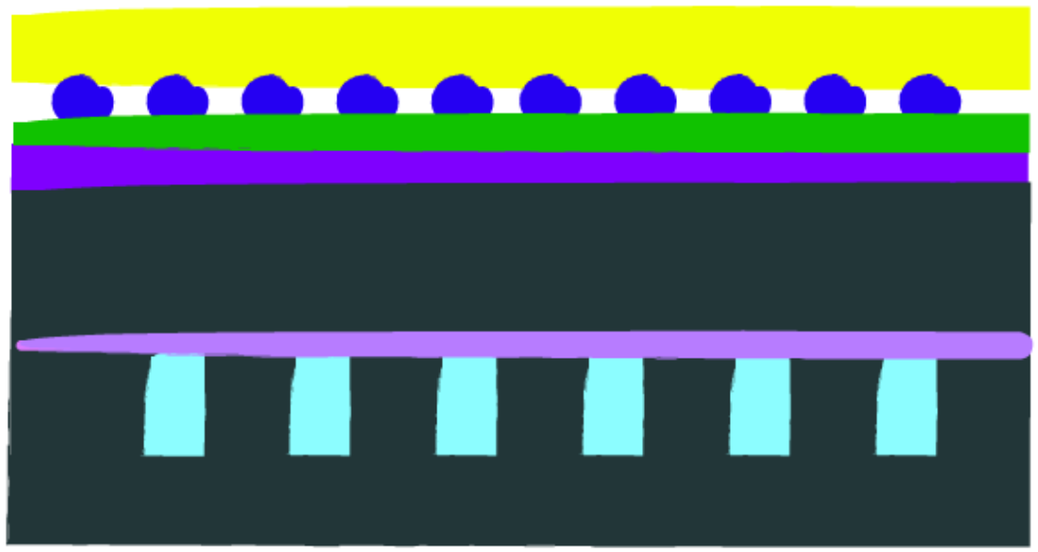
Micro-channel cooling in HEP



Marcel Vos
IFIC (UVEG/CSIC) Valencia
VERTEX 2016
Elba, La Biodola, September 2016

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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), Miguel-Angel Villarejo (IFIC)

Cooling of silicon detectors

Modern strip and pixel detectors have large channel density

→ high power consumption

Sensor temperature must be low and uniform

→sub-0 at hadron colliders

FE-electronics and sensor are tightly coupled

→heat source and cold sensors

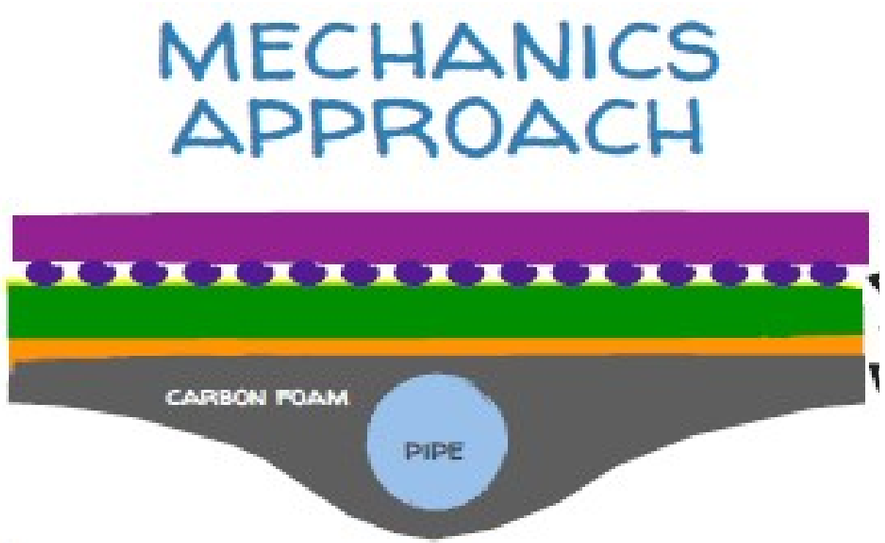
Minimize material in services and supports

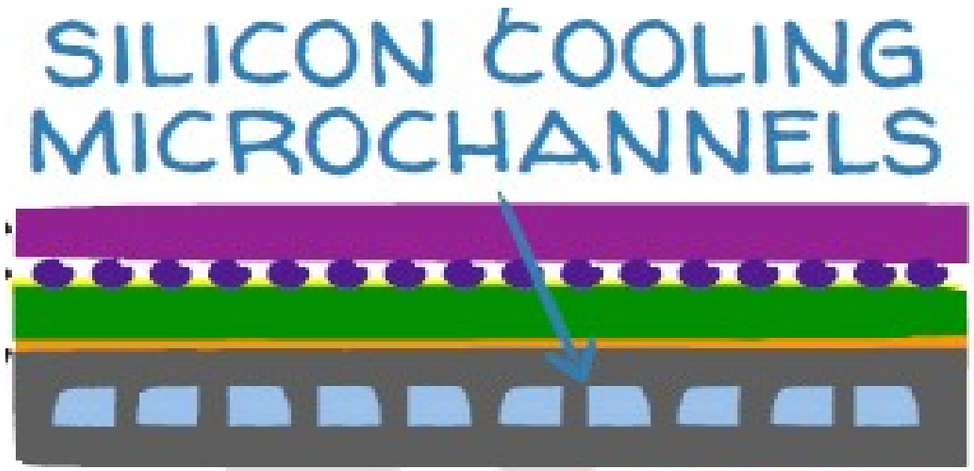
Micro Channel Cooling seems to be the natural solution

Indeed, quite some interest

- Part of one running experiment (NA62 GigaTracker)
- Focused R&D ongoing in LHCb for VELO upgrade
- Exploratory R&D work in ALICE, ATLAS, DEPFET collaborations
- WP9 of AIDA-2020 provides a forum, “standards” & generic R&D funding

The case for MCC in HEP



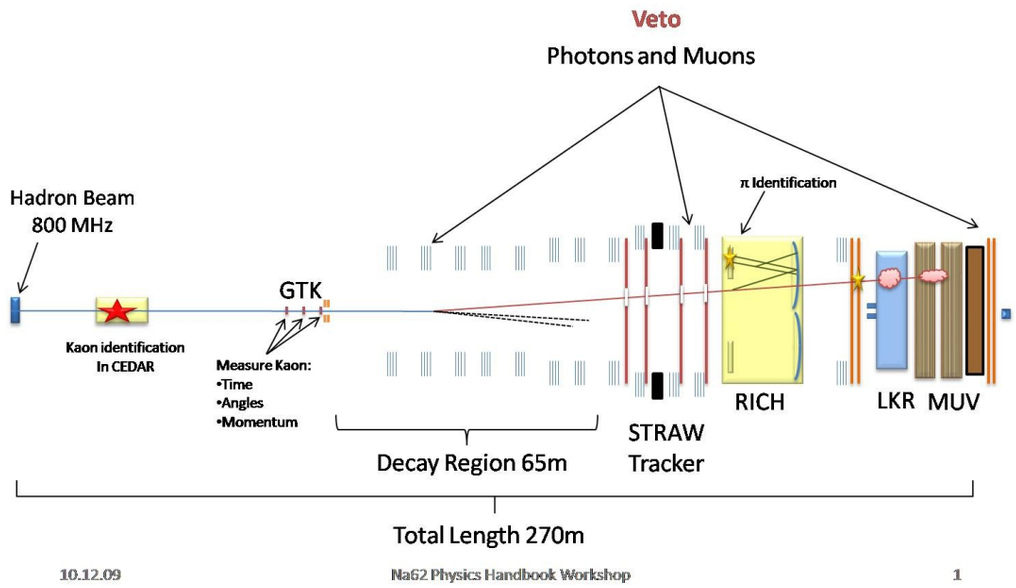


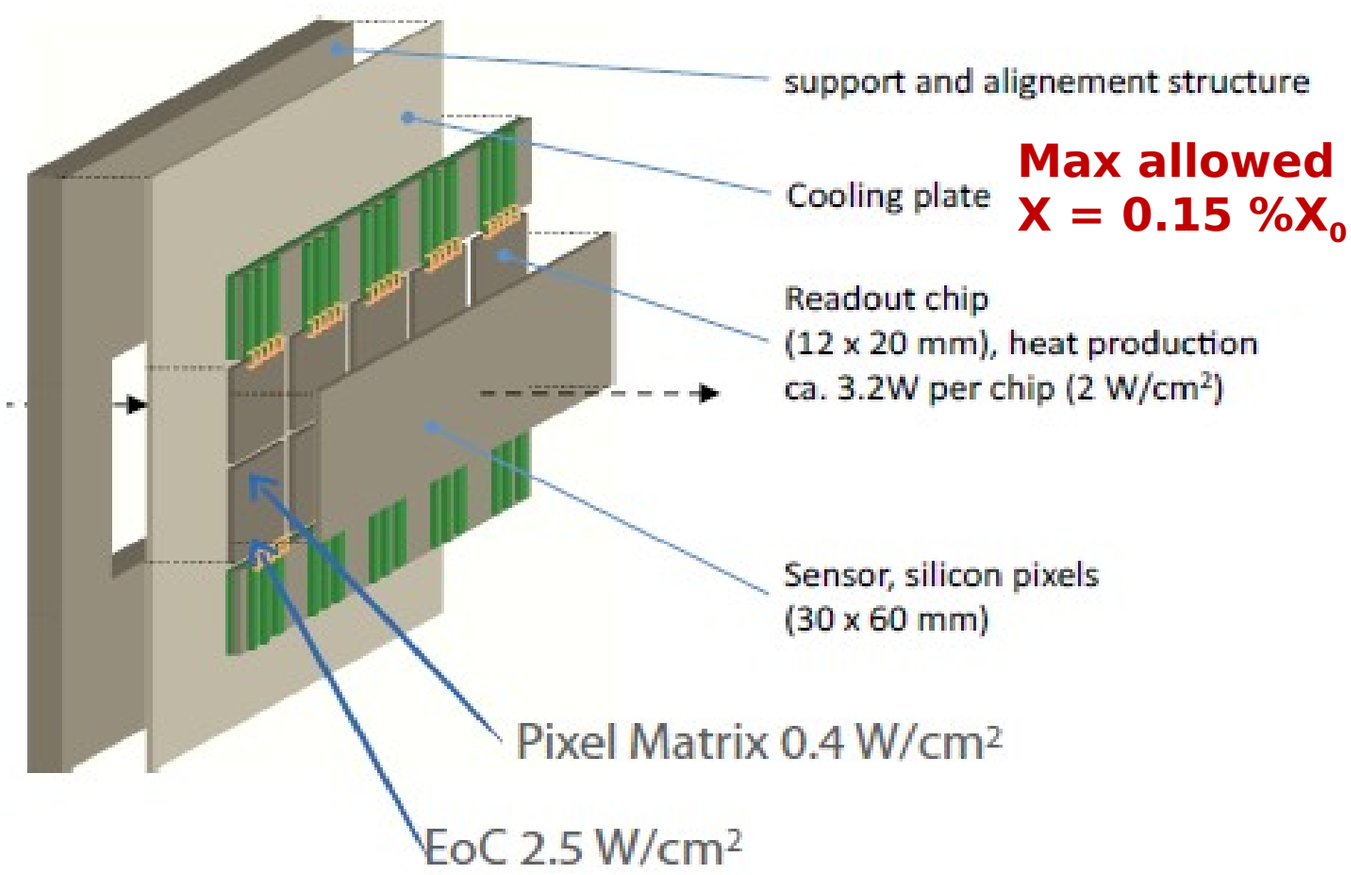
Issues:

→ 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)

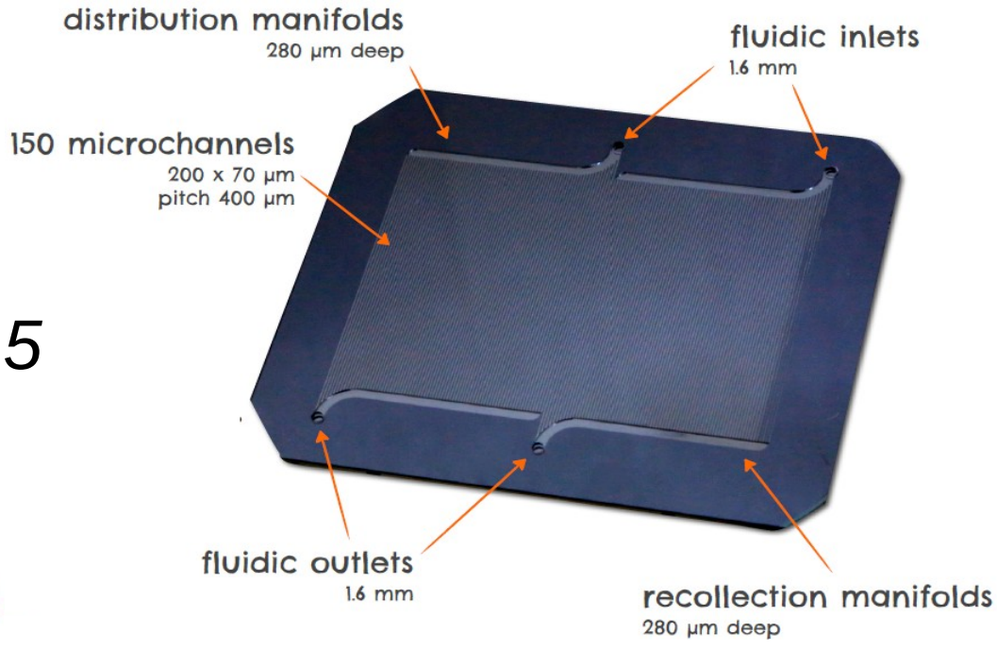




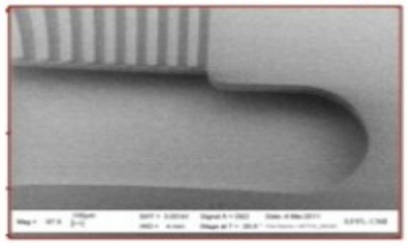
Hybrid pixel detector: 40 W on 3x6 cm^2
Liquid cooling (mono-phase C6F14 at -20C)

