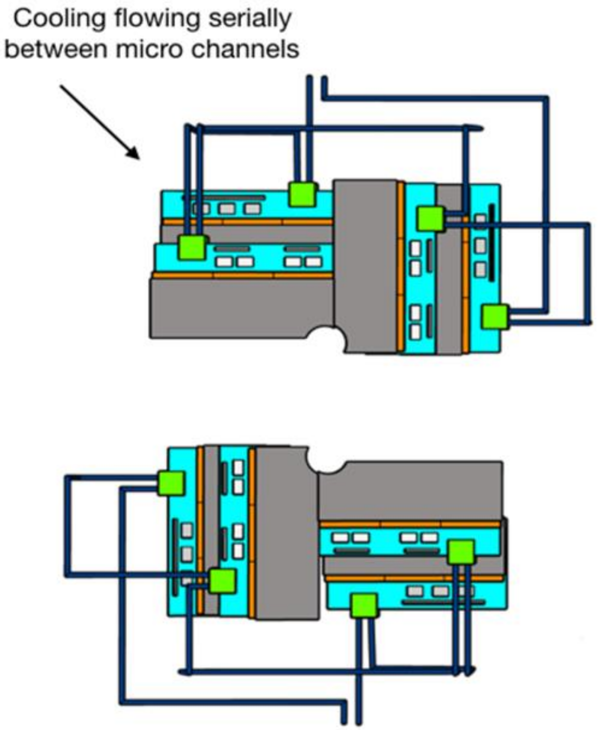
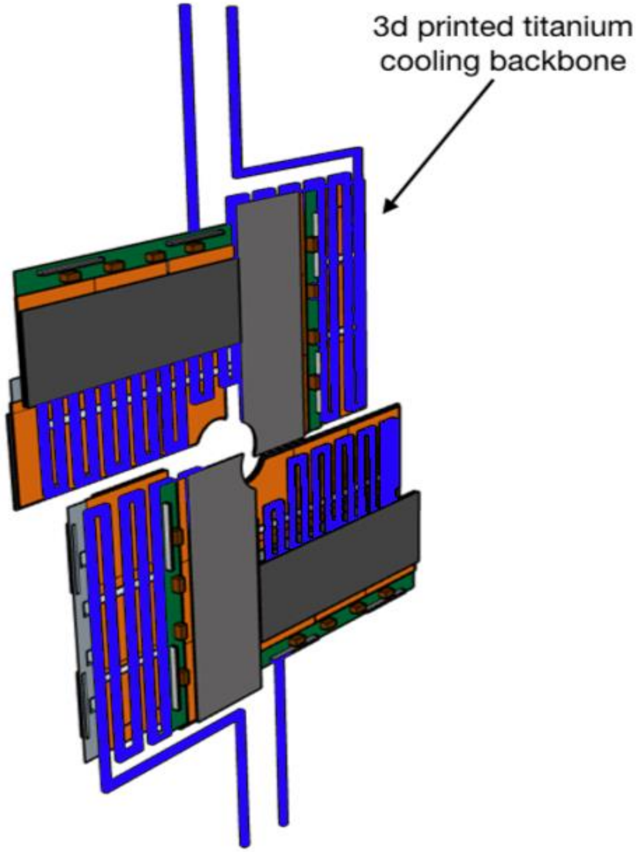
VELO U2 cooling substrates

Oscar Augusto on behalf of the VELO Upgrade 2 group

VELO Module/Cooling concepts (FTDR)

- Smaller microchannel coolers to reduce the overall cost
- More challenging to integrate (interface between pipes and coolers)
- Cooling structure could be potentially re-used (NA62 talk)
- Better cooling performance





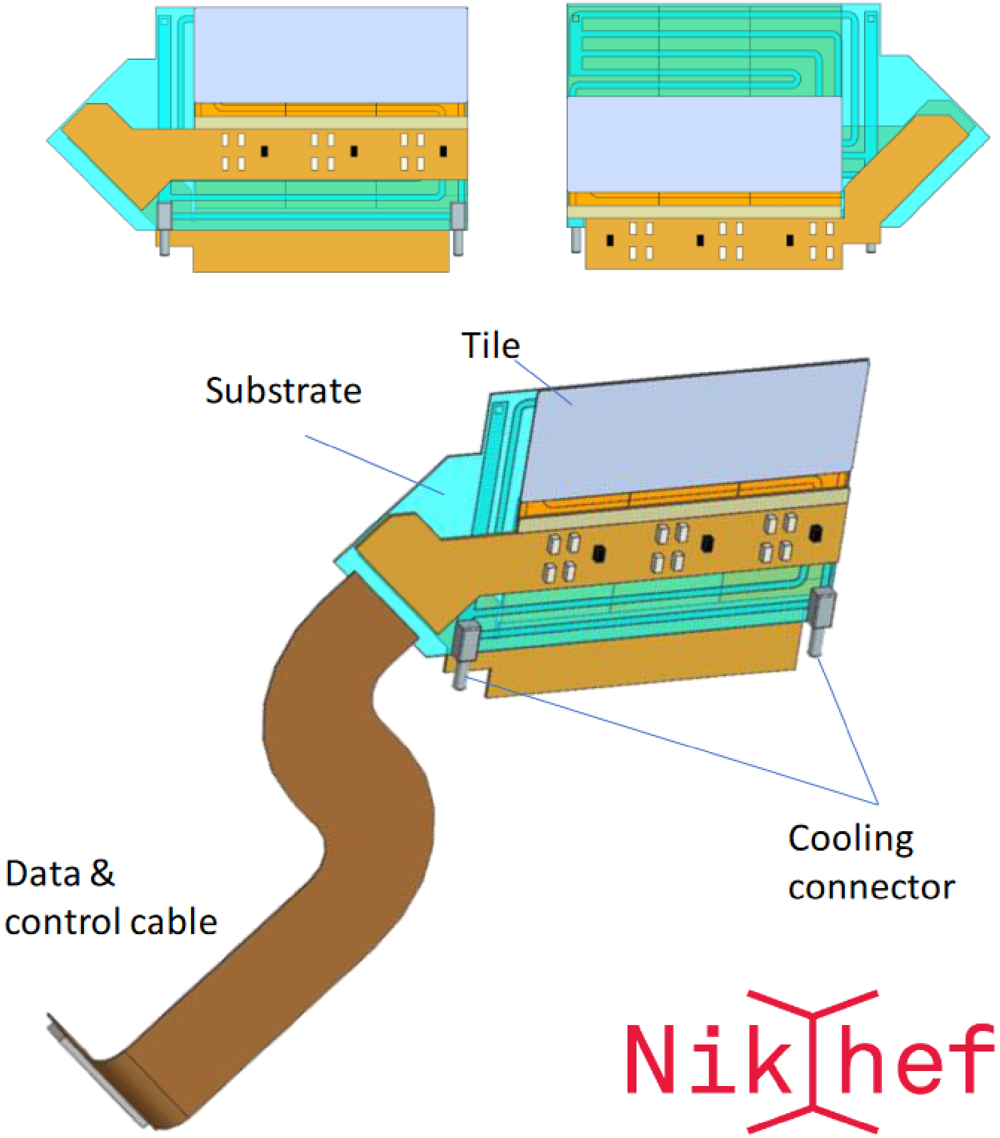
- Cheaper and more flexible design
- Easier to integrate (cooling plant)

VELO Module/Cooling concepts (NIKHEF)

Kazu/Yutaro presentation

Module concept idea

- Features:
    - One module type for all stations (but with different cabling)
    - Two tiles (front & back of substrate), with each tile consisting out of 3 ASIC's.
    - Cooling substrate (material TBD) with thickness equivalent to ~50% of current budget (0.25 mm if Silicon)
    - Two cooling connectors

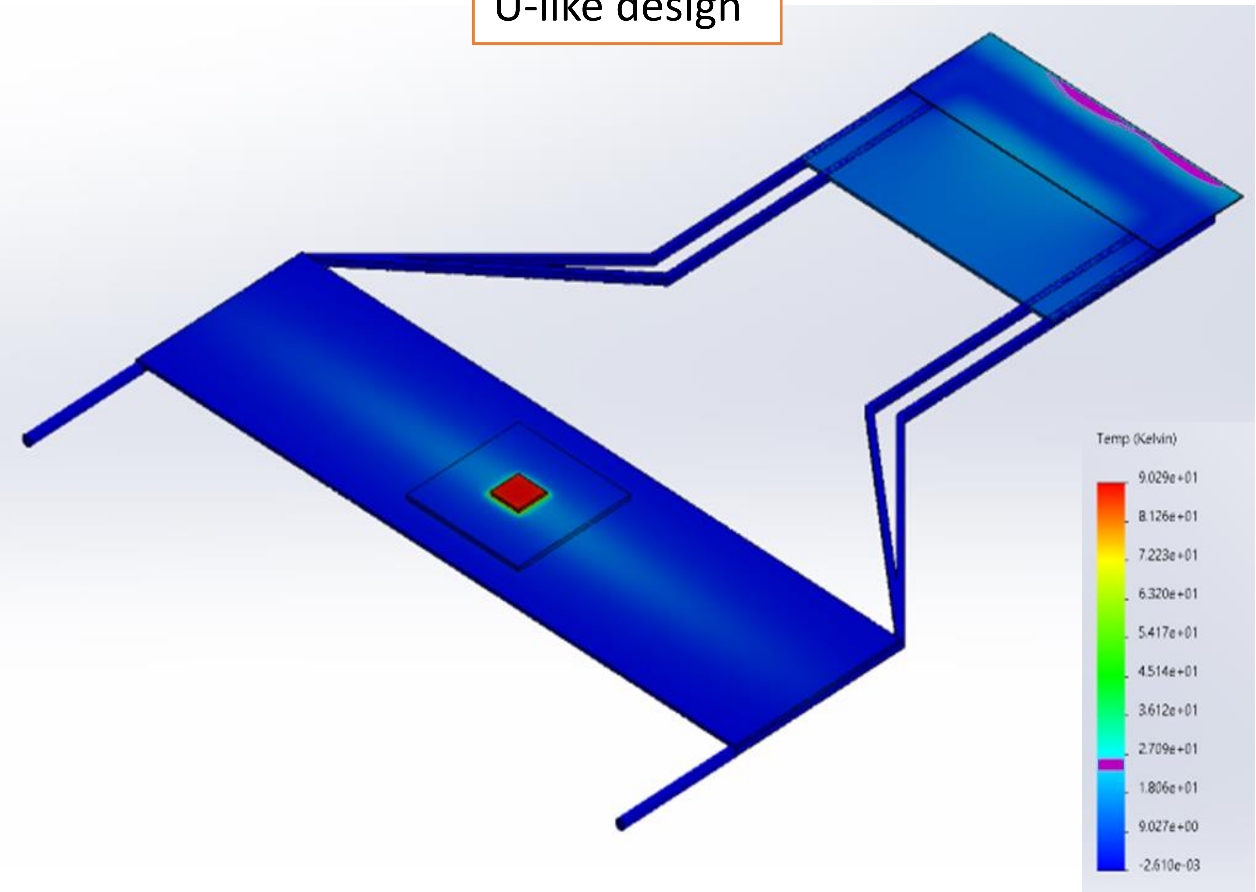


3D metal

- Exploration phase
- Considering evaporative CO_2 as baseline solution
- Power dissipation of up to $2 W/cm^2$
- Different designs submitted to the Royce Institute (Sheffield)
- At the moment, considering different designs which could lead to a material budget reduction compared to plan-Z
- More aggressive designs (larger ΔT) would require lower operating temperature (Krypton?) to keep the max. sensor temperature $< -20°C$

U-like design

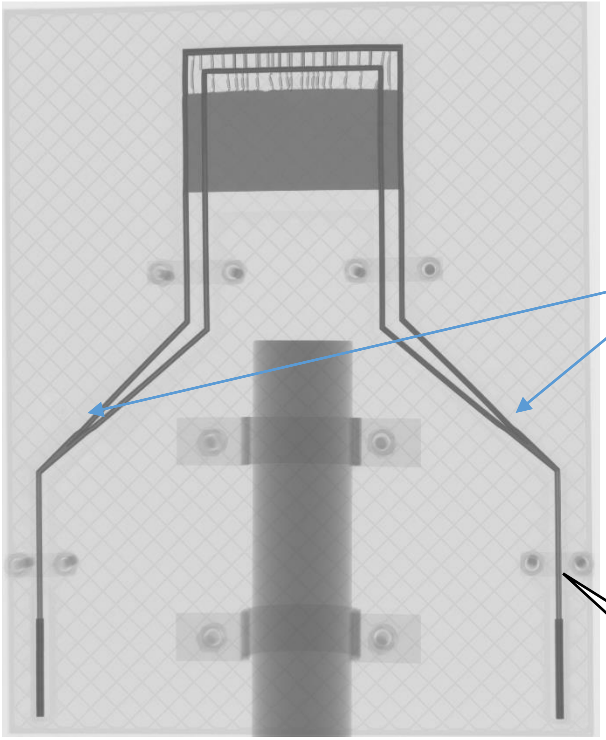
- Largest variation of temperature on the sensor part around $25°C$ (with respect to the inner side wall)
- Alternative strategy to cooldown off-chip electronics would have to be improved (cooling routing lines)


U-like design

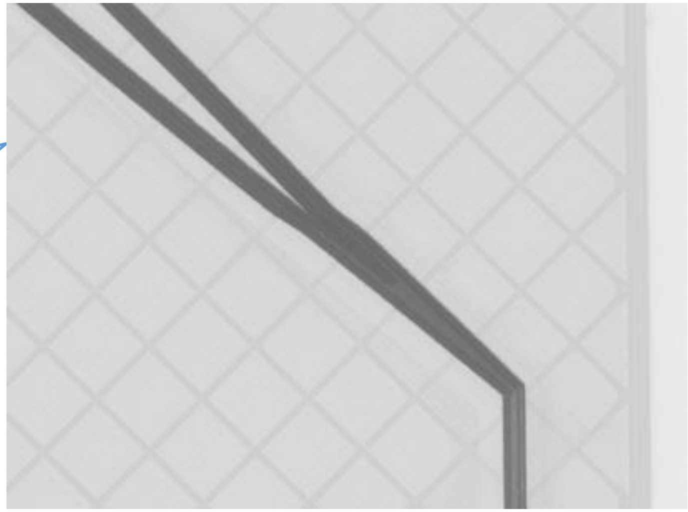
3D metal: LHCb VELO

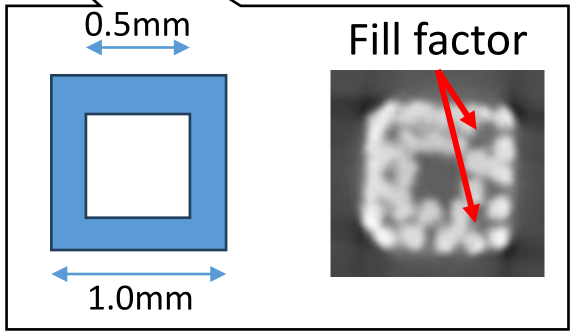
- Different designs
  - U-shaped design
  - Squared tube and connector prototypes
- X-ray tomography via NXCT

X-ray 2D tomography (one projection)



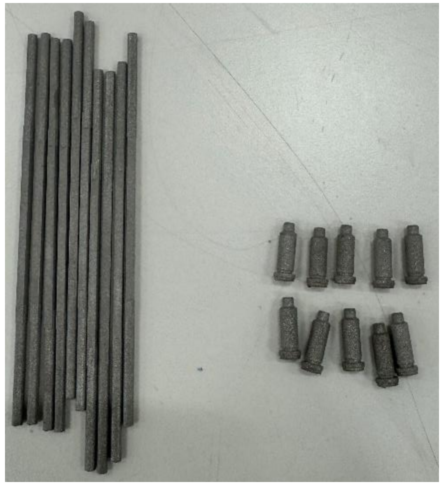
Printing distortion and blockage

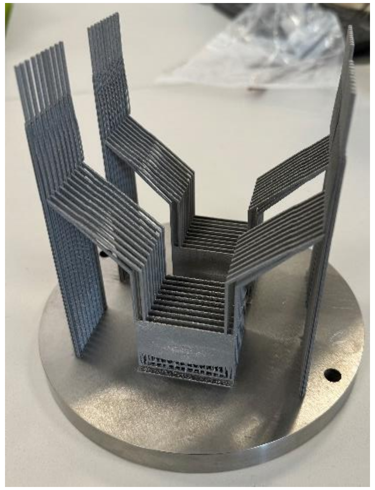




New round of printing:

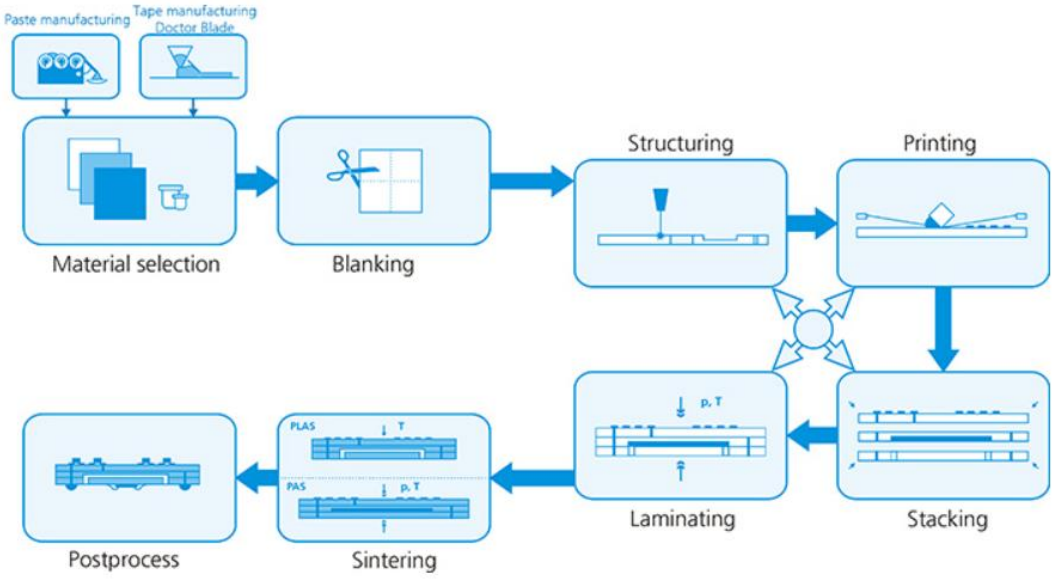
- Filling factor being improved
- Different printing parameters to improve distortions and fill factor
- Half of the samples will be electro-polished (easier integration?)
- Samples are being post-processed

