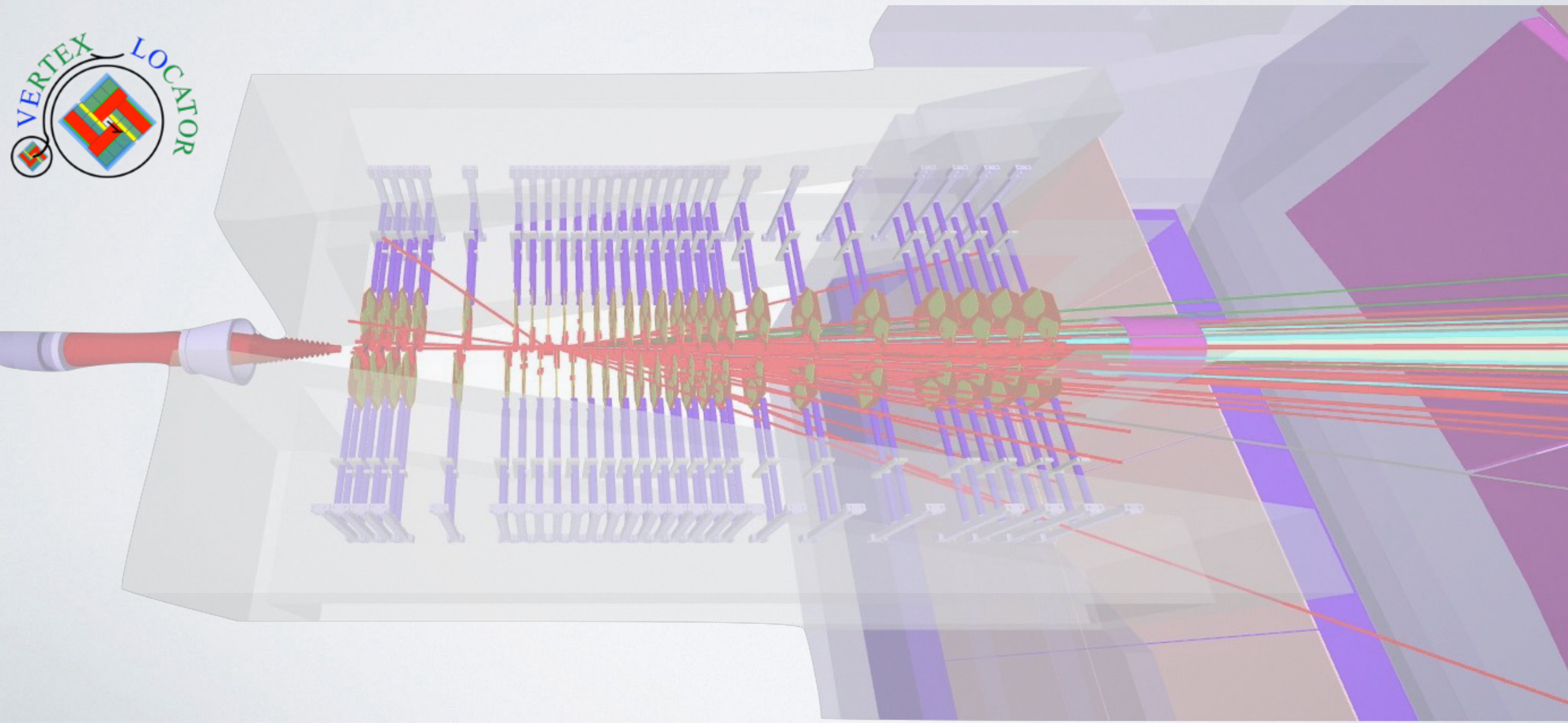
The LHCb VELO Upgrade

design, construction, installation

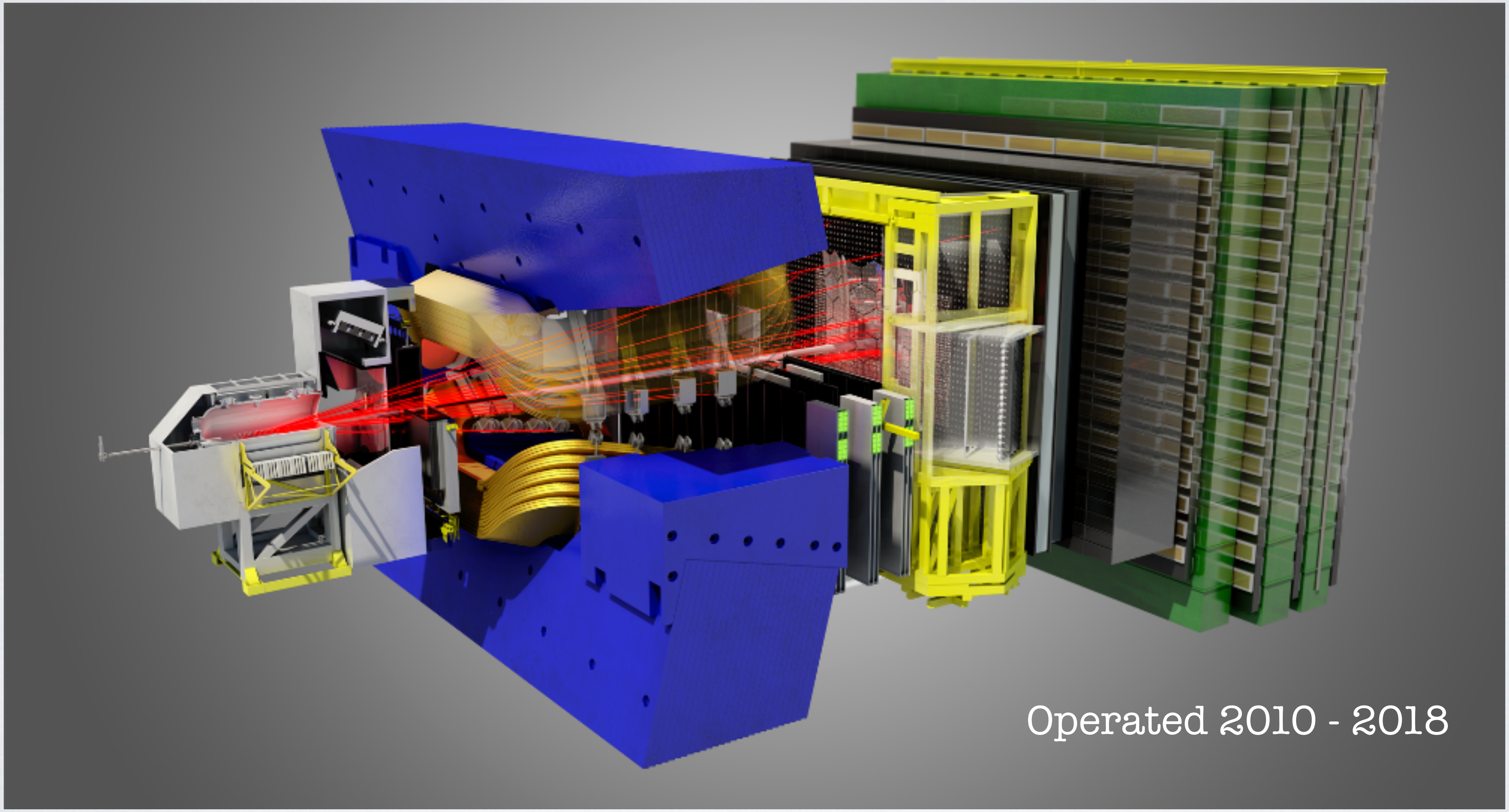
Stefano de Capua
on behalf of the LHCb VELO Group

CERN Detector Seminar
February 10th, 2023



Overview

LHCb detector / VELO Upgrade / Module design and construction / Detector installation and commissioning



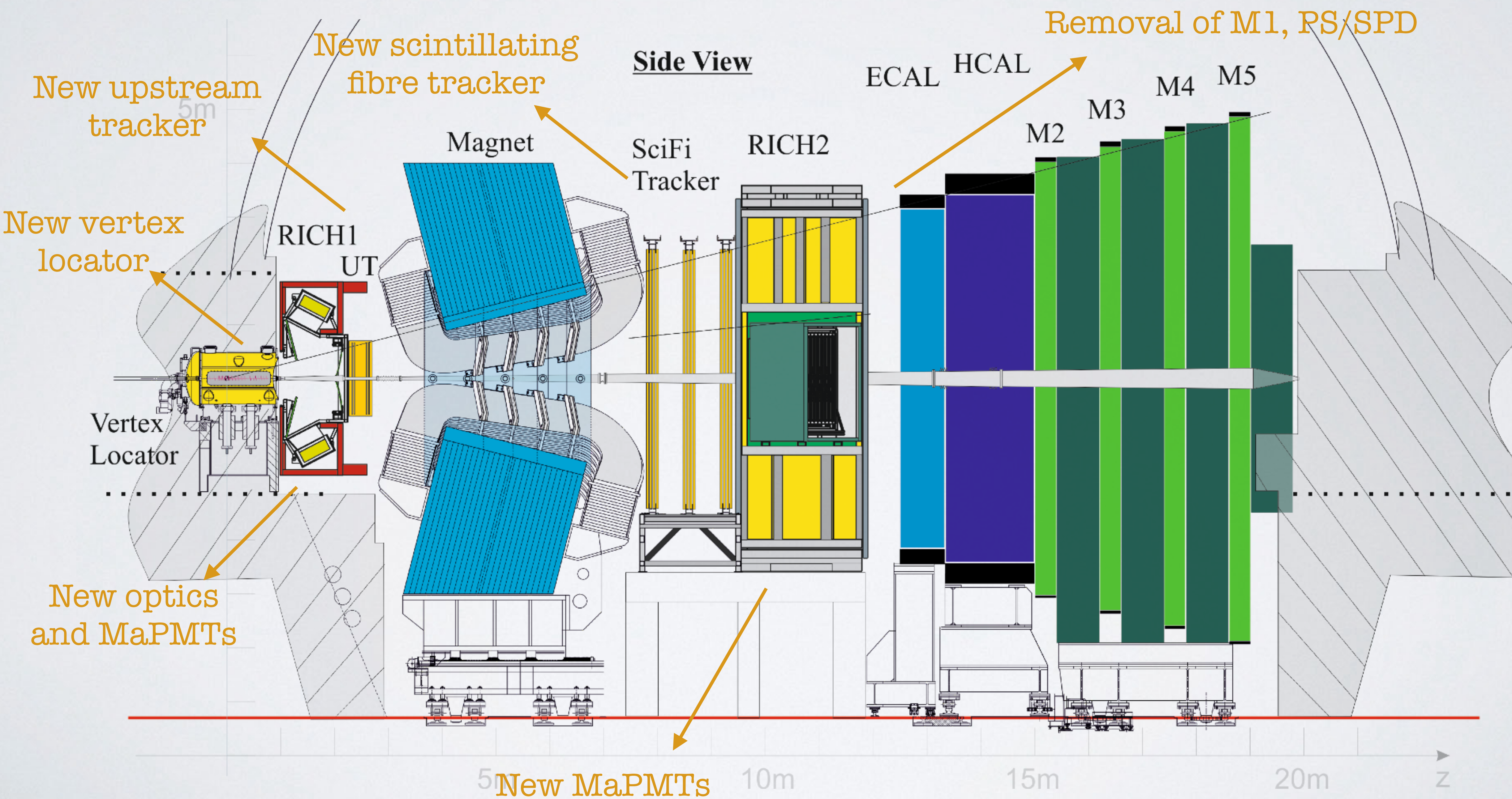
LHCb / VELO

LHCb is a single-arm forward spectrometer dedicated to the study of b- and c-physics.

- Increase luminosity to boost statistics: $4\times10^{32}\ cm^{-2}s^{-1}$ ➔ $2\times10^{33}\ cm^{-2}s^{-1}$
- $50\ fb^{-1}$ expected after LS2

VErtex LOcator is a silicon detector surrounding the collision region, providing excellent

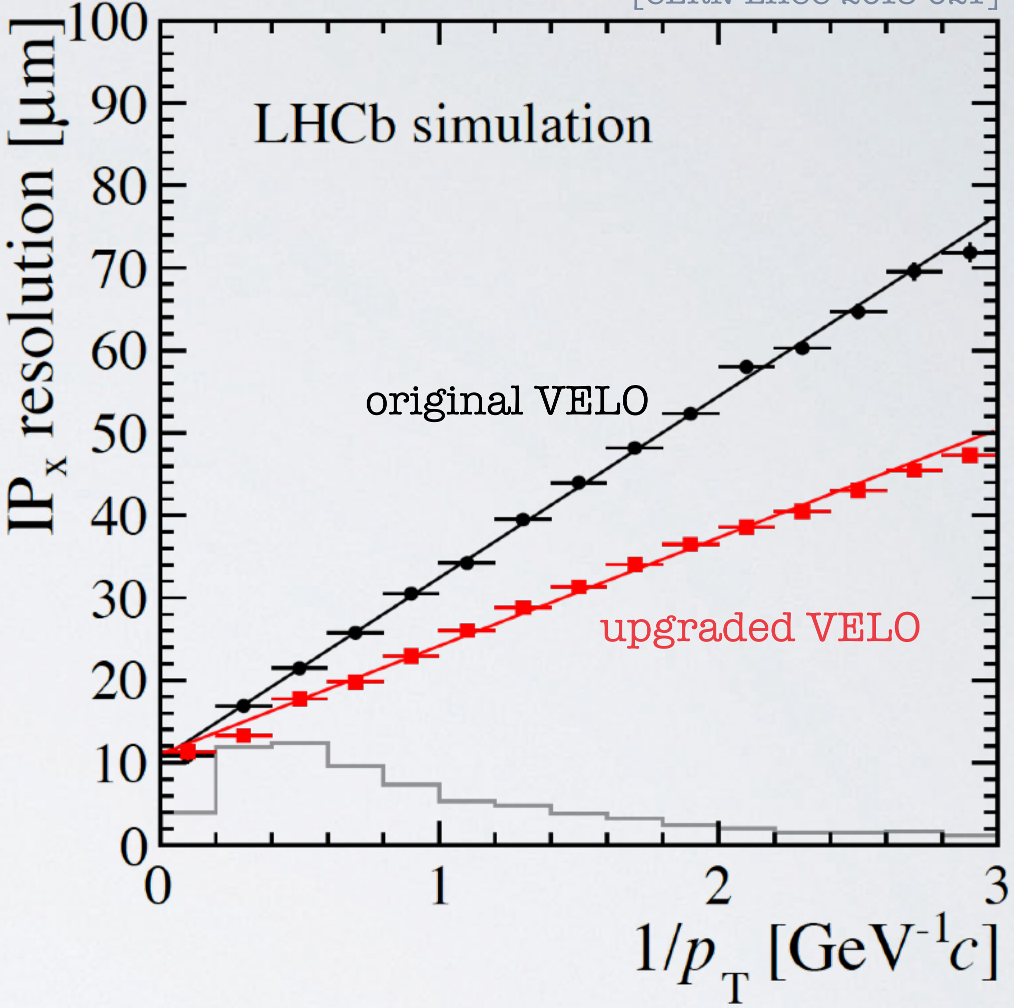
- impact parameter resolution / identification of secondary vertices
- Remove hardware trigger: 1 MHz ➔ 40 MHz readout rate



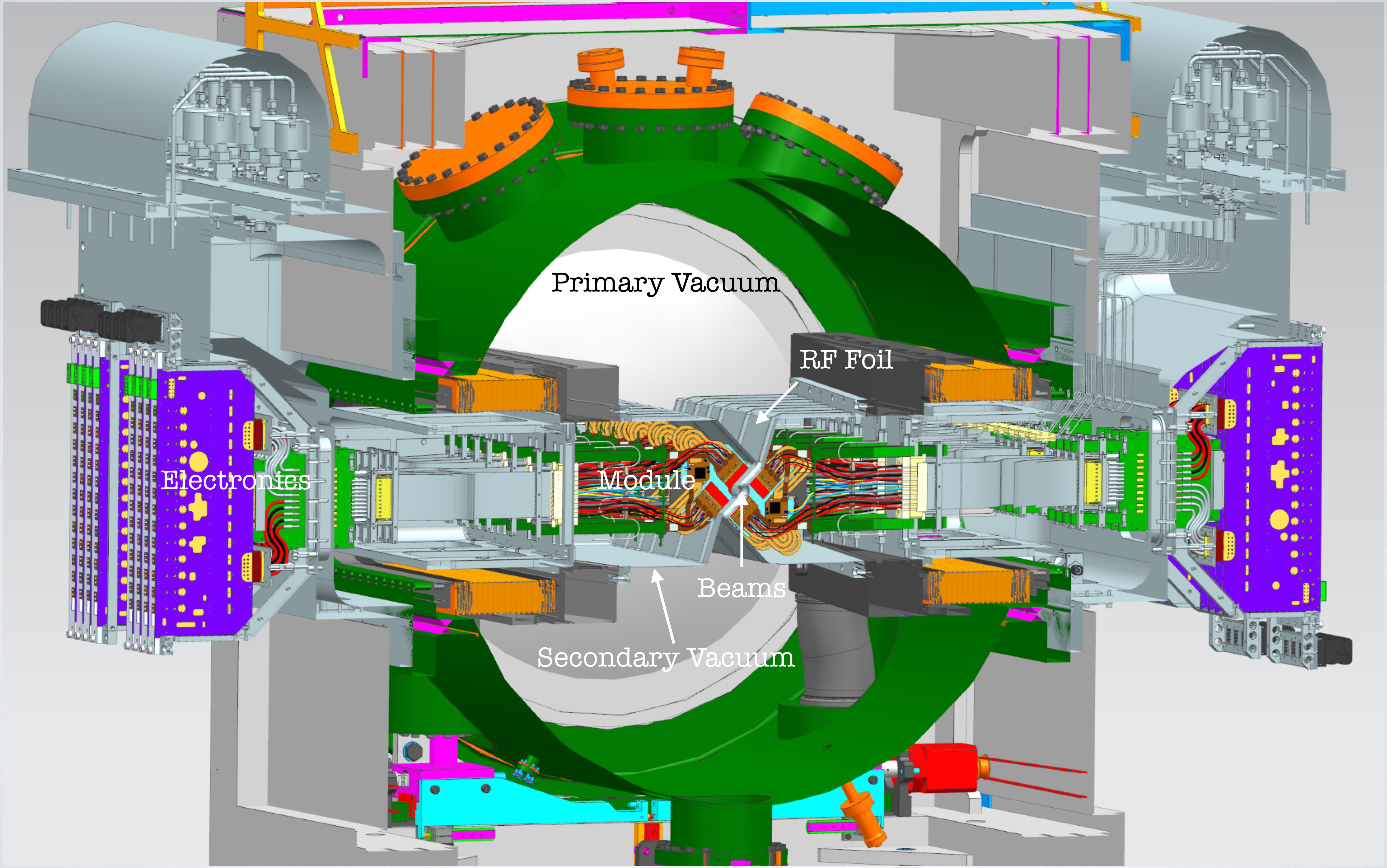
VELO Upgrade

- To be operated @ 40 MHz and $2x10^{33}$ $cm^{-2}s^{-1}$ and at 5.1 mm from the beams
  - 2.8 Tb/s data rates
  - 8×10^{15} 1MeV n_{eq} cm^{-2} max fluence
  - sensors to be kept < -20 °C
- Improve detector performance
  - track reconstruction
  - resolution
- The plan:
  - new pixel detector
    - no ghost tracks
    - faster reco algorithm
  - new front-end electronics
  - thinner RF-foil
  - more efficient cooling interface

[CERN-LHCC-2013-021]



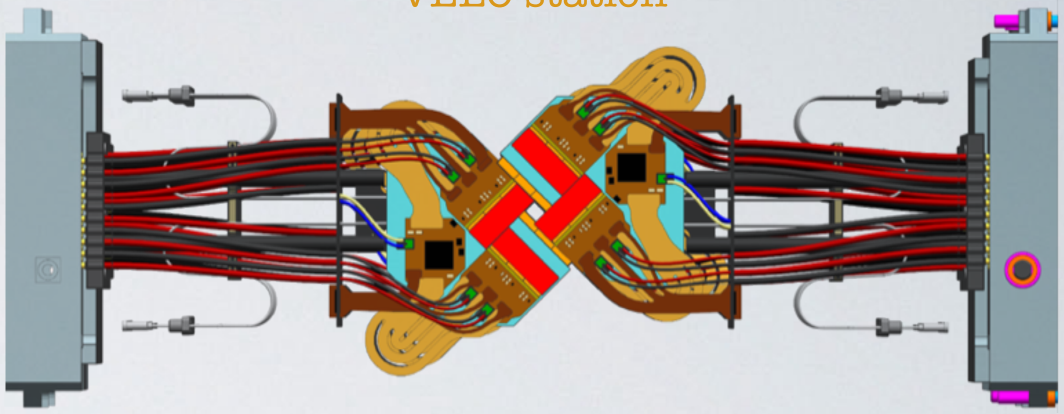
VELO Upgrade



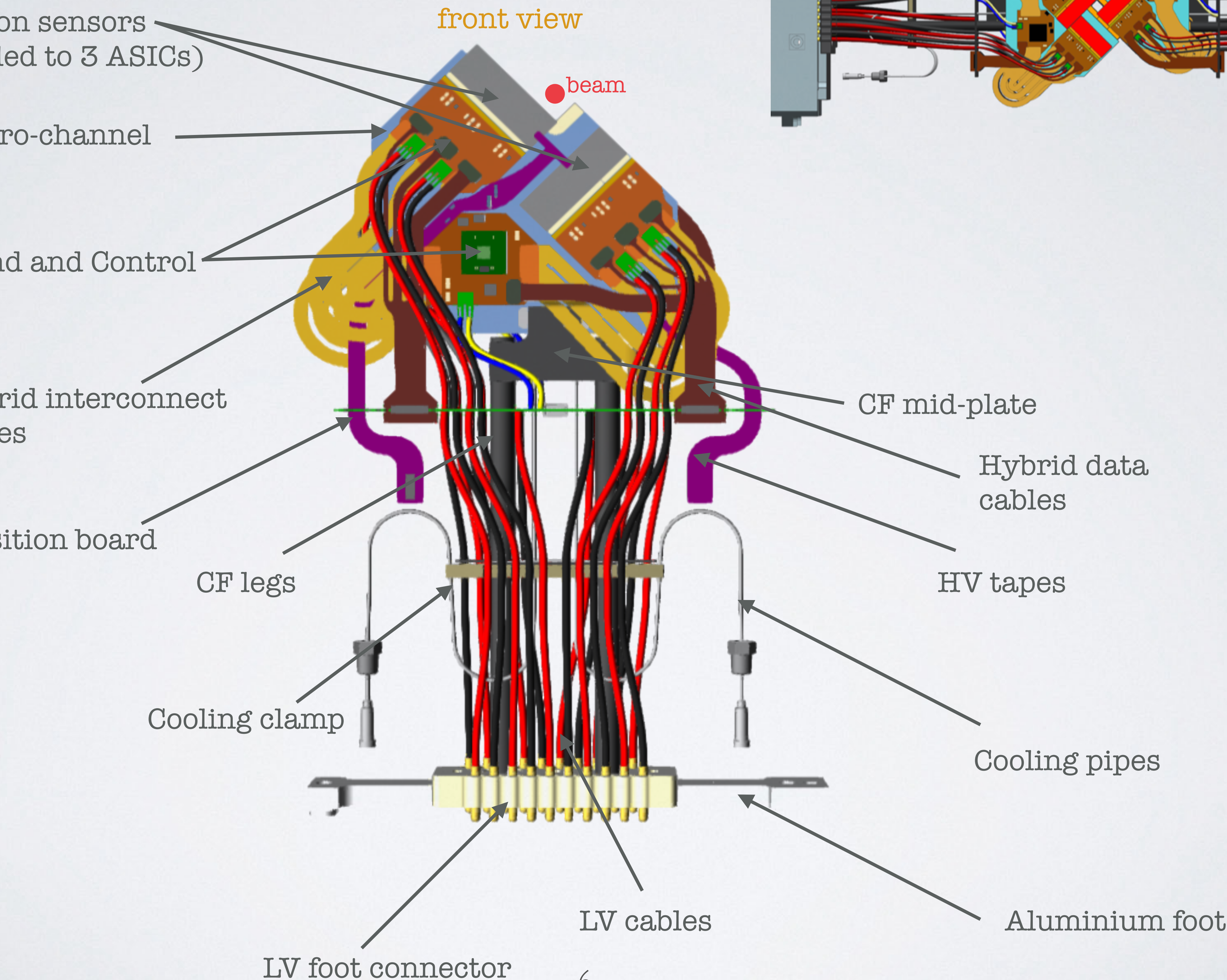
VELO Module design

Different materials brought together into a module

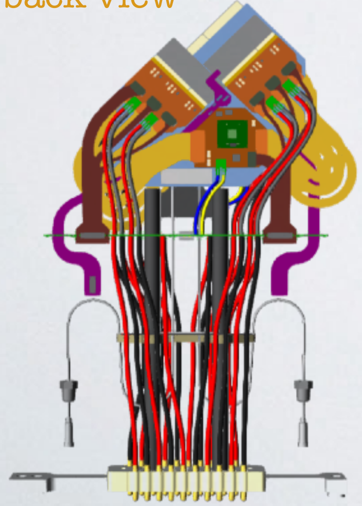
VELO station



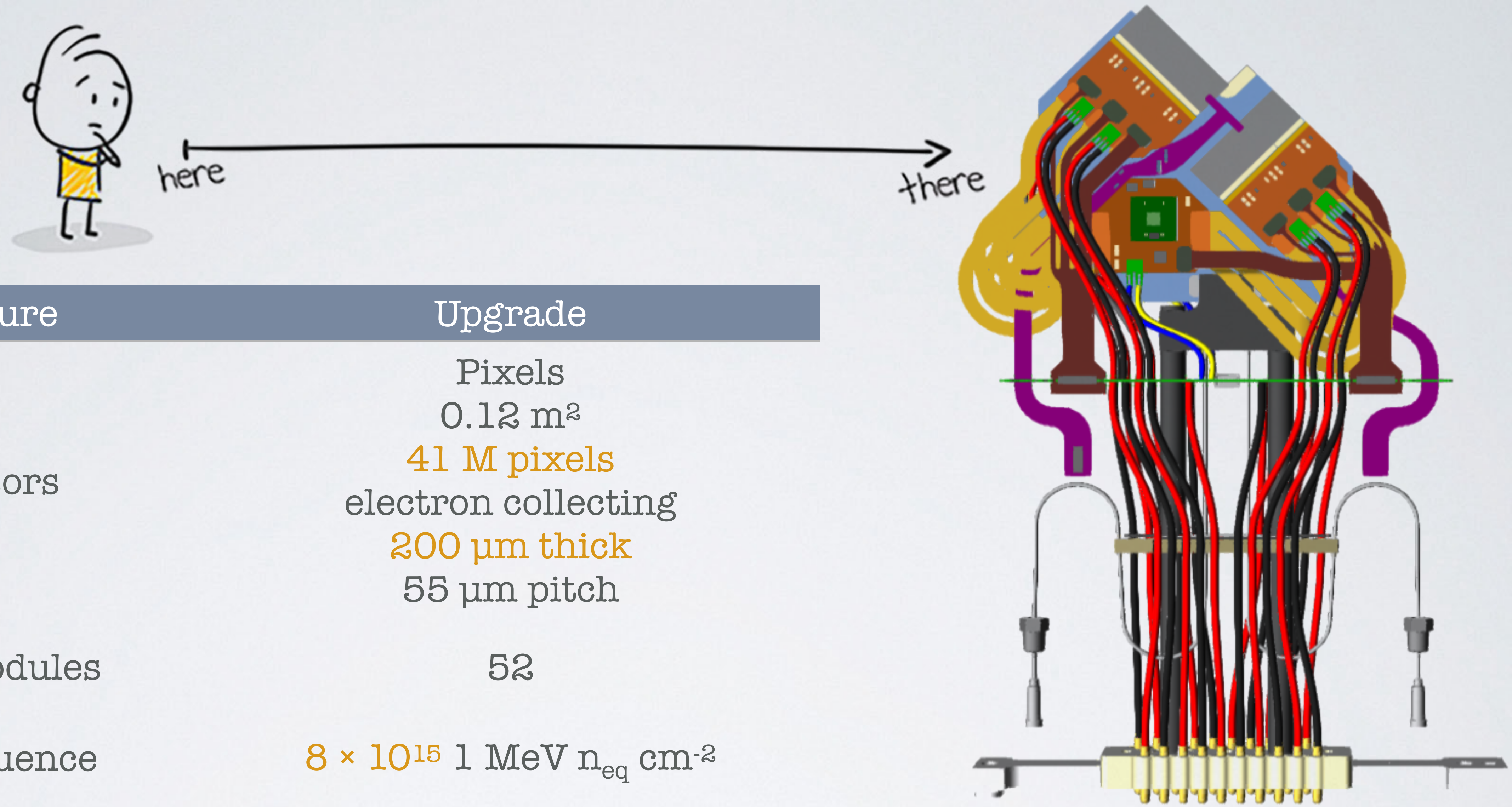
front view



back view



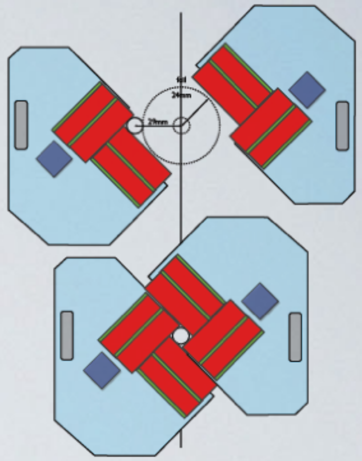
The VELO journey*



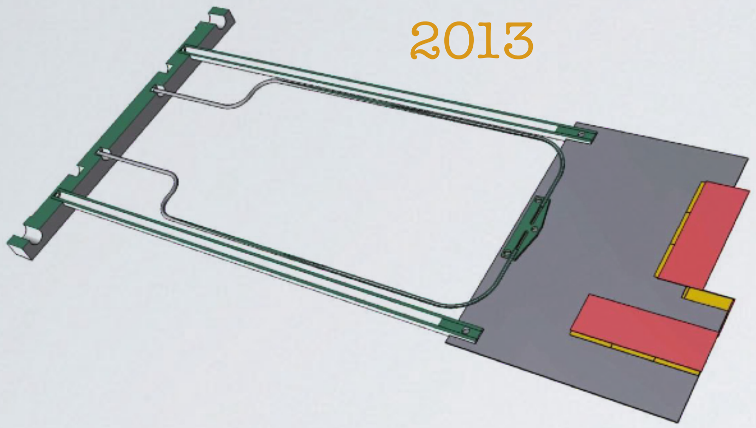
Feature	Upgrade
Sensors	Pixels 0.12 m² 41 M pixels electron collecting 200 µm thick 55 µm pitch
# of modules	52
Max fluence	8×10^{15} 1 MeV n_{eq} cm^{-2}
HV tolerance	1000 V
ASIC readout rate	40 MHz
Total data rate	2.8 Tb/s
Power consumption	1.6 kW (30 W/module)

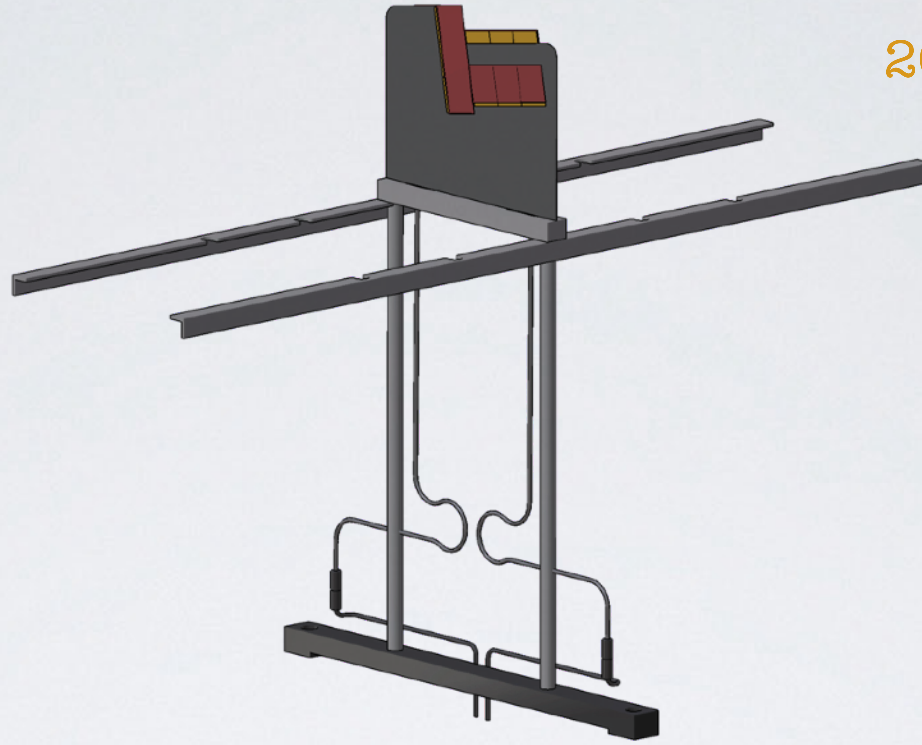
* From the module assembly perspective. Not mentioning R&D on sensors, ASICs, off-chip electronics, DAQ, ...

