THE DMAPS UPGRADE OF THE BELLE II VERTEX DETECTOR: MECHANICS AND INTEGRATION

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on behalf of the VTX mechanical team

OUTLINE

- Belle II current vertex detector overview
- Vertex detector upgrade proposals: the DMAPS upgrade
- The Obelix sensor
- iVTX concepts
- oVTX L5 Mechanical, vibrational and thermal characterization
- Conclusions

BELLE II CURRENT VERTEX DETECTOR

- 2 layers of PiXel Detector (PXD)
- – DEPFET sensor @ 14 and 22 mm
- – 50 x 55-85 µm² pixel size
- – 20 µs integration time,
- – 10 µm impact parameter resolution

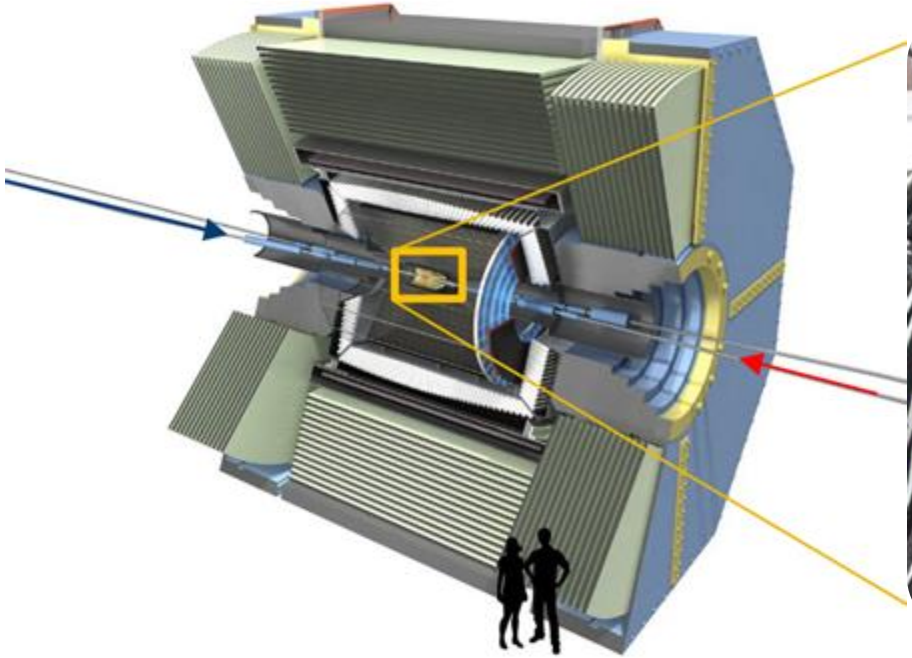
4 layers of Silicon Vertex Detector (SVD)

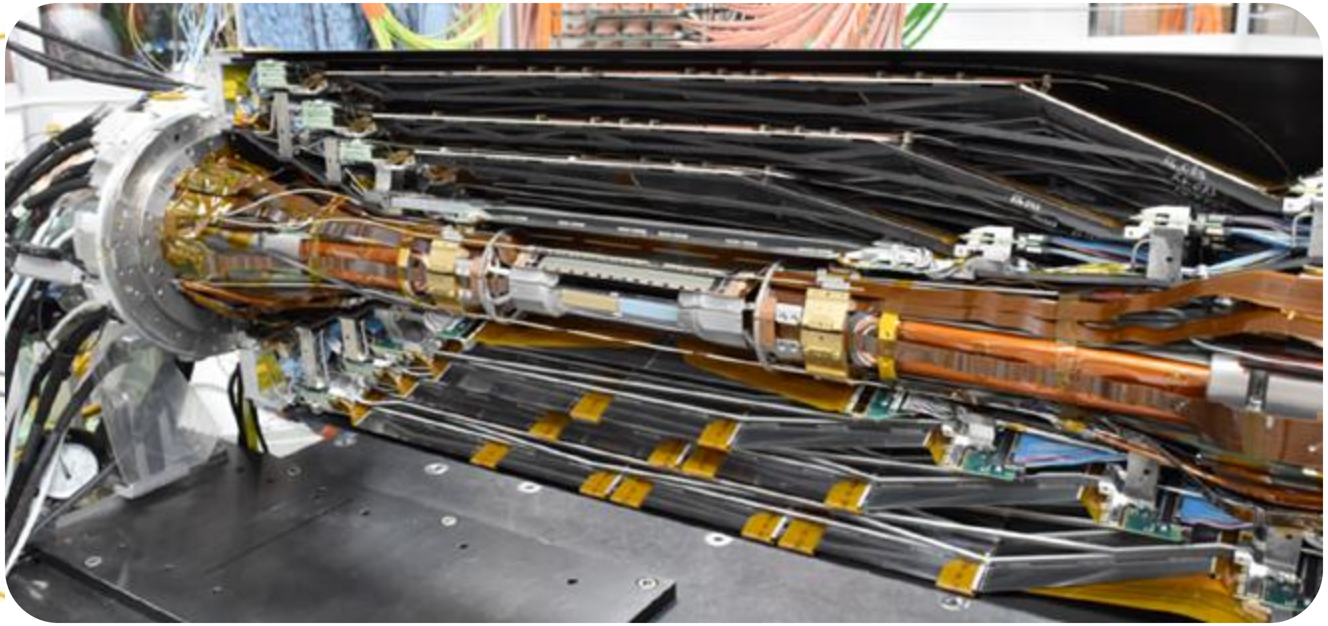
– Double-sided silicon strip detector (DSSD)

– Radii of 39, 80, 104, 135 mm

– Strip pitch of 50/75 µm (r-φ) and 160/240 µm (z)

– 8 µm spatial resolution on innermost layer, 3 ns cluster time resolution





BELLE II VERTEX DETECTOR PROPOSALS

Rationale

- Be prepared for IR redesign (higher Background conditions)
- Improve performance / IP resolution, low p_T tracks
- Be prepared to cover inner CDC (radii 135-240 mm)
- Triggering: possible contribution to L1

- Target **Medium-term**

Requirements

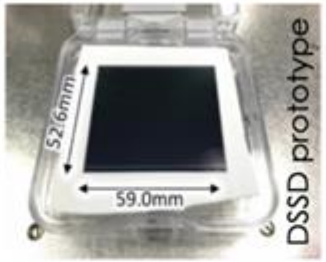
5-6 layers over radii	14-135 mm
Spatial resolution	< 15 µm
Total material budget	< (2x0.2% + 4x0.7%) X_0
Hit rate	120 ↘ 1 MHz/cm²
Total Ionizing Dose (inner)	100 kGy / year
NIEL fluence (inner)	5×10^{13} n_{eq}/cm²

⇒ Higher granularity in time and/or space / current VXD

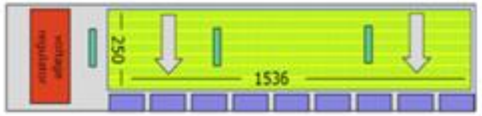
Various proposals

Prototyping & tests on-going

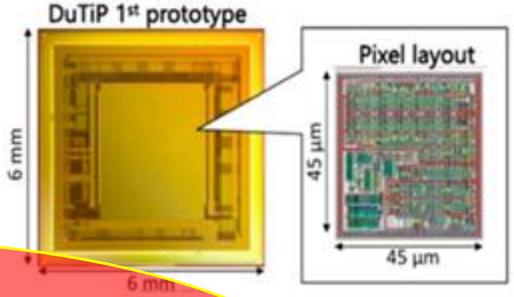
- **Thin and fine-pitch DSSD**
  - Sensor 140 µm thin & z-pitch < 80 µm
  - New ASIC for low noise



- **Upgraded DEPFET**
  - Higher radiation tolerance through higher gain
  - Faster read-out (few µs) with re-orientation and new ASICs



- **SOI pixels**
  - Lapis 200 nm process
  - Dual Time pixel sensor (DuTiP)
  - pitch 45 µm 2x60 ns integration



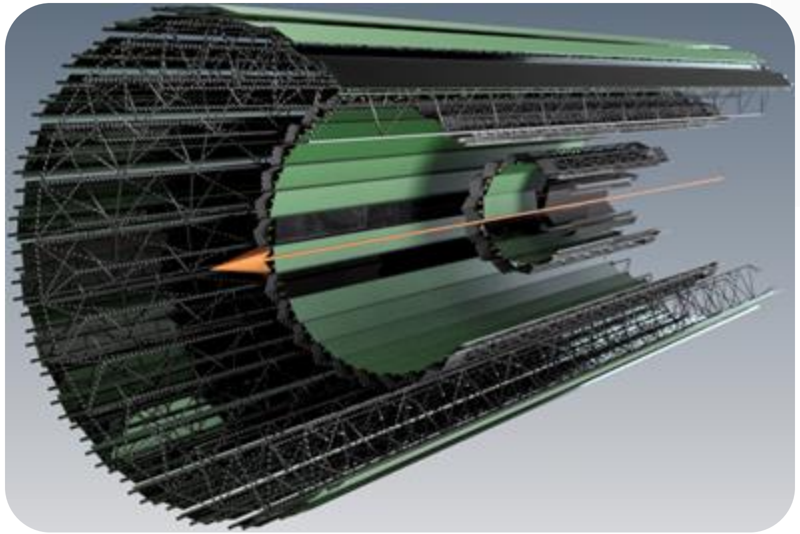
- **CMOS-MAPS**
  - Tower 180 nm process
  - Extension of TJ-MONOPIX2 ⟶ OBELIX sensor
  - Pitch <40 µm with 100 ns integration
  - Fully pixelated VXD concept = **VTX** with all-Si modules or ALICE-ITS-like ladders

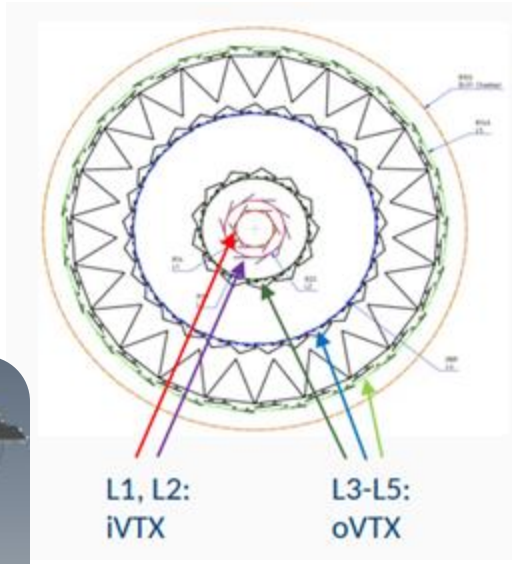
CMOS-MAPS UPGRADE: BELLE II VTX CONCEPT

SuperKEKB upgrade during LS2 in 2026/2027 ⇨ Redesign of interaction region ⇨ Opportunity to install new vertex detector

