DRD7: Cooling plates

On behalf of the DRD7.4c collaborators

DRD7.4: EXTREME ENVIRONMENT AND LONGEVITY

IMPLEMENTING DRD7:
AN R&D COLLABORATION ON ELECTRONICS AND ON-DETECTOR PROCESSING

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Introduction

- No single solution for the cooling structure nor coolant
  - Different material budget constraints, power dissipation, …

- Three (sub-)projects will be described today:
  - Ceramics cooling plate and metal 3D printing (UoM)
  - Microchannel cooling and active interconnection developments (CNM, DESY, IFIC)
  - Microchannel cooling manufacturing via thermocompression (CPPM)

- DRD7:
  - DRD7.4c – "covers the cooling structures in direct contact with electronics"
    - Cooling plates are included (e.g.: coolant R&D not included)
  - Recently approved
    - DRDC open session on June 3rd (link)

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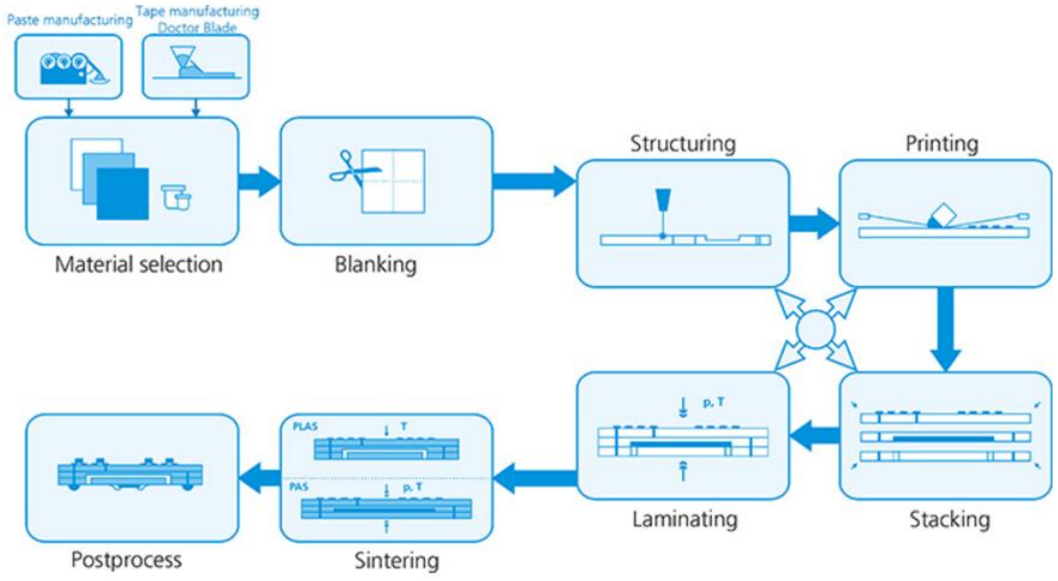
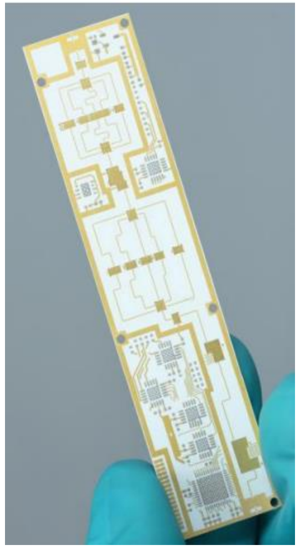
Ceramics

- Manufacturing at IKTS Fraunhofer (Germany)
- Different base materials: YSZ, $\mathrm{Al_2O_3}$, … including **SiC** and **AlN**
- Manufacturing based on several layers
- **Why?**
    - Robustness, reliability, stability in ultra-high-vacuum
    - Possible to embed conductive layers in between ceramics layers and metalize the surface
        - Potential to integrate electronics or high conductivity elements
    - Mechanically robust and compatible with high ultra vacuum





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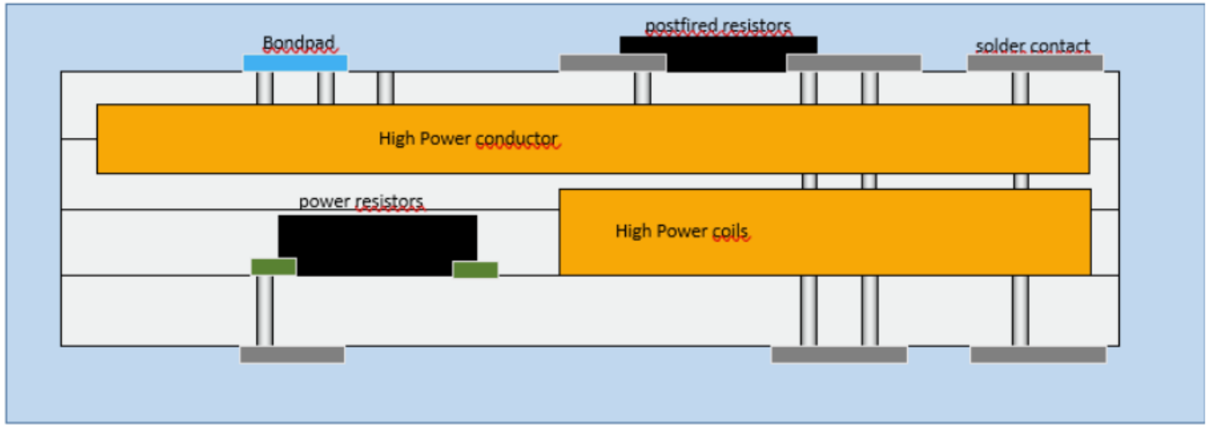
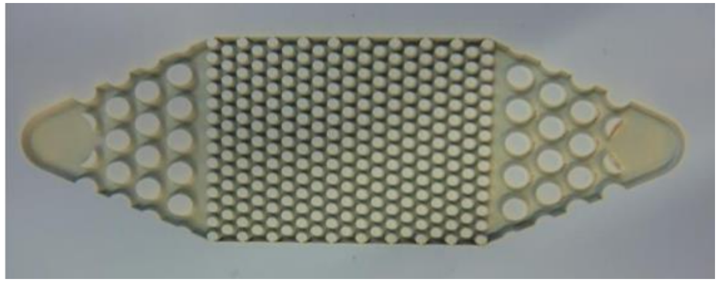


Ceramics

- Experience with fluidic applications
- First prototype based on the early VELO Upgrade I CERN design
  - Initial channel with $70\mu m$ width (restrictions)
  - Channels height $100\mu m$
  - Overall dimensions: $40 \times 60mm^2$
  - Based on LTCC
    - $Al_2O_3/Glass \sim 1:1$
    - Al_2O_3 HTCC is $\sim 96\%$
  - Possible to move to SiC or AlN
- Encouraging results from FEA studies
  - Geometry based on the VELO Upgrade I design (5 mm overhang)
  - For $2W/cm^2$, $\Delta T \sim 9°C$ (coolant heat transfer coefficient not considered)



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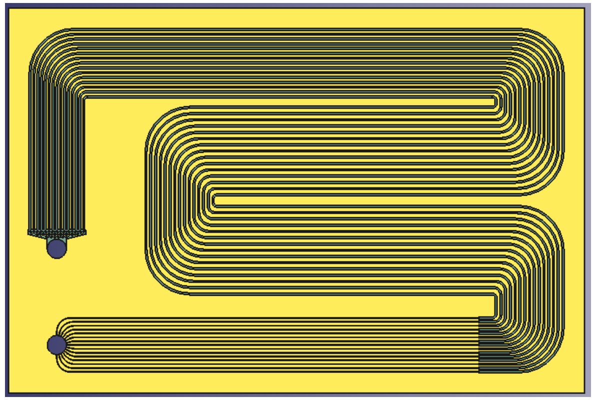
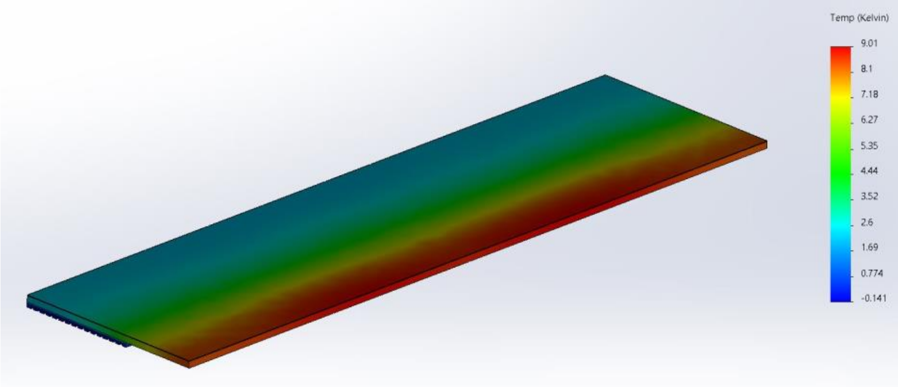
SNAKEI based design to optimize printing parameters/test feasibility