Module evolution

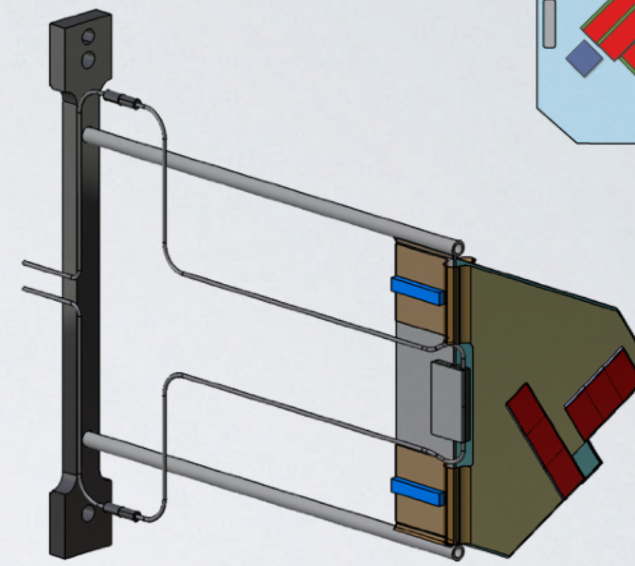


2013

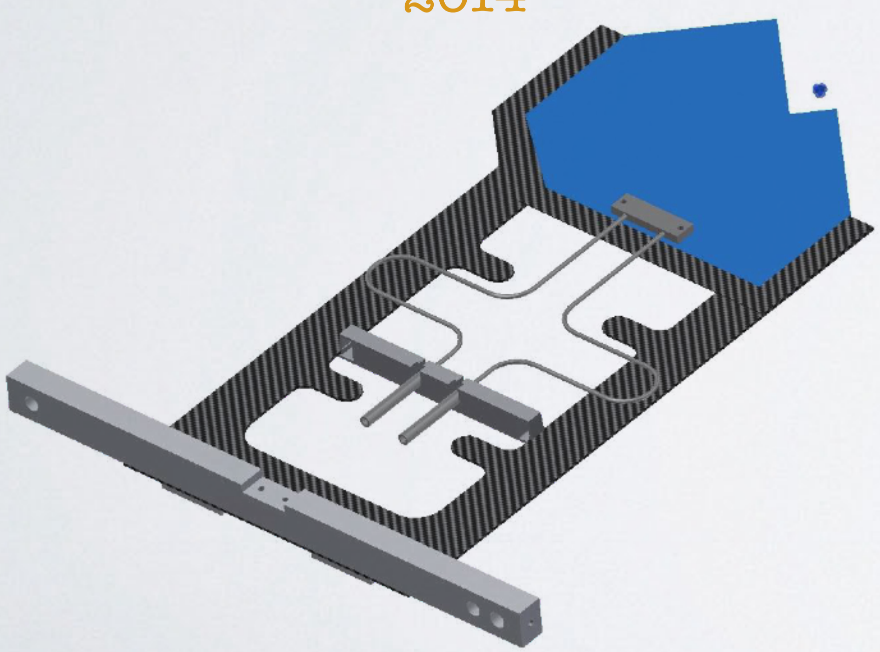




2014

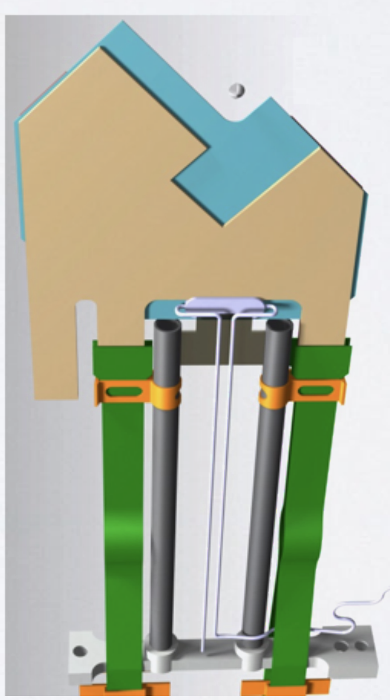


2014

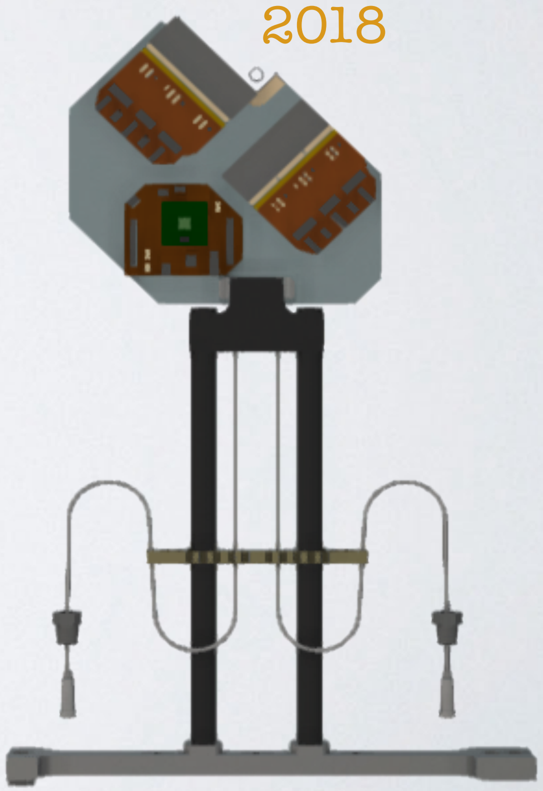


2015

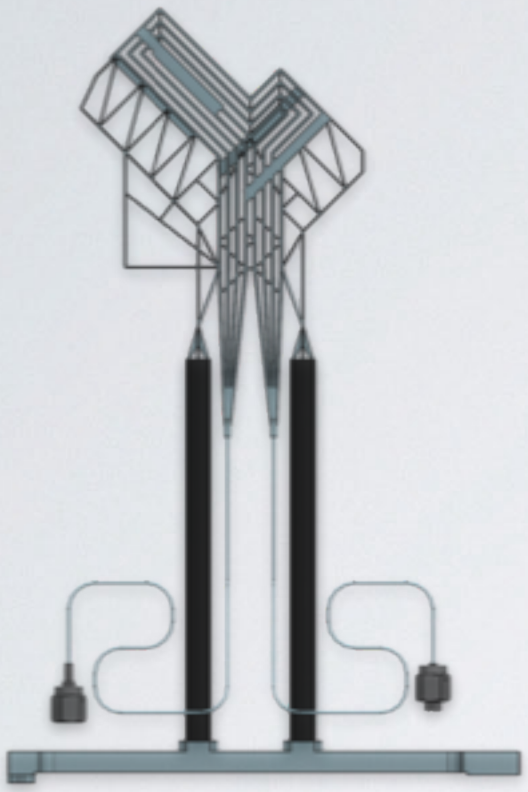
2016



2018

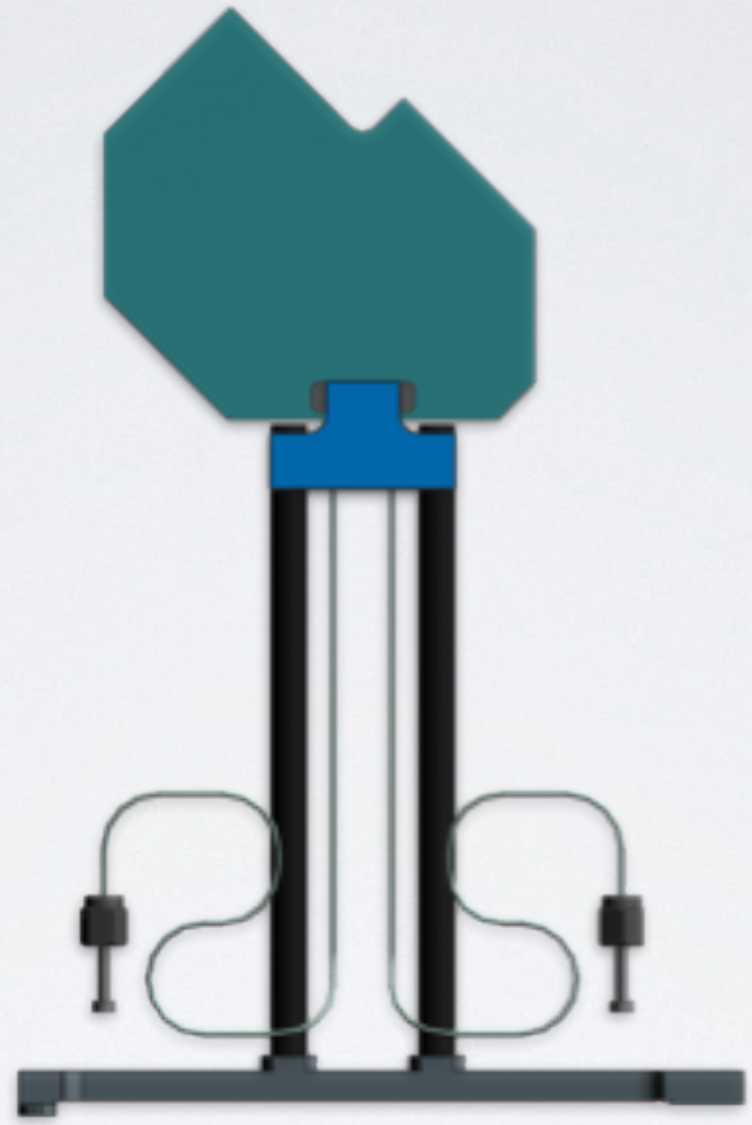


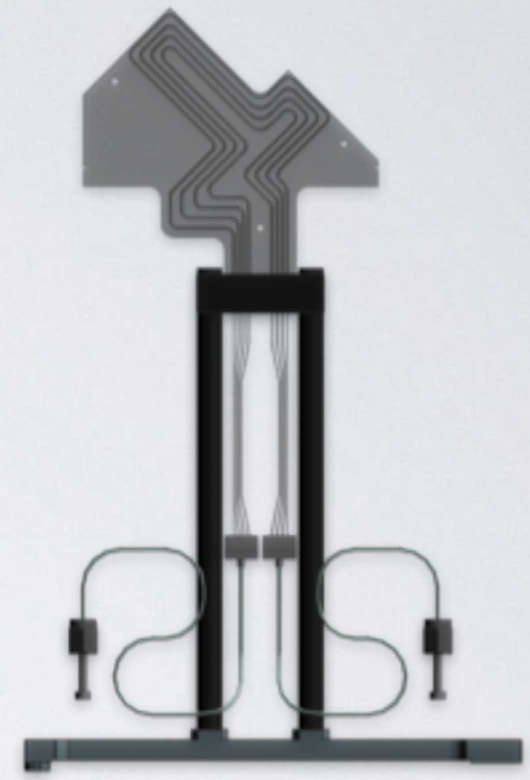
Cooling alternatives



3D-printed Titanium substrate

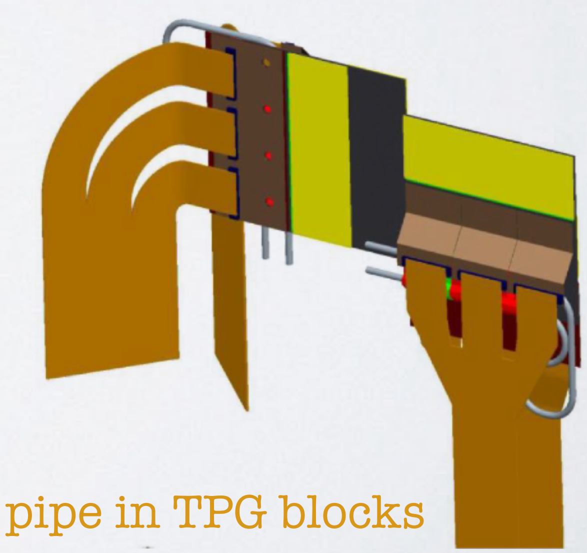
Silicon micro-channel substrate





Ceramic (AlN) substrate
with embedded pipes

Carbon Foam substrate

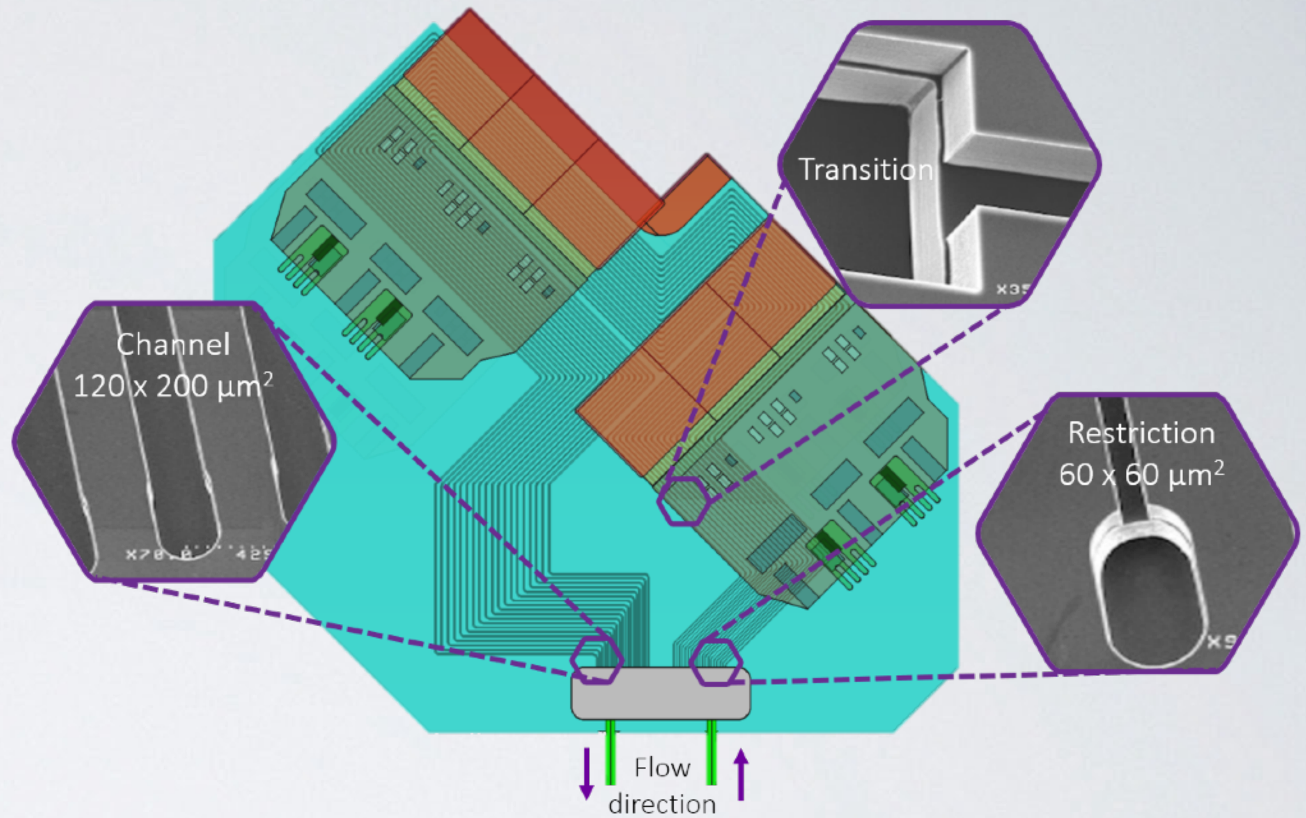


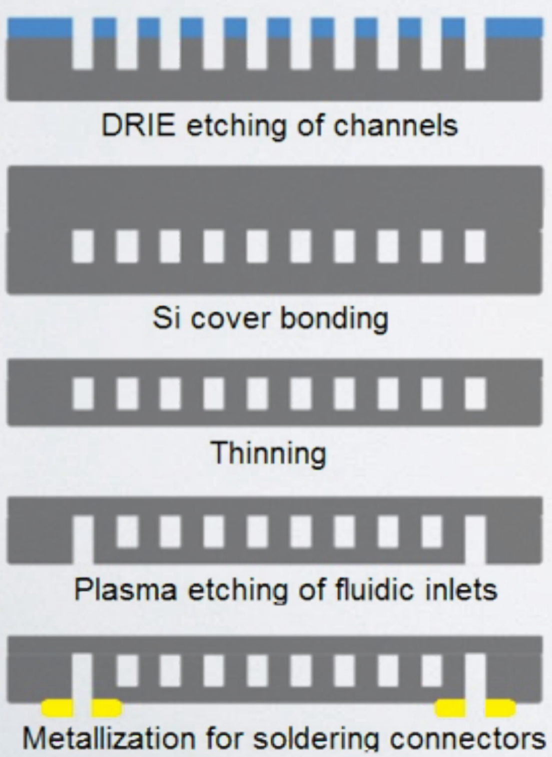
cooling pipe in TPG blocks

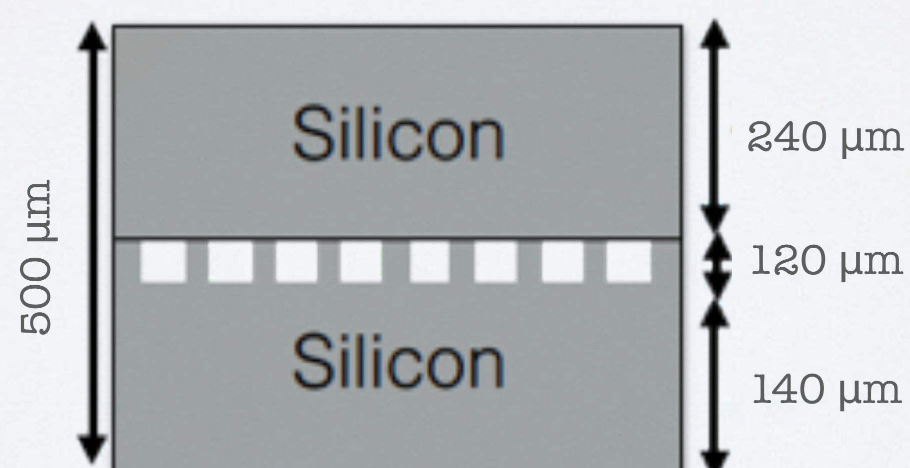
Micro-channel cooling interface

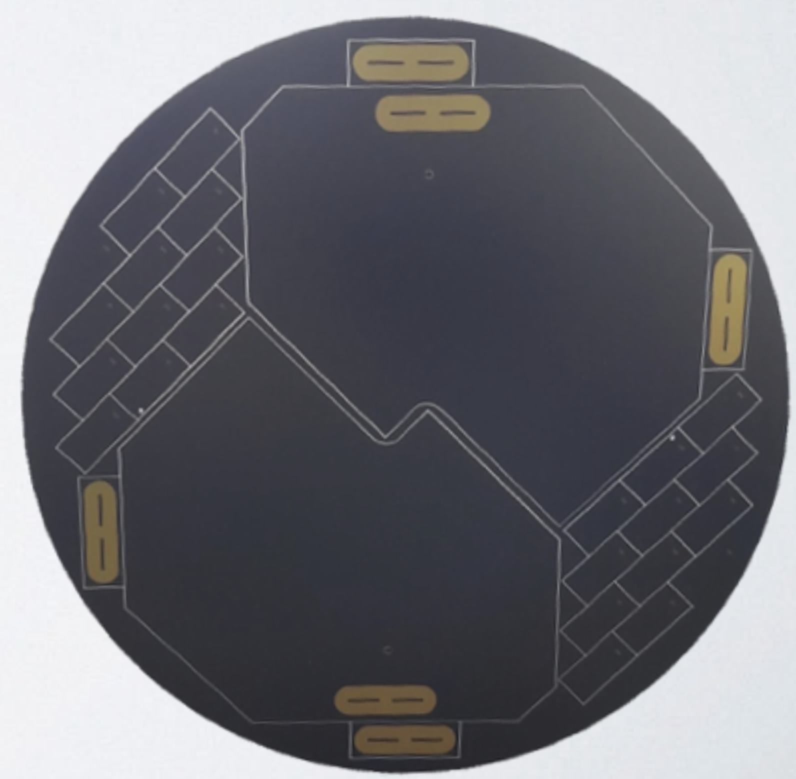
[NIMA-1039-166874]

- 500 µm thick silicon substrate with integrated micro channels.
- same CTE as sensors + low material budget
- high thermal efficiency
- routing of channels customisable
  - 120 × 200 µm micro-channels (19×)
  - 60 × 60 µm high impedance restrictions
  - cooling power ~50 W
- pressure: 14 bar @ -30 °C, 60 bar @ 22 °C



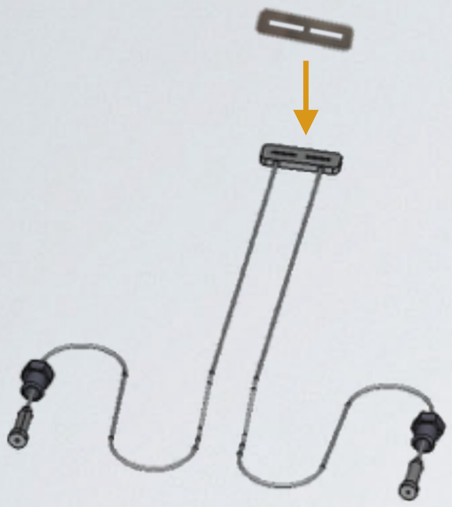




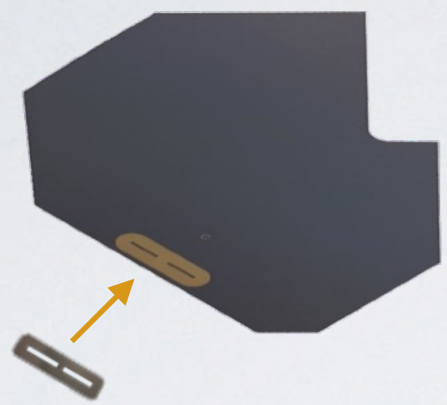


Micro-channel cooling interface

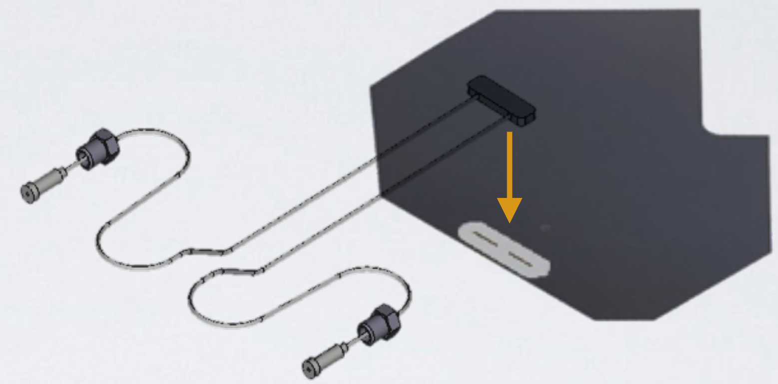
[NIMA-1039-166874]



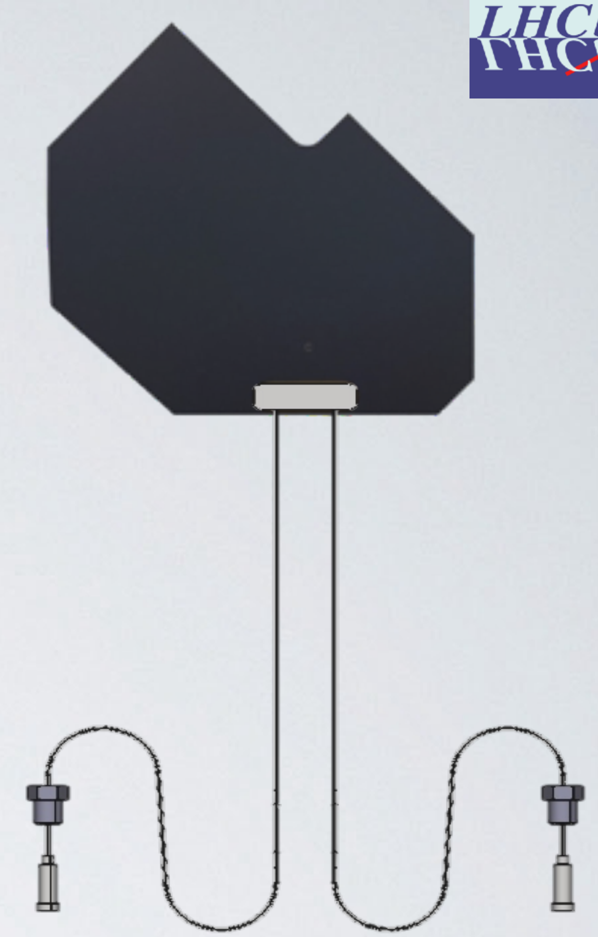
1. connector pre-tinning



2. silicon pre-tinning

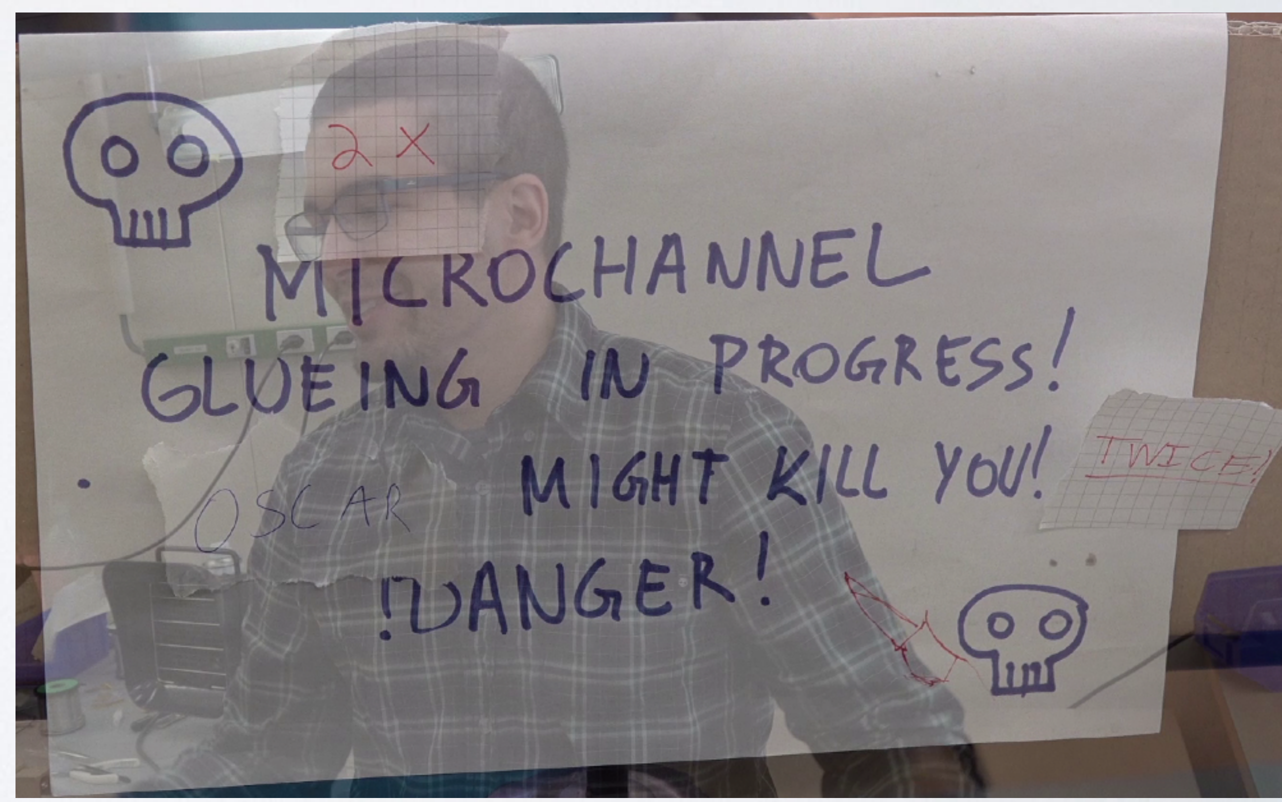


3. alignment

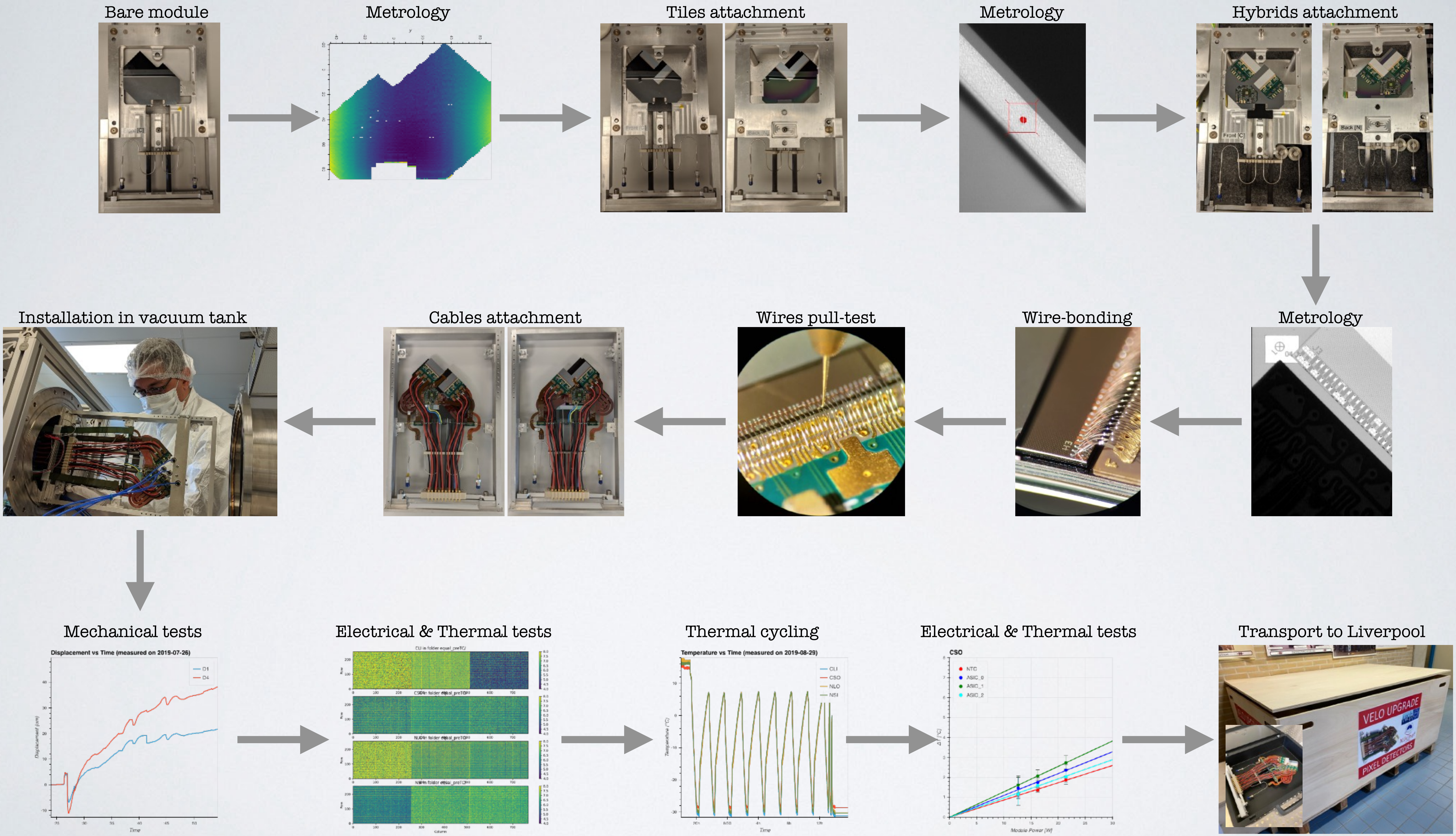


4. soldering

- high quality soldering is essential
  - leak tightness
  - planarity
  - minimum voids in the solder layer
  - no flux
  - metallization with Ti+Ni+Au
  - high pressure qualification: 186 bar

