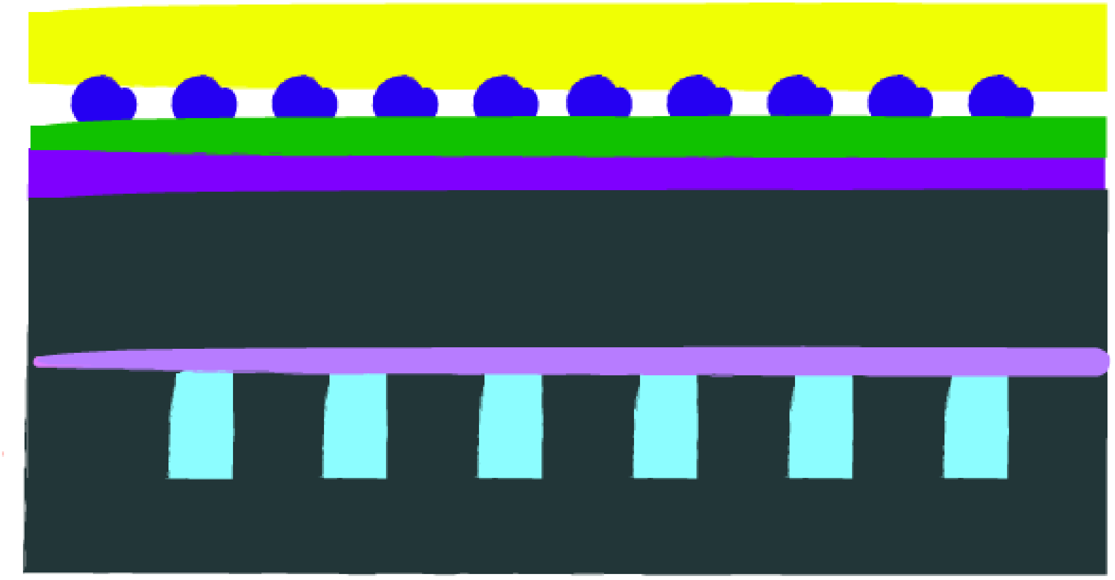
Micro-channel cooling in HEP

Marcel Vos
IFIC (UVEG/CSIC) Valencia
DEPFET workshop,
Ringberg, March 2019



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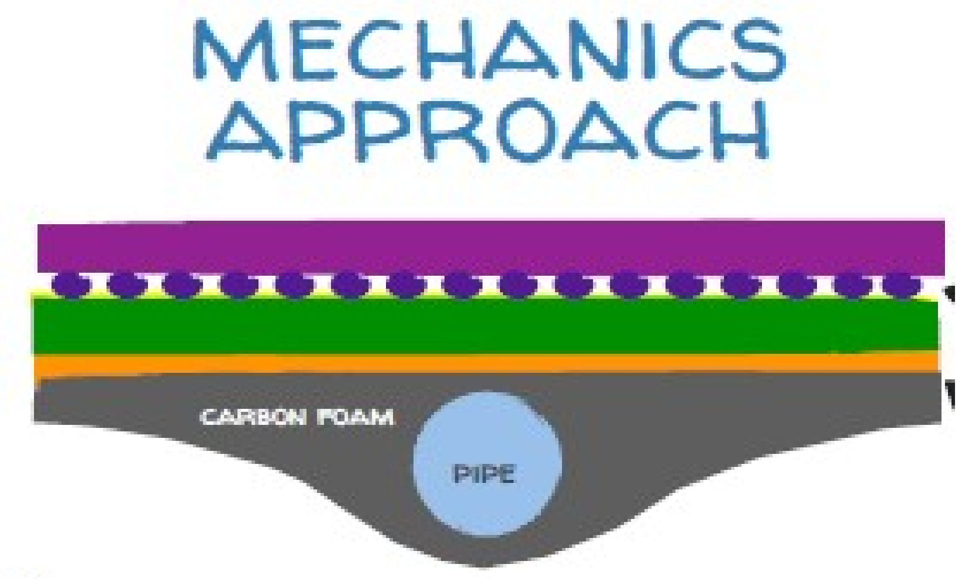
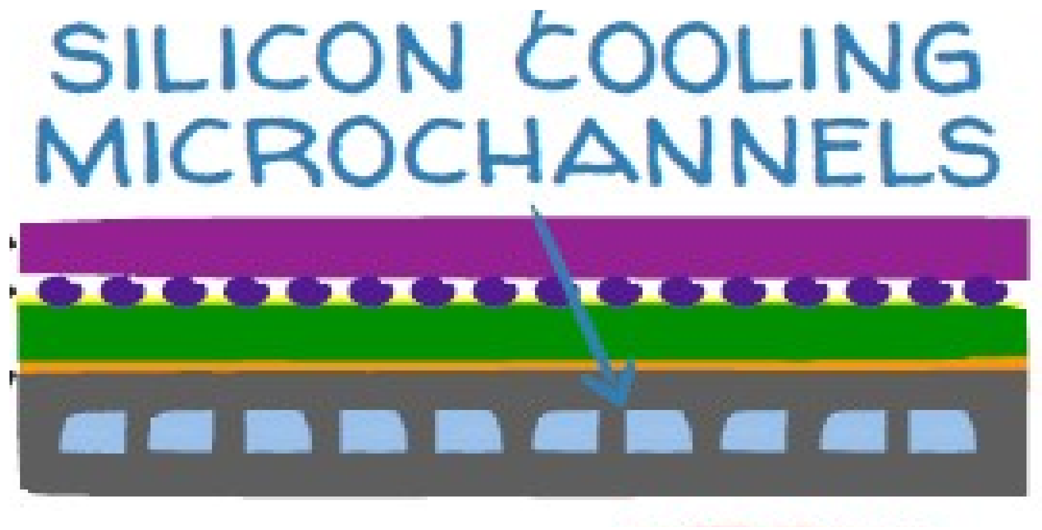
Special thanks to: Laci Andricek (MPG-HLL), Lars Eklund (Glasgow), Nils Flaschl (DESY), Pawel Jalocha, Malcolmn John (Oxford), Alessandro Mapelli (CERN), Carlos Mariñas (U. Bonnn), Paolo Petagna (CERN), Miguel Ullan (CNM), Nacho García, Guillem Vidal, Miguel-Angel Villarejo (IFIC)

The case for MCC in HEP

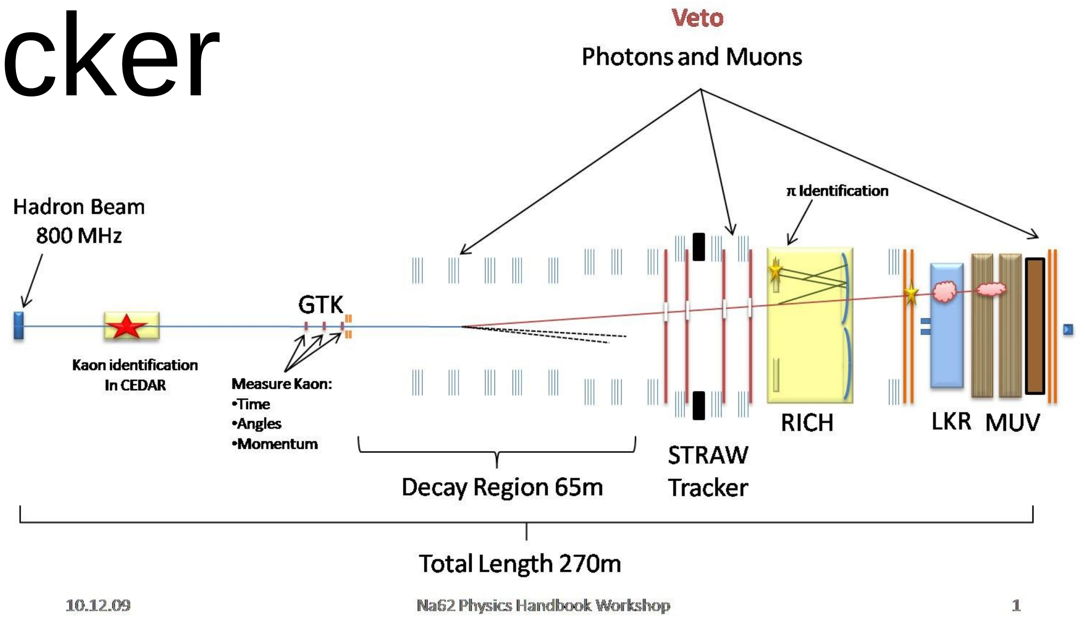




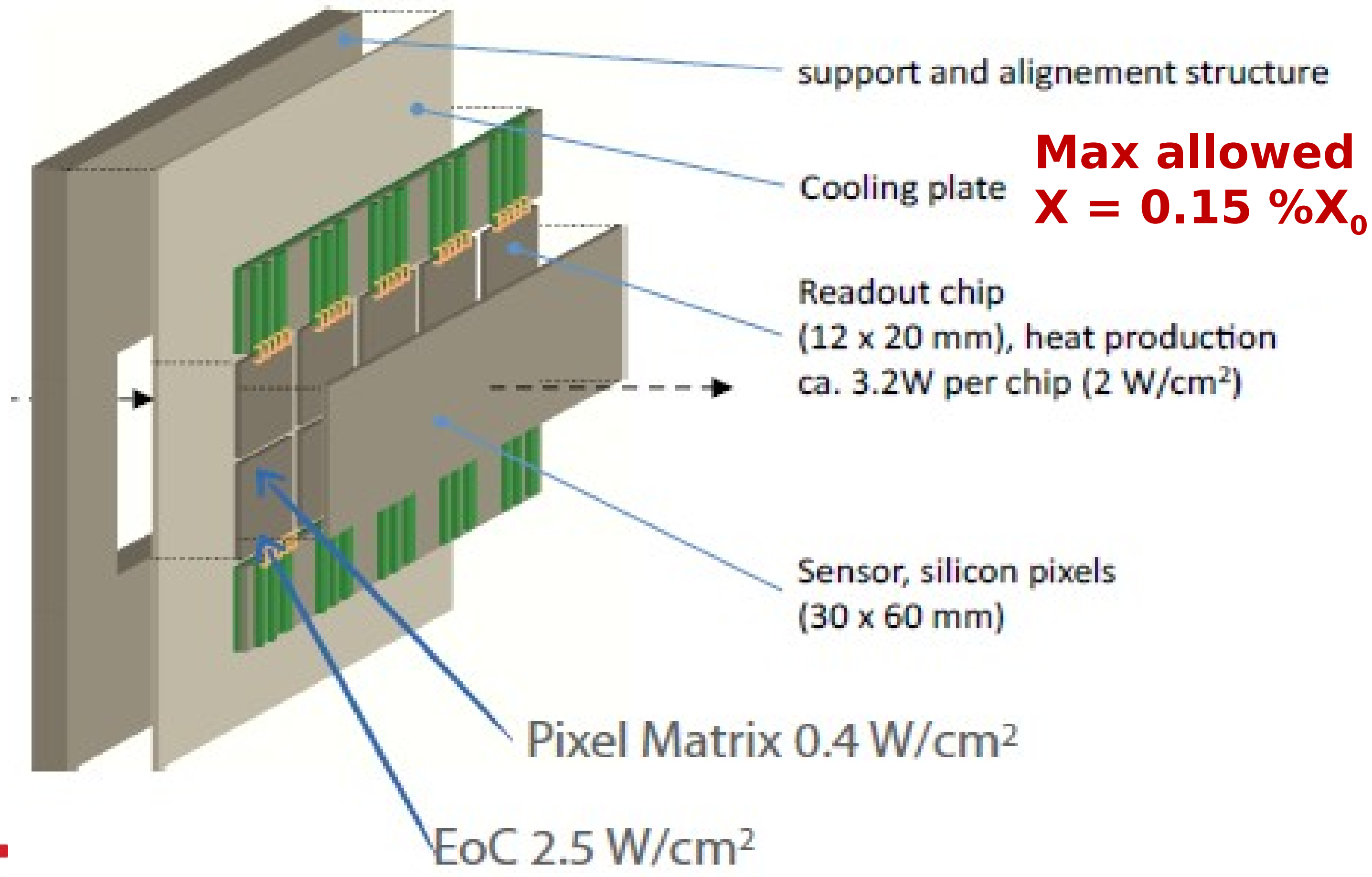
Issues:

→ thermal barriers (glue layers at each interface)
→ material budget (avoid high-Z material)
→ coolant contact area
→ CTE mismatch (cf. ATLAS IBL experience)

NA62 GigaTracker



Rare Kaon decay experiment around CERN North Area beam line (very forward: 270 m long)



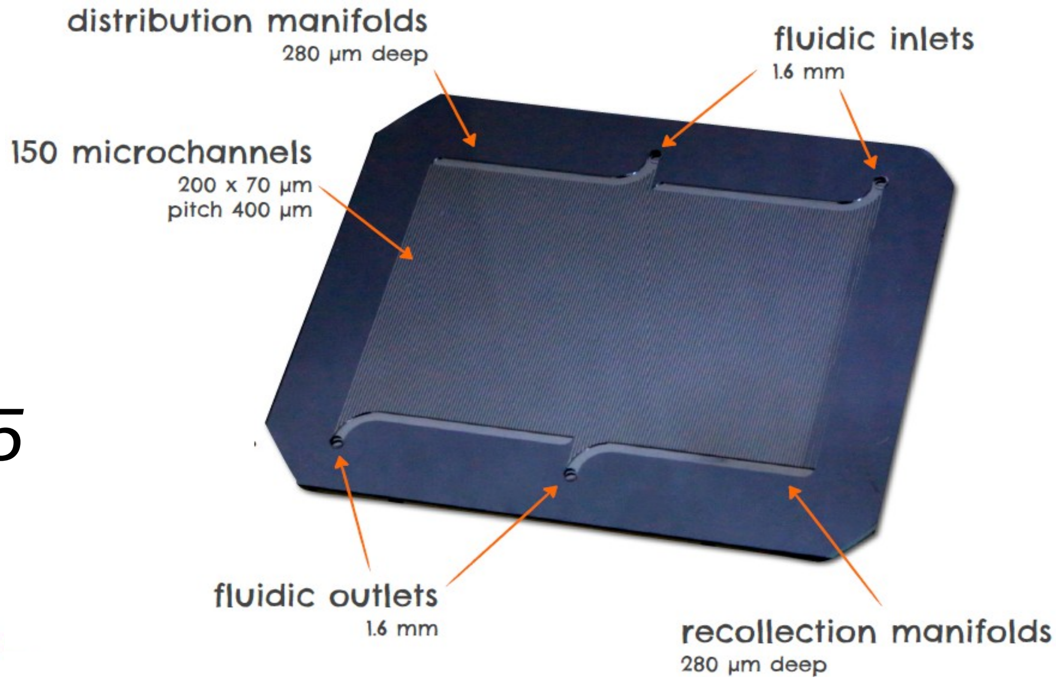
Max allowed $X = 0.15\ \%X_0$

Hybrid pixel detector:
40 W on 3x6 cm^2

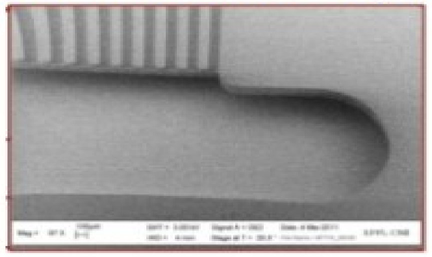
Liquid cooling (mono-phase C6F14 at -20C)

NA62 MCC

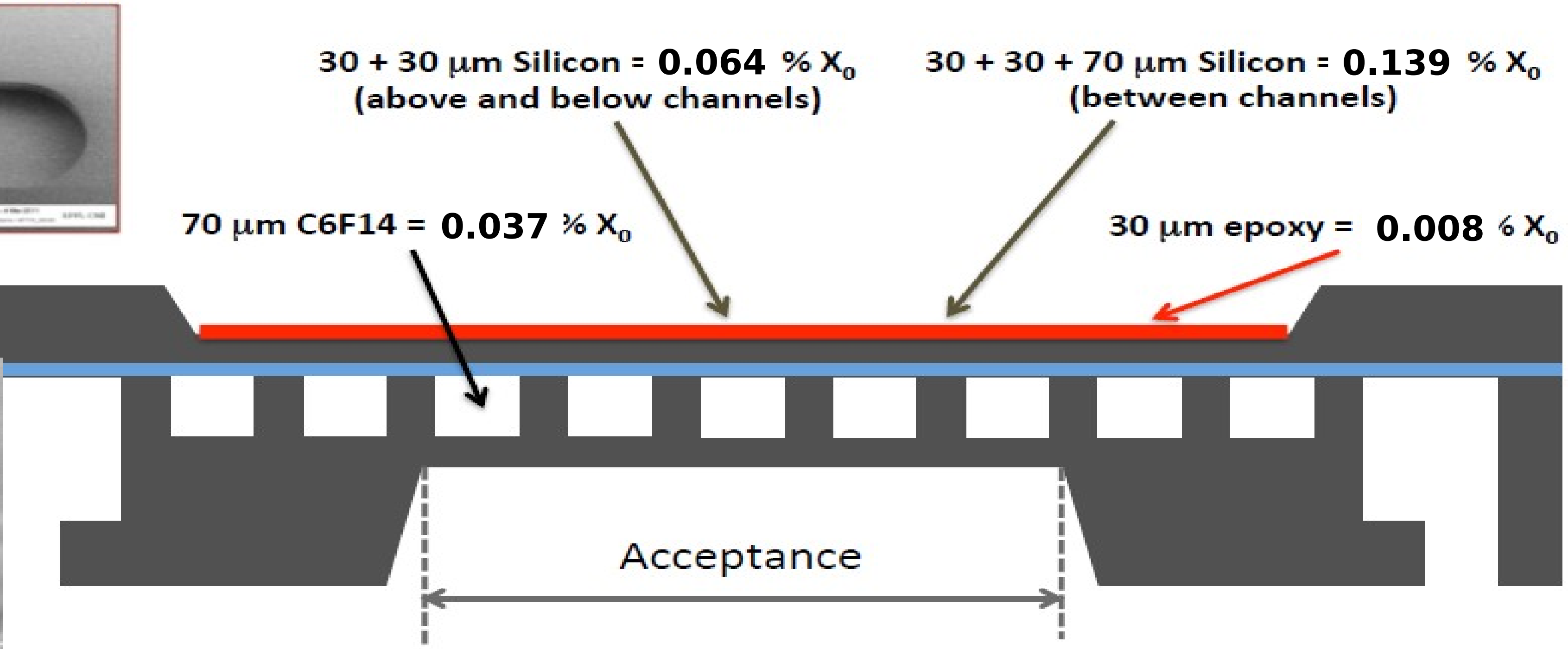
PhD thesis G. Nussle, UC Louvain, October 2015
Microelectron.Eng. 145 (2015) 133-137



Channels =200 x 70 µm
Wall thickness = 200 µm
Cover thickness = 30 µm



Final cross section
of the cooling plate

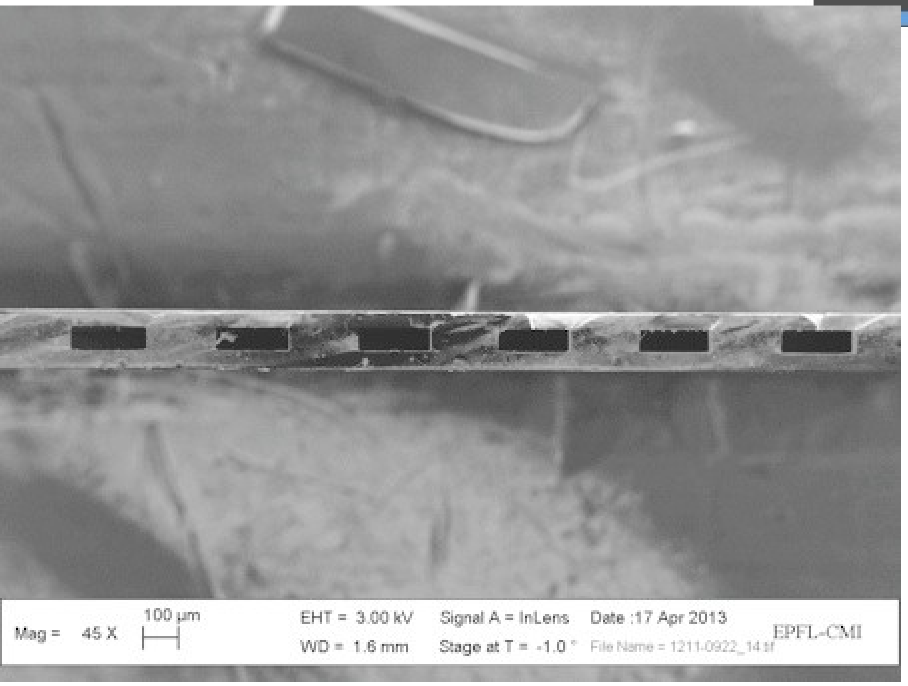


30 + 30 µm Silicon = 0.064 % X_0
(above and below channels)

30 + 30 + 70 µm Silicon = 0.139 % X_0
(between channels)

70 µm C6F14 = 0.037 % X_0

30 µm epoxy = 0.008 % X_0



Total material budget in the acceptance area = 0.13 % X_0
(min 0.11 % - Max 0.15 %)

Very, very thin!