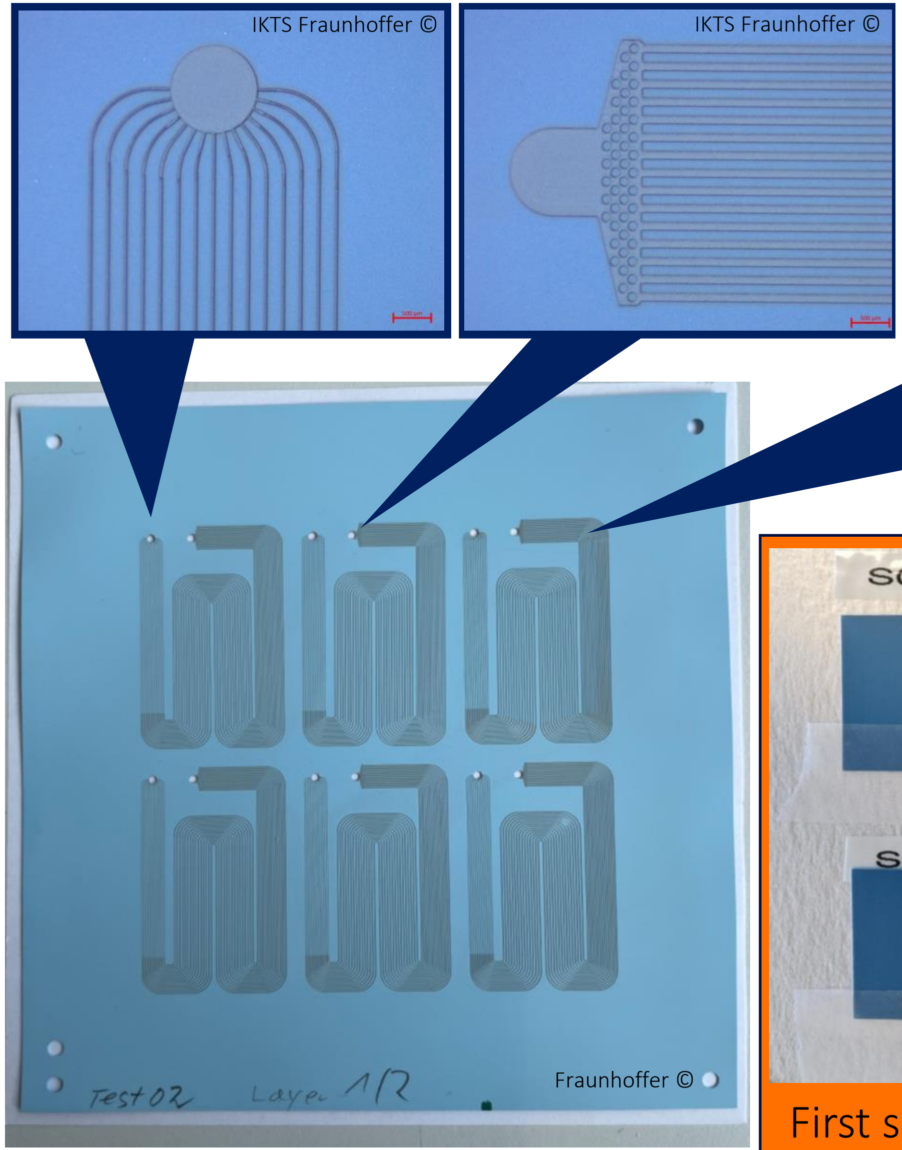




Simplified FEA focusing on the 5 mm overhang. Substrate in alumina and heat conduction on one side of the cooling plate and Stycast (100um).

Ceramics: Goal and status

- Goal:
  - ✓ Manufacture first samples (IKTS)
    - ✓ Miniaturized version (2x smaller in-plane)
    - ✓ Expected 35um and 100um width restrictions and main channels respectively!
  - Second round being prepared
  - Validate initial prototypes to high pressure, leak tightness and cooling performance
  - Benchmark: LHCb VELO Upgrade 2 requirements (High pressure 186 bar, leak tight (vacuum operation) and excellent thermal performance
- Very encouraging first manufacturing results!!!



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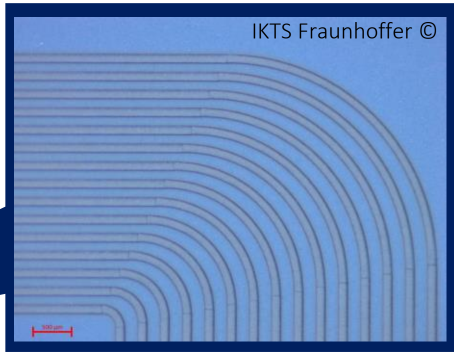

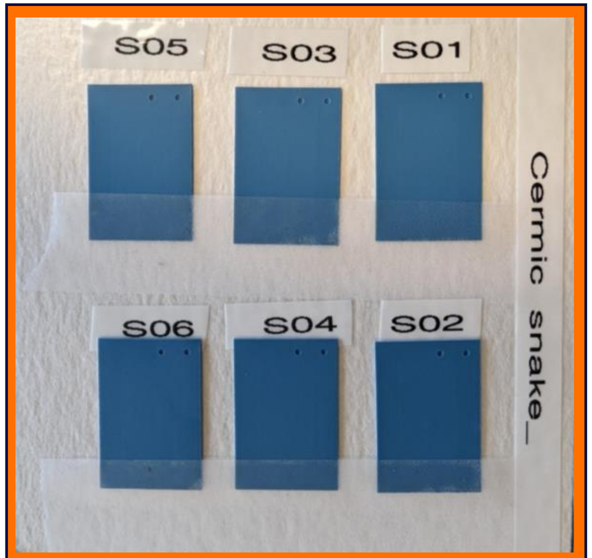

First samples in-house
(eagerly waiting to be tested)

3D metal

- Exploration phase
- Considering evaporative $\mathrm{CO_2}$ as baseline solution
- Power dissipation of up to $2\mathrm{W/cm^2}$

Aggressive U-track like design

- More aggressive design for reduced material budget due to the cooling substrate
- Largest variation of temperature on the sensor part around $25℃$ (with respect to the inner side wall)
  - Larger $\Delta\mathrm{T}$ would have to be compensated by the coolant working temperature
- Alternative strategy to cooldown off-chip electronics would have to be improved (cooling routing lines)

Passive medium integration

- Lower material budget contribution compared to same silicon thickness (factor x2)
- Cooling line integration via soldering (NanoFoil, 35–50W/mK)
- FEA indicates a $\Delta\mathrm{T}{\sim}21℃$ when pushing away the Ti2 cooling lines by $\sim 30\mathrm{mm}$