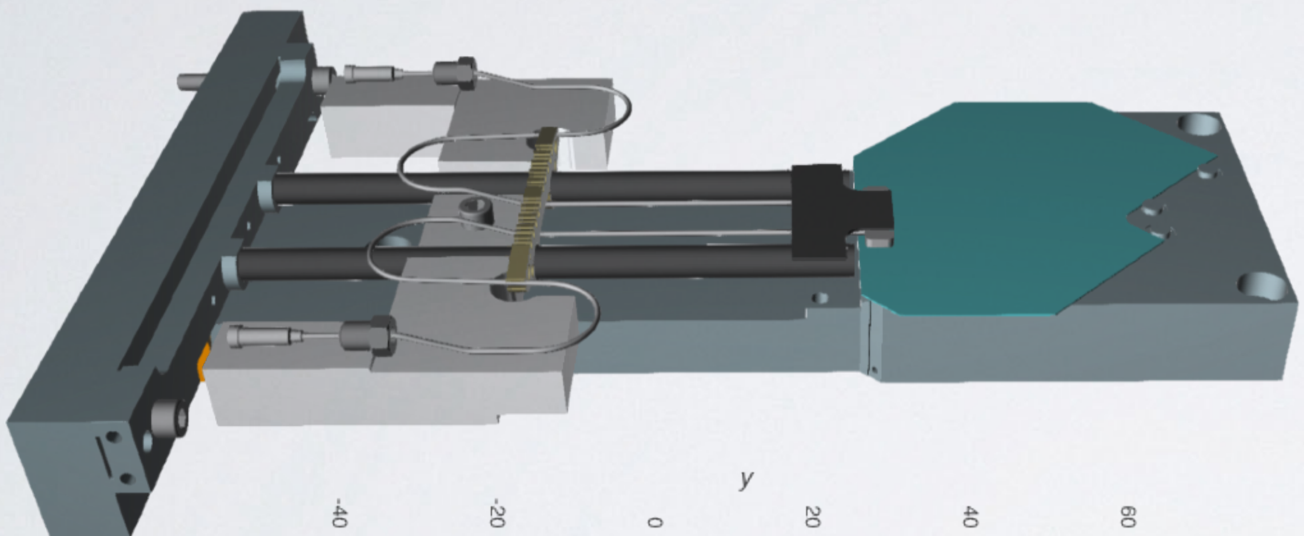


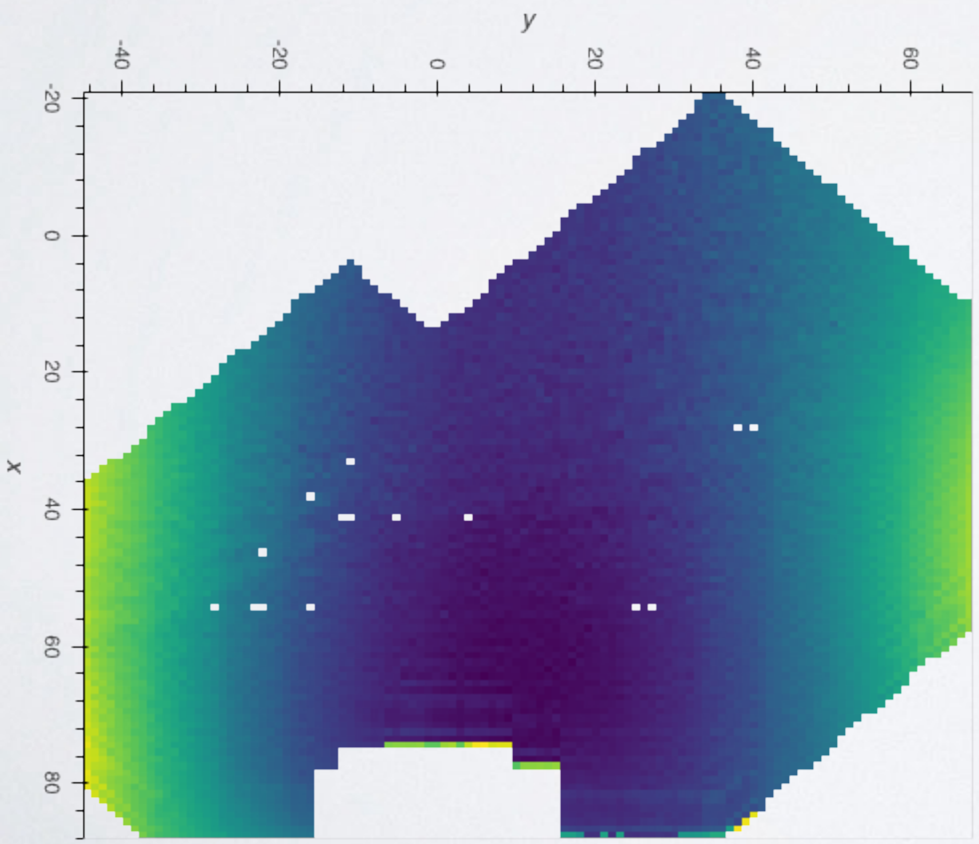
Module construction flow

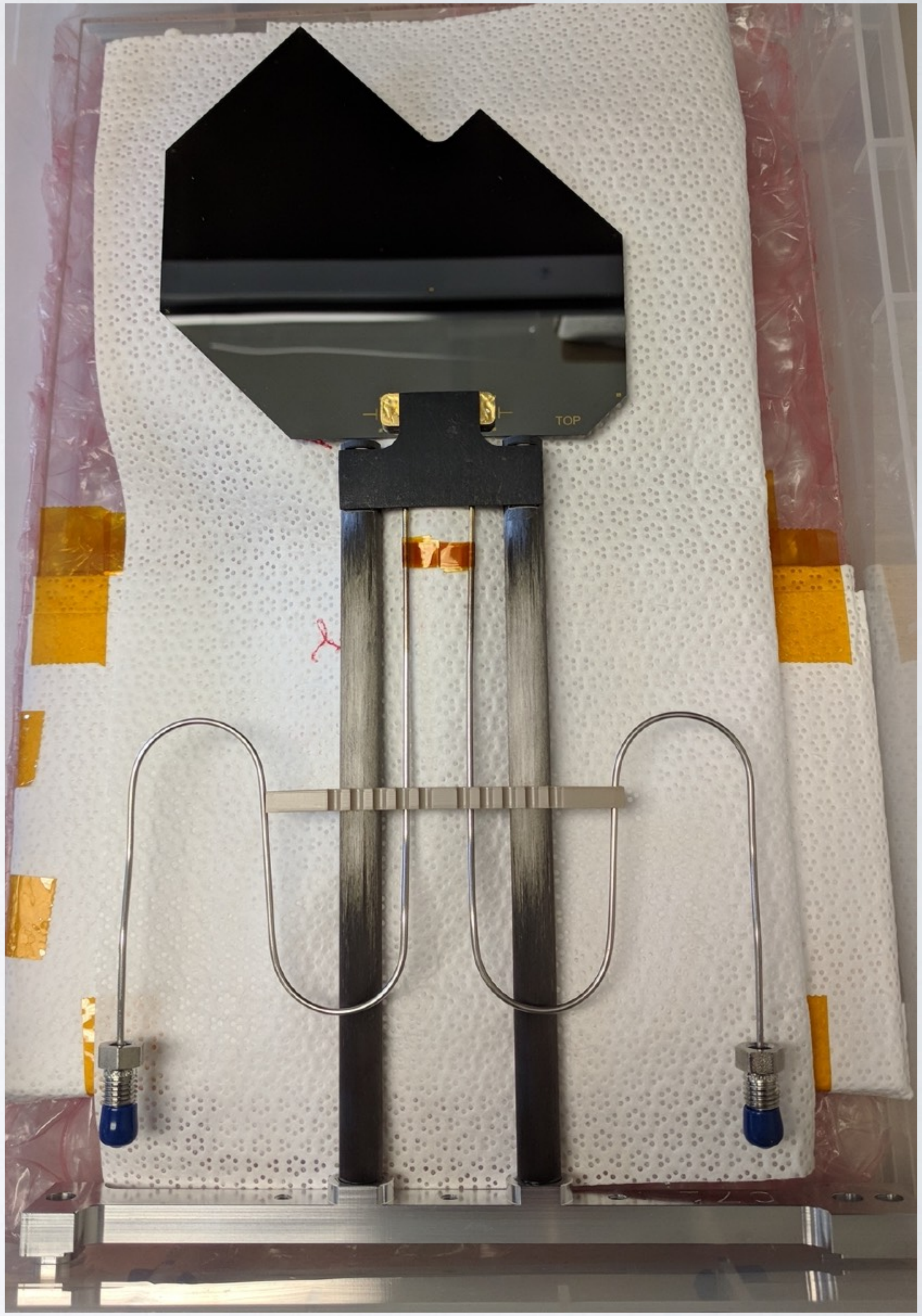


Bare module assembly

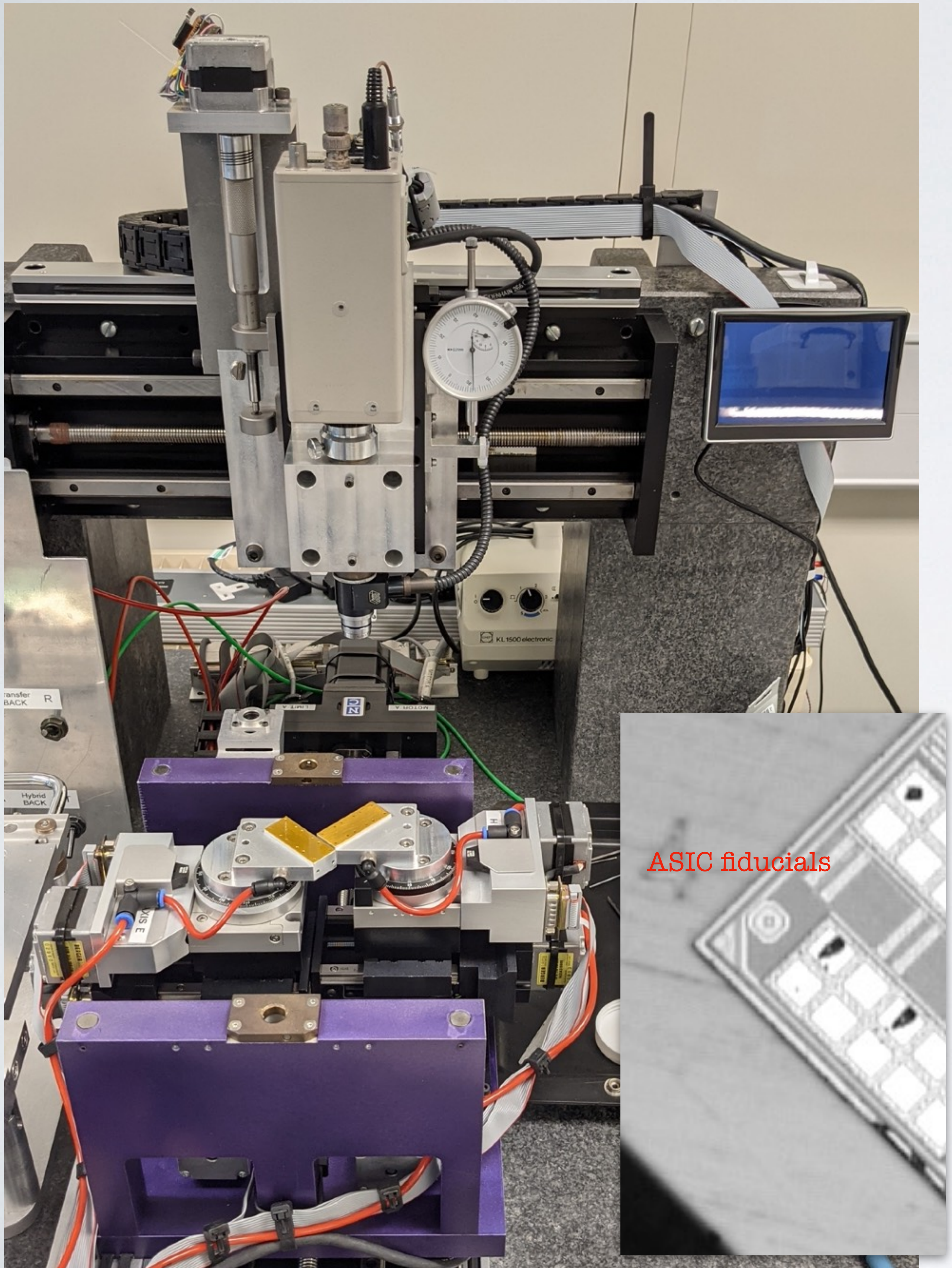
- Assembly of a micro-channel substrate
  (with cooling connector, capillaries and VCR fittings)
  with a CF mid-plate, 2 CF legs, a cooling clamp and an Al foot.
- Jig used for alignment and glueing.
- Flatness measured with 3D optical system (camera+laser).

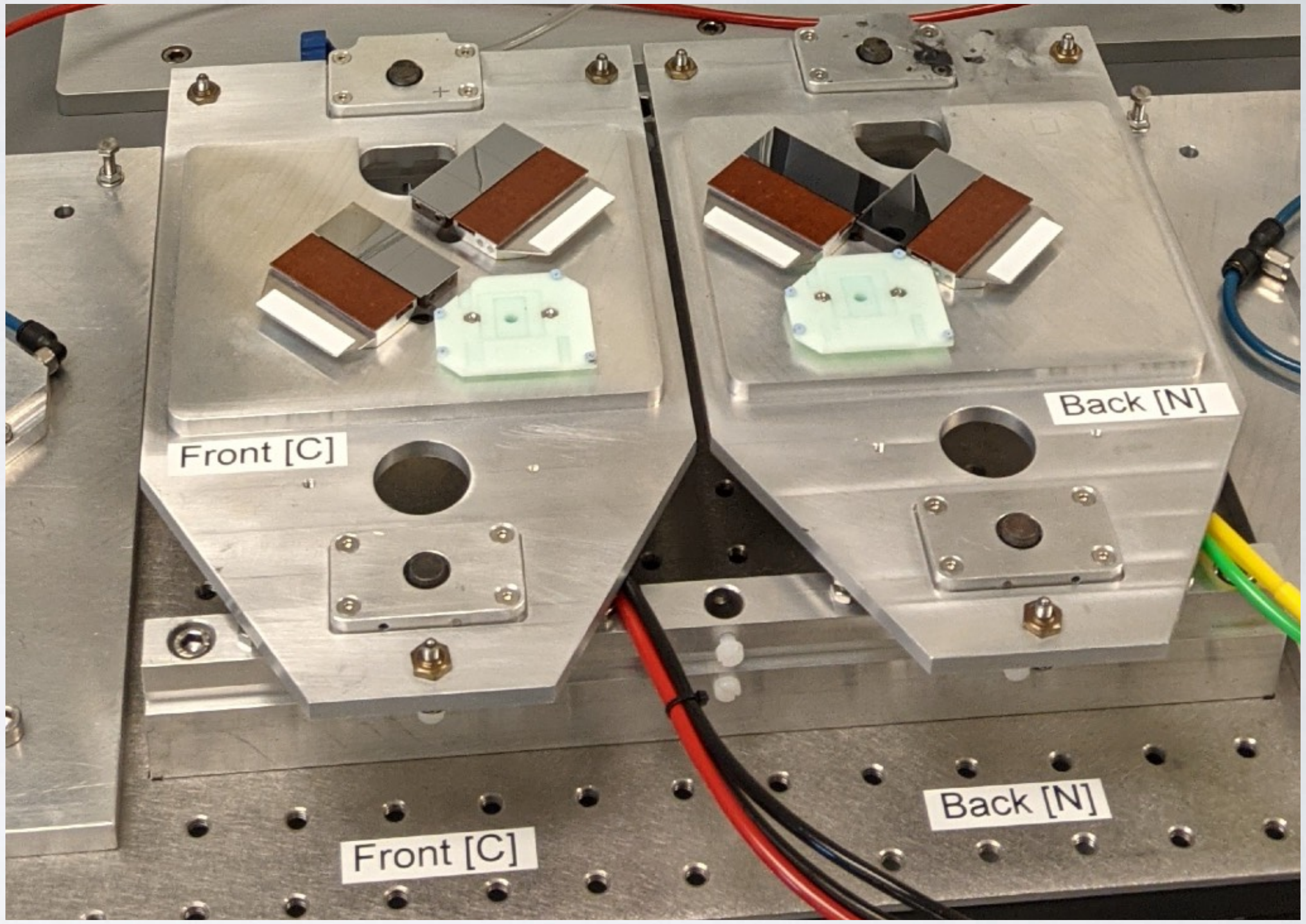






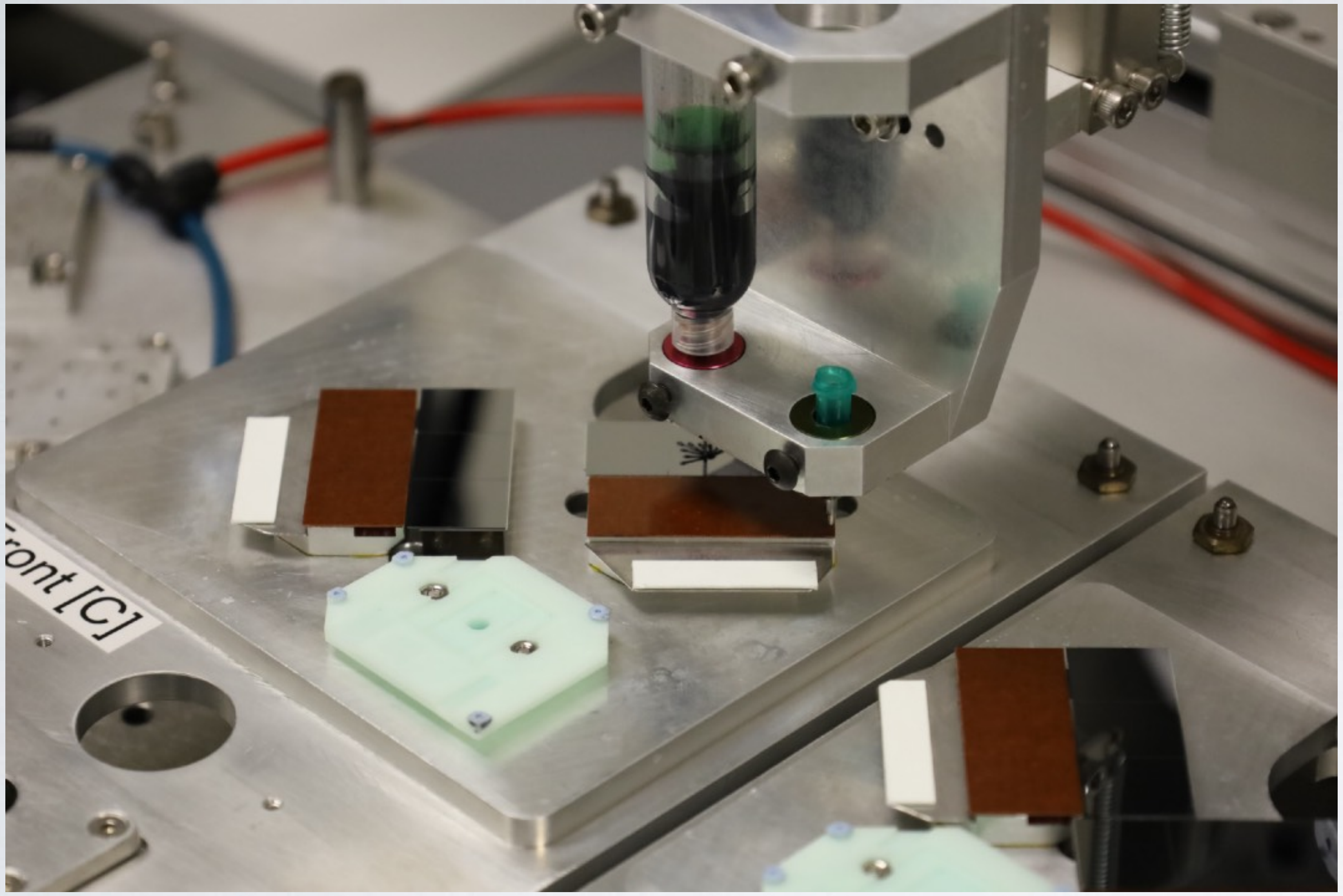
Tiles alignment and glueing





- Aim to position with ±30μm precision
- Alignment done with stages (Manchester) or pick-and-place machine (Nikhef)
- Camera to find fiducials on ASICs and set target position
- Transfer plates to take tiles from stages and bring them to the glue dispenser

Tiles alignement and glueing



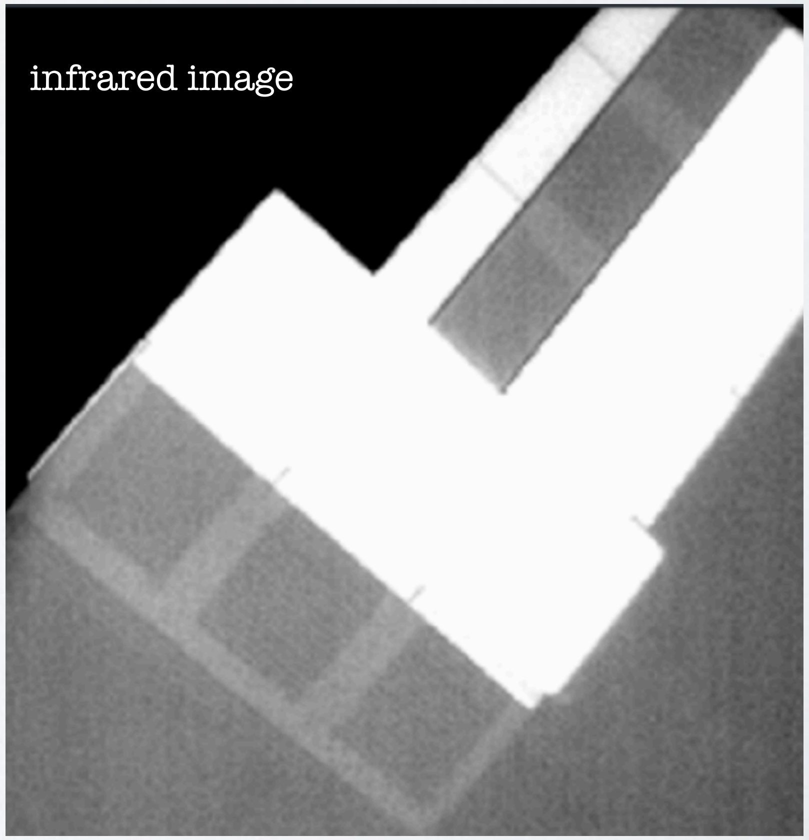
- Module in vacuum, glue layer only path for heat
- Glue needs to be thermally conductive, rad-hard, good CTE match with silicon

- Maximum glue coverage
- No glue in-between ASICs and no air trapped

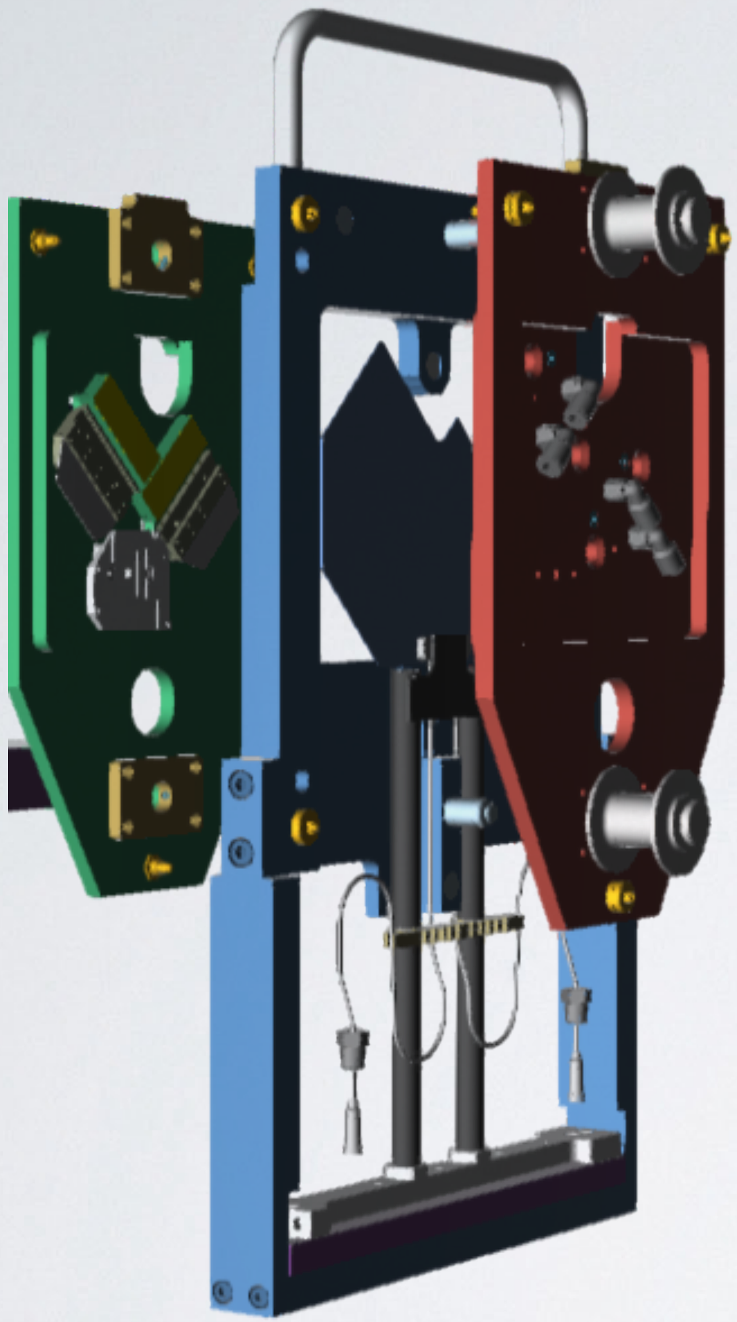
- Minimum thickness
- Mechanically/thermally reliable

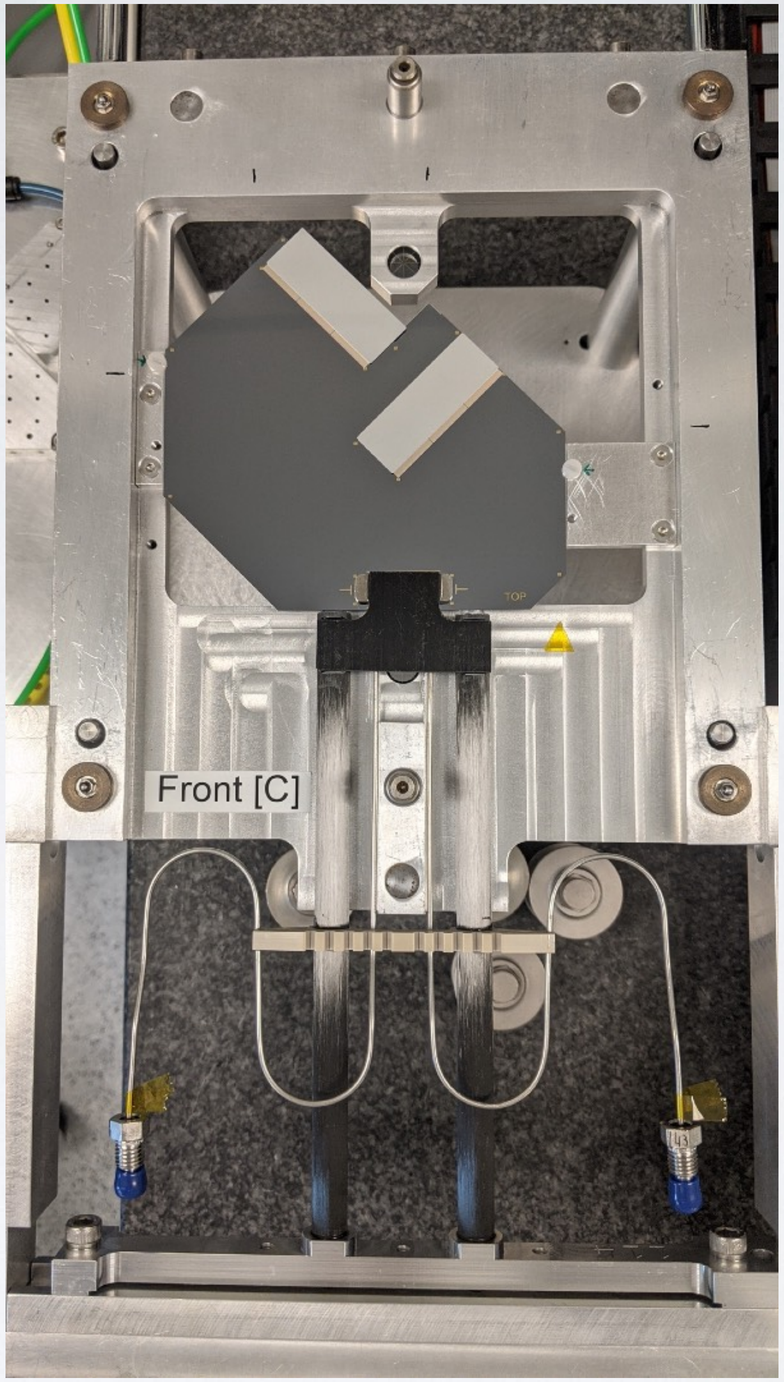
- Stycast 2850FT with catalyst 23LV
- Hourglass star pattern

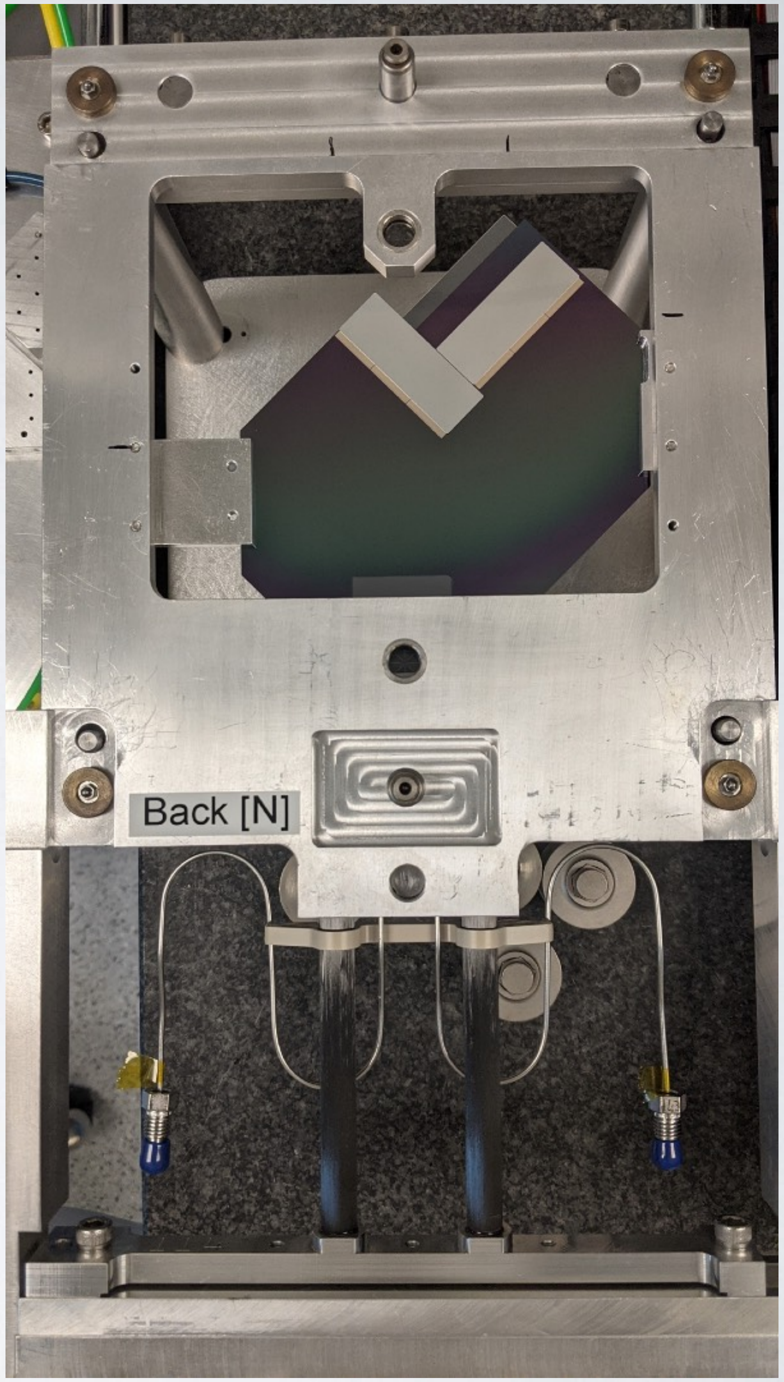
- Most stressful step in the whole module assembly!