The first MCC application in HEP

Experiment started running end of 2014

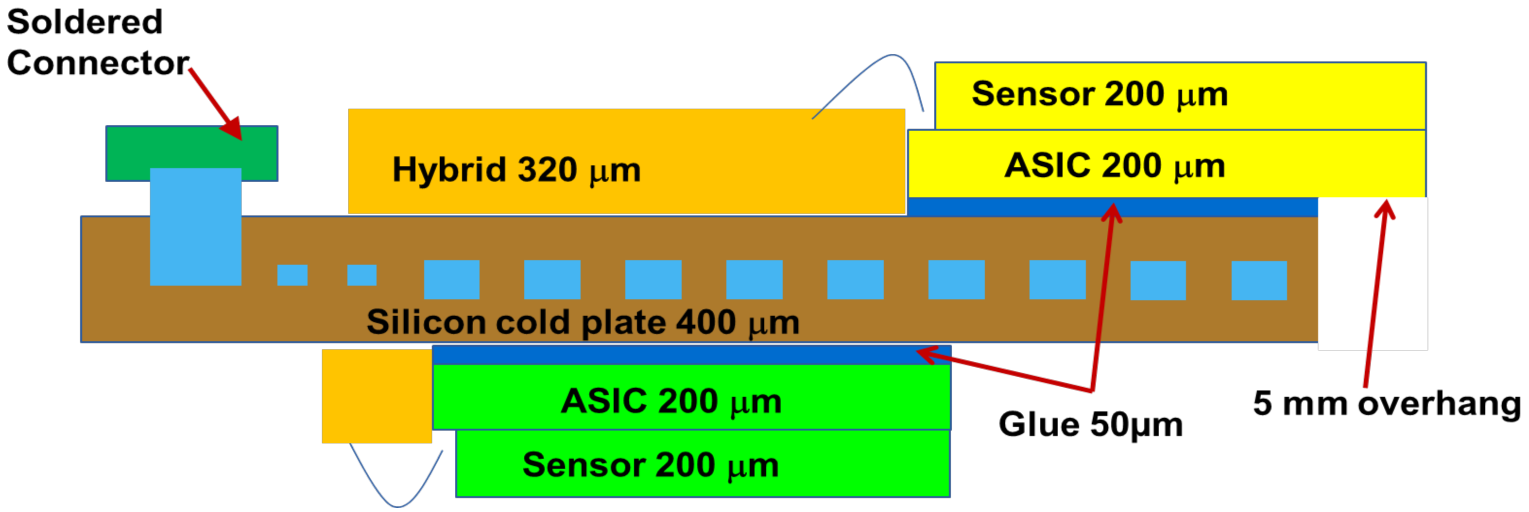
See talk by Massimiliano Fiorini on Monday

A.Francescon et al: *Application of micro-channel cooling to the local thermal management of detectors electronics for particle physics*, Microelectronic Journal, Volume 44, Issue 7, July 2013, Pages 612–618

LHCb VELO upgrade

- Pixel-based upgrade after LS2 (2020)
- Nearly 10^{16} 1 MeV n/cm^2 (non-uniform)
- Leakage current 1W/sensor (@1000V and -20C)
- Basic assembly dissipates 4 x 1W in sensors,
- 12 x 3W in VeloPix chips and 5W in hybrid

JINST 10 (2015) no.05, C05014



Evaporative system: must deal with high pressure!!

LHCb VELO upgrade

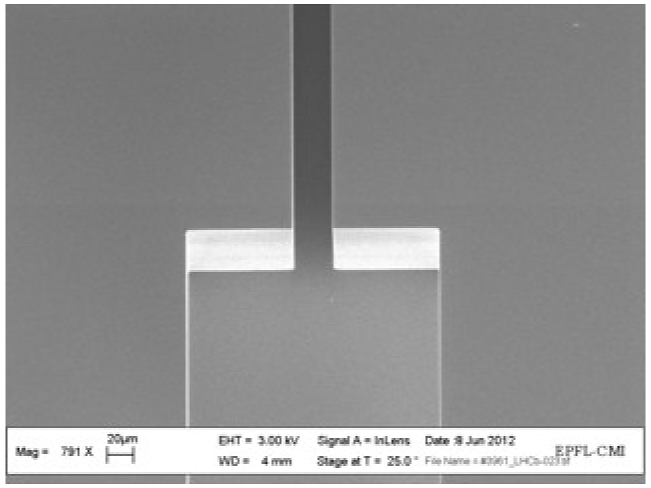
Silicon cooling plate

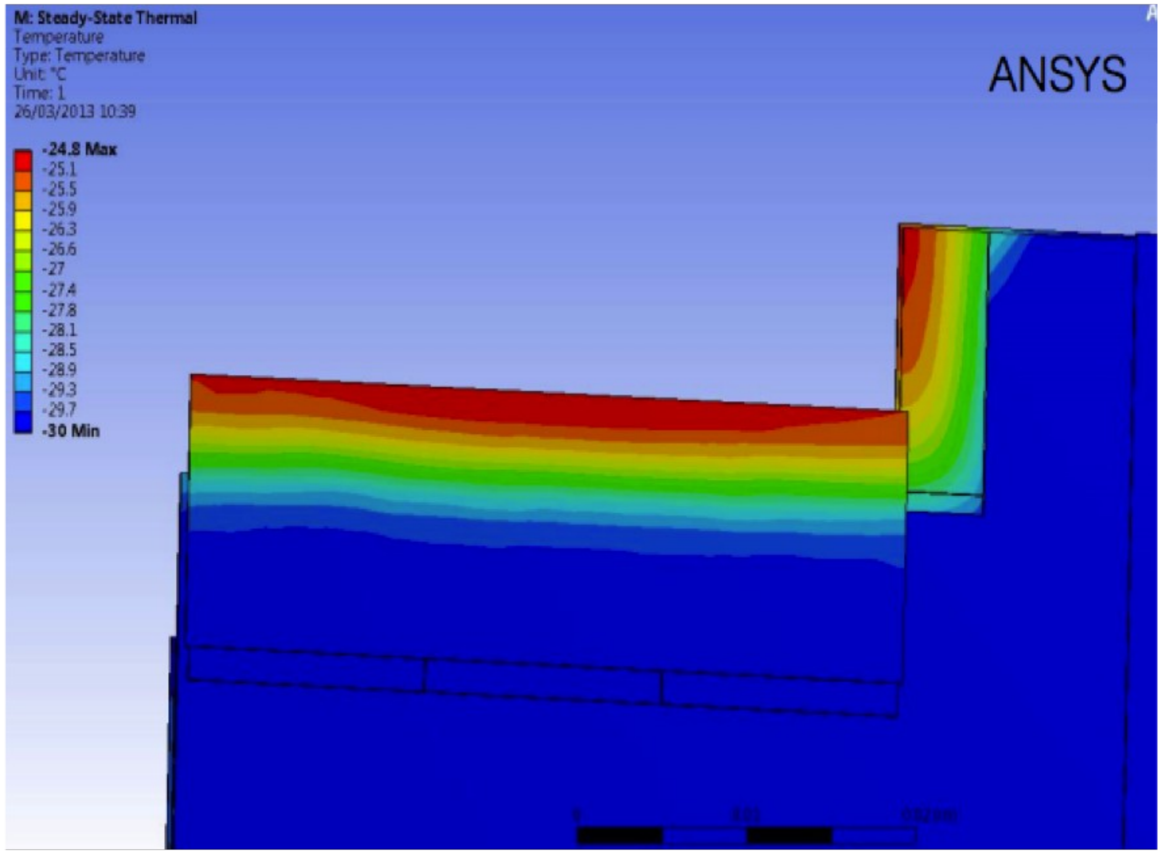
evaporative cooling → create regions to “boil” the CO2

high pressure (60 bar at +20C)

- thick cover (~200 μm)
- narow channels (70 x 200μm)
- solid metal “Kovar” connectors
- welded to metal layer on Si surface

Key components verified to 100s of bars



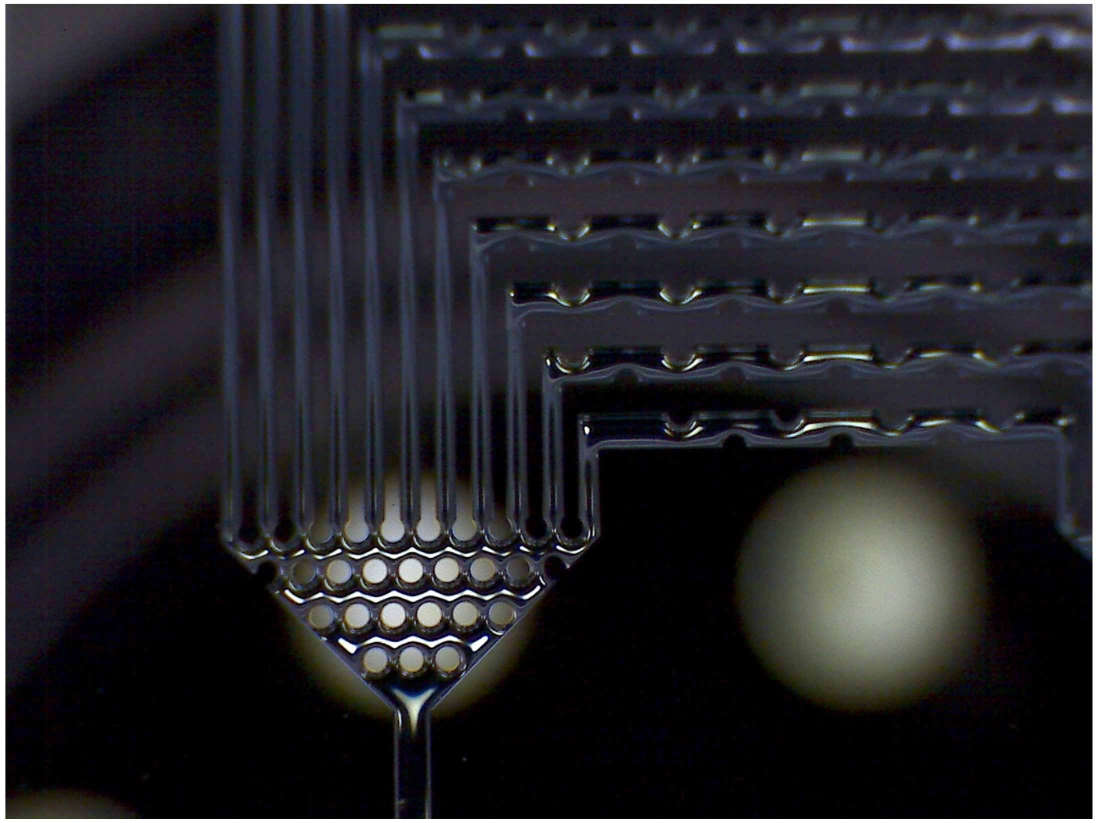


- Good thermal performance
- Temperature gradient at overhang

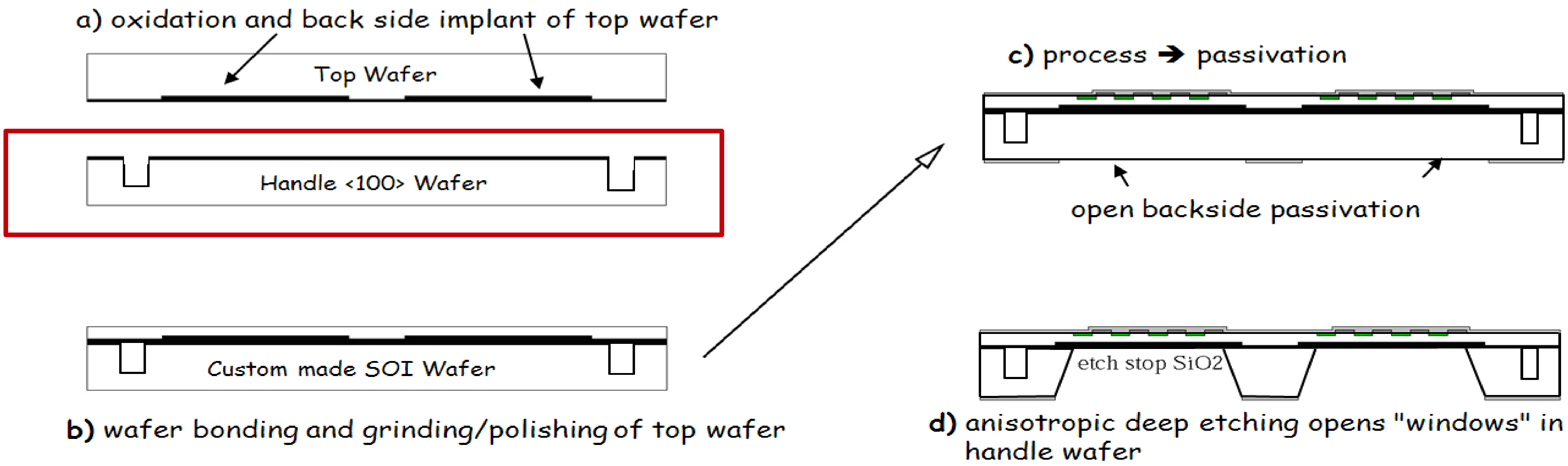
Micro-channel cooling, our take...

- Liquid cooling provides excellent temperature control, but is too bulky
- DEPFET, with localized power dissipation and SOI process, provides an interesting application → integrate cooling in all-silicon ladder
- Compared to existing effort, aim at relatively high temperature, low pressure
- Keep it simple: mono-phase

- Small team at University of Bonn MPG-HLL Munich and IFIC Valencia
- Embedded in larger effort of AIDA2020



All-silicon ladder with integrated cooling

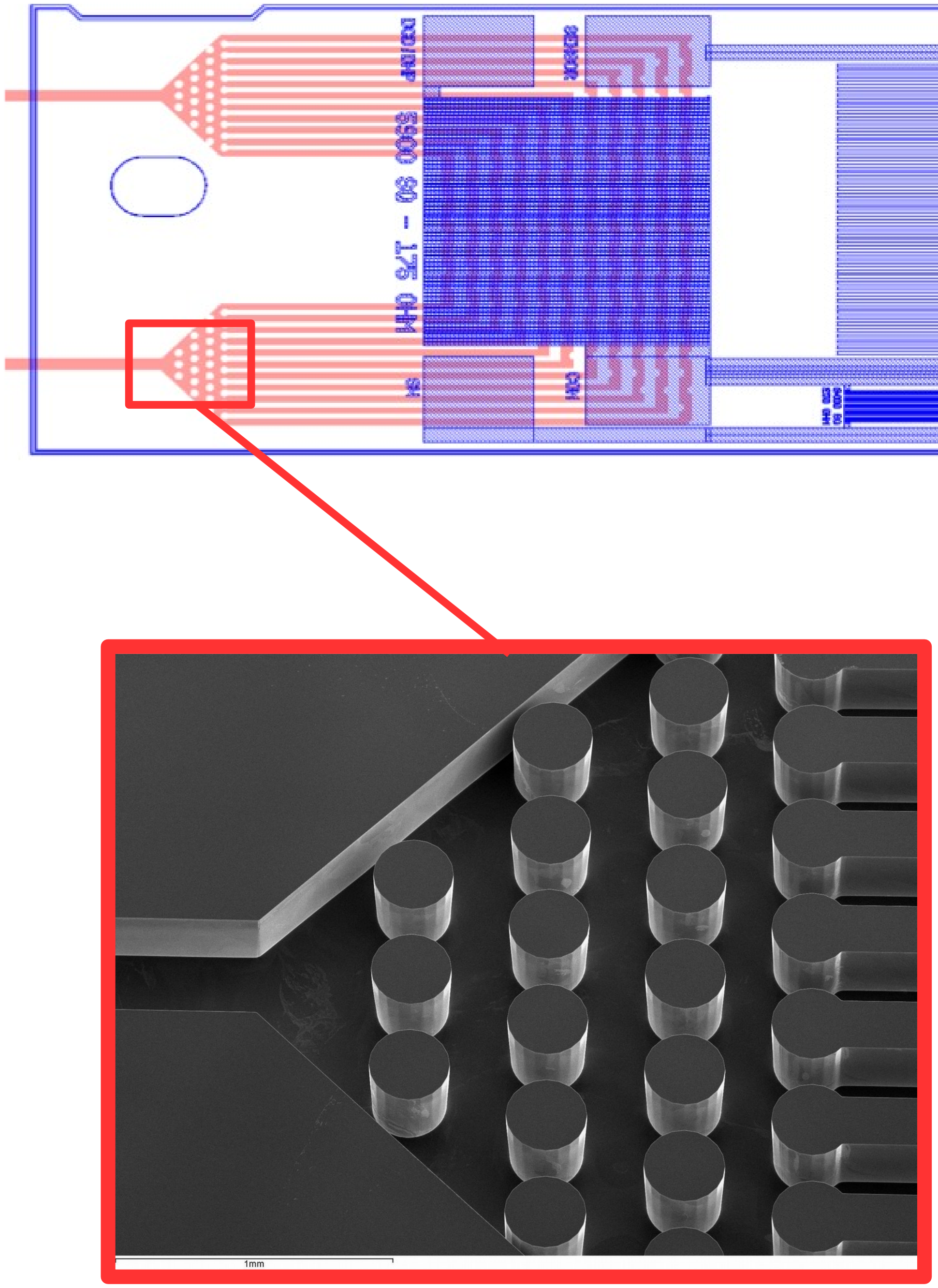


thinned all-silicon module with integrated cooling channels

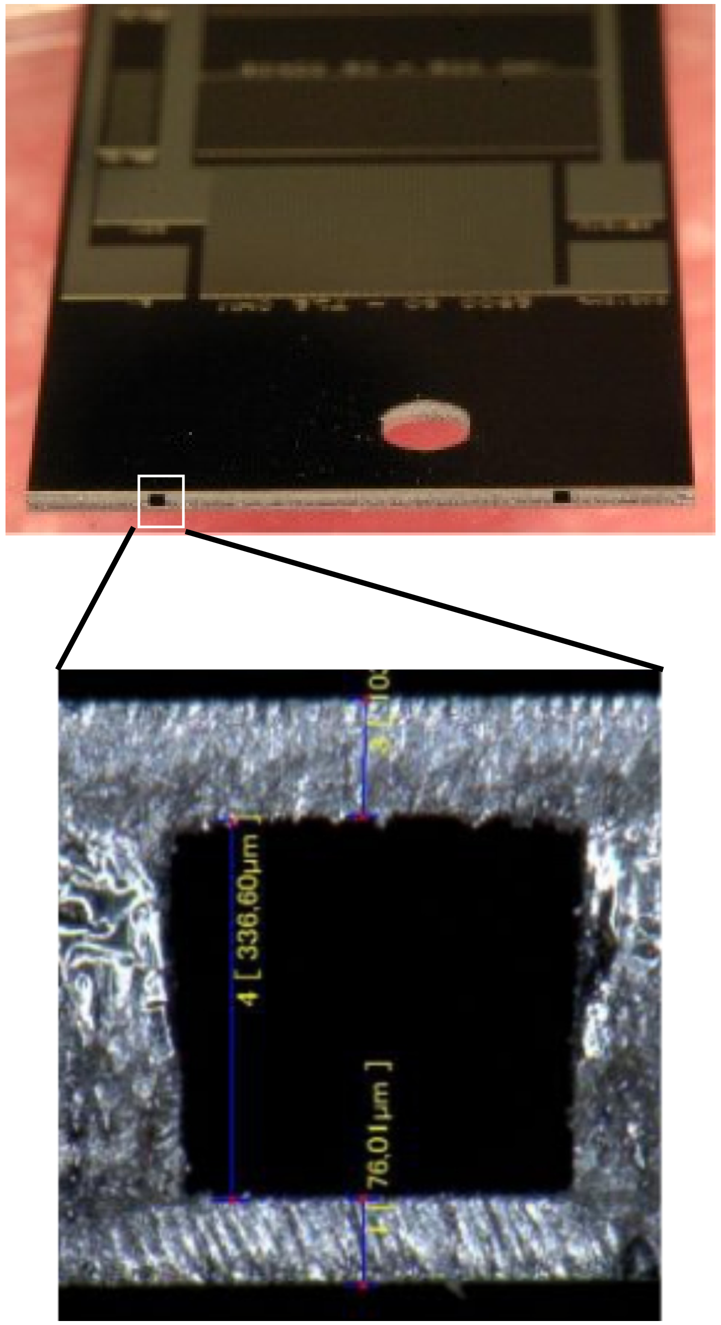
:- integrate channels into handle wafer beneath the ASICs
:- channels etched before wafer bonding → cavity SOI (C-SOI)
:- full processing on C-SOI, thinning of sensitive area
:- micro-channels accessible only after cutting (laser)