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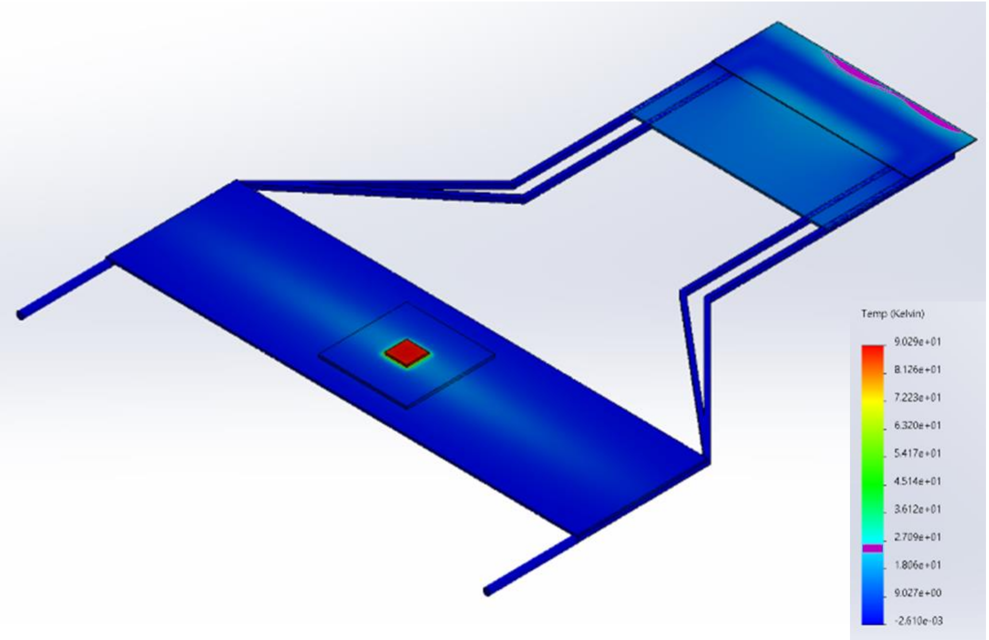
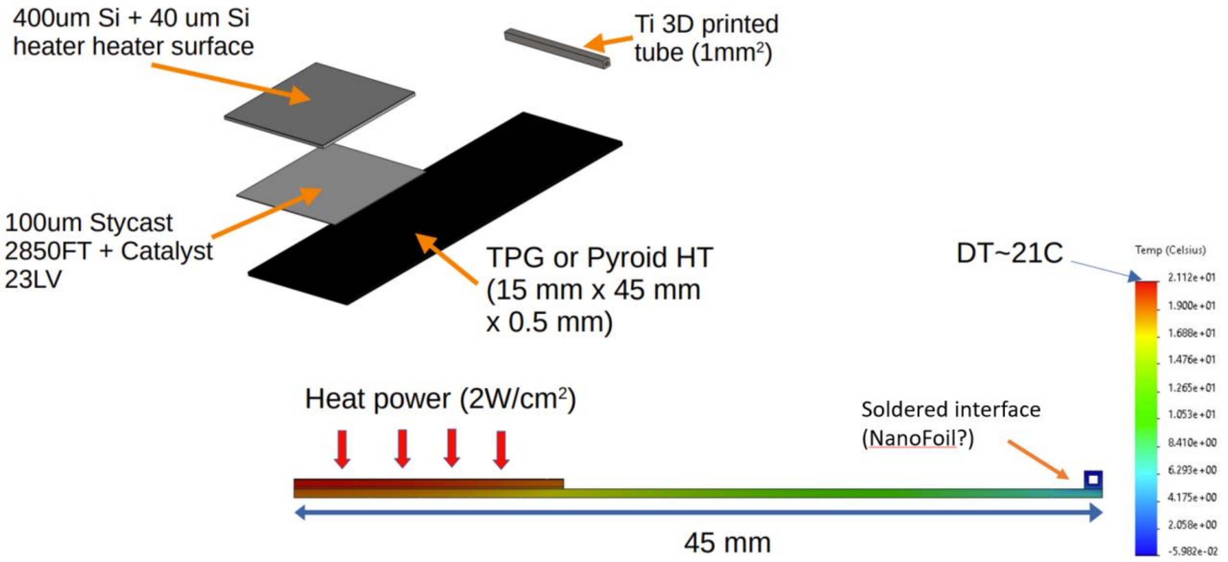
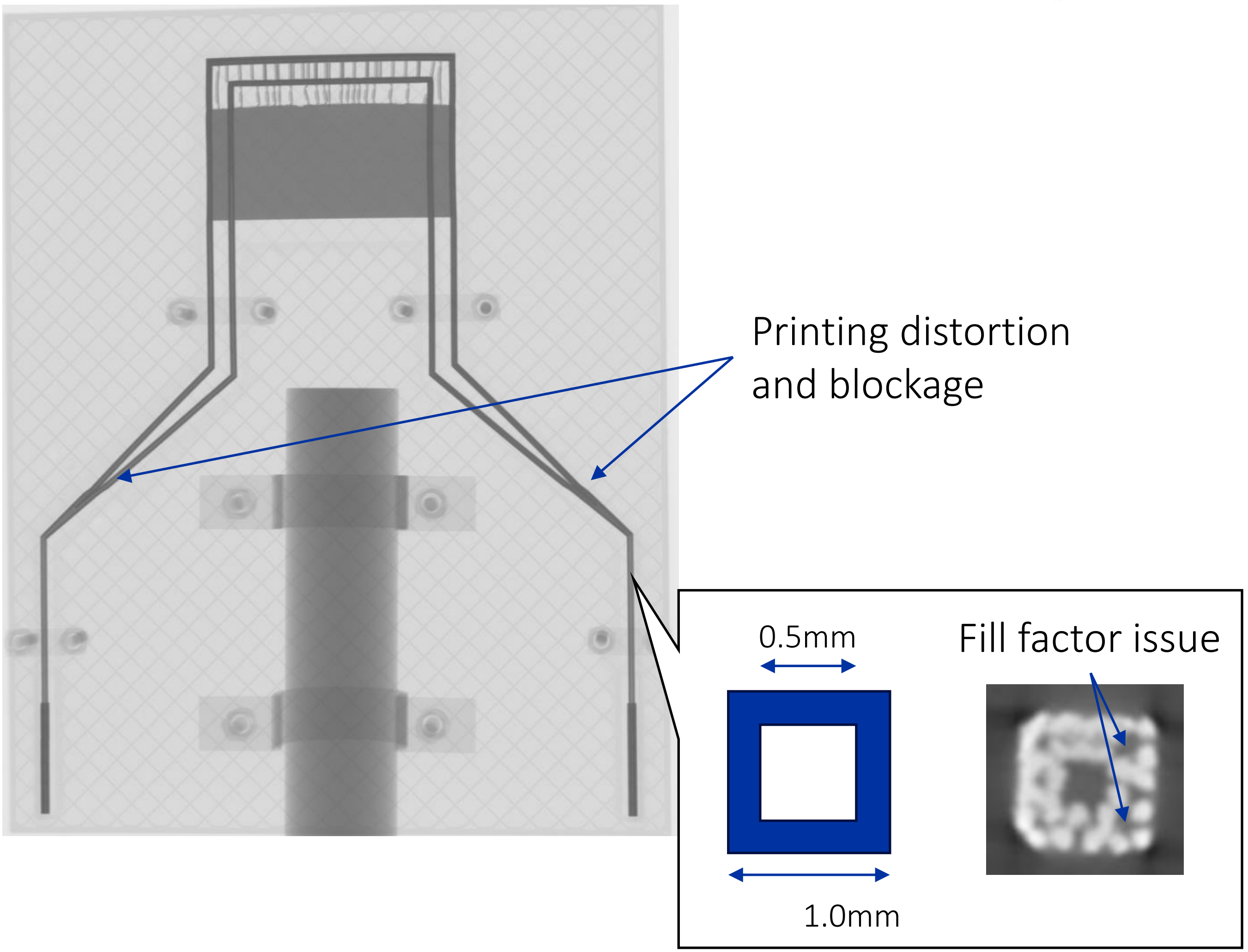




3D metal: LHCb VELO

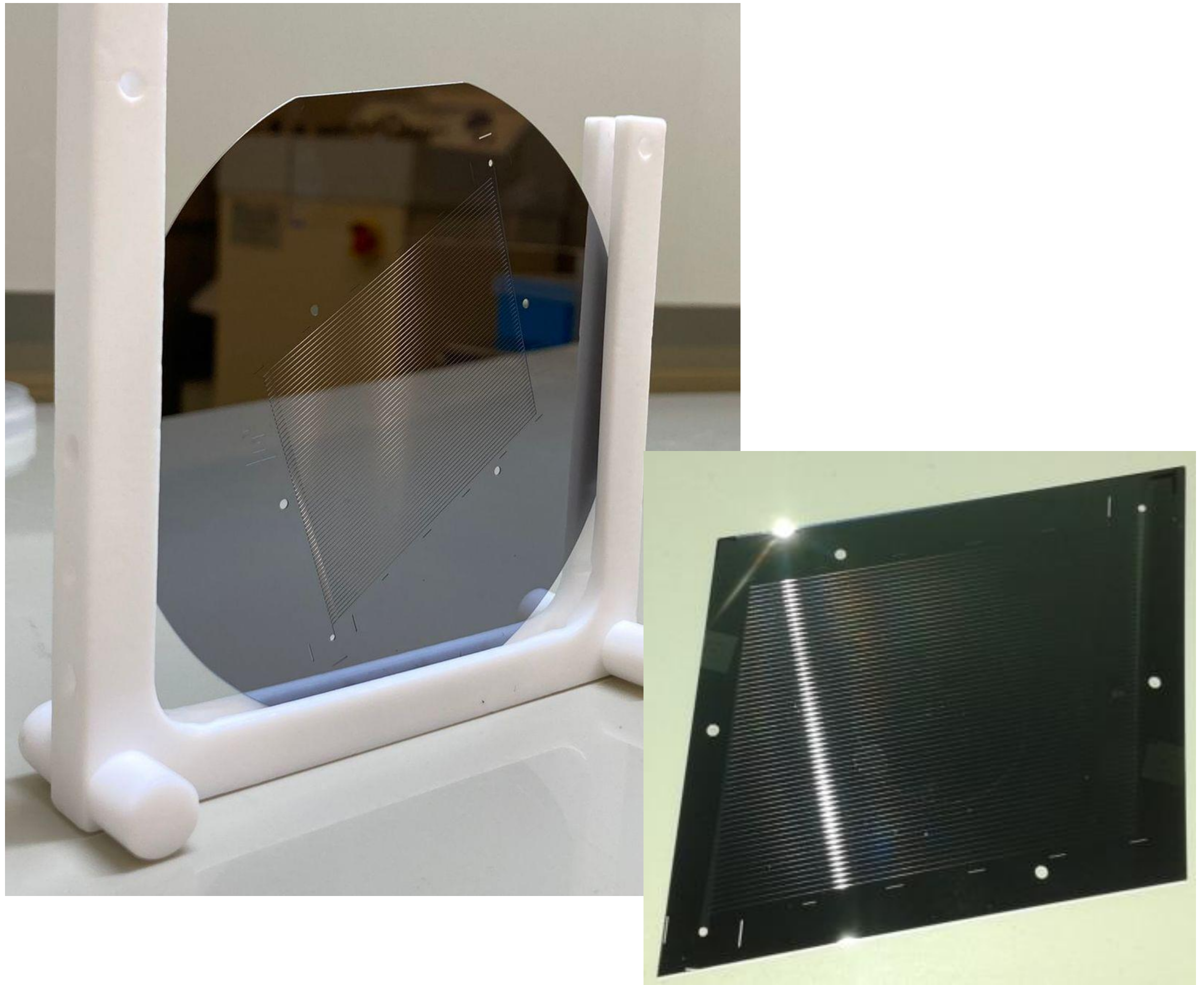
- Different designs were submitted to Royce Institute (Innovation Center - Sheffield)
  - U-shaped design
  - Squared tube and connector prototypes
- X-ray tomography via NXCT
- Filling factor being improved, and different approaches being tested
  - Single squared tubes and easier integration with a plate-like design
  - Potential to also explore better integration
- New round of printing on-going:
  - Different printing parameters to improve distortions and fill factor
  - Half of the samples will be electro-polished (easier integration?)