Tiles attachment

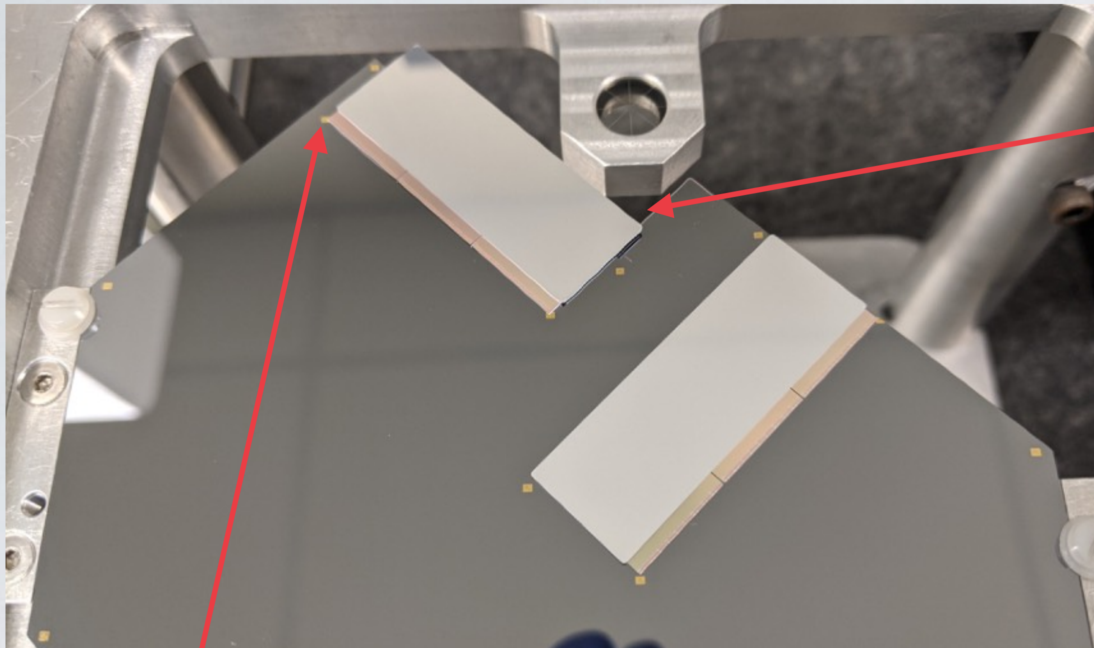


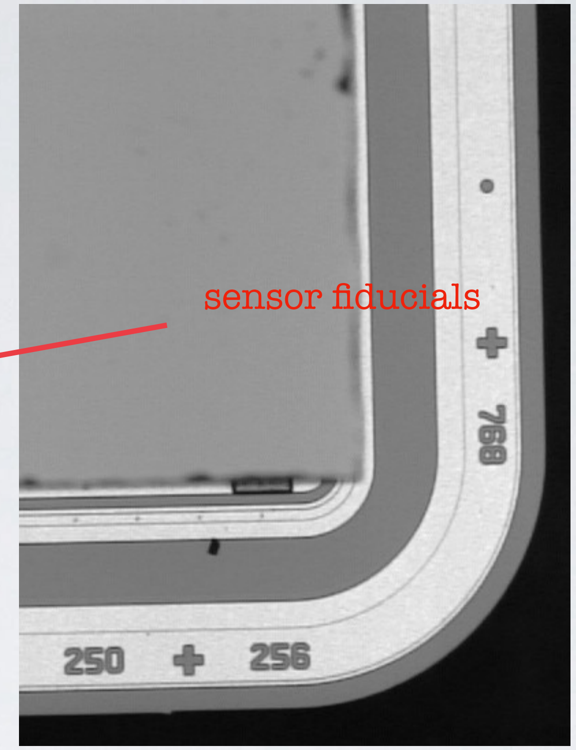




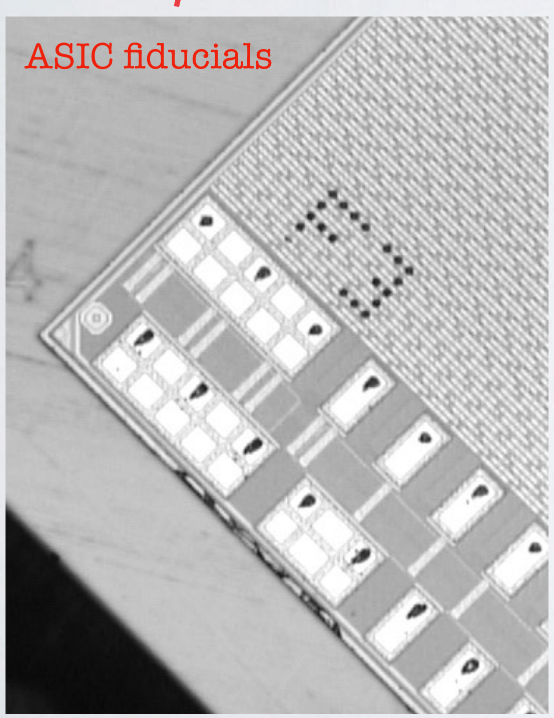
- Module held in turnplate jig
- Both front and back tiles attached in one go
- Small openings in transfer plate for final confirmation

Tiles metrology



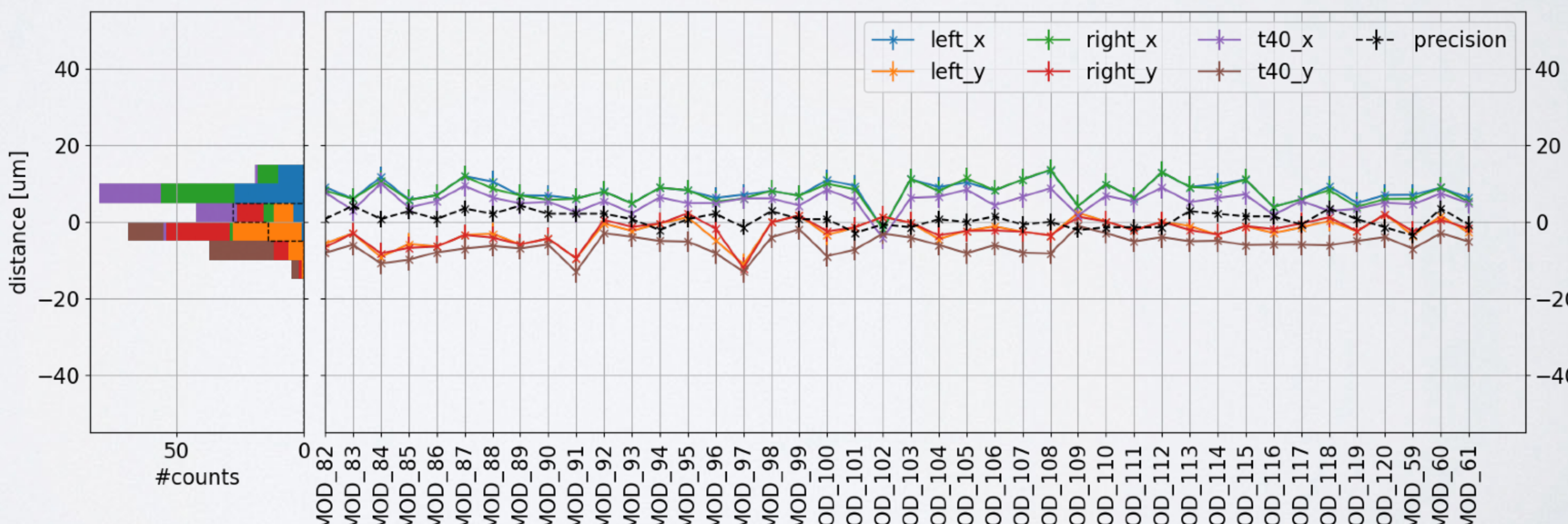


- 3D optical measurement system
- Data uploaded to DB and analysed on the spot -> grade
- Any issue fed back to assembly step for correction



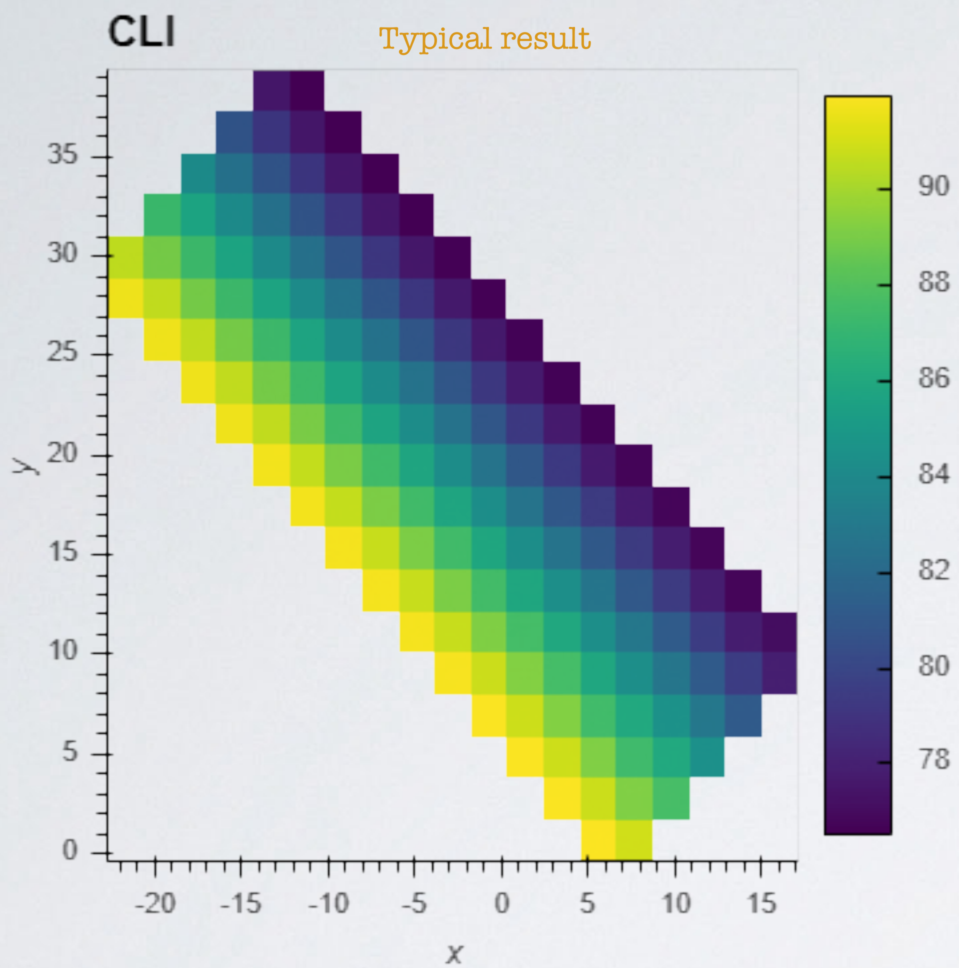
Tile distance to target position

[CERN-THESIS-2021-309]

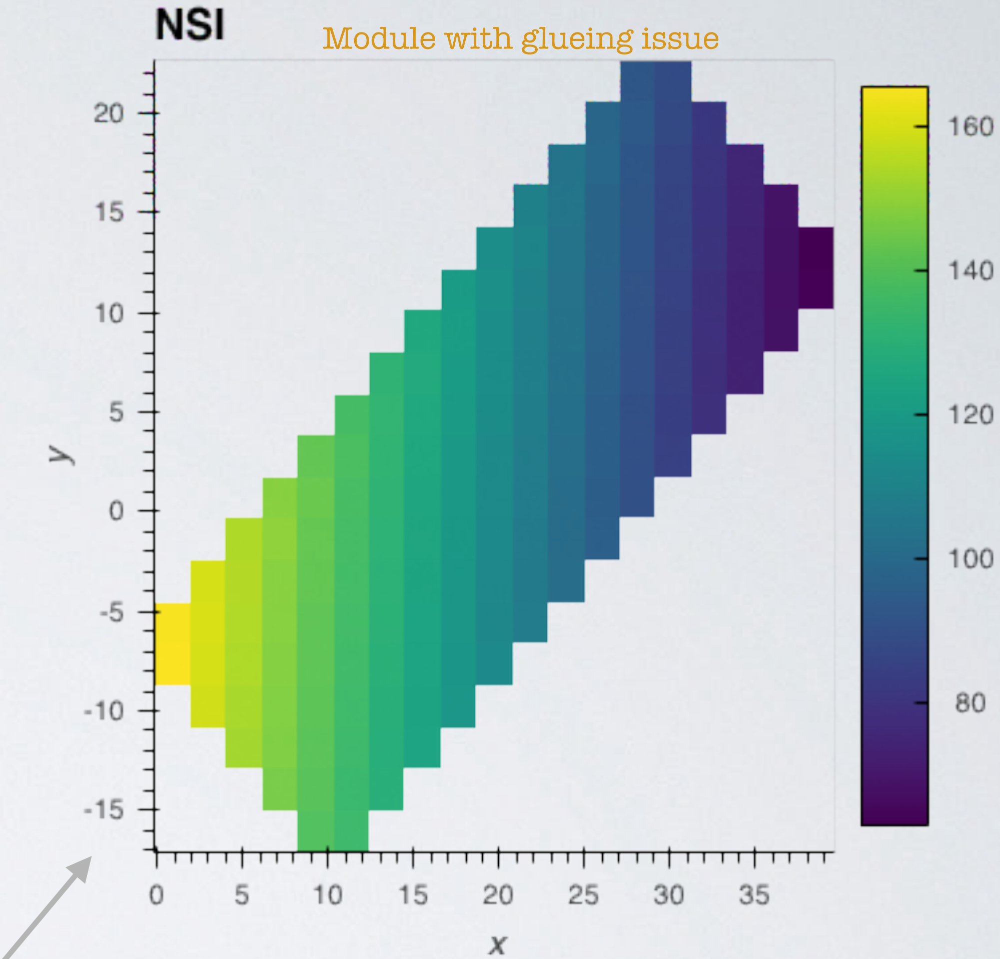


Tiles metrology

Typical result

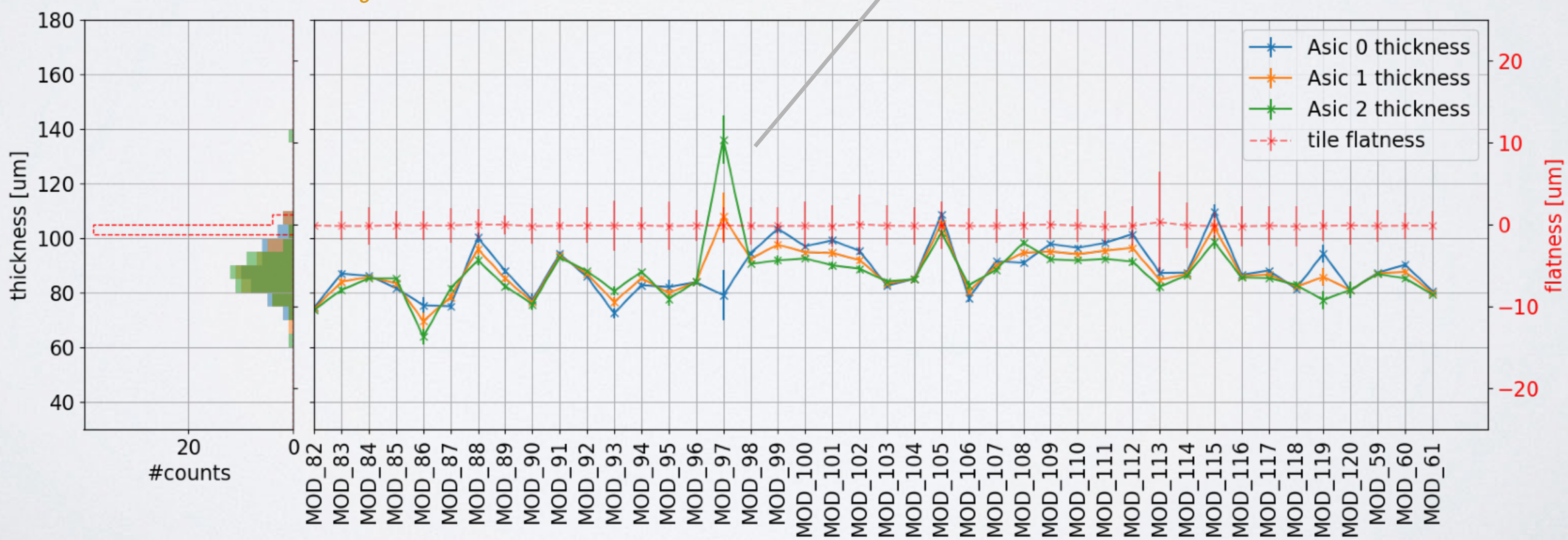


Module with glueing issue

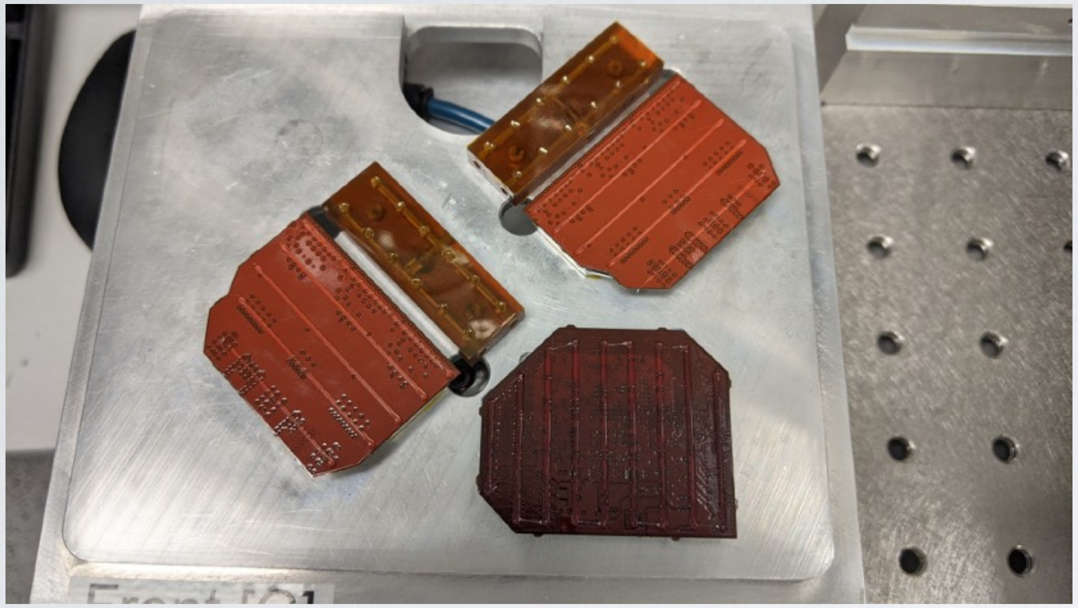


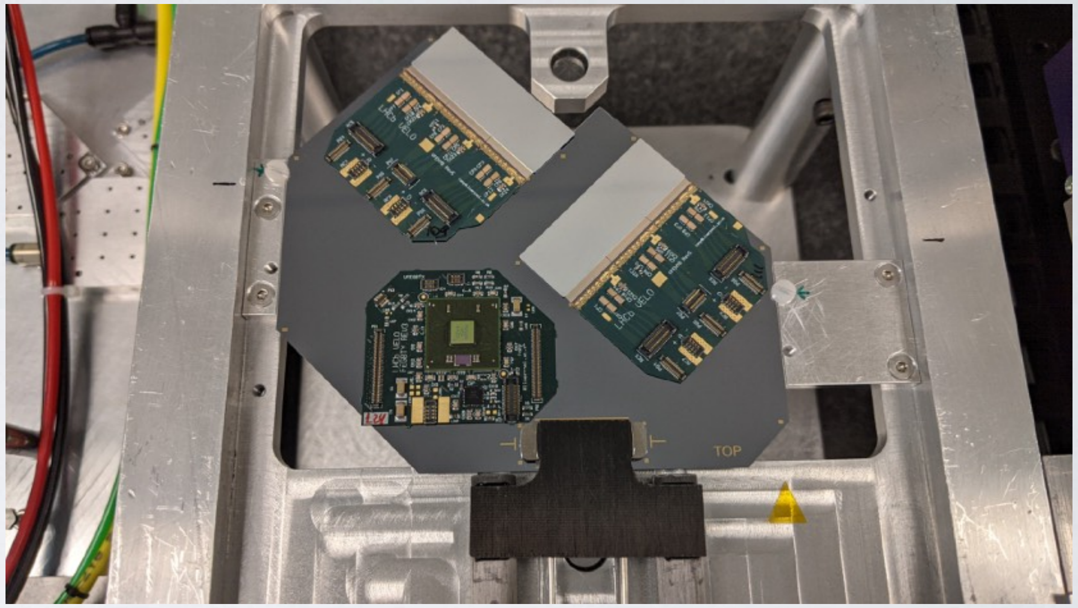
Glue layer thickness

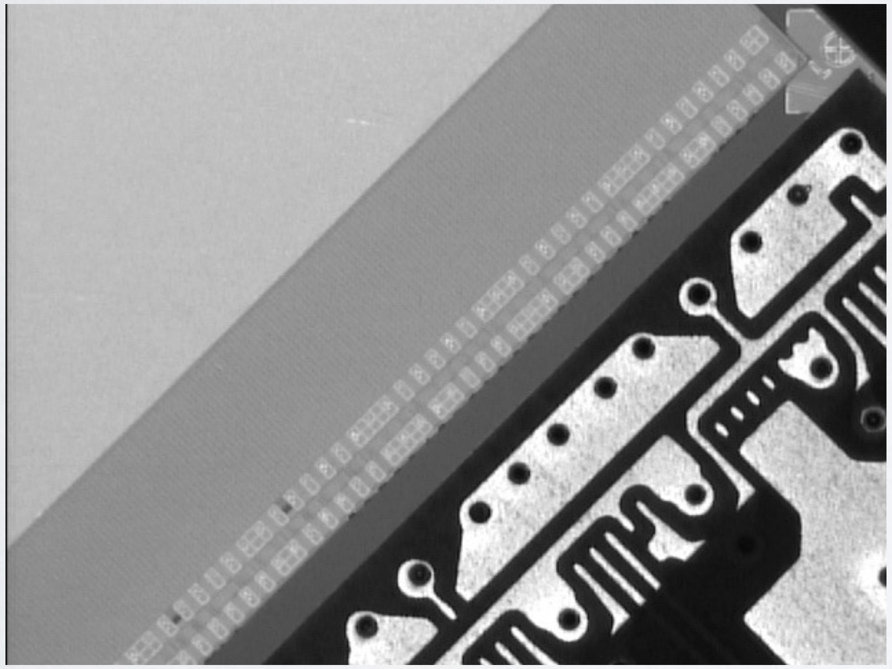
[CERN-THESIS-2021-309]