NA62 MCC

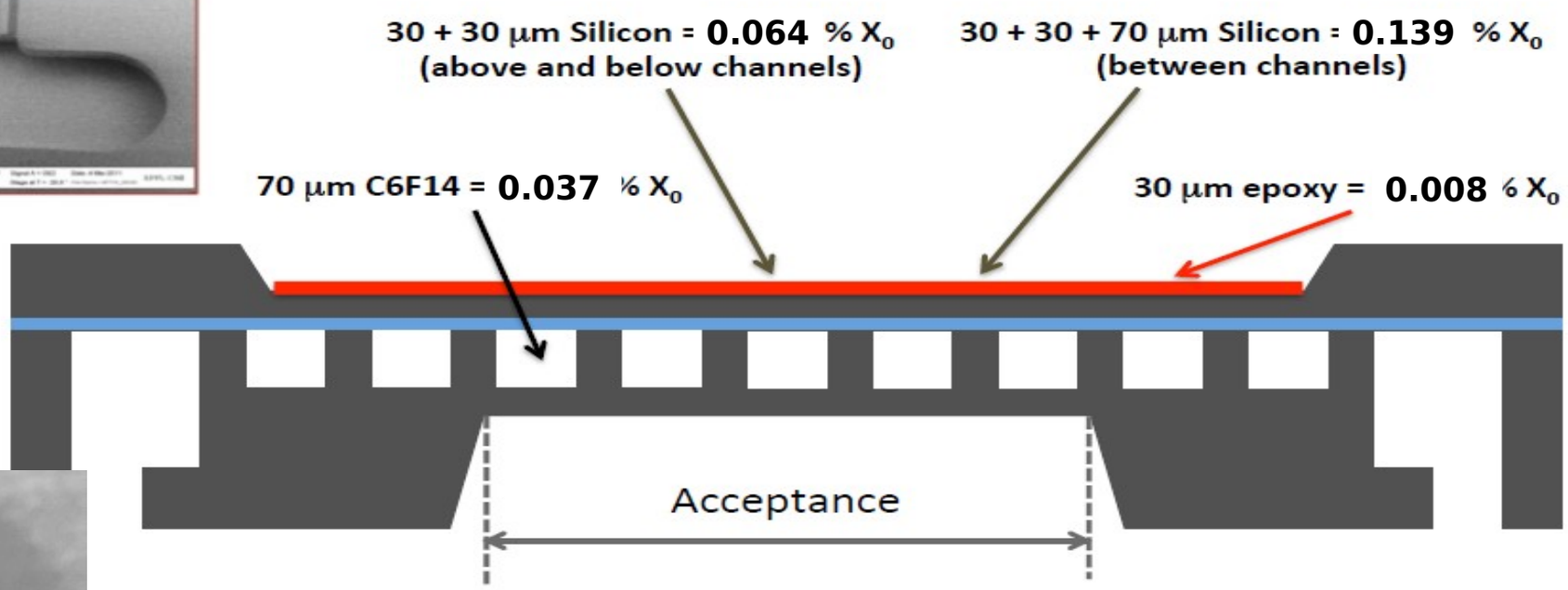
PhD thesis G. Nussle, UC Louvain, October 2015
Microelectron.Eng. 145 (2015) 133-137



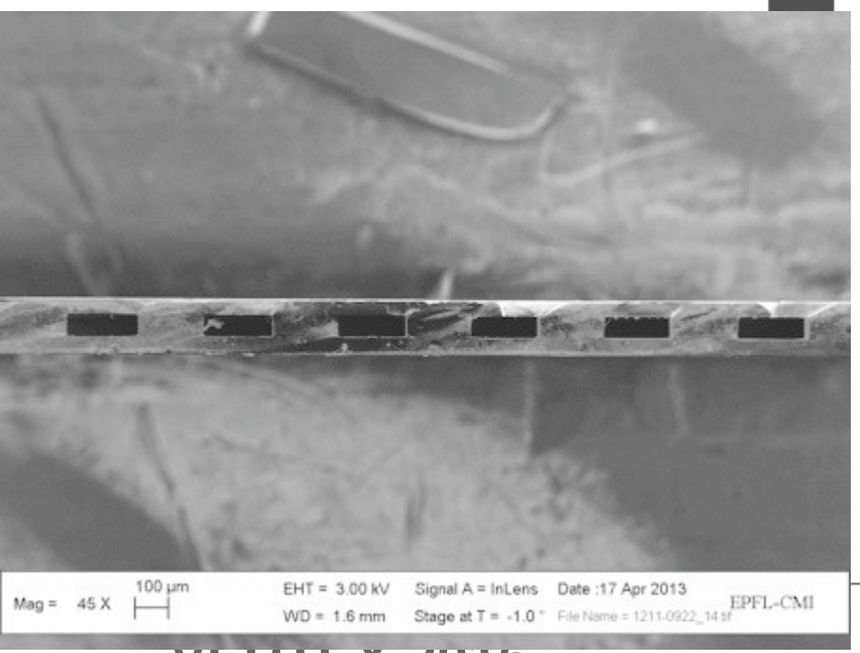
Channels =200 x 70 µm
Wall thickness = 200 µm
Cover thickness = 30 µm



Final cross section
of the cooling plate



Total material budget in the acceptance are 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)

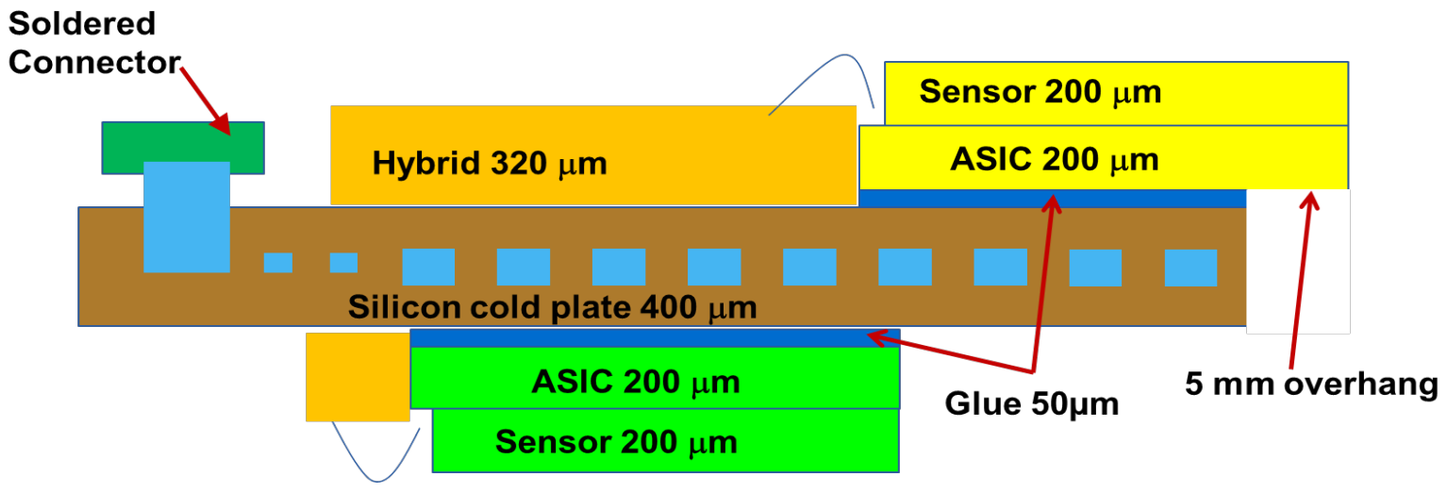
Leakage current 1W/sensor (@1000V and -20C)

Basic assembly dissipates 4 x 1W in sensors,

12 x 3W in VeloPix chips and 5W in hybrid

Talk by Cameron Dean in this workshop

JINST 10 (2015) no.05, C05014



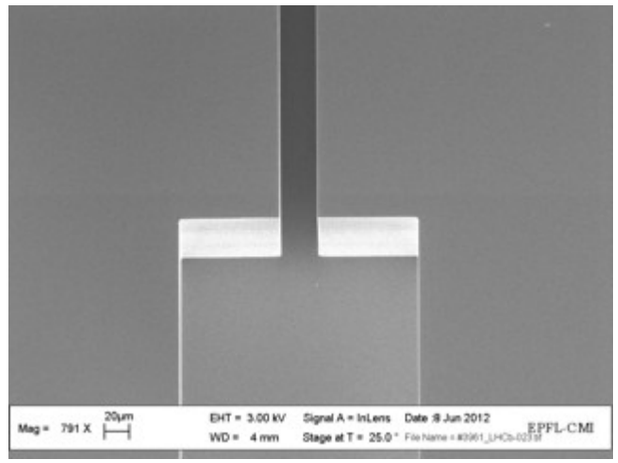
Evaporative system: must deal with high pressure!!

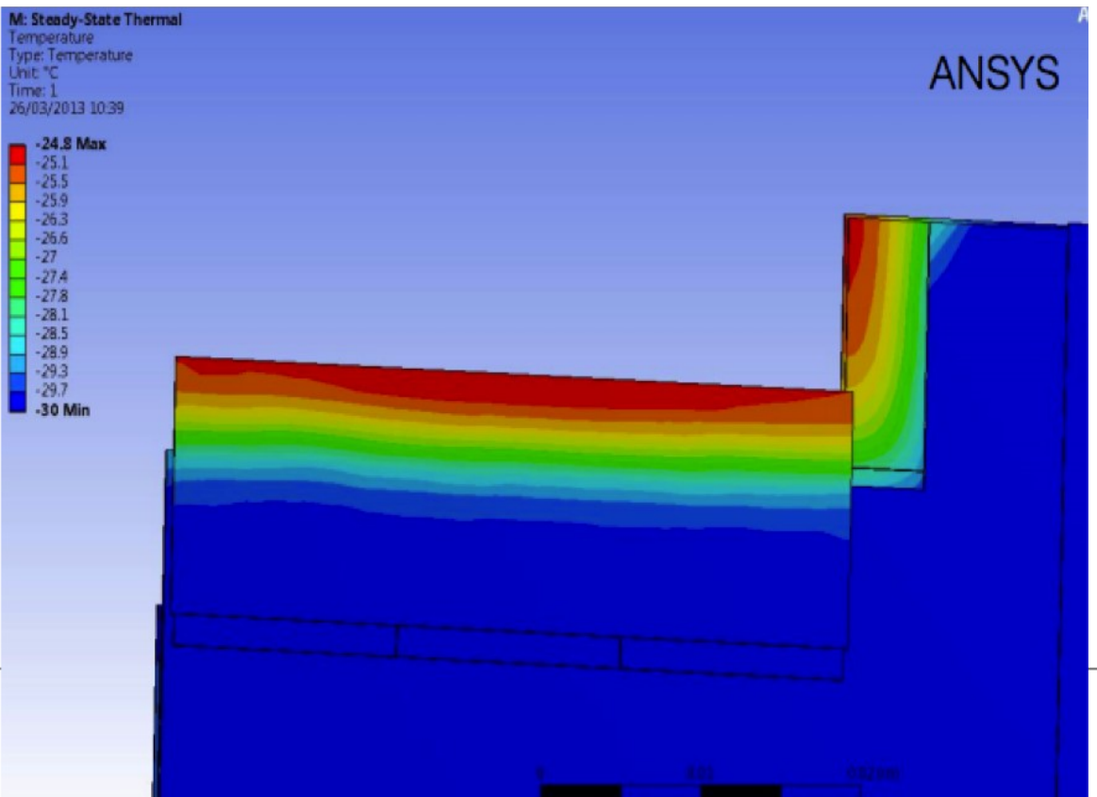
LHCb VELO upgrade

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





Expecting very good thermal performance

Temperature gradient at the overhang

ALICE-ITS

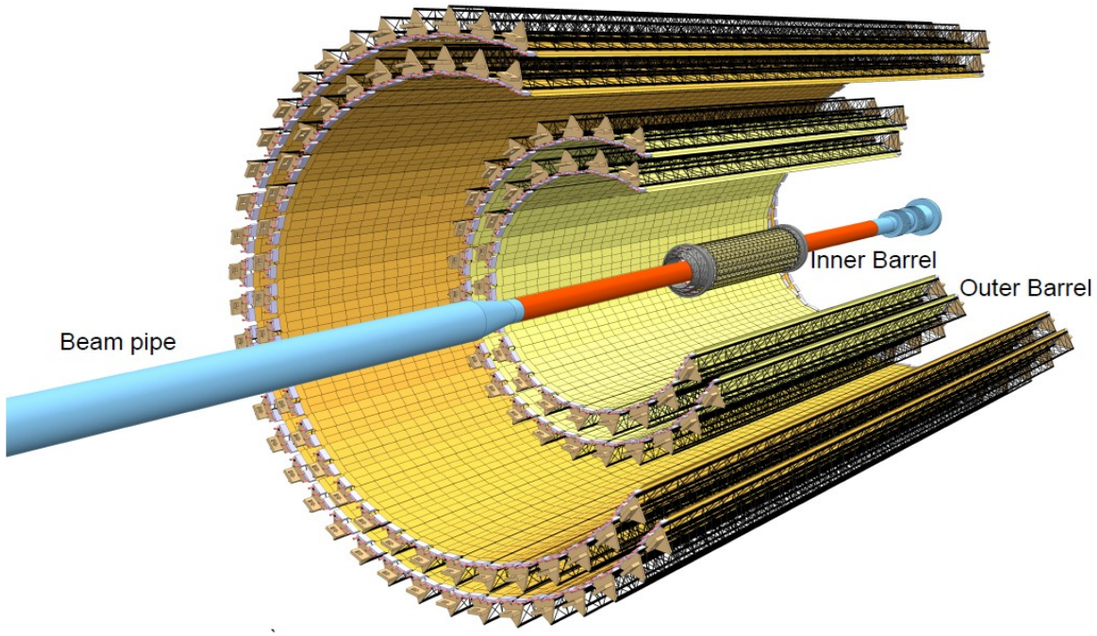
ALICE-ITS to be upgraded after LS2 (2020)