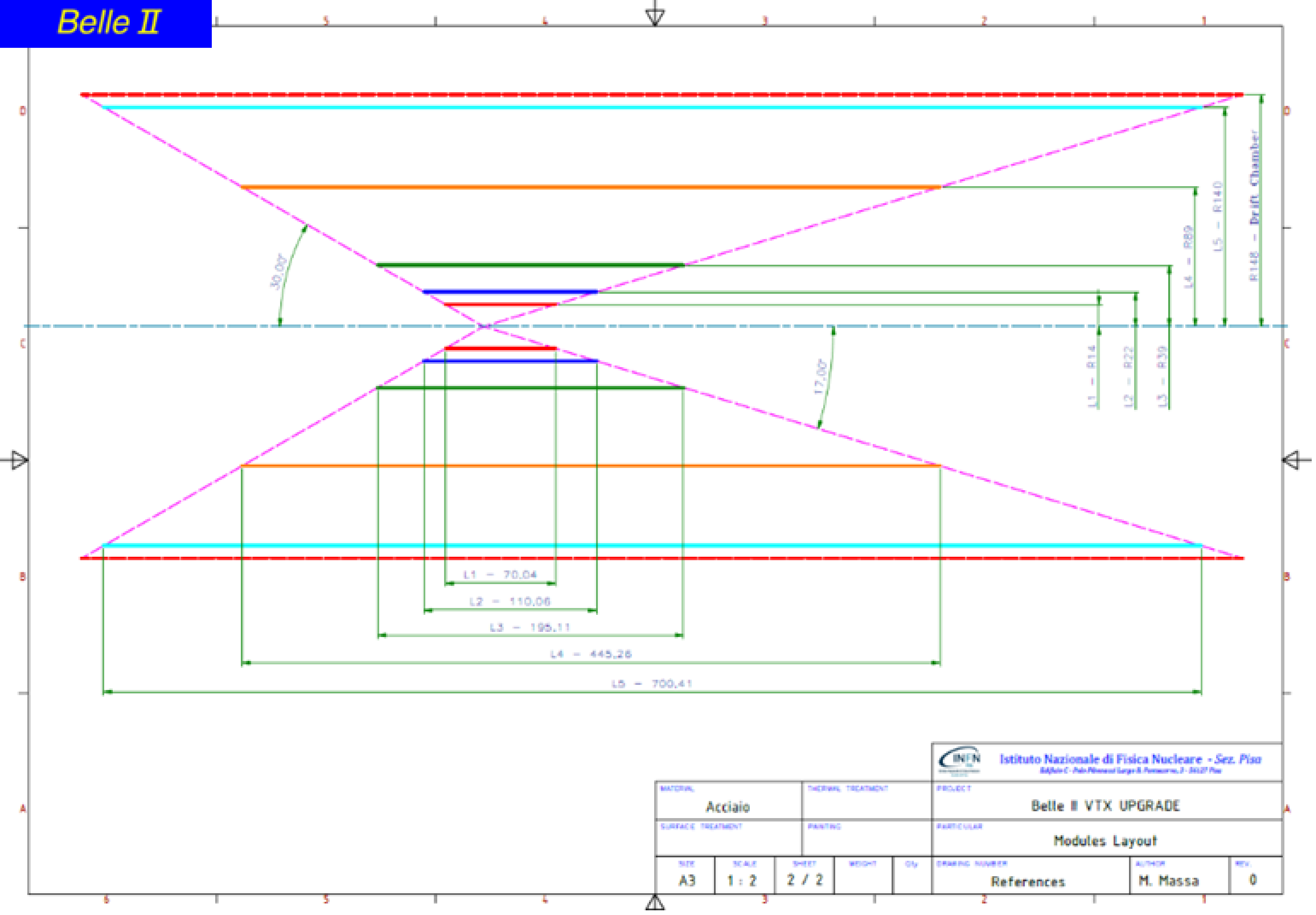
VTX: successor to VXD

- 5 straight fully pixelated barrel layers
- Low material budget: 0.1% X0 (L1+L2), 0.5% X0 (L3), 0.8% X0 (L4+L5)
- Depleted Monolithic Active CMOS pixel sensors
- 2 x 3 cm², pixel pitch of 30-40 µm²
- Same sensor type for all layers
- iVTX: innermost 2 layers, self-supported, air cooled
- oVTX: 3 outer layers, CF structure, water cooled
- Power dissipation of about 200 mW / cm²





BELLE II VTX LAYOUT



5 layers	1	2	3	4	5
Radius (cm)	1.4	2.2	3.9	8.9	14.0
# ladders	6	10	8	18	26
Sensor type	A	A	A	A	A

iVTX (layers 1–2) | oVTX (layers 3–5)

Following the radii inputs from the geometry the lengths of the ladders are:

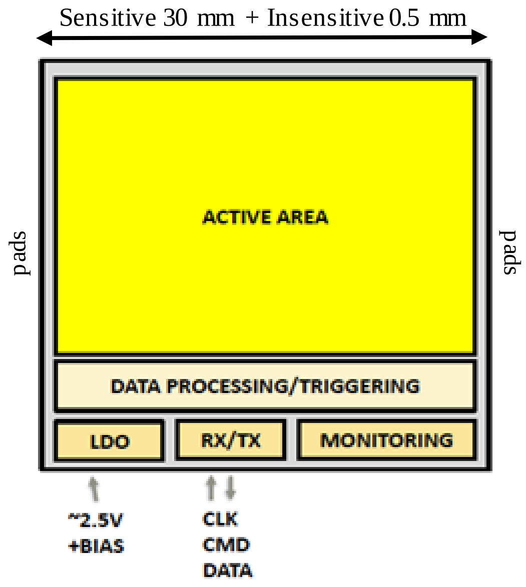
L1 ⇨ ~ 70 mm
L2 ⇨ ~ 110 mm
L3 ⇨ ~ 195 mm
L4 ⇨ ~ 445 mm
L5 ⇨ ~ 700 mm

The most challenging layer/ladder is the L5 ⇨ We focused our attention on the L5 mechanical structure

THE OBELIX CHIP

Target: First complete prototype **OBELIX-1 fabricated in 2022**

- Reminder on guidelines
  - Keep pixel matrix core from **TJ-Monopix2** but
    - **enlarged** to reach sensitive width along z **~3 cm**
    - possible **pitch increase** toward **40 μm**, if beneficial for pixel design robustness
  - Adapt digital logic to Belle II triggering
  - **Short integration time < 100 ns** and trigger rate of **30 kHz**
    → limit the data throughput to **~320 Mbps**



- Sensor layout & powering
  - Baseline matrix powering sticks to TJ-Monopix2 with **additional on-sensor regulators**
  → **~300 μm** insensitive gaps on the side

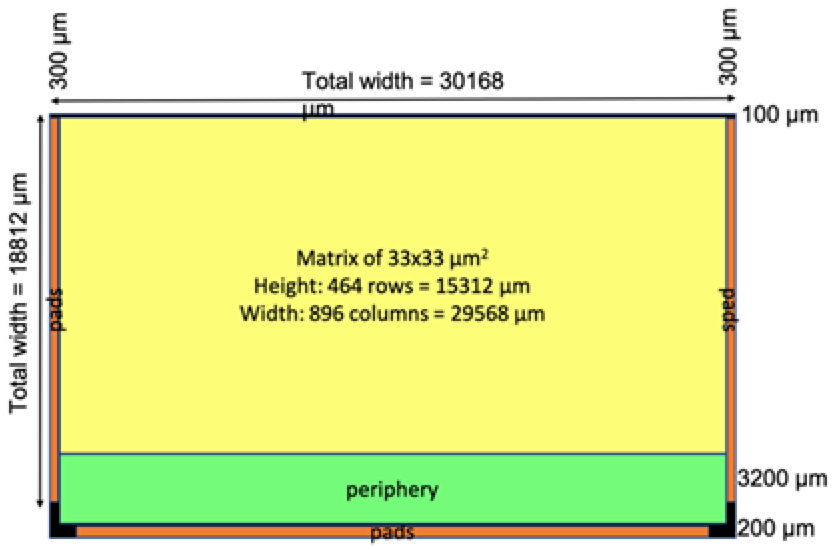
- Power dissipation
  - Initial target: **~200 mW/cm2**
  - Decreasing timing resolution from **25 ns** to **50 ns** mitigates power dissipation from clock propagation within matrix → Dissipation closer to **~100 mW/cm²** expected (limit for air-cooling)

OBELIX OVERALL LAYOUT

Plan A - baseline

This geometry corresponds to TJ-Monopix2 most direct extrapolation. The pixel matrix is simply extended.

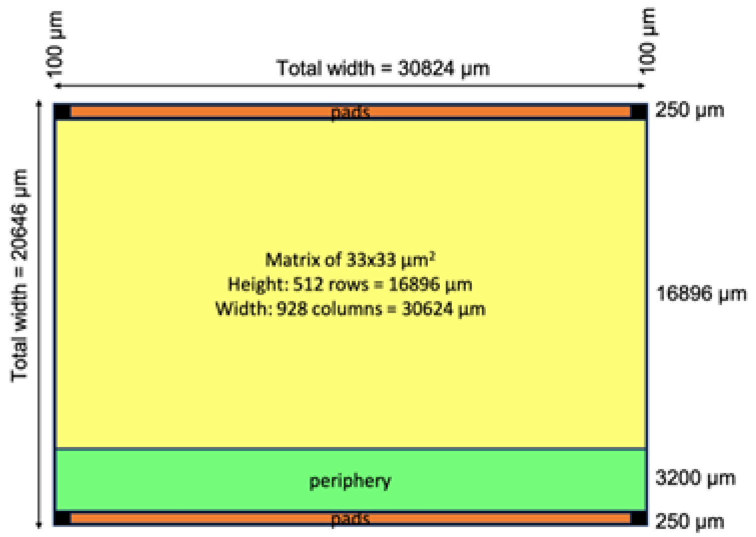
33 µm pitch (896x464 pixels adjusted to fit 30x19 mm2 size)



Not completely defined but the candidate one!

Plan B - alternative

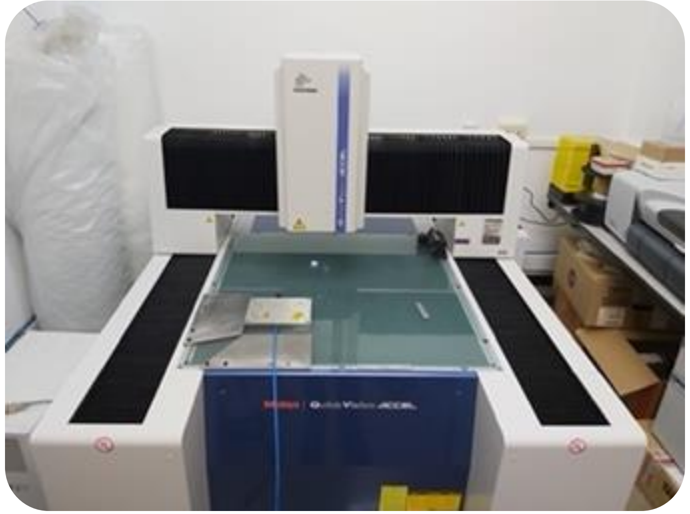
This geometry corresponds to vertical distribution of the power lines. It requires a major re-working of the pixel matrix.

