/m/°C
Insulation Resistance (test voltage = 100 VDC, MIL-I-46058C)
Before moisture resistance >1.0 x 1015 ohms
Cycle #4 1.5 x 1011 ohms
Cycle #10 9.4 x 1010 ohms
24 hr after moisture resistance 9.7 x 1012 ohms
Surface Resistance >1.0 x 1015 ohms
Surface Resistivity >5.6 x 1016 ohms
Volume Resistance 3.9 x 1011 ohms
Volume Resistivity (ASTM D257-92) 4.0 x 1015 ohm-cm
Dissipation Factor 0.025 (@1 kHz)
Dielectric Constant (ASTM D-150-92) 2.92 (@1 kHz)
Dielectric Strength (500 vac, rms. [60 Hz]/sec.) 1100 volts/mil **(ASTM D149-92)**

28/08/2013 NA62 - GTK meeting 8

https://www.3m.com/3M/en_US/company-us/all-3m-products/~/3M-Adhesive-Transfer-Tape-9461P/?N=5002385+3293241965&rt=rud

µ-channel cooling frame studies

ALICE-TDR-017 CERN-LHCC-2013-024
02 December 2013

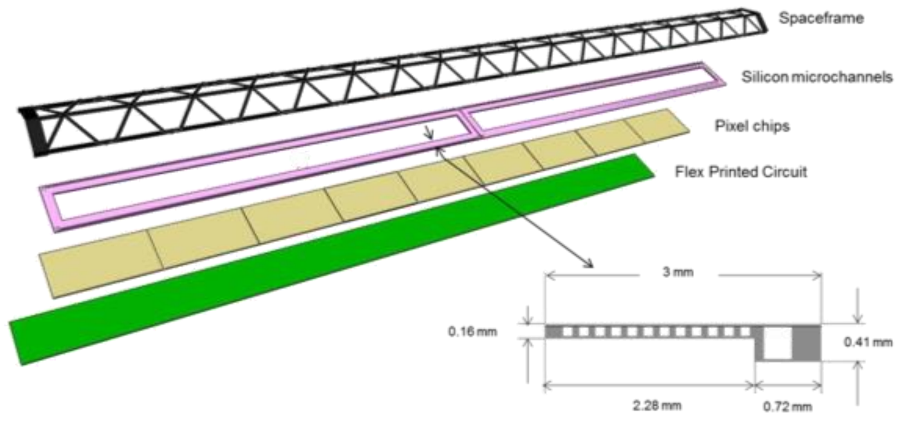


Figure B.8: Concept of the integration of the silicon micro-channel frames into the ITS IL stave.

- Silicon frames with embedded microchannels were studied for flow boiling of perfluorobutane (C_4F_{10}) in the framework of the ALICE ITS LS2 upgrade.
- Frames minimise the material budget contribution of the cooling system in the most inner layers.
- The study was carried out in collaboration between ALICE, the EP-DT group at CERN, University of Padova, the CMi and LTCM groups at EPFL and the Thai Micro Electronic Centre (TMEC) in Thailand.

- Further … budg…
  - Frames …

- Staves for barrel configurations.
  - Microfluidic interconnections have to be developed.

Figure B.4: The silicon frame with embedded microchannels (left) and a particular of the inlet manifold (right).

- …a… for the ALICE ITS LS2 Upgrade
  - …dev… schedule …

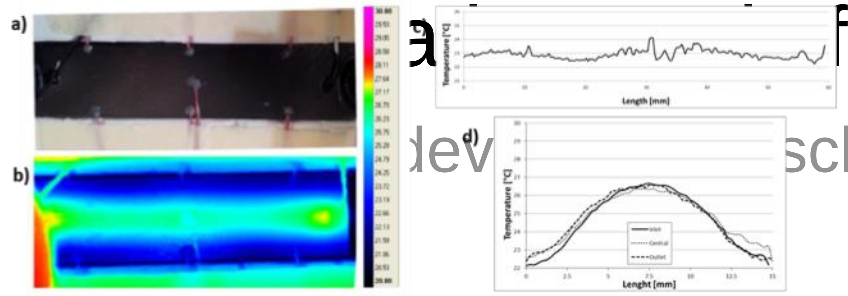


Figure B.5: The silicon dummy chip instrumented with thermocouples (a), IR image of the dummy chip at the nominal dissipation heat flux $P_{diss} = 300\,\mathrm{mW\,cm^{-2}}$ (b), the temperature profile along the microchannels (c) and radial temperature profiles at different longitudinal location (d).

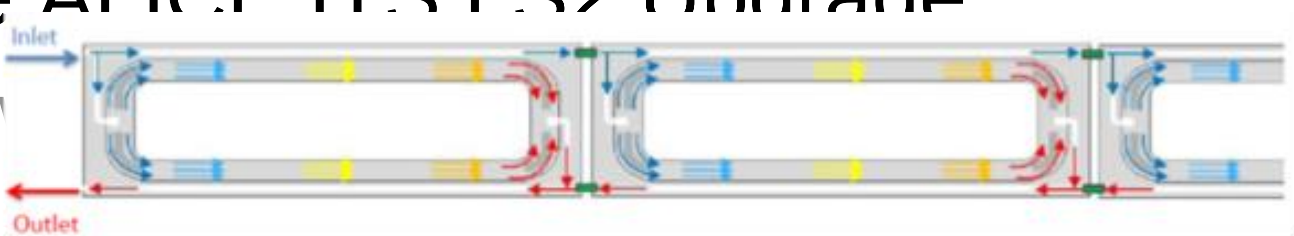


Figure B.6: Interconnection of silicon frames for the Stave cooling.

TDR for the upgrade of the ALICE ITS, J. Phys. G: Nucl. Part. Phys. 41 (2014) 087002 (195pp)