X-ray 2D tomography (one projection)



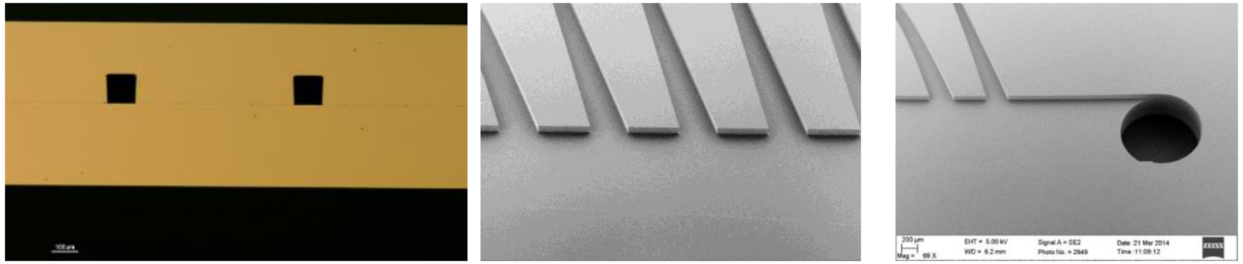
Microchannel cooling and active interconnection developments

- **Miguel Ullán (IMB-CNM, CSIC)**, Carlos Mariñas (IFIC-UV, CSIC), Marcel Vos (IFIC, CSIC-UV), Ingrid Gregor (DESY), Sergio Díez (DESY) and Jonathan Correa (from DESY)
- In the past, we developed a technology of micro-channel cooling for High Energy Physics detectors
  - N. Flaschel, et al. “Thermal and hydrodynamic studies for micro-channel cooling for large area silicon sensors in high energy physics experiments”, NIMA, vol. 863, pp. 26-34, 2017. (link)
  - Ph.D Thesis: Micro-channel Cooling For Silicon Detectors. Nils Flaschel. Hamburg University. 2017 (link)

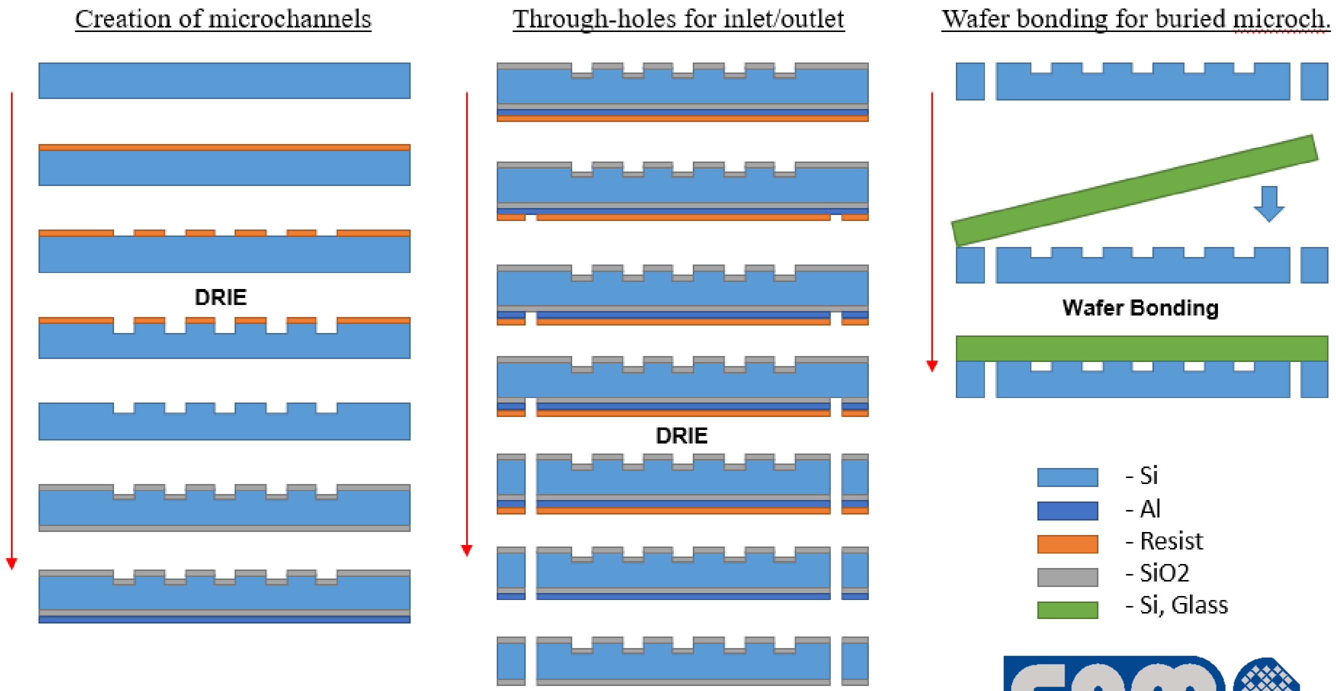


Microchannel cooling and active interconnection developments

- Technological process for micro-channels at IMB-CNM



- Creation of microchannels:
  - Deep Reactive ion etching (DRIE)
- Microchannels enclosure via:
  - Wafer bonding


Creation of microchannels

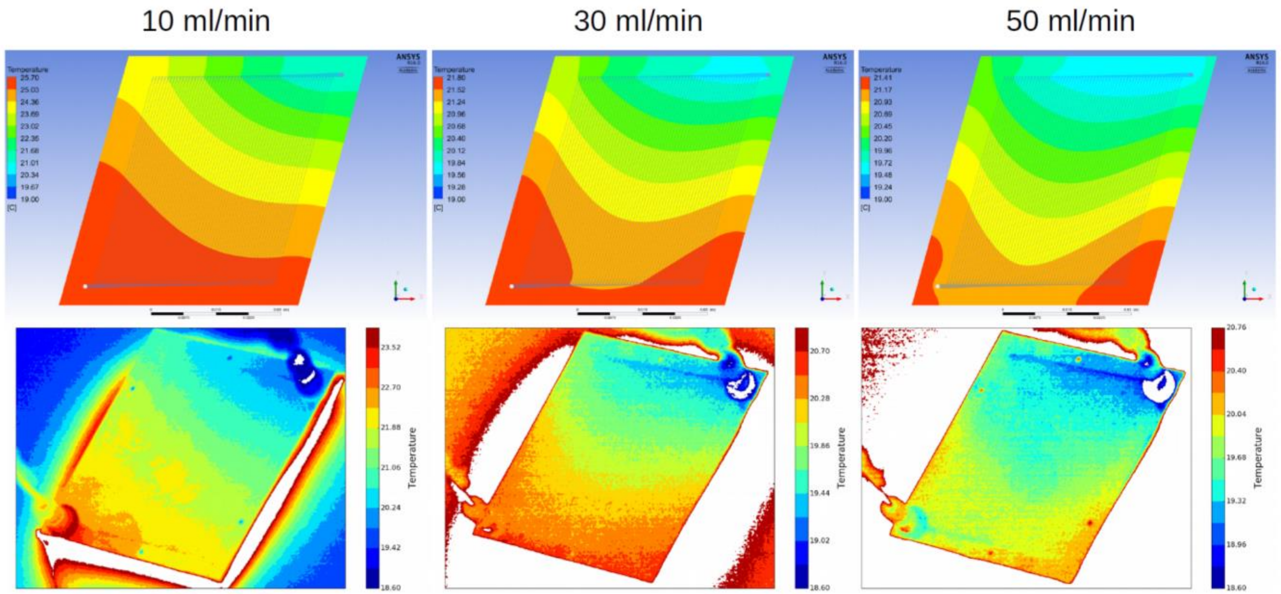
Through-holes for inlet/outlet

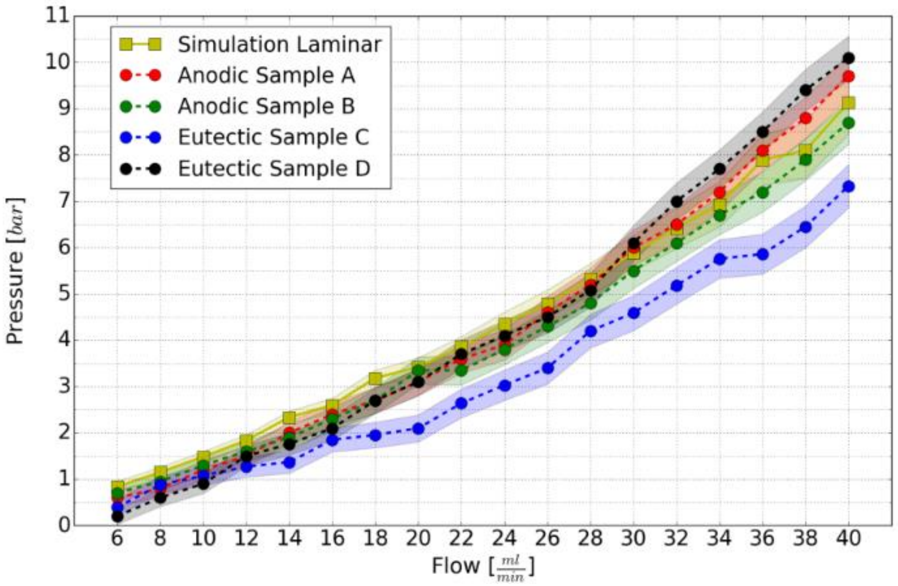
Wafer bonding for buried microch.