First attempt

Silicon sensors with integrated micro-channels based on DEPFET process:



Micro-channel pattern in handle wafer



Inlet and outlet: ~380 x 340 µm

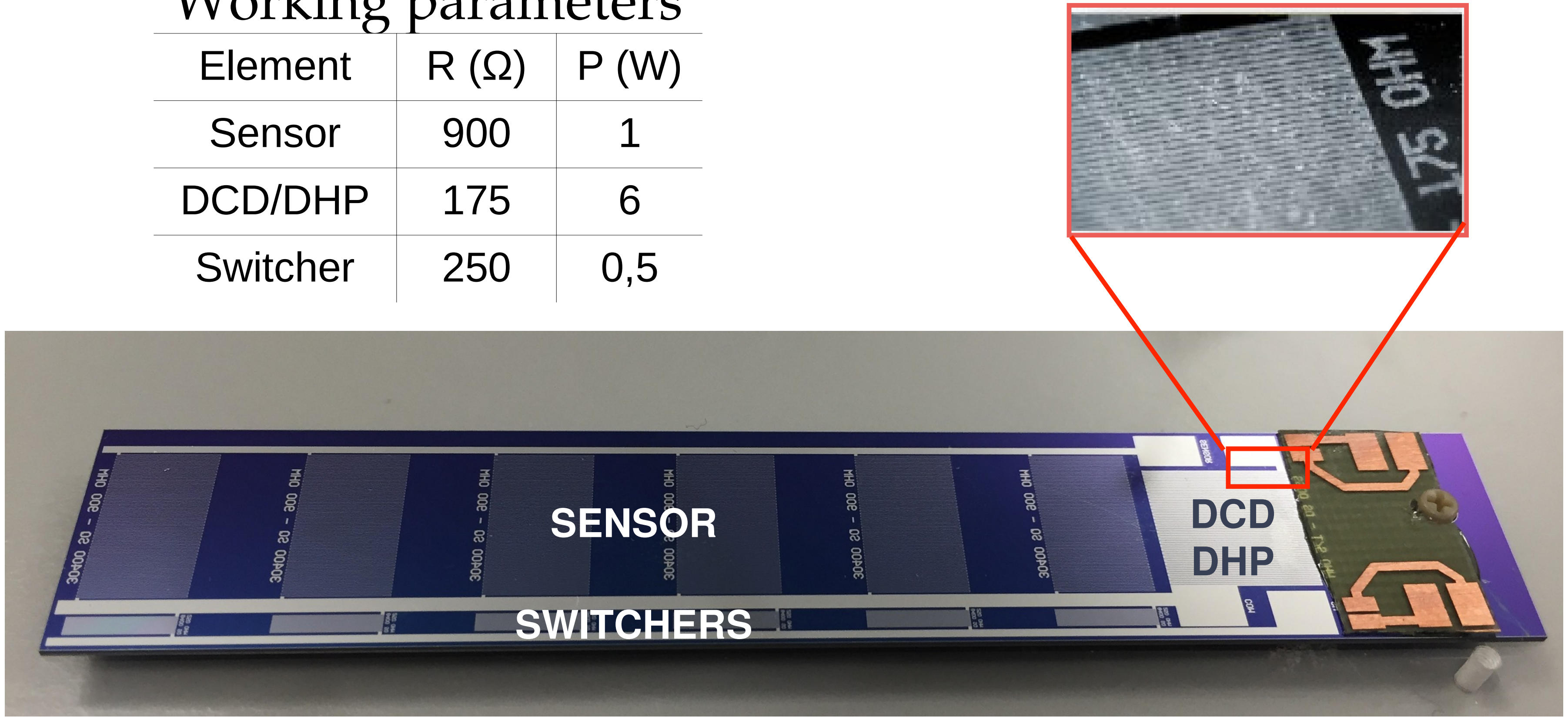
First attempt

Silicon sensors with integrated micro-channels based on DEPFET process:

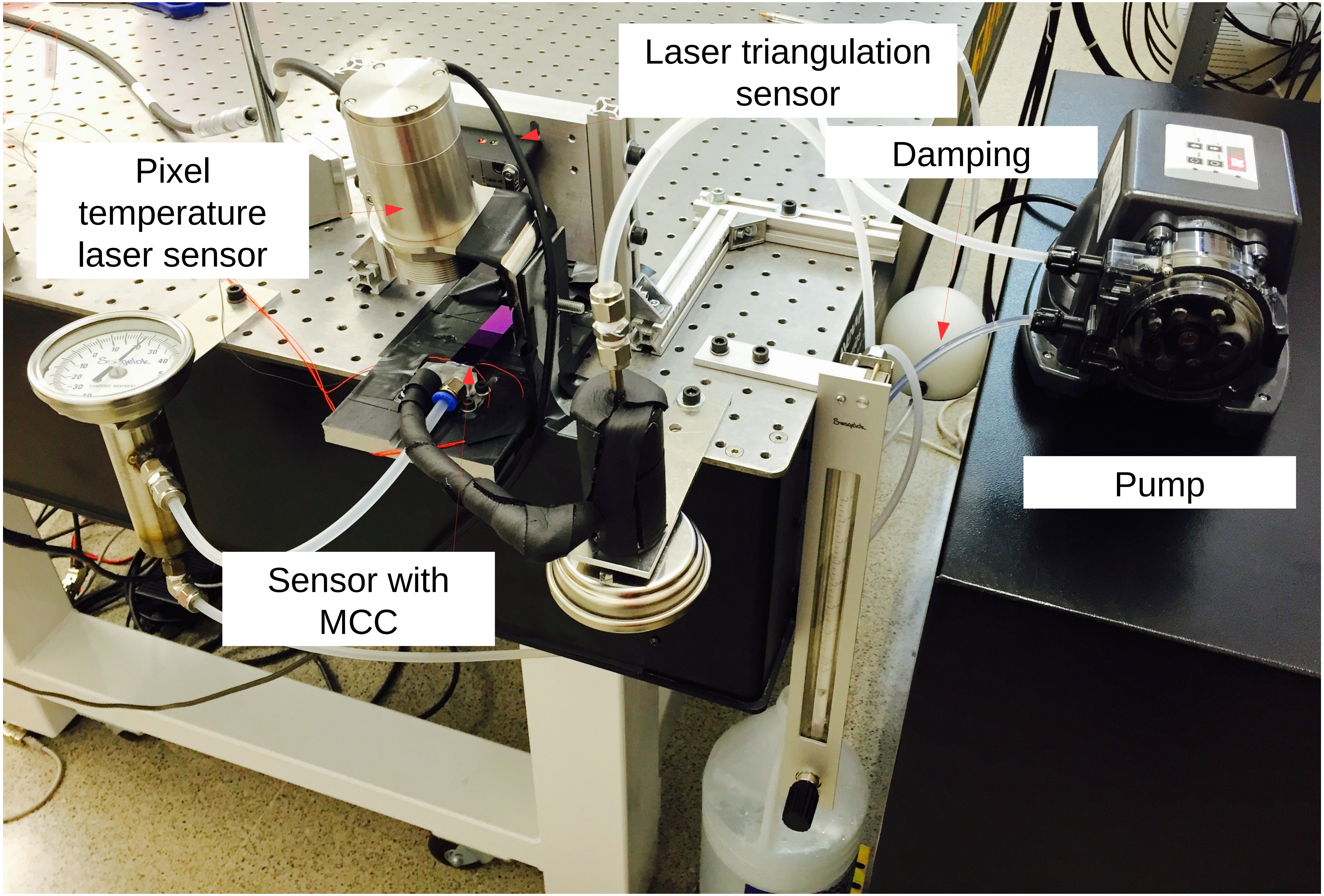
- Si modules with the designed dimensions of the DEPFET detectors
- Homogeneous thickness: sensor area not thinned
- Aluminum layer with resistors **simulates the DEPFET power distribution**

Working parameters

Element	R (Ω)	P (W)
Sensor	900	1
DCD/DHP	175	6
Switcher	250	0,5

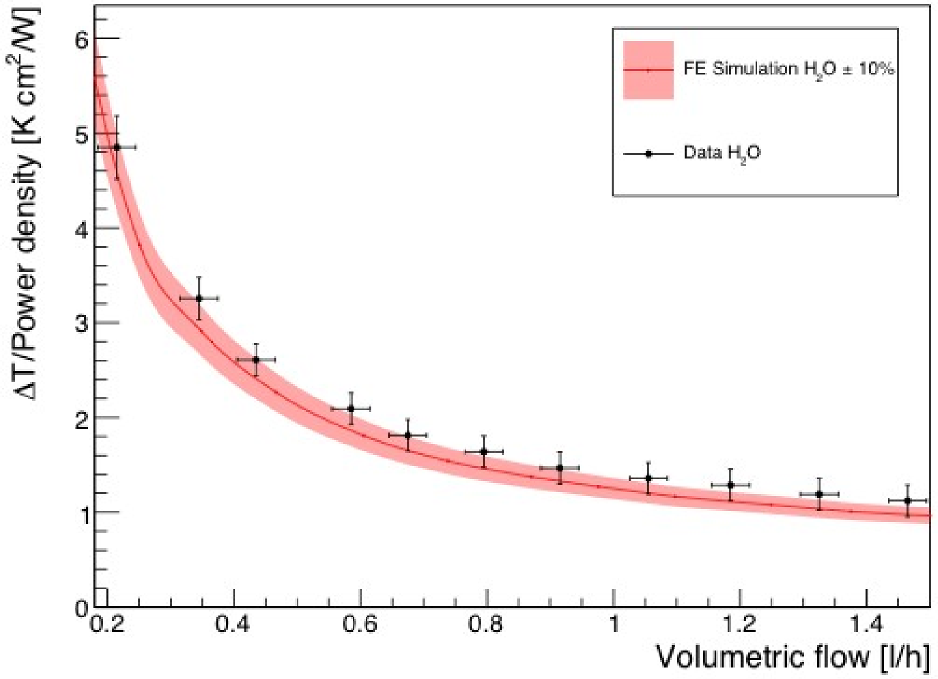


Measurements

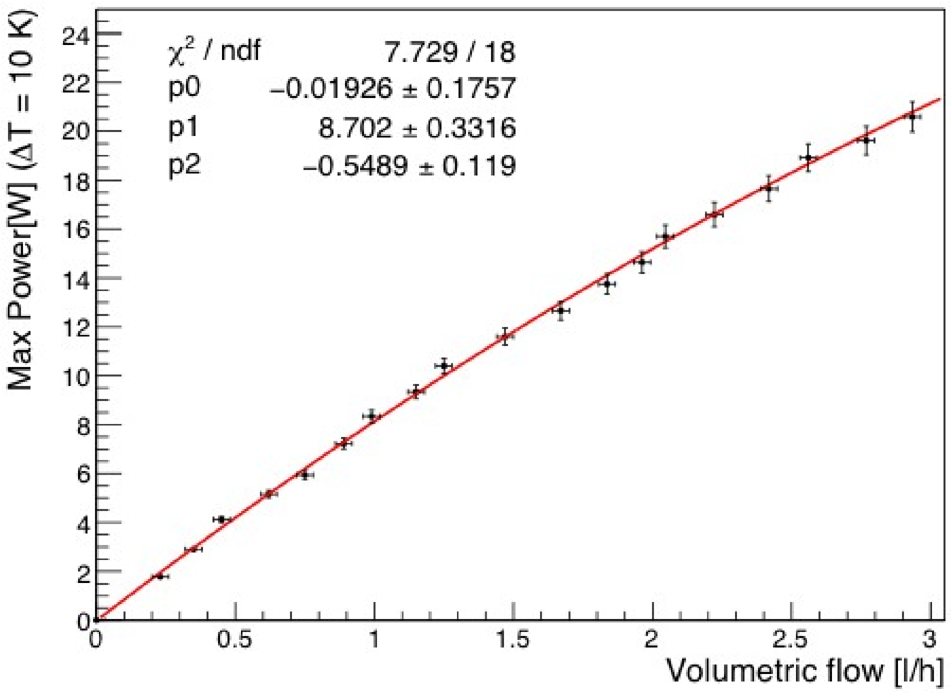


First results

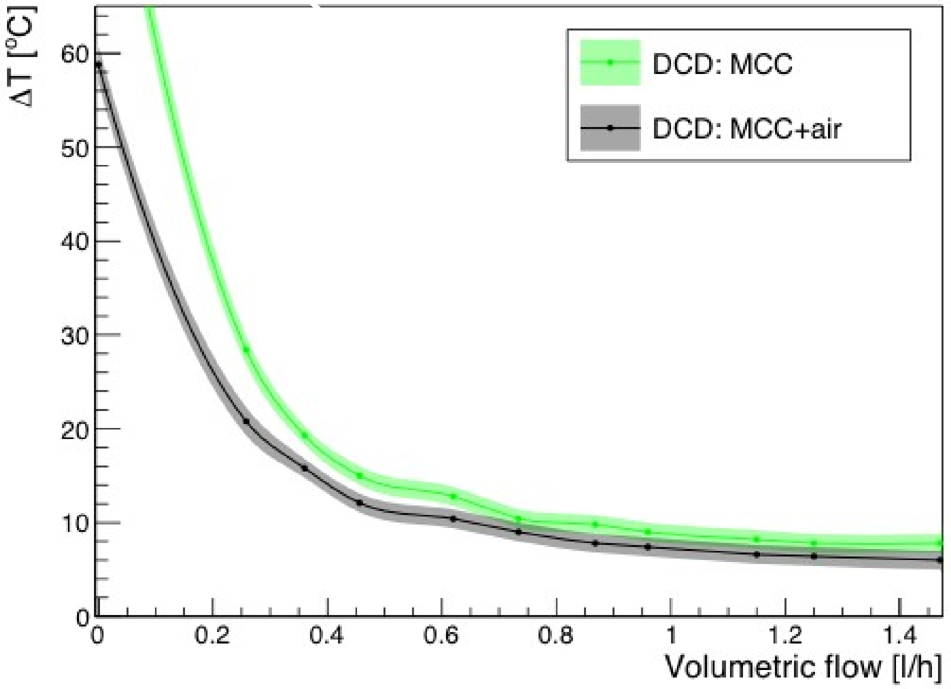
TFM: lab vs sim results



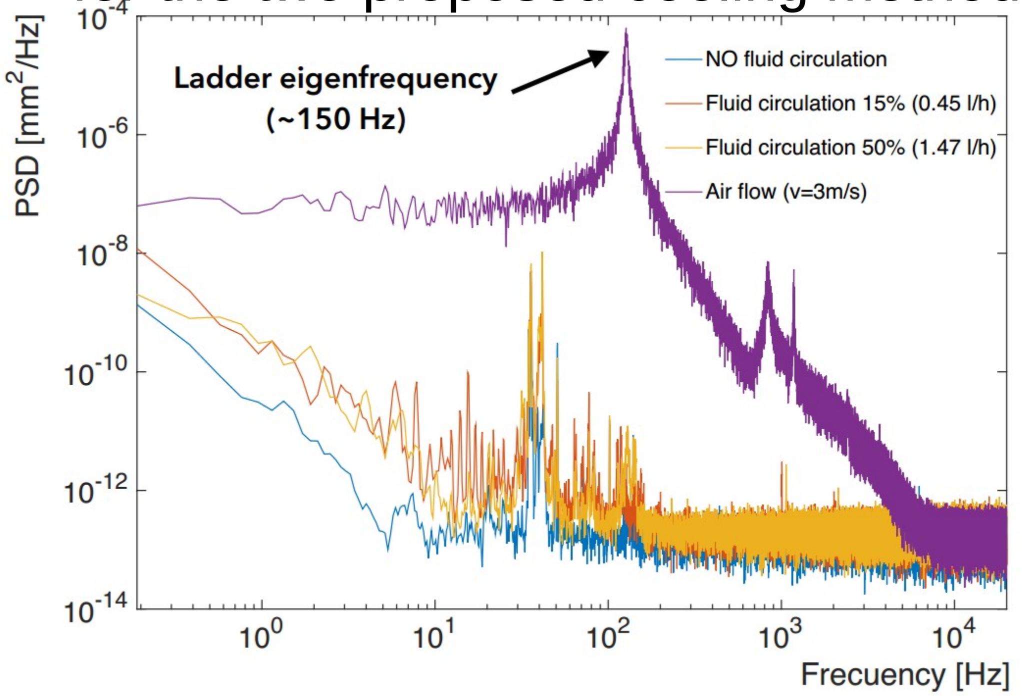
Max. power for ΔT=10K



Difference between mcc and mcc+air

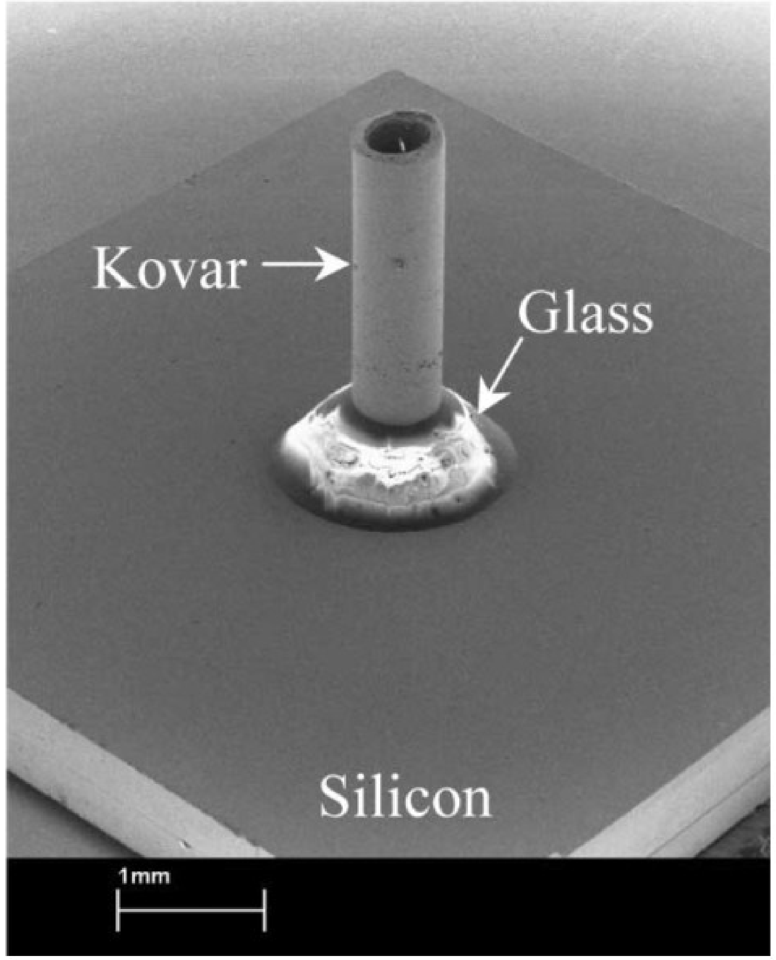


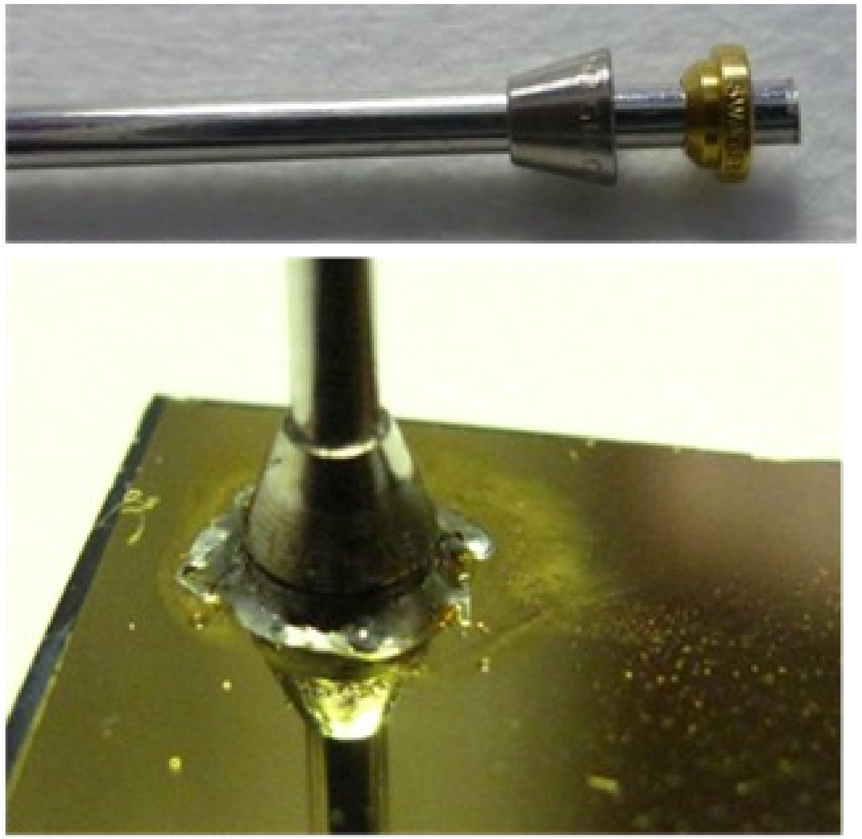
First frequency mode and deformation influence for the two proposed cooling methods