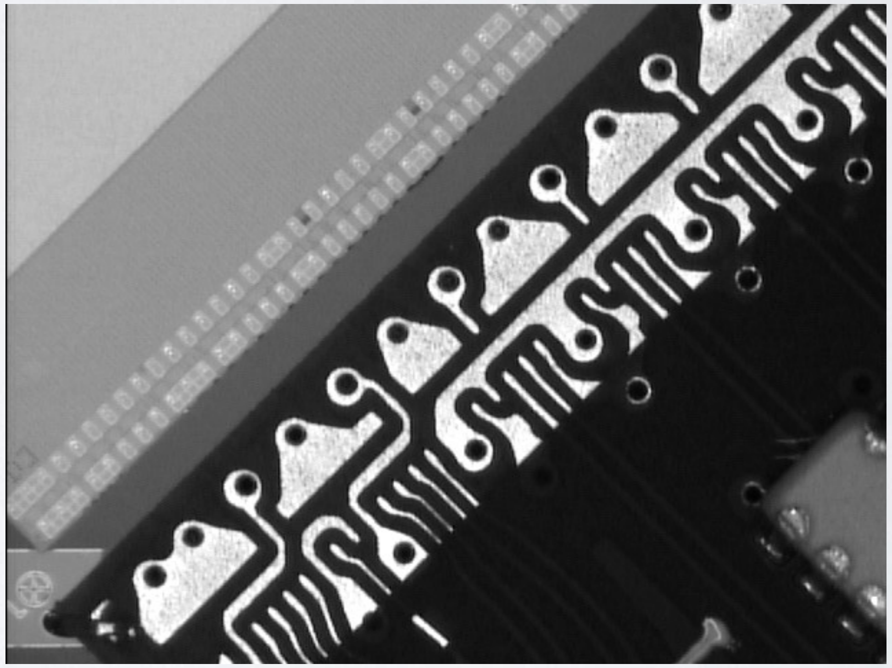


Front-end and control hybrids attachment



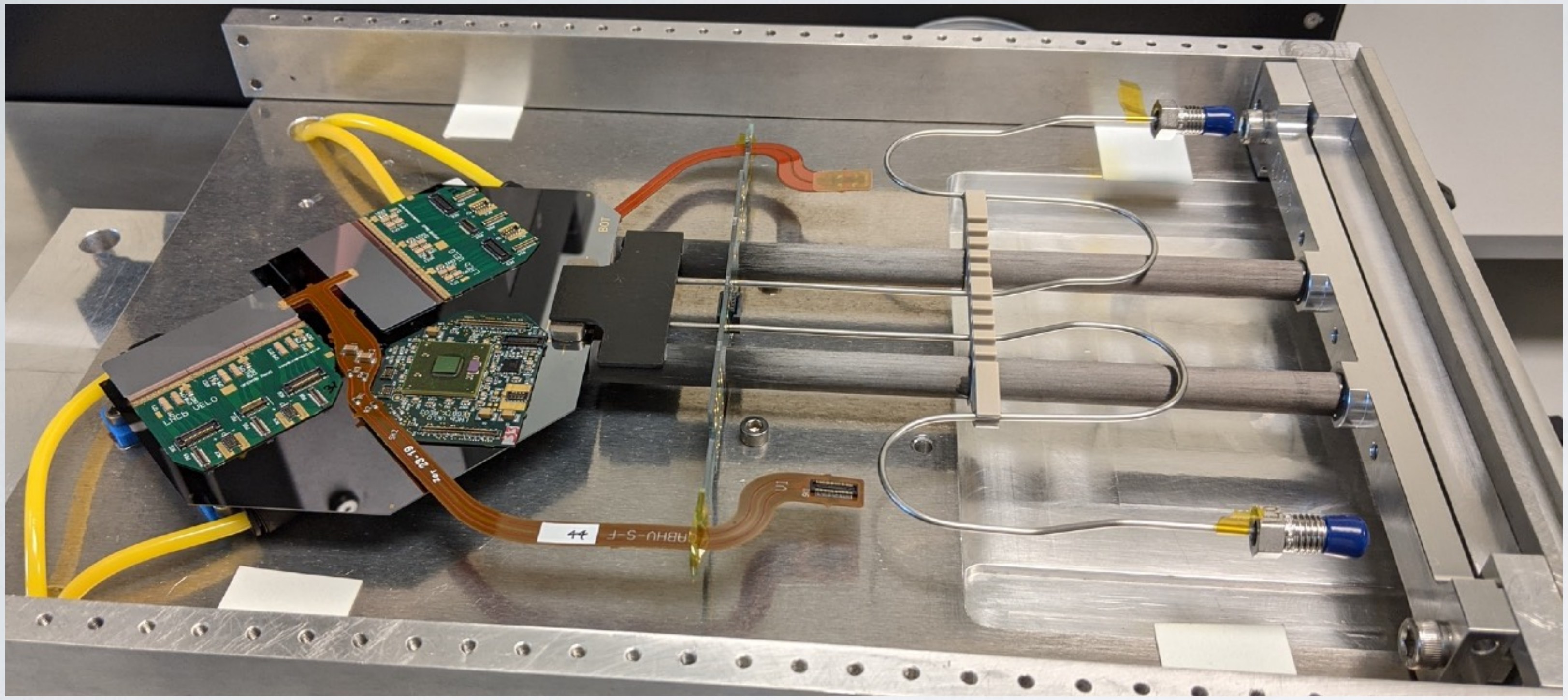


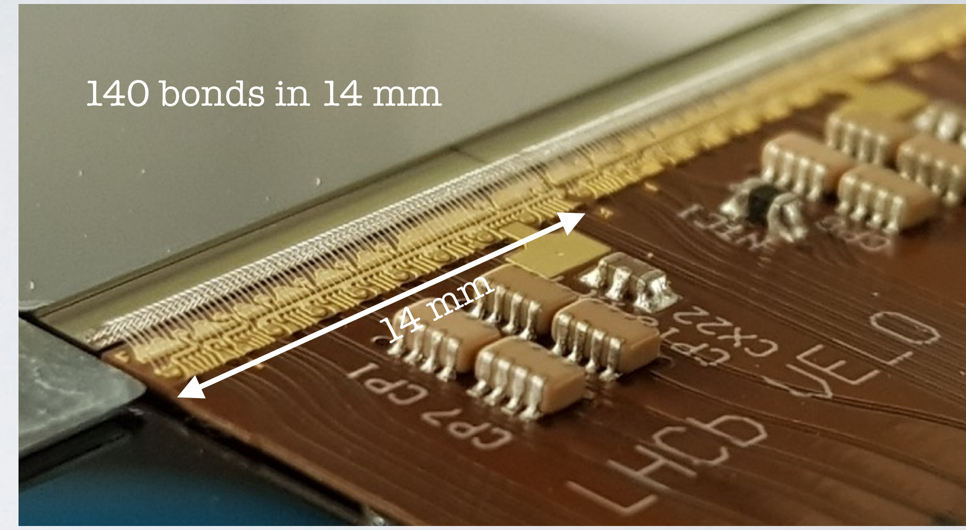


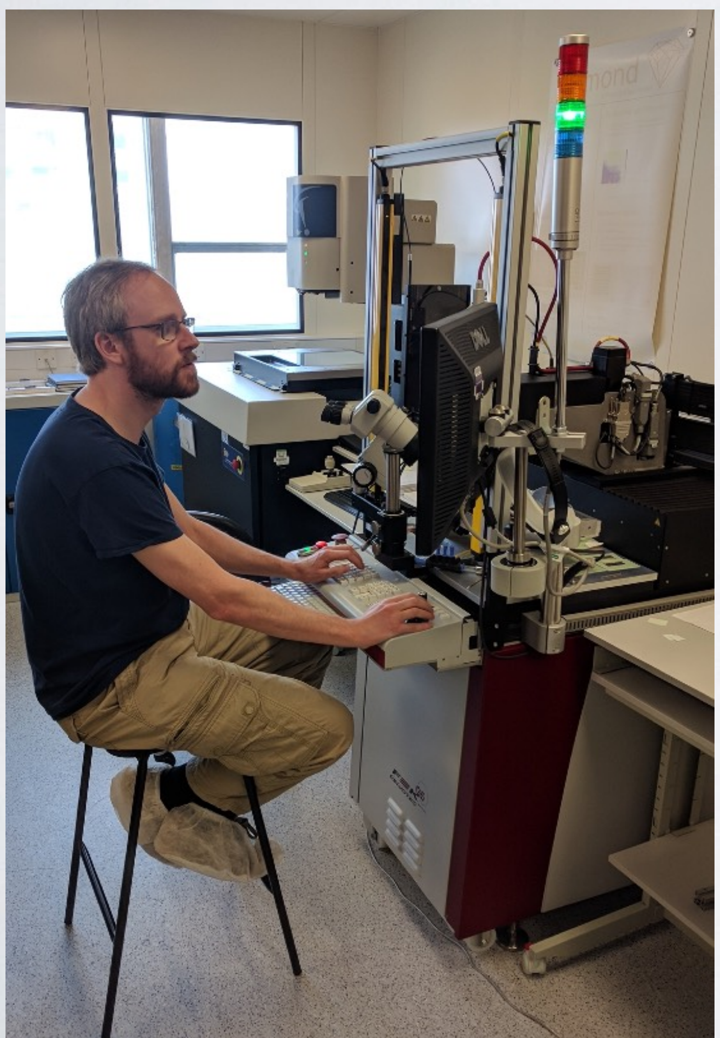


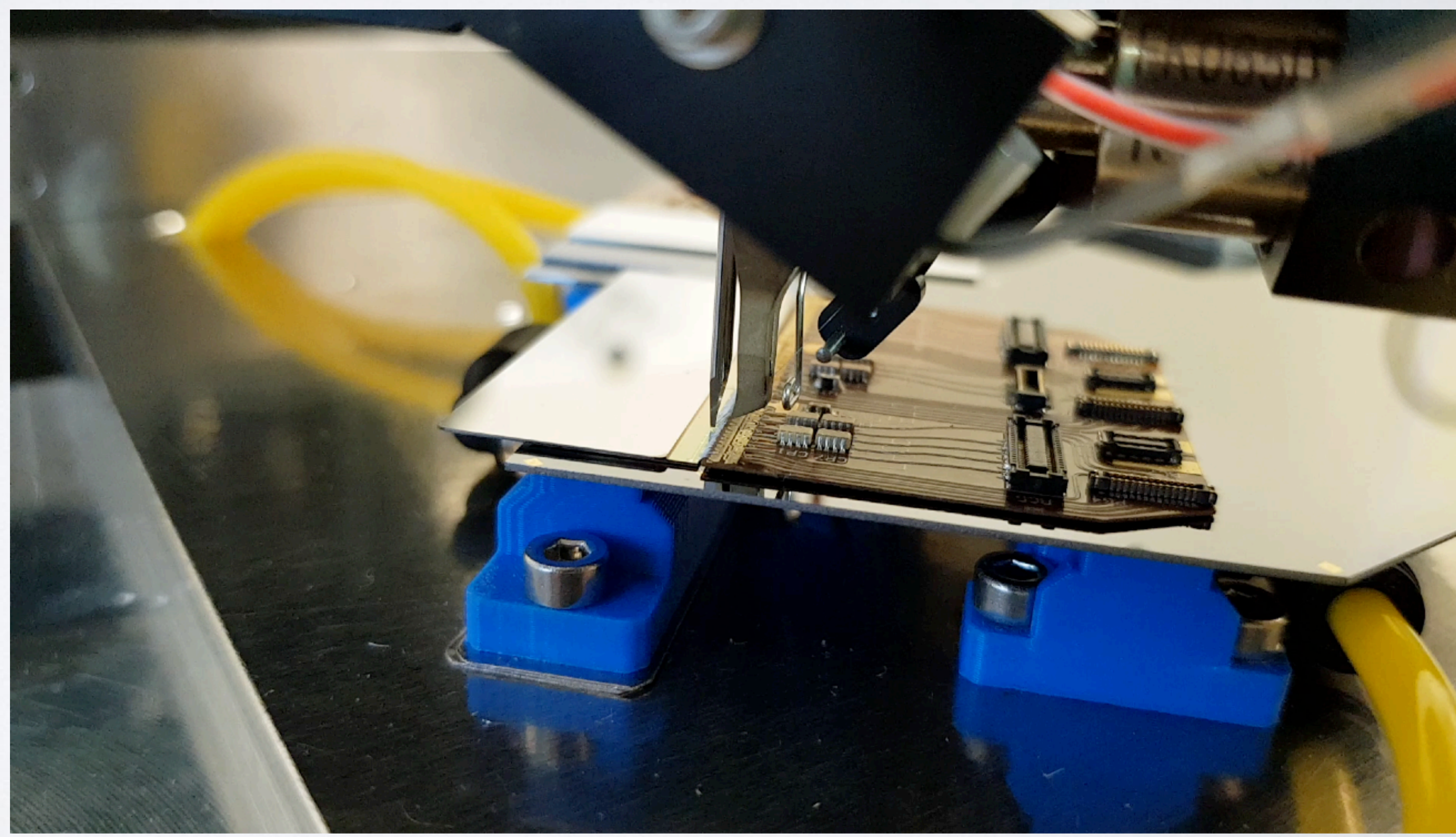
- Loctite SI 5145
- Flexible silicone glue
- Absorbs stresses due to CTE mismatch with silicon

Wire-bonding



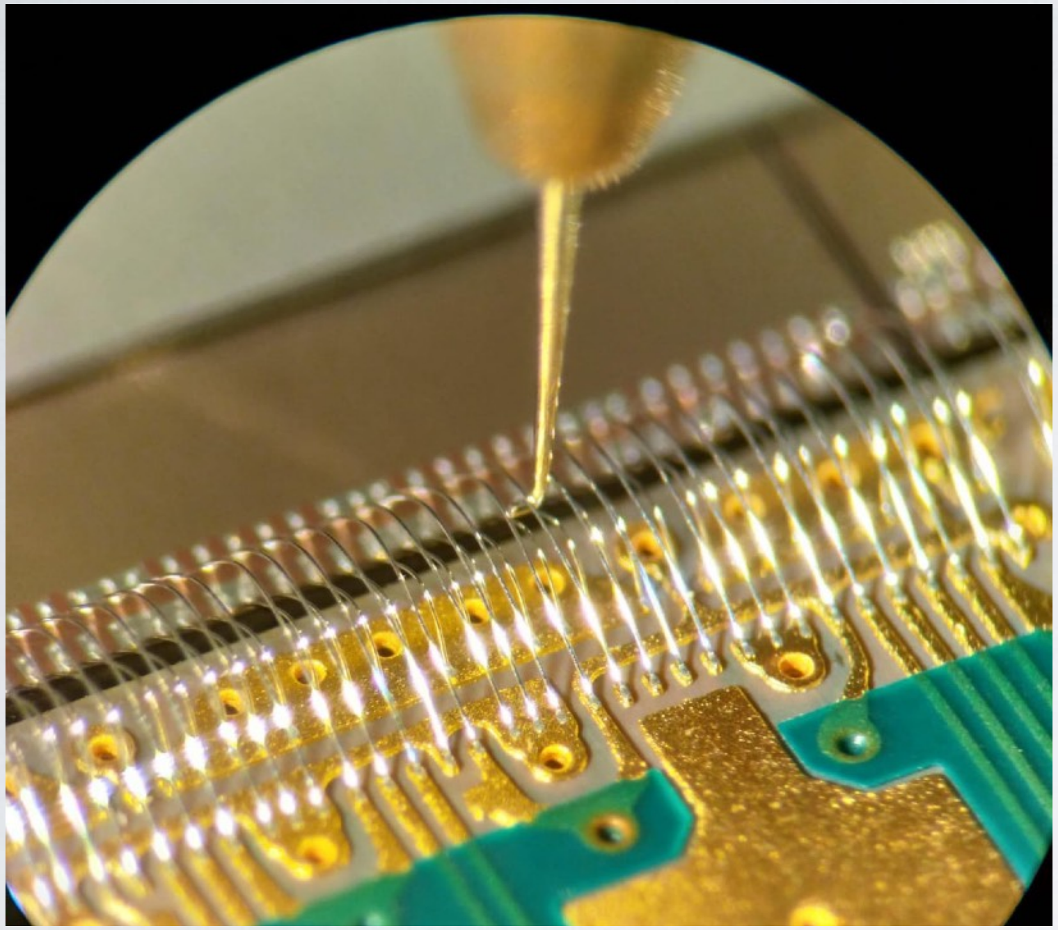


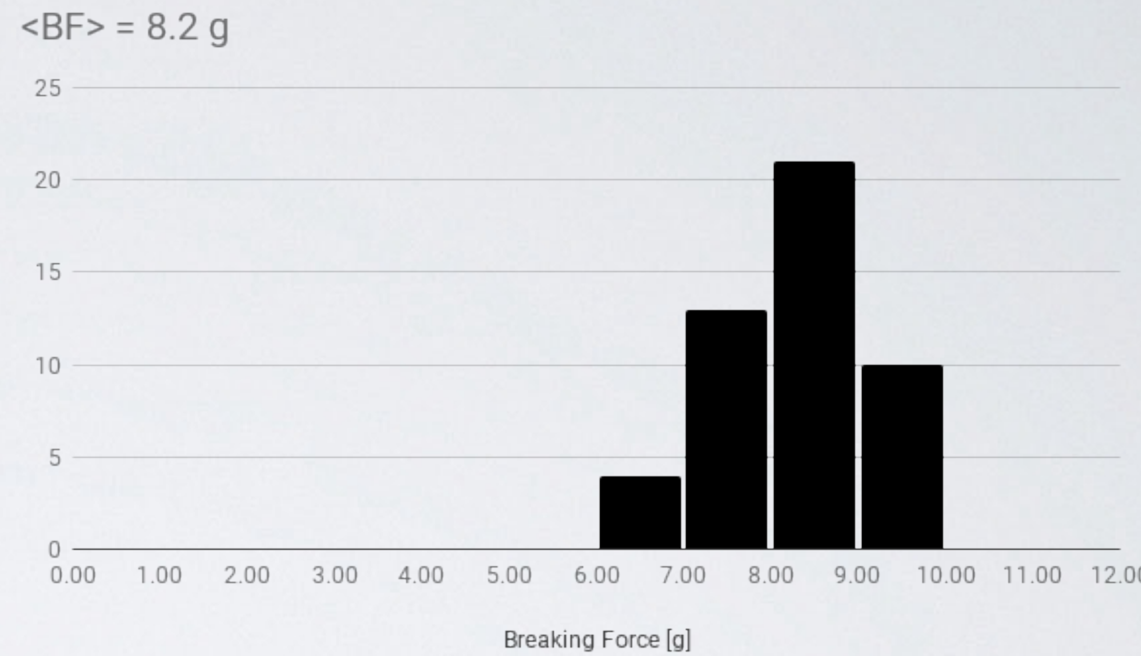


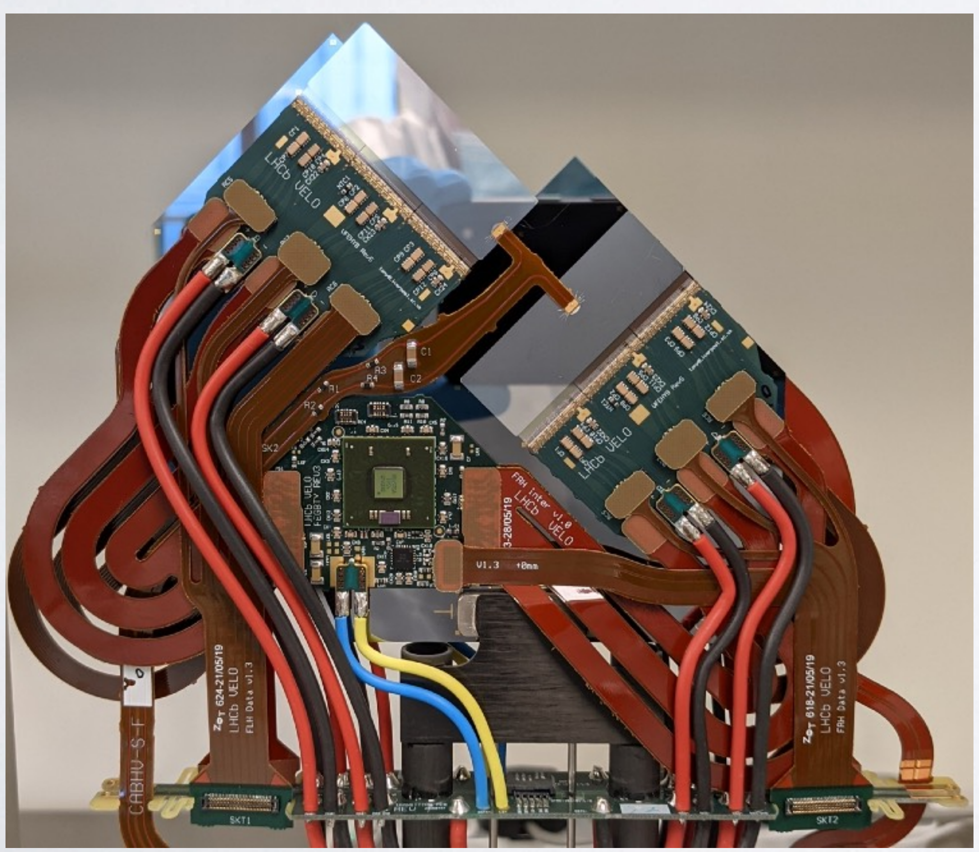


Pull-testing and cabling

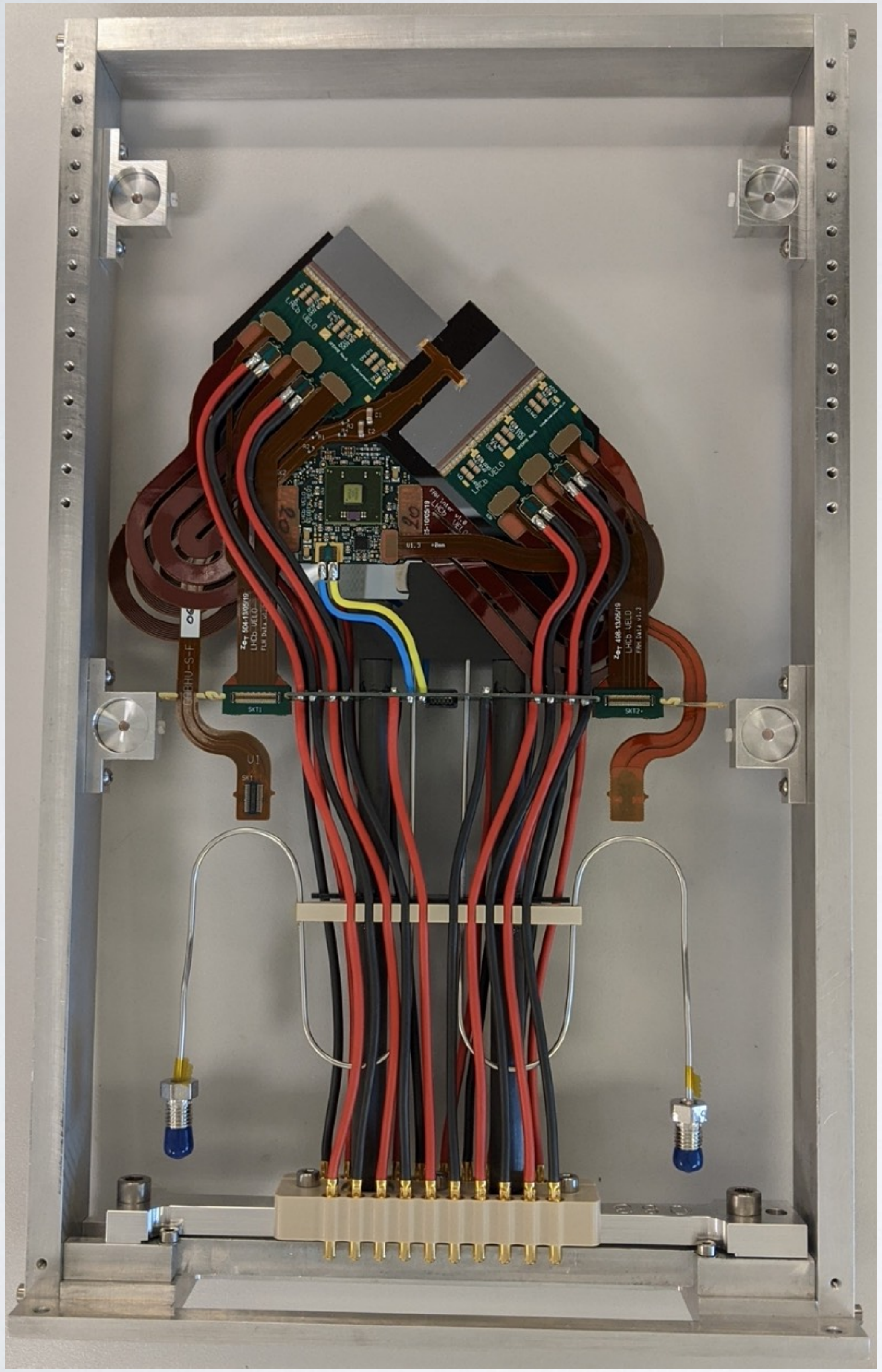
- 4 sacrificial wire-bonds per chip
- Aim at a breaking force of 8g
- Require breaking force larger than 5g