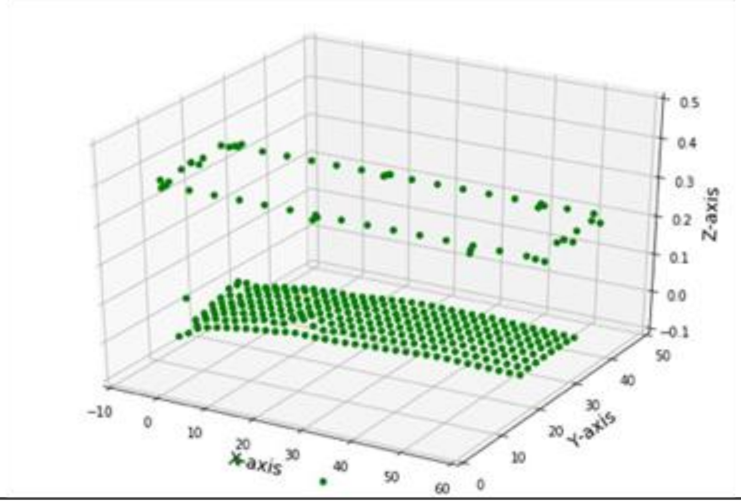


iVTX THERMO-MECHANICS

- **iVTX concept**: All-silicon CMOS ladder
- Multichip CMOS thinned ladders produced with different thickness and geometries
- First ladders characterized: Homogeneous thickness over 10 cm^2 area (with some outliers)

Thinned Ladder (units in mm)		
Frame	Nominal thickness	0.428 ± 0.008
	Planarity	0.01647
Center	Nominal thickness	0.09 ± 0.04
	Planarity	0.0176
	Length/Width	71.0638 ± 0.0009 15.9730 ± 0.0016

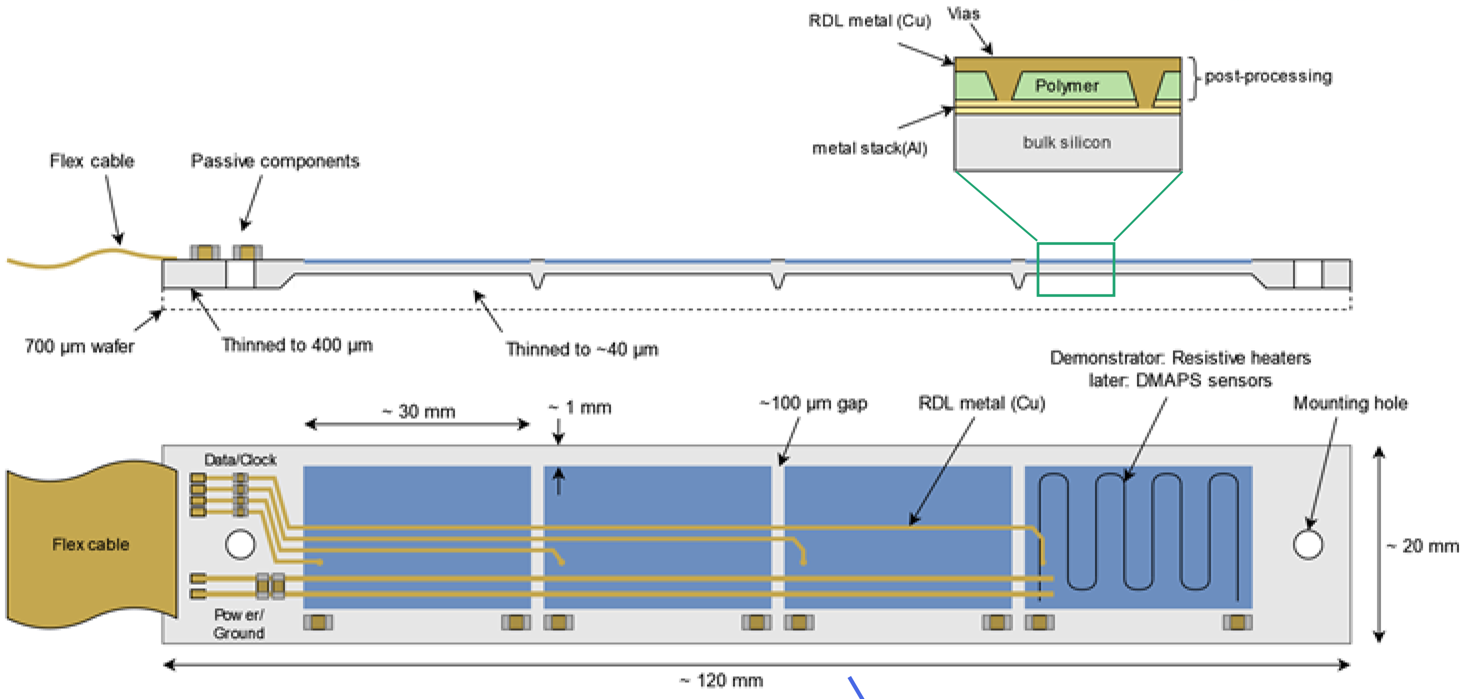




iVTX DEMONSTRATOR

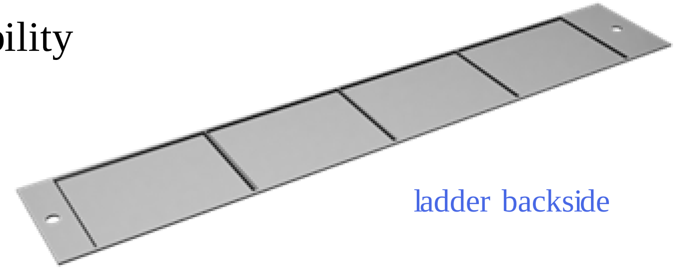
All-silicon ladder:

- Single piece of silicon
- 4 sensors per ladder
- Re-distribution layer (RDL) for data, power
- Selective thinning of active areas to ~ 40 µm

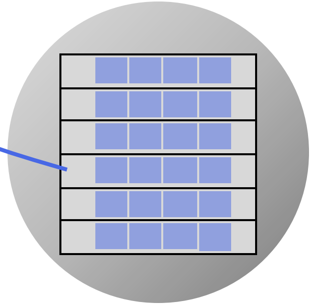


Goals for the demonstrator:

- process evaluation (RDL and thinning)
- thermal studies (resistive heaters instead of sensors), mechanical stability
- signal quality, power delivery, component assembly



ladder backside

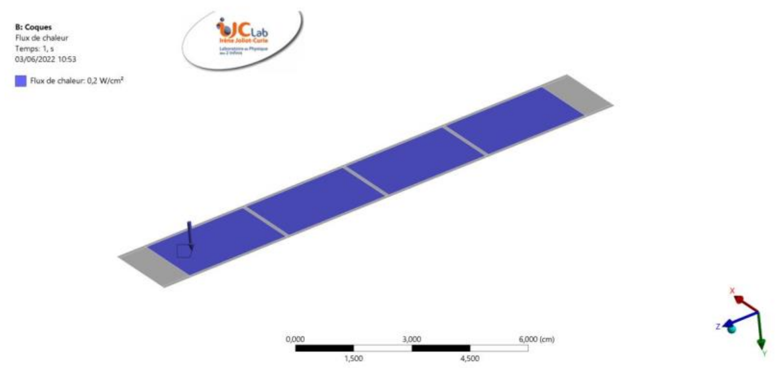


200 mm wafer

IZM (Berlin) will produce the first dummy wafers: Design RDL and establish the process

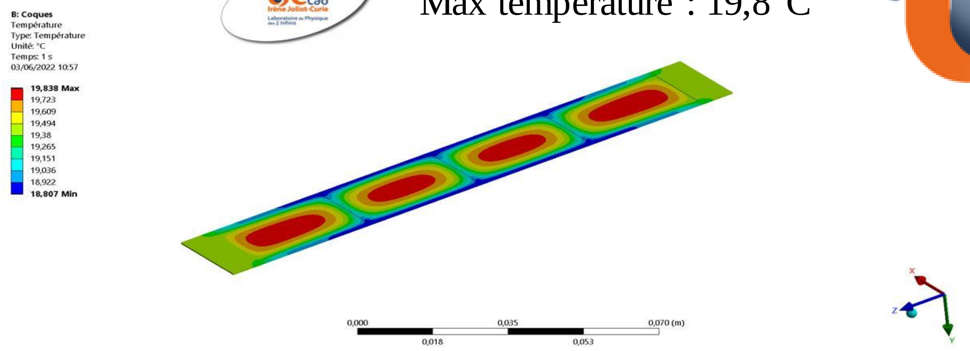
iVTX THERMO-MECHANICS STUDIES

Basic Modeling:
- Isolated single ladder
- Power uniformly distributed with density : 0.2 W/cm²

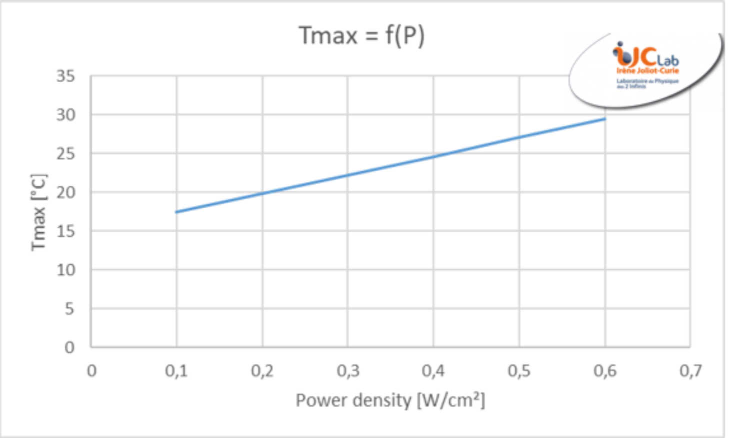


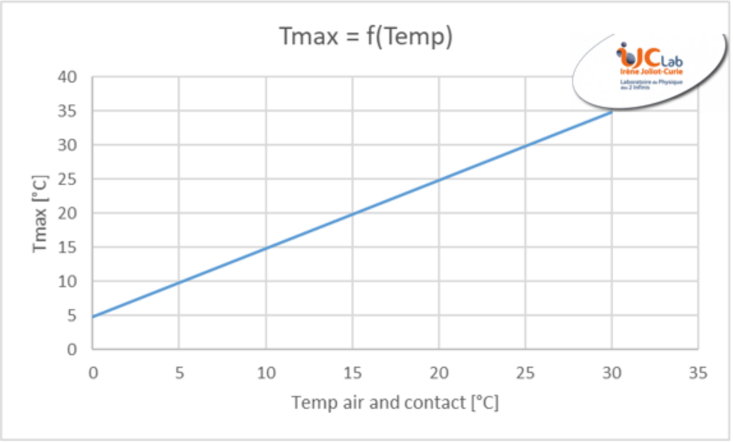
Dry air cooling
(air temp. **15 °C**)

Max temperature : 19,8°C



Our study so far shows that the air cooling is sufficient though, it depends strongly on the detail of the geometry. More detailed study is to follow. We also found that the thermal contact cooling (cooling block on the sides of the ladder) is not useful as the sensor is too thin to have enough thermal convection.