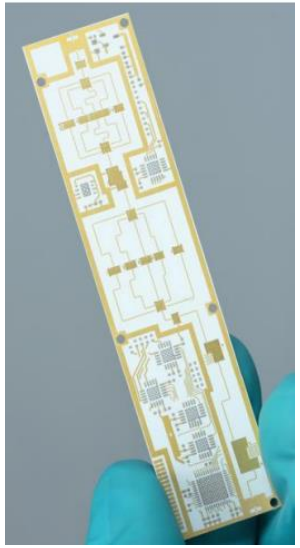




Ceramics

- 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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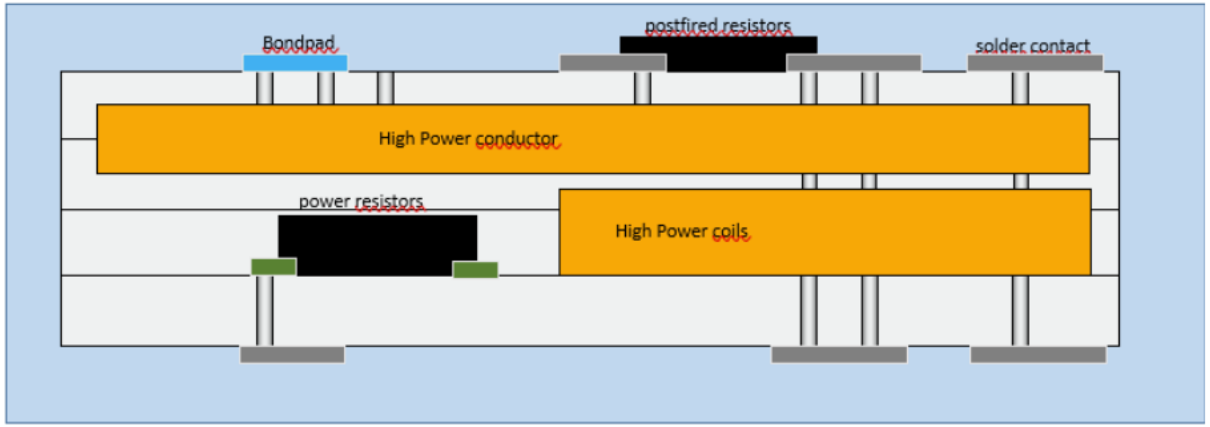
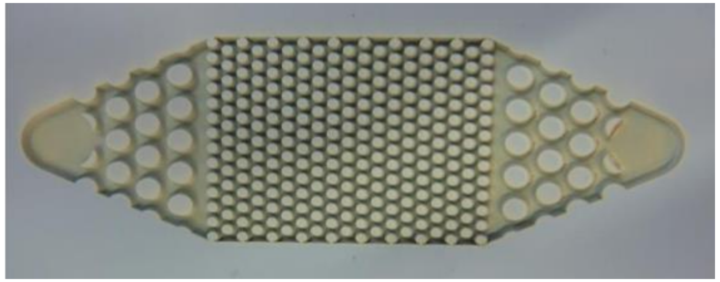


Ceramics

- Experience with fluidic applications
- First prototype based on the early VELO Upgrade I CERN design
  - Initial channel with 70µm width (restrictions)
  - Channels height $100\mu m$
  - Overall dimensions: $40 \times 60\mathrm{mm}^2$
  - Based on LTCC
    - $\mathrm{Al_2O_3}/\mathrm{Glass} \sim 1:1$
    - HTCC at a later stage ($\mathrm{Al_2O_3}$ $\sim 96\%$)
  - Possible to move to SiC or AlN



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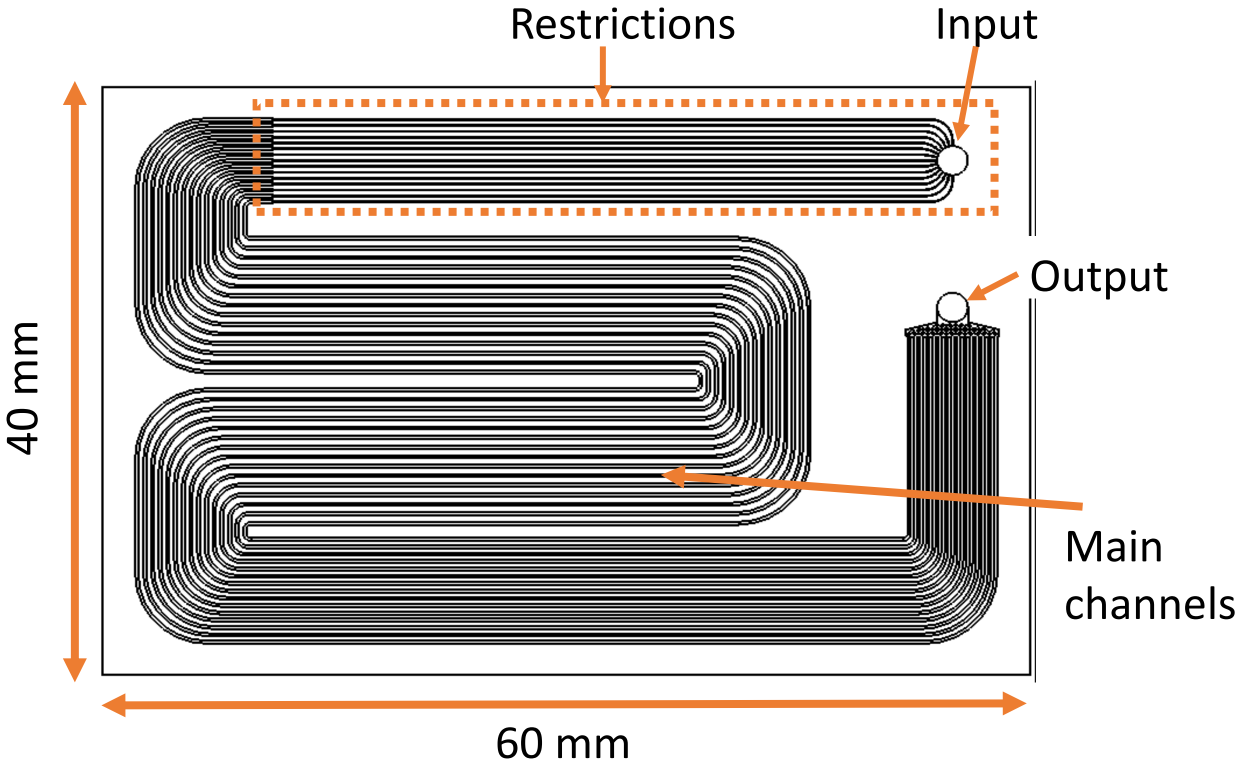
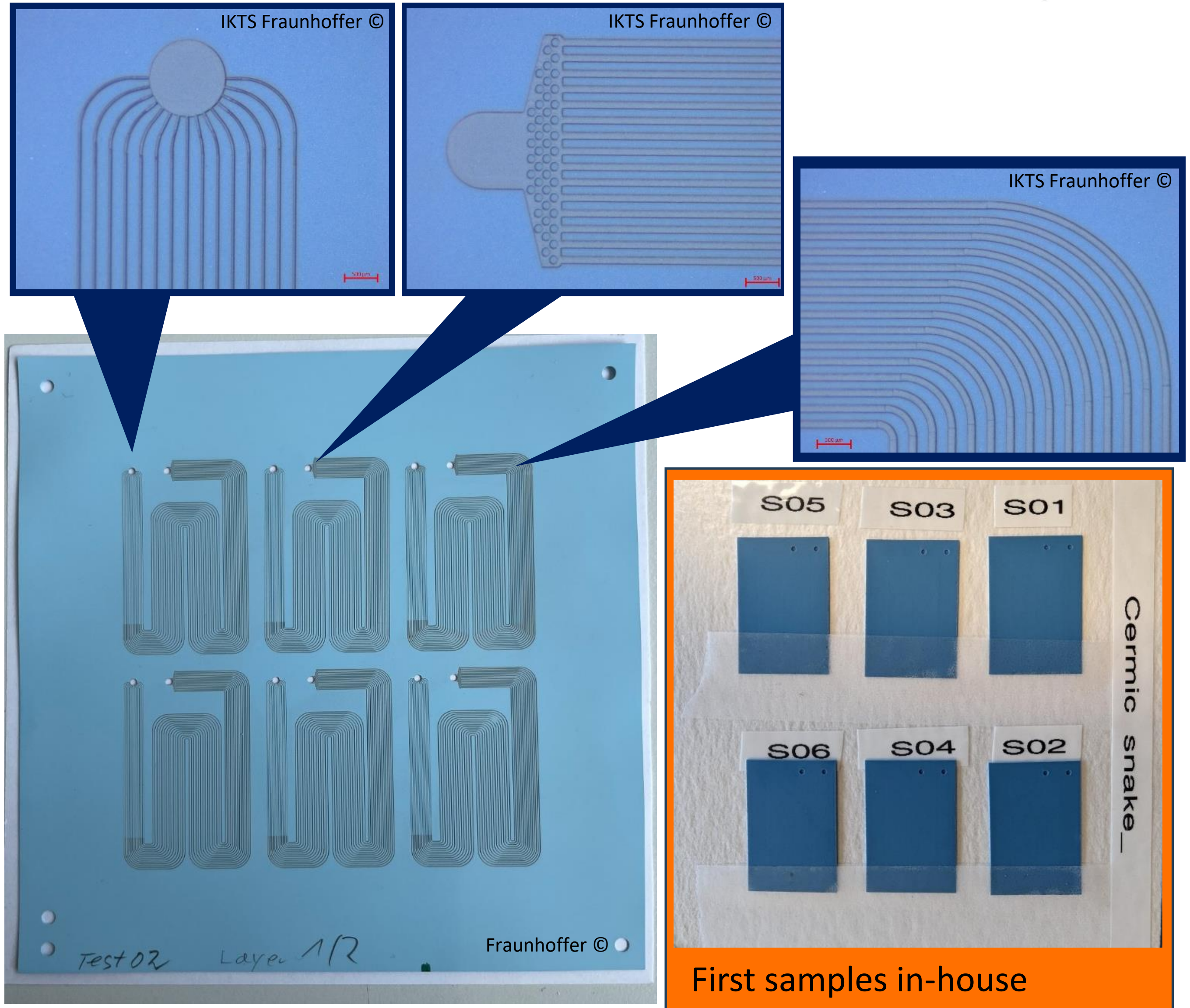


Ceramics: Goal and status

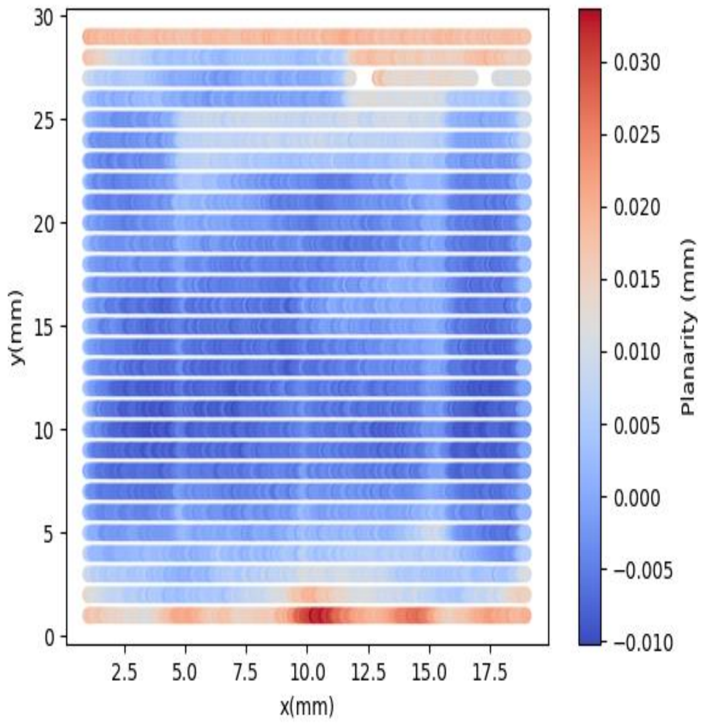
- Goal:
  - ✓ Manufacture first samples (IKTS)
    - ✓ Miniaturized version (2x smaller in-plane)
    - ✓ Expected 35um and 100um width restrictions and main channels respectively!
  - Second round being prepared
  - Validate initial prototypes to high pressure, leak tightness and cooling performance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

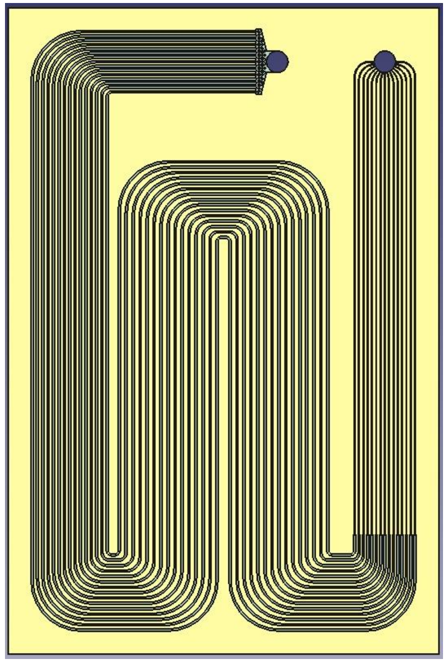


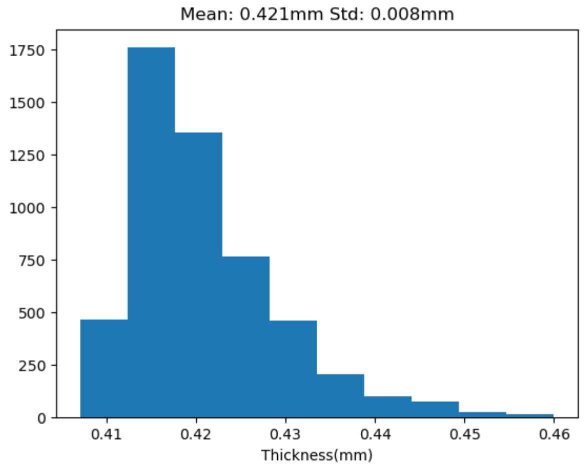
First samples in-house (eagerly waiting to be tested)

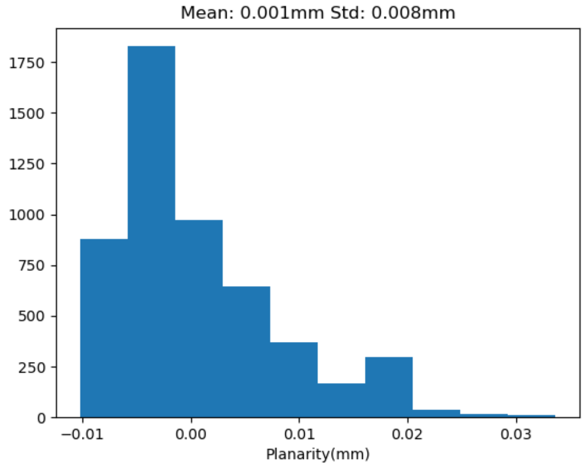
Metrology

- Measurements done using the smartscope
- Planarity deviation of order of tenths of μm
  - An additional layer can be deposited and machined for better planarity as we scale it up (Massimo thesis)
  - Discussion with the manufacturer this week
- The microchannels pattern can be seen in the surface survey
  - Cross section analysis on-going

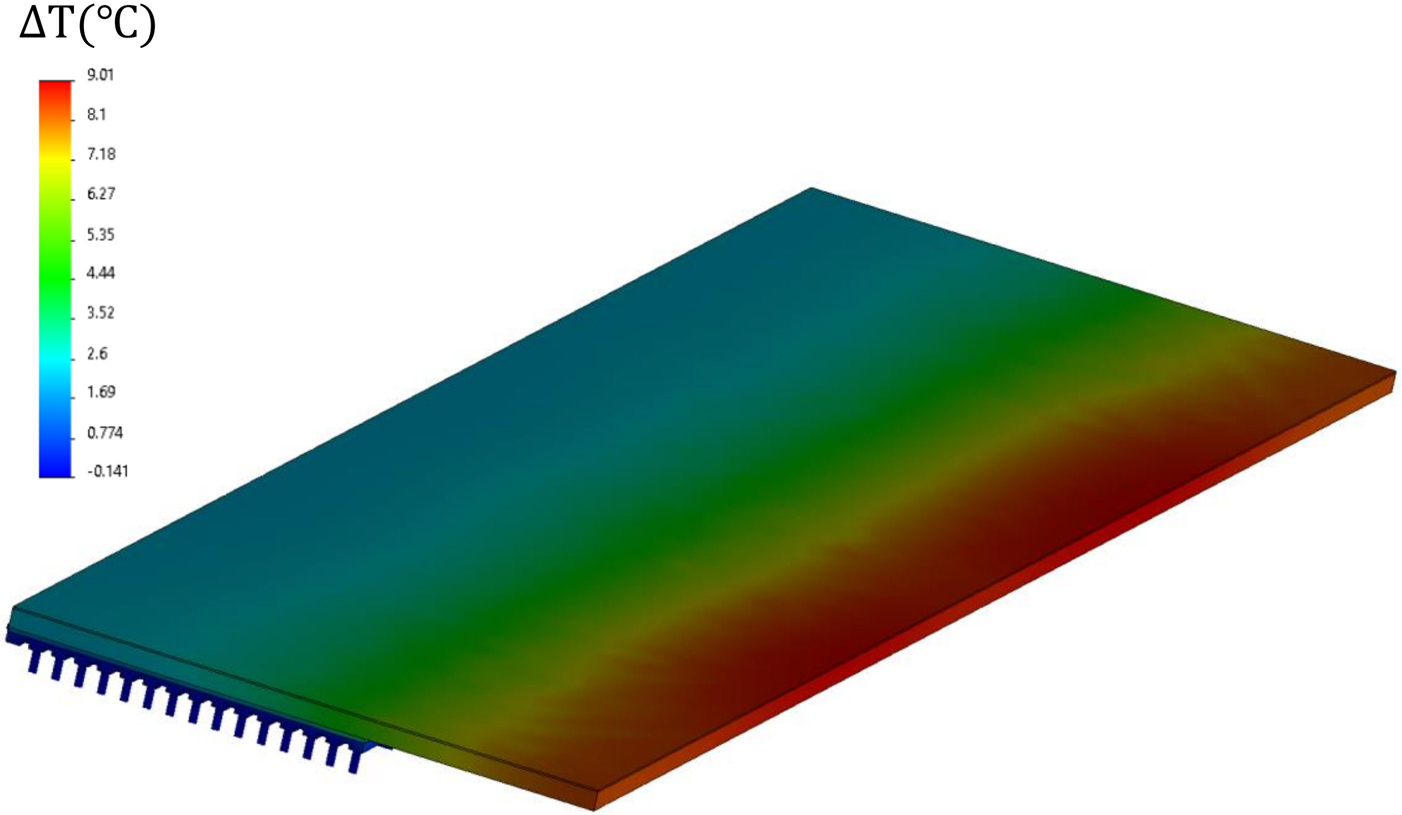





Mean: 0.421mm Std: 0.008mm


Mean: 0.001mm Std: 0.008mm

Simplified FEA



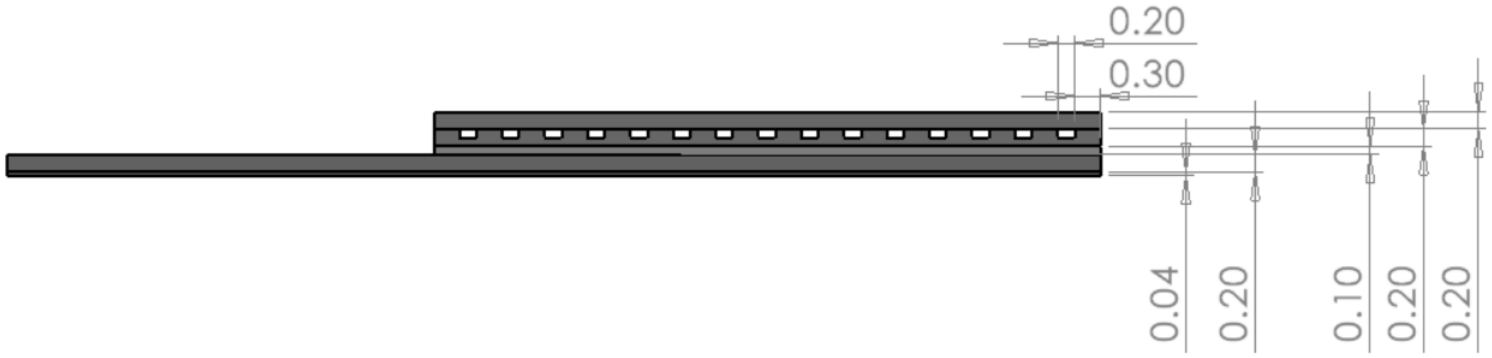
Sensor + ASIC (400um Silicon)
-> Power dissipation: $2W/cm^2$