- 🟦 - Si
- 🟦 - Al
- 🟧 - Resist
- ⬜ - SiO2
- 🟩 - Si, Glass

Microchannel cooling and active interconnection developments

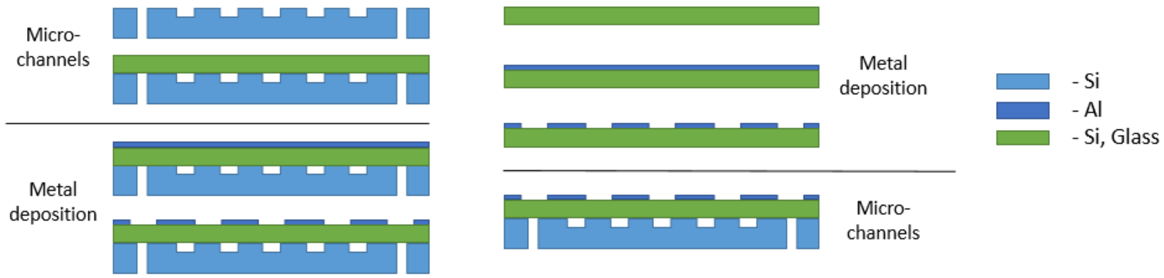
- Previous results on fluidic and thermal tests
- Laminar flow
- Coolant: 3M HFE7100
- Low power density: $30.8\mathrm{mW/cm^2}$
- Good agreement with simulation
- Thermal homogeneity across the sample($\sim 4 \times 4\ \mathrm{cm}^2$ large), < ±1 ºC (for lowest flow rate)

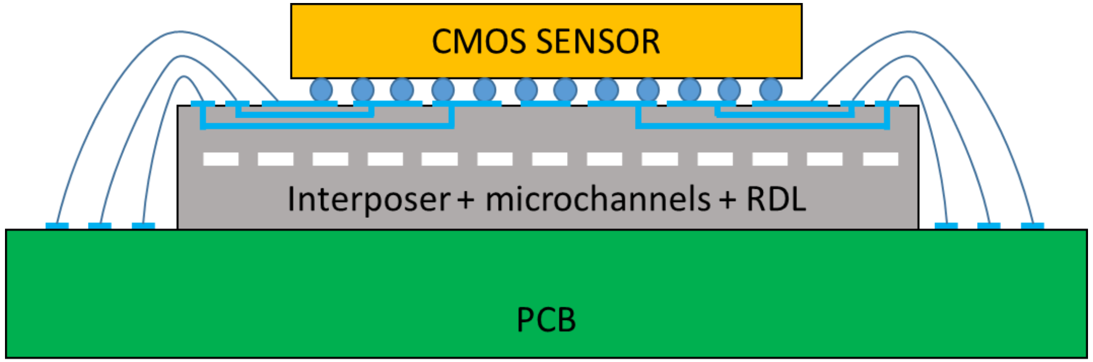




Microchannel cooling and active interconnection developments

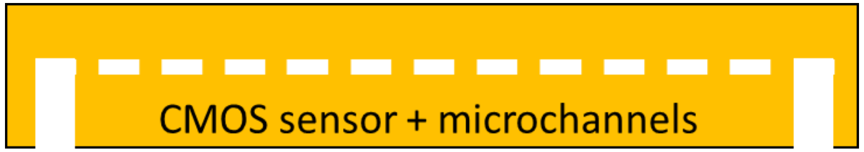
- Main Objective I: Integration of micro-channels in silicon interposers with integrated signal and power routing (RDL)





Main Objective II: Full integration of the sensor (CMOS technology) with the microchannel cooling in a single silicon piece

- Full integration of DMAPS chip with the microchannels in a single monolithic piece
- Post-processing at wafer level with a CMOS compatible process
- Following the “post-processing” technique developed previously
- Additional technological developments
  - ✓ Low temperature ($350^{\circ}\mathrm{C}$) anodic bonding
  - ➢ Microchannels created on glass substrates (isotropic wet etching)
  - ➢ Eutectic and/or fusion bonding
  - ➢ Improve post-processing compatibility
  - ➢ Full demonstrator



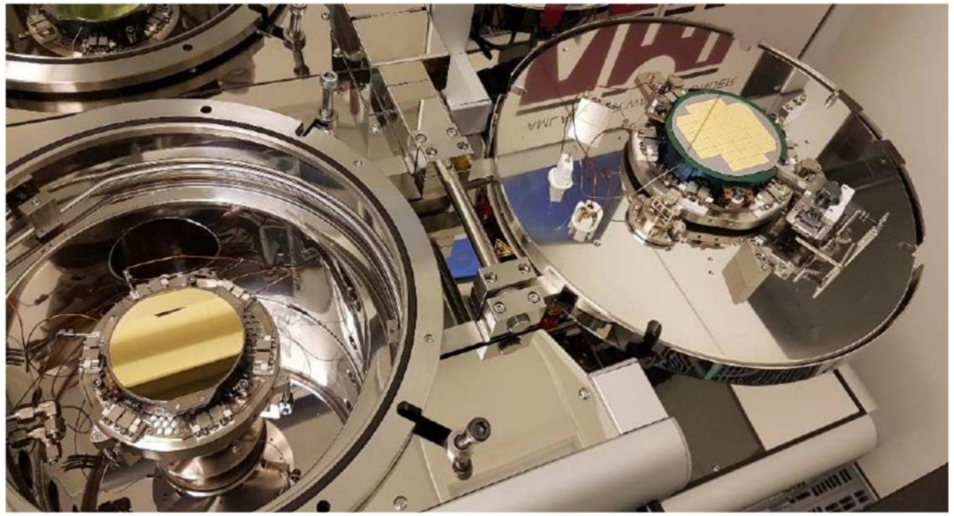
Microchannel cooling manufacturing via thermocompression

R&D to develop a low-cost micro-channel production process

As an alternative to the complicated and costly direct Si/Si bonding, investigate bonding techniques with intermediate thin layers:

- Anodic bonding with glass (BF33)
- Thermocompression with gold

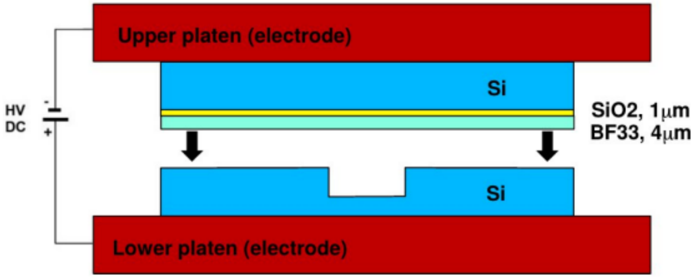
Bargiel et al., Micromachines 2023, 14, 1297

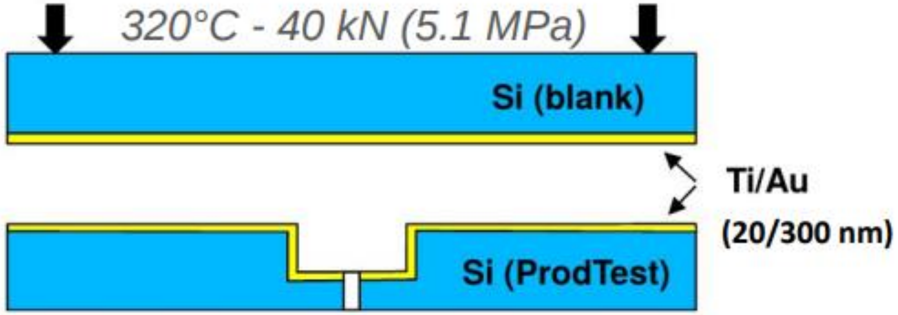


Thermocompression

Anodic bonding

50V - 400°C - 50kg





Microchannel cooling manufacturing via thermocompression

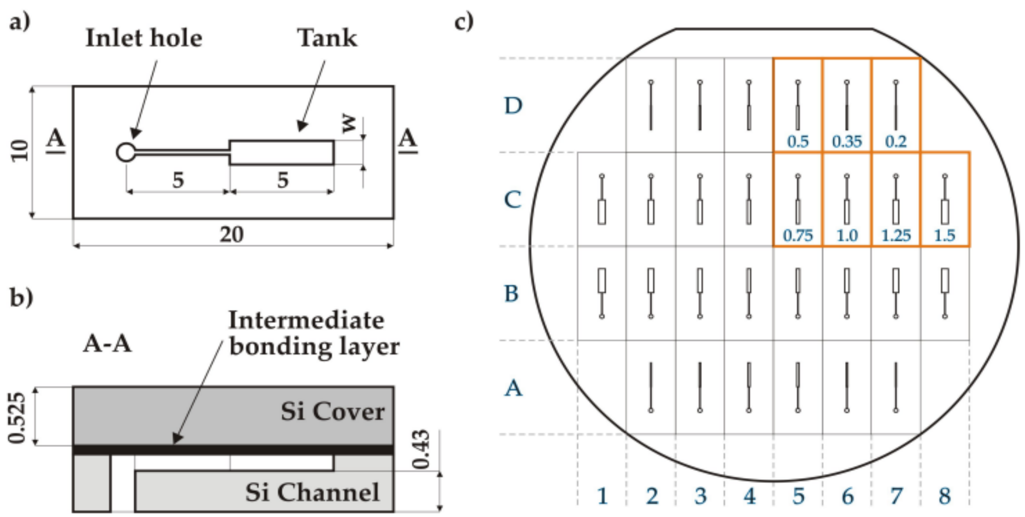
Bargiel et al., Micromachines 2023, 14, 1297