J. Bonis- IJCLab – Paris

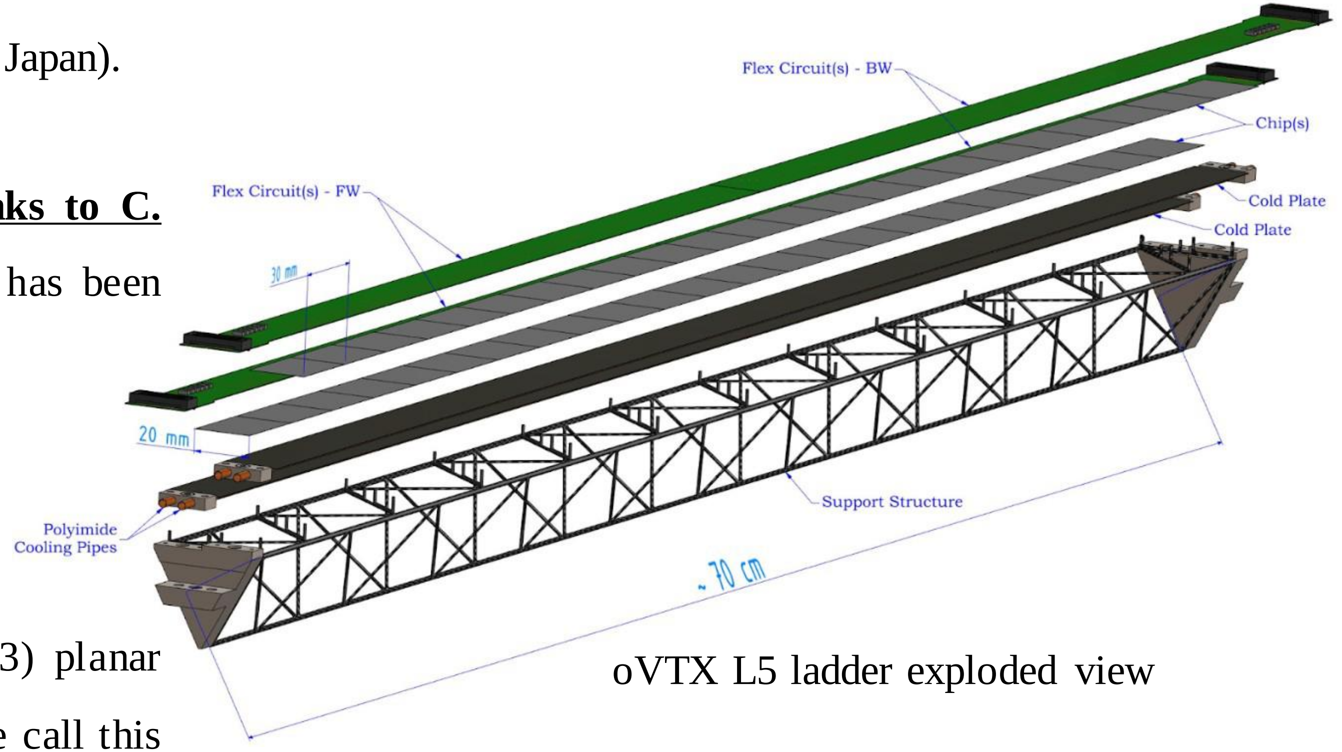
oVTX L5 REQUIREMENTS & DESIGN

The thermo-mechanical requirements of the L5 structure are:

- Physical and chemical stability over time: e.g., capability to cope with thermal variations
- Capability to cool sensors: maximum power density to be considered 200 mW/cm^2
- High dynamic stability due to earthquakes (High rates in Japan).

The ladder design of the ALICE ITS UPGRADE, **many thanks to C. Gargiulo and his team** for the precious job done and shared, has been adopted.

The Belle 2 L5 demonstrator has been realized gluing three (3) planar carbon fiber plates obtained by a micro waterjet technology. We call this method as the **"subtractive method"**.

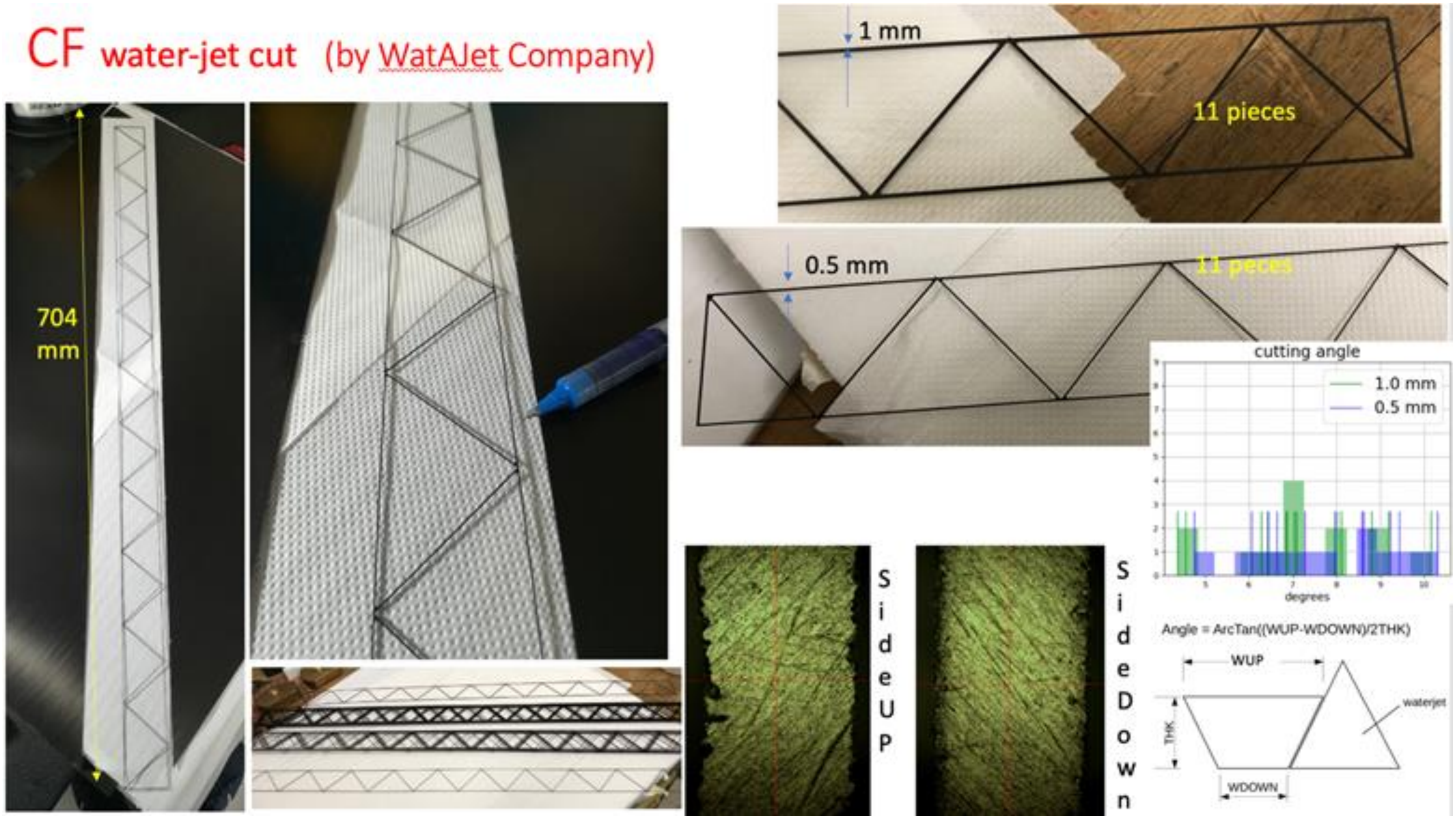


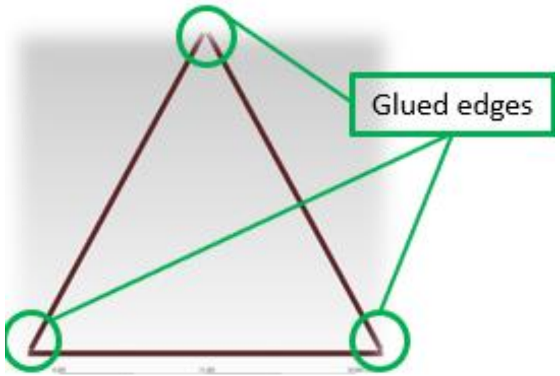
oVTX L5 ladder exploded view

THE "SUBTRACTIVE METHOD"

Starting from some M46J UD prepreg plates we have obtained the three structures needed for the L5 truss.

The M46J was laminated with 4 symmetrical plies (0-90-90-0) 0.5 mm-thick and then a metrological survey was done before gluing.

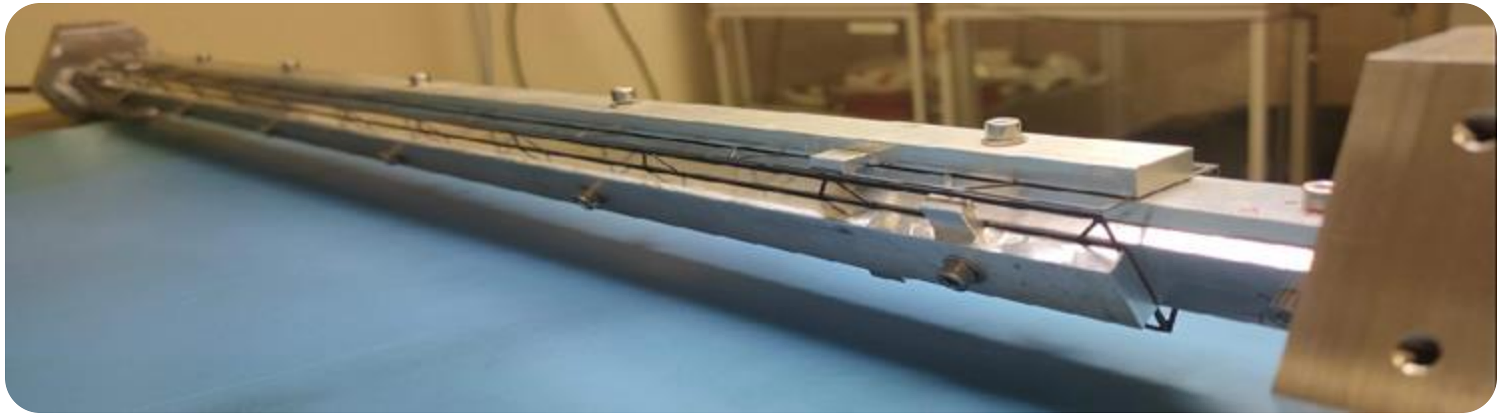


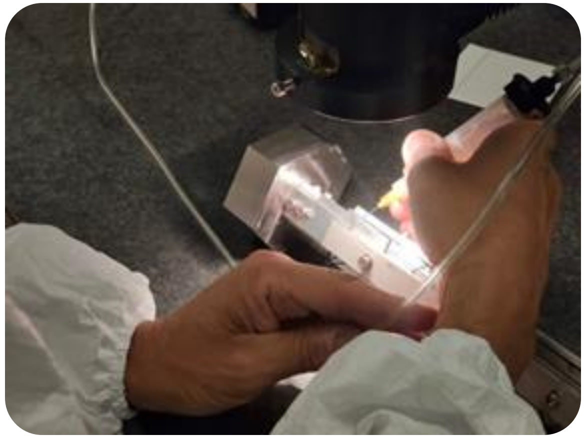


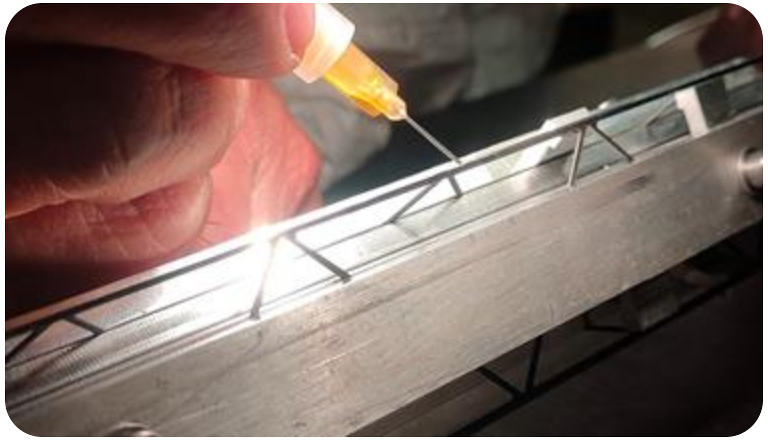
The cutting jet is not orthogonal, and the conical shape can be seen under an optical CMM also in a 0.5 mm-thick plate.