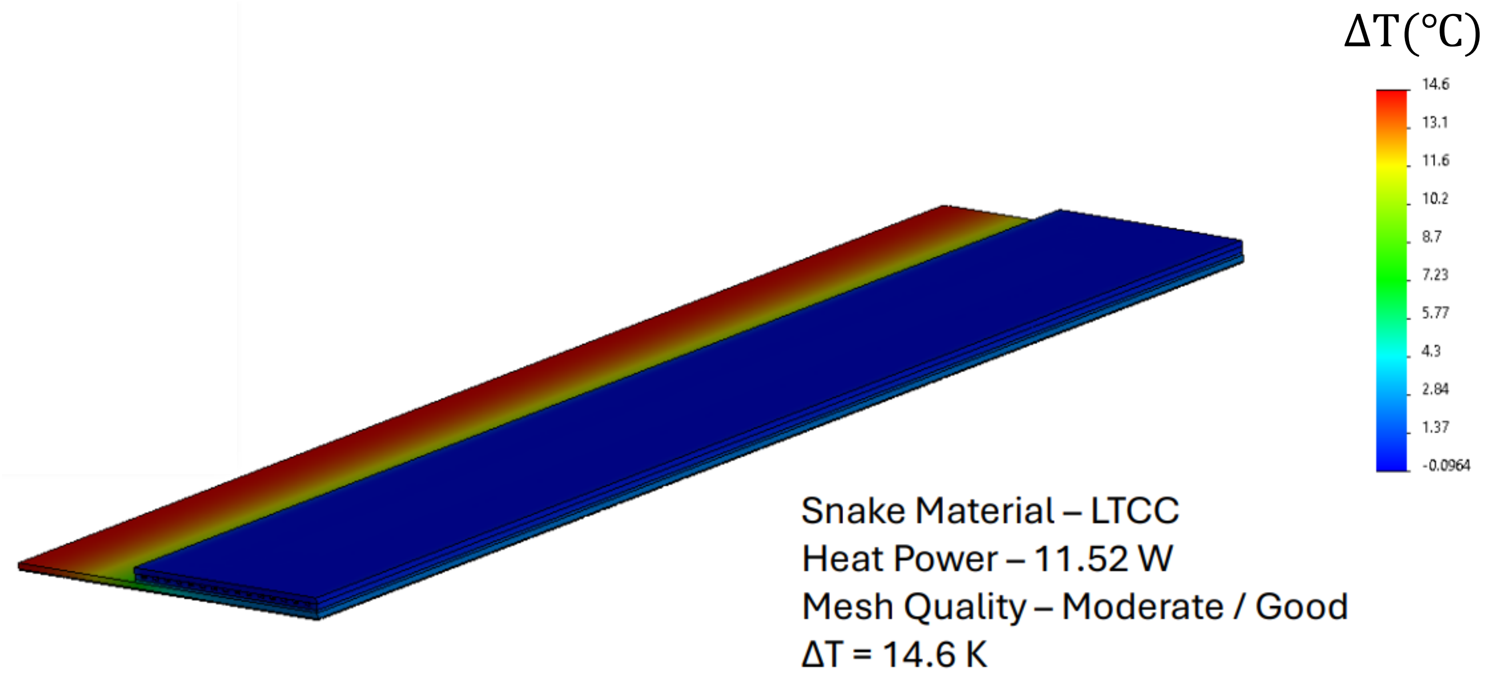
Cooling structure in Al2O3 (20W/m.K)

Overhang of 5 mm as in the VELO U1

$\Delta T \sim 9°C$

FEA (Alumina LTCC)





Snake Material – LTCC
Heat Power – 11.52 W
Mesh Quality – Moderate / Good
$\Delta T = 14.6$ K

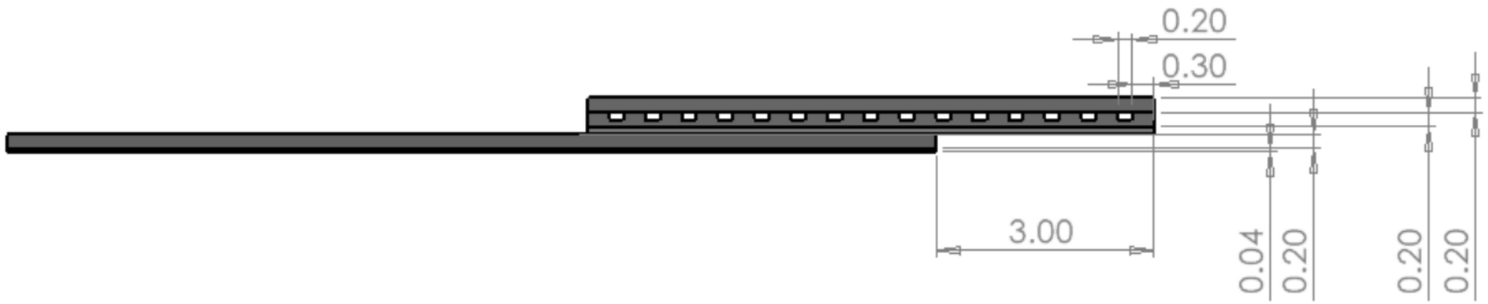
Sensor + ASIC (200um Silicon)
-> Power dissipation: $2\mathrm{W/cm}^2$

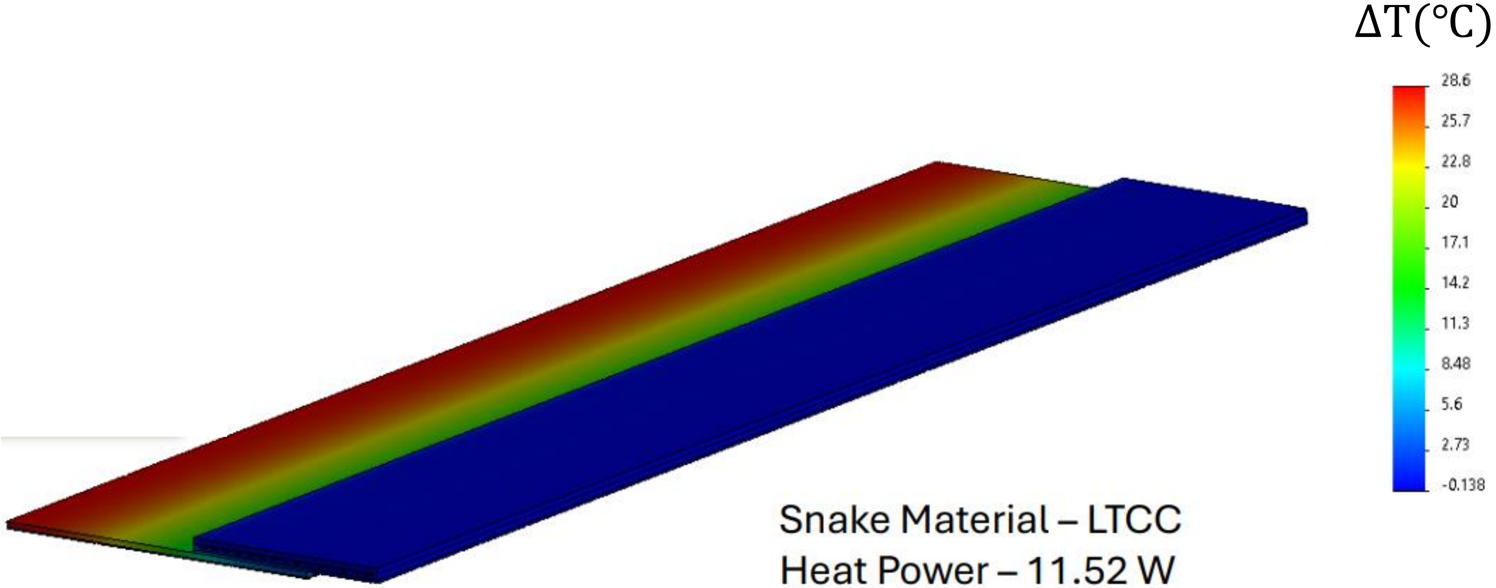
Cooling structure in LTCC Al2O3 (5W/m.K)

Overhang of 5 mm as in the VELO U1

$\Delta T \sim 14.6°C$

FEA (Alumina LTCC)





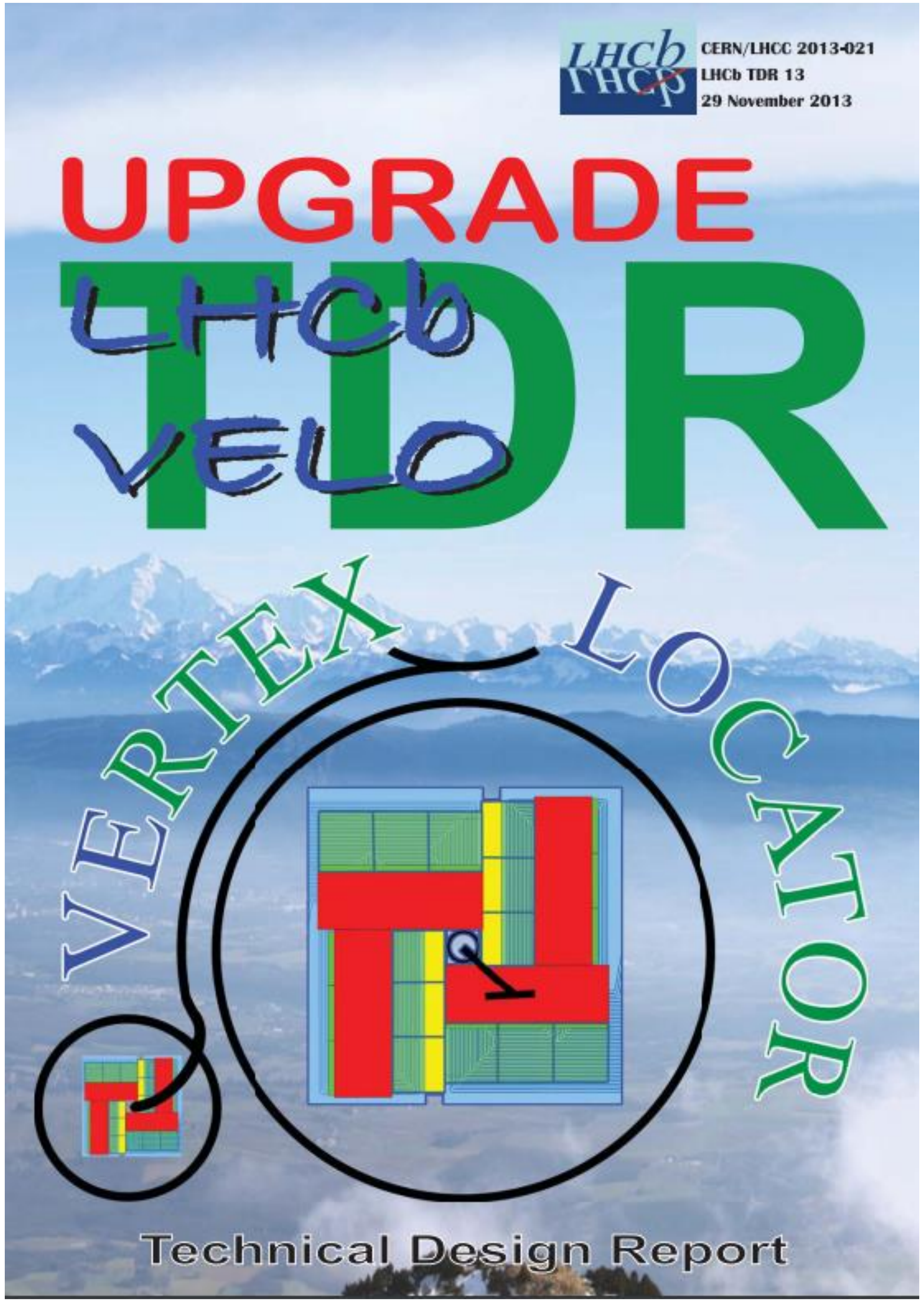
Snake Material – LTCC
Heat Power – 11.52 W
Mesh Quality – Moderate / Good
ΔT = 28.6 K

Sensor + ASIC (200um Silicon)
-> Power dissipation: $2\mathrm{W/cm}^2$

Cooling structure in LTCC Al2O3 (5W/m.K)

Overhang of 8 mm as in the VELO U1

$\Delta\mathrm{T}\sim 28.6℃$



LHCb
CERN/LHCC 2013-021
LHCb TDR 13
29 November 2013

UPGRADE
LHCb
VELO
TDR

VERTEX LOCATOR

Technical Design Report

VELO U1 TDR

VELO Upgrade I TDR

1. Cooling substrate at ***baby* prototypes** level
    - SNAKEI, 40 mm x 60 mm
    - Main channel 200 um x 70 um (Restriction 30 um x 70 um)

2. **Robustness tests** running
    1. High pressure and cycling

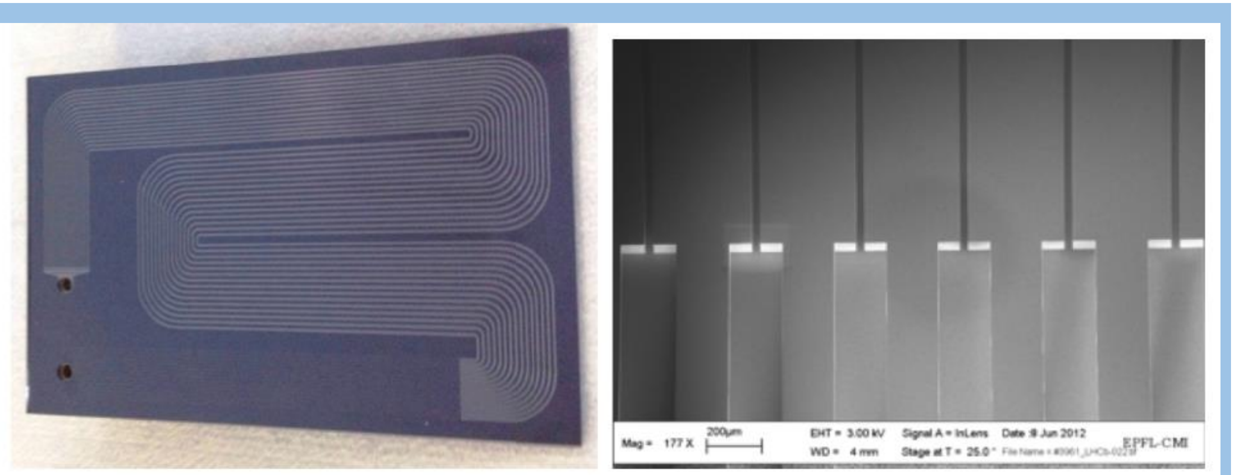
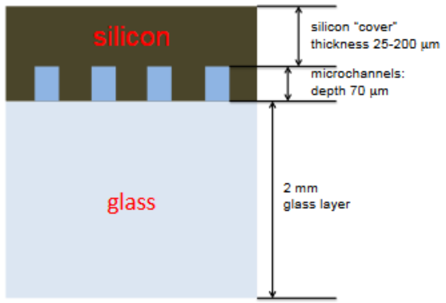
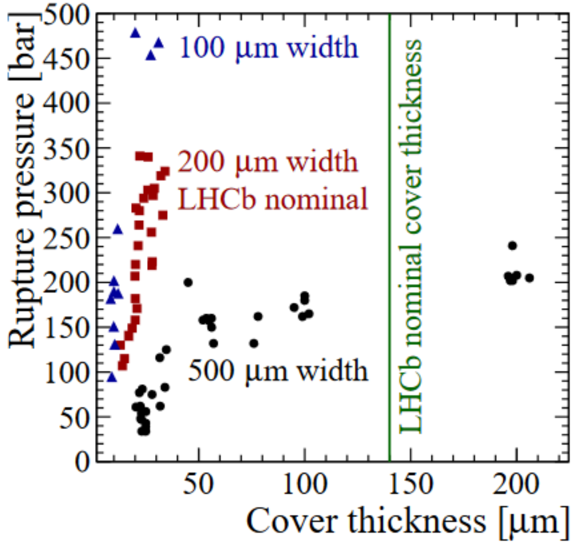


Figure 61: (left) The 2012, $6 \times 4\,\mathrm{cm}^2$ silicon-glass prototype. (right) The end of the high-impedance, restricted-width region where the evaporation is triggered in the larger volume.





VELO U1 TDR

VELO Upgrade I TDR

1. Cooling substrate at ***baby* prototypes** level
   - SNAKEI, 40 mm x 60 mm
   - Main channel 200 um x 70 um (Restriction 30 um x 70 um)
2. **Robustness tests** running
   1. High pressure and cycling
3. Fluidic and **cooling performance** test ($\Delta T \sim 6.5°C$)

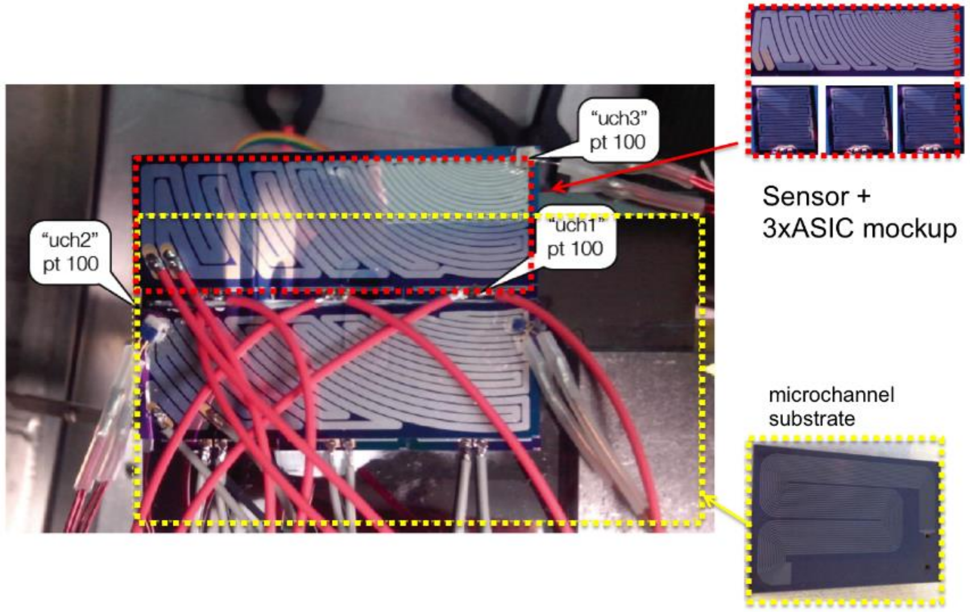


Figure 64: Experimental setup used to test cooling performance. Heater mockups are used to simulate the heat dissipation of the ASICs and irradiated silicon sensors. Cooling is provided by a microchannel substrate.

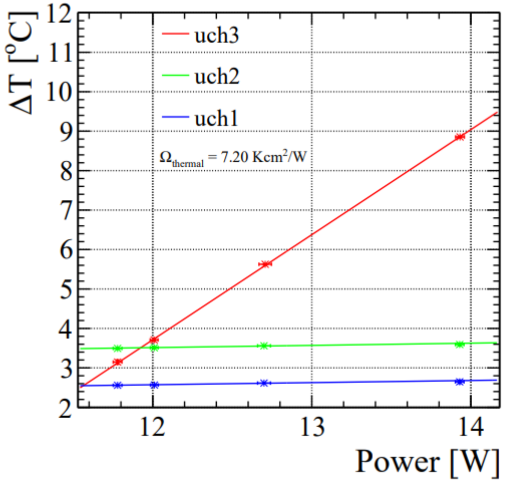


Figure 65: Measured temperature differential with fully powered ASICS and a gradual increase in power dissipation in the sensor. The end-of-lifetime expectation corresponds to a power dissipation of ∼13 W. The three colours correspond to three temperature probes; probe uch3 is located furthest from the microchannels and is hence the hardest point to cool.