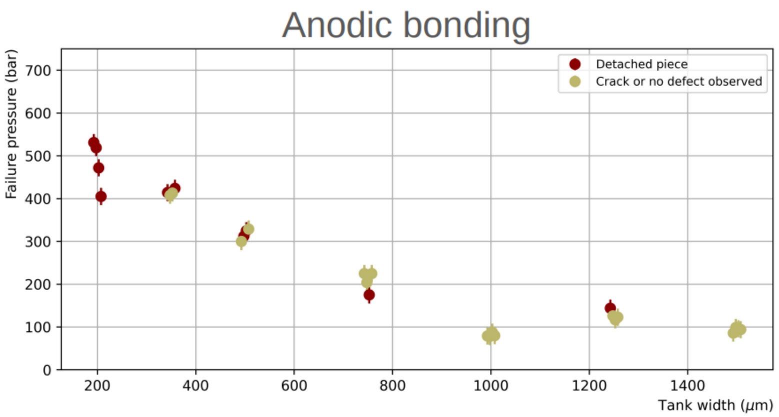
Bonding strength evaluated through a series of destructive pressure burst tests, recording the maximum pressure reached in microfluidic test structures before breakage (à la LHCb)

⇒ Test chips produced both with the anodic and with the thermocompression bondings can sustain very high pressure

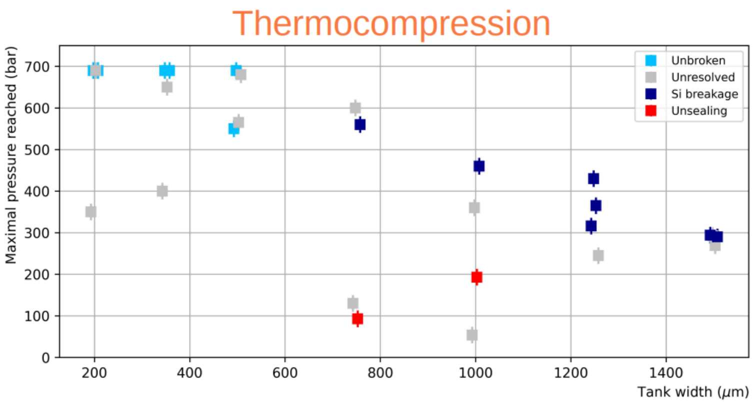
⇒ Focus on thermocompression as

- It generally allows to reach higher maximal pressures
- It is a widespread technique available in most clean room facilities




Anodic bonding

Maximum pressure limited by the adhesion force of the deposited BF33/SiO_2 layers

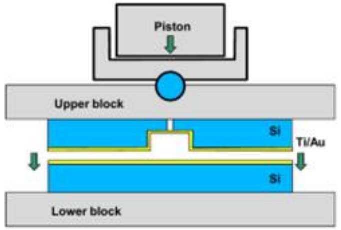

Thermocompression

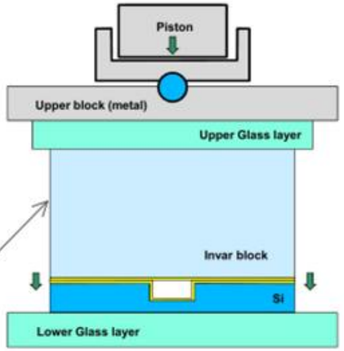
Maximum pressure limited by the silicon strength (except for a few outliers)

Microchannel cooling manufacturing via thermocompression

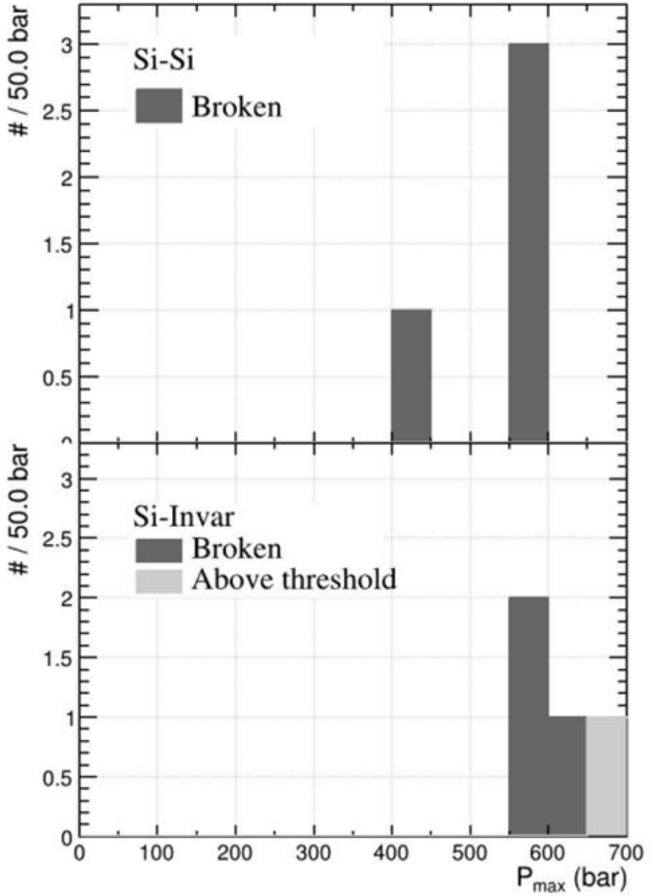
- Towards the bonding of a connector using thermocompression process:
  - Investigate chip level bonding replacing the bonder with a mechanical press at atmospheric pressure outside the clean room
- Two configurations tested:

  -Si/Si bonding (for reference)
  -Si/Invar
  → Both types can sustain high pressure
  → Proof of concept validated!





Polished block of Invar mimicking a connector

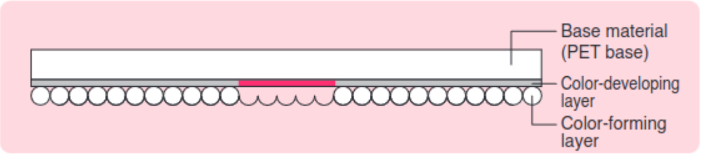


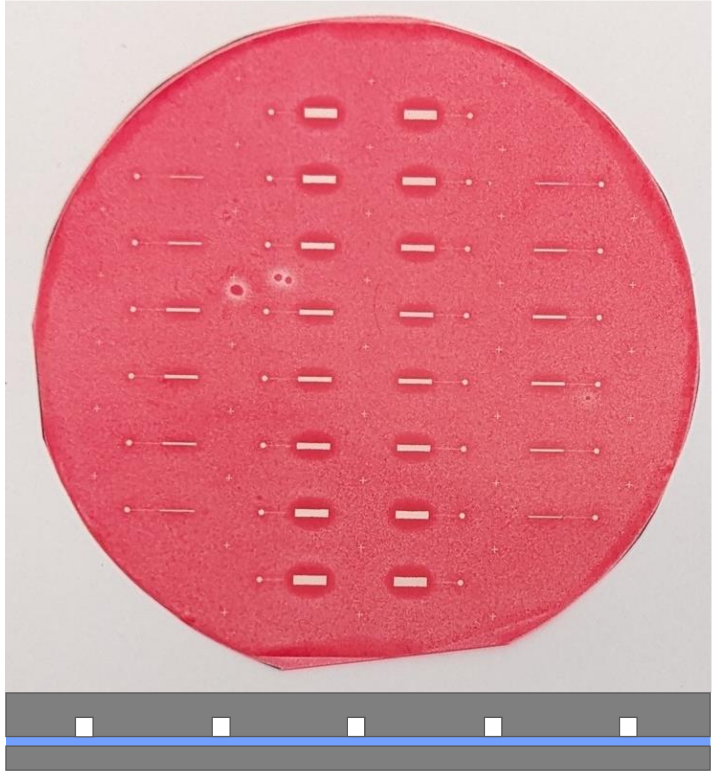
Hyperbar bonding

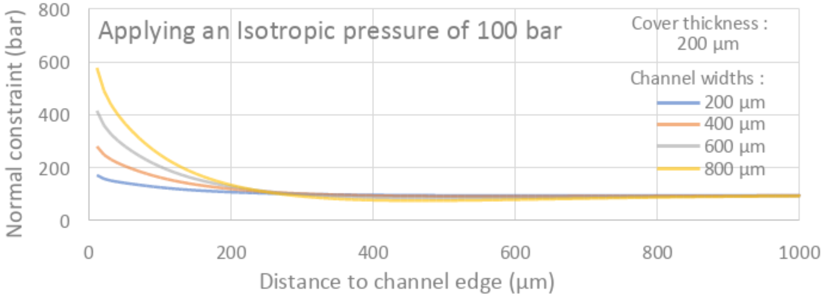
Replace the mechanical press with an hyperbar chamber

- Allow to reach very high pressure on large surface
  - ≥ 400 bar in chamber
  - Force applied in bonder typically limited to 40kN
  - (i.e. 5.1MPa for 4” wafer, 2.3MPa for 6” wafer)
- Pressure more uniform
- Less stress applied on wafer
- Bonding at room temperature
- Can adapt various geometries