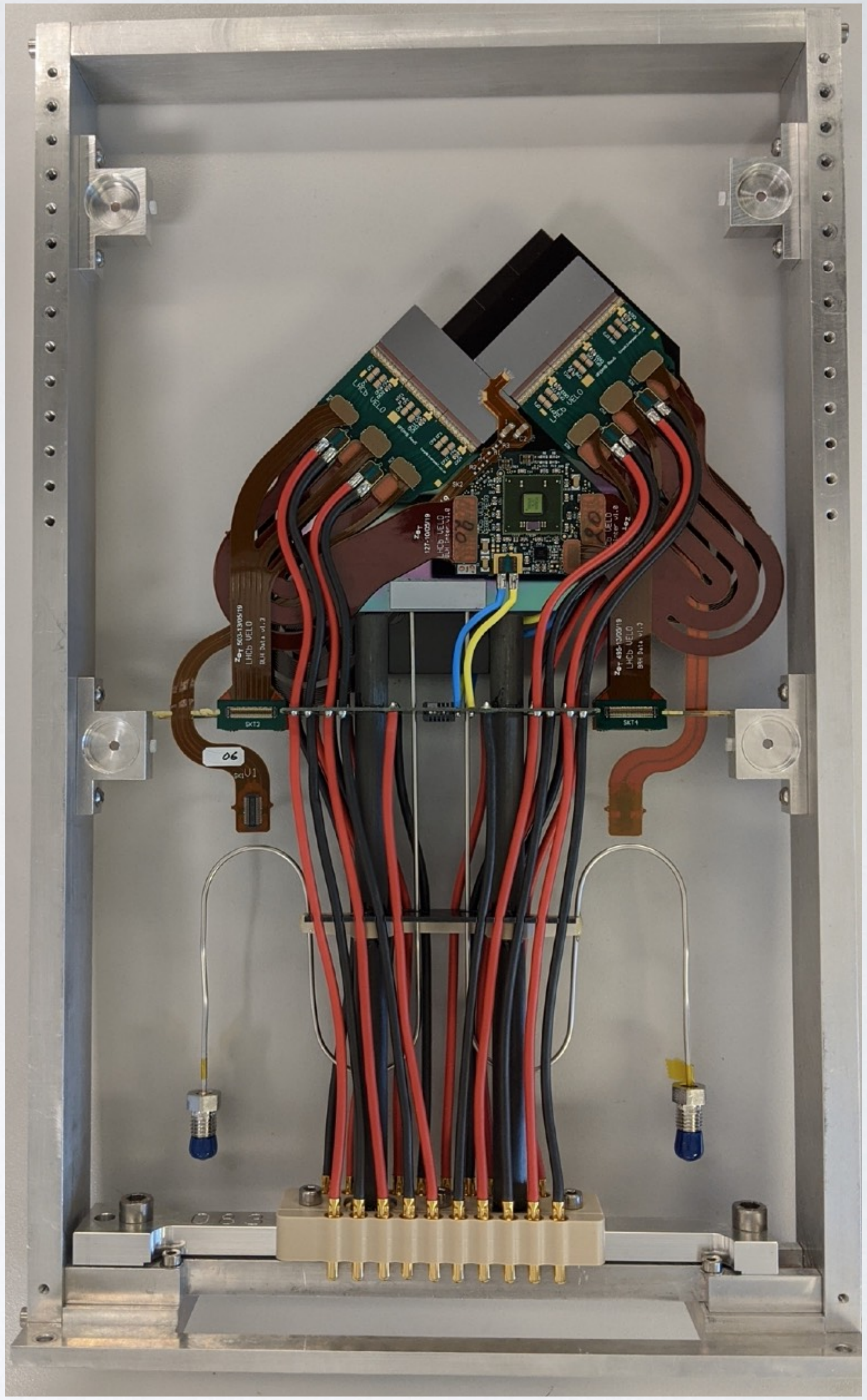




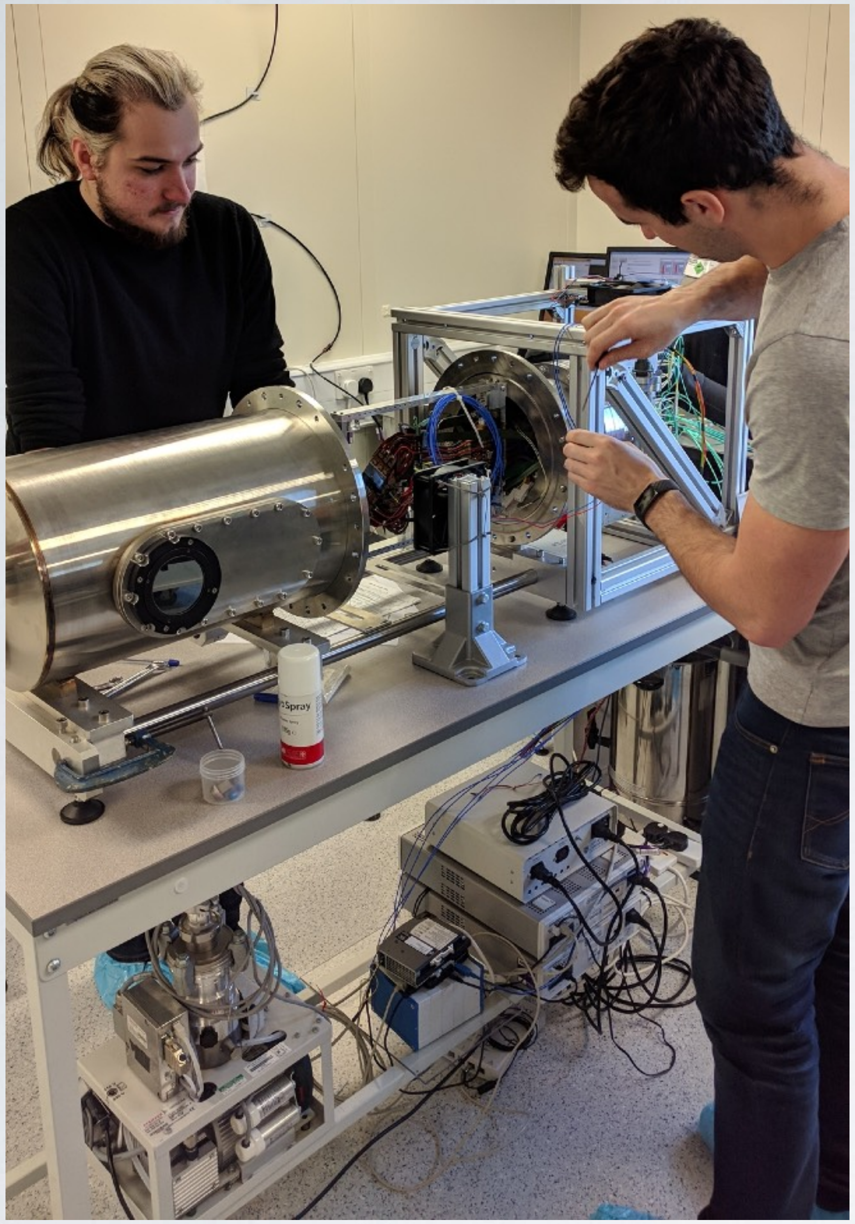


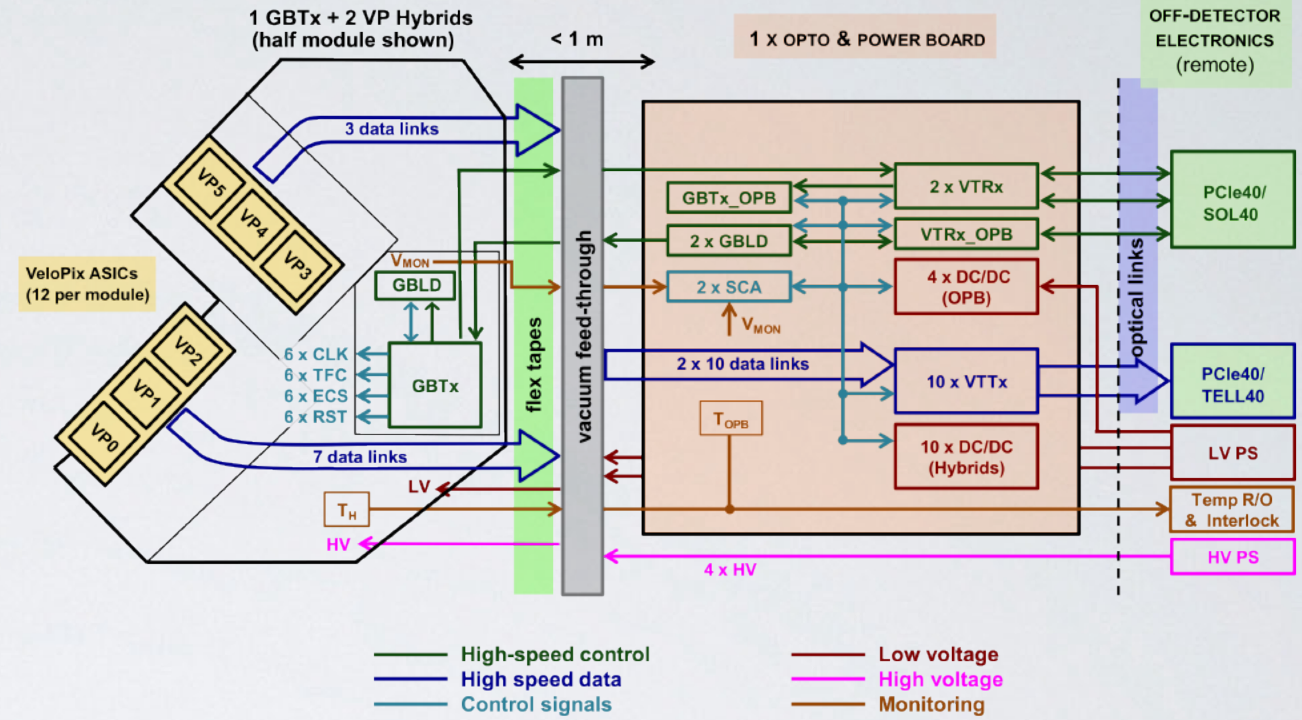
Complete module

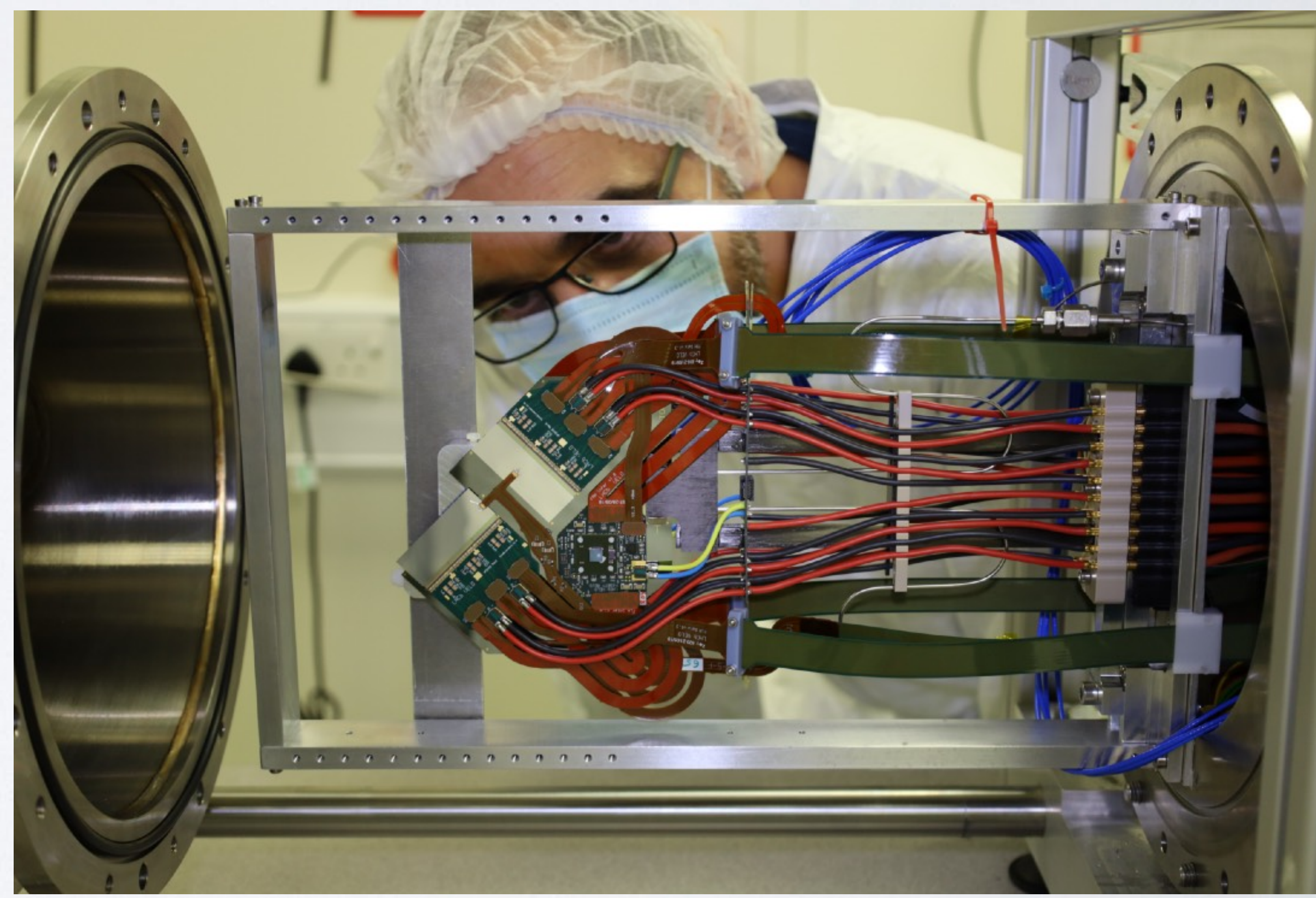




Installation in vacuum tank

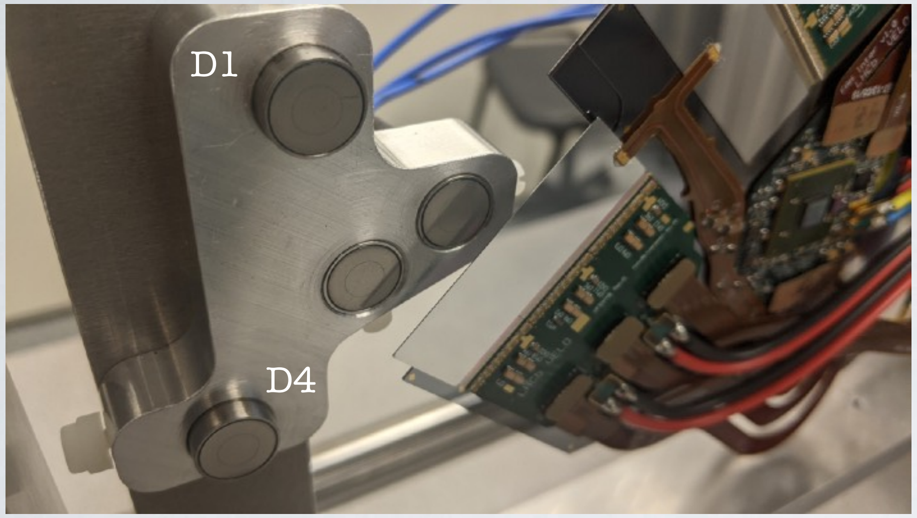


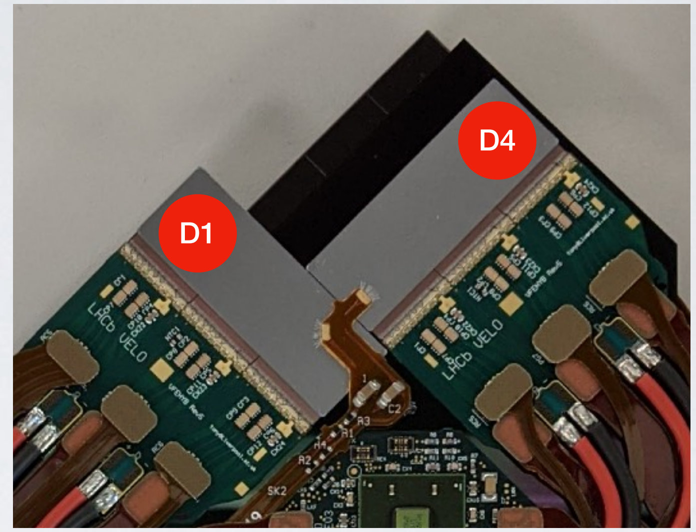


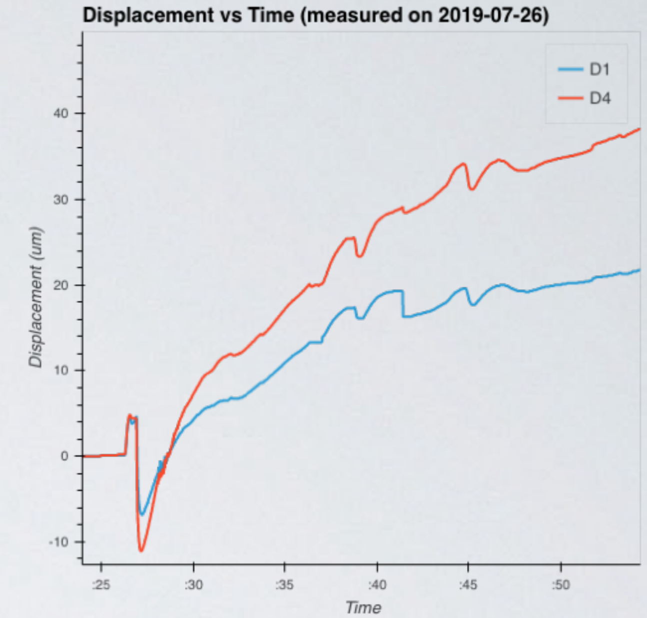


- Installation of displacement sensors
- Connection to cooling plant
- Connection to data tapes
- First mechanical and electrical checks in air

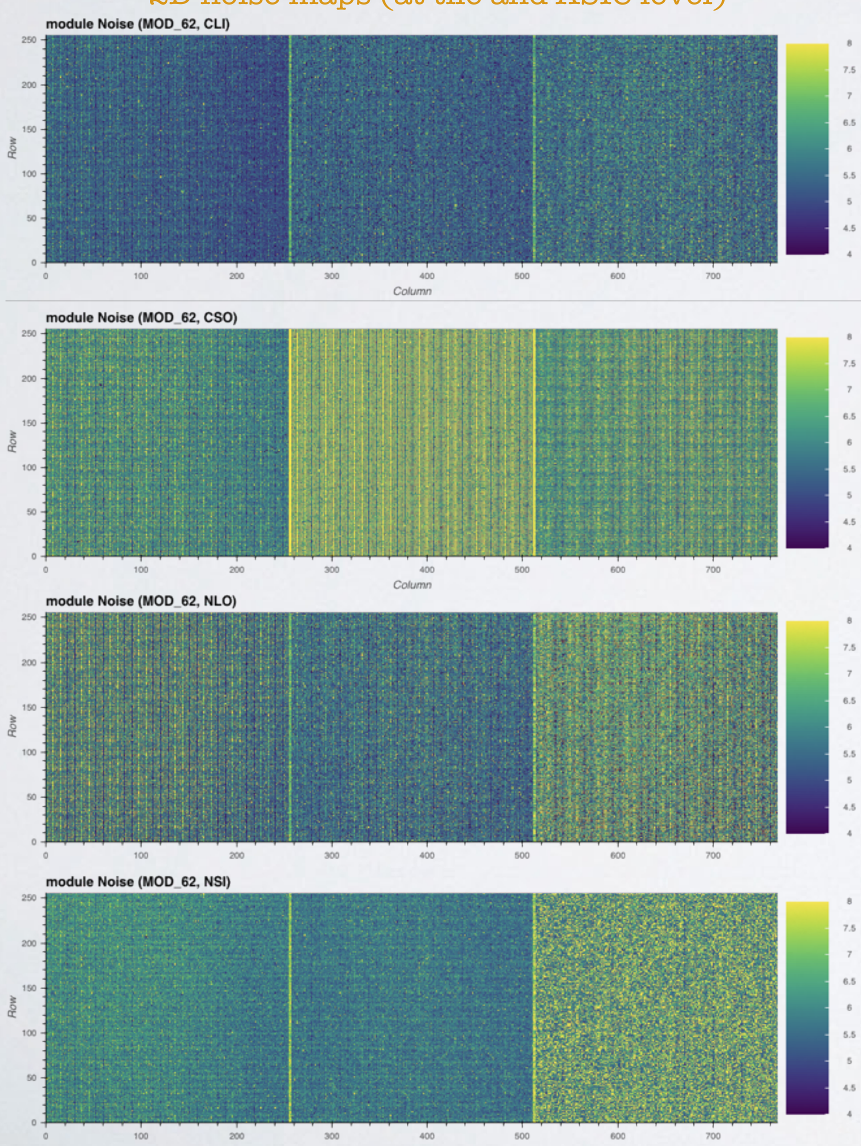
Quality assurance



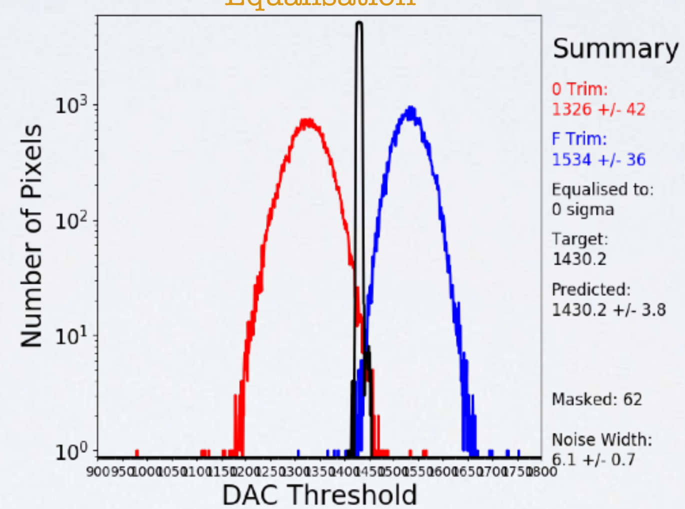


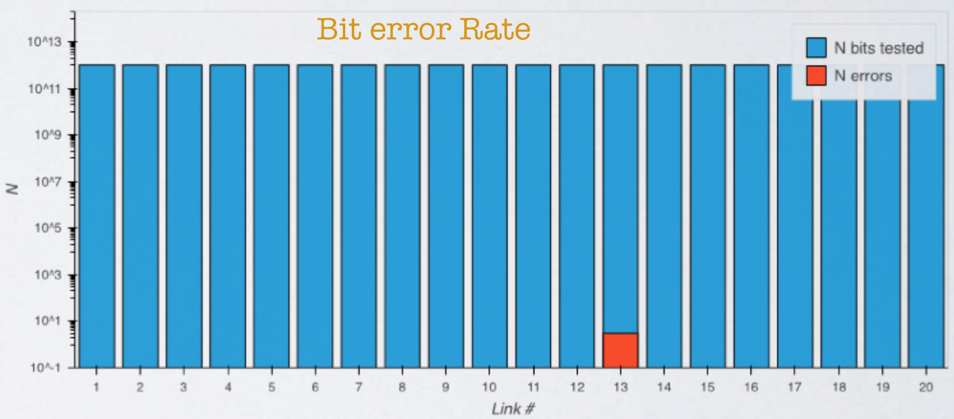


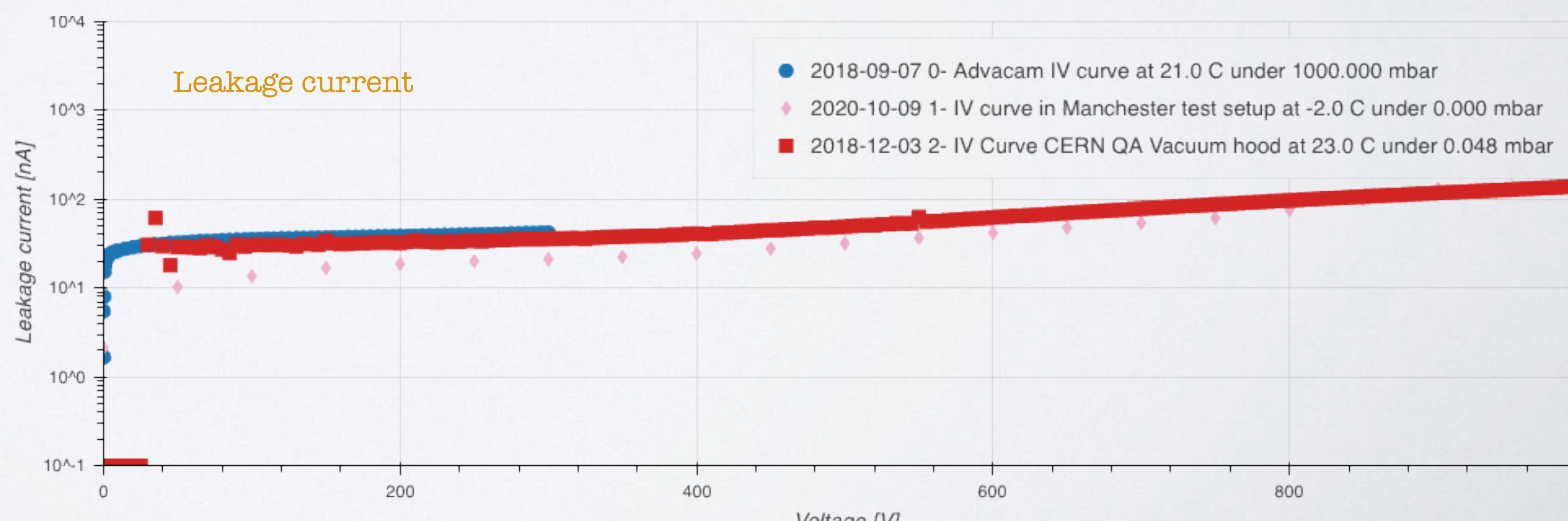
2D noise maps (at tile and ASIC level)



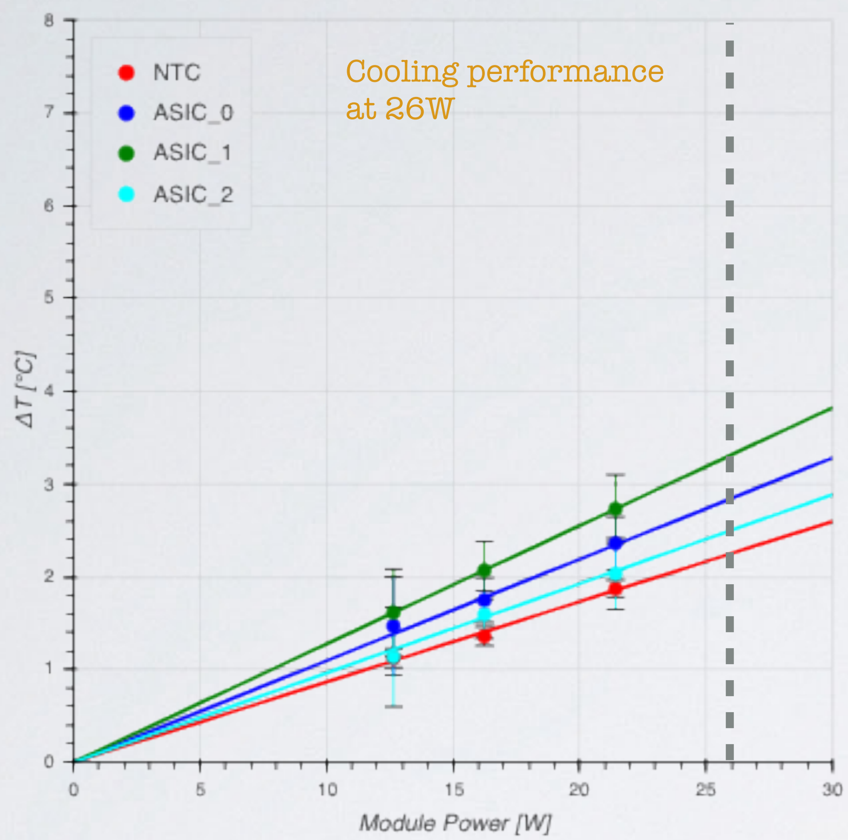
Equalisation



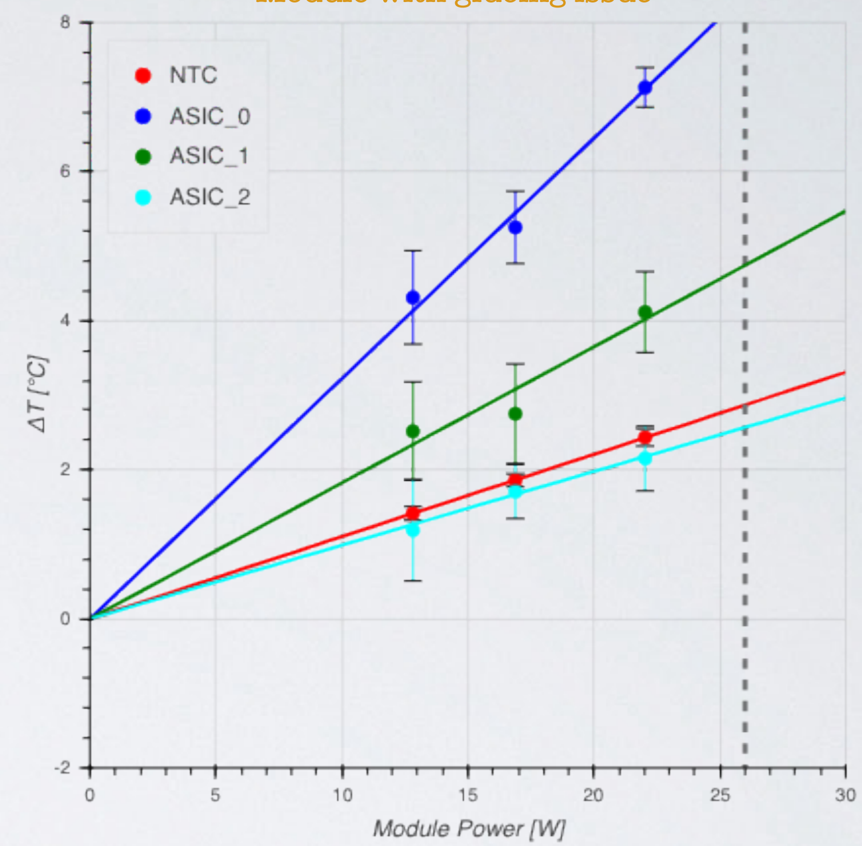


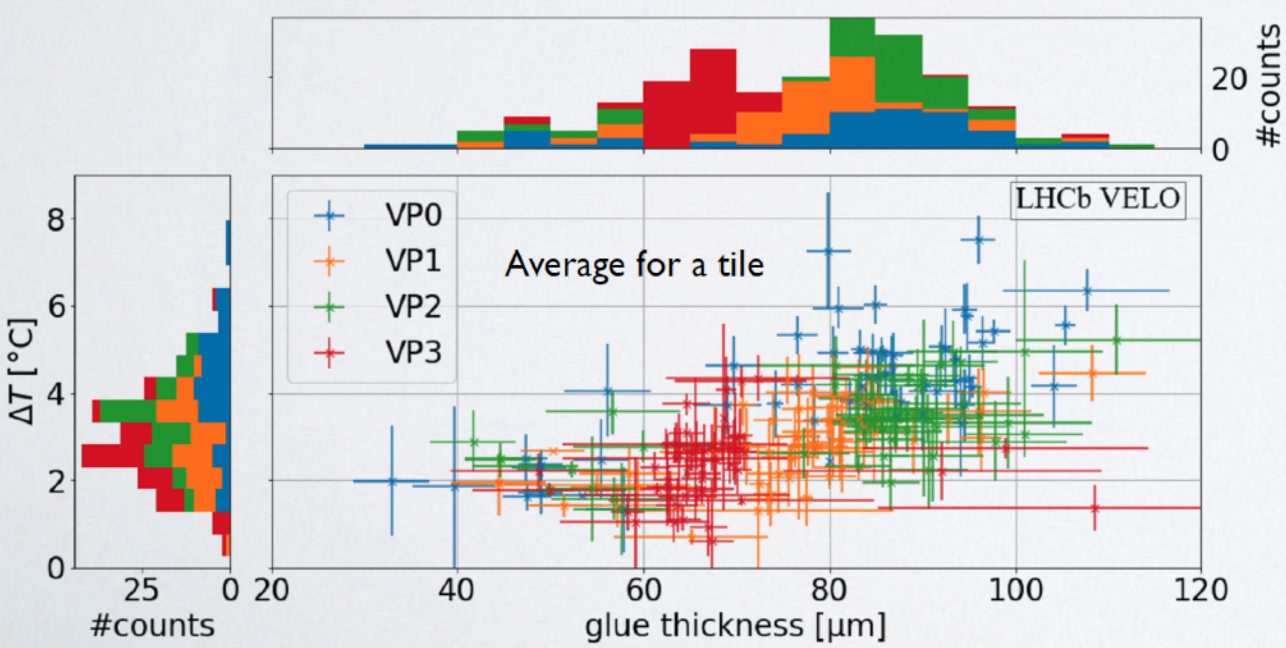


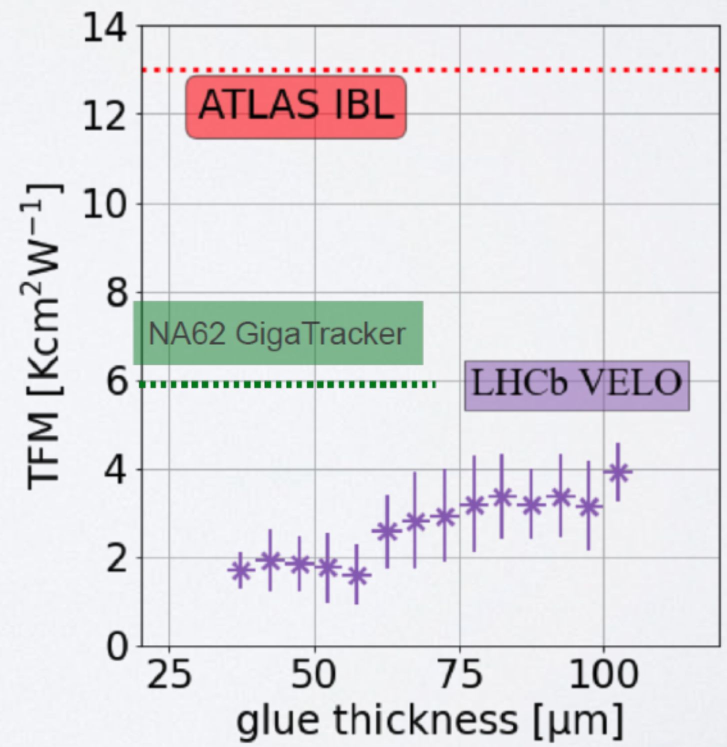
Cooling performance



Module with glueing issue







Thermal Figure of Merit

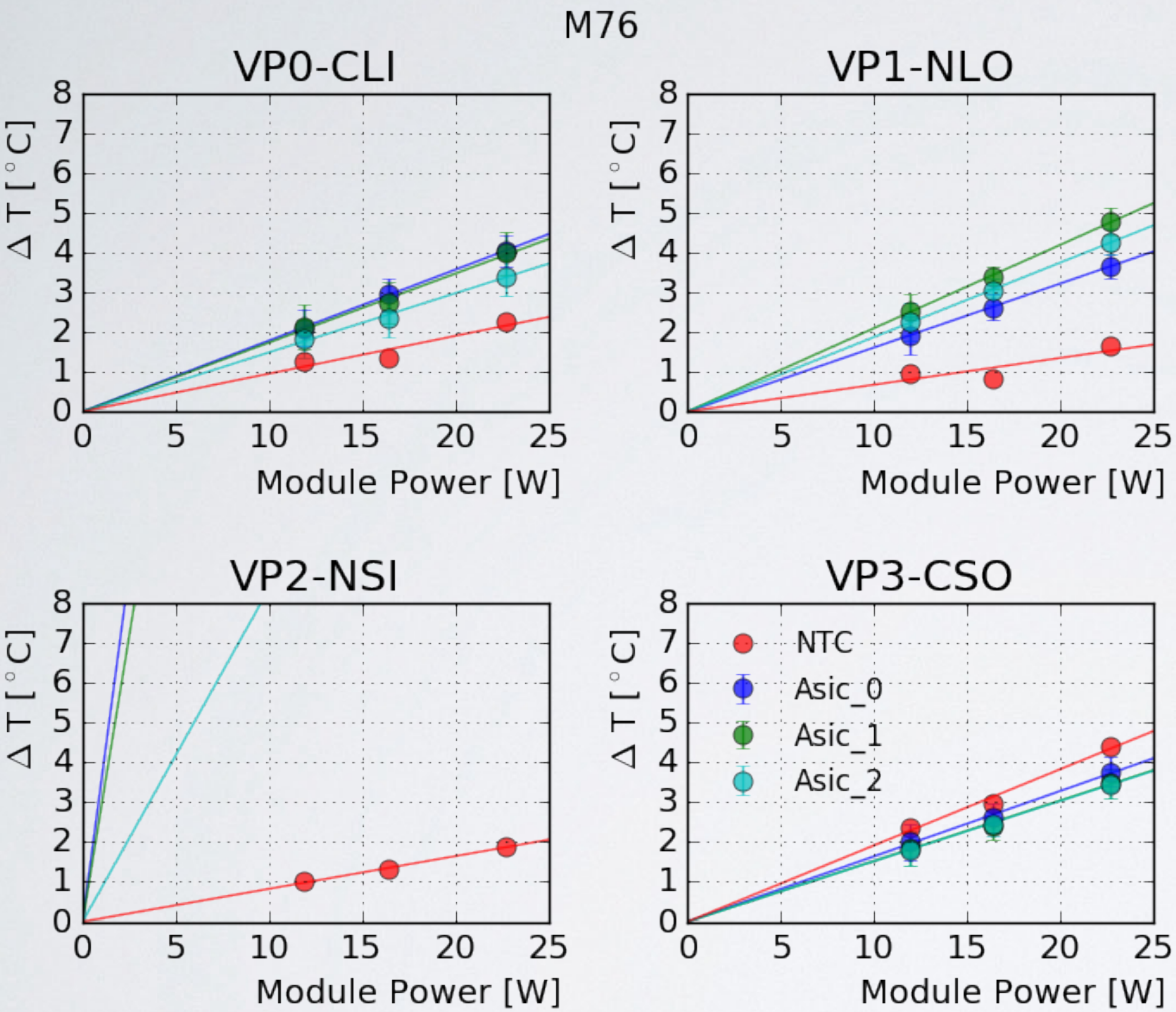
$$\mathrm{TFM} = \frac{\Delta T(\text{coolant - heat source})}{\text{Power Density}}$$