VELO U1 TDR

VELO Upgrade I TDR

1. Cooling substrate at ***baby* prototypes** level
   - SNAKEI, 40 mm x 60 mm
   - Main channel 200 um x 70 um (Restriction 30 um x 70 um)

2. **Robustness tests** running
   1. High pressure and cycling

3. Fluidic and **cooling performance** test ($\Delta T \sim 6.5°C$)

4. Finite element analysis (**FEA**) to optimize the channels distribution and cooling performance

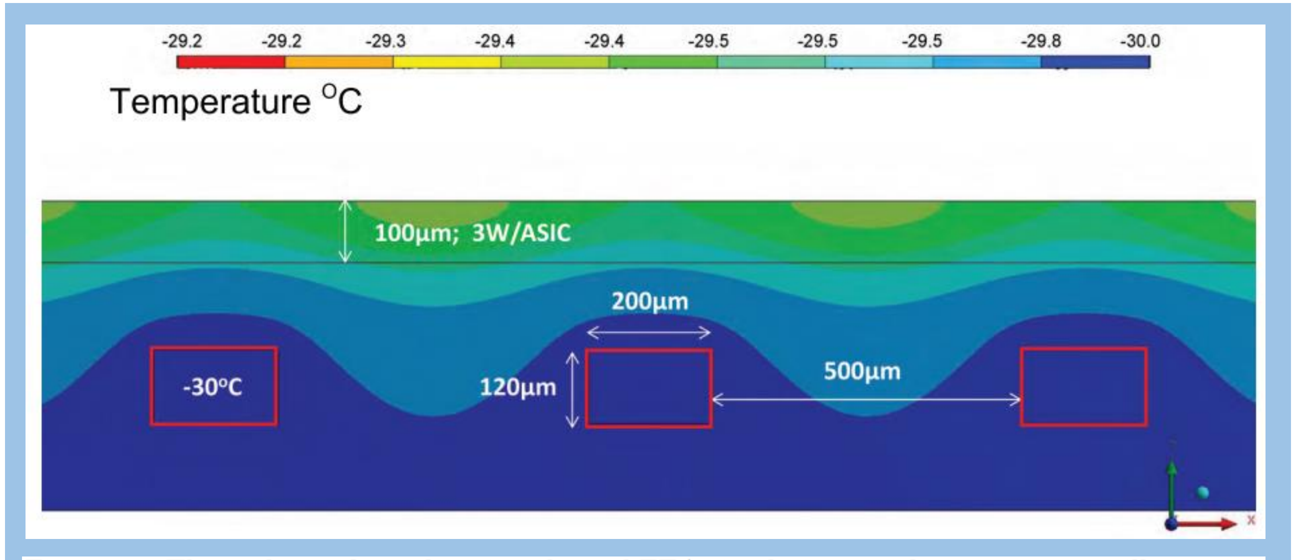


Figure 66: Thermal map from the microchannel FEA simulations, with a cross section illustrating the optimal channel separation and the very small temperature gradients to the heat source.

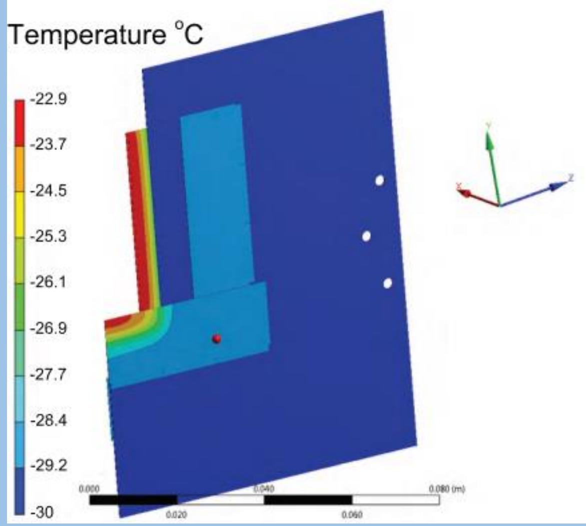


Figure 67: Thermal map from the microchannel FEA simulations, with a a view of the full module with nominal heating. The maximum ΔT to the silicon tip, from which the cooling substrate is retracted, is estimated to be about 7°C.

VELO U1 TDR

VELO Upgrade I TDR

1. Cooling substrate at ***baby* prototypes** level
    - SNAKEI, 40 mm x 60 mm
    - Main channel 200 um x 70 um (Restriction 30 um x 70 um)

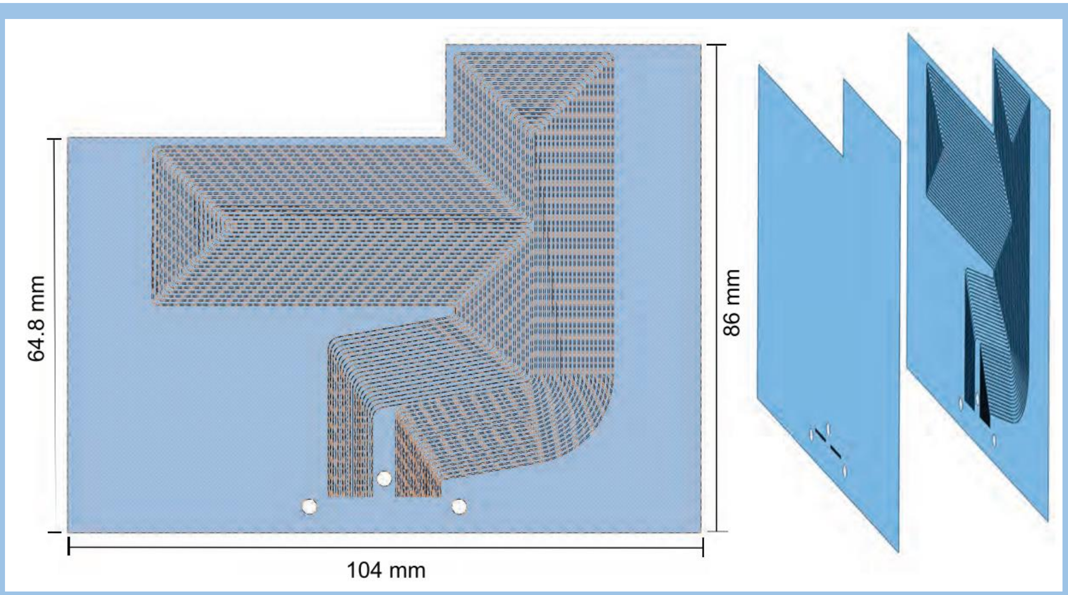
2. **Robustness tests** running
    1. High pressure and cycling

3. Fluidic and **cooling performance** test
   $(\Delta \mathrm{T} \sim 6.5^{\circ}\mathrm{C})$

4. Finite element analysis (**FEA**) to optimize the channels distribution and cooling performance

5. Scale the cooling substrate to **module size**

6. **Connector** attachment at the very early stages



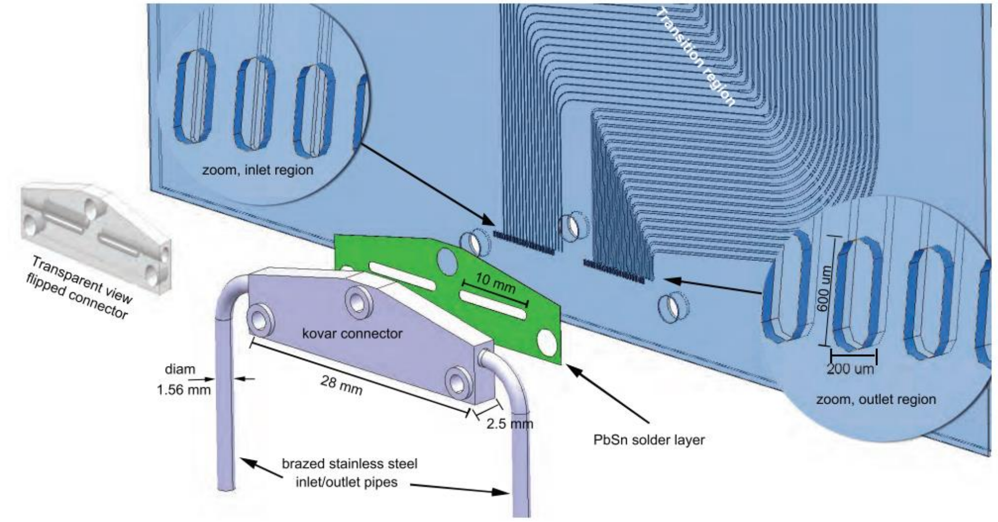


Figure 69: Schematic of the microchannel connector, showing details of the microchannel network at the point of attachment. The metallic connector partially enters the LHCb acceptance so must be kept as small as possible, and further optimisation is envisaged.

VELO U1 TDR

VELO Upgrade I TDR

	Ceramics	3D metal
Baby prototypes	Thinner channels were already manufactured Nominal samples by End/July	Samples produced show distortion and fill factor issues Second round should have better fill factor (TBC)
Robustness tests	Miniaturized connector glueing at the moment (based on the CERN design) – High pressure test in-house New connector for nominal size Cyclic tests	Connector is required (see last row)
Cooling performance	Heaters ordered and vacuum tank/CO2 in place (To be recommissioned)	In principle, same heaters/set-up can be used
Cooling FEA	On-going (large contribution due to the overhang)	On-going (large contribution due to the overhang)
Module scaling and Mod0	Aiming for timepix4 prototype by mid/2025 (40 mm x 60 mm – nominal size)	Pursuit another manufacturer in parallel (Terms and conditions?)
Connector	IKTS has experience with integration, soldering, Hyperbar bonding (CPPM), brazing(?)	More samples are required (smoother finishing would be beneficial)

Summary

- Scaling up towards the final design (highly dependent on the geometry – not defined yet!)
- Cooling plates
  - Ceramic plates
    - ✓ Miniaturized samples in-house (20 x 30 mm^2)
    - Nominal dimension expected by end of July $(40 \times 60\ \mathrm{mm}^2)$ – compatible with the first prototypes specs (timepix4 single board)
    - Robustness validation (high pressure / cyclic tests?)
      - Connector being assembled
    - Finite element analysis of the sample (including design optimization)
    - Connector: different approaches can be considered
      - IKTS integration, soldering, hyperbar bonding (CPPM), brazing, …

Summary

Cooling plates

- 3D metal printing
  - First run shows fill factor issue and distortions
  - Second run should have better fill factor
  - Additional samples produced to understand better the printing (straight samples)
  - Another manufacturer to be identified (Alloyed, BA systems, ?)
  - Connector R&D requires more samples
    - Smoother surface is desirable

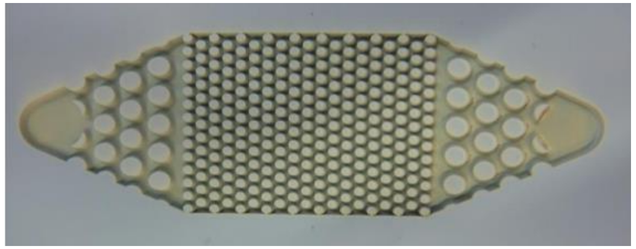
Thank you for your attention

Ceramics 3D printing

- Experience with fluidic applications

- First prototype based on the SNAKEI design
  - Restrictions of 70μm instead of 30μm
  - Channels height 100μm
  - Overall dimensions: $40\text{x}60\text{mm}^2$
  - Based on alumina (Al_2O_3)
    - Possible to move to SiC afterwards

- Currently, initial quote being discussed



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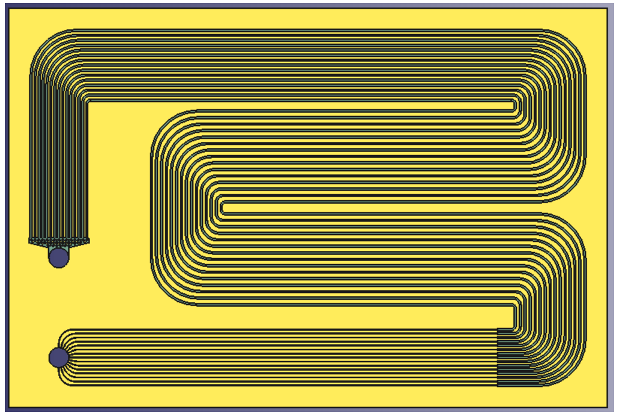
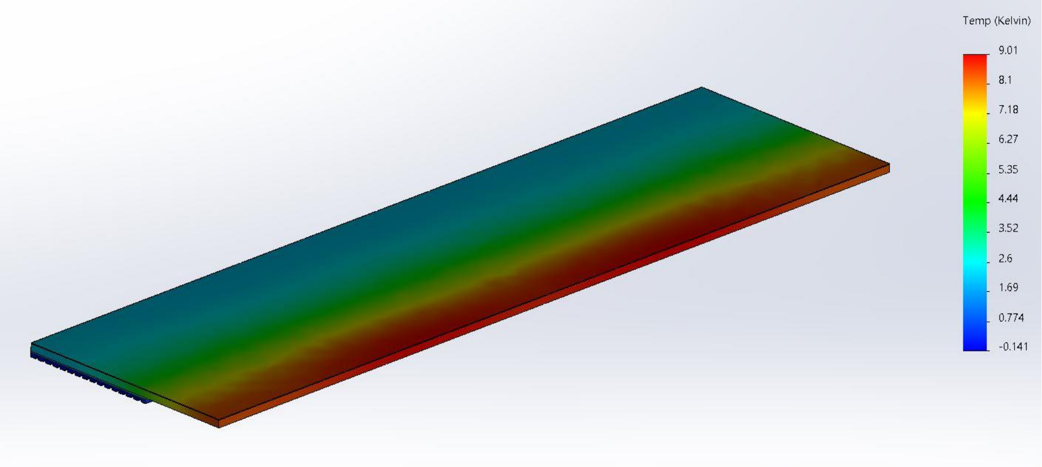


SNAKEI based design to optimize printing parameters/test feasibility



Simplified FEA focusing on the 5 mm overhang. Substrate in alumina and heat conduction on one side of the cooling plate and Stycast (100um). For $2\text{W}/\text{cm}^2$, $\Delta\text{T} \sim 9$ C.

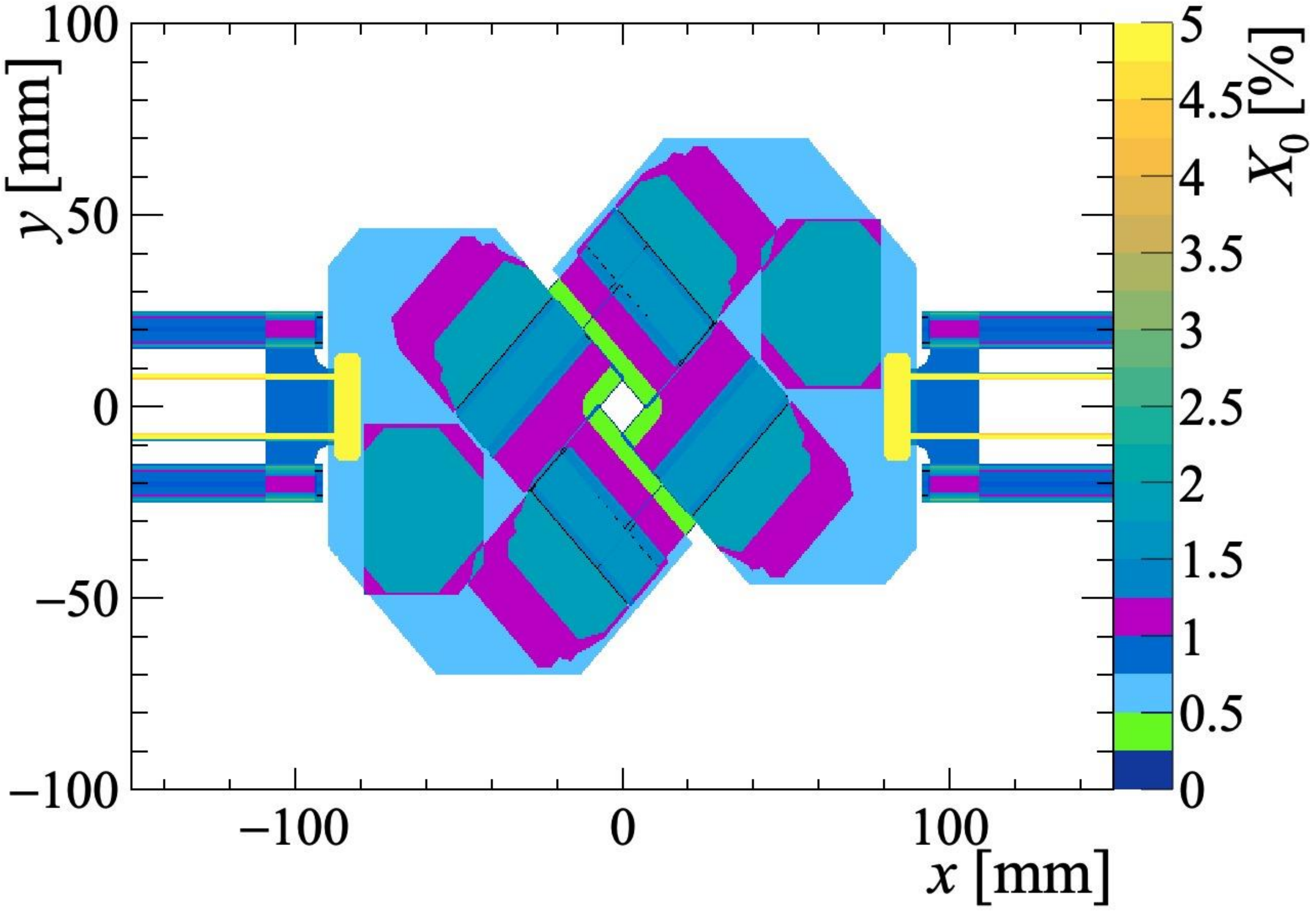
Cooling material budget (U1)

Not all services are present (no cables)

Material budget for perpendicular incidence

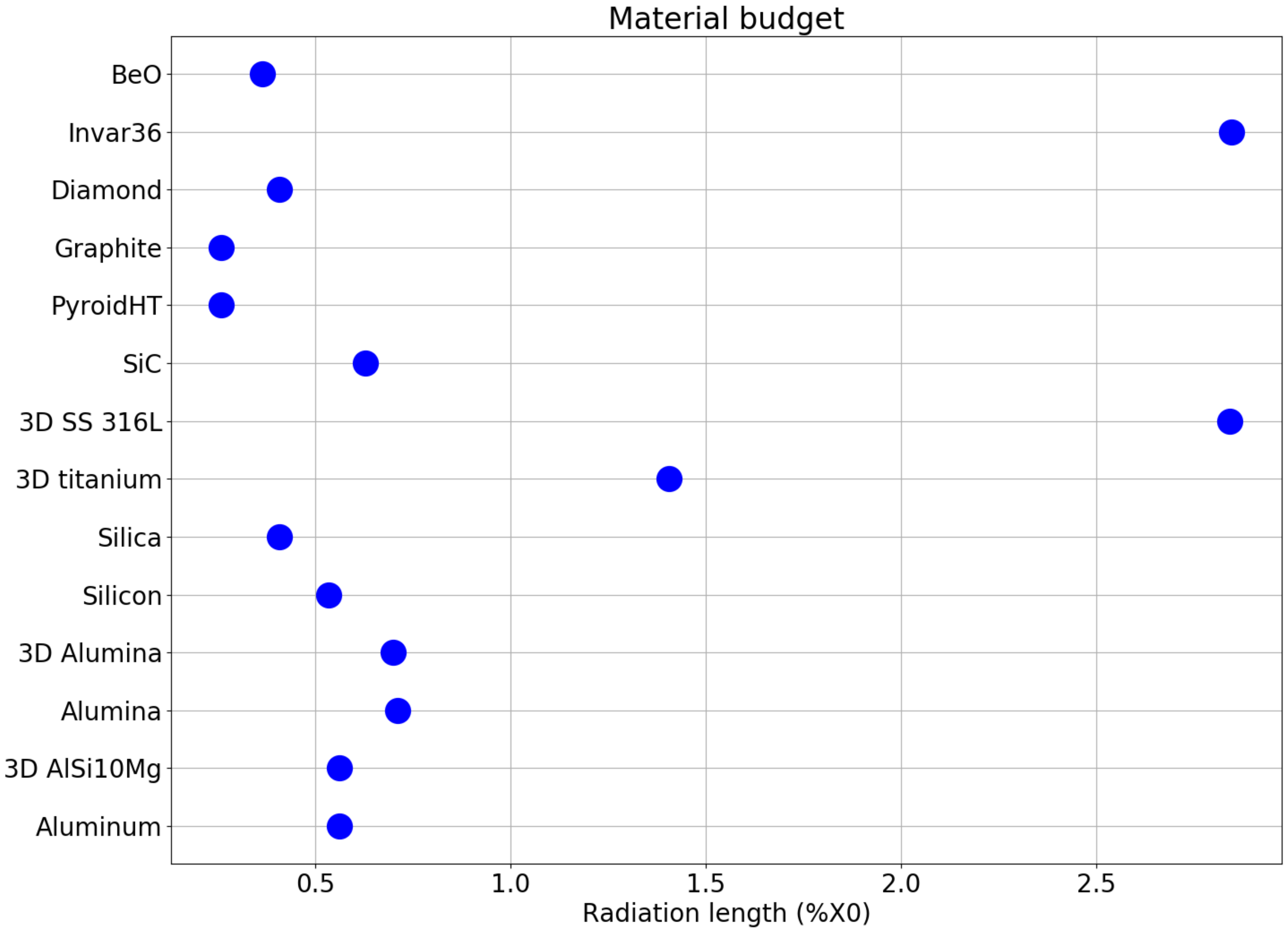
Inner most region has only the contribution from the sensor+ASIC (~0.4% X0)