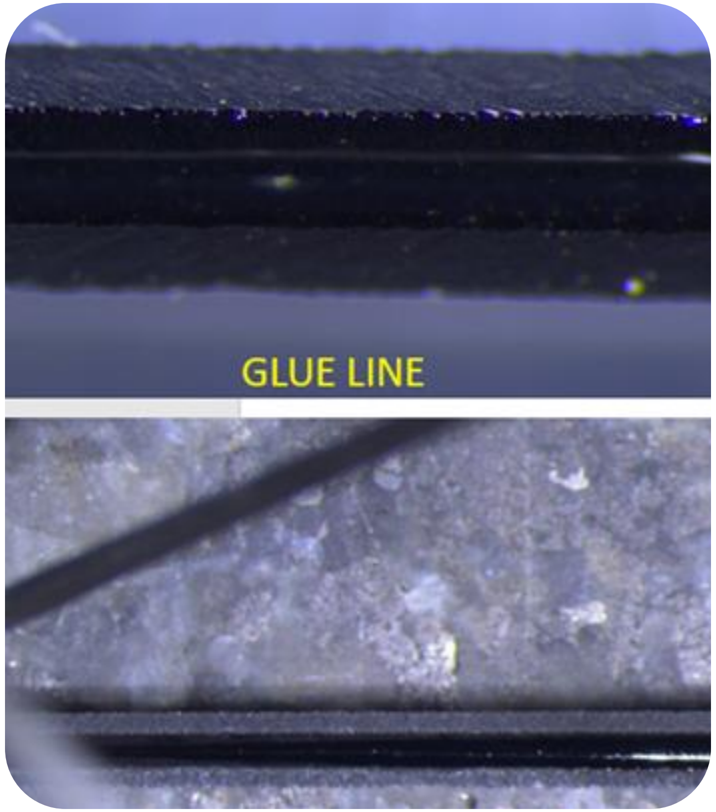
GLUING JIG

- An aluminum gluing mask has been used to assemble the 3 CF plates in their final position.
- Araldite 2011 with manual gluing was used
- **NO** gluing issues to report







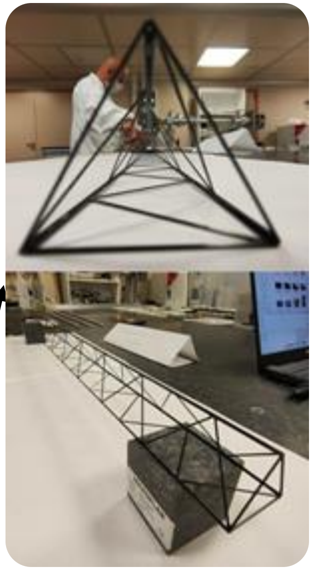


L5 TRUSS ASSEMBLY

After glue's curing and the removal of the truss from the mask, two peek end pieces have been manually glued (Araldite 2011) at the two ends.

The end pieces are the two mechanical interfaces to assemble the L5 inside Belle 2 (outside the sensitive region)

Two other truss was realized with 3D printed end pieces using ABS plastic



The total weight of the 704 mm length carbon fiber truss is about **5.8 g**.

The glue accounts for **0.36 g** (~6 %).

The weight of the peek end pieces is around **9.7 g each**

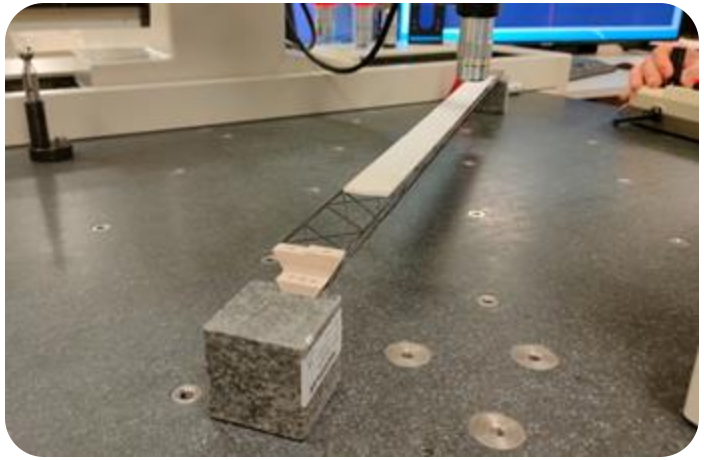
oVTX L5 Mechanical structure prototype

The truss is ready for characterizations

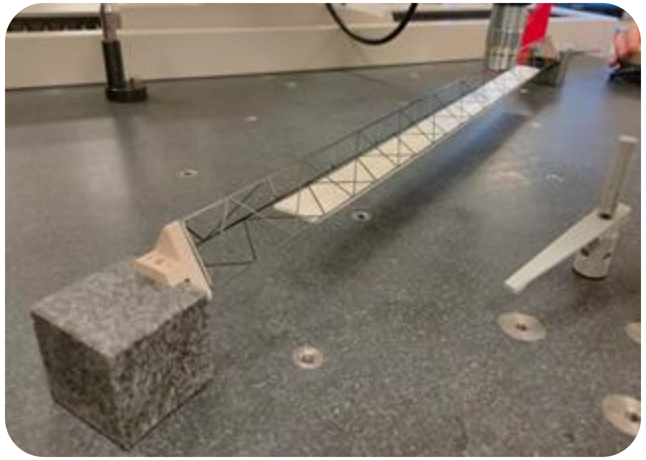
L5 FLEXURAL TESTS

Bending test: Simply supported beam and optical inspection with CMM Mitutoyo BHN 607 with no contact method (precision on Z coordinates with focus technique + 5 μm)

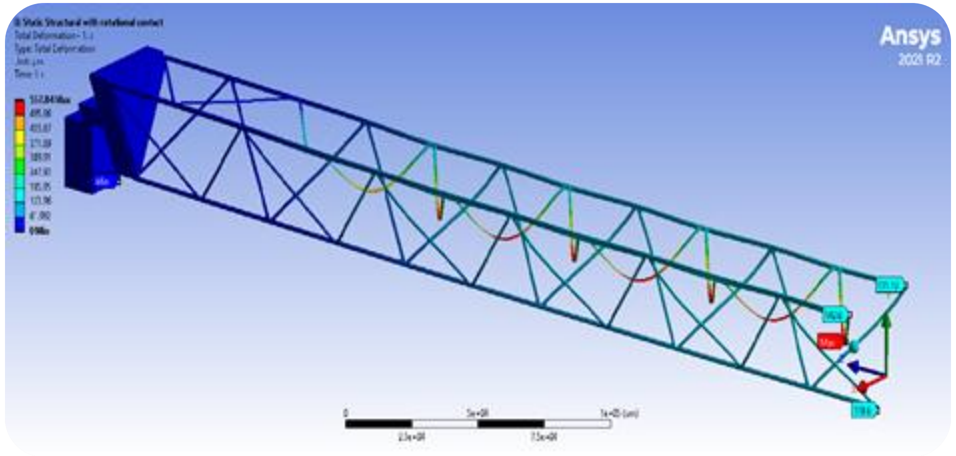
Test with load @ 0°



Test with load @ 180°



Ansys simulation



In order to simulate the weight of the estimated 60 grams of the sensor and the flex a piece of rubber has been used.

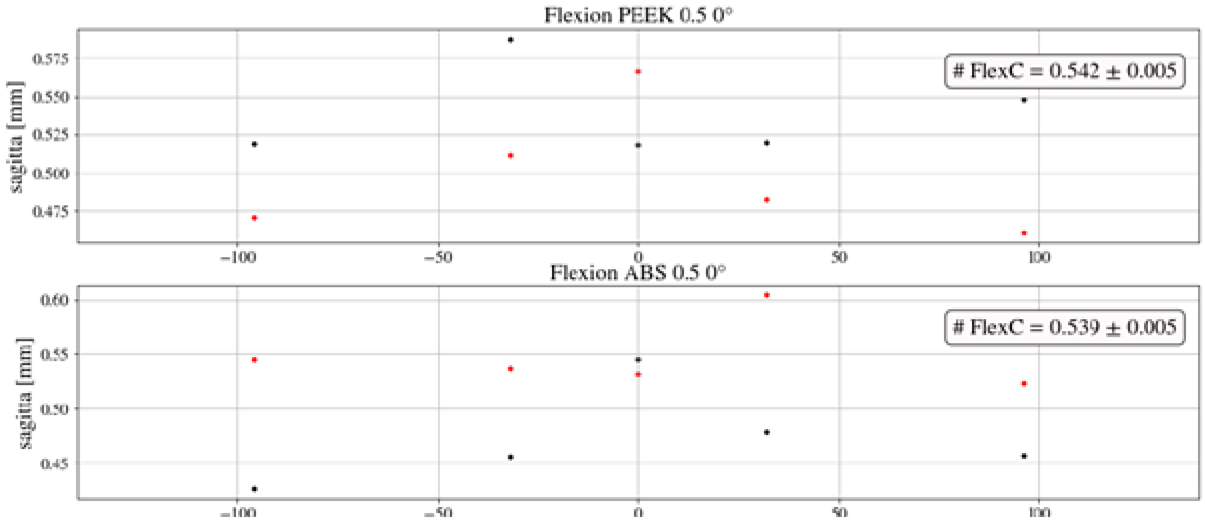
(Knowing the density of the rubber, the length of the load was 525 mm while the length of the truss is 700 mm)

The choice is conservative because a load distributed over the entire length would lead to a smaller sagitta.

L5 FLEXURAL TEST RESULTS

The **metrological survey** with optical inspection has been done taking the z coordinate of 5 points, from – 100 mm to + 100 mm, to the center point in both sides of the truss.

The maximum sagitta of the 0.5 thick truss is ~ **0.542 mm**

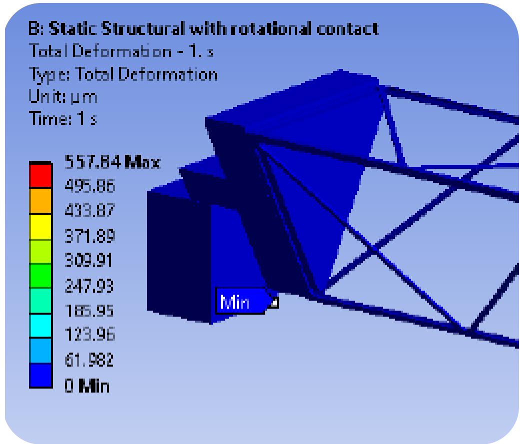


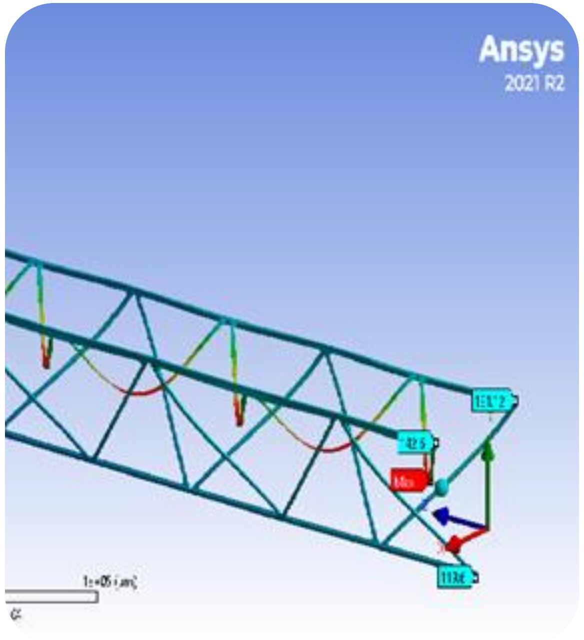
This discrepancy (probably) is due to:

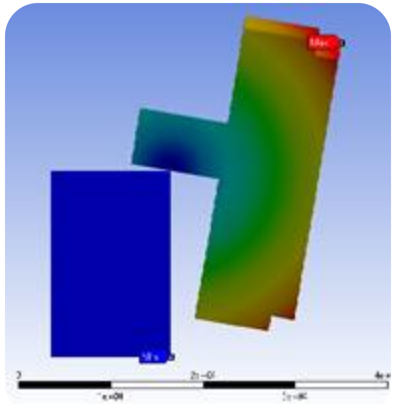
- Ideal VS real characterization of the CF material
- Idealization of the glue lines in Ansys
- Internal stresses and deformation due to the plate's gluing

Using **Ansys ACP** to characterize the CF

The maximum sagitta of the 0.5 thick truss is ~ **0.560 mm** in the middle of the truss but… **0.142** mm and **0.131** mm where the optical inspection has been done







L5 VIBRATIONAL TEST

The Vibrational qualification is mandatory to stay well above the typical earthquake frequencies (requirement > 20 Hz).