- Visualizing the pressure applied in the hyperbar chamber
- Using a pressure sensitive film
- “Pressure boost” around the channel as expected from numerical simulation







Microchannel cooling manufacturing via thermocompression

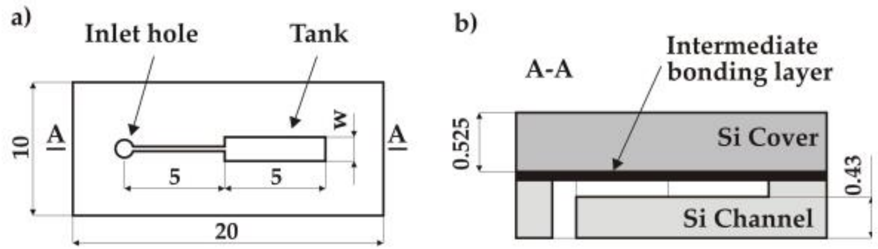
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

- Replace the mechanical press with an hyperbar chamber
  - Allow to reach very high pressure
  - ≥ 400 bar in chamber
  - Force applied in bonder limited to 40kN
  - (i.e. 5.1MPa for 4” wafer, 2.3MPa for 6” wafer)
  - Pressure more uniform
  - Less stress applied on wafer
  - Bonding at room temperature
  - Can adapt various geometries
- Test wafer bonding with fixed width pressure test structures (w=850µm)

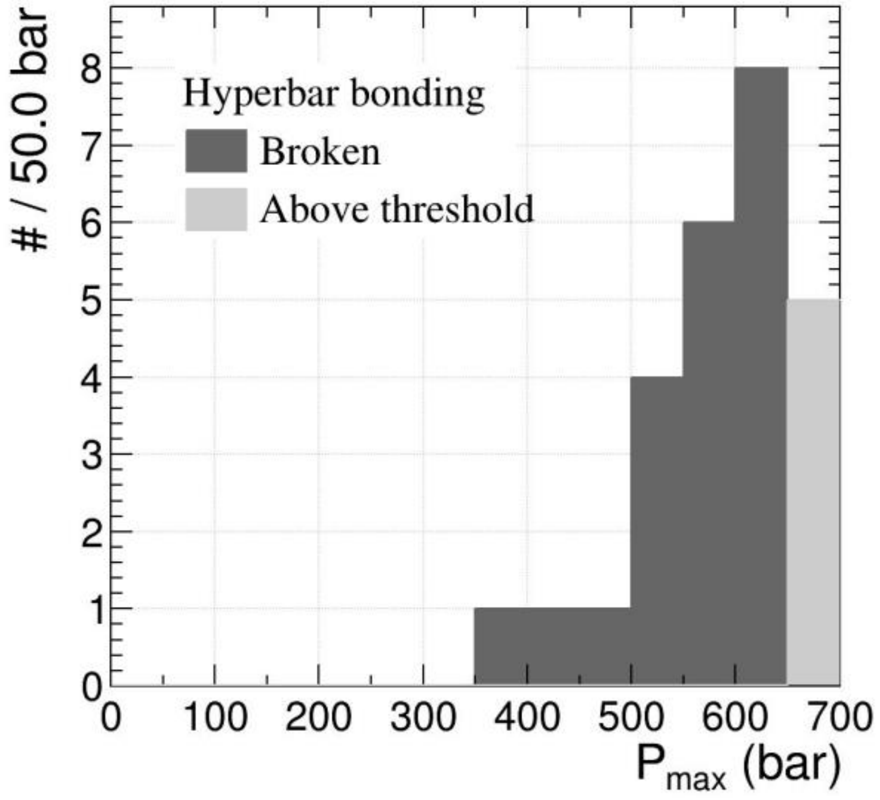
⇒ All samples sustained very high pressure

⇒ All breakage occurred in the silicon (i.e. bonding has held)

⇒ Proof of concept validated !



w=850 µm



Microchannel cooling manufacturing via thermocompression

R&D to develop low-cost micro-channel production process is being pursued at CPPM

Currently focusing on the bonding process, very appealing technique identified:
– “Hyperbar” bonding with thin intermediate Au layers
– Can be used to bond wafer
– Bonding of connector in hyperbar chamber being investigated

Goal is a functional prototype in the coming years

Part of a global R&T effort in CNRS/IN2P3, shared among 3 French laboratories and including developments on boiling flow modelling and testing.

Conclusion

- Microchannel cooling and active interconnection developments (CNM, DESY, IFIC)
  - Aiming to bring more functionalities to the cooling plate
    - Redistribution layer could be an interesting solution for ASICs with through-silicon vias
  - CMOS compatible process to integrate the cooling to the sensor

- Microchannel cooling manufacturing via thermocompression (CPPM)
  - Main motivation to reduce the manufacturing cost
    - Very promising results “hyperbar” chamber (resistance to high pressure)
  - Techniques developed can be also explored for integration (chips and connecturization)

- Ceramics
  - It has also the potential to include electronic features
  - Fully validated initial prototypes in the coming years to high pressure, leak tightness and cooling performance in the following years
  - LHCb VELO Upgrade 2 as benchmark requirements (High pressure, CO_2 evaporative cooling)

- Metal 3D printing
  - X-ray tomography indicates issue with the fill factor
  - Distortion observed created a choke point
  - Next run: focus on improving distortion and fill factor and investigation of electropolishing (material reduction/easier integration?)

Contacts

- Microchannel cooling and active interconnection developments (CNM, DESY, IFIC)
  - Miguel Ullan (miguel.ullan at imb-cnm.csic.es)

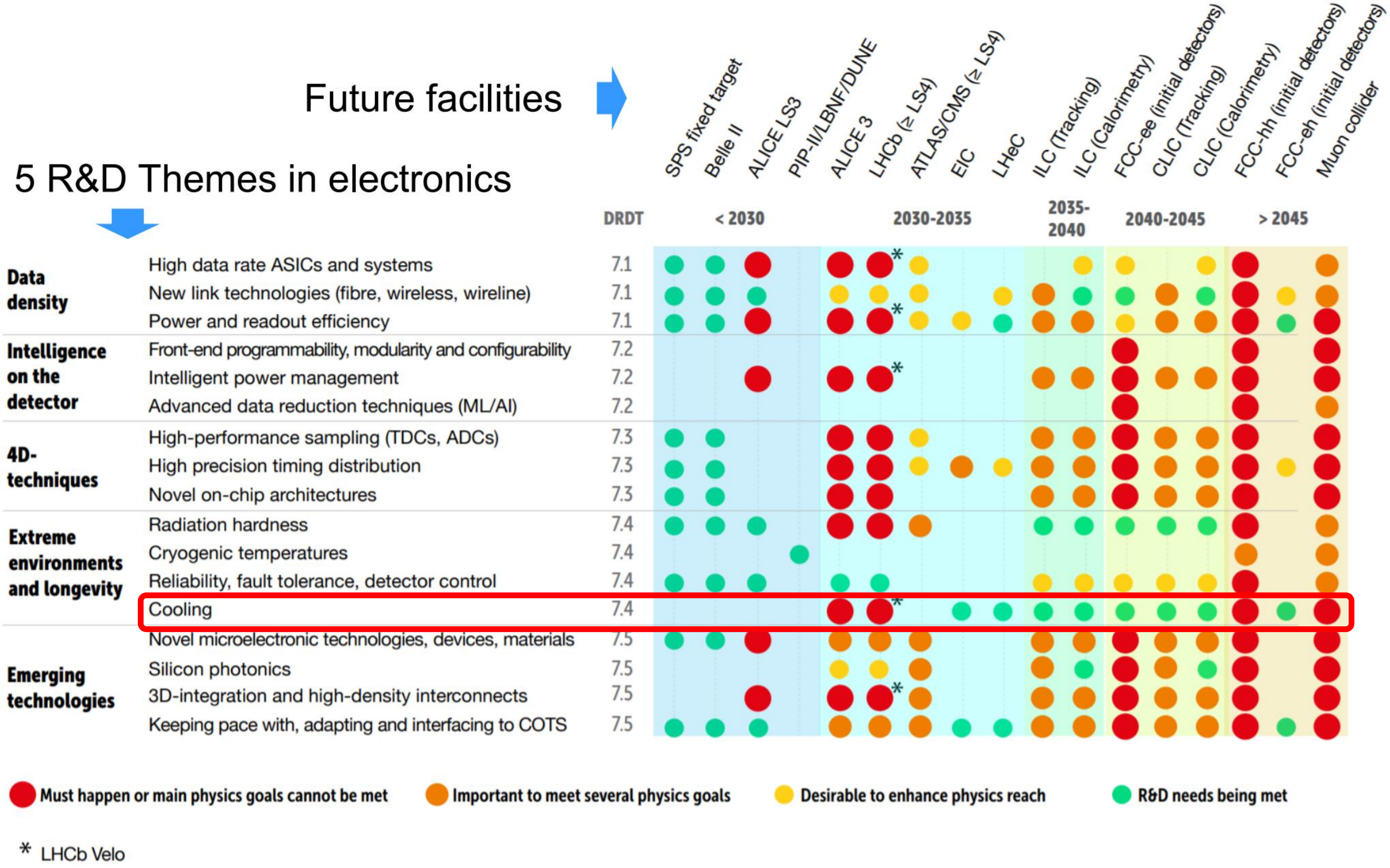
- Microchannel cooling manufacturing via thermocompression (CPPM)
  - Julien Cogan (cogan at cppm.in2p3.fr)