Second innermost region contains the contribution from sensor, cooling plate and glue layer (~1.0% X0)



VELO U1 cooling material budget

Materials considerations (500μm)



Materials considerations (Minimum wall, OD 1 mm / 200 bar)

Exercise to take into account the resistance to stress of the material

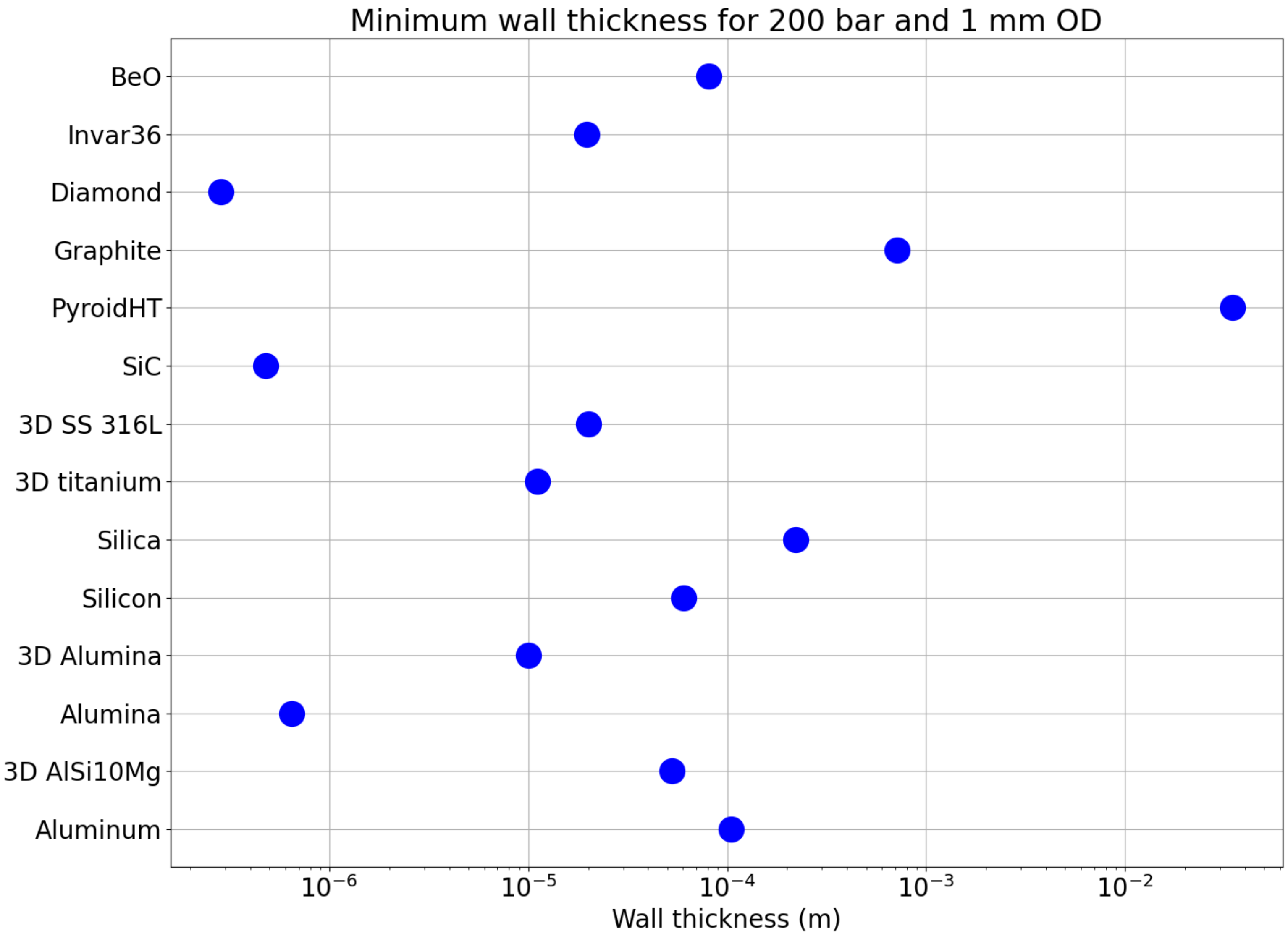
Rounded tubes maximum pressure (Barlow equation):

$$P = \frac{2\sigma w_t}{D}$$

σ: yield strength
w_t: wall thickness
D: outer diameter

Very small in some cases (should be taken with a pint of salt)

Same exercise will be repeated using flexural strength



Materials considerations (Minimum wall, OD 1 mm / 200 bar)

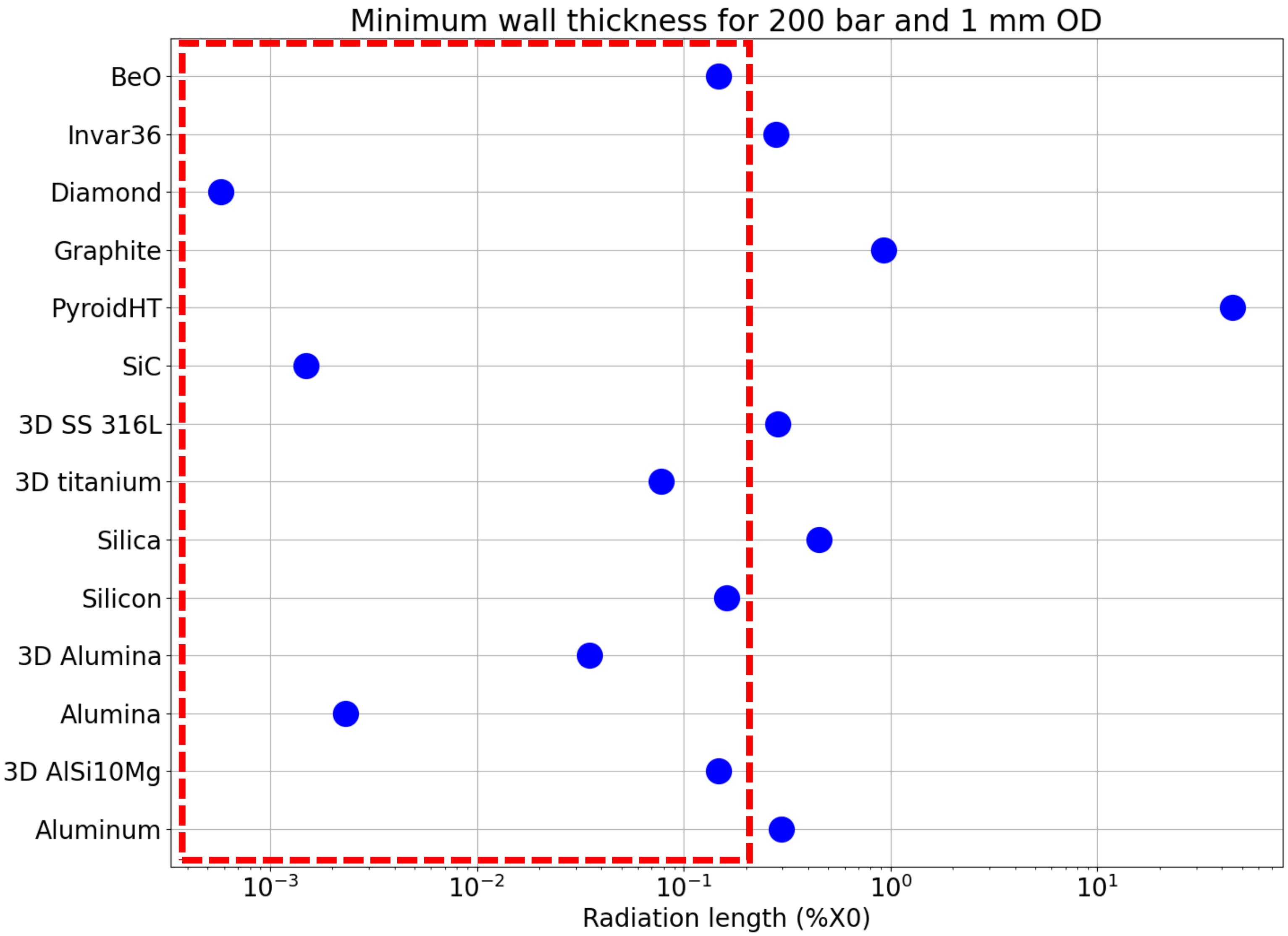
This is just an initial exercise for the selection of materials

Indicates that diamond/ceramics would be good candidates for the substrate

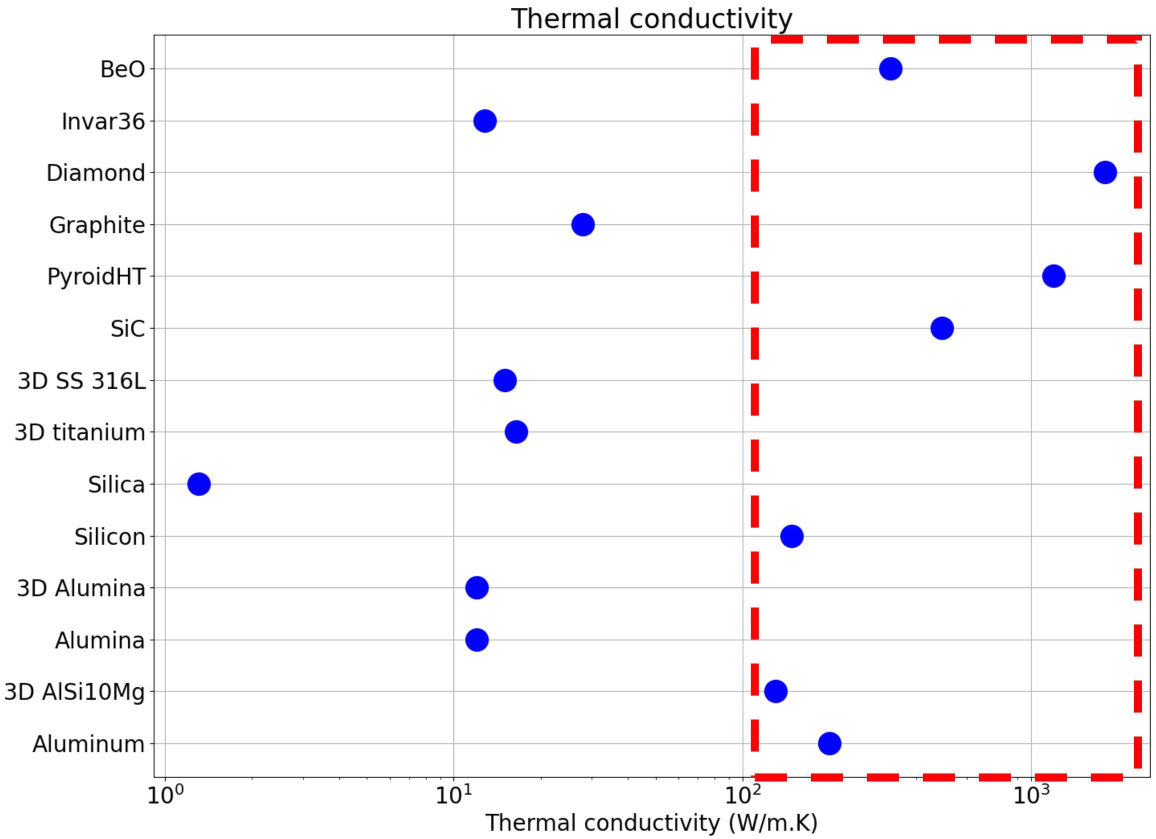
- Taking into account the capacity to deal with high pressure and material budget

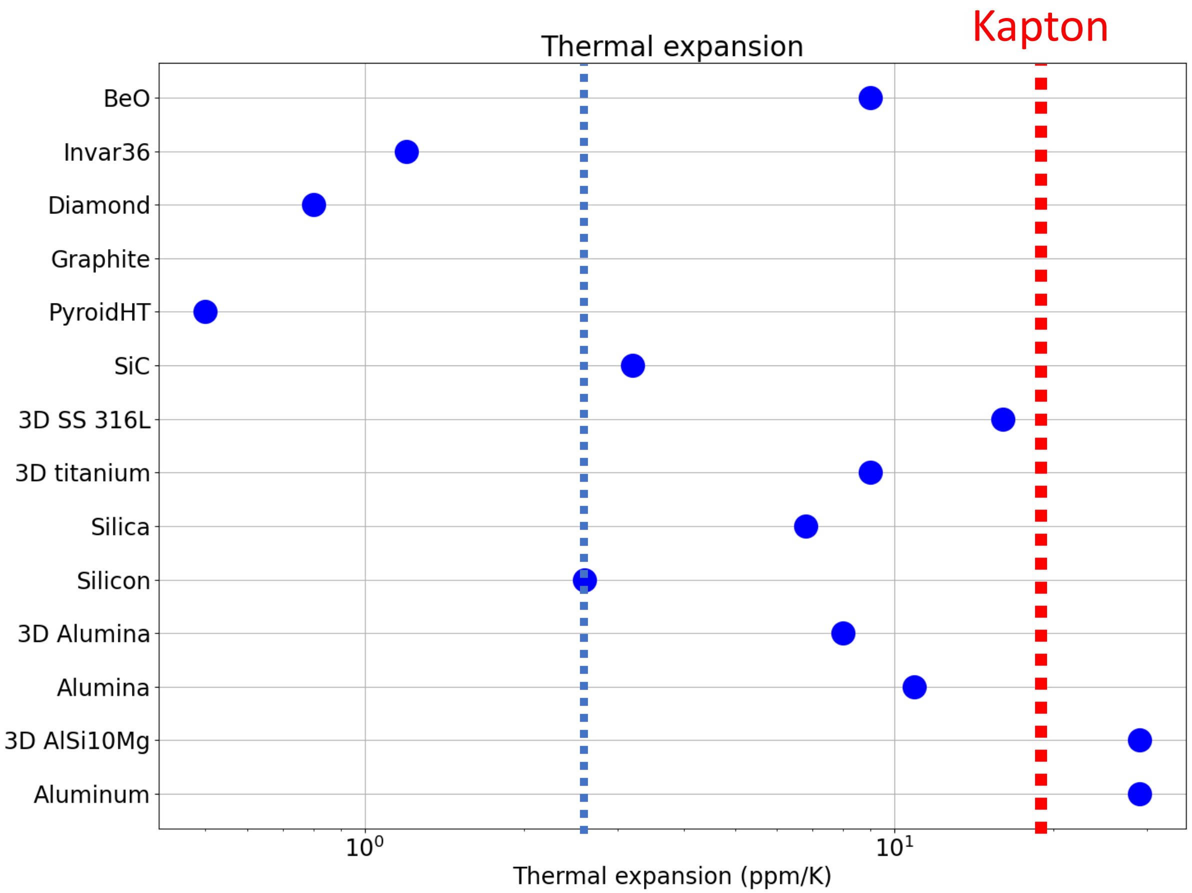
Those number should still take into account thermal conductivity and thermal expansion mismatch

Preference for Diamond, SiC, (3D) Alumina, 3D titanium and BeO



Materials considerations (Minimum wall, OD 1 mm / 200 bar)

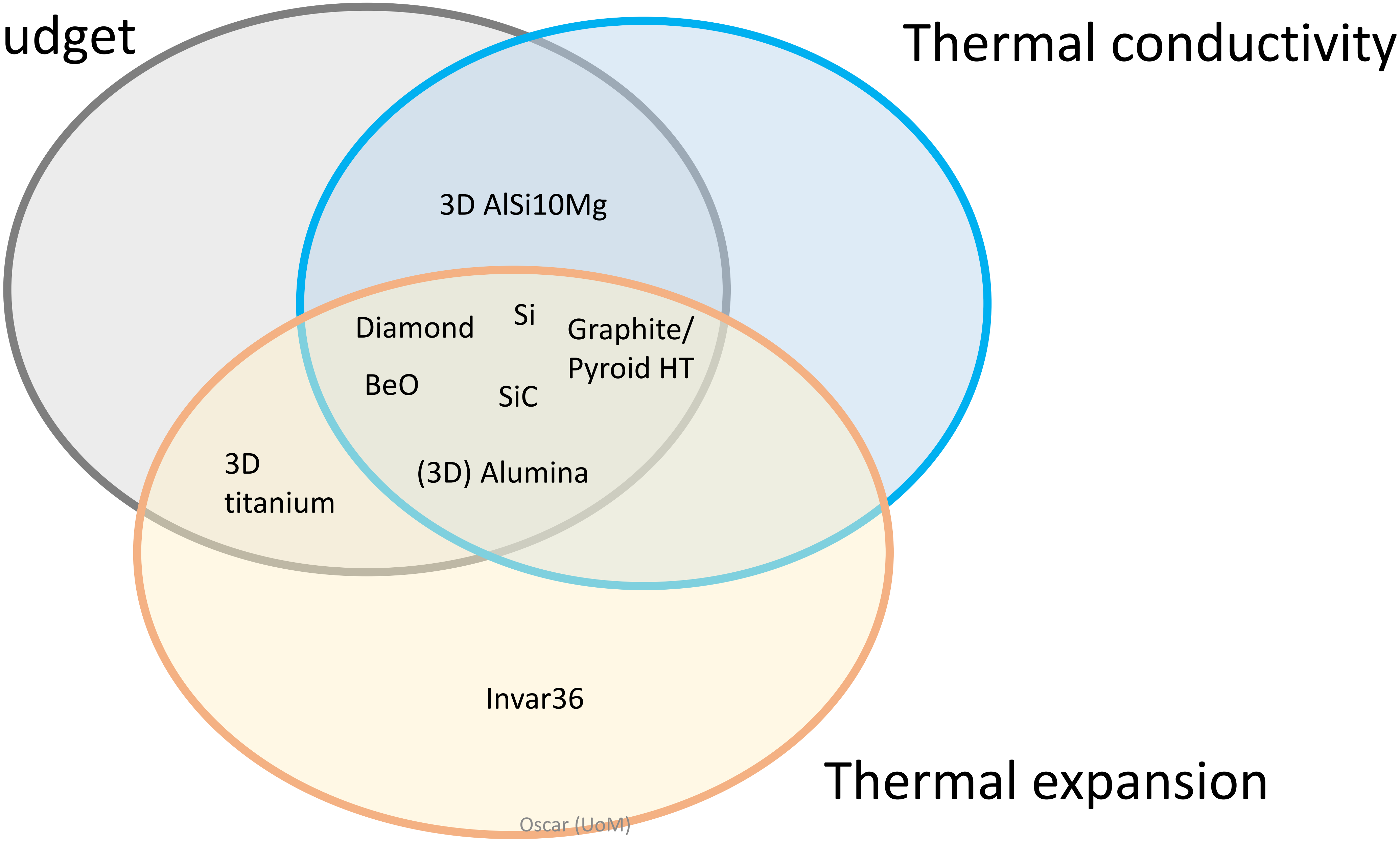




Preference for BeO, Diamond, Graphite, PyroidHT, SiC, Aluminum, Si and 3D AlSi10Mg based on thermal conductivity