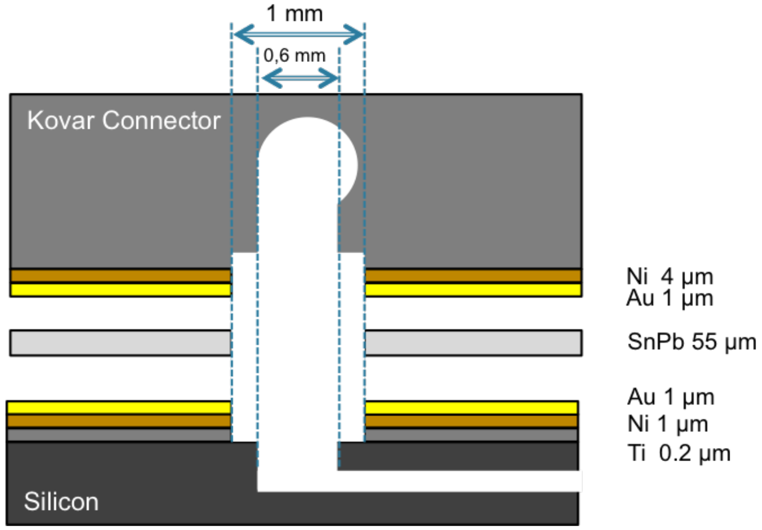


More information available in JINST, Volume 11, June 2016

Connectors – forward experiments





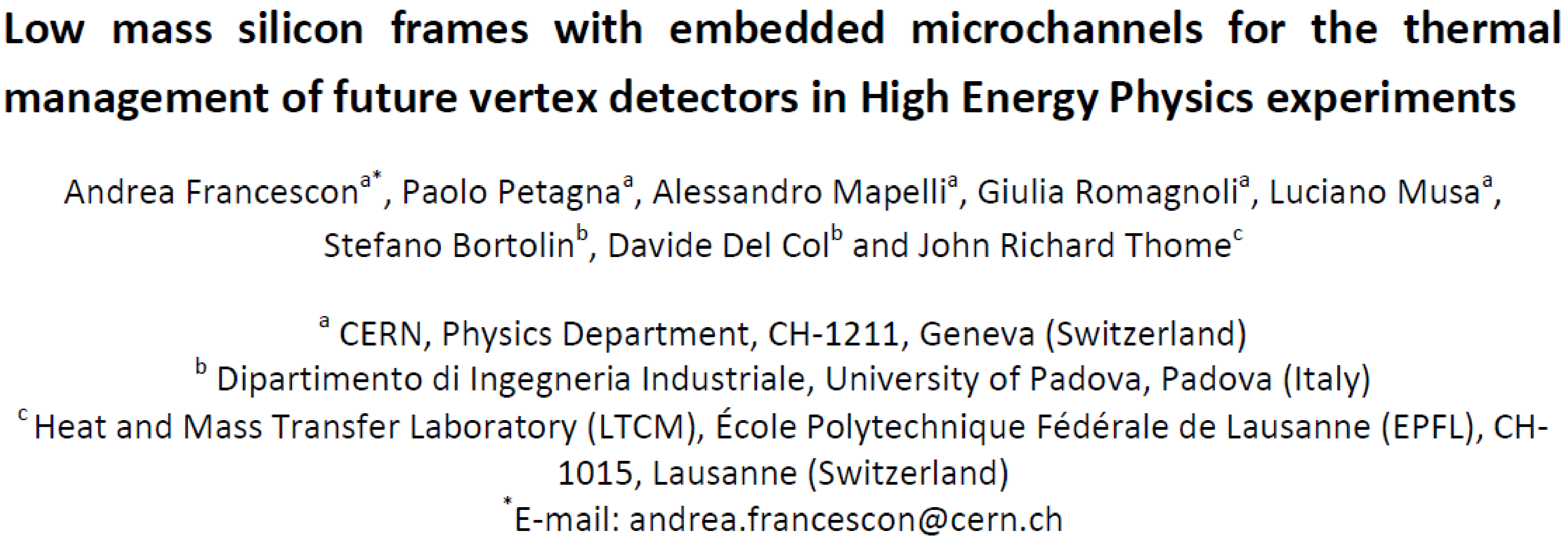


LHCb VELO upgrade, JINST 11 C05014

- Solution adopted by experiments who leave the connectors outside acceptance:
  - Out-of-plane connection with relatively large diameter
  - Kovar (nickel/cobalt) soldered onto silicon with metal layer
- Very solid connection: shown to stand a pressure of 400 bar and a pull force of 600 N

Connectors – ALICE ITS

NanoportTM
PEEK connectors

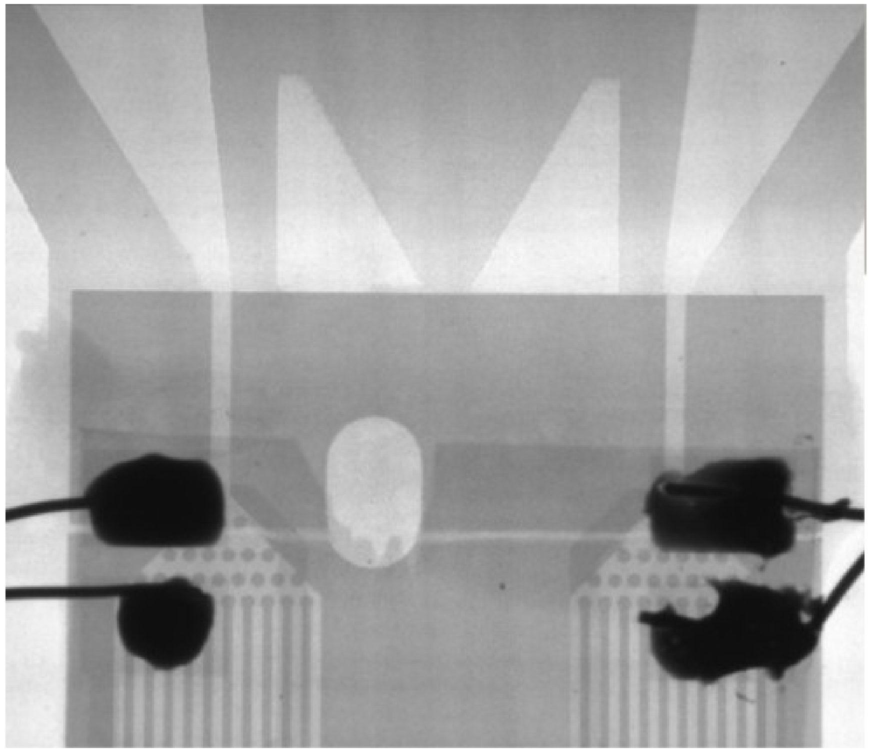


Low mass silicon frames with embedded microchannels for the thermal management of future vertex detectors in High Energy Physics experiments

Andrea Francescon[a*], Paolo Petagna[a], Alessandro Mapelli[a], Giulia Romagnoli[a], Luciano Musa[a],
Stefano Bortolin[b], Davide Del Col[b] and John Richard Thome[c]

[a] CERN, Physics Department, CH-1211, Geneva (Switzerland)
[b] Dipartimento di Ingegneria Industriale, University of Padova, Padova (Italy)
[c] Heat and Mass Transfer Laboratory (LTCM), École Polytechnique Fédérale de Lausanne (EPFL), CH-1015, Lausanne (Switzerland)
[*] E-mail: andrea.francescon@cern.ch

Low-mass in-plane connectors

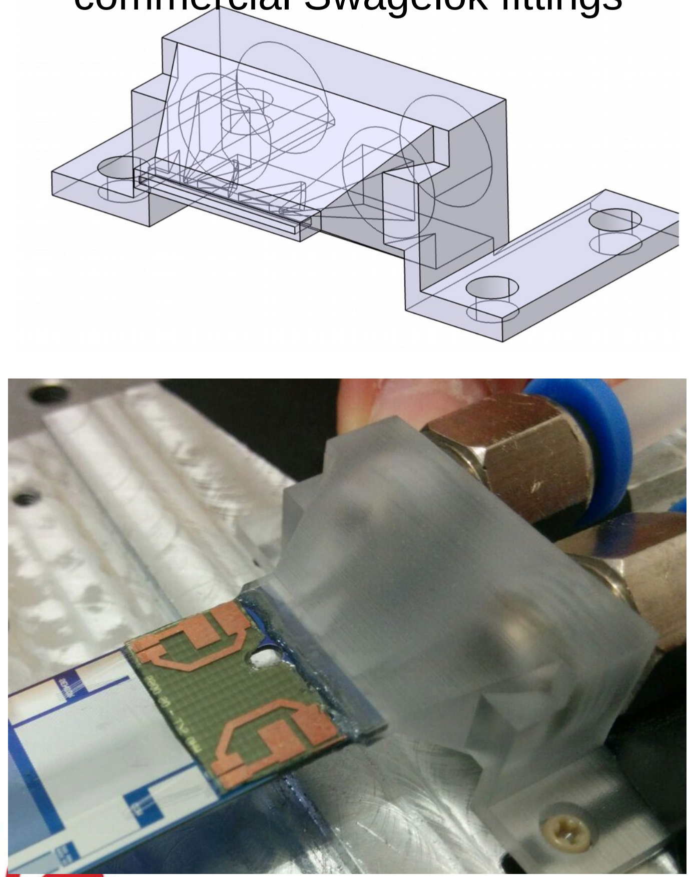


Low-Z 3D-printed connectors

Arbitrary complexity, 30 μm tolerance
→ self-align with silicon channels
Very rapid prototyping, very cheap
Pressure-tested to >100 bars
(connector, glue connection to be improved)

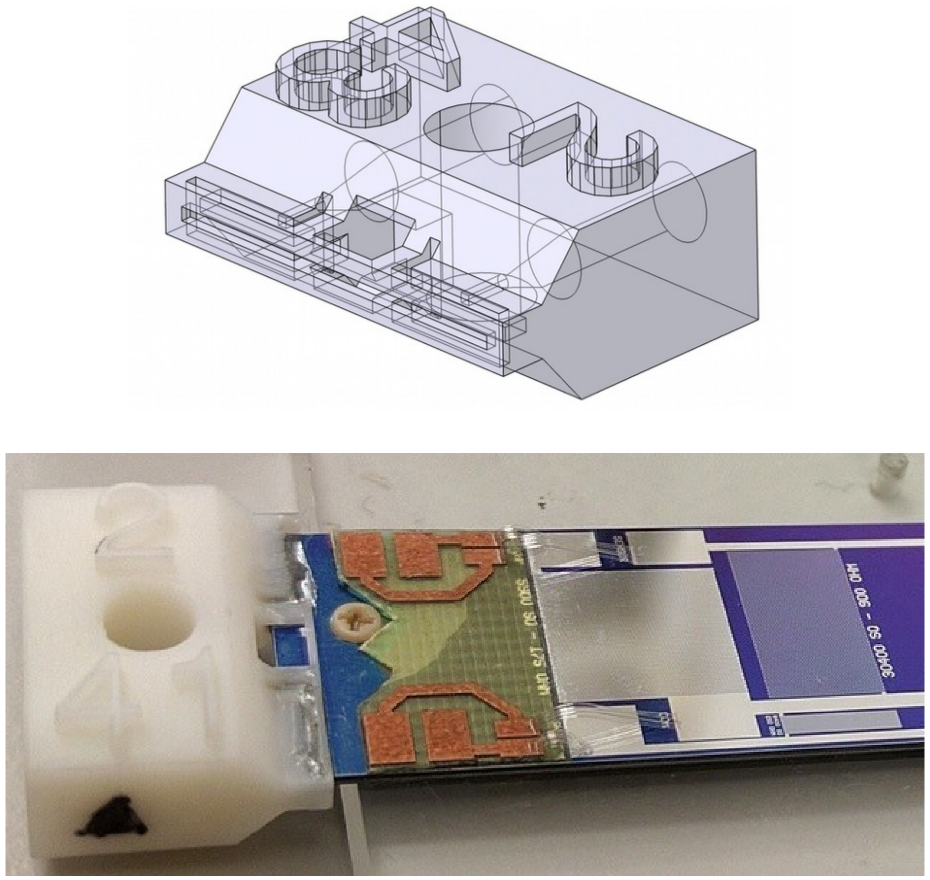
First attempt (0.81% X/X₀)

Mechanical interface to standard commercial Swagelok fittings



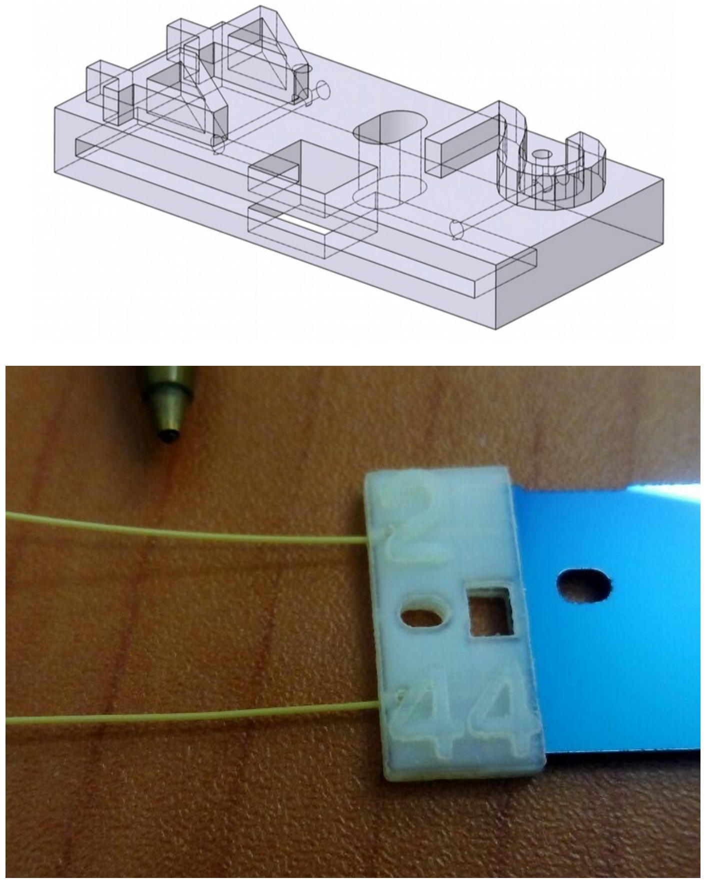
Past (0.21% X/X₀)

Smaller fittings



Present (0.05% X/X₀)