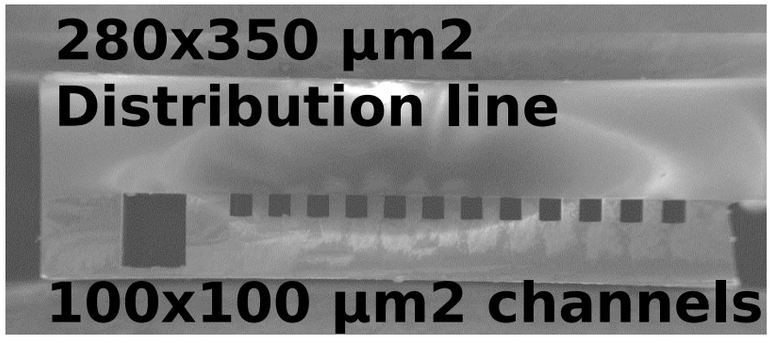
L. Greiner/S. Beolè in this workshop

Baseline: CF cold plate with 1l/h water flow

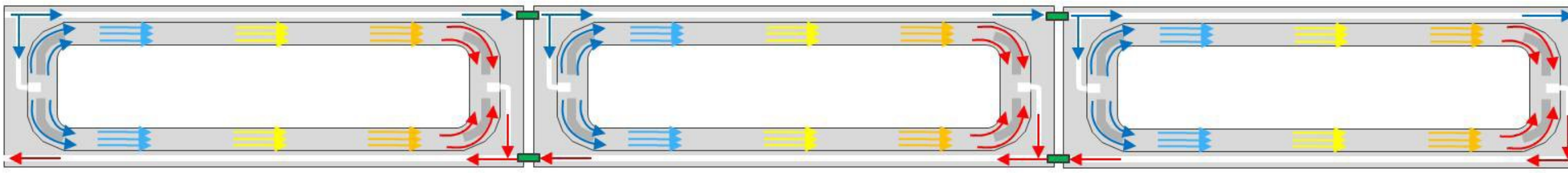
Alternative cooling option based on MCC

2-phase (evaporative) $\mathbf{C_4F_{10}}$



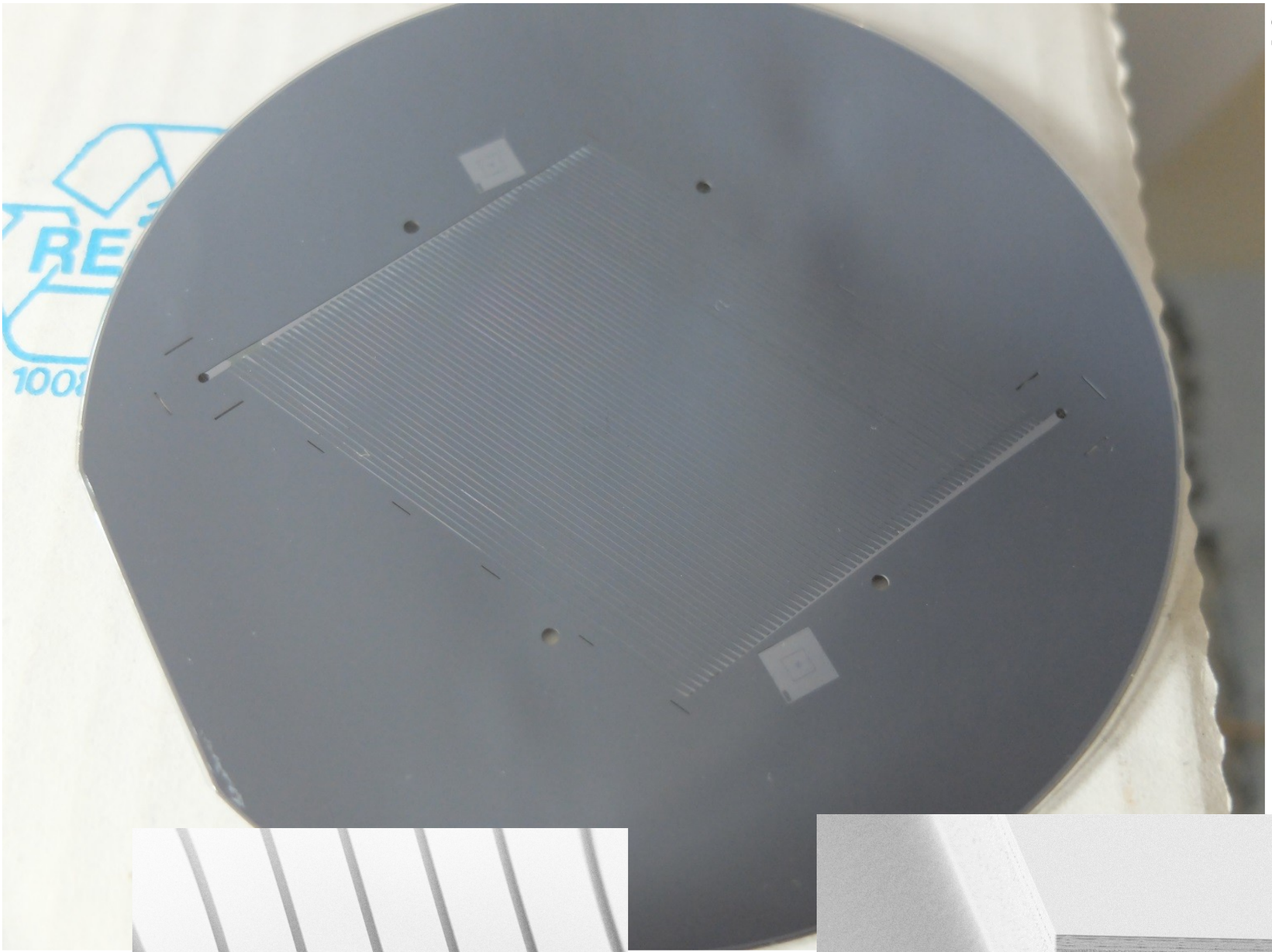


No place to hide: long ladders in acceptance require low-X_0 connectors

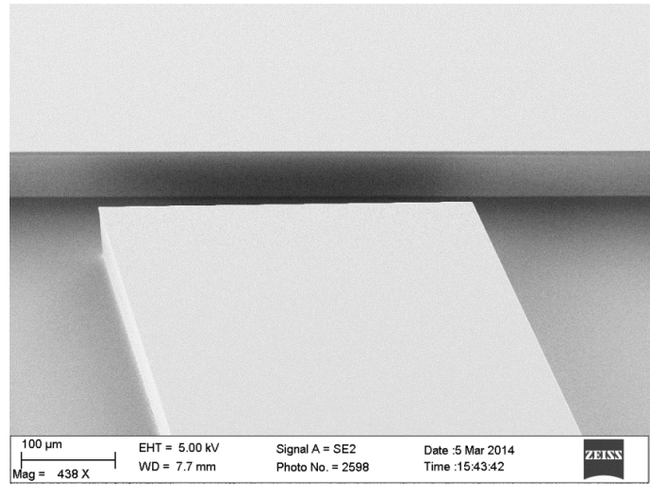


CNM/DESY

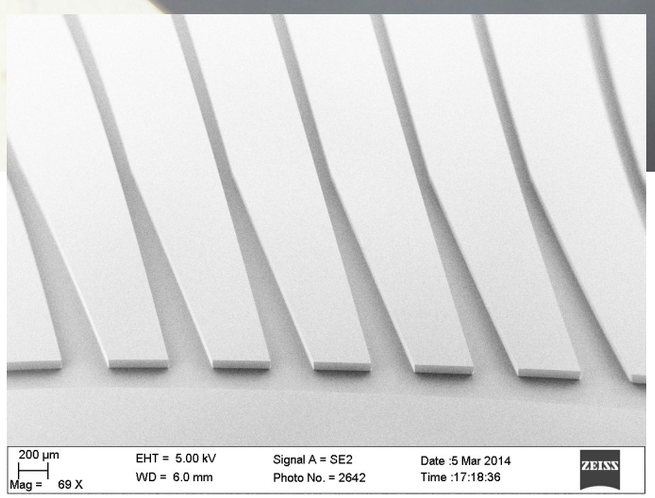
Courtesy of Nils Flaschl, DESY

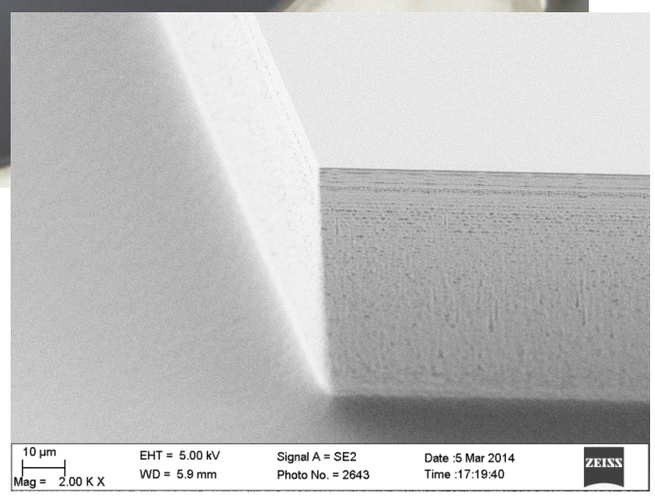


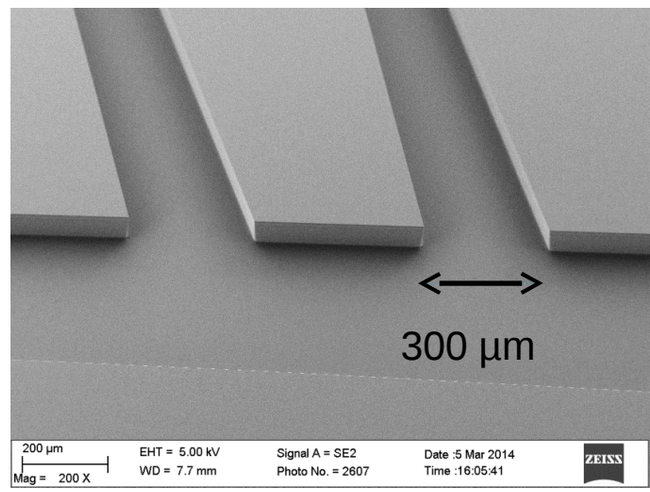
Sample with a Pyrex top to close the channels
Silicon thickness: 375 µm
Pyrex thickness: 500 µm