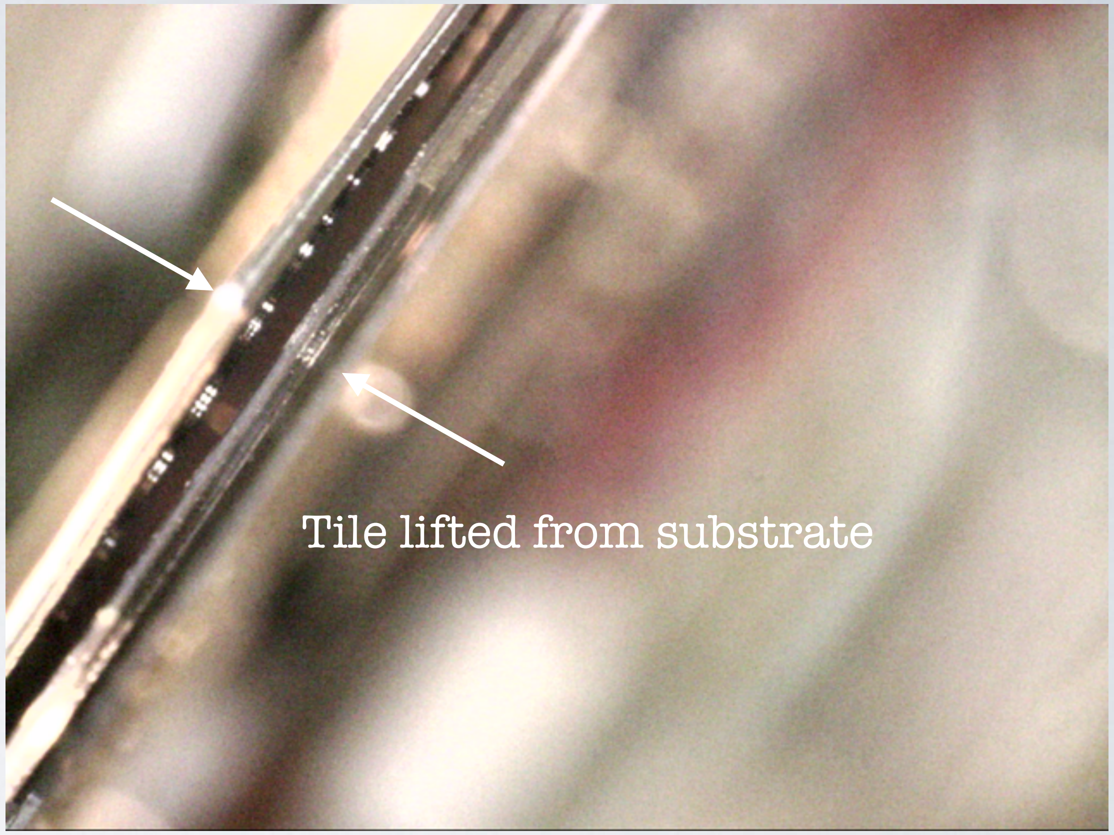
~20 for classical systems

~12-13 for integrated pipe systems

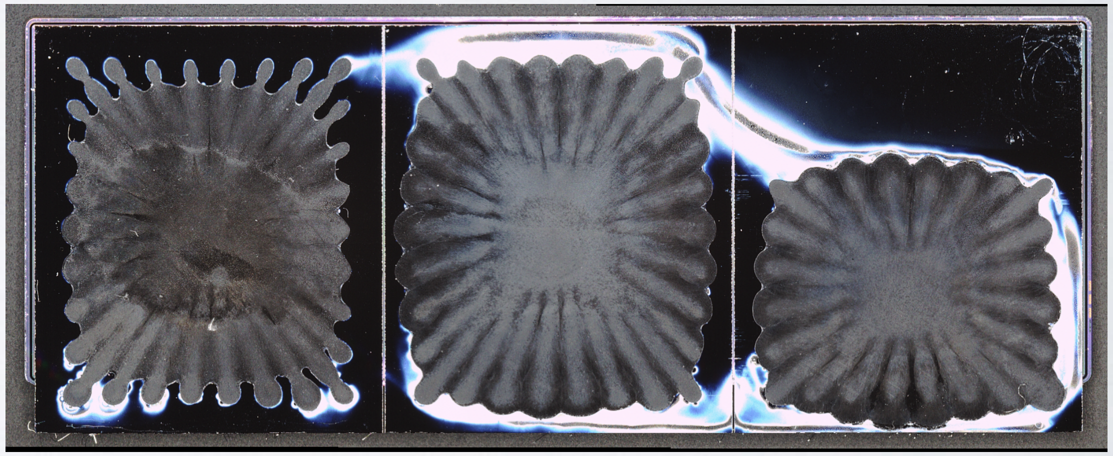
~5-6 for single phase micro-channels

Tile detachment



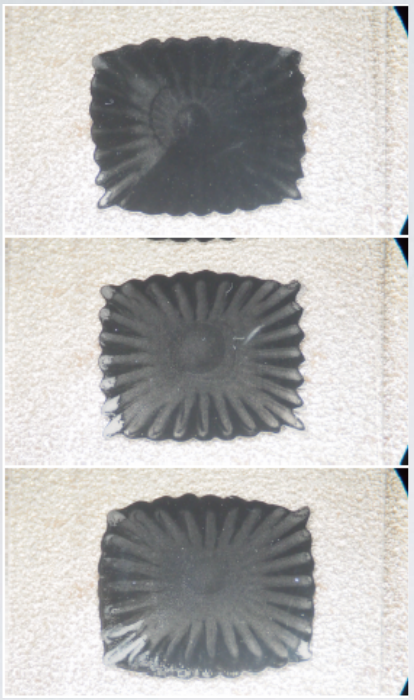


Glue discolouration

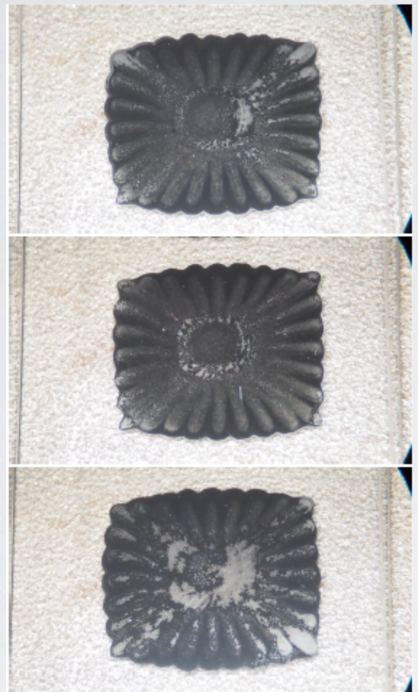


Glue adhesion issue

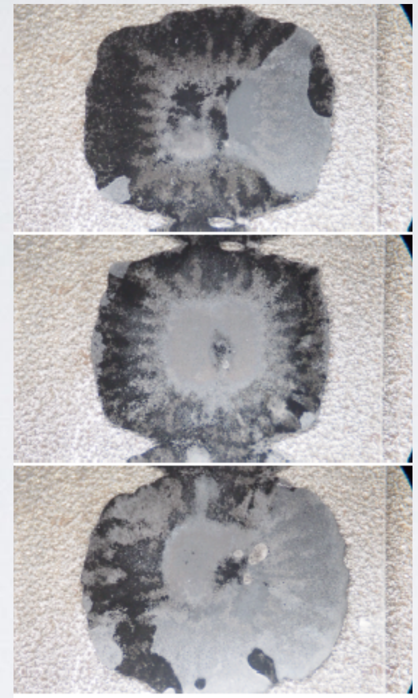
Direct



Dry Environment

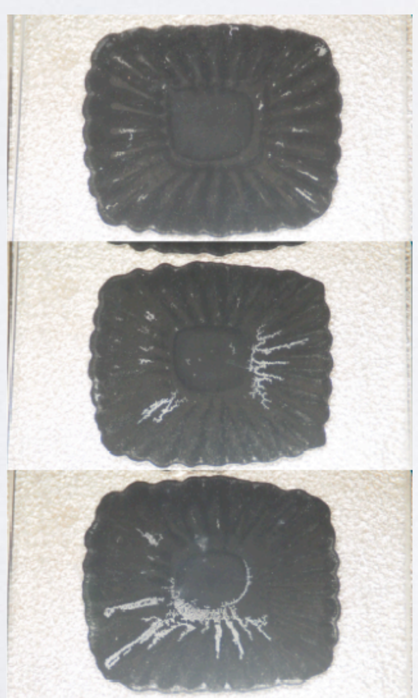


Wet Environment

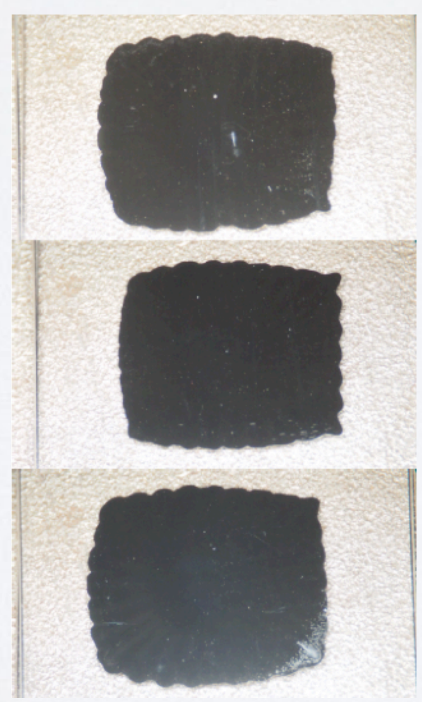


No heat treatment

20 s heat treatment



60 s heat treatment



Hypothesis

Bad adhesion is due to a water layer forming on the surface of the glue patterns, because of the hygroscopic nature of the catalyst.

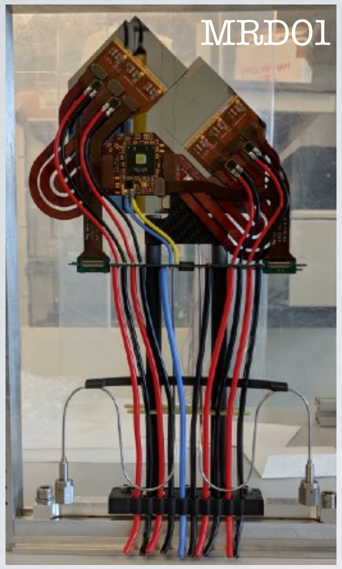
Tests

- Environmental samples I: glass on glass samples, left exposed to different environments with different levels of moisture.
- Heated samples: glass on glass samples, left exposed to air for different amounts of time and then heated to remove the water layer.
- All samples visually inspected before and after ageing them in the oven at 70 °C.
- All samples pull-tested to evaluate joint strength.

Solution

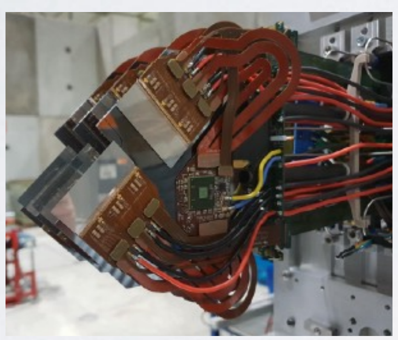
- Change glue catalyst (cat9 → 23LV).
- Heat glue layers to 60 °C for 1 minute and attach straight away.

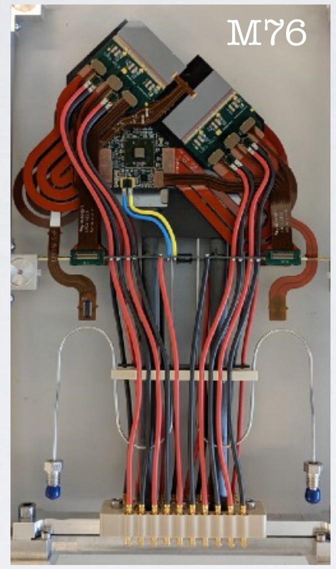
Production milestones



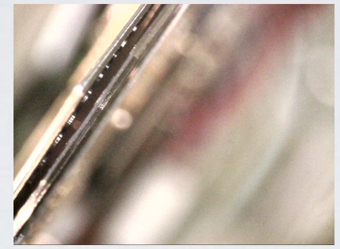
May 2018
1st full mechanical module

September 2018
1st electrical modules (testbeam)

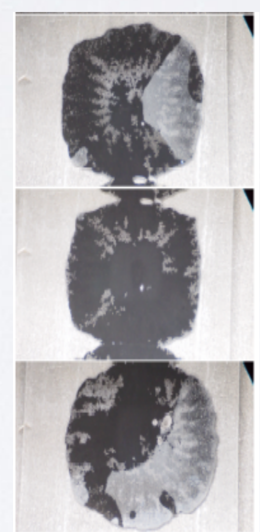




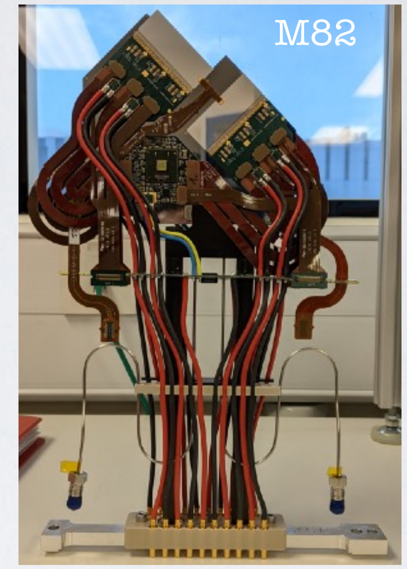
August 2019
1st production module (cat9)



glue crisis

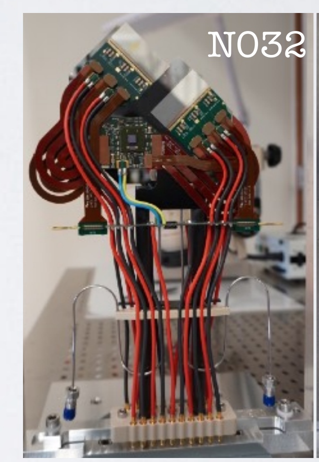


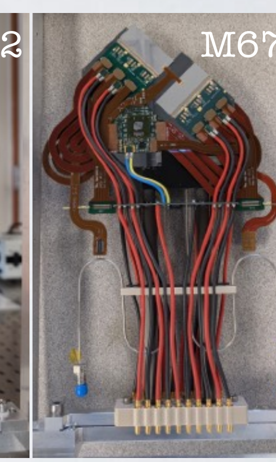
No access to labs for months



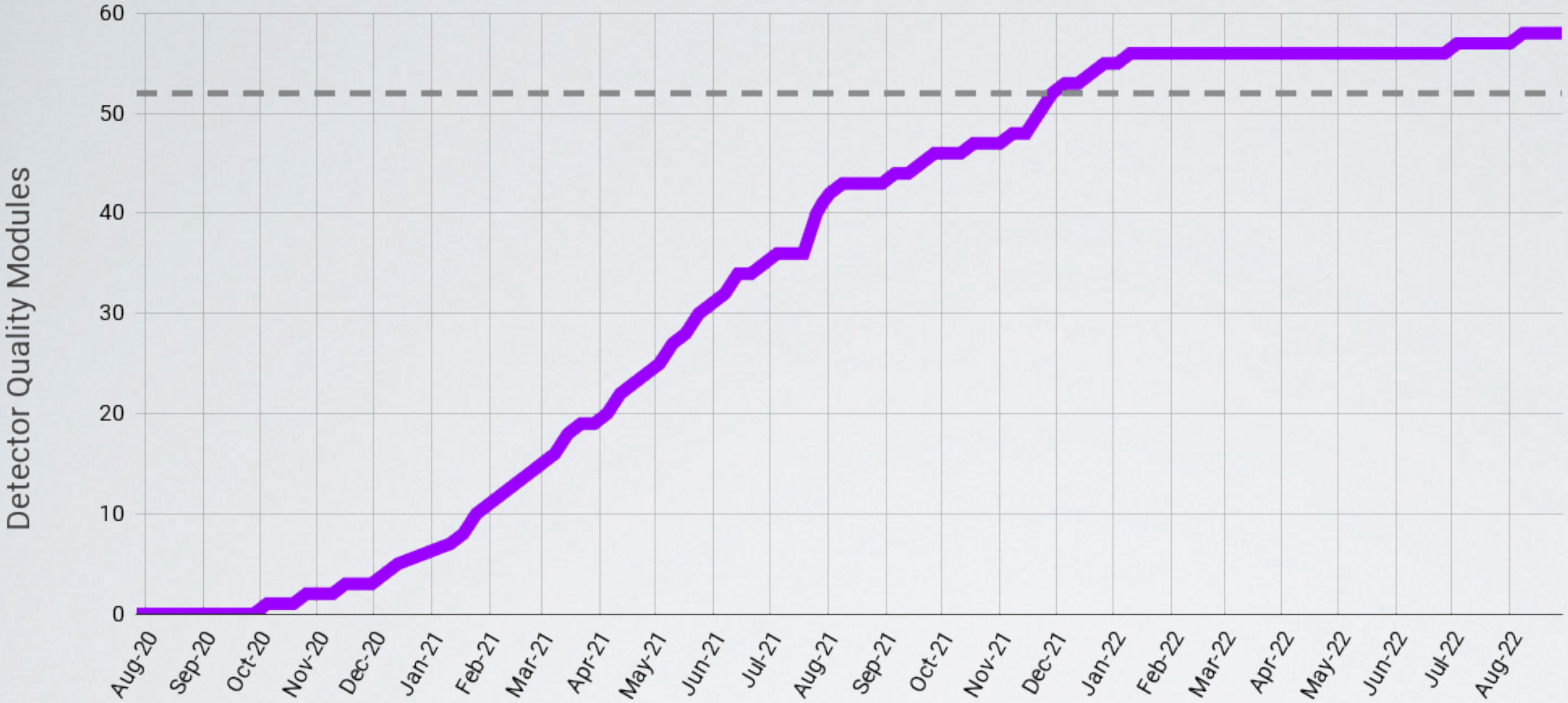
August 2020
“new” 1st production module (cat23LV)

November 2021
51st and 52nd production modules

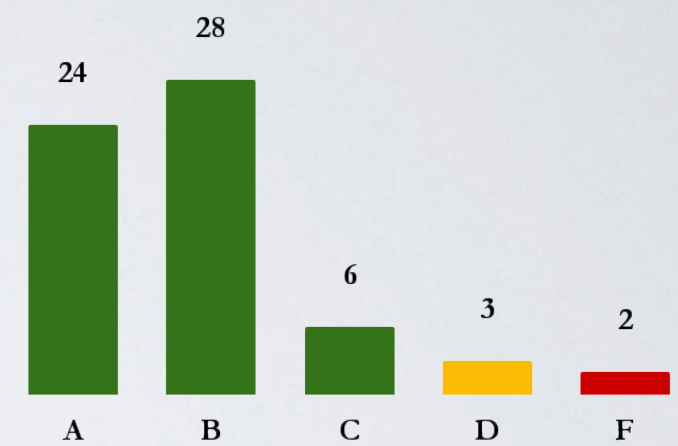




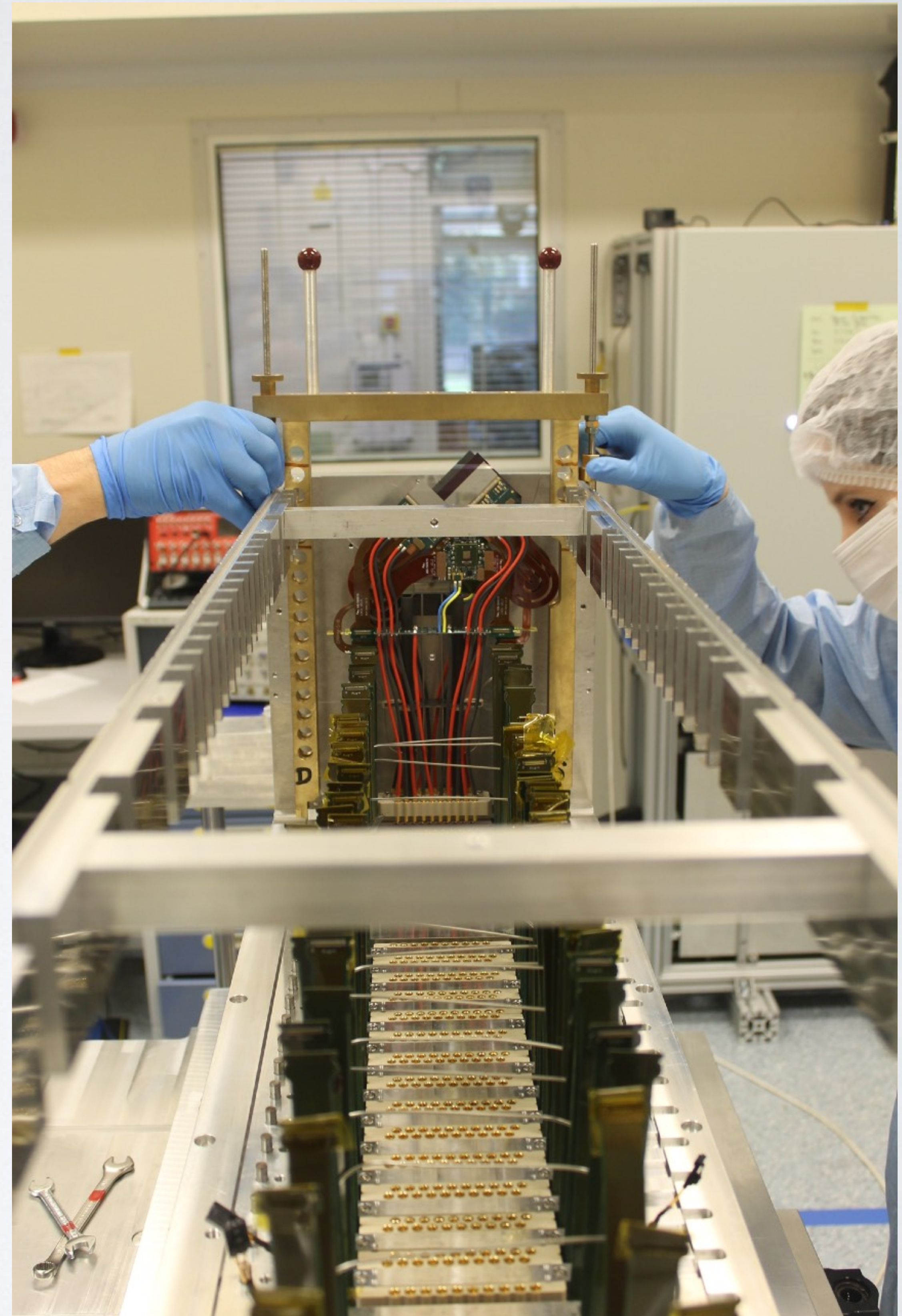
Summary of production



- First 52 modules produced in 16 months
- 63 modules produced
- 58 of detector quality

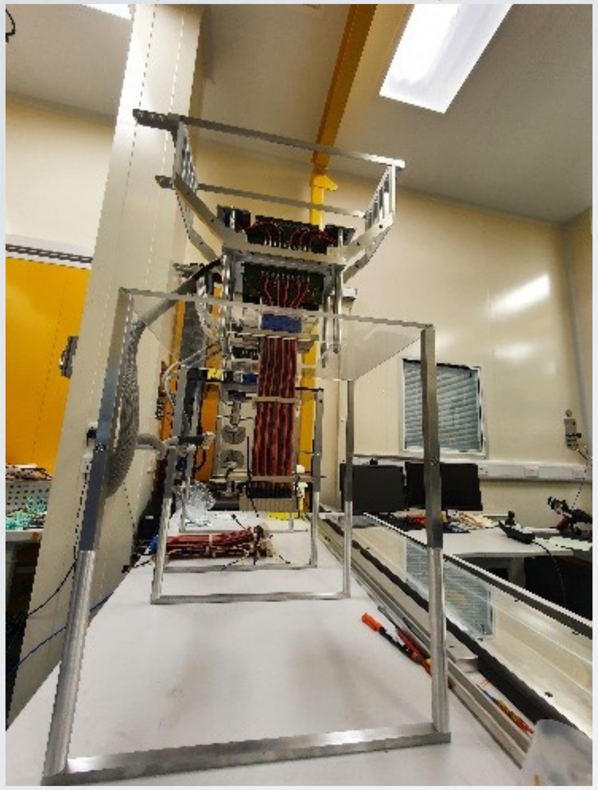


Installation on VELO base



Production of VELO mechanics

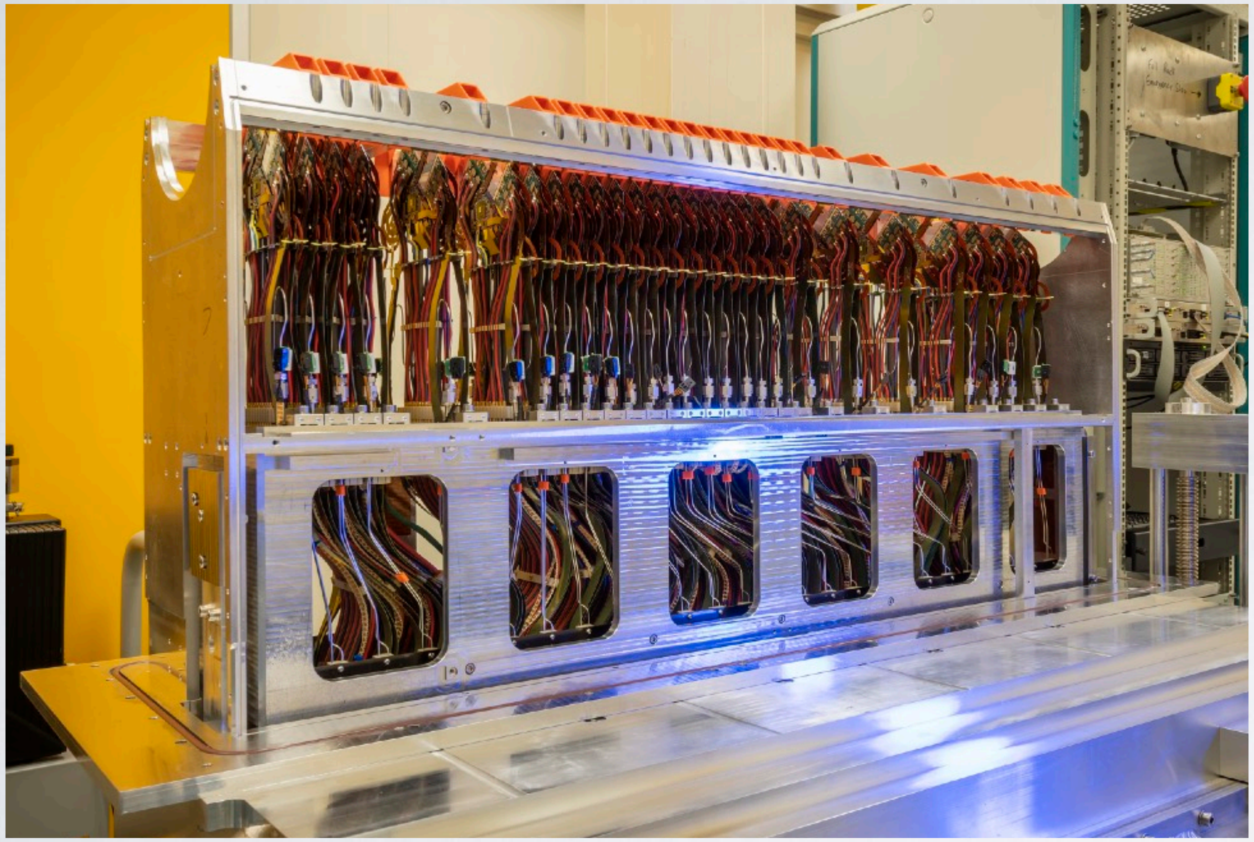
feed-through flanges
(LV, HV, data)

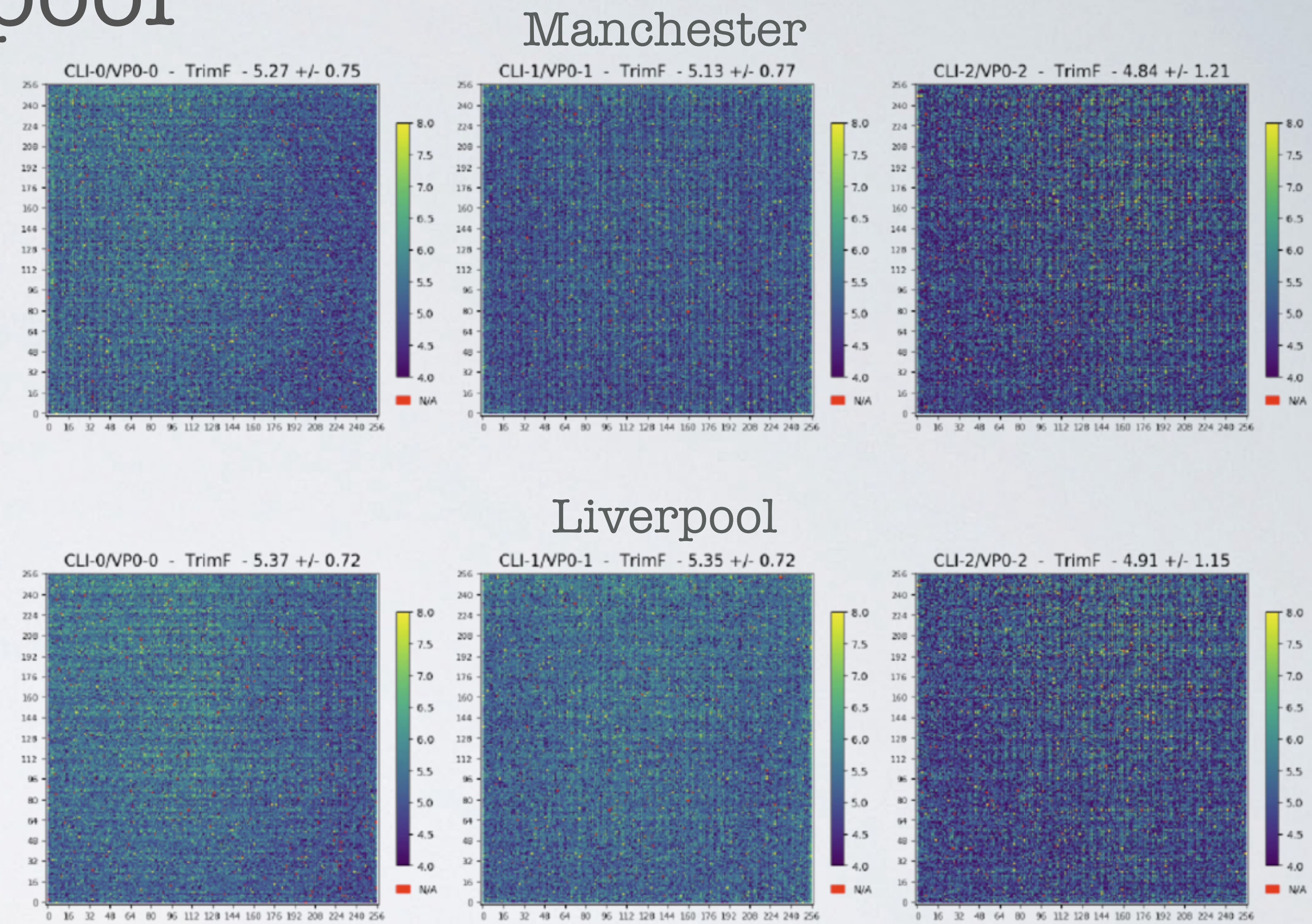


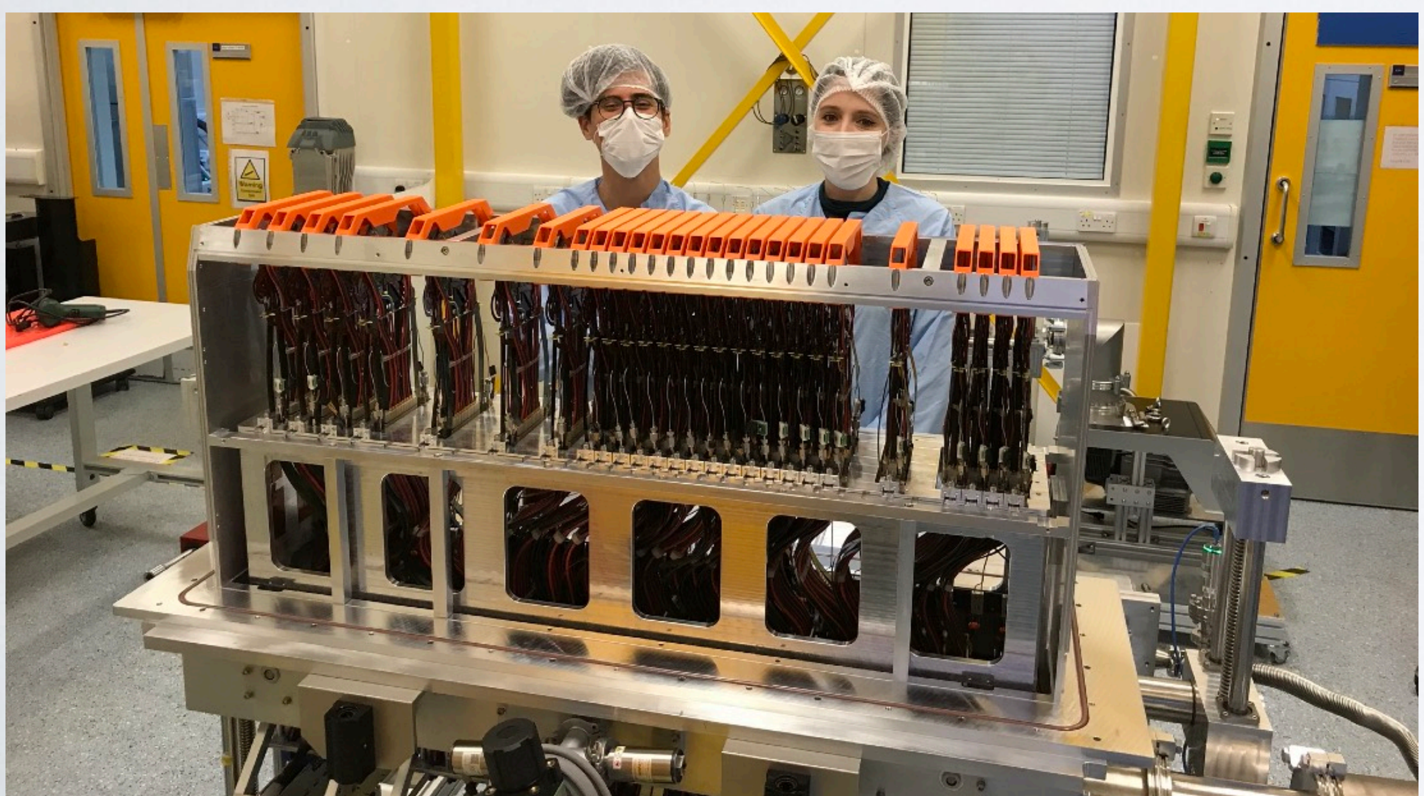
base and hood for module population

Transport frames

Commissioning at Liverpool





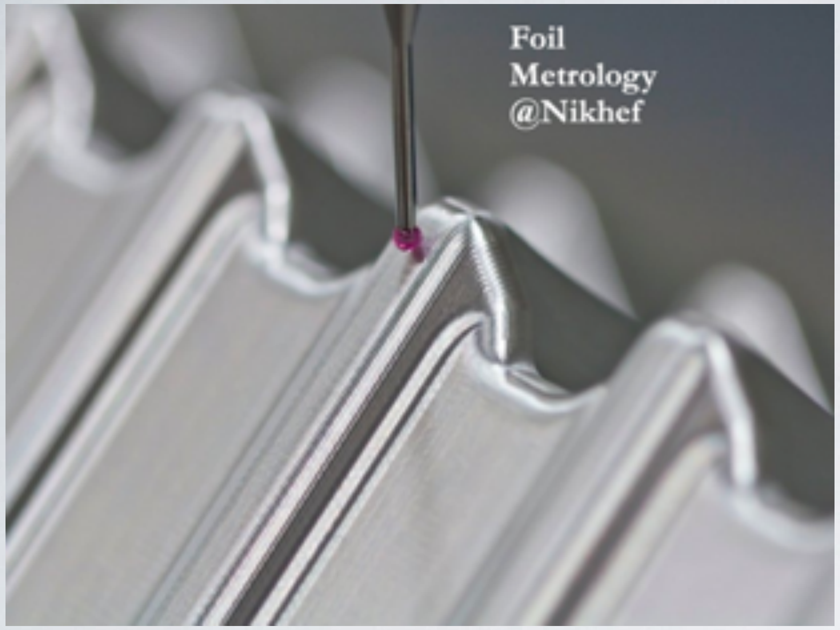


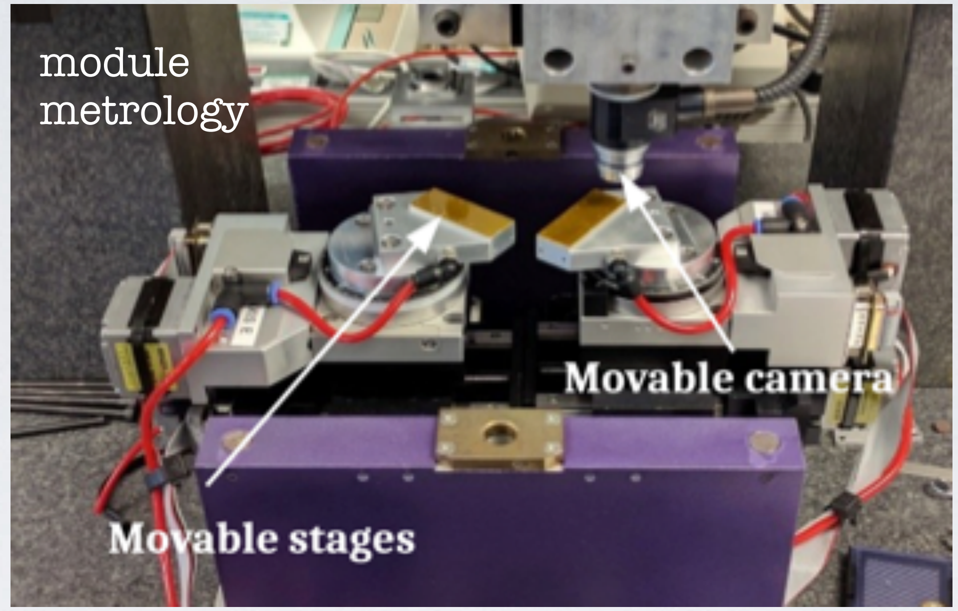
- Machined to high precision
- Tested in vacuum and cold
- Complete electrical tests in agreement with production sites
- Metrology at cold temperature