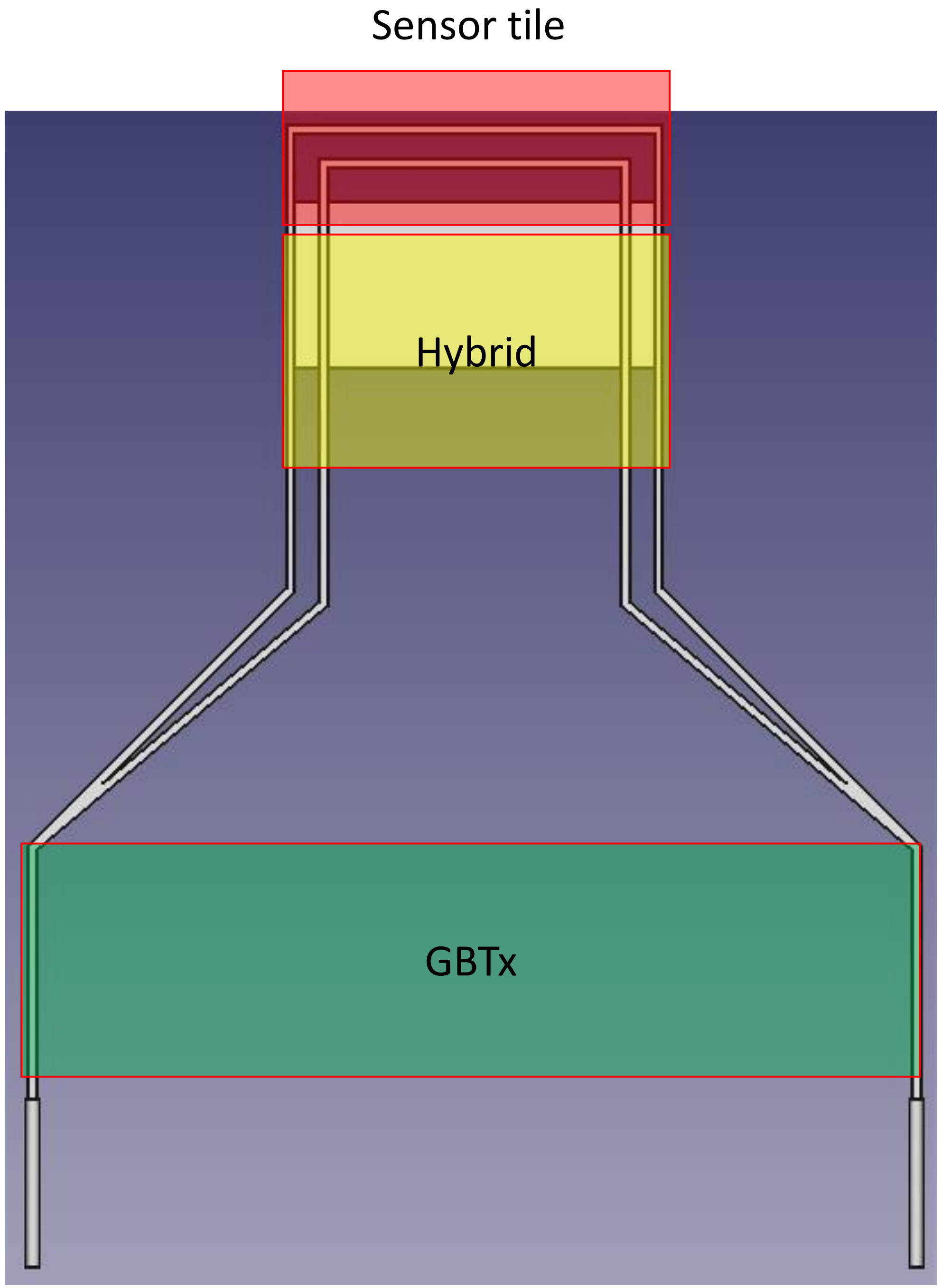
To be as inclusive as possible, all possibilities below Kapton thermal expansion or below 10ppm/K (?)

Materials considerations



Metal 3D printing

- Collaboration with the Royce Institute (UK) based on Selective Laser Melting
- Revisit the plan-Z alternative and try to further reduce the material budget contribution
  - Main motivation: design flexibility and replaceability/price
- Three prototypes manufactured with different wall thicknesses (250 um, 150um and 100um)
  - To be tested for high pressure, leak tightness, …
  - A quarter of a module approach (sensor, hybrid and GBTx region)



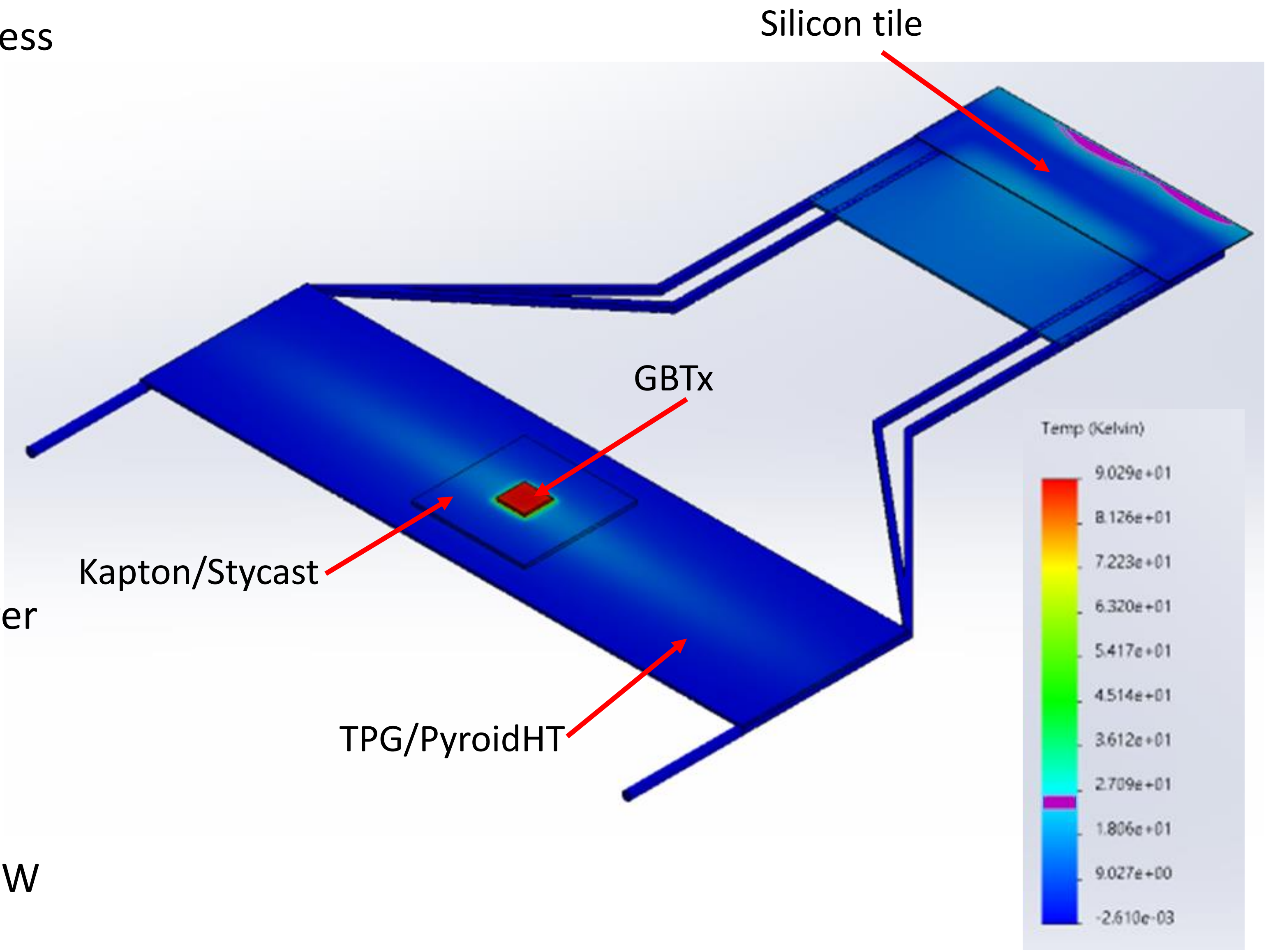
Metal 3D printing (FEA)

- Ti cooling tubes: with 250 um wall thickness

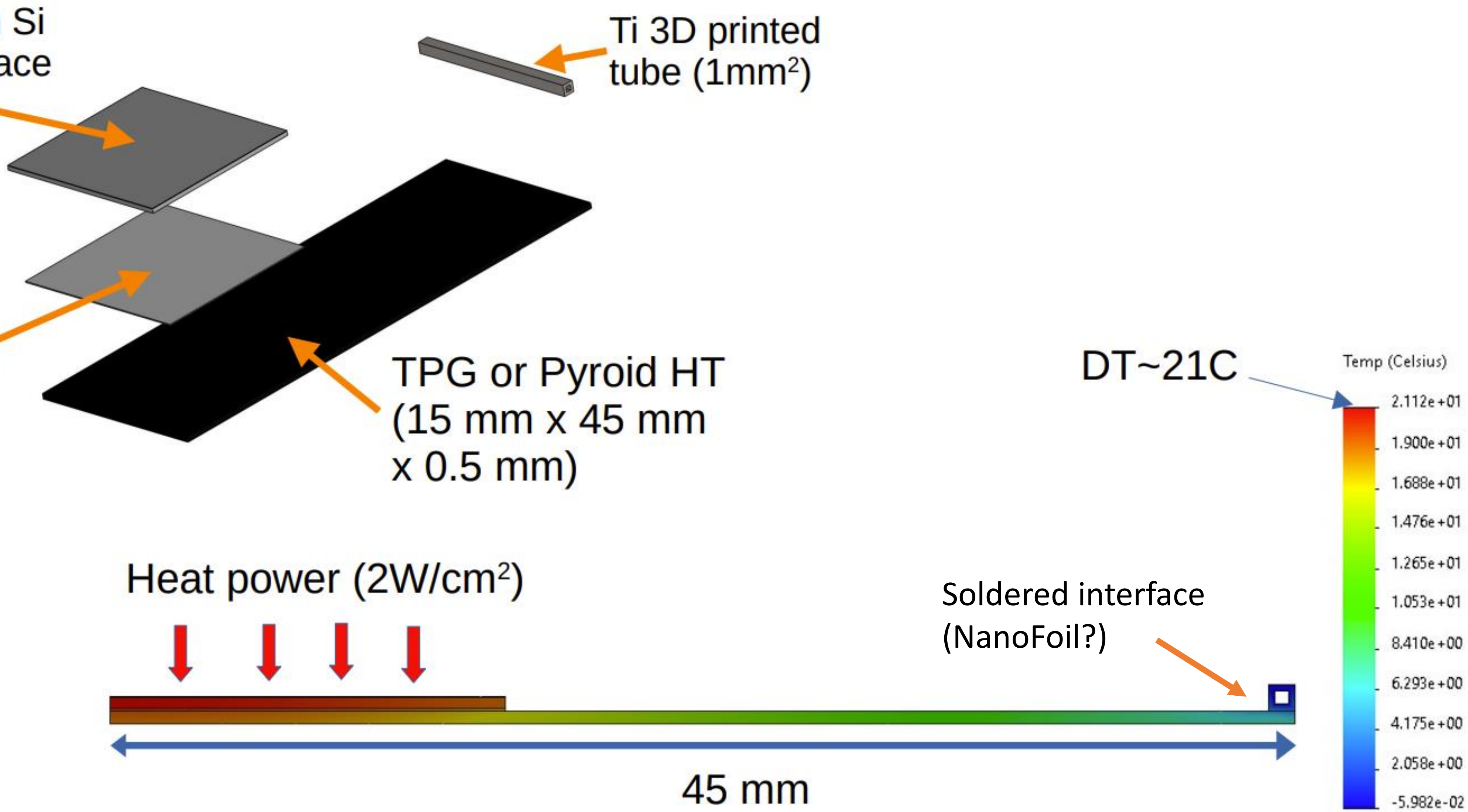
- Two cooling tubes under the silicon tile (similar to U1)
  - Silicon tile (400 um thick)
  - 12 W (2x higher than U1)

- Hottest region of the tile ~25°C
  - About 3x higher than the plan-Z U1 measurements (around 8C)

- On the same model, TPG or graphene layer (1200 W/m.K) was considered to remove the heat of the GBTx
  - GBTx on top of Kapton/stycast layer (600um total, 1.25W/m.K)
  - Simulated as silicon 0.5x0.5cm and 5W
  - High $\Delta T \sim 90°C$



3D metal printing + Pyroid HT (Very preliminary FEA)



400um Si + 40 um Si heater heater surface

Ti 3D printed tube (1mm²)

100um Stycast 2850FT + Catalyst 23LV

TPG or Pyroid HT (15 mm x 45 mm x 0.5 mm)

DT~21C

Heat power (2W/cm²)

Soldered interface (NanoFoil?)

45 mm

VELO U1 (TDR stage)

VELO Upgrade I TDR

Production of cooling/fluidic prototypes

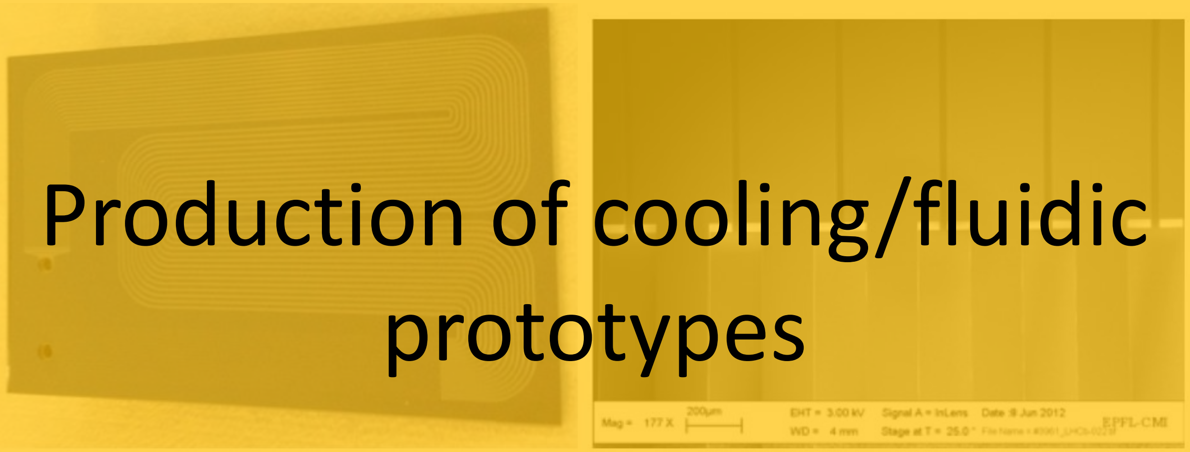
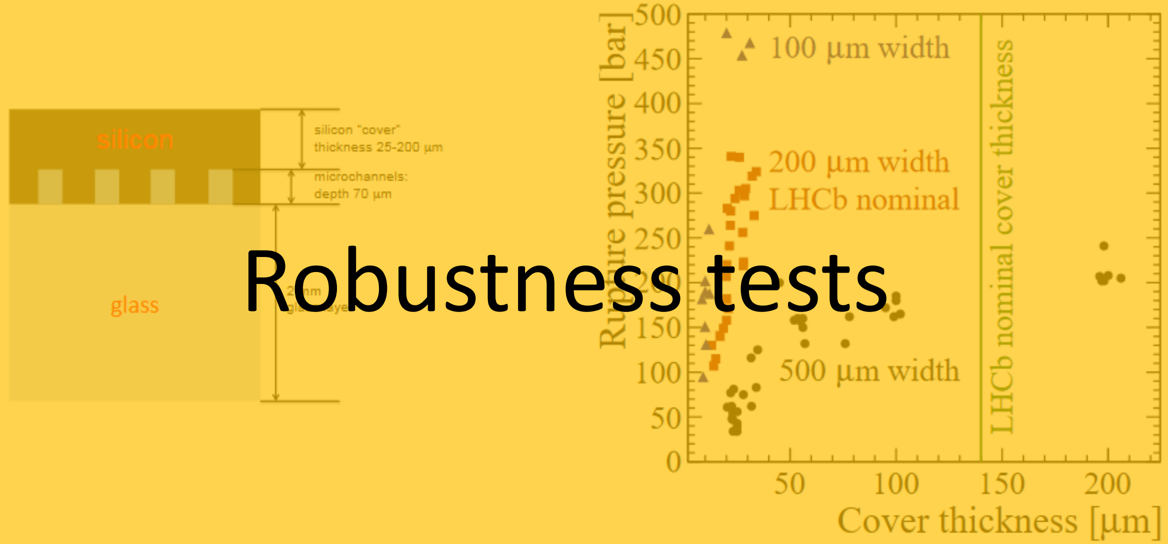


Figure 61: (left) The 2012, 6 × 4 cm^2 silicon-glass prototype. (right) The end of the high-impedance, restricted-width region where the evaporation is triggered in the larger volume.

Robustness tests



Cooling performance

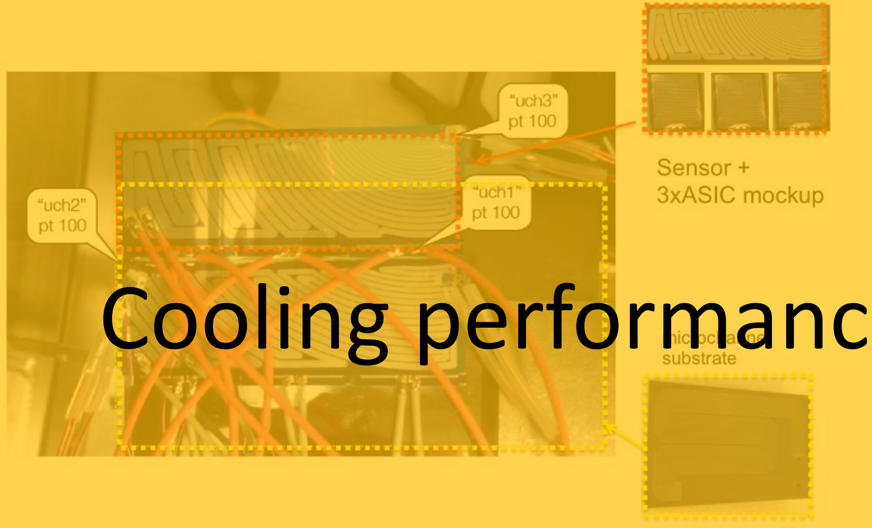


Figure 64: Experimental setup used to test cooling performance. Heater mockups are used to simulate the heat dissipation of the ASICs and irradiated silicon sensors. Cooling is provided by a microchannel substrate.

Cooling performance

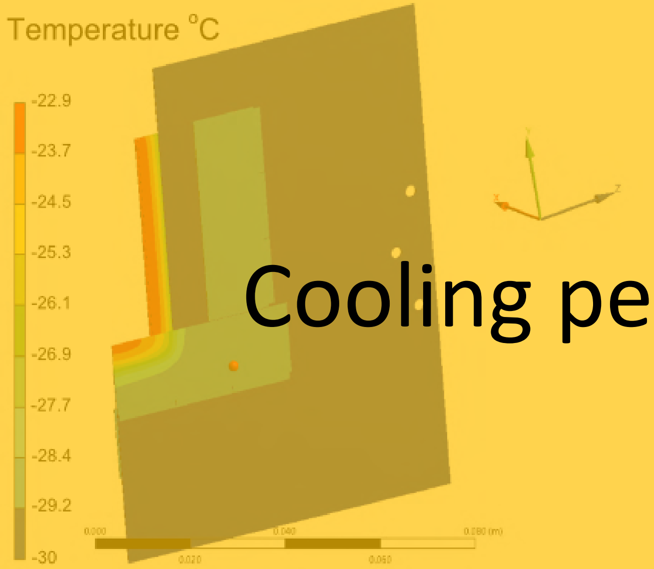


Figure 67: Thermal map from the microchannel FEA simulations, with a a view of the full module with nominal heating. The maximum ΔT to the silicon tip, from which the cooling substrate is retracted, is estimated to be about 7°C.