Glue PEEK tubes

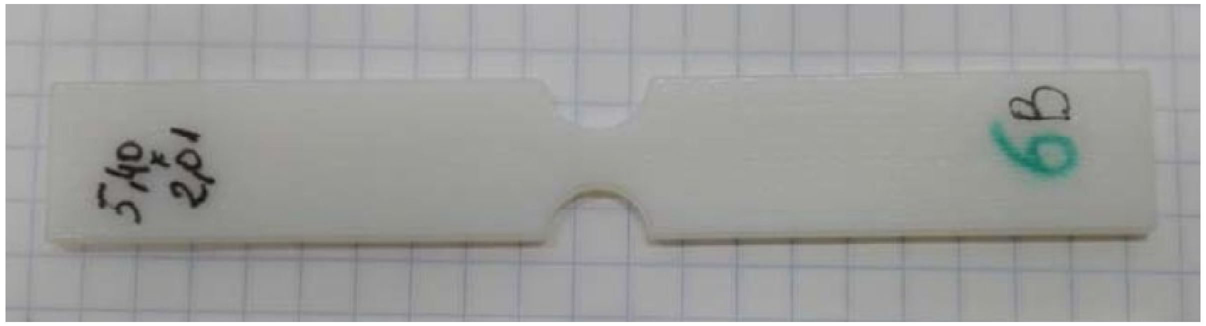


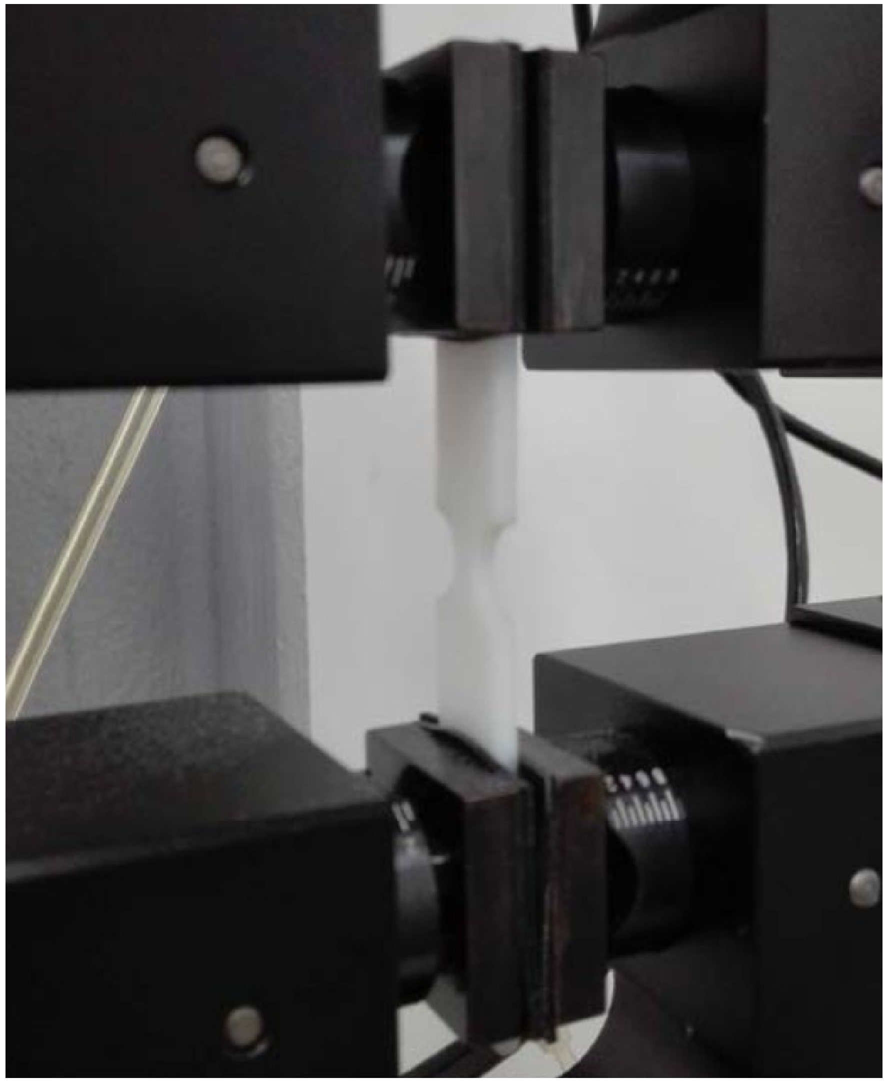
MCC qualification: connector material

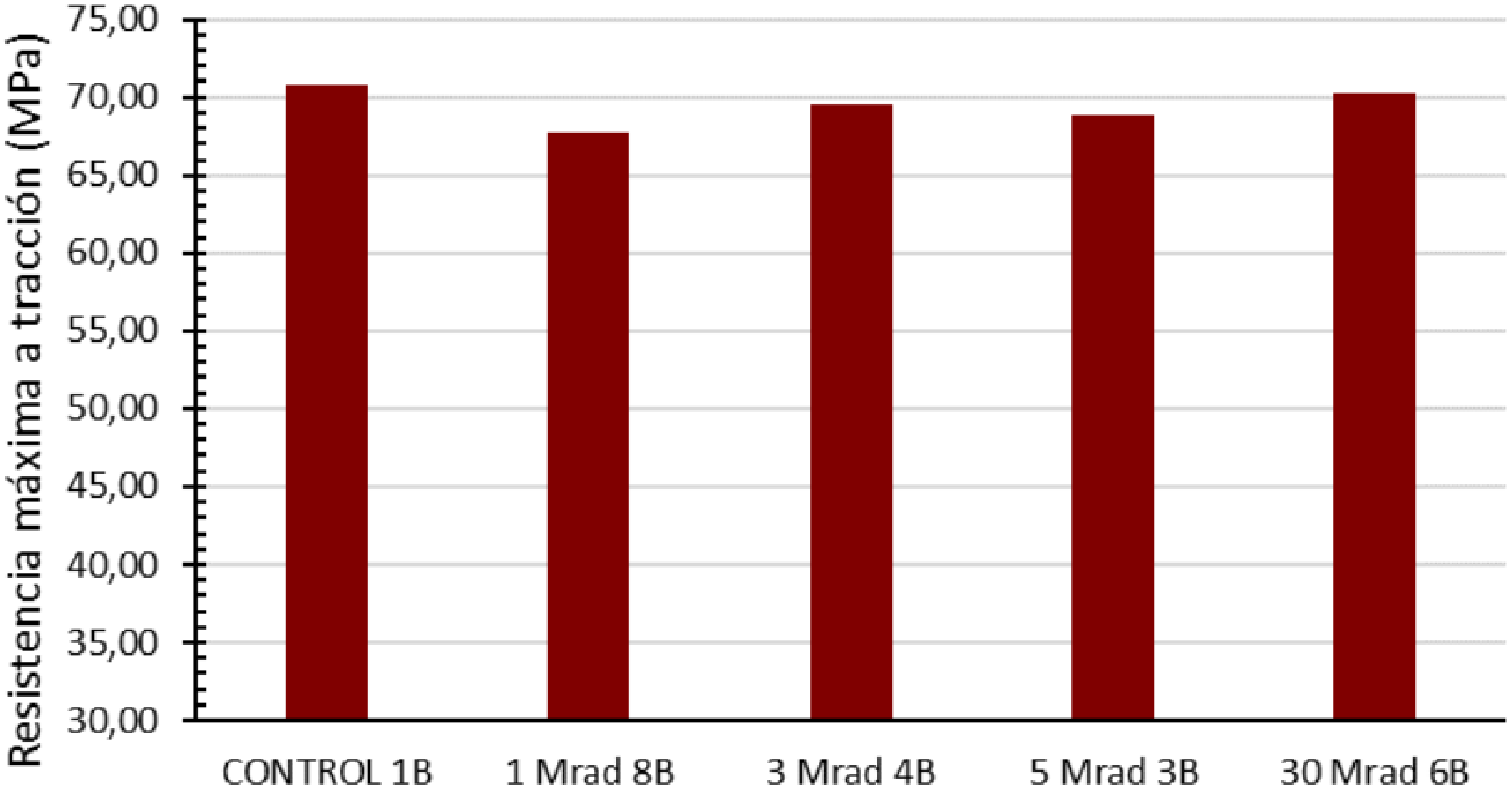
Different radiations levels

Two type of radiation:
- Neutrons (not done yet)
- **X-Rays**

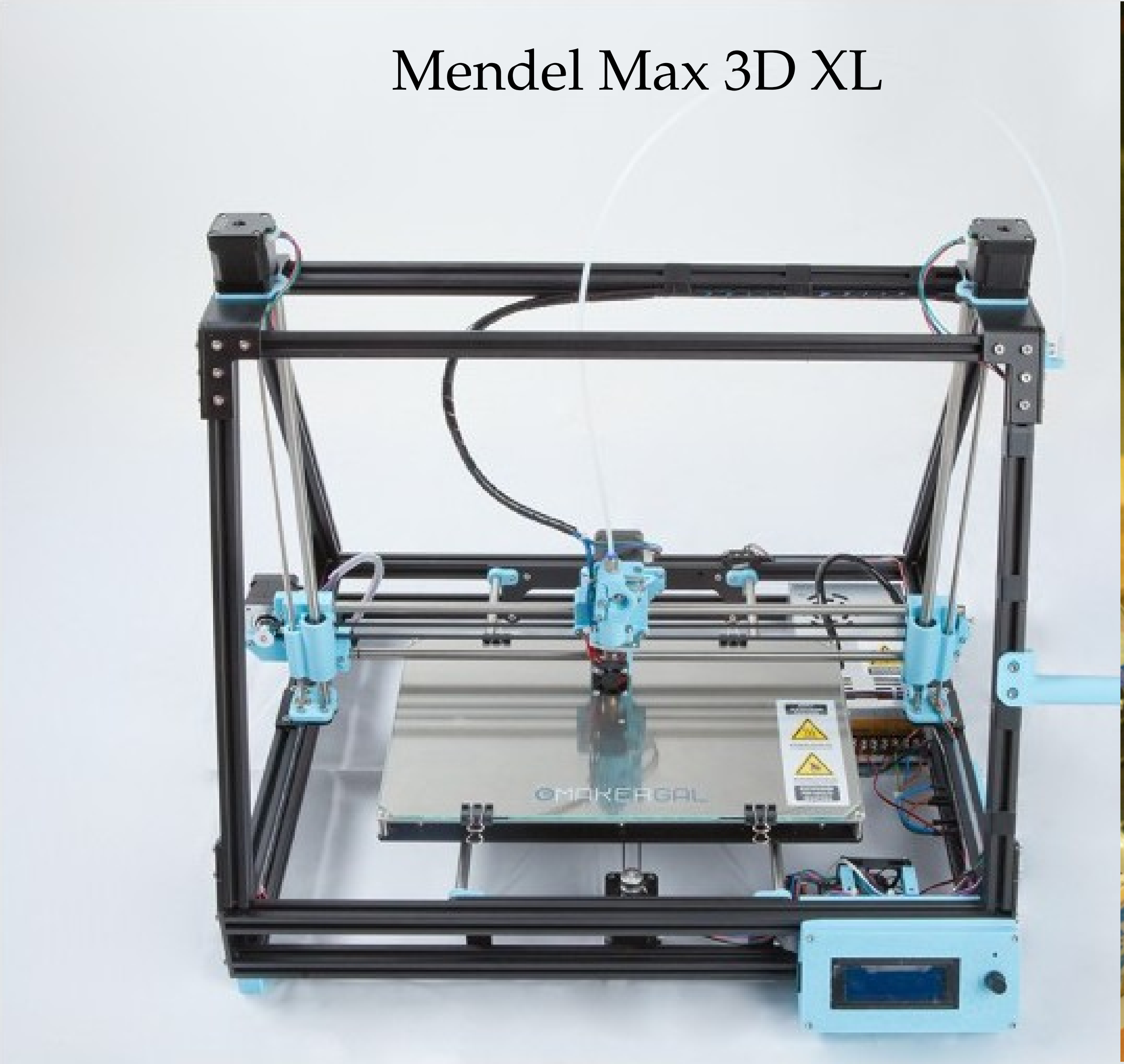
MCC qualification: connectors material

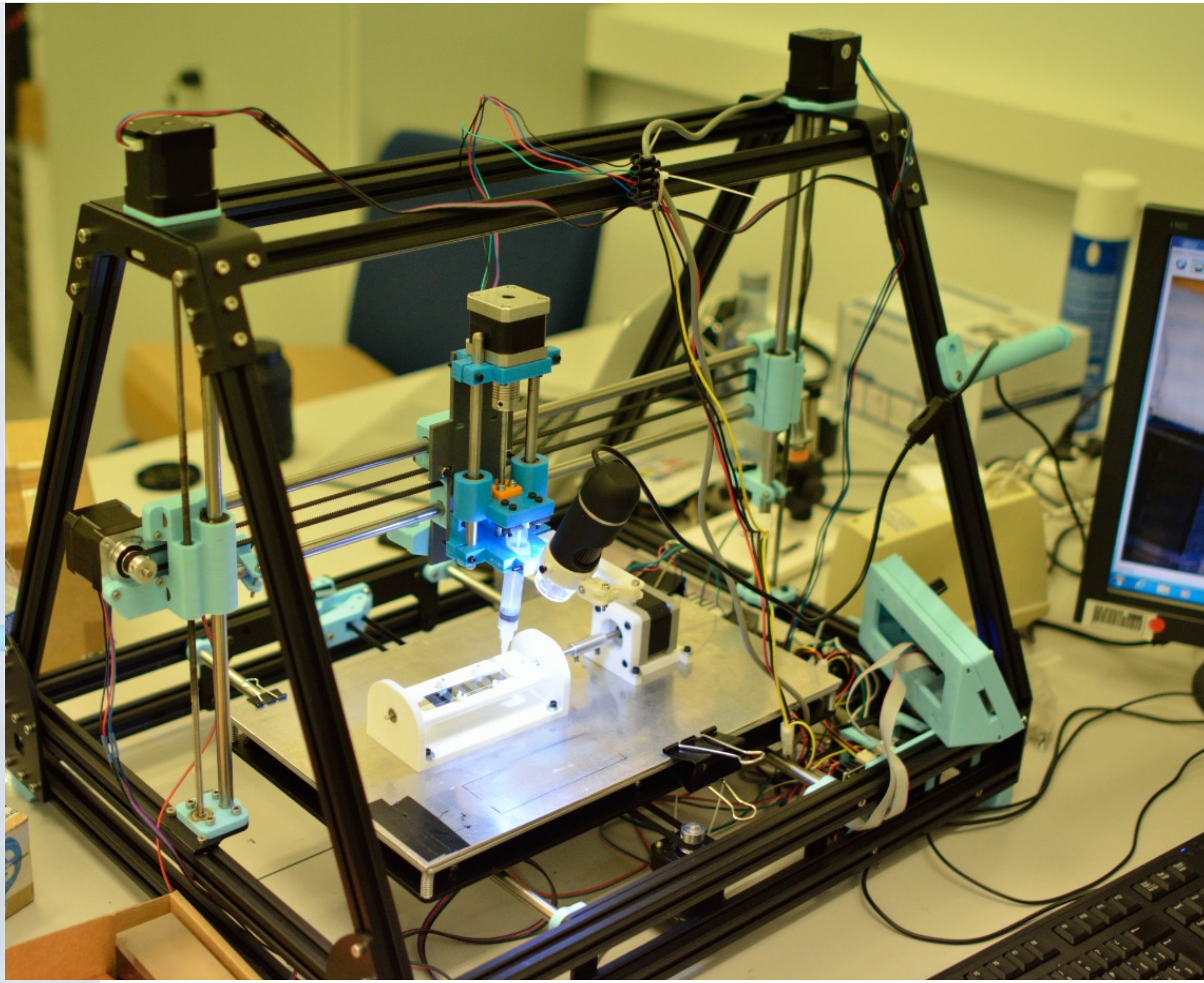






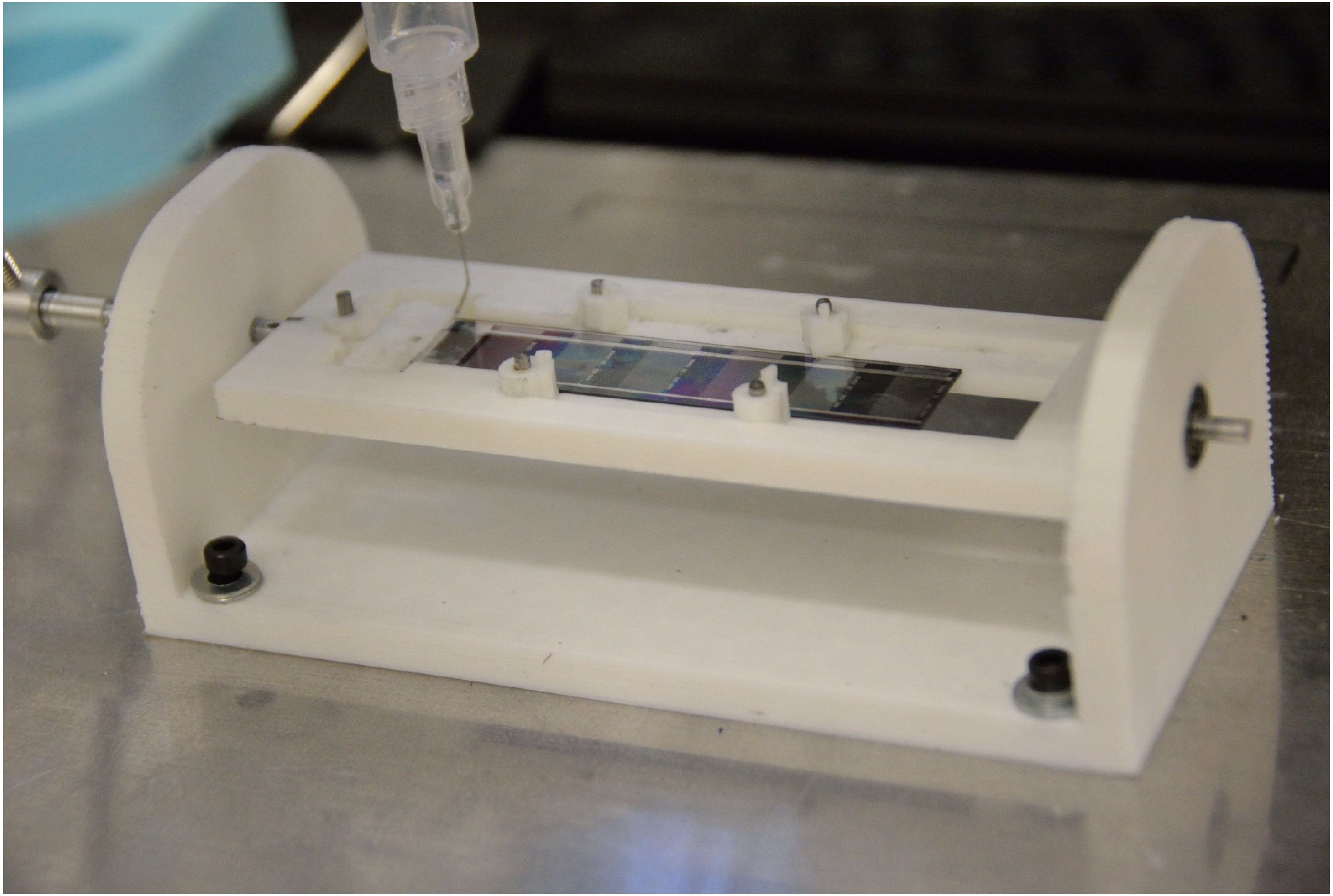
MCC qualification: automatic assembly


Mendel Max 3D XL



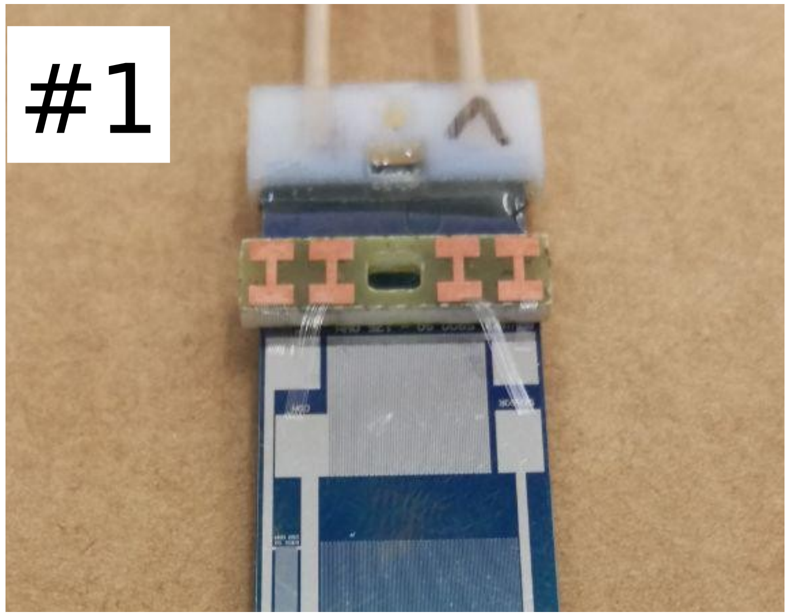
- Glue robot based on low-cost 3D printer: open hardware and software
- Adapted to incorporate syringe with controlled glue volume