Electron microscope images of the channels after being etched into the silicon

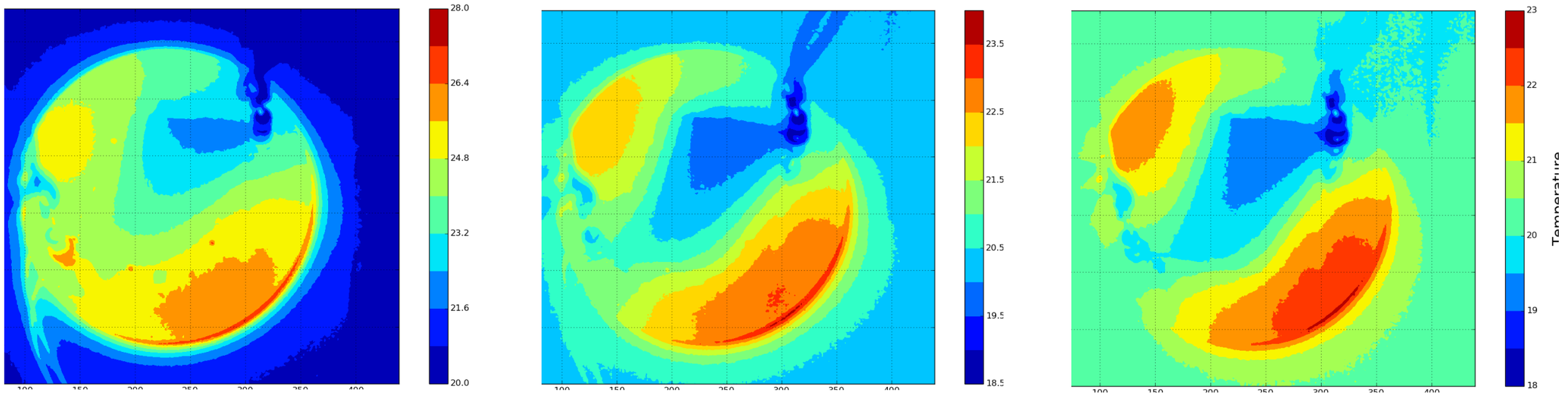






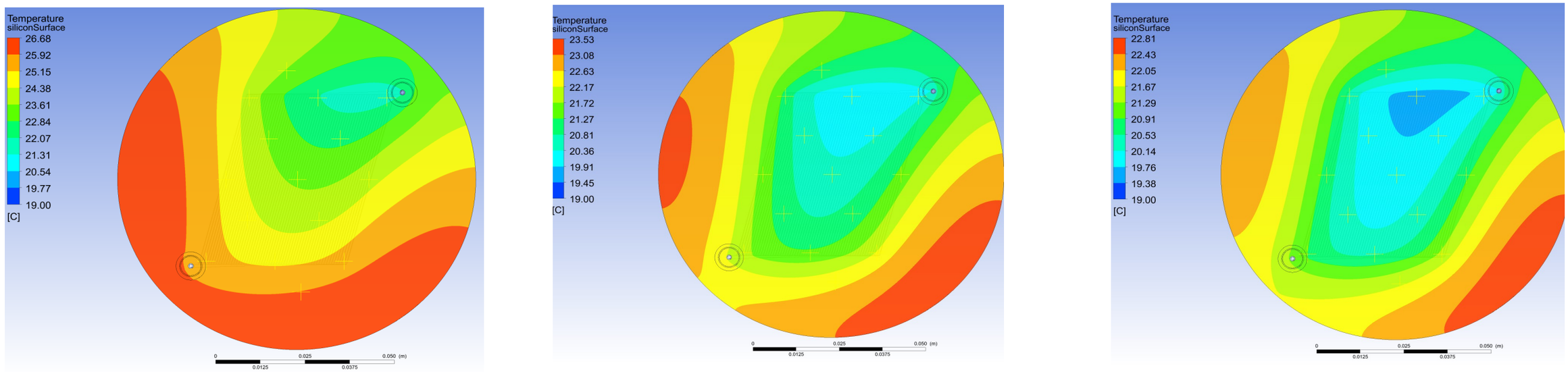
Results

Infrared camera



10 ml/min 30 ml/min 50 ml/min

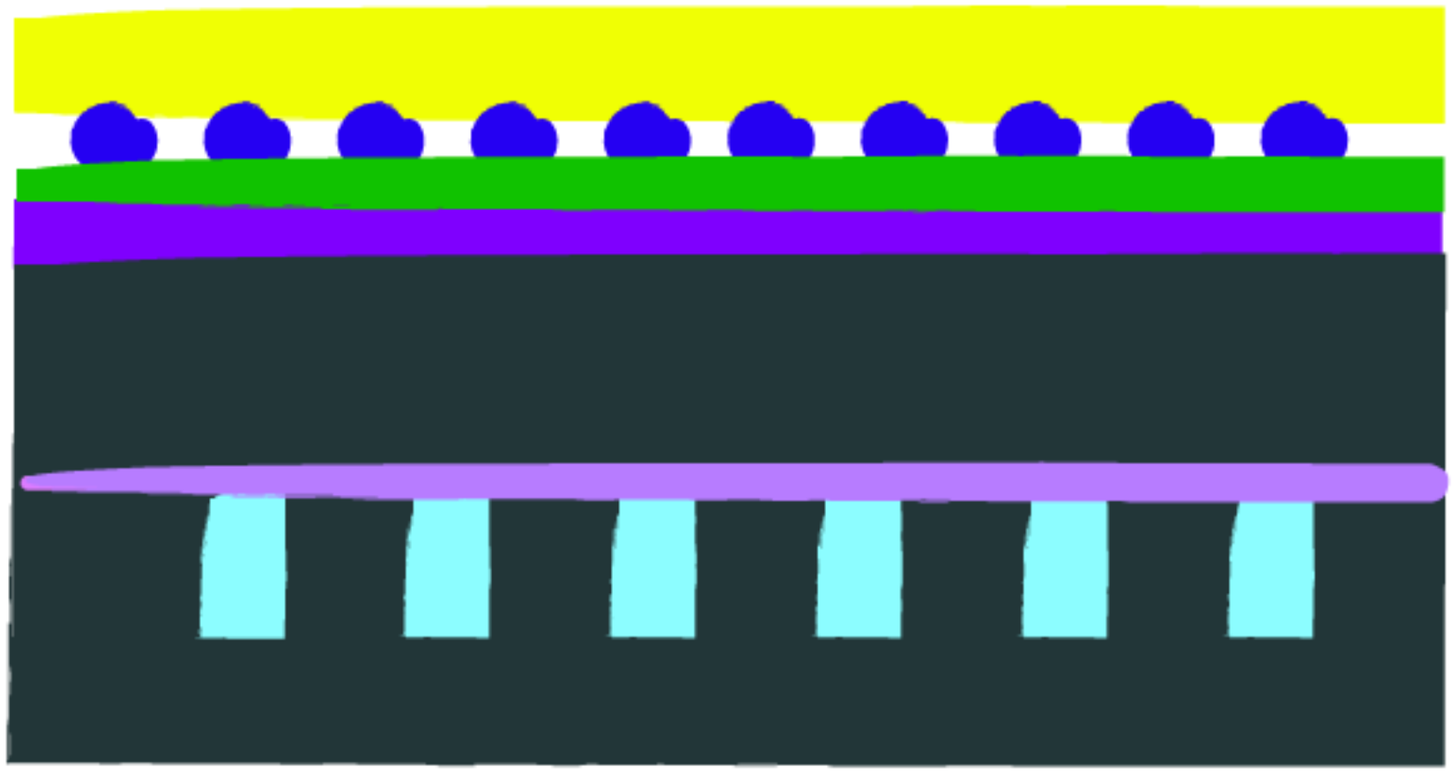
Simulation



Integrating MCC in active silicon

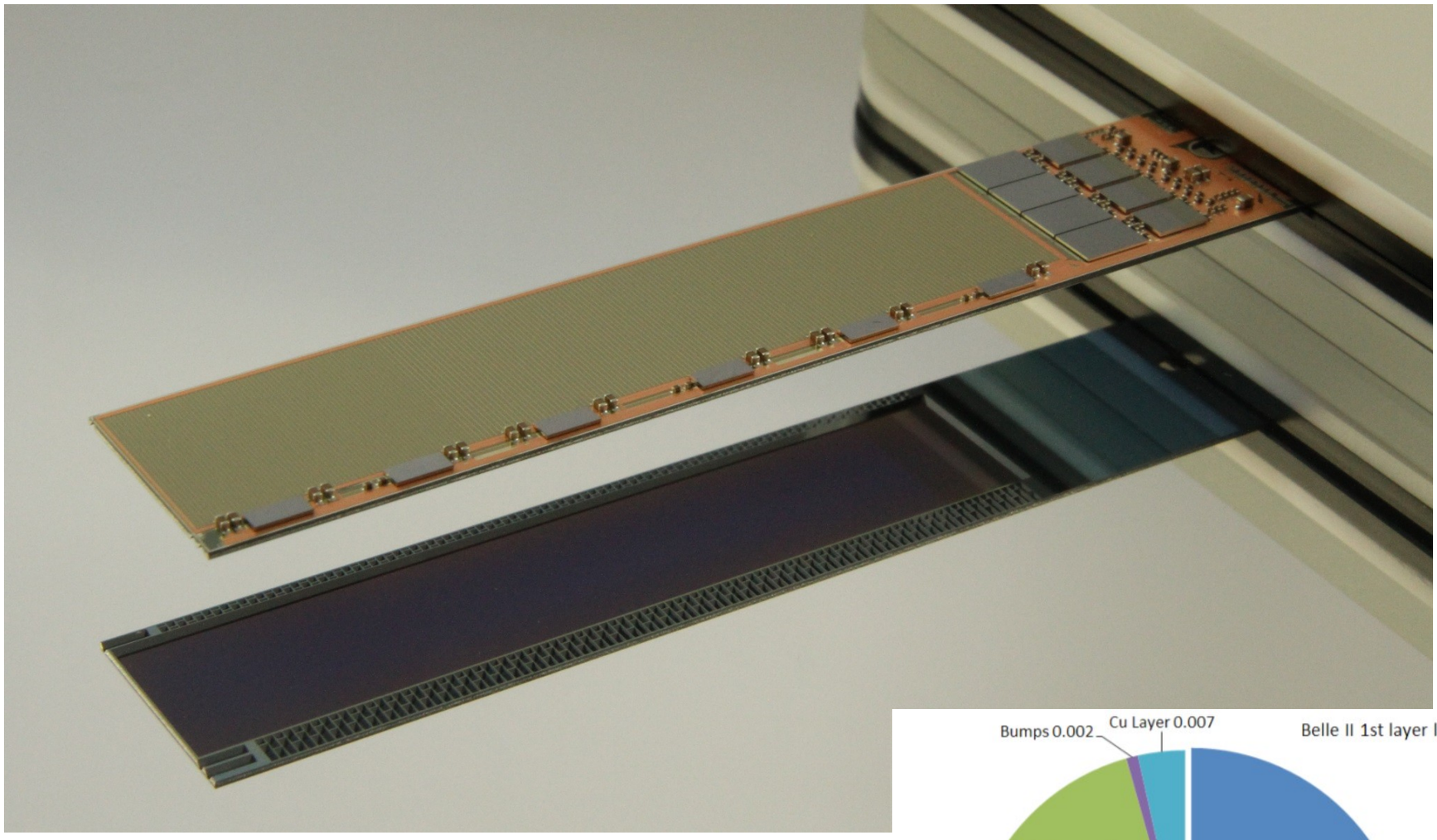
Integrated cooling channels in position-sensitive silicon detectors,
JINST 11 (2016) no. 06, P06018
L. Andricek[1], M. Boronat[3], J. Dingfelder[2], J. Fuster[3], I. Garcia[3], P. Gomis[3], C. Lacasta[3], G. Liemann[1], C. Marinas[2], D. Markus[2], J. Ninkovic[1], M. Perelló[3], E. Scheugenpflug[1], M.A. Villarejo[3], M. Vos[3]
[1]MPG Halbleiterlabor Munich, [2]Bonn University, [3]IFIC Valencia

Cartoon by A. Mapelli

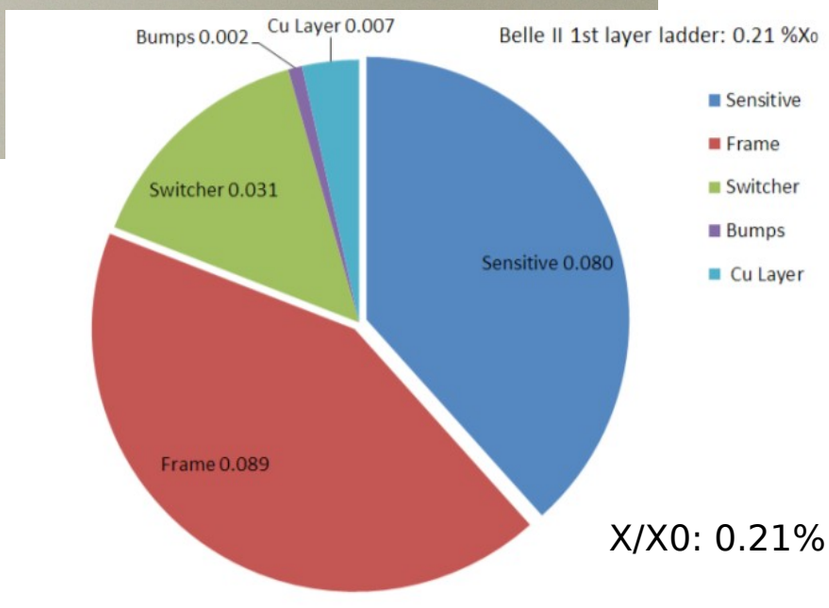


Ultra-thin and ultra-precise

Increasing precision and reducing material budget. Challenge for supports, cooling and services.



Belle II Module 0. See: DEPFET overview by B. Schwenker



X/X0: 0.21%

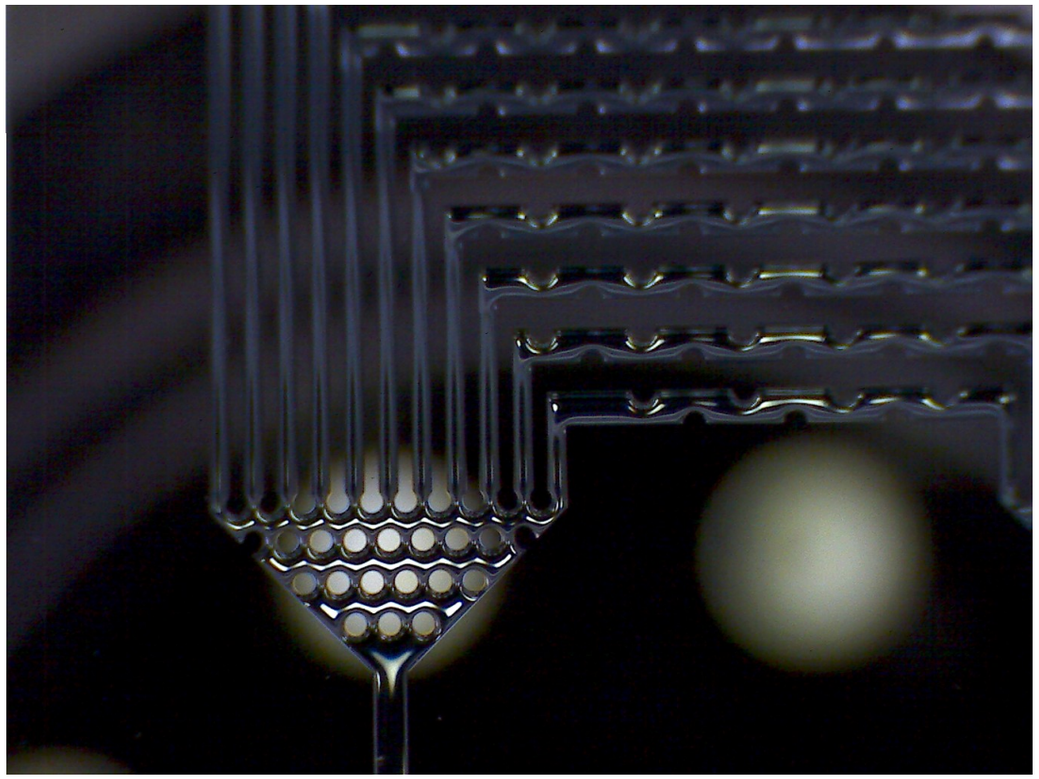
Integrate everything on the silicon:
FE electronics, mechanics, signal/power routing

And cooling?

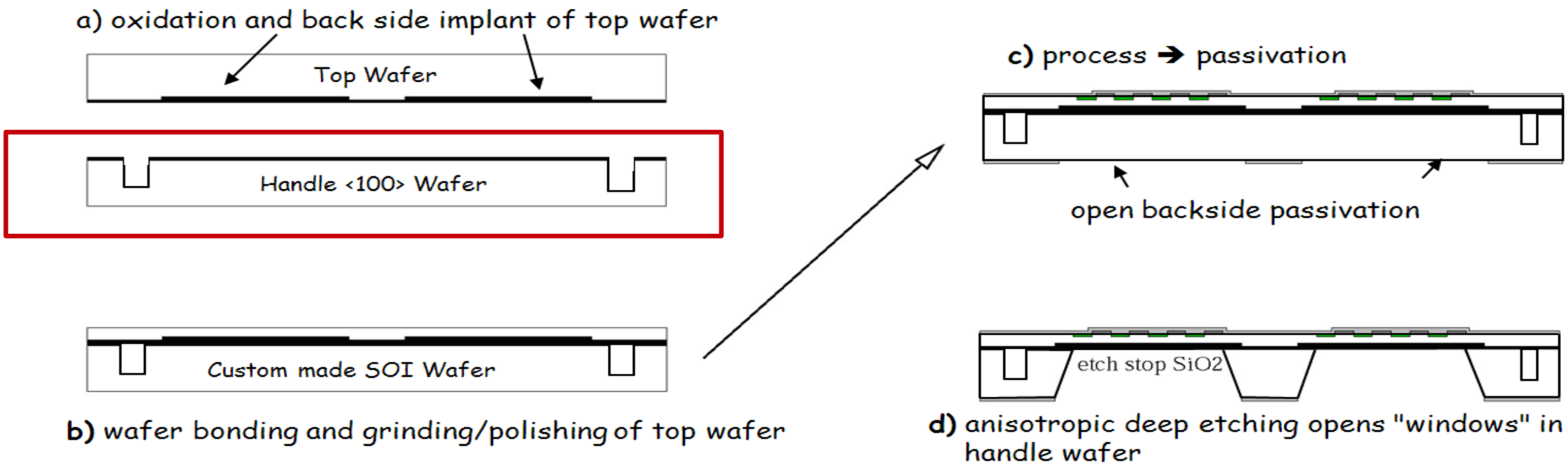
Micro-channel cooling, our take...