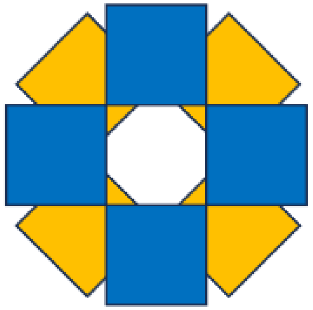
VELO Module/Cooling concepts (CERN)

Jan Buytaert (CERN)

Sensor retraction during injection.

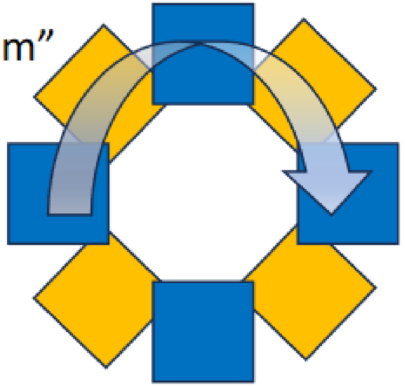
- In U0 and U1 the complete detector halves move.
- This scenario allows to move only the sensors of the inner rings, while the outer rings stay in place.
  - Rotating diaphragm mechanism similar as ALICE ? Any closing position is good, i.e. leaves no gaps !
  - Or 2 halves ?
  - More light-weigth, More precise ?

Closed position

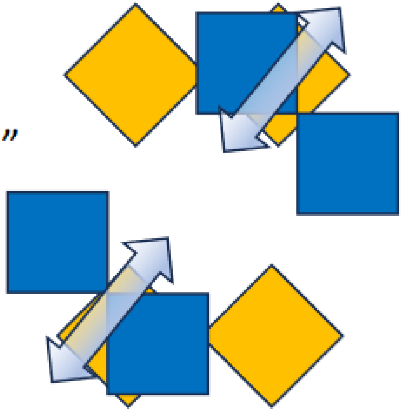


Open positions

“Diaphragm”

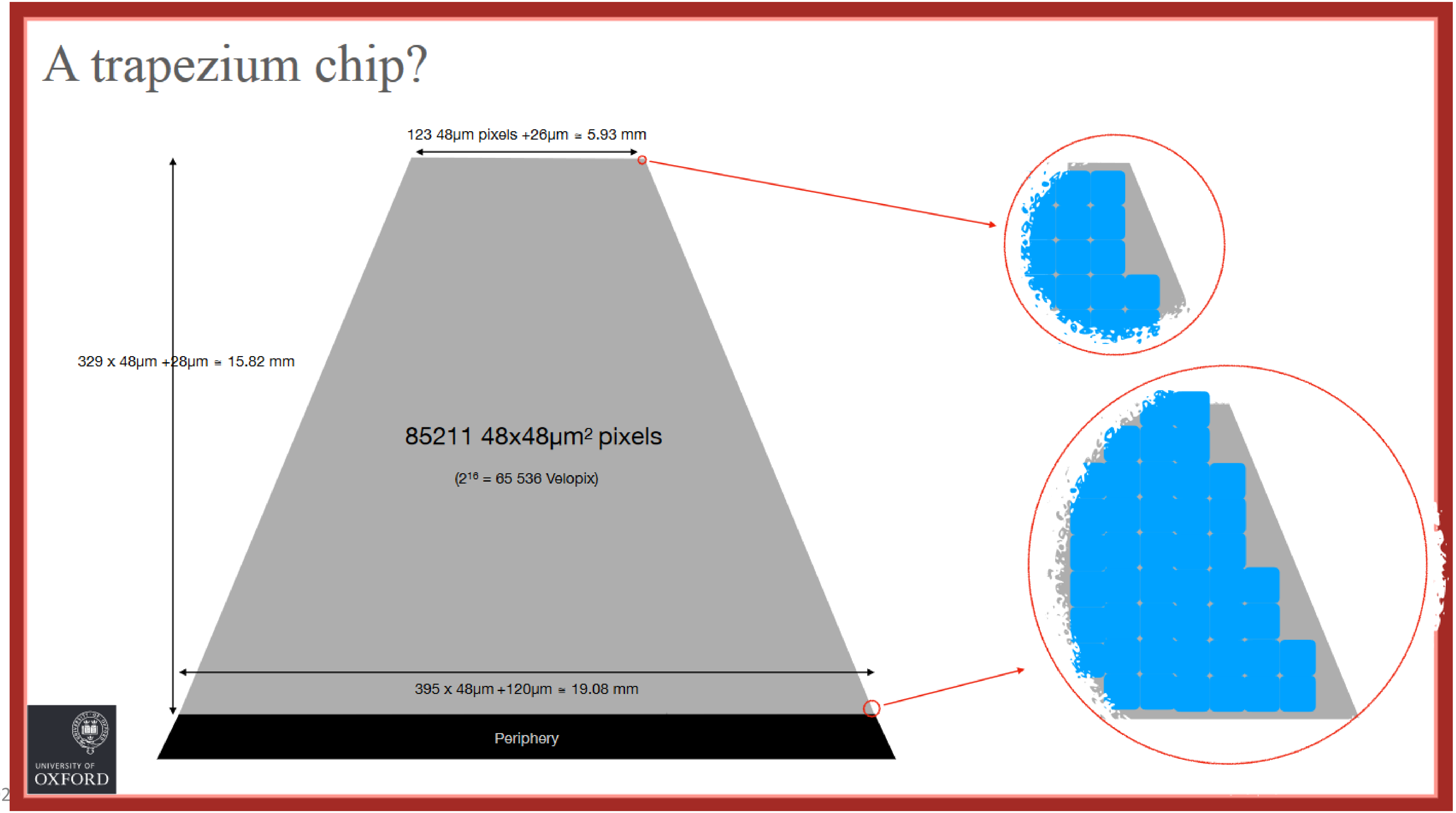


As “halves”



VELO Module/Cooling concepts (Oxford)

Malcolm and Adam (Oxford)



A trapezium chip?

123 48µm pixels +26µm ≃ 5.93 mm

329 x 48µm +28µm ≃ 15.82 mm

85211 $48\times48\mu m^2$ pixels

(2^{16} = 65 536 Velopix)

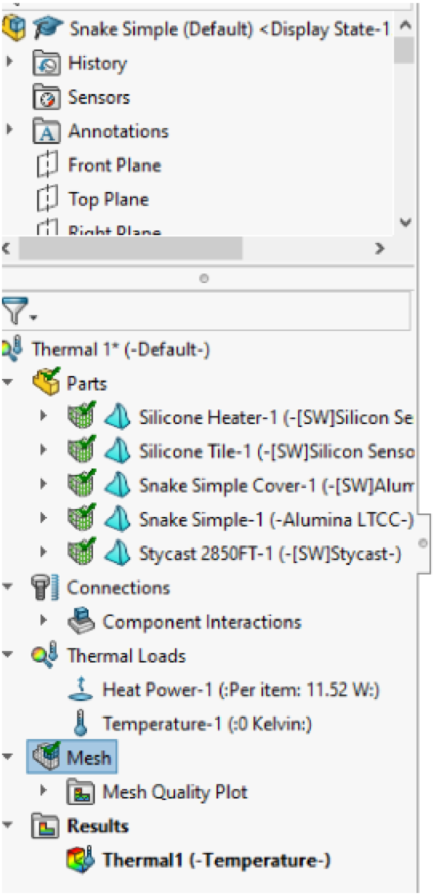
395 x 48µm +120µm ≃ 19.08 mm

Periphery

UNIVERSITY OF OXFORD

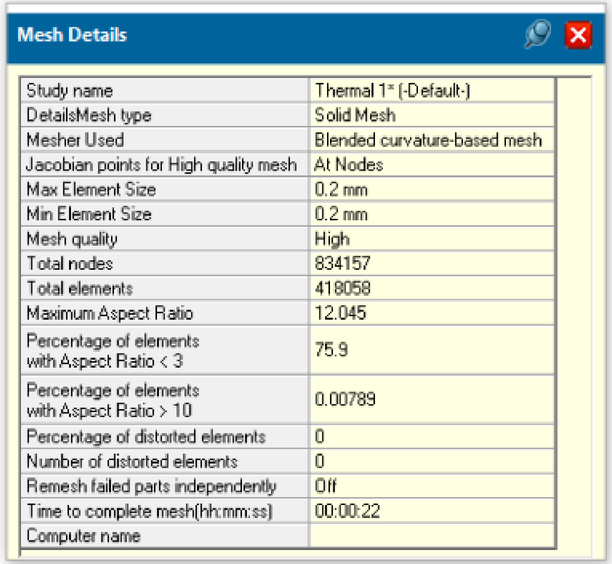
Simplified FEA

5mm Overhang Added



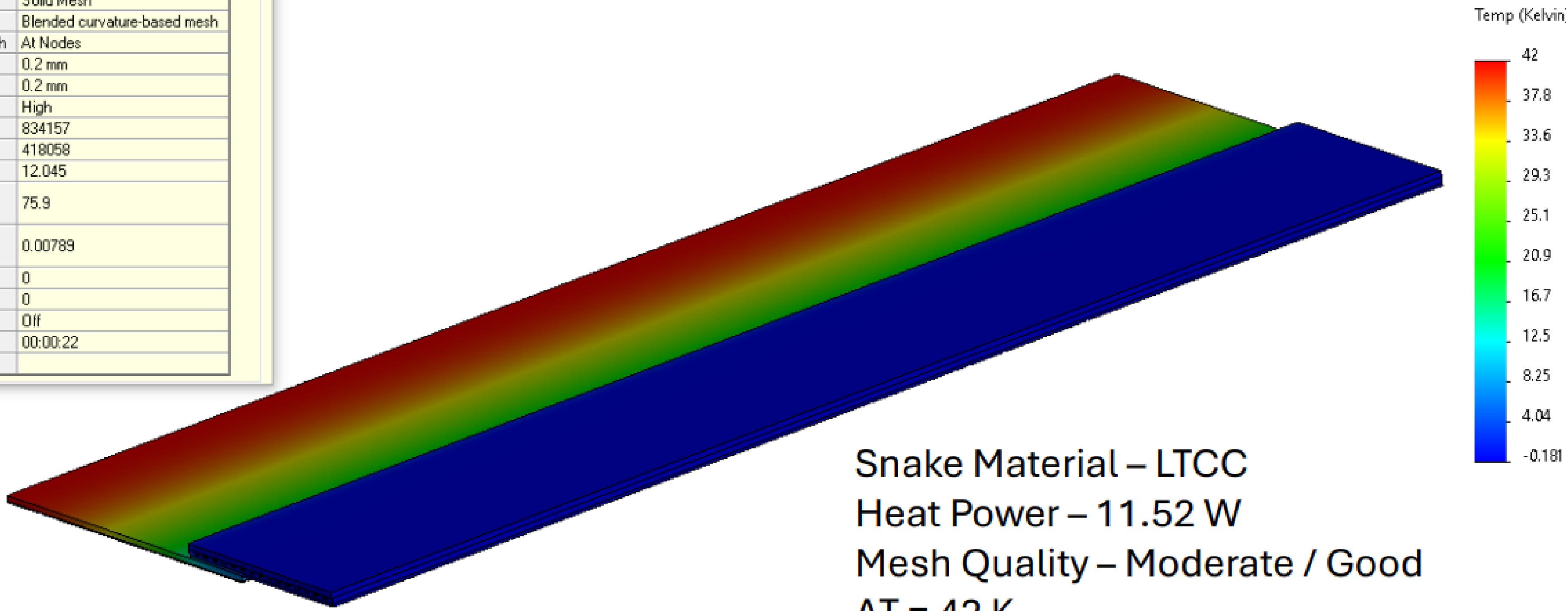
Snake Simple (Default) <Display State-1
- History
- Sensors
- Annotations
- Front Plane
- Top Plane
- Right Plane

Thermal 1* (-Default-)
- Parts
  - Silicone Heater-1 (-[SW]Silicon Se
  - Silicone Tile-1 (-[SW]Silicon Senso
  - Snake Simple Cover-1 (-[SW]Alum
  - Snake Simple-1 (-Alumina LTCC-)
  - Stycast 2850FT-1 (-[SW]Stycast-)
- Connections
  - Component Interactions
- Thermal Loads
  - Heat Power-1 (:Per item: 11.52 W:)
  - Temperature-1 (:0 Kelvin:)
- Mesh
  - Mesh Quality Plot
- **Results**
  - **Thermal1 (-Temperature-)**



Mesh Details

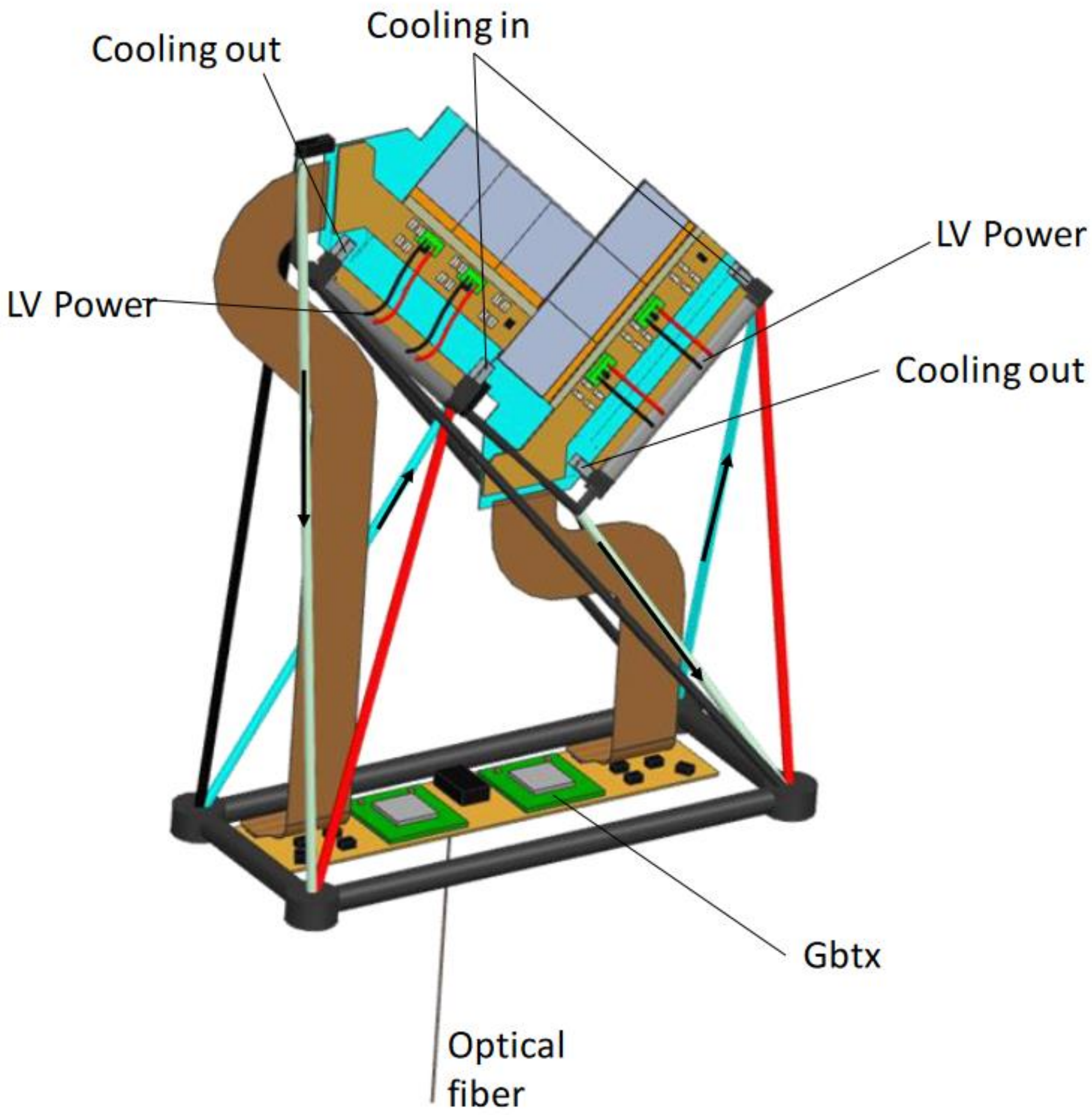
Study name	Thermal 1* (-Default-)
DetailsMesh type	Solid Mesh
Mesher Used	Blended curvature-based mesh
Jacobian points for High quality mesh	At Nodes
Max Element Size	0.2 mm
Min Element Size	0.2 mm
Mesh quality	High
Total nodes	834157
Total elements	418058
Maximum Aspect Ratio	12.045
Percentage of elements with Aspect Ratio < 3	75.9
Percentage of elements with Aspect Ratio > 10	0.00789
Percentage of distorted elements	0
Number of distorted elements	0
Remesh failed parts independently	Off
Time to complete mesh(hh:mm:ss)	00:00:22
Computer name	



Snake Material – LTCC
Heat Power – 11.52 W
Mesh Quality – Moderate / Good
ΔT = 42 K

VELO Module/Cooling concepts (NIKHEF)

Kazu/Yutaro presentation



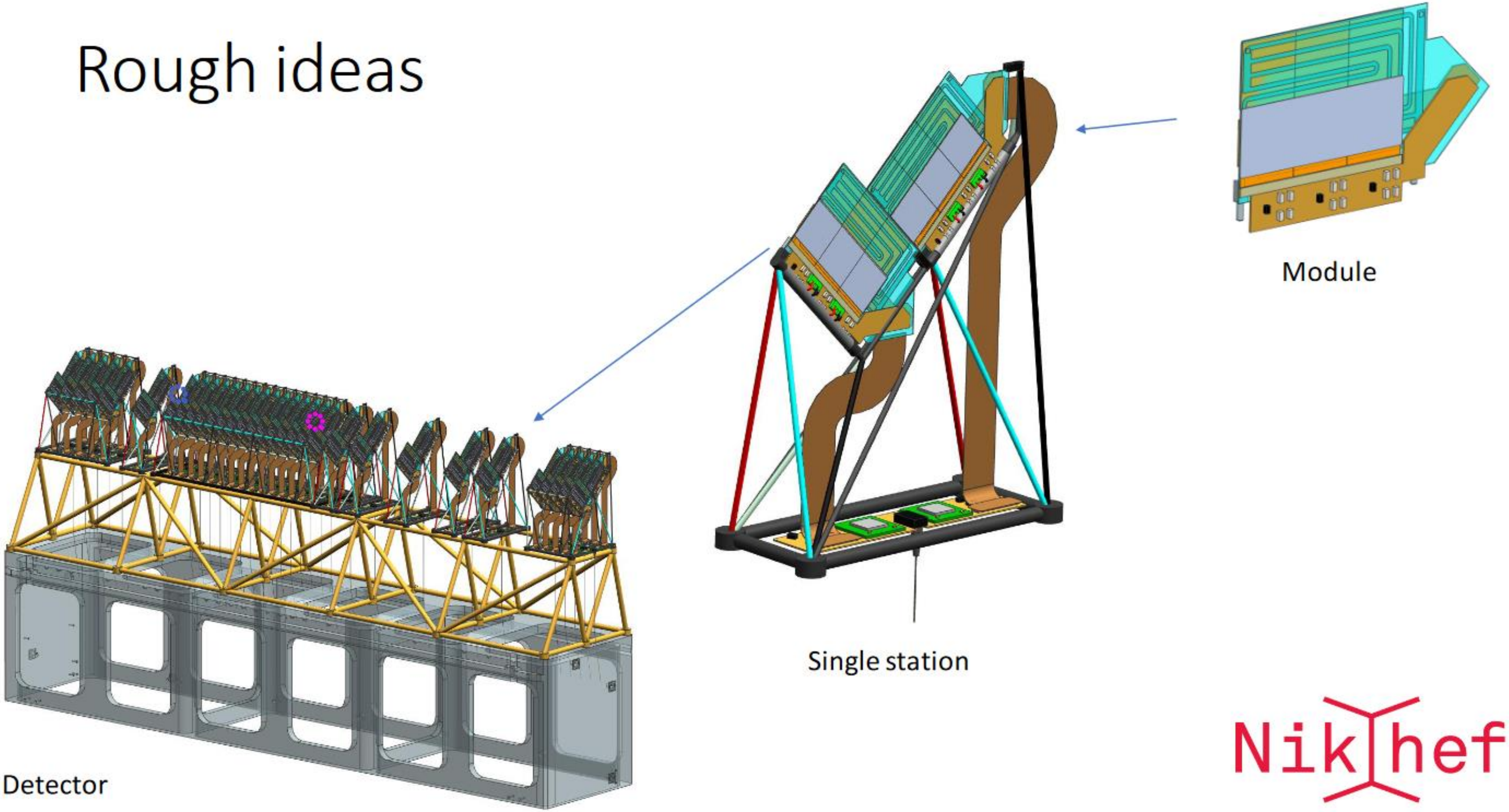
- Features:
  - Mountable modules using cooling connectors
  - Carbon fiber (or aluminum, etc) frame with high stiffness for all degrees of freedom (DoF) with minimal material
  - Allows different station design depending on location.
  - Integrated supply of power and coolant (next slide).