MCC qualification: automatic assembly



MCC qualification: Vacuum test

Sample number	#1	#2	#3	#4
Vacuum test [mbar l/h]	5.5×10^{-9}	9.0×10^{-9}	8.6×10^{-9}	6.1×10^{-9}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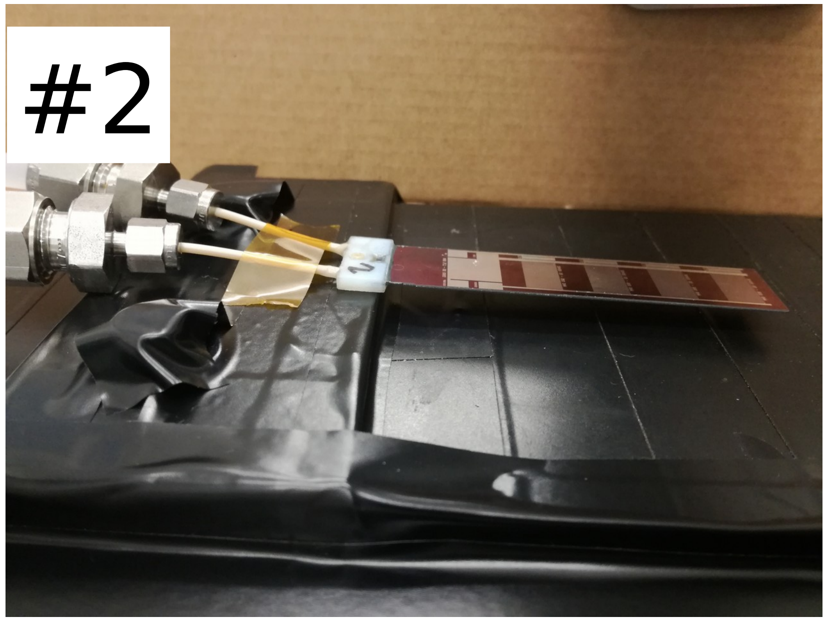
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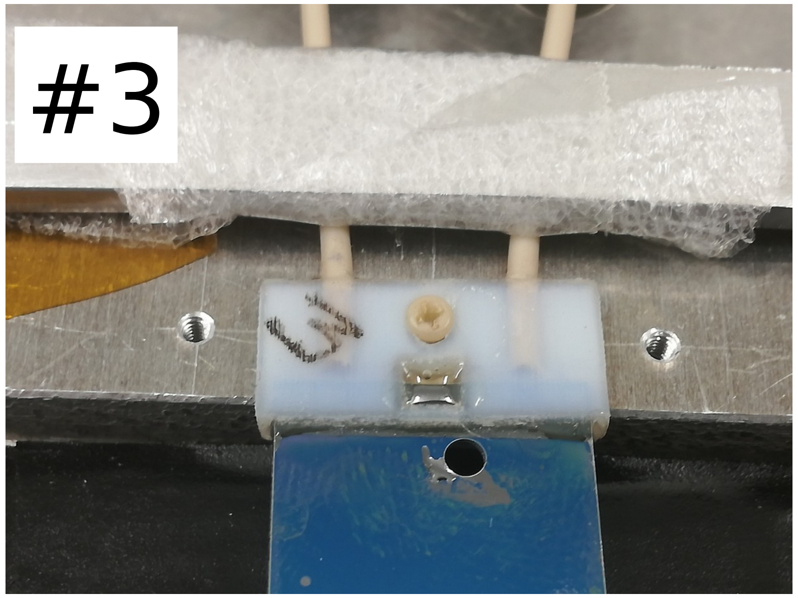
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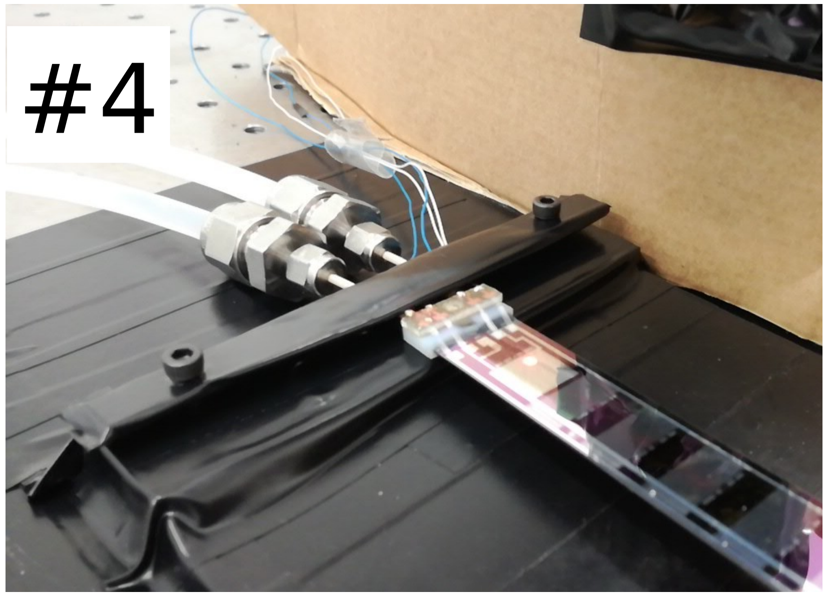
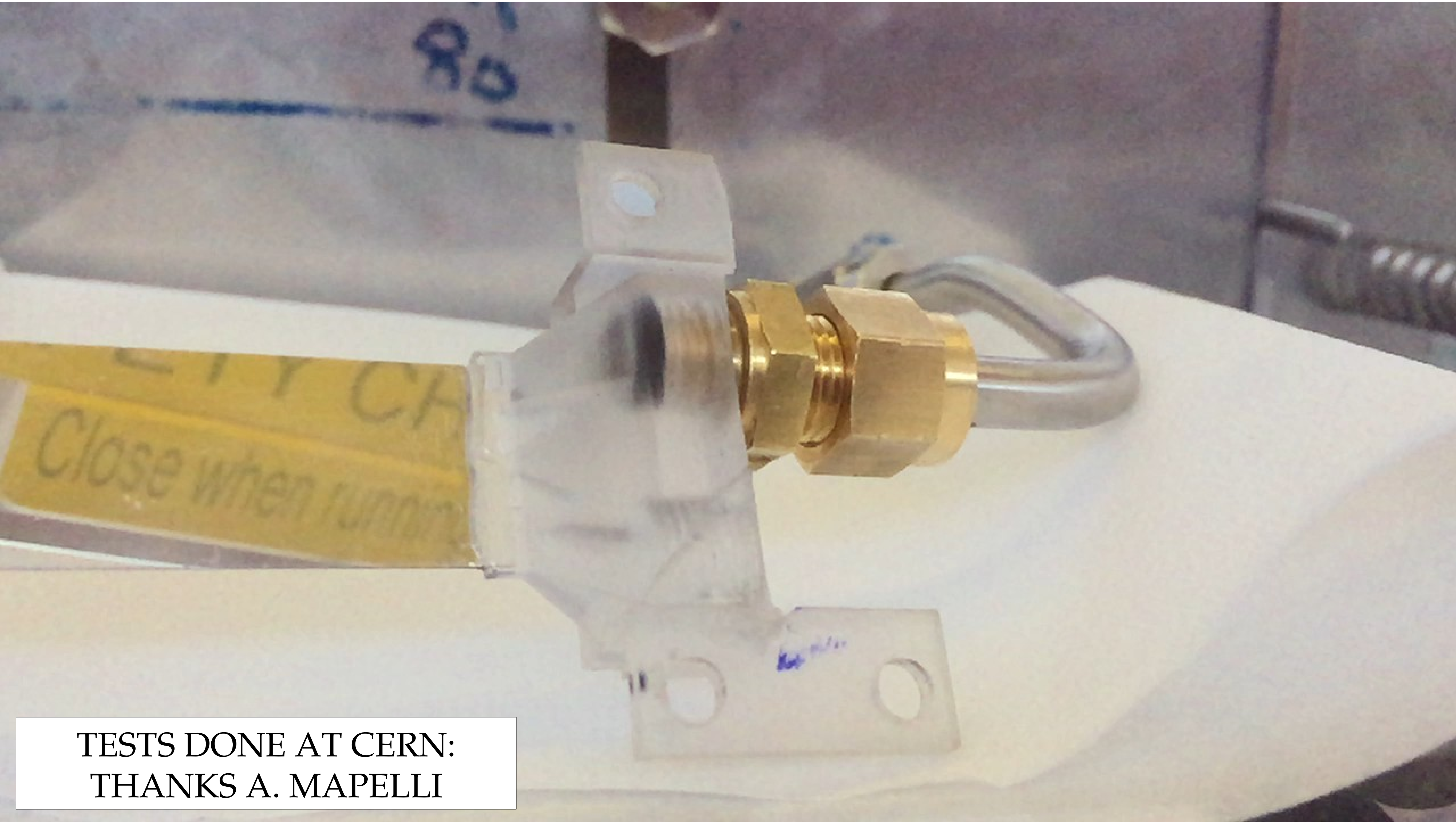