- 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 AIDA2020 (P. Petagna CERN)



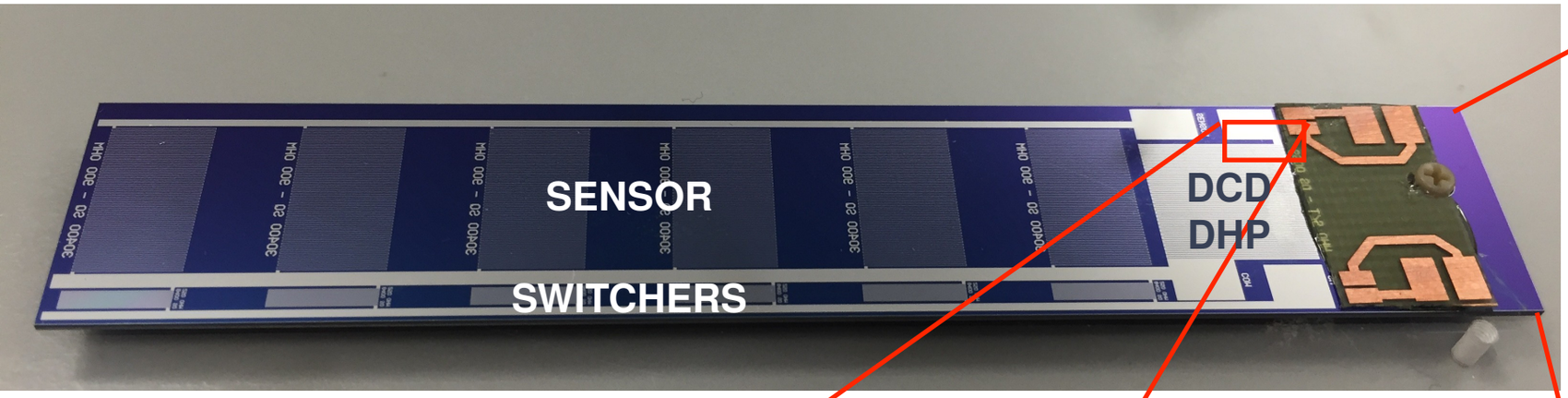
All-silicon ladder with integrated cooling



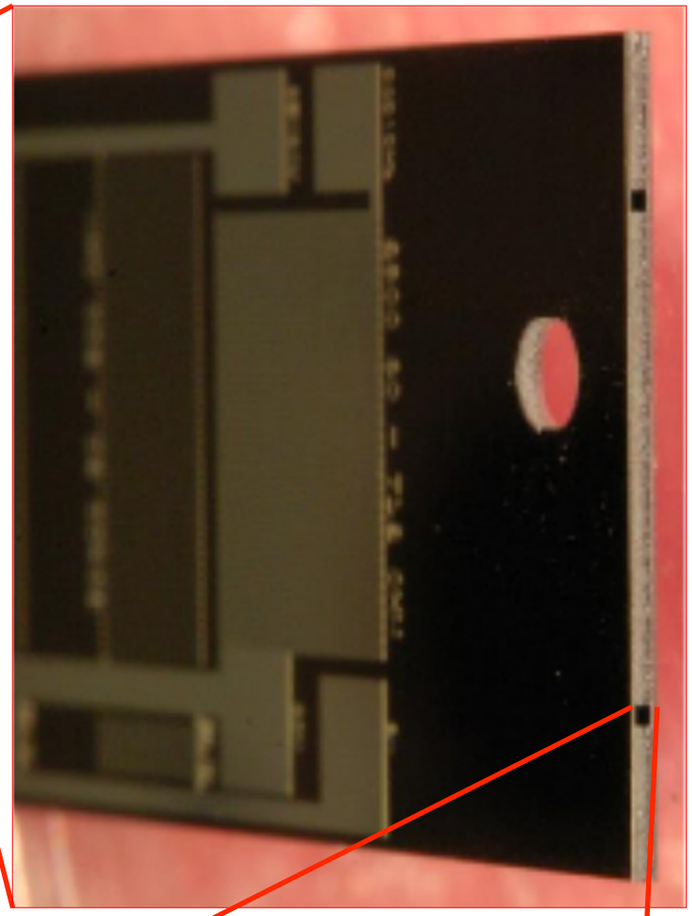
thinned all-silicon module with integrated cooling channels

:- 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)

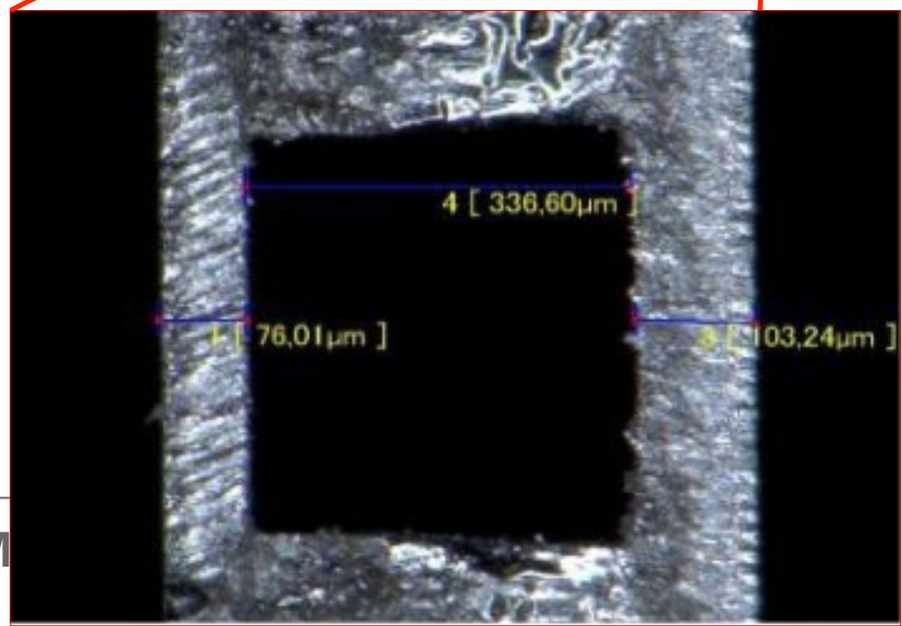
All-silicon ladder with integrated cooling



Resistor circuits to mimic DEPFET power dissipation

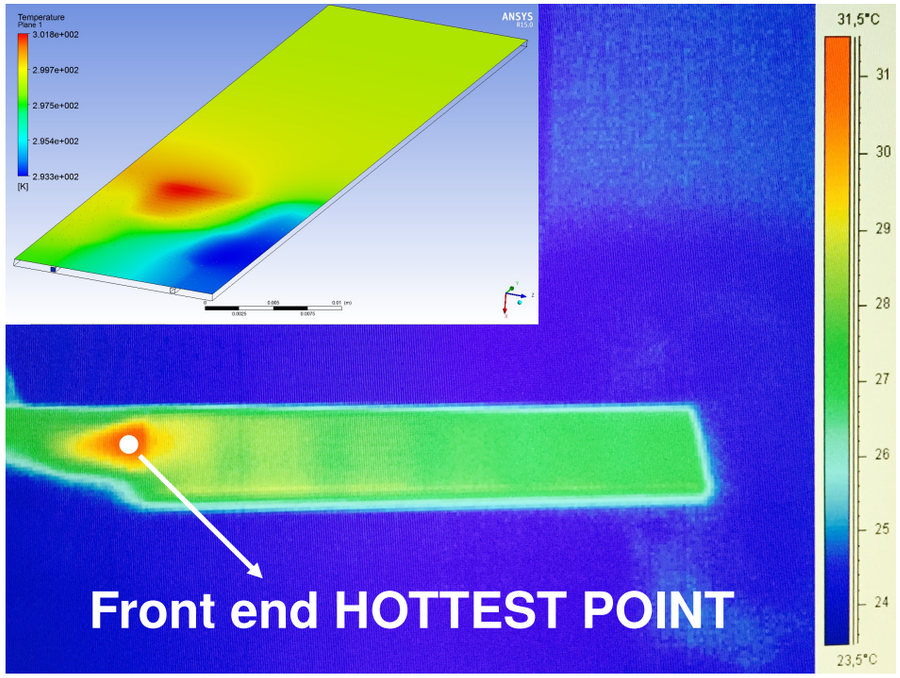


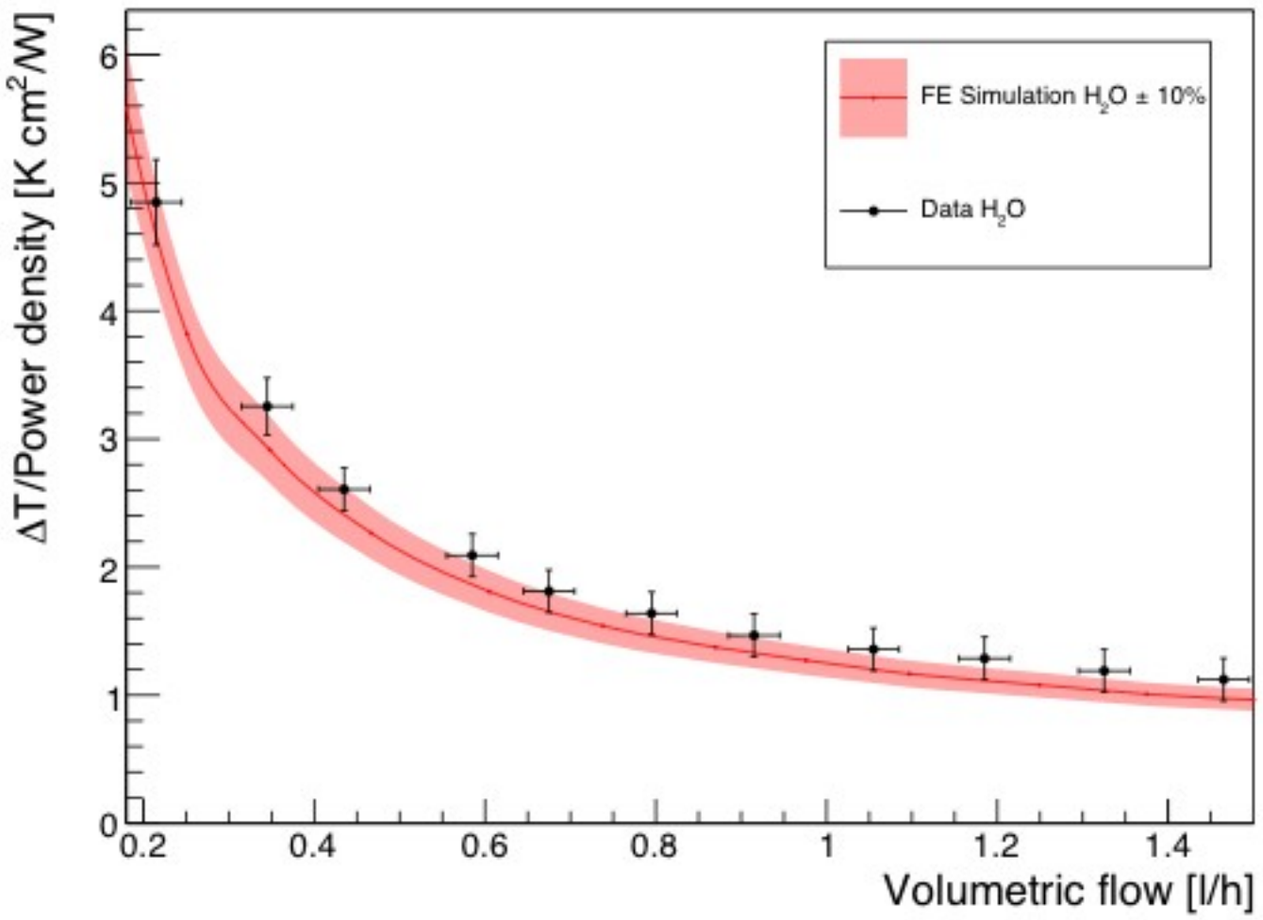
Thermo-mechanical DEPFET half-ladder



Inlet and outlet visible after wafer cutting

Thermal measurements



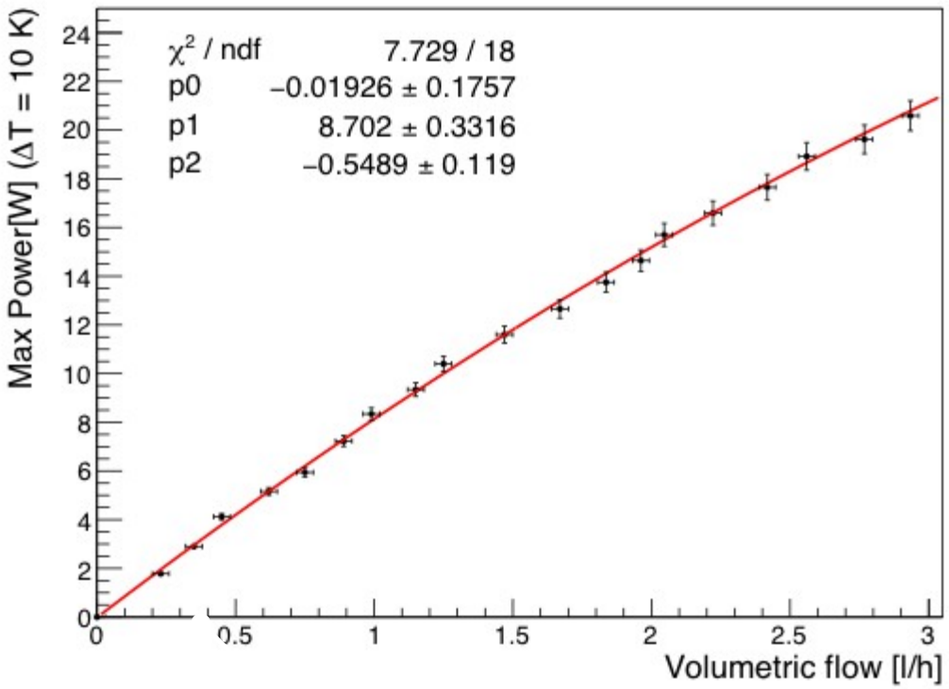


Good agreement with the **FE simulation** within 10%

Thermal figure of merit (temperature gradient/power density) = 1

Other coolants being investigated (C6F14 at CERN)