VELO transport to CERN

- First half transported to CERN in January 2022
- Second half transported in April 2022

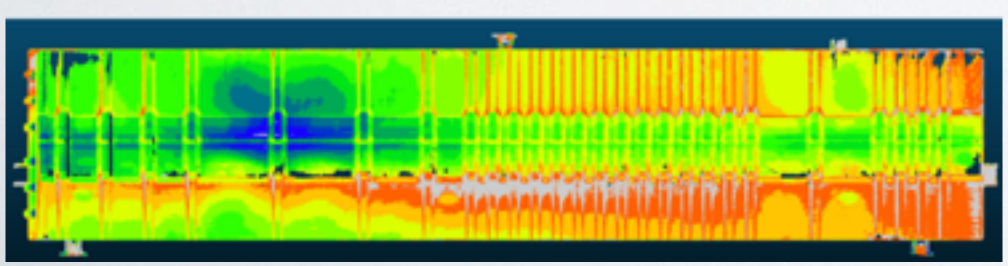
VELO: the many metrologies



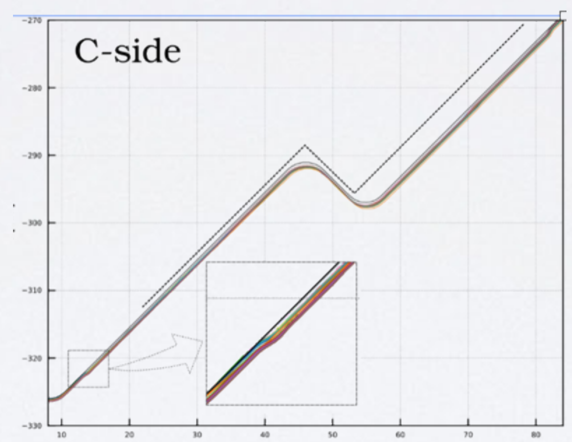


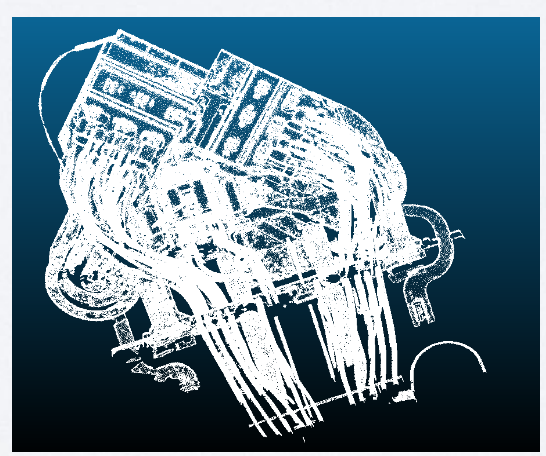
base metrology

foil metrology in situ



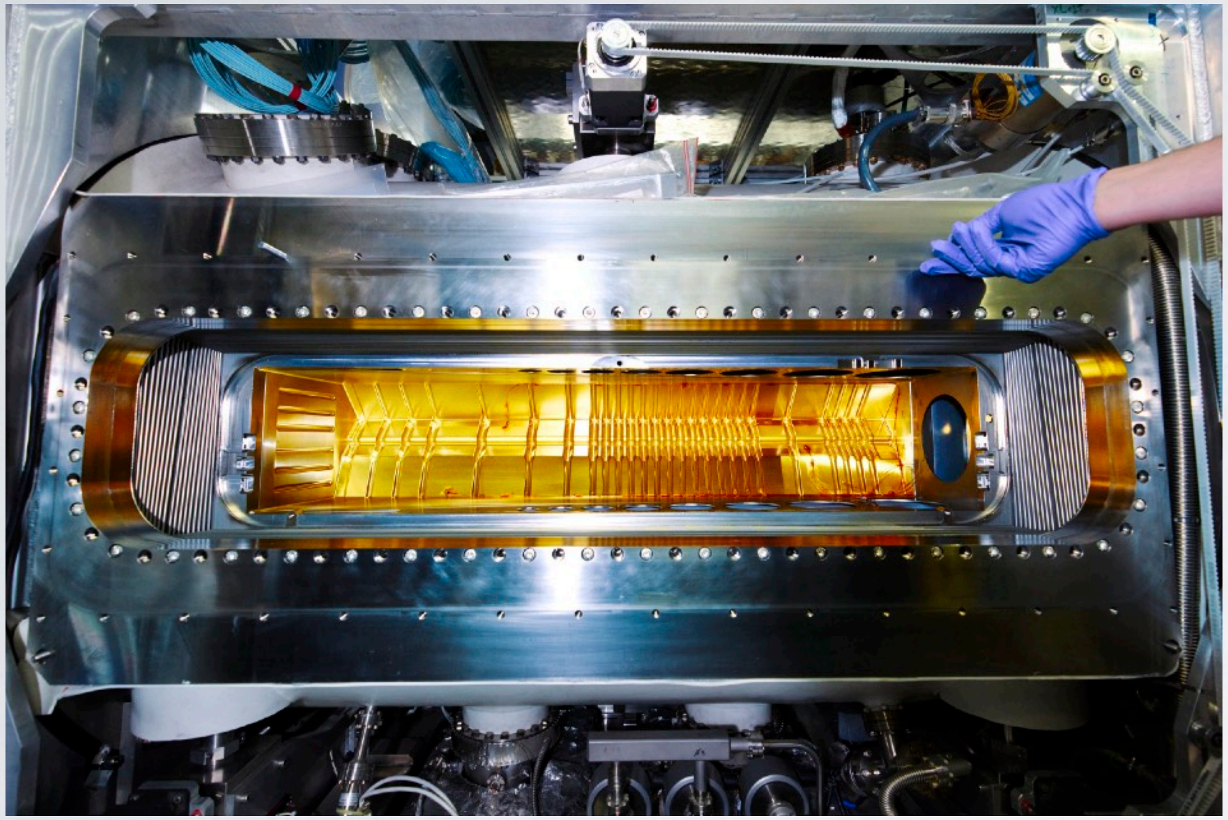
Laser metrology, 1 module

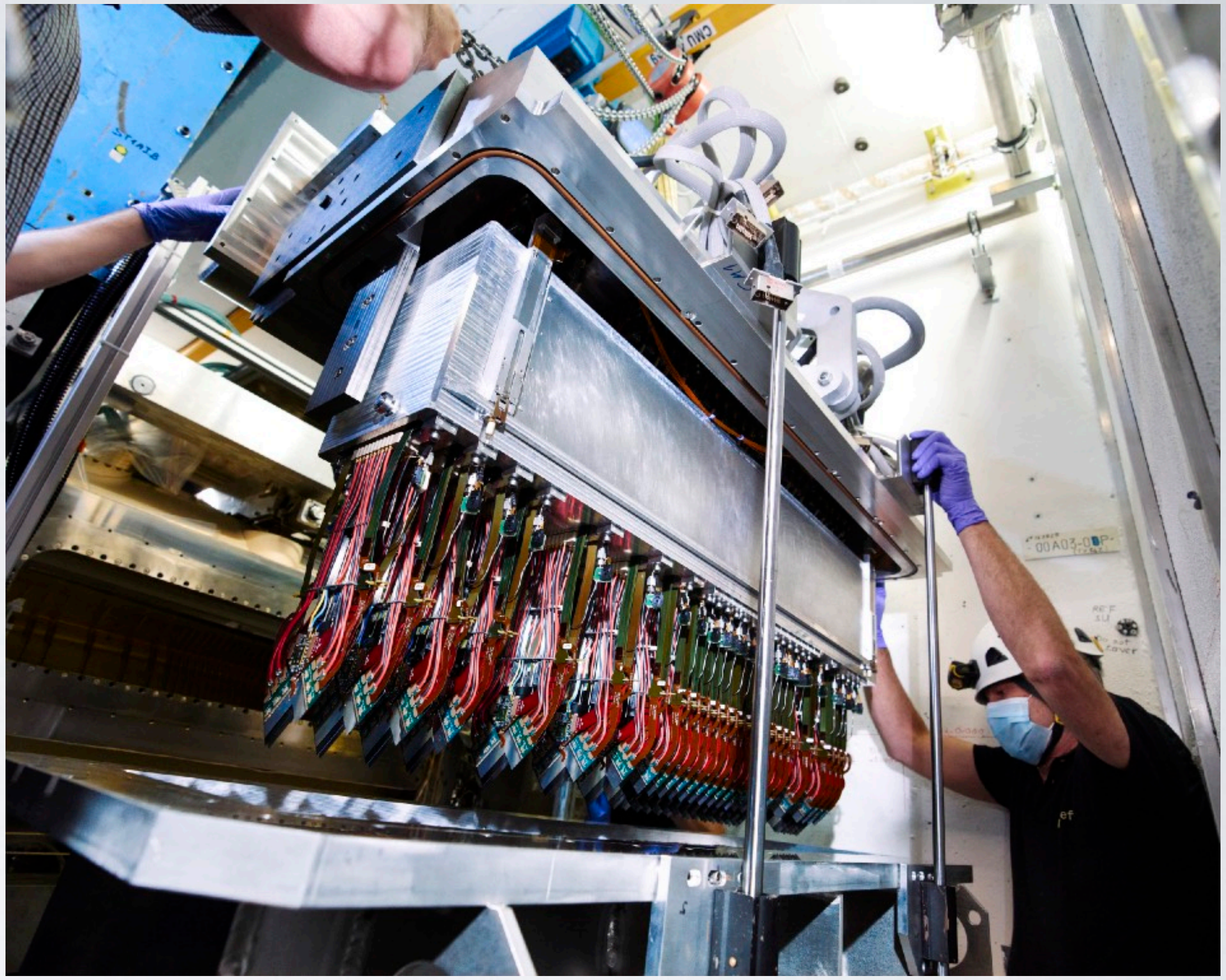


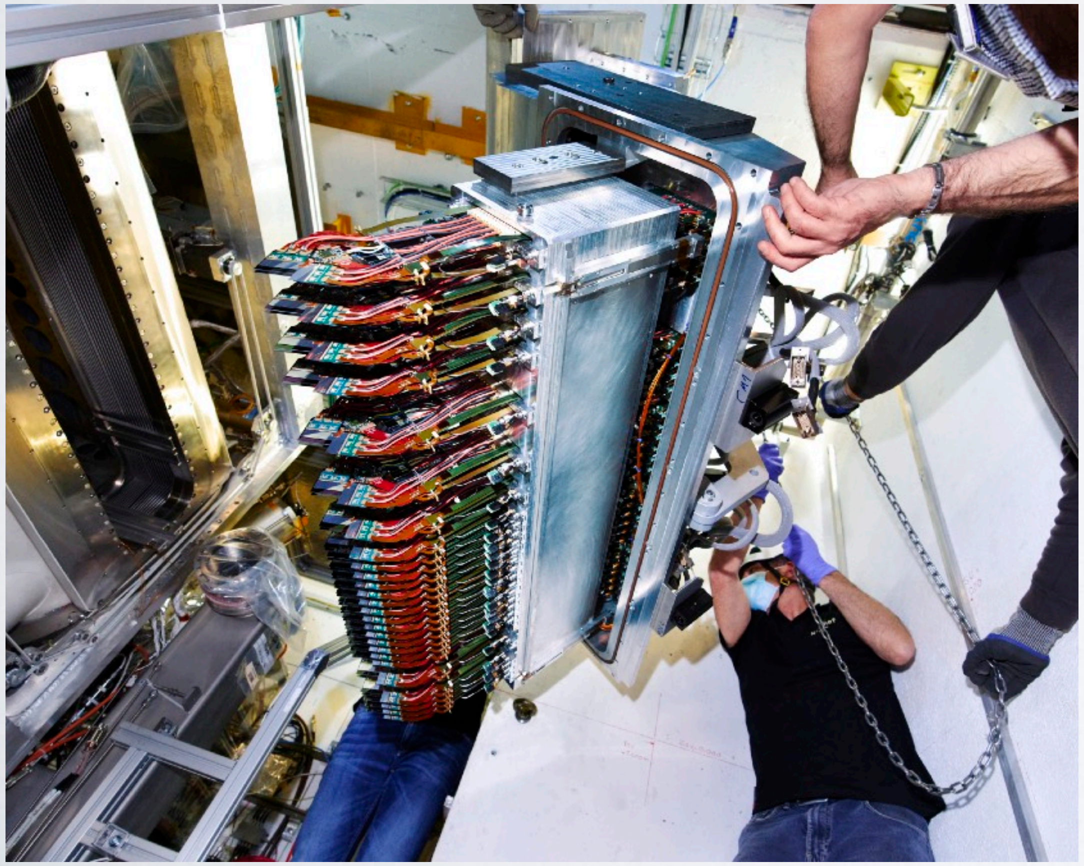


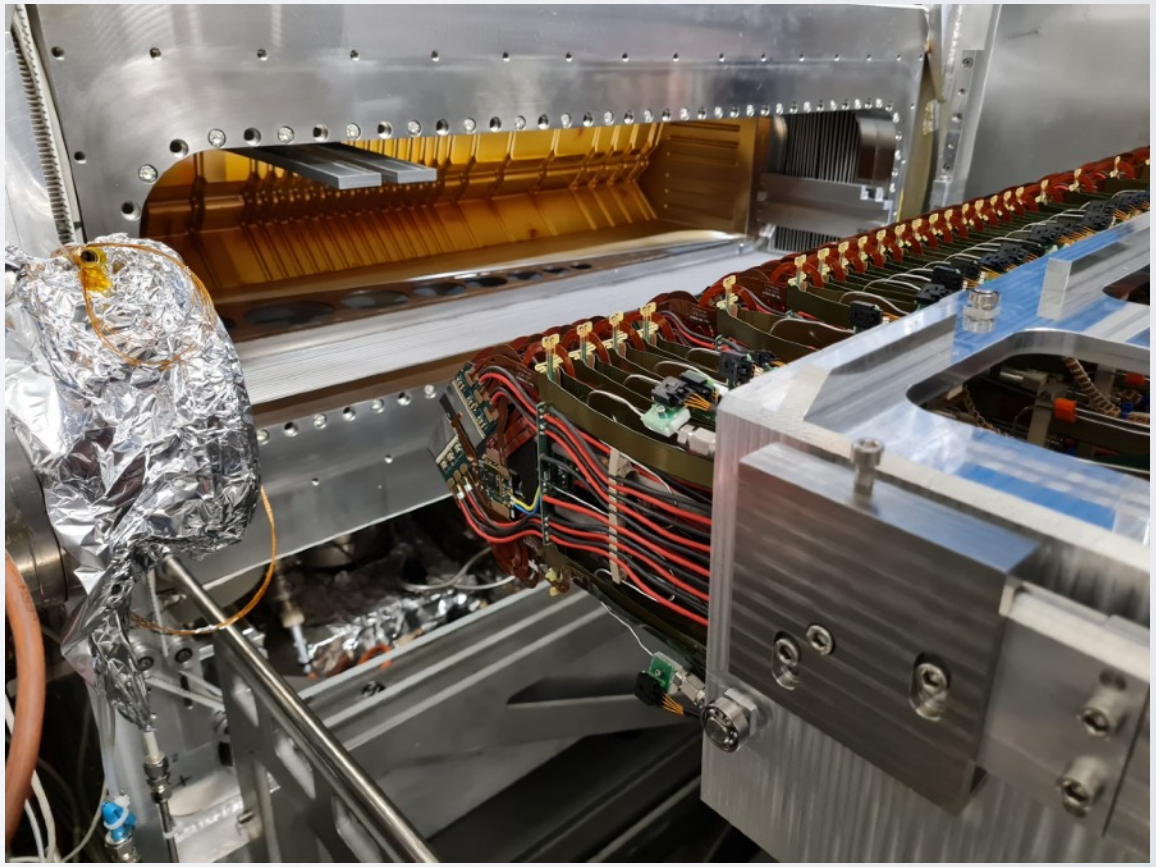
Laser metrology, before installation

Installation at P8



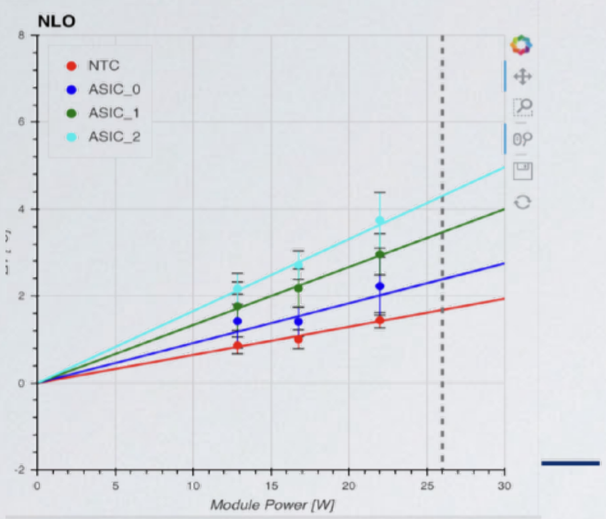




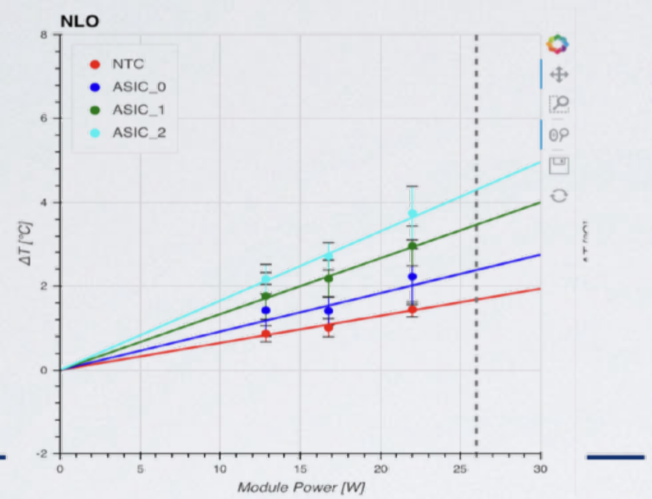


Commissioning

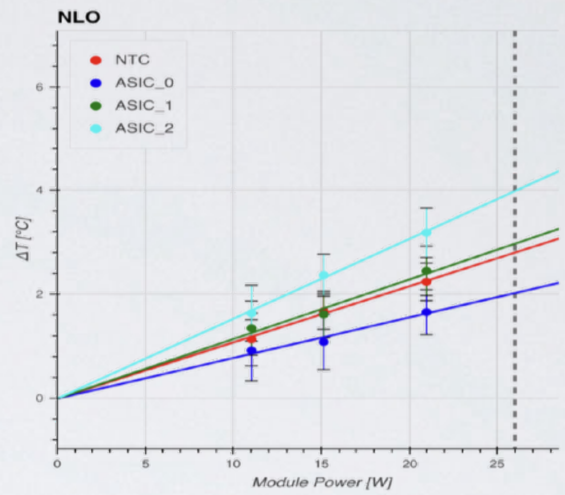
M42, Manchester, before thermal cycling



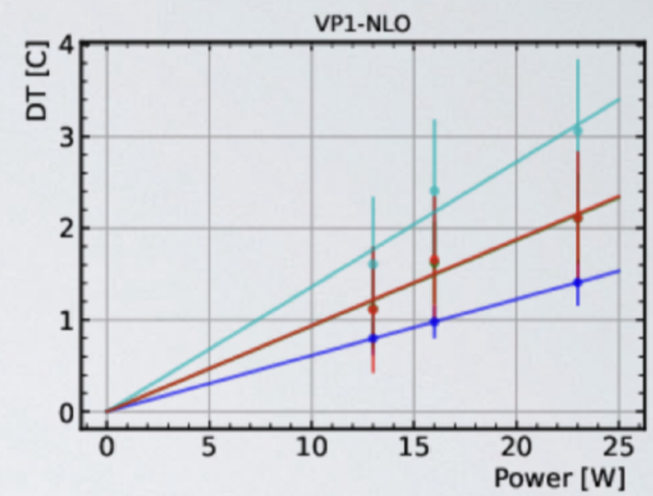
M42, Manchester, after thermal cycling

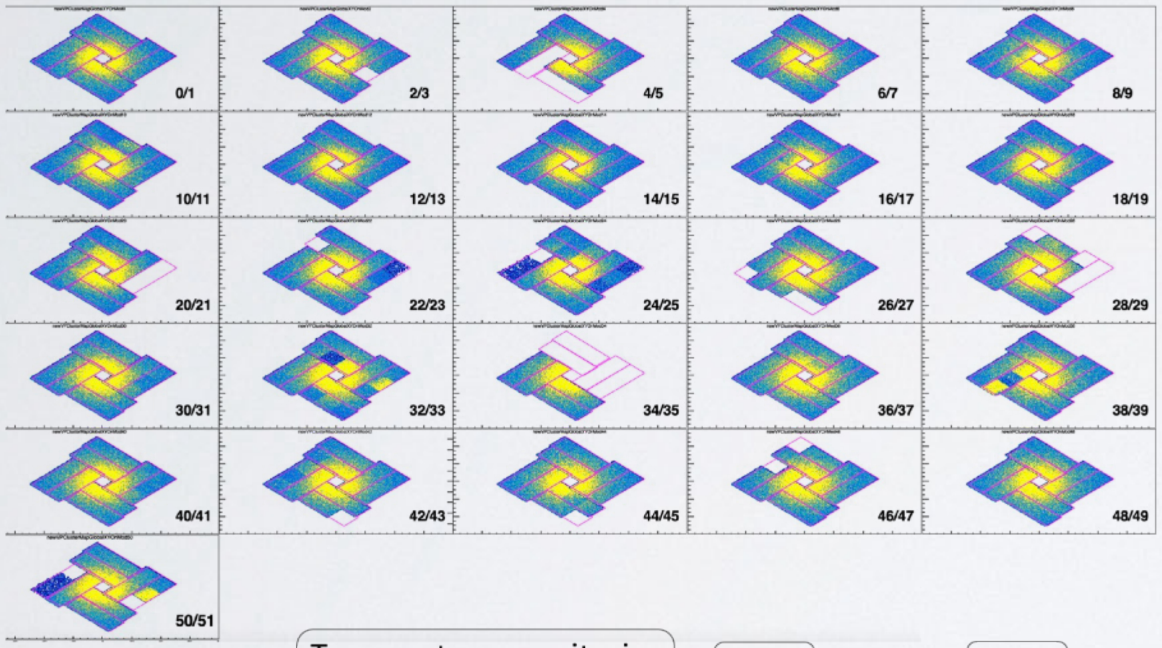


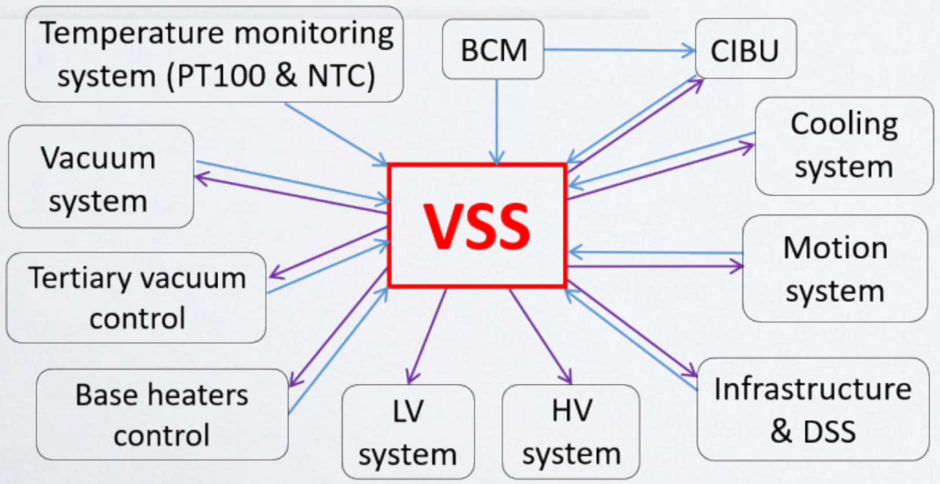
M42, Liverpool, after assembly

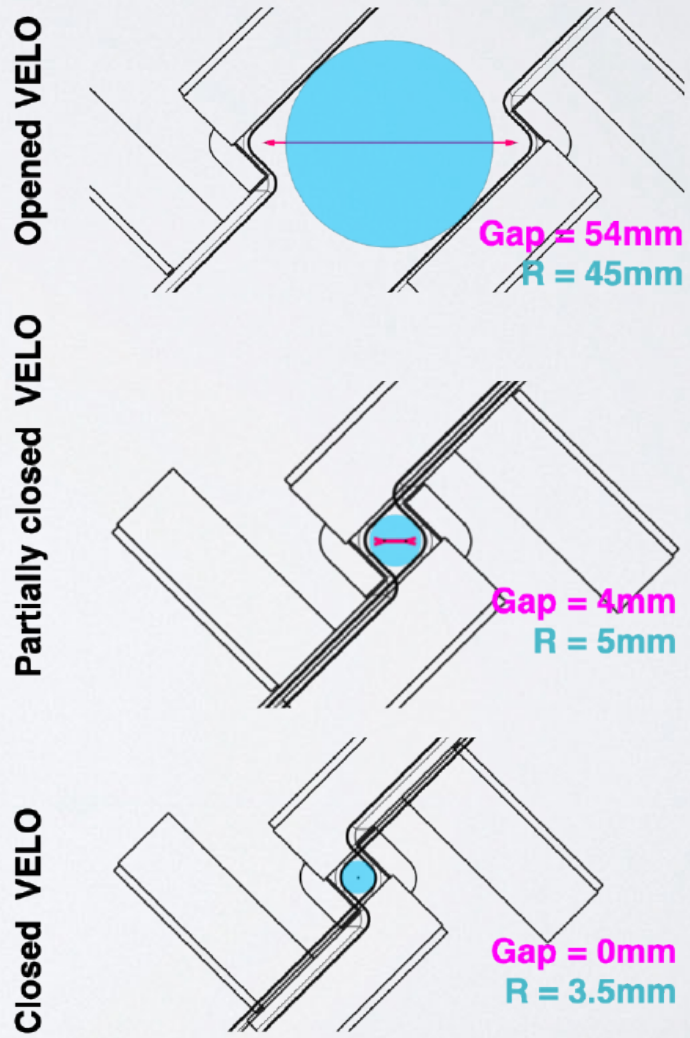


M42, CERN, after installation



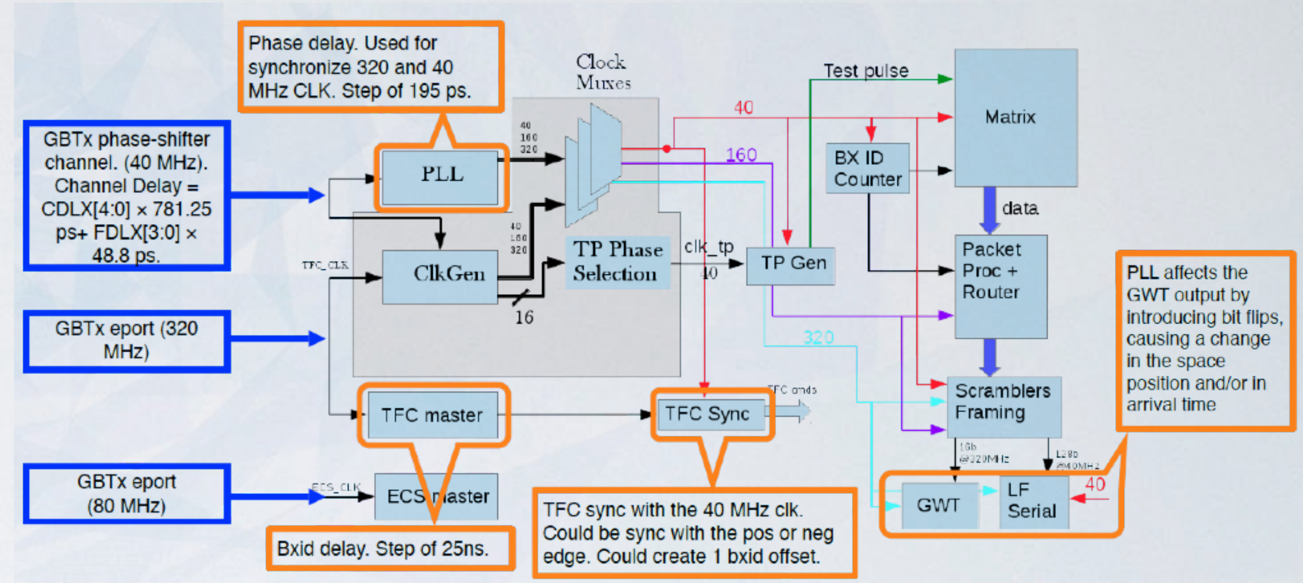