#4

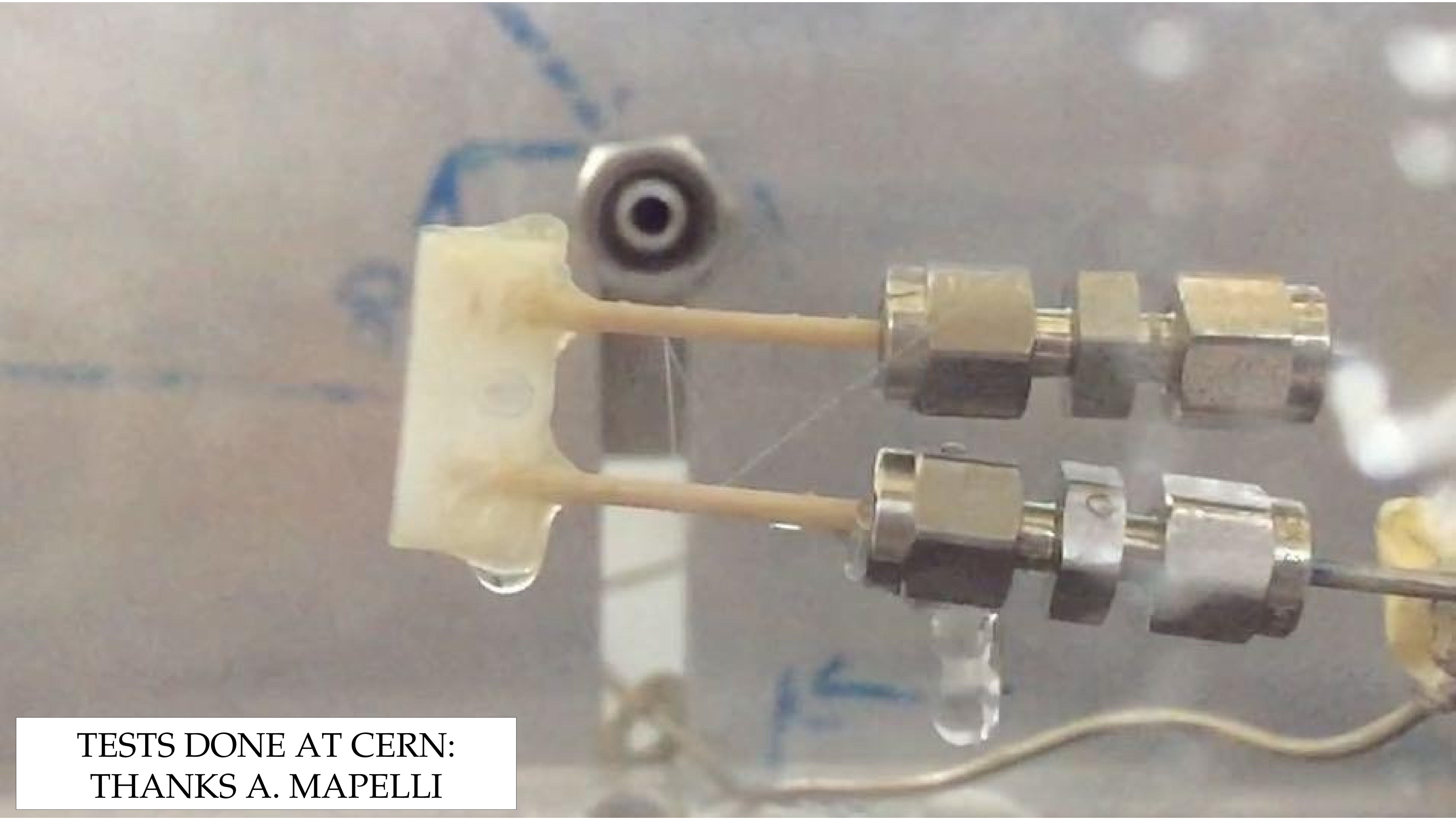
MCC qualification: pressure test



TESTS DONE AT CERN:
THANKS A. MAPELLI

180 bar achieved

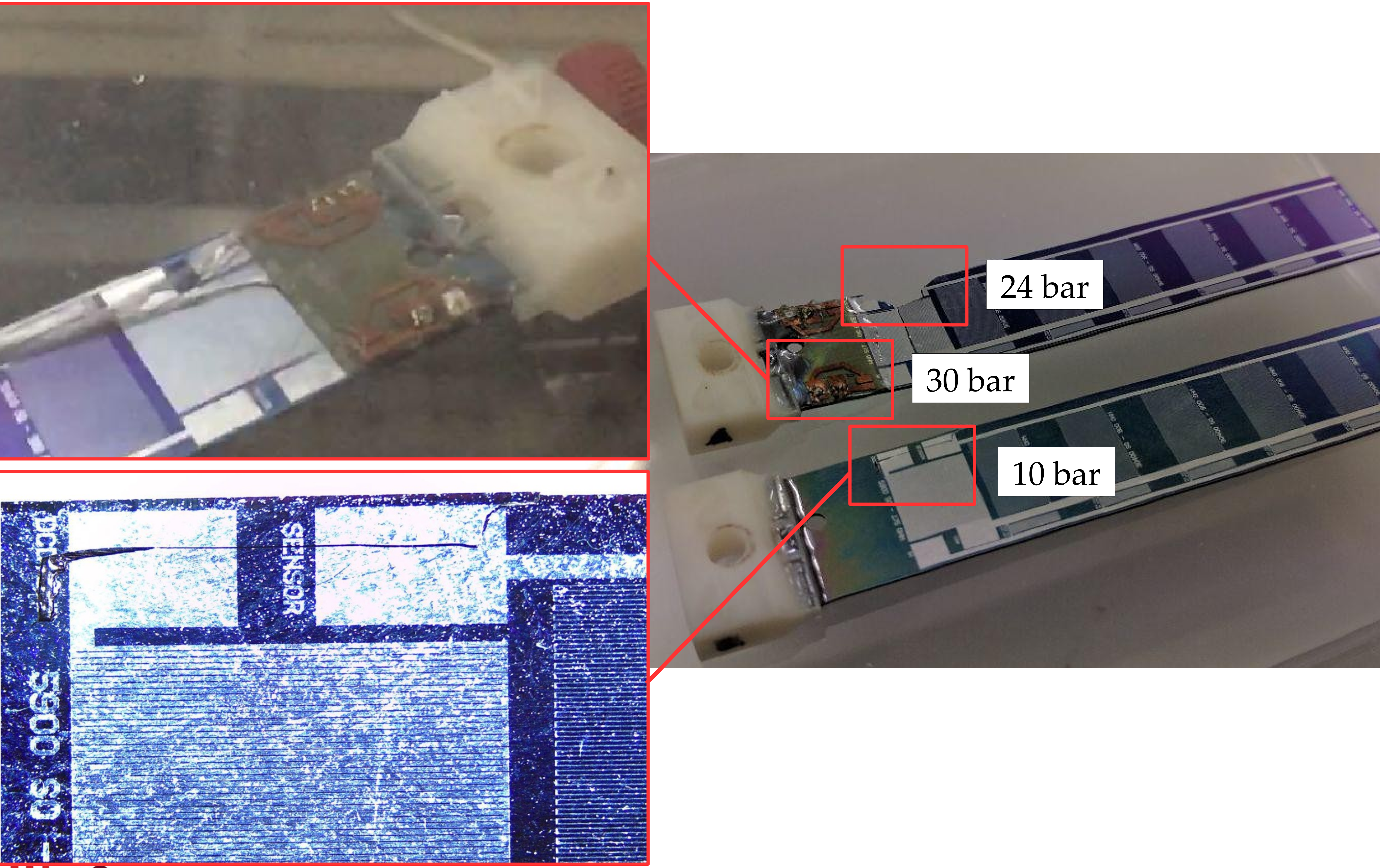
MCC qualification: pressure test



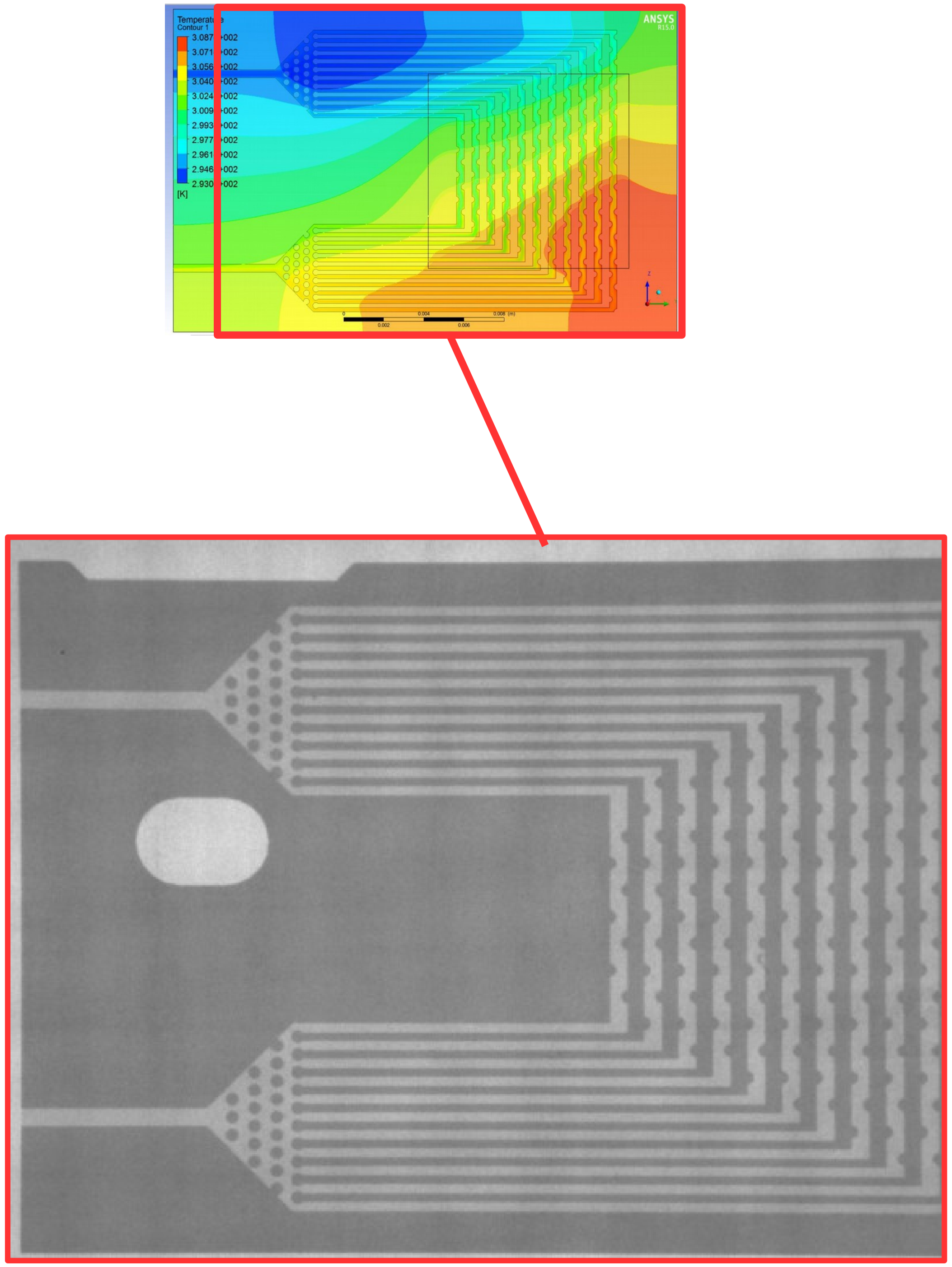
TESTS DONE AT CERN:
THANKS A. MAPELLI

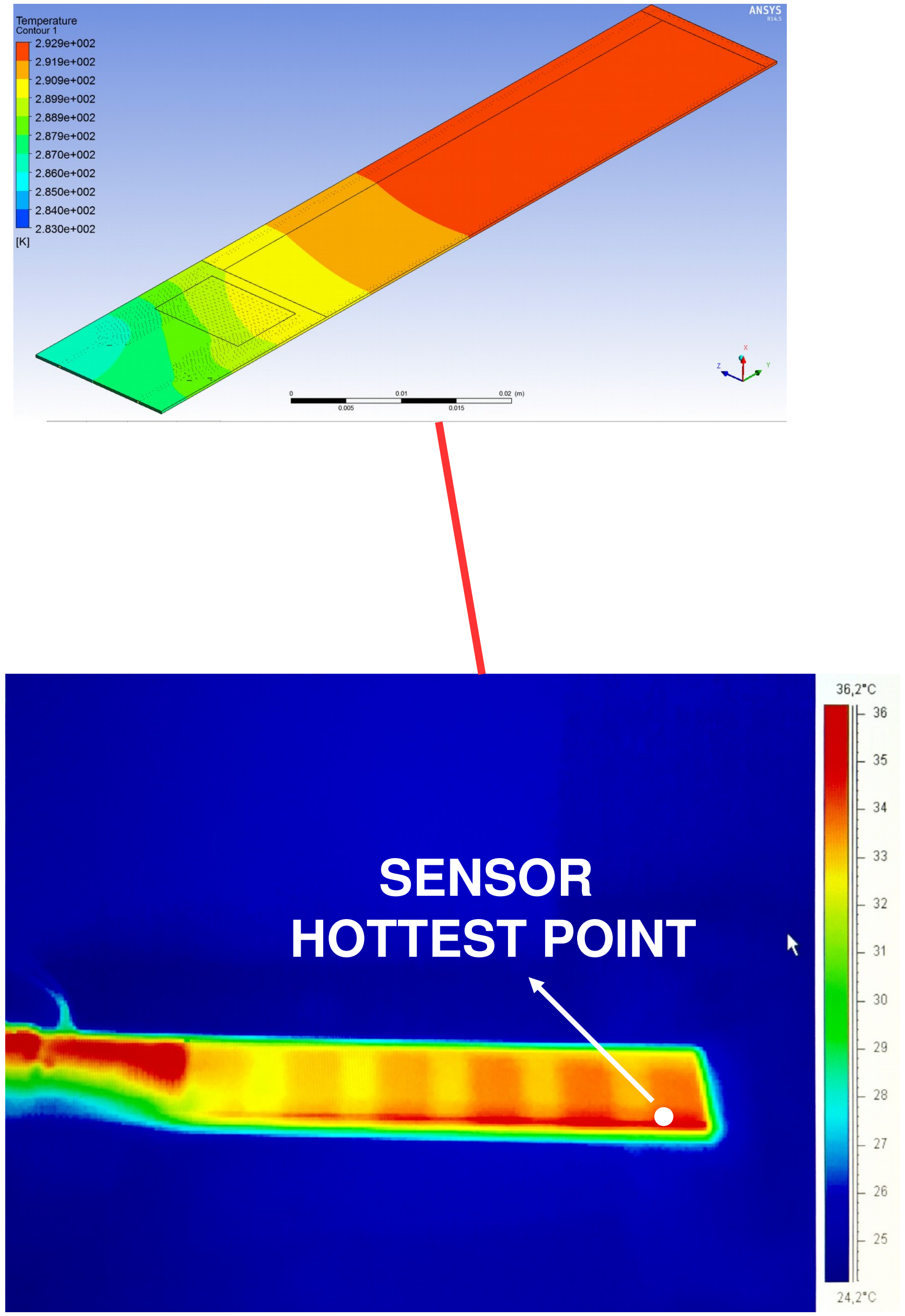
50 bar achieved

MCC optimization: pressure test

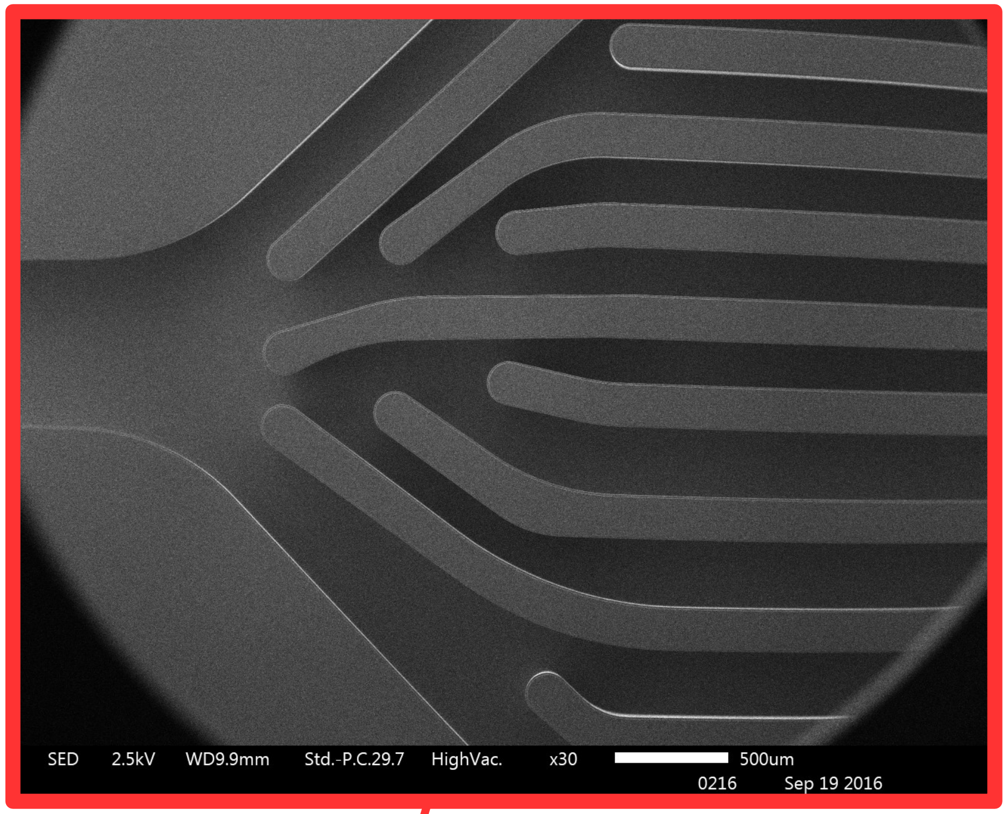


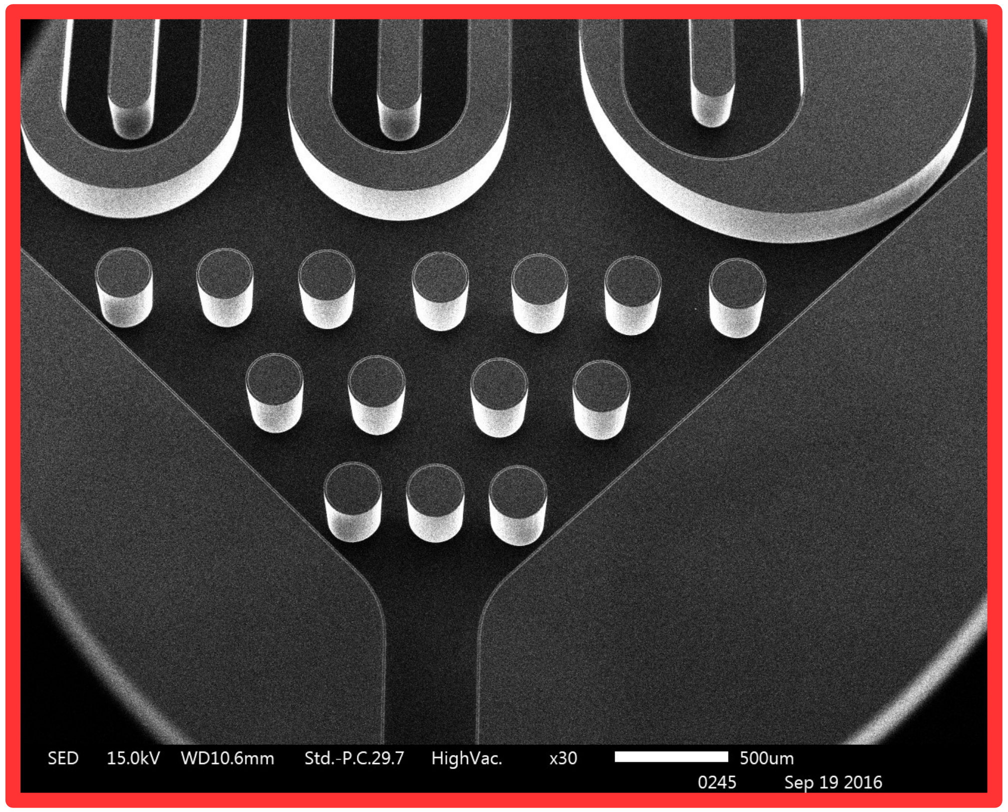
MCC manifold design

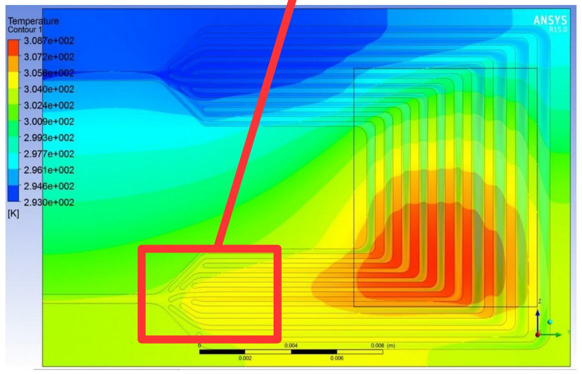




MCC qualification: new channels layout

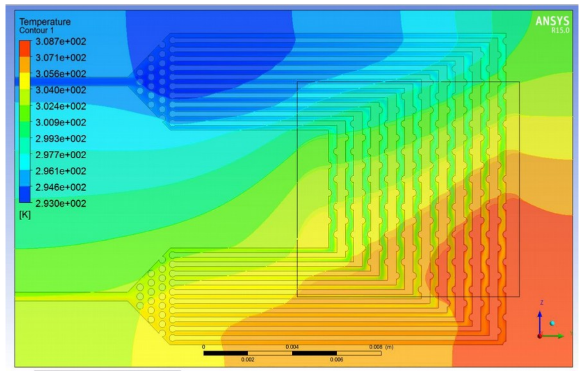


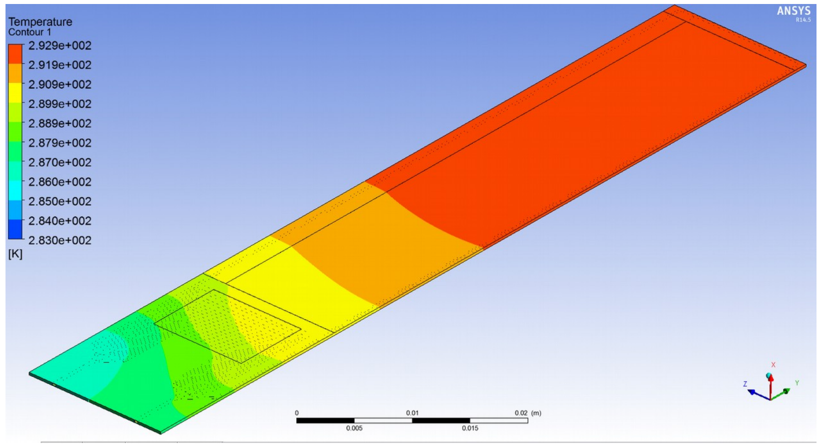


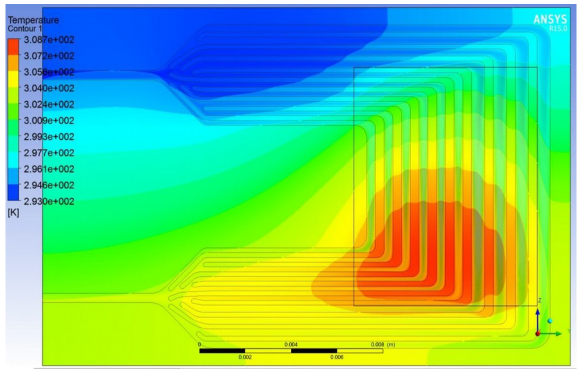


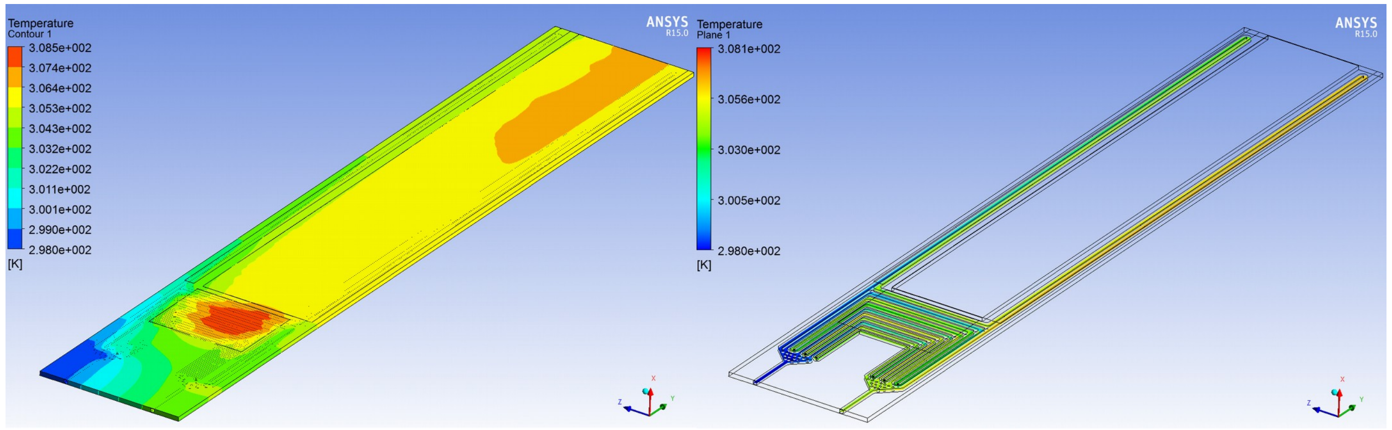
New MCC layout has been manufactured:
- Optimized layout for MCC: better performance
- Avoid pillar structures

MCC manifold design



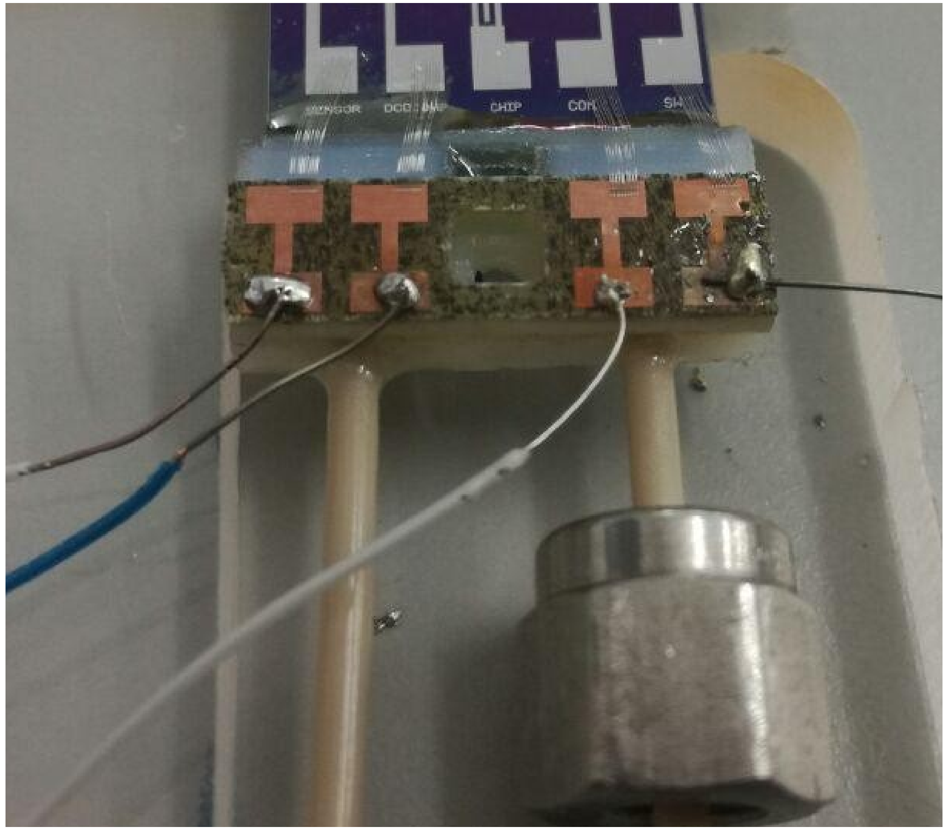




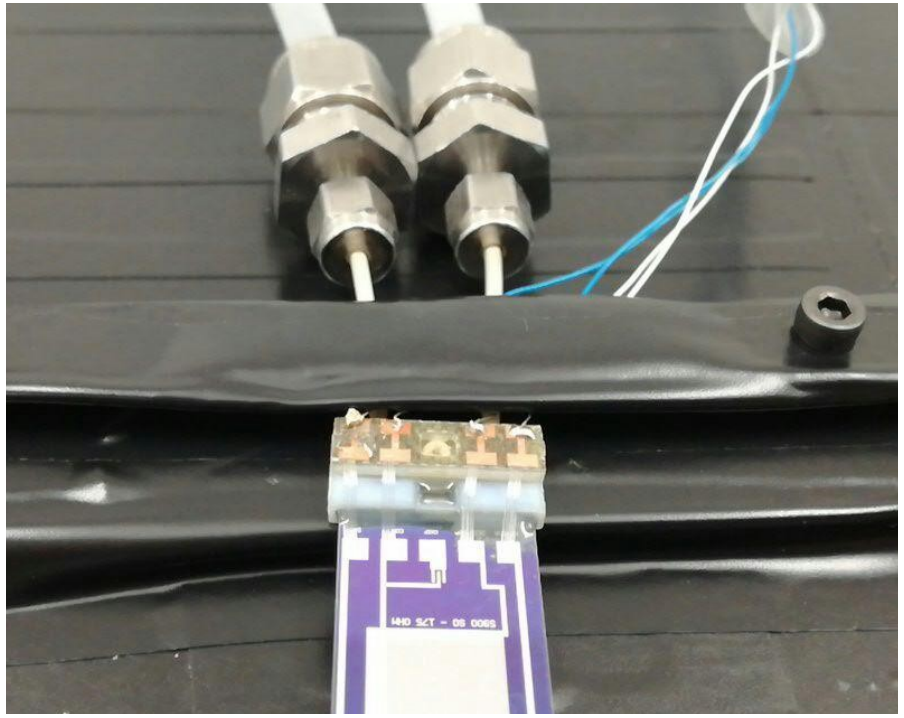


New MCC layout has been manufactured:
- MCC along the edge of the sensor to cool sensor area