Thermo-mechanical measurements

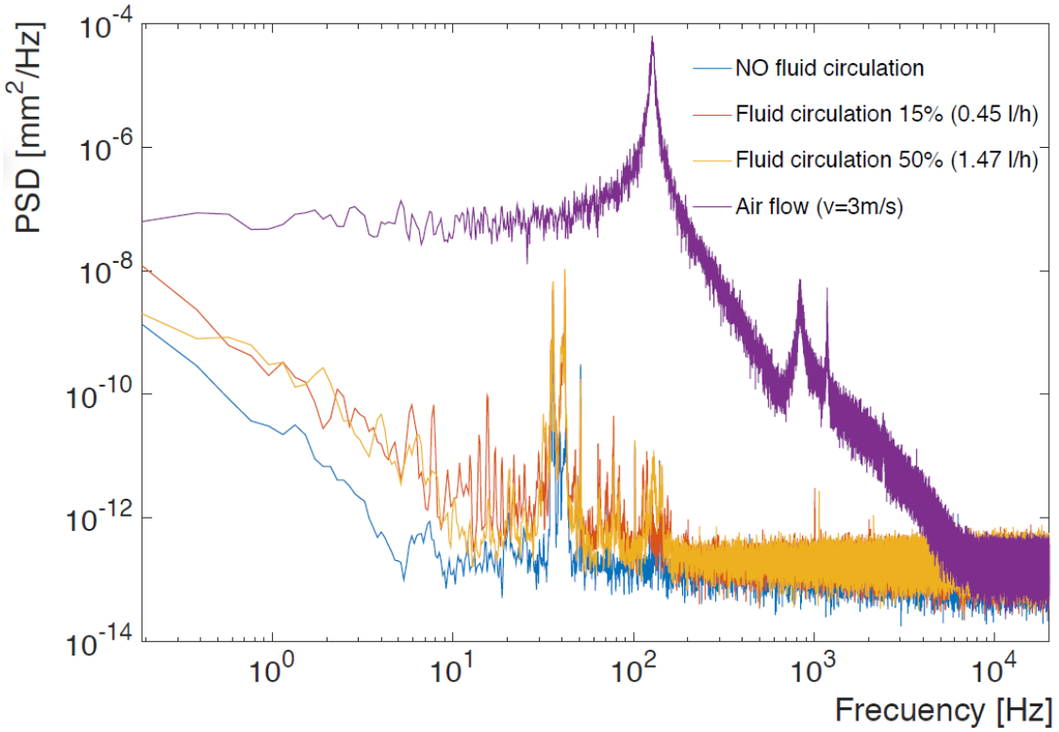


Max. power for a ΔT of 10 ºC vs. coolant flow

- Power density up to 25 W/cm²
- Continues to improve with flow rate up to 3 l/h
- Low pressure: 0.2 - 1.5 bar

Mechanical stability

- Maximize effects by using single-point support
- Measure position with sub-μm resolution
- Impact of air flow shows sensitivity
- Liquid flow has negligible impact (RMS ~ 0.5 μm)



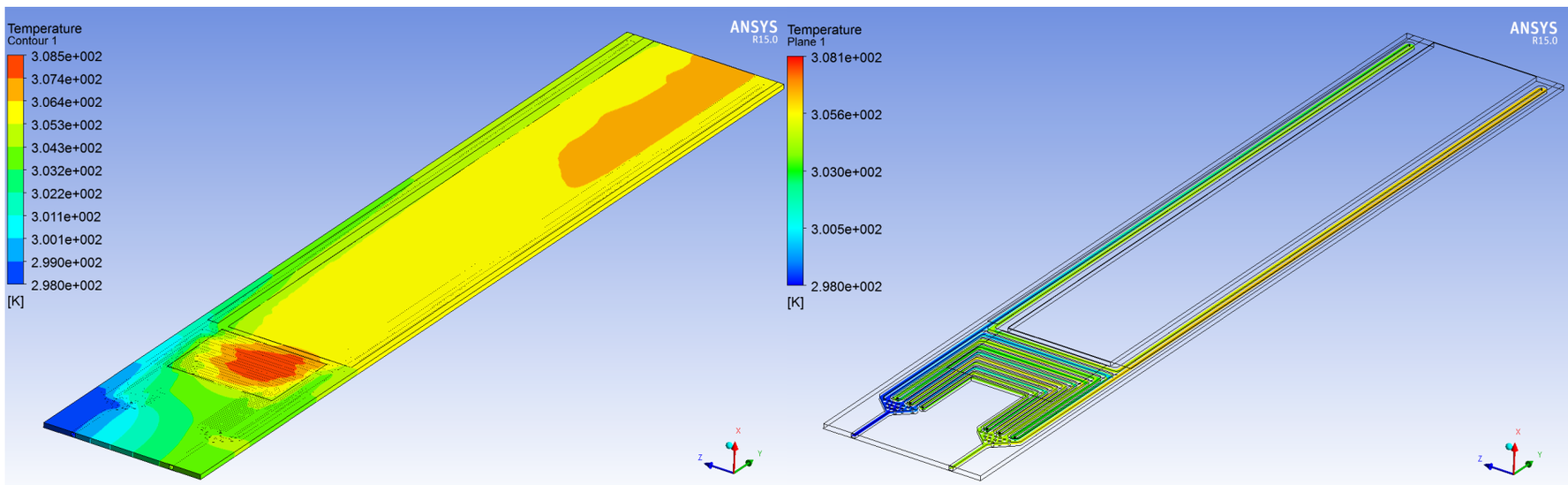
Low pressure mono-phase liquid flow of few l/h removes local heat very efficiently. Insignificant impact on mechanical stability.

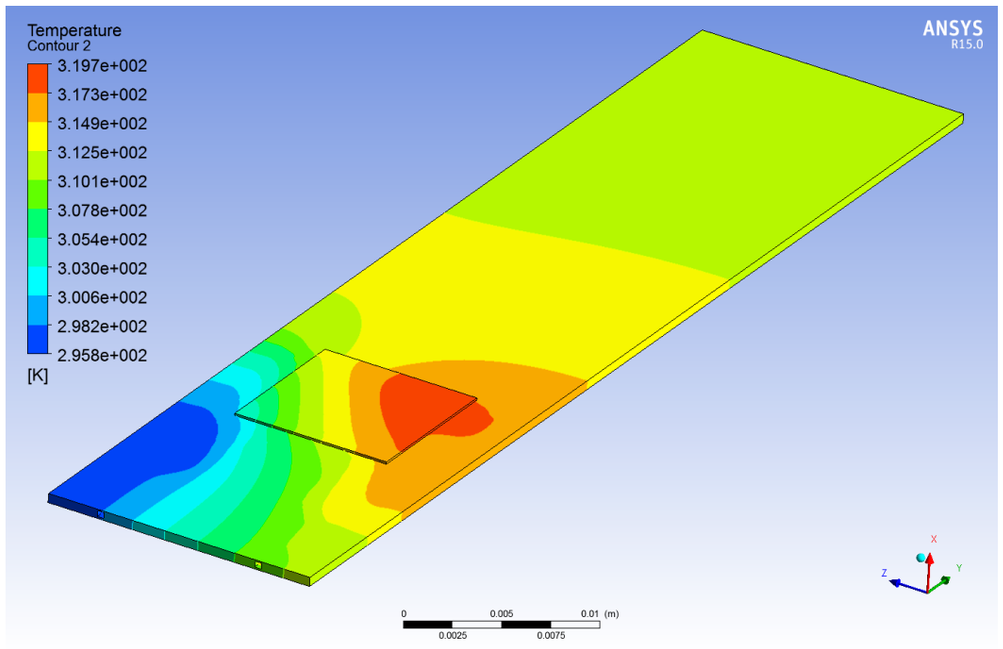
FE simulations

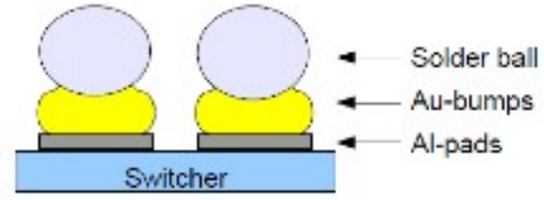
Thinned samples

Full-ladder MCC

Run a single channel around the sensor:
ΔT~5 K (nominal load)







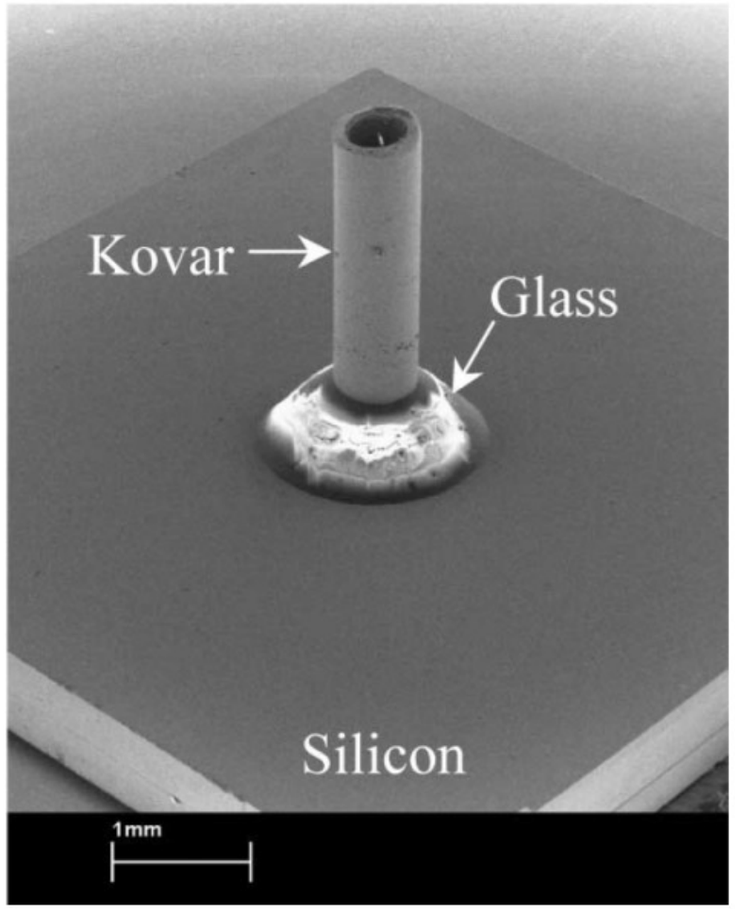
Thermal barrier formed by bump bonds

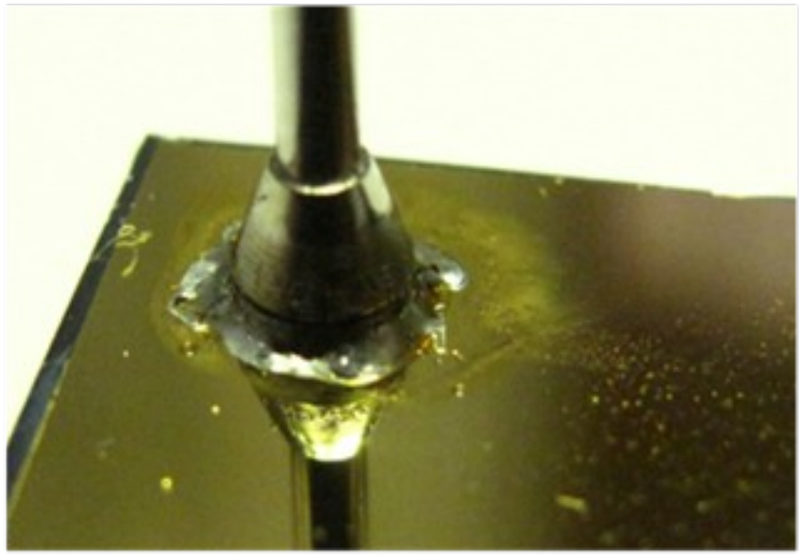
300 μm Si ASICS + 100 μm Bump-bonds
thermal resistivity of 6 W/m·K
Figure of merit increases by 5 K cm² / W

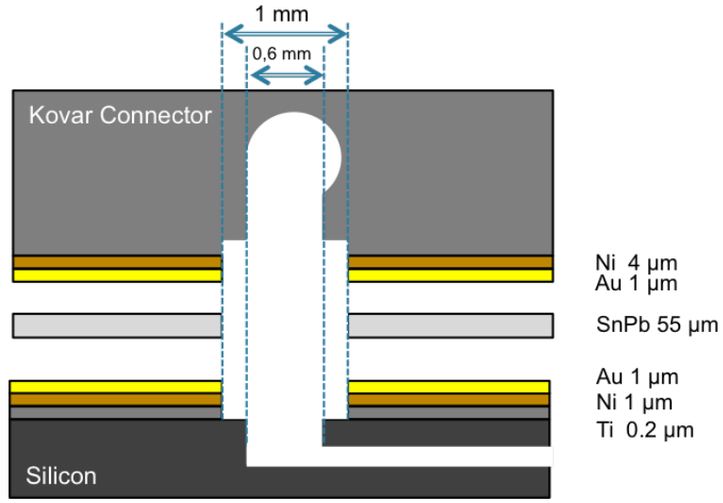
C.Mariñas PhD thesis link

New production has all these structures

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

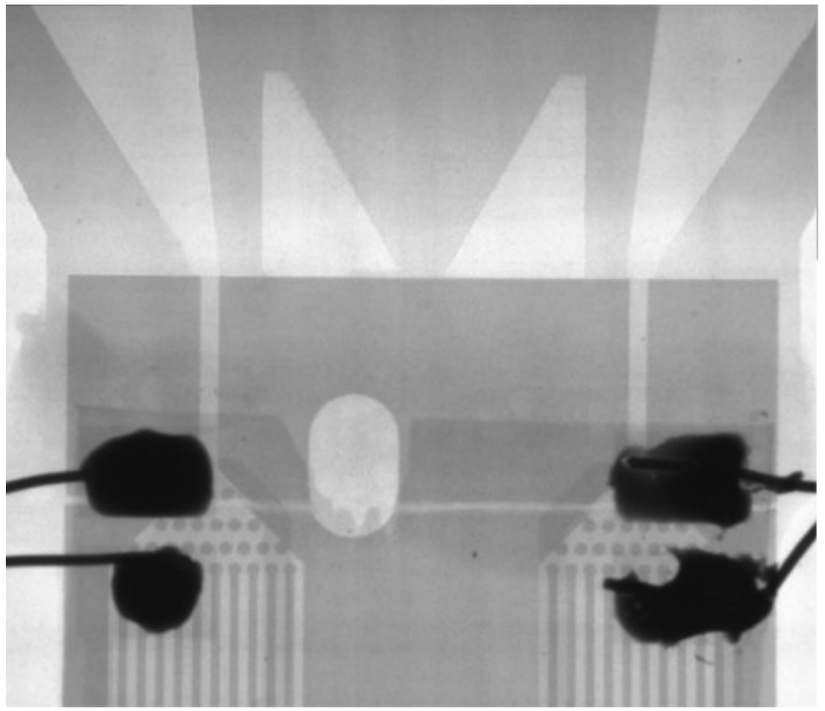
Low mass silicon frames with embedded microchannels for the thermal management of future vertex detectors in High Energy Physics experiments