Furthermore, the VTX ladder will not assembled on KEK site, so it's important to perform a vibrational run with the power spectrum (g^2/Hz) provided by the transport company (Air and truck).

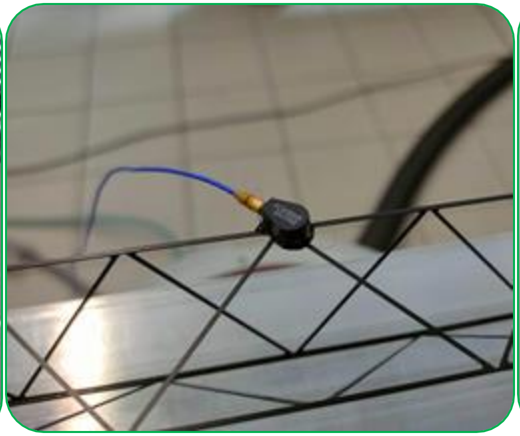
A preliminary test in the Z direction was performed @ INFN Pisa with our Vibrational Test System Tira-VIB TV 5220-120.

A specific fastening system to connect stiffly the truss to the shaker, aluminum made, was designed by INFN-Pisa and machined in our mechanical workshop.

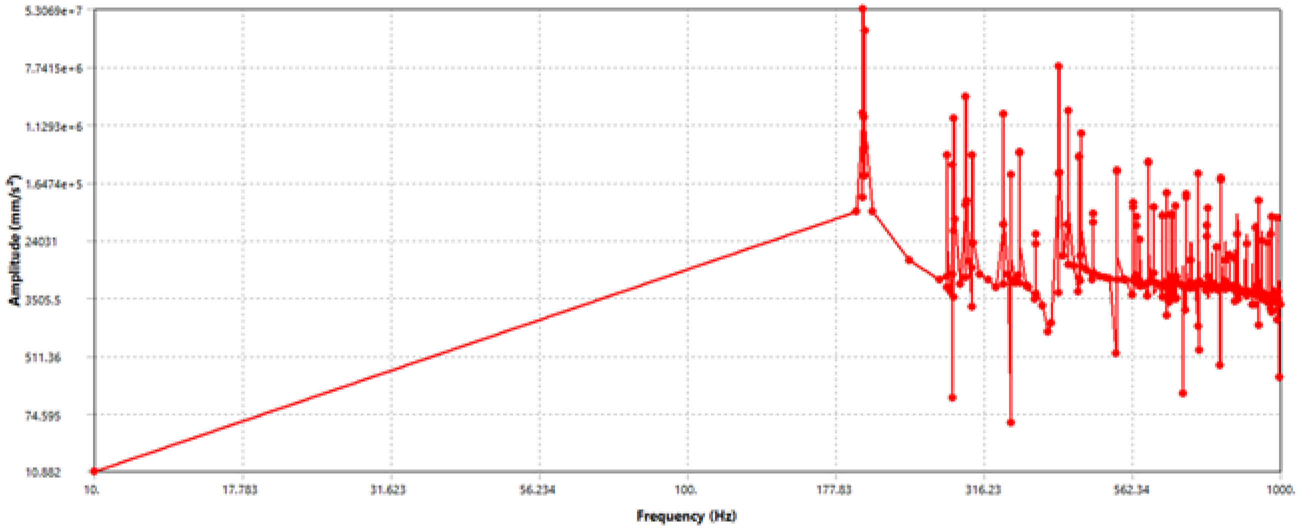
Inputs of the run, same of the test of the Belle 2 L5:

- 0.6 g^2/Hz ⇨ Amplitude coming from past experiences
- 10 < Hz < 1000 ⇨ Frequencies range

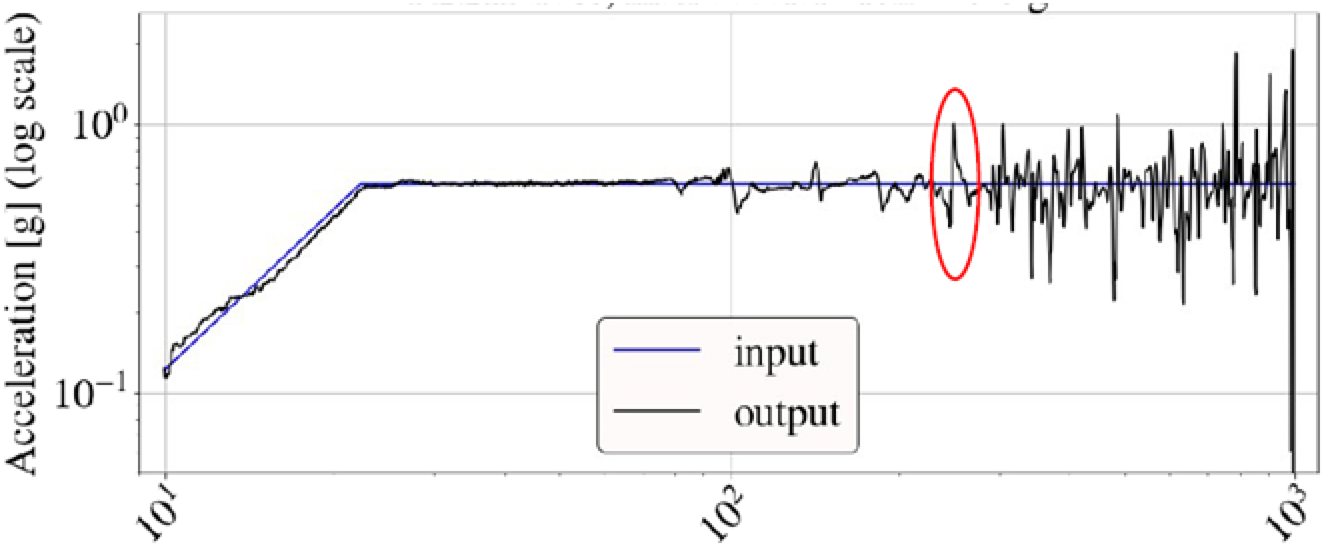





L5 VIBRATIONAL TEST RESULTS



First resonance frequency expected from an **Ansys simulation:** ~ 200 Hz



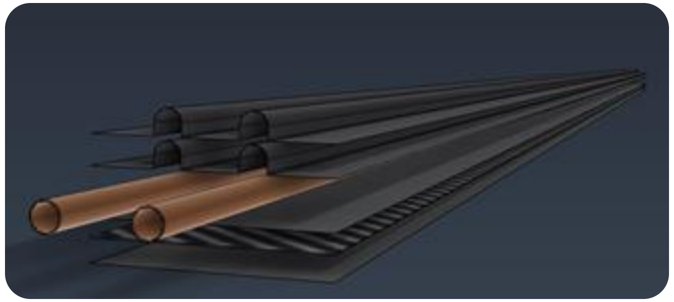
First resonance frequency from **test:** ~ 250 Hz

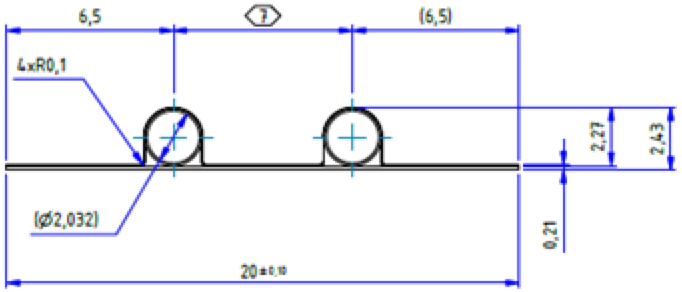
Quite good results but we must further investigate in the three direction with an external service.

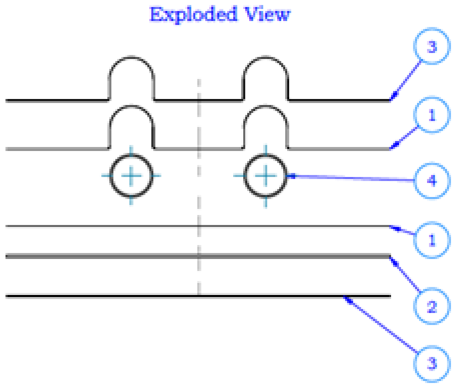
However, the first frequency is much bigger than the earthquake ones!

L5 COLD PLATE THERMAL TEST

The cold plate designed for the cooling of the VTX L5 is quite similar to the one designed for the ALICE ITS UPGRADE.







Pos.	Description
4	Kapton tube
3	Th=0.02 - FAW 8g/m2 Carbon fleece layer
2	Th=0.12 - FAW 120g/m2 Cyanate ester UNI-directional CFRP prepreg (EX1515/M60J)
1	Th=0.025 Graphite layer

The objective of the test is to understand the behavior of the cold plate ranging the power density from 20 mW/cm^2 to 200 mW/cm^2

Tests Targets:

- T_{sensor} **< 50 °C**
- Maximum longitudinal thermal gradient **< 5 °C on each sensor**

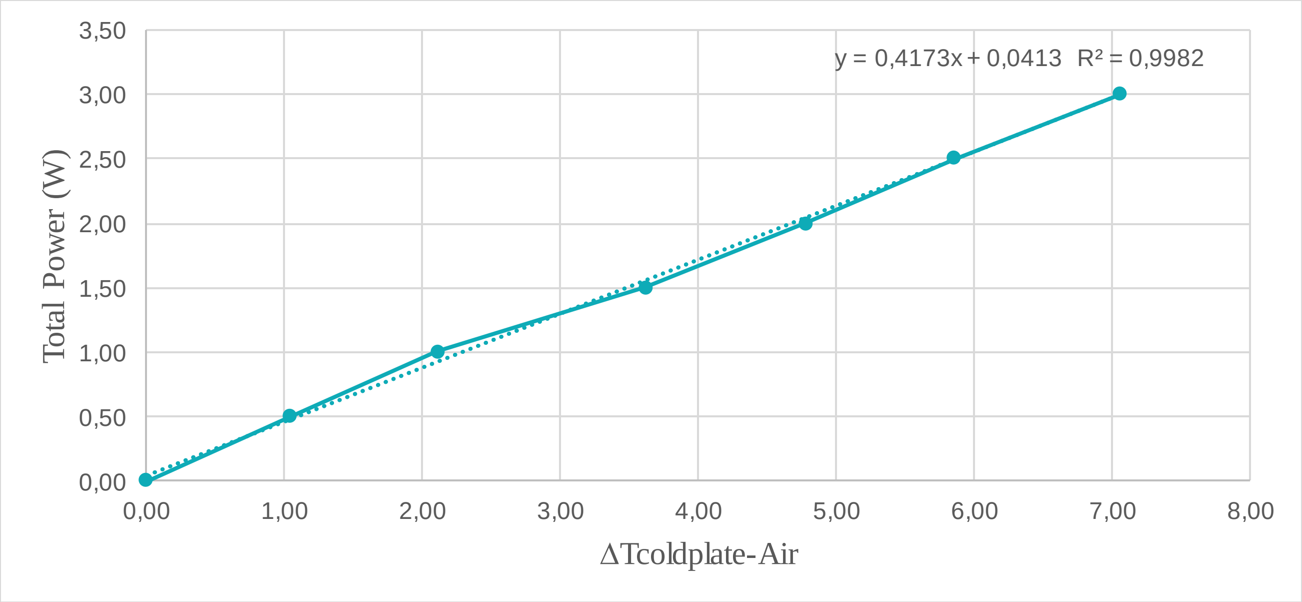
The thermal load has been simulated with 3 Kapton heaters, 290 mm x 30 mm each, assembled using a grease with a thermal conductivity close to Araldite 2011's one (0.3 W/mK).