- Ceramics and Metal 3D printing
  - Oscar Augusto de Aguiar Francisco (oscar.augusto at manchester.ac.uk)

Backup slides

Future facilities

5 R&D Themes in electronics



		DRDT	SPS fixed target	Belle II	ALICE LS3	PIP-II/LBNF/DUNE	ALICE 3	LHCb (≥ LS4)	ATLAS/CMS (≥ LS4)	EIC	LHeC	ILC (Tracking)	ILC (Calorimetry)	FCC-ee (initial detectors)	CLIC (Tracking)	CLIC (Calorimetry)	FCC-hh (initial detectors)	FCC-eh (initial detectors)	Muon collider
			< 2030				2030-2035					2035-2040		2040-2045			> 2045		
Data density	High data rate ASICs and systems	7.1	🟢	🟢	🔴		🔴	🔴*	🟡				🟡	🟡		🟡	🔴		🟠
	New link technologies (fibre, wireless, wireline)	7.1	🟢	🟢	🟢		🟡	🟡	🟡		🟡	🟠	🟢	🟢	🟠	🟢	🔴	🟡	🟠
	Power and readout efficiency	7.1	🟢	🟢	🔴		🔴	🔴*	🟡	🟡	🟢	🟠	🟠	🟡	🟠	🟠	🔴	🟢	🔴
Intelligence on the detector	Front-end programmability, modularity and configurability	7.2												🔴			🔴		🔴
	Intelligent power management	7.2			🔴		🔴	🔴*				🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Advanced data reduction techniques (ML/AI)	7.2												🔴			🔴		🟠
4D-techniques	High-performance sampling (TDCs, ADCs)	7.3	🟢	🟢			🔴	🔴	🟡			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	High precision timing distribution	7.3	🟢	🟢			🔴	🔴	🟡	🟠	🟡	🟠	🟠	🔴	🟠	🟠	🔴	🟡	🔴
	Novel on-chip architectures	7.3	🟢	🟢			🔴	🔴				🟠	🟠	🔴	🟠	🟠	🔴		🔴
Extreme environments and longevity	Radiation hardness	7.4	🟢	🟢	🟢		🔴	🔴	🟠			🟢	🟢	🟢	🟢	🟢	🔴		🟠
	Cryogenic temperatures	7.4				🟢											🟠		🟠
	Reliability, fault tolerance, detector control	7.4	🟢	🟢	🟢		🟢	🟢				🟡	🟡	🟡	🟡	🟡	🔴		🟠
	Cooling	7.4					🔴	🔴*		🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🔴
Emerging technologies	Novel microelectronic technologies, devices, materials	7.5	🟢	🟢	🔴		🟠	🟠	🟠			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Silicon photonics	7.5					🟡	🟡	🟠			🟠	🟢	🔴	🟠	🟢	🔴		🔴
	3D-integration and high-density interconnects	7.5			🔴		🔴	🔴*	🟠			🟠	🟠	🔴	🟠	🟠	🔴		🔴
	Keeping pace with, adapting and interfacing to COTS	7.5	🟢	🟢	🟢		🟠	🟠	🟠	🟢	🟢	🟠	🟠	🔴	🟠	🟠	🔴	🟢	🔴

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

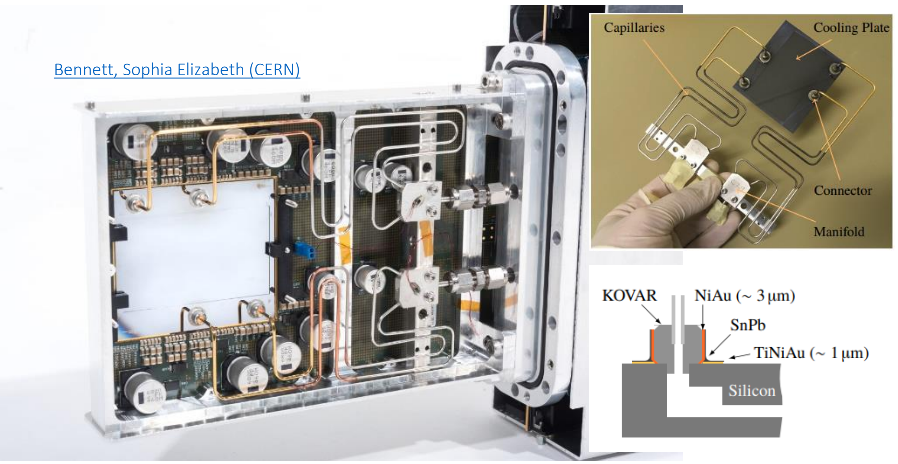
* LHCb Velo

Cooling

- Vacuum
- Operating Temperature
- Material Budget
- Power density
- Thermal figure of merit
- Integration
- Area/Cost

NA62 GTK

JINST **14** P07010

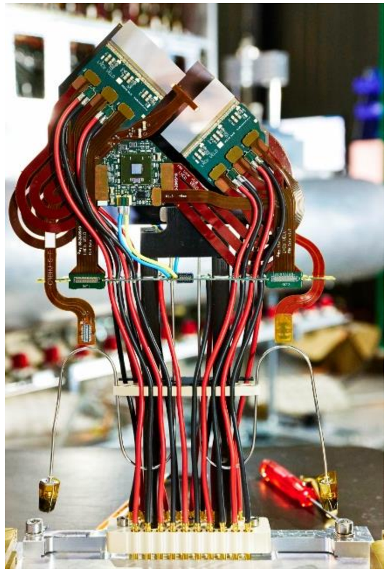


Bennett, Sophia Elizabeth (CERN)

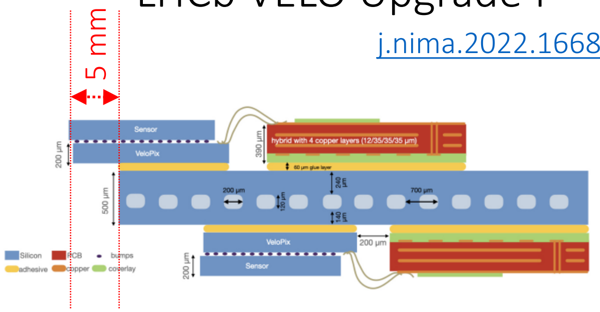
0.5% X_0, 200 × 70 μm^2 micro-channels, C6F14 liquid coolant, vacuum, $0.32\ W/cm^2$ in the pixel matrix, < 5C

LHCb VELO Upgrade I

j.nima.2022.166874



Brice, Maximilien; Ordan, Julien Marius (CERN)



0.4-0.9% X_0 (innermost region)
ASIC/Sensor overhangs by 5 mm,
Micro-channels 120x200 μm^2,
CO2 bi-phase, 1W/cm^2, Sensor < $-20°C$,
vacuum

Mu3e

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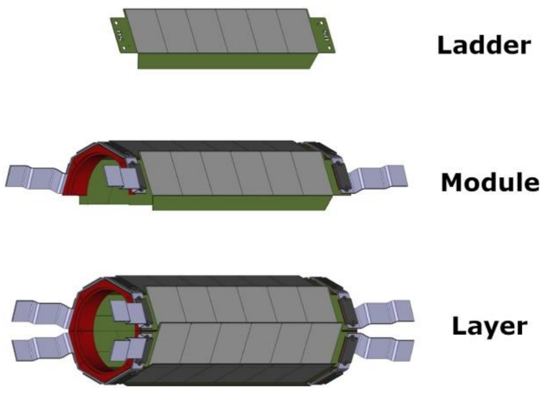
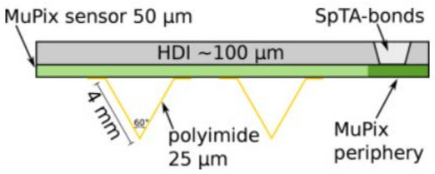
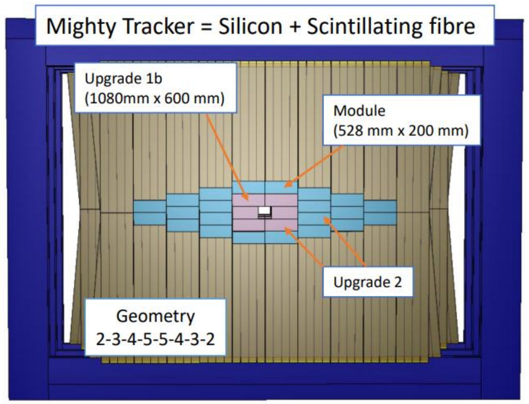


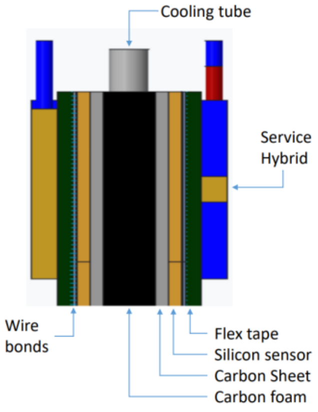
0.1% X_0, Helium gas cooling, $0.4 W/cm^2$, Temperature < $70°C$



LHCb Mighty Tracker (2032)

FTDR





$18m^2$, 1-2% X_0, Kapton tubes, Liquid cooling (?), $0.3W/cm^2$, Temperature ≤ $0°C$