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

To be submitted soon

Low-mass in-plane connectors

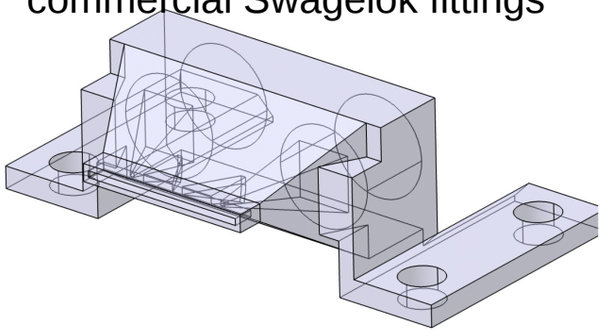


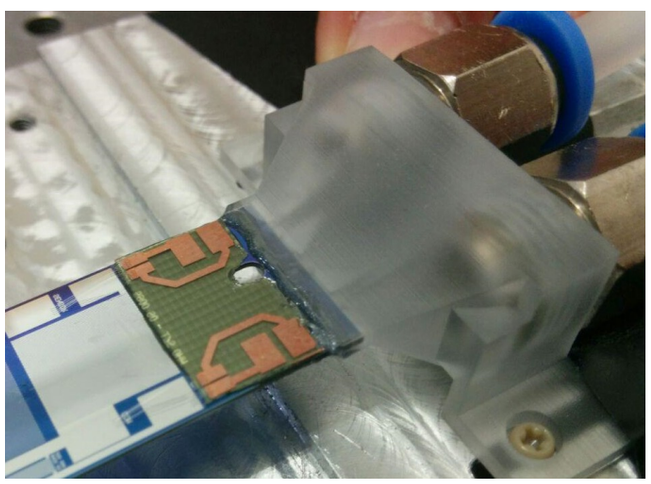
Low-Z 3D-printed connectors

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/X_0)

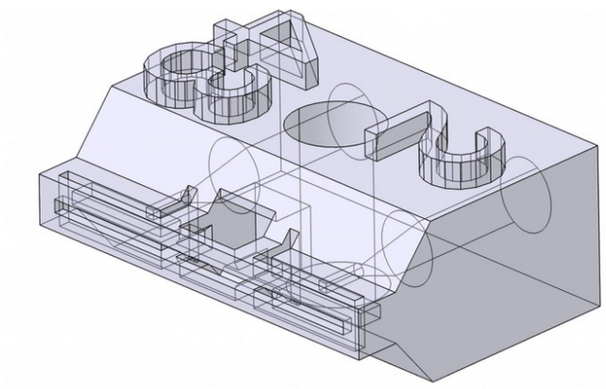
Mechanical interface to standard commercial Swagelok fittings

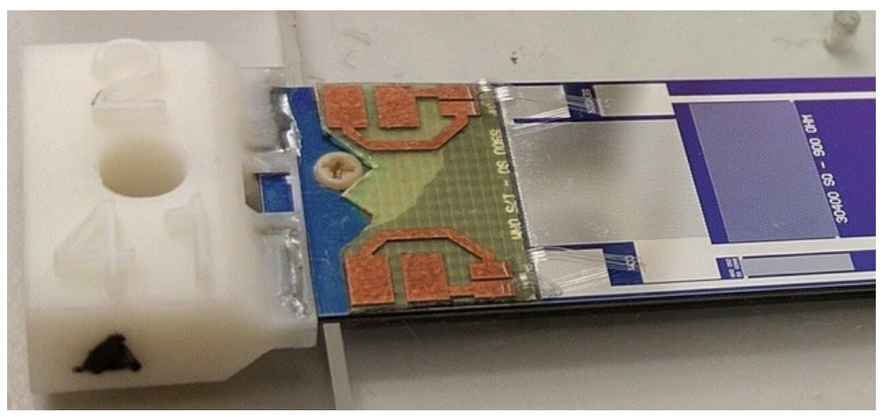




Past (0.21% X/X_0)

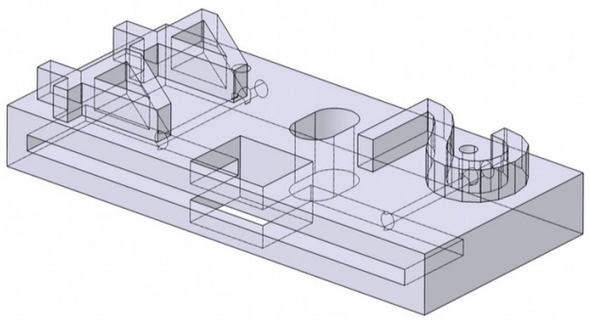
Smaller fittings

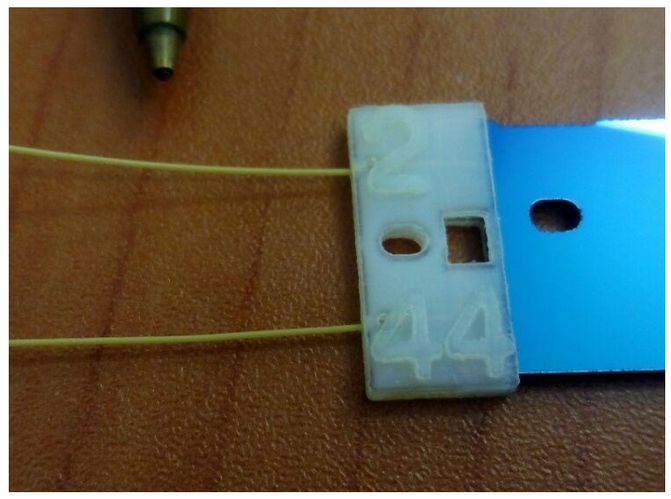




Present (0.05% X/X_0)

Glue PEEK tubes





Foundries/vendors

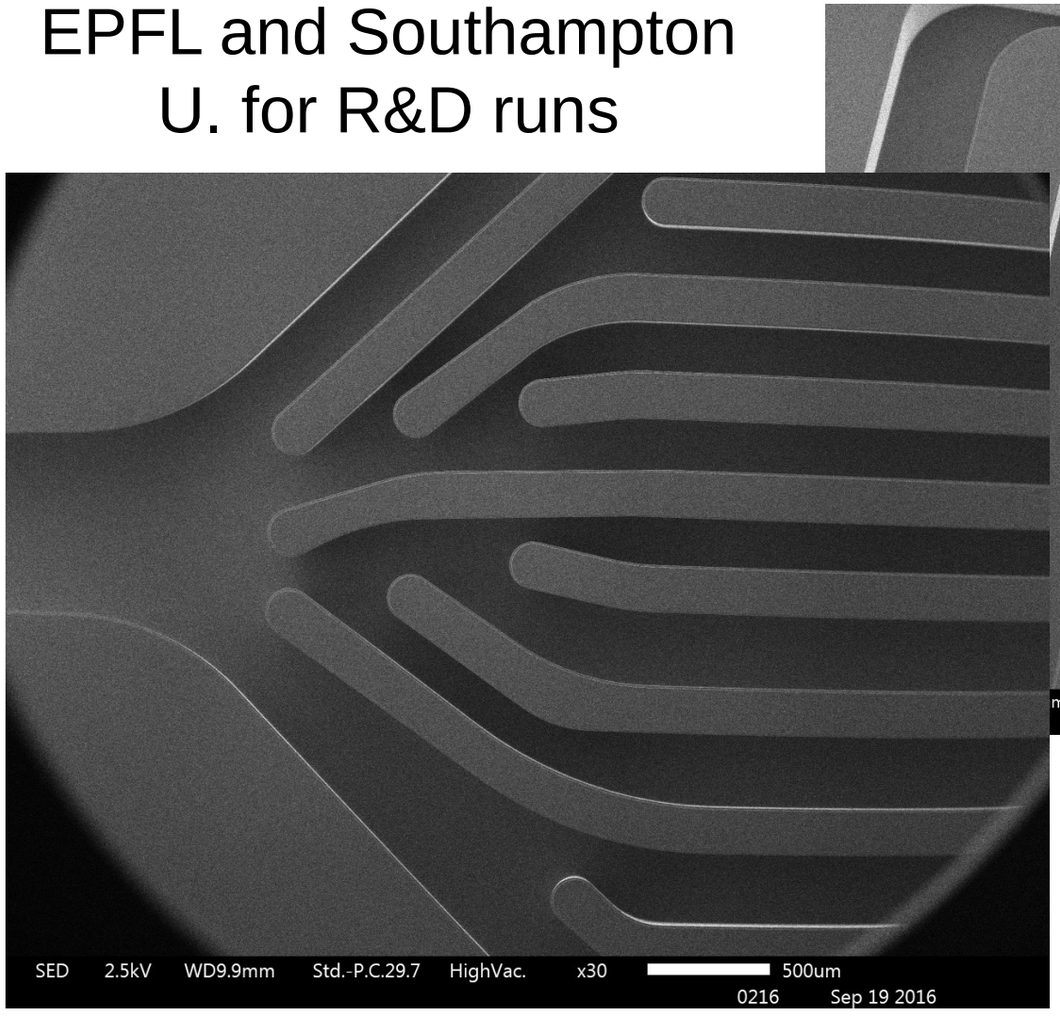
Slide corrected after the talk

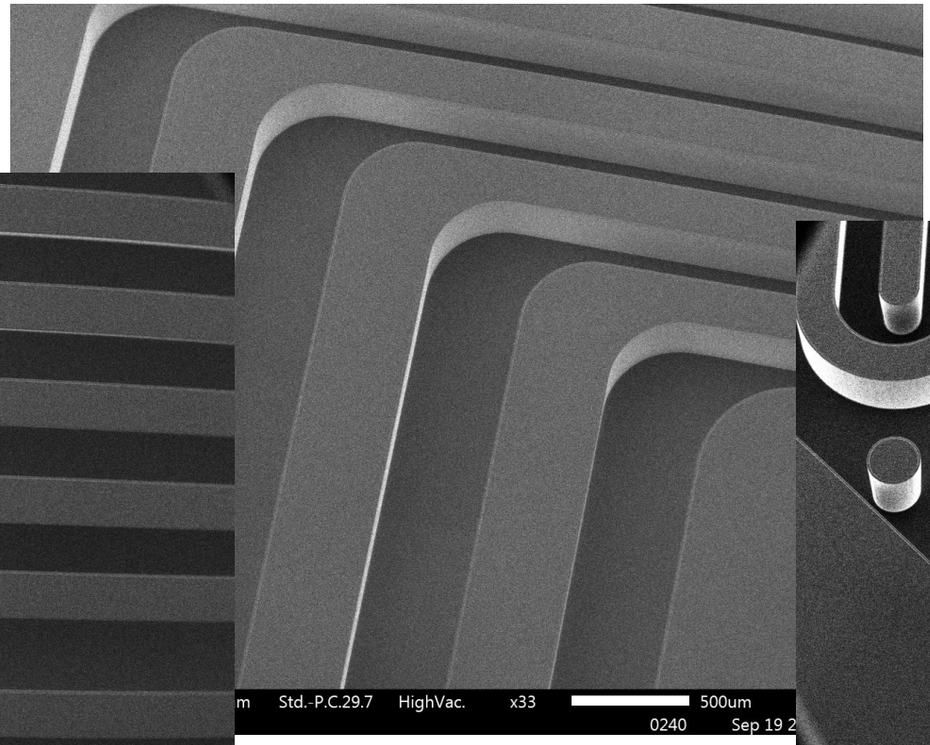
CEA-LETI used for pioneering work in NA62 and LHCb
(P. Petagna, CERN)
IMB-CNM Barcelona (M. Ullan)
MPG-HLL Munich (L. Andricek)
FBK Trento (M. Boscardin)

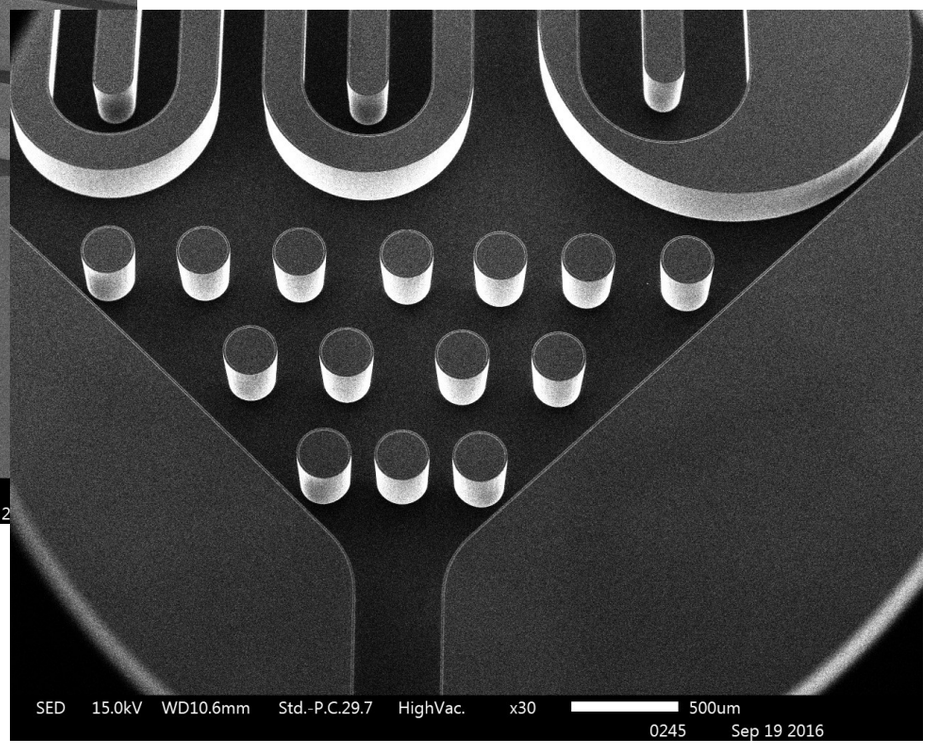
} In-house capacity

EPFL and Southampton U. for R&D runs

Trials ongoing with CSEM and IceMOS







Conclusions

LHC upgrades and future colliders require better integration of silicon detector elements (sensor, FE) with the cooling system

→ reduce ΔT wrt coolant, reduce material

MCC embedded in silicon cooling plates succesfully demonstrated in HEP

→ Forward experiments: NA62 (2014) + LHCb VELO upgrade (~2020)

Explore low-mass MCC solutions with connectivity in the acceptance

→ CERN (ALICE), CNM/DESY (ATLAS), Bonn/HLL/IFIC (DEPFET, ATLAS)