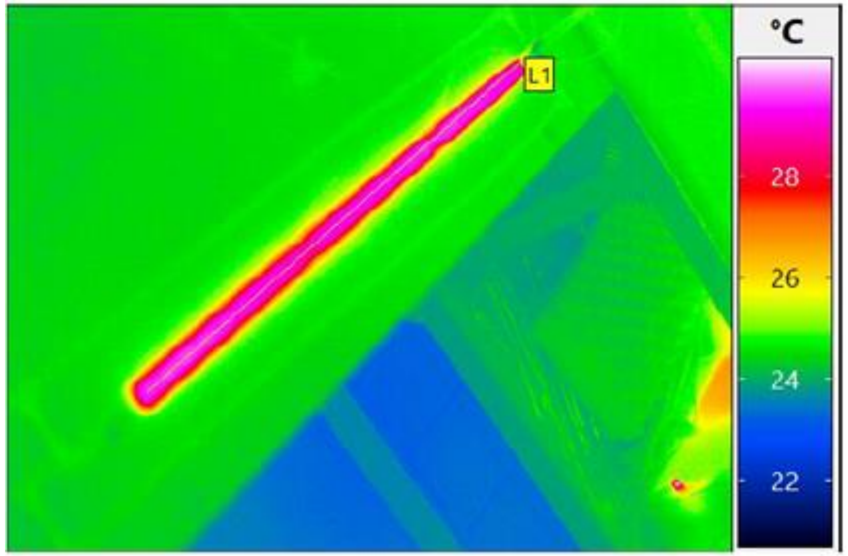
The coolant used is demineralized water.

Single heater's Area (cm^2)	*Total heated Area (L5) (cm^2)*	*Power Density (mW/cm^2)*	*Total Power (W)*
46,00	138,00	20,00	2,76
		40,00	5,52
		60,00	8,28
		80,00	11,04
		100,00	13,8
		120,00	16,56
		140,00	19,32
		160,00	22,08
		180,00	24,84
		200,00	27,6

L5 COLD PLATE DRY TEST

The DRY test with no coolant flowing is useful to evaluate the thermal exchange between Cold plate and Air ($\Delta T_{coldplate}$-Air @ the equilibrium) – **Heat load dissipated to Air** in natural convection conditions

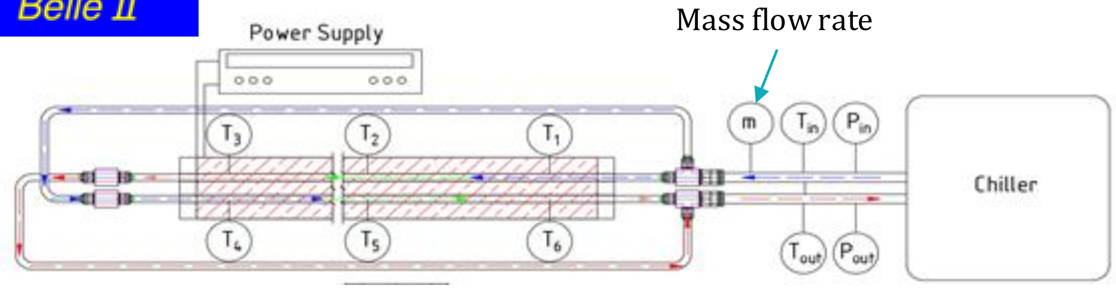




With a total power of 2 Watts the temperature gradient between cold plate (average temperature) and air is near to 5 °C.

e.g., When cooling the ladder, if the total Power is P and the final gradient is 5 degrees, **2 W** are taken away with **natural convection** and (P – 2W) is the power evacuated by the liquid coolant.

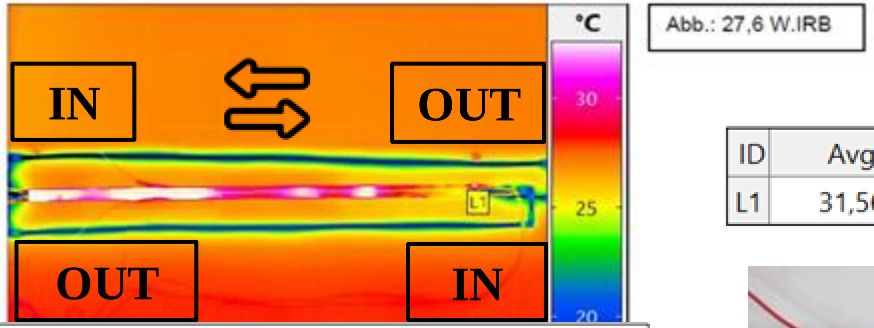
L5 COOLING TEST- 1ST RUN - ⇆

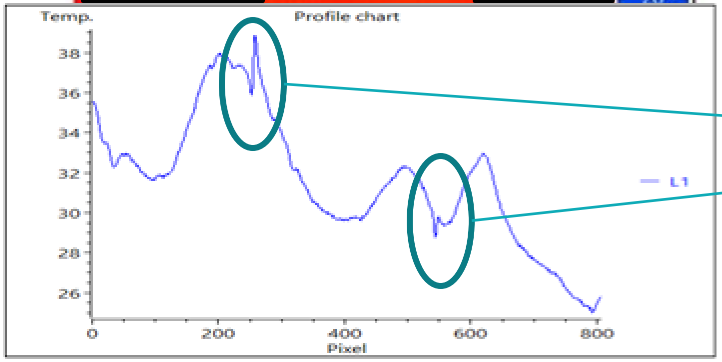


Case: δ = 200 mW/cm² ⇨ Total power 27.6 W

Operating conditions:

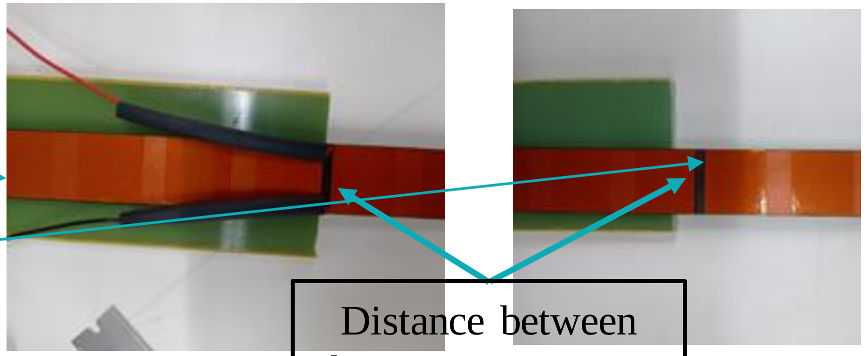
- Cold flow from both sides (FW and BW)
- P_{in} ~ 0 bar – P_{out} ~ -0.19 bar ⇨ Leak-less configuration
- T_{in} ~ 10 °C
- m ~ 0.44 ÷ 0.45 kg/min
- Power density ranging from 20 mW/cm² to 200 mW/cm²
- Ambient temperature too high (**27 °C**) but stable (±1 °C). Big issue on lab air conditioning





Data taken in the middle line L1

ID	Avg	Min	Max	Span	SDev
L1	31,56	24,99	38,86	13,87	3,22



Distance between heaters: ~ 2÷3 mm

- The requirement of T_{max} was completely met
- Too high longitudinal thermal gradient

BUT…

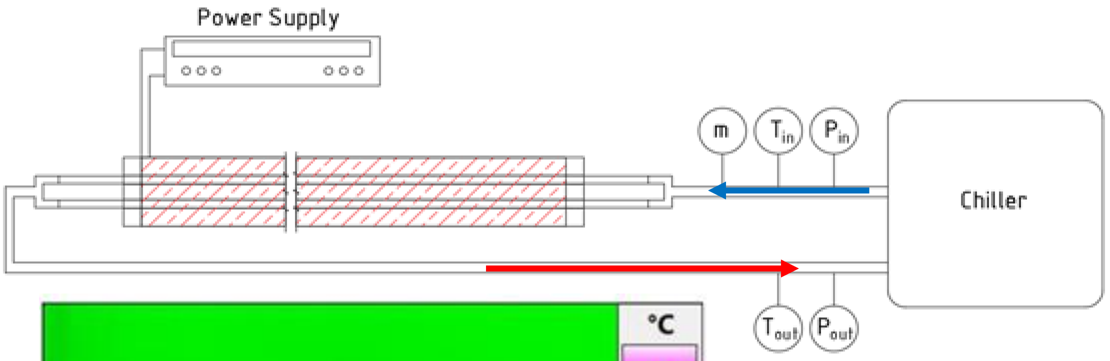
Why the temperature profile is not left-right symmetric?

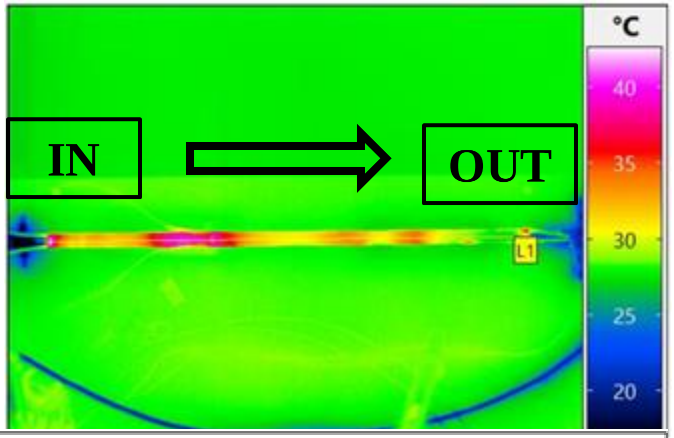
Probably this discrepancy is caused by the thermal interface (thermal grease not properly dispensed, quite difficult to apply the correct pressure without an appropriate jig)

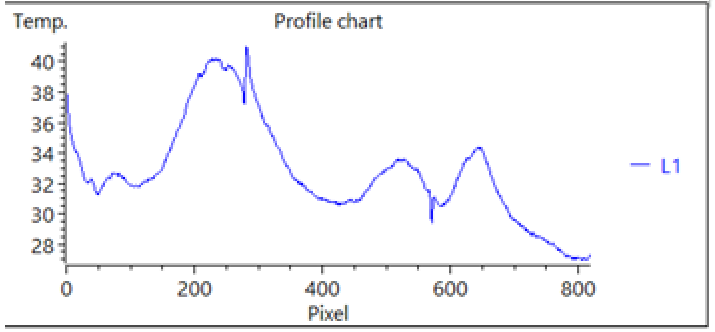
L5 COOLING TEST- 2ND RUN - ⇨

Simplified cooling loop in order to evaluate the thermal interfaces between cold plate and Kapton heaters

Case: δ = 200 mW/cm^2 ⇨ Total power 27.6 W







Operating conditions for unidirectional flow:

- Flow from one side (Inlet is the same of the previous test)
- Pressure, temperature and mass flow are the same of 1st run
- Power density ranging from 20 mW/cm^2 to 200 mW/cm^2

Data taken in the middle line L1

ID	Avg	Min	Max	Span	SDev
L1	32,77	26,97	40,95	13,98	3,30

Same temperature profile of the 1st run

↓

What happens swapping inlet and outlet?