Nikhef

VELO Module/Cooling concepts (NIKHEF)

Kazu/Yutaro presentation

Rough ideas



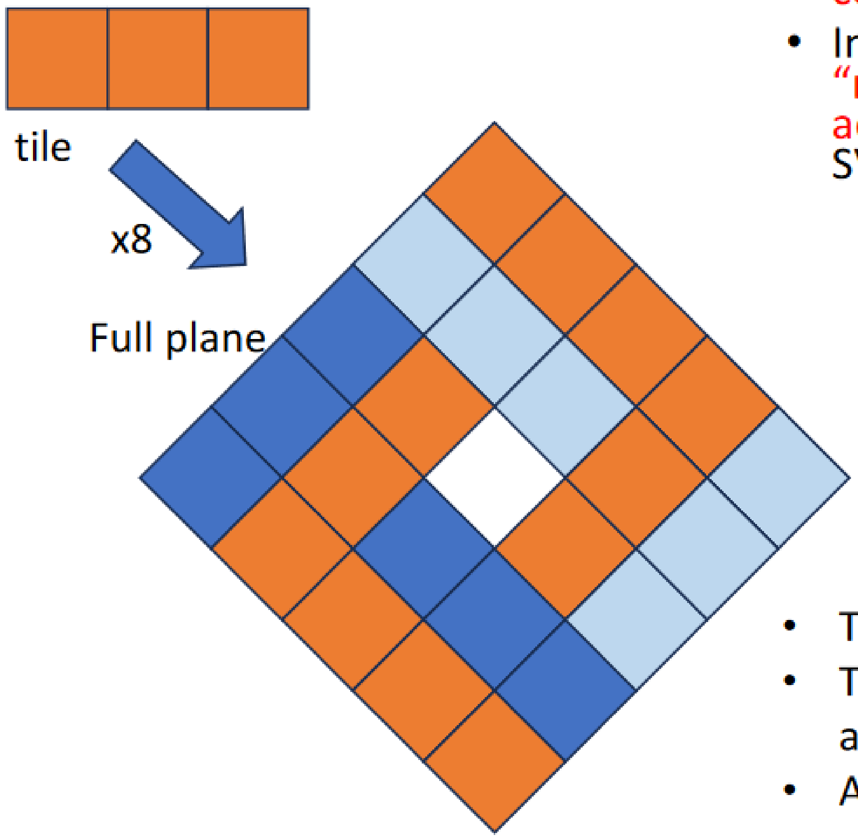
VELO Module/Cooling concepts (CERN)

[Jan Buytaert (CERN)]

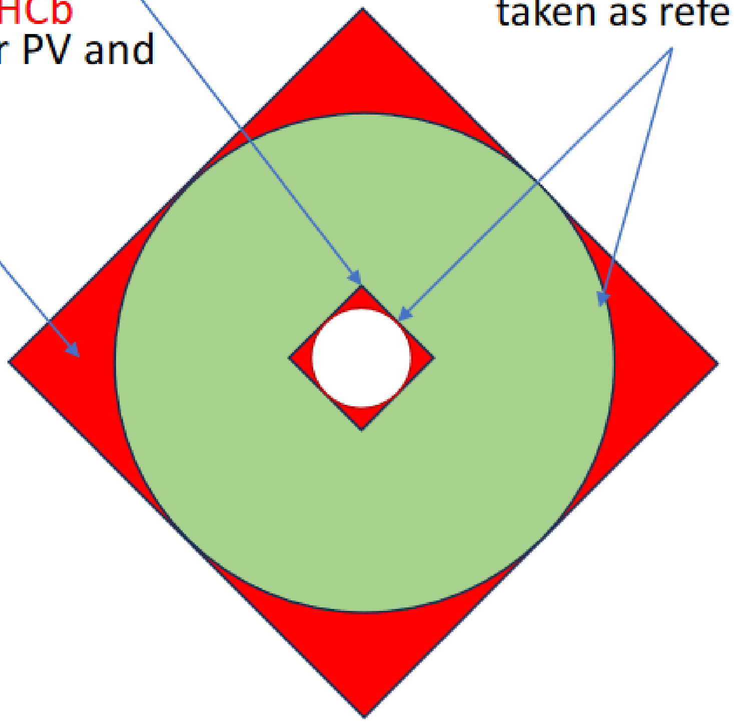
Current VELO (U1)

Non-uniform phi coverage:

- In the center hole: corners not covered.
- In the periphery: corners are not "necessary" for tracks in LHCb acceptance. (but useful for PV and SV reconstruction)



- Total of 24 asics.
- Tiles with different colors are on different z-planes.
- Asic is 14mmx14mm



2 inscribed circles taken as reference

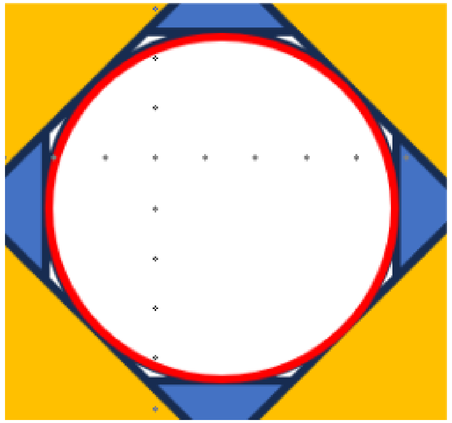
VELO Module/Cooling concepts (CERN)

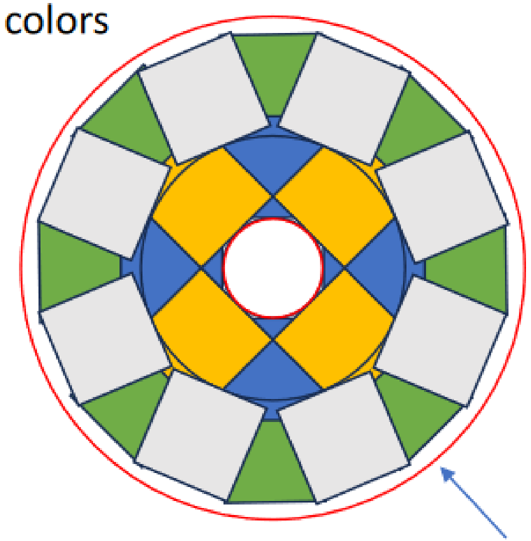
Jan Buytaert (CERN)

Circular layout

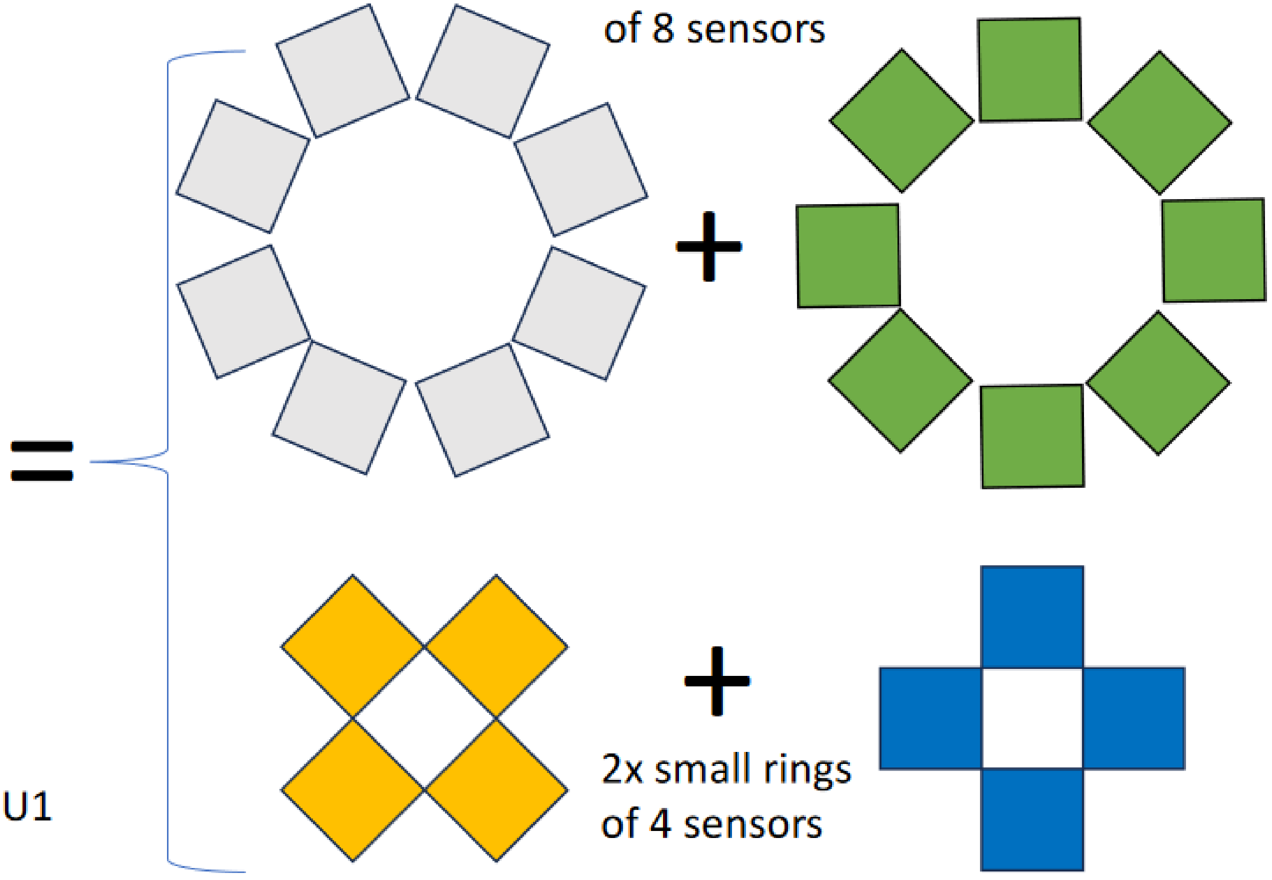
- Aim for more uniform phi coverage in center and periphery.
- Also 24 sensors. Each sensor is 14mmx14mm
- Composed of 2 large and 2 small “rings”. Different colors on different z-planes

Zoom on center hole





Red circles are the reference circles from U1 layout (previous slide)

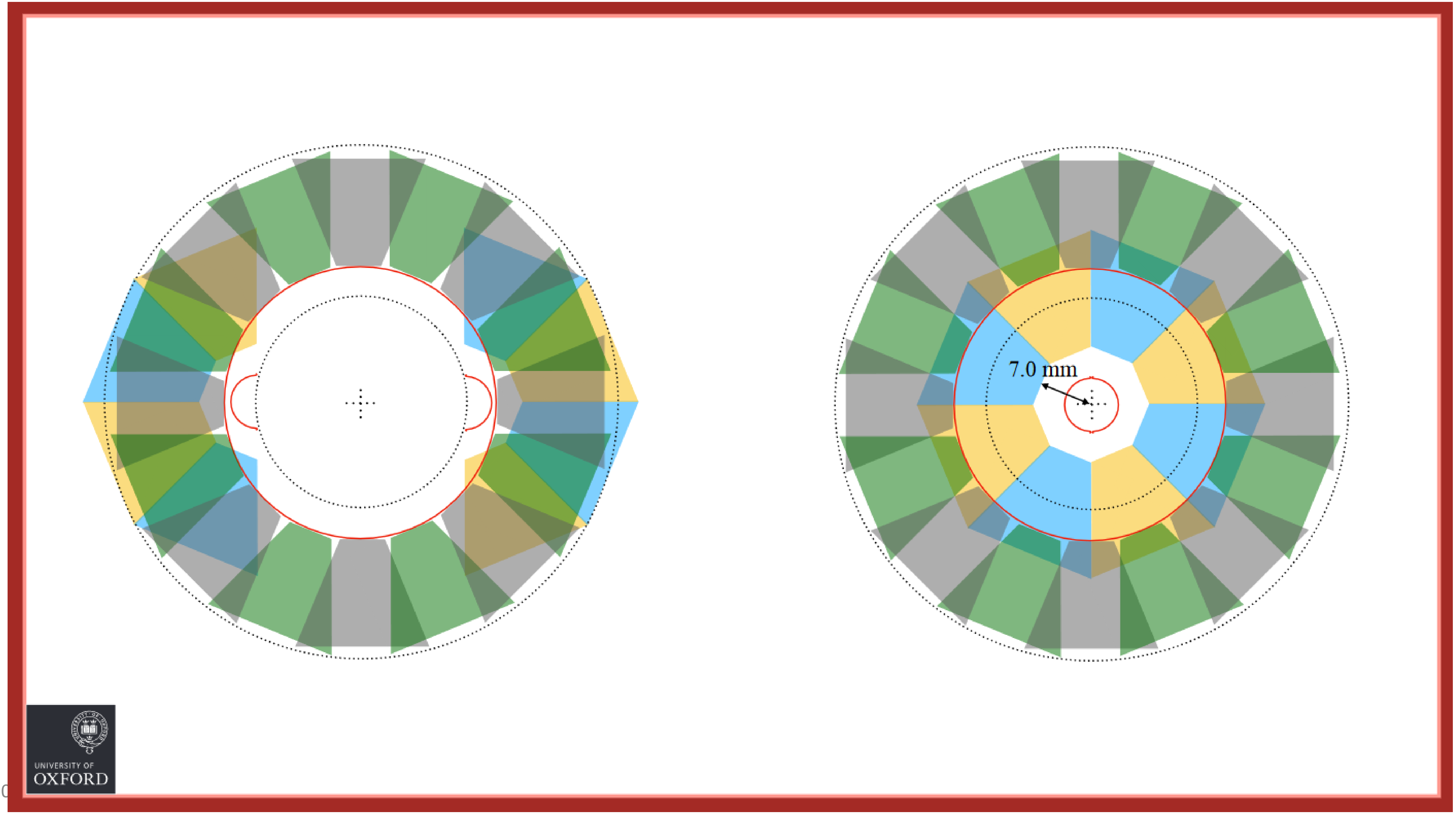


2x large rings of 8 sensors

2x small rings of 4 sensors

VELO Module/Cooling concepts (Oxford)

Malcolm and Adam (Oxford)

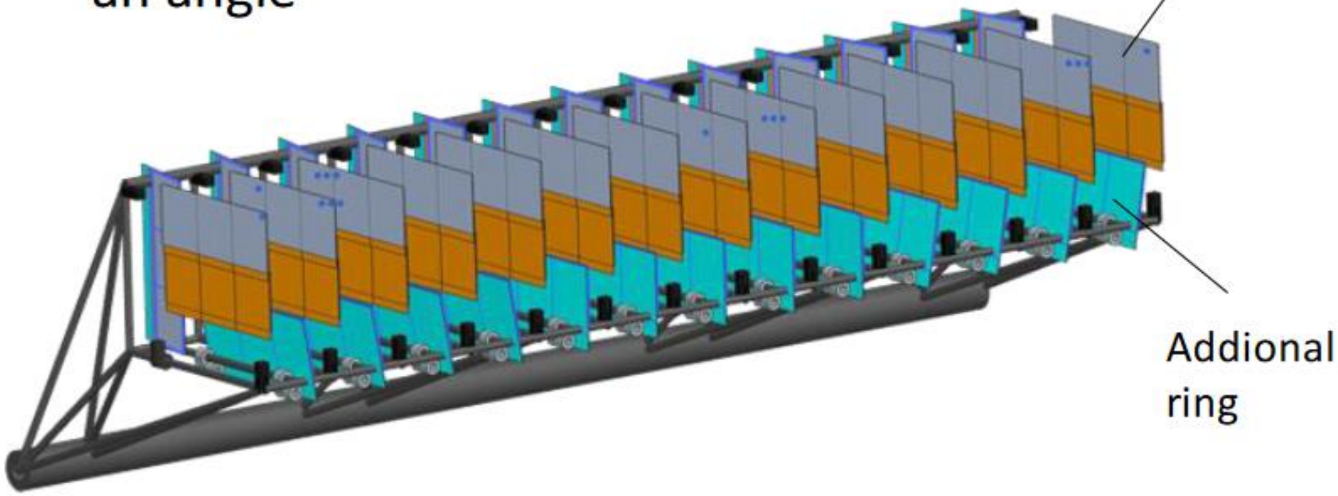


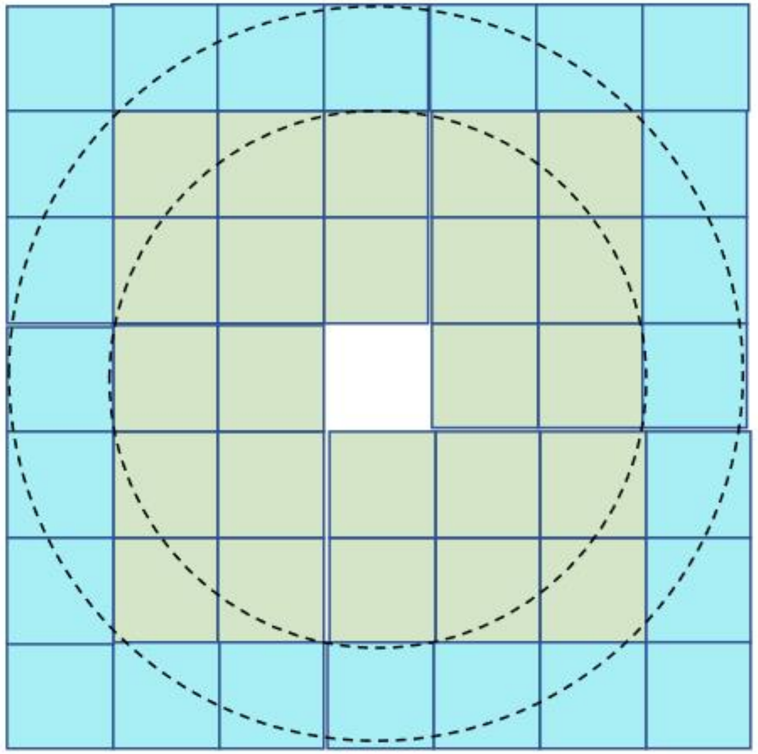
VELO Module/Cooling concepts (NIKHEF)

Kazu/Yutaro presentation

Some additional ideas

- Additional sensor ring
  - Increases outer radius
  - Reduces number of stations (Avg. Number of hits)
  - Allows sensors in the outer ring at an angle





Nikhef