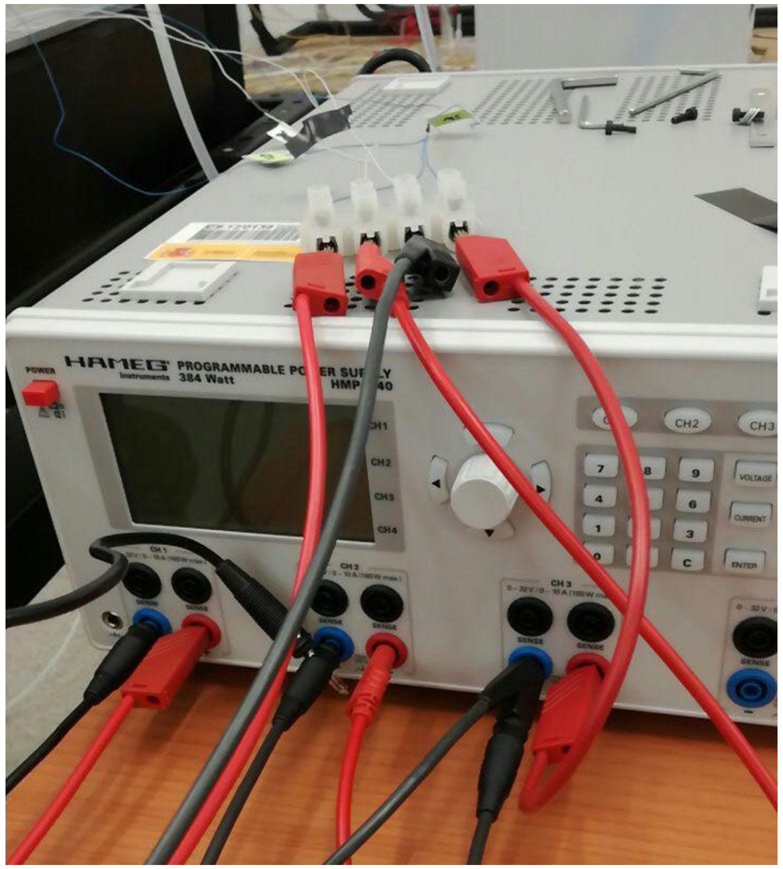
MCC qualification: new channels layout



Tubes fittings

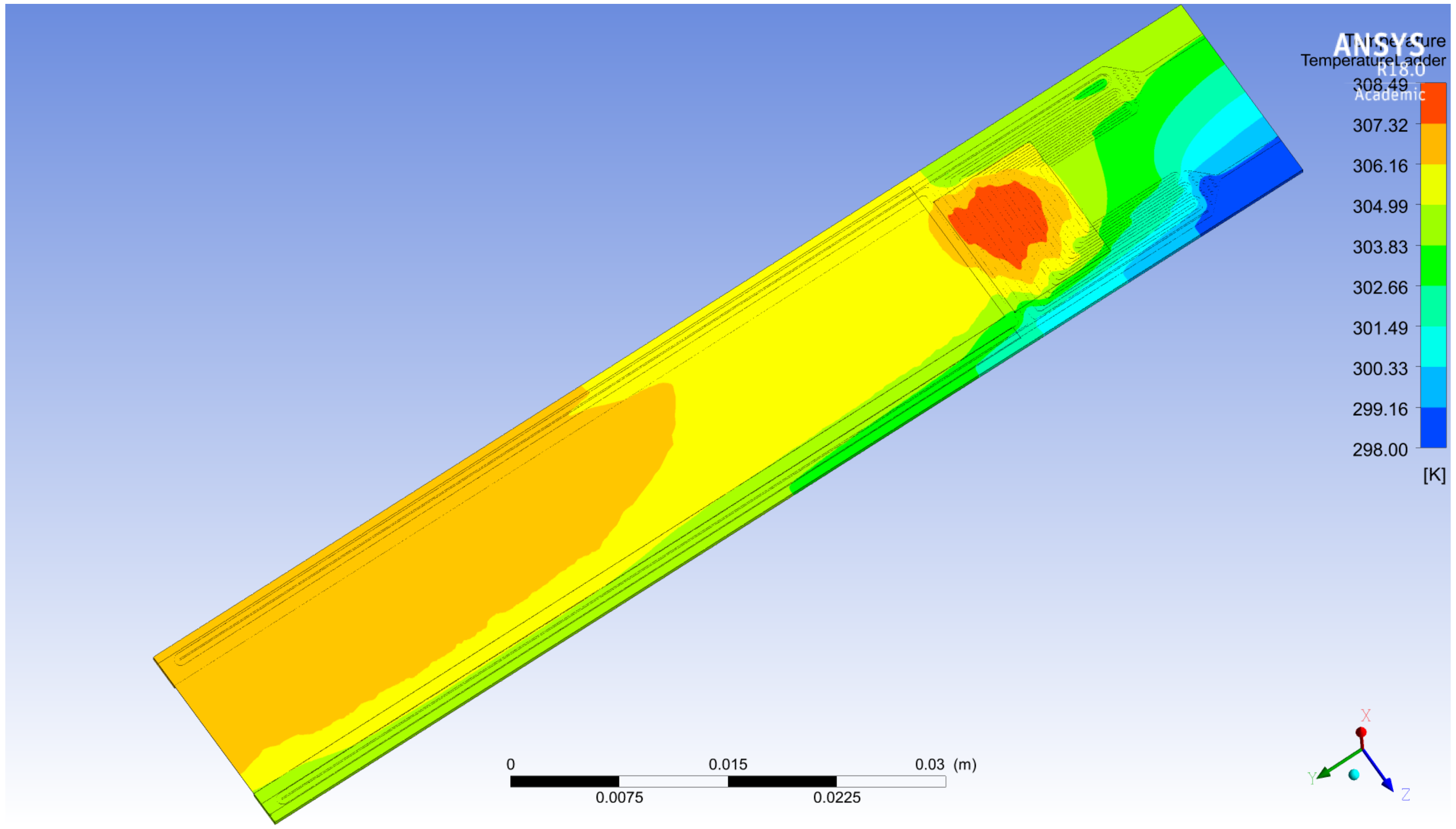


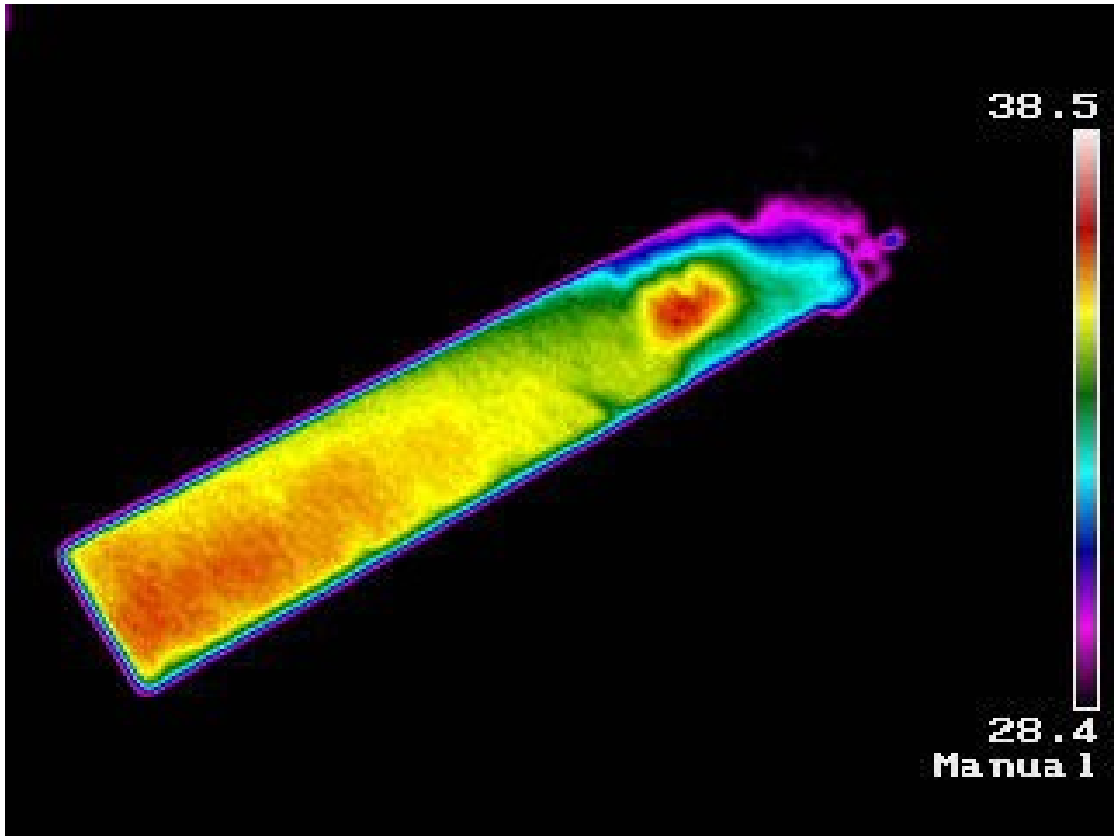
Power Connexion



Black box

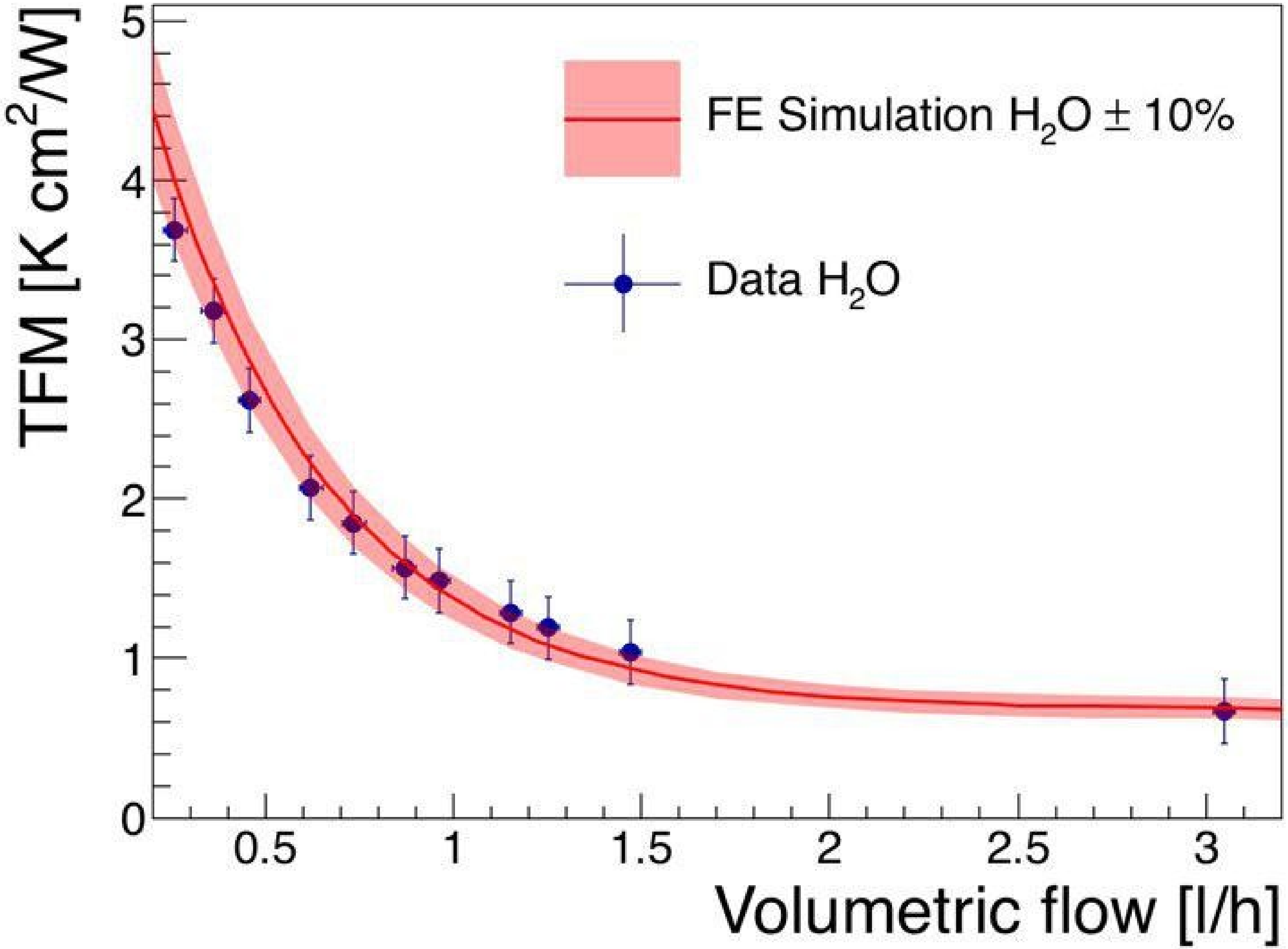
MCC qualification: new channels layout





- Thermal camera inside black box
- Simulation ΔT=10,5K and test ΔT=10,1K

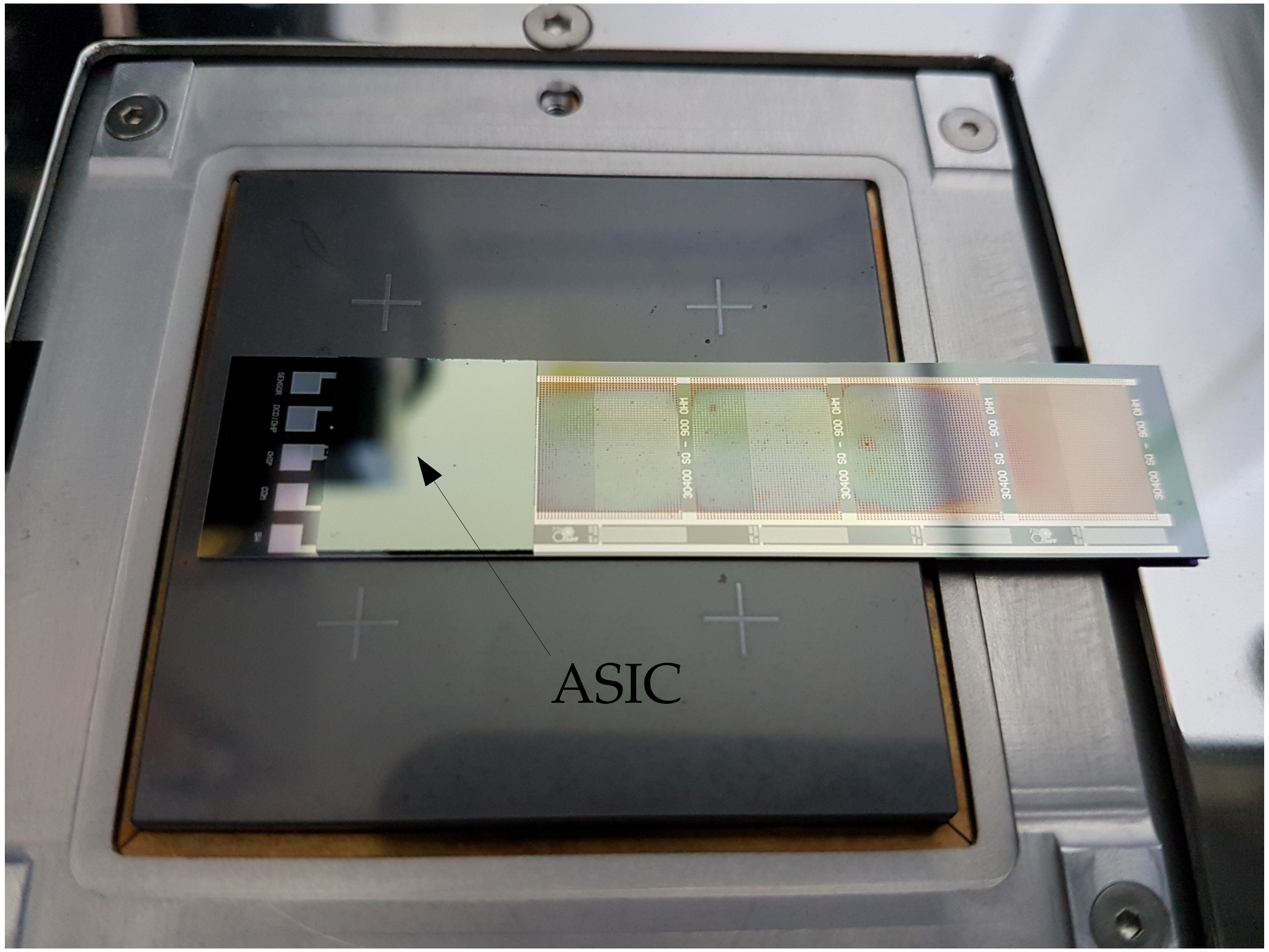
MCC qualification: new channels layout

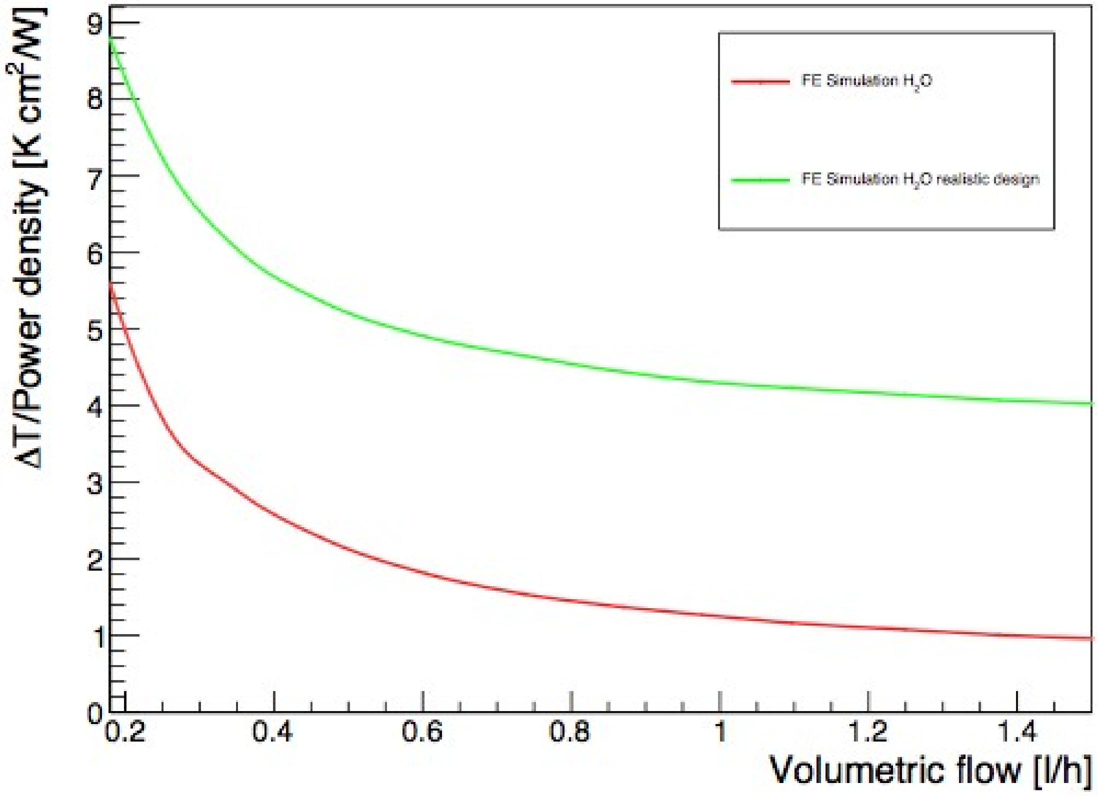


MCC sample cooled non-stop for 2 days with no leaks and no clogging

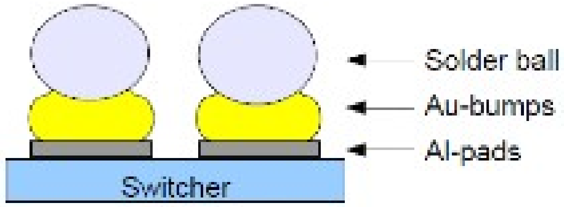
Agreement with FE simulation within 10%

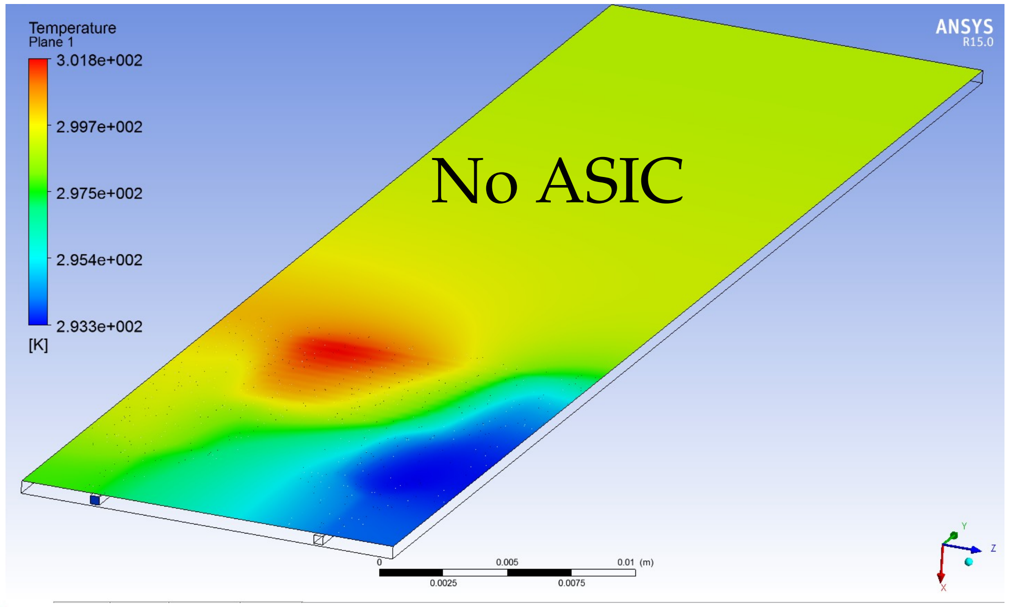
Current work

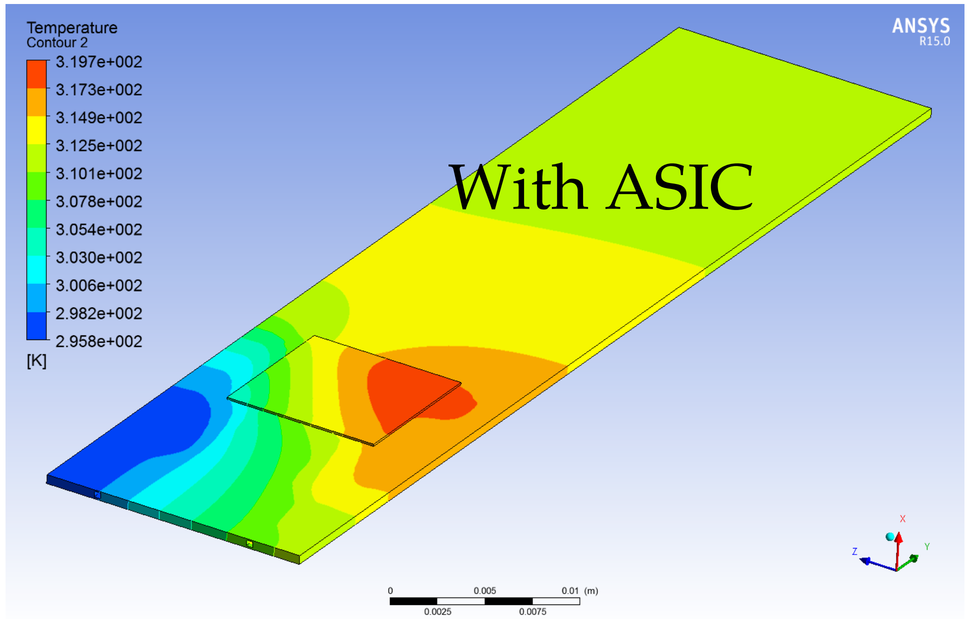




Realistic design
300 µm Si ASICS +
100 µm Bump-boundings
thermal resistivity of 6 W/m·K







Summary

- Microchannels can be integrated in active sensor
  - Excellent thermal figure of merit, virtually no material
- Low-mass 3D-printed connector with reliable glue procedure
  - Bring connections into tracking volume
- FE simulation describes performance to within 10%
  - Reliable predictions help design
- New MCC layouts provide cooling over entire ladder
  - Belle 2/Higgs factory