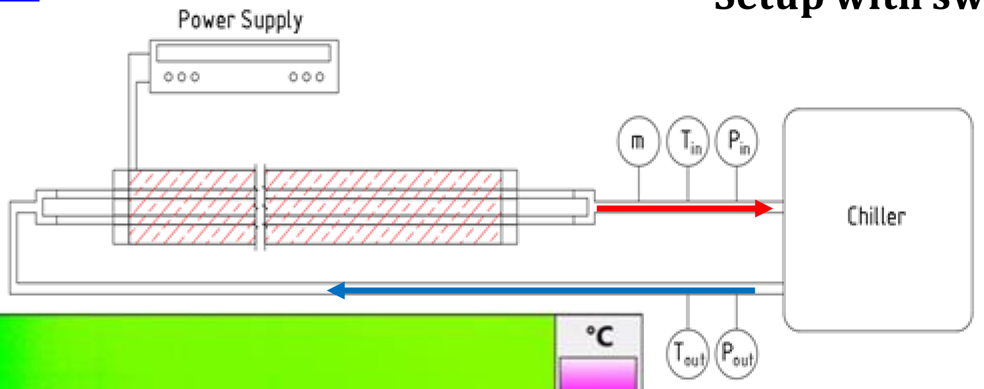
↓

If the temperature profile will remain the same, probably, the problem is really in the thermal interfaces

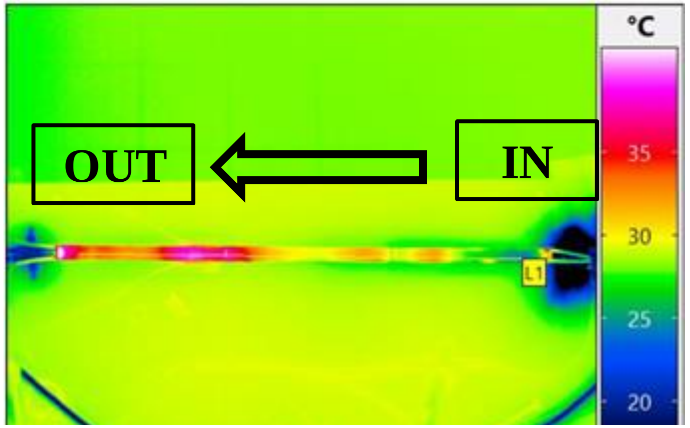
Total power 0 W ⇨ T_{amb} ~ 27 °C

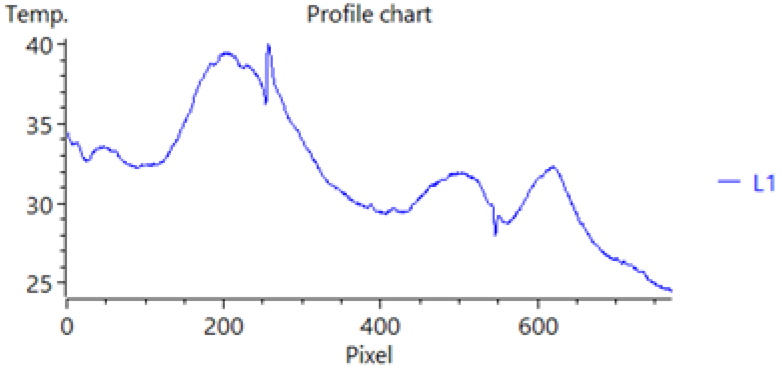
L5 COOLING TEST- 3RD RUN - ⇦

Setup with swapped input and output



Case: δ = 200 mW/cm² ⇨ Total power 27.6 W





Operating conditions for unidirectional flow:

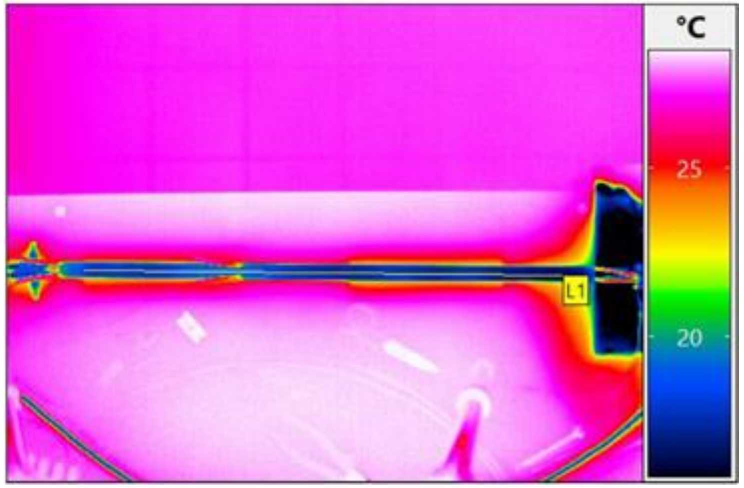
- Flow from one side (Inlet swapped with outlet)
- Pressure, temperature and mass flow are the same of 1st run (and 2nd run)
- Power density ranging from 20 mW/cm² to 200 mW/cm²

Data taken in the middle line L1

ID	Avg	Min	Max	Span	SDev
L1	31,81	24,39	40,00	15,61	3,69

The temperature profile is **roughly the same** and this means a different behavior of the thermal bridge along the cold plate

Total power 0 W ⇨ T_{amb} ~ 27 °C



SUMMARY

- Belle II experiment is considering a **vertex detector upgrade in 2026/27**
- **All-layer monolithic** vertex detector upgrade (**VTX**):
  - more performant and resilient against higher machine backgrounds
- **OBELIX**: First steps towards a Belle II CMOS sensor **submission in autumn 2022**
- Realization of prototypes and characterizations of inner/outer layers ongoing:
  - iVTX ladder demonstrator on-going
  - iVTX thermal simulation is promising
  - oVTX L5 mechanical, vibrational and thermal characterization done and the preliminary results are within spec's
  - oVTX L3 & L4 design on-going
- VTX CDR foreseen by the end of 2022.

BACKUP

L5 RADIATION LENGTH SPREADSHEET

Layer 5 Radiation length

SUPPORT STRUCTURE

Component	Qty	Volume (mm^3) from cad	Width (mm)	Length (mm)	Equivalent thickness (mm)	Material Radiation length (cm)	Equivalent radiation length (%)
CF Reticular structure M60J + "C"	1	4049,7	36	700	0,161	26,08	0,062%

COLD PLATE

Component	Qty	Volume (mm^3) from cad	Total volume (mm^3)	Nominal Thickness (mm)	Width (mm)	Length (mm)	Equivalent thickness (mm)	Material Radiation length (cm)	Equivalent radiation length (%)	Total
Carbon fleece (upper)	2	374	748	0,020	39	700	0,027	106,8	0,003%	0,066%
Graphite paper	2	523,073	1046,146	0,025	39	700	0,038	26,56	0,014%	
K13D2U	2	1689,6	3379,2	0,120	39	700	0,124	26,08	0,047%	
Carbon fleece (lower)	2	281,6	563,2	0,020	39	700	0,021	106,8	0,002%	

PIPES & COOLANT

Component	Qty	Inner diameter (mm)	Outer diameter (mm)	Cross section (mm)	Length (mm)	Total Volume (mm3)	Width (mm)	Equivalent thickness (mm)	Material Radiation length (cm)	Equivalent radiation length (%)	Total
Polyimide pipes (141-0083)	4	2,032	2,223	0,638	700	1786,326	39	0,065	28,41	0,023%	0,116%
Demineralized water	4	-	2,032	3,241	700	9075,595	39	0,332	35,76	0,093%	

GLUE

Position	Qty	Weight (g)	Glue density (g/cm3)	Total Volume (mm3)	Length (mm)	Width (mm)	Total Width (mm) with overlap	Thickness (mm)	Equivalent thickness (mm)	Material Radiation length (cm)	Equivalent radiation length (%)
Araldite 2011 between the 3 plates of the beams	1	0,36	1,1	327,27	700	x	39	x	0,012	33,5	0,004%
Araldite 2011 between cold plate and chips	2	x	x	1400,0	700	20	39	0,05	0,051	33,5	0,015%
Araldite 2011 between Chips and flex	2	x	x	1400,0	700	20	39	0,05	0,051	33,5	0,015%
Araldite 2011 between C pieces and CF structure	26			15,47	17	0,7	39	0,05	0,001	33,5	0,0002%
Araldite 2011 between C pieces and Chips	52			1,27	0,7	0,7	39	0,05	0,000	33,5	0,00002%
											0,034%

FLEX FW

Component	Material	Volume (mm^3) from cad	Width (mm)	Length (mm)	Equivalent thickness (mm)	Material Radiation length (cm)	Equivalent radiation length (%)	Total
PCB	Polyimide	1602,612	20	360,55	0,222	28,57	0,078%	0,148%
Signal and Power	Aluminum	105,626	20	360,55	0,015	8,897	0,016%	
Pixel Chips	Silicon	360,000	20	360,55	0,050	9,369	0,053%	

FLEX BW

Component	Material	Volume (mm^3) from cad	Width (mm)	Length (mm)	Equivalent thickness (mm)	Material Radiation length (cm)	Equivalent radiation length (%)	Total
PCB	Polyimide	1455,930	20	330,5	0,220	28,57	0,077%	0,144%
Signal and Power	Aluminum	82,249	20	330,5	0,012	8,897	0,014%	
Pixel Chips	Silicon	330,000	20	330,5	0,050	9,369	0,053%	

Layer 5 Radiation length summary

COMPONENT	X/X_0 (%)	
Support Structure	0,062%	0,244%
Cold Plate	0,066%	
Pipes & Coolant	0,116%	
Glue	0,034%	
Flex FW	0,148%	
Flex BW	0,144%	
Grand Total	0,570%	

oVTX FLEX

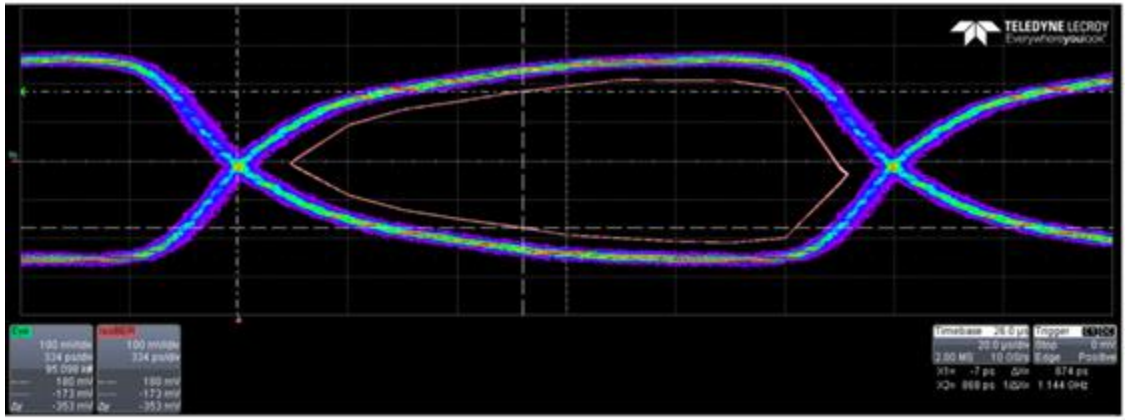
First prototype of the power and signal bus available (Cu flex)

The final prototype in Al, to minimize the material.

Testing ongoing:

- Verification of signal integrity at the far end
- Estimation of BER at 160 MHz
- First results are encouraging!

eye diagram @250 MHz (500 Mbit/s)-->



BER (Bit Error Rate) – Peggior occhio ogni 10^{19} - 10^{21} fronti d'onda

Frequenza in ingresso 250 MHz (OBELIX ~160 MHz)

Stima frequenza raggiungibile ~670 Mbits/s (stima conservativa)