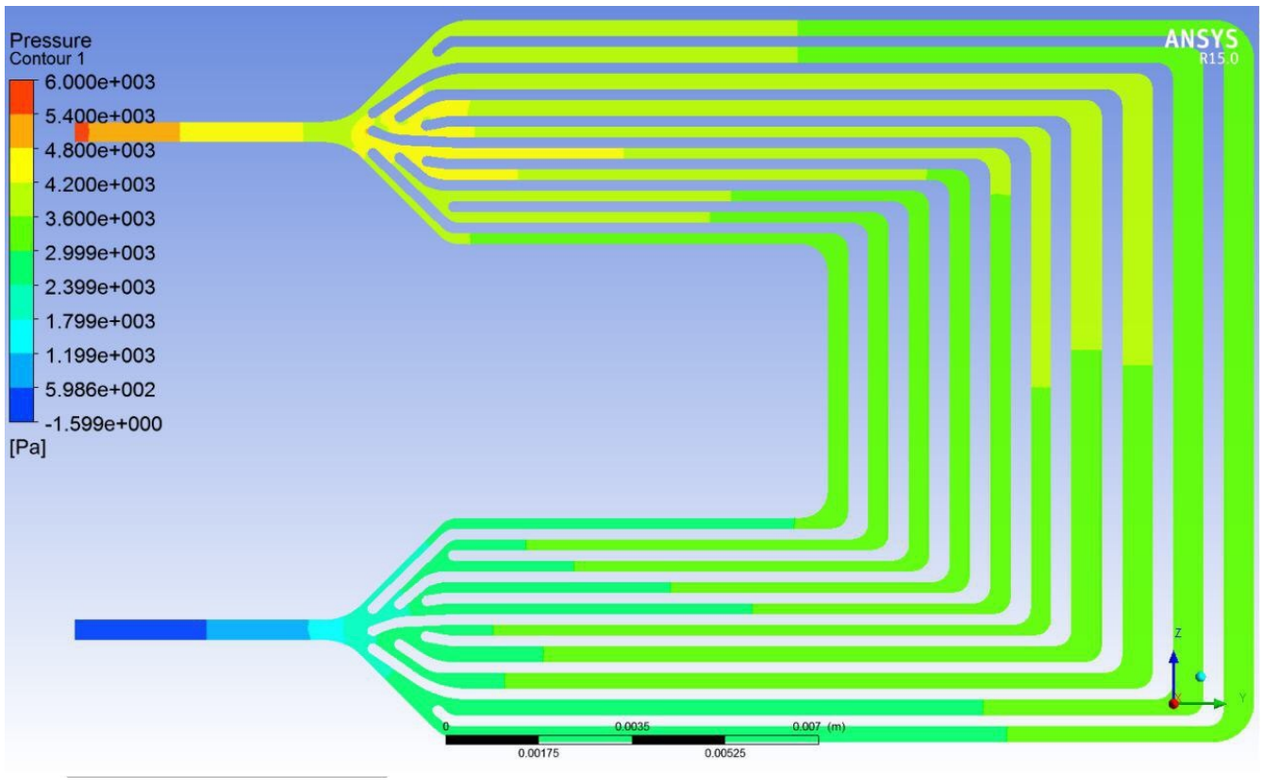
Integration of the MCC into the active silicon

→ process compatible with sensor demonstrated (*JINST 11 (2016) no. 06, P06018*)

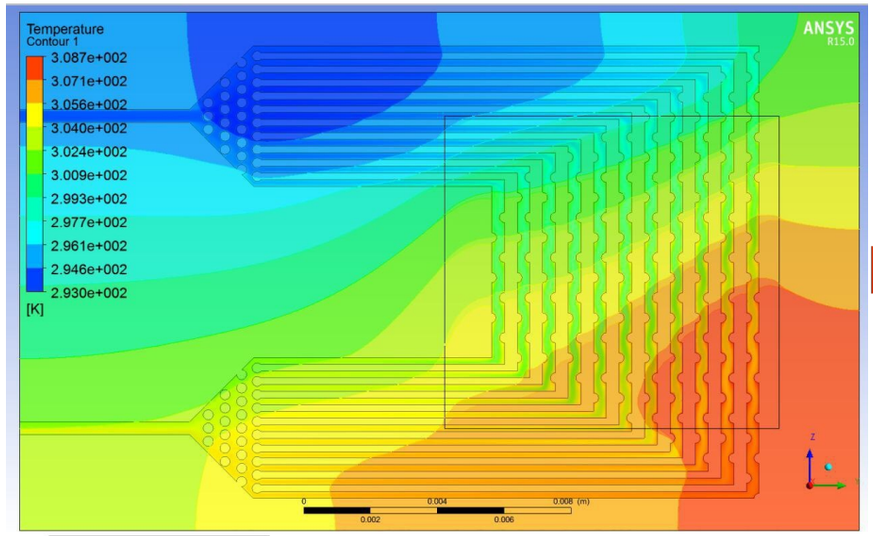
→ first micro-cooled active detector in a few years!

Thank you for your attention

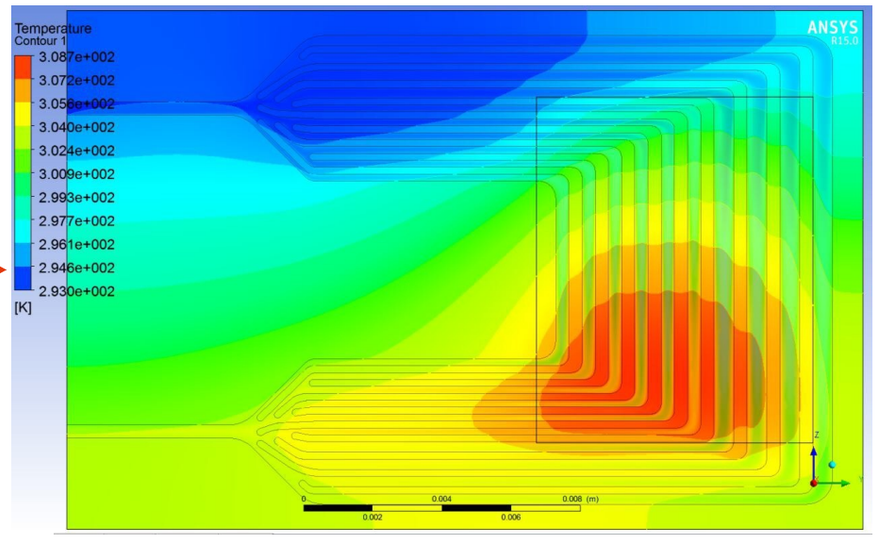
Optimized MCC geometry



- More homogenous flow
- Reduce pressure gradients
- Minimize and confine the heat spread

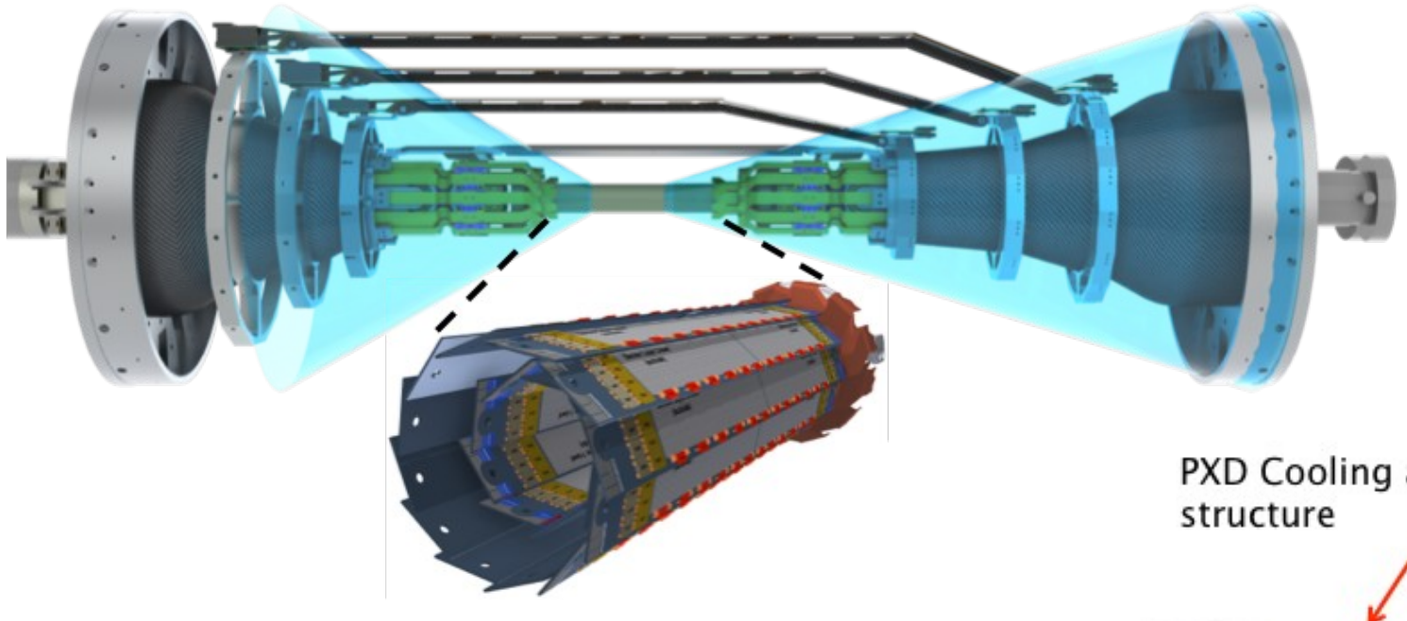


Recent geometry

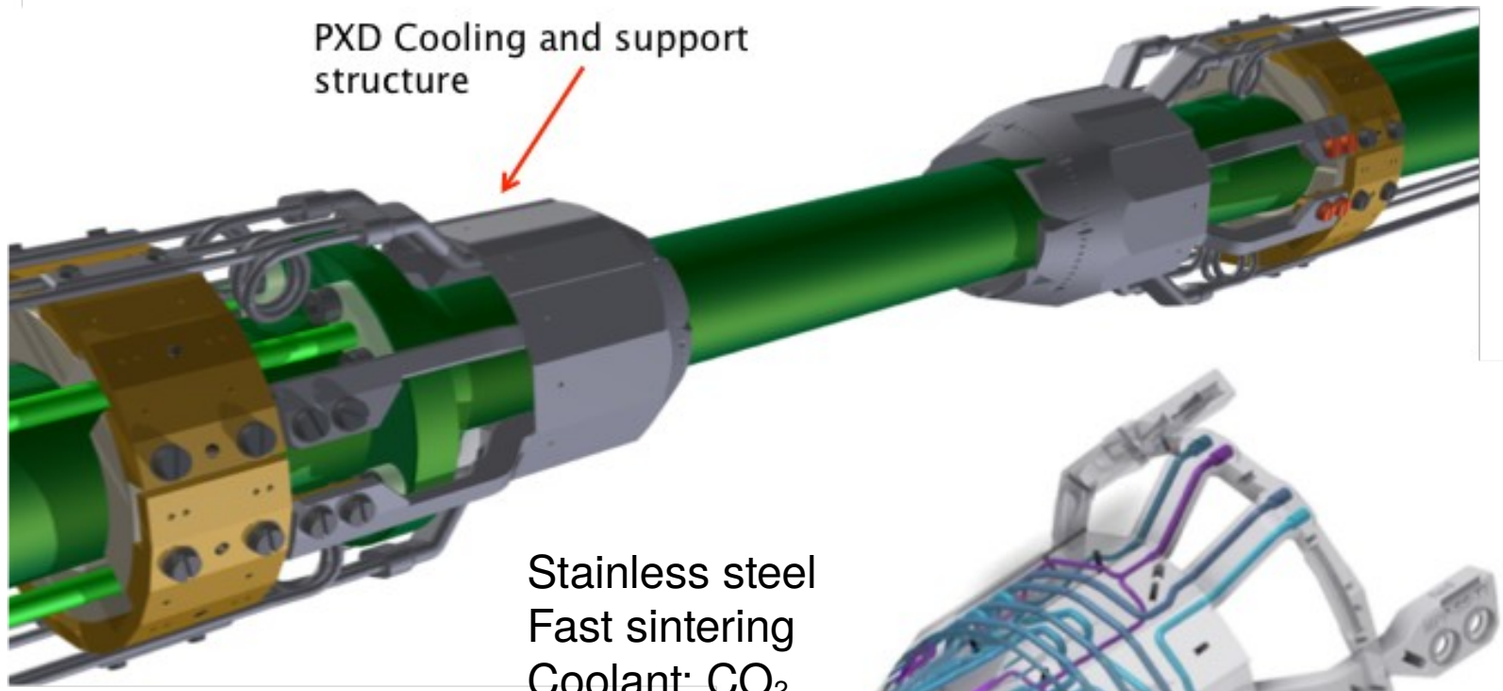


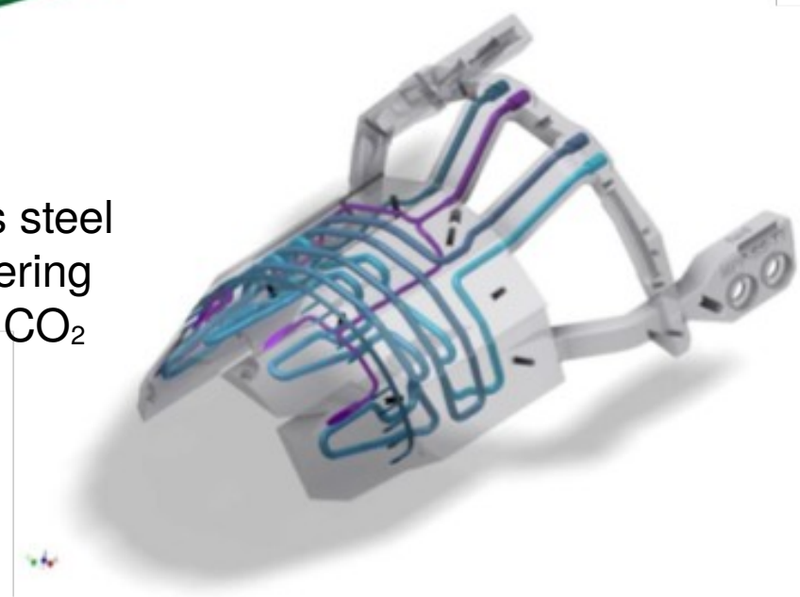
Optimized geometry

Cooling strategies



Belle II



Massive structures outside the acceptance to cool down the readout chips

Stainless steel
Fast sintering
Coolant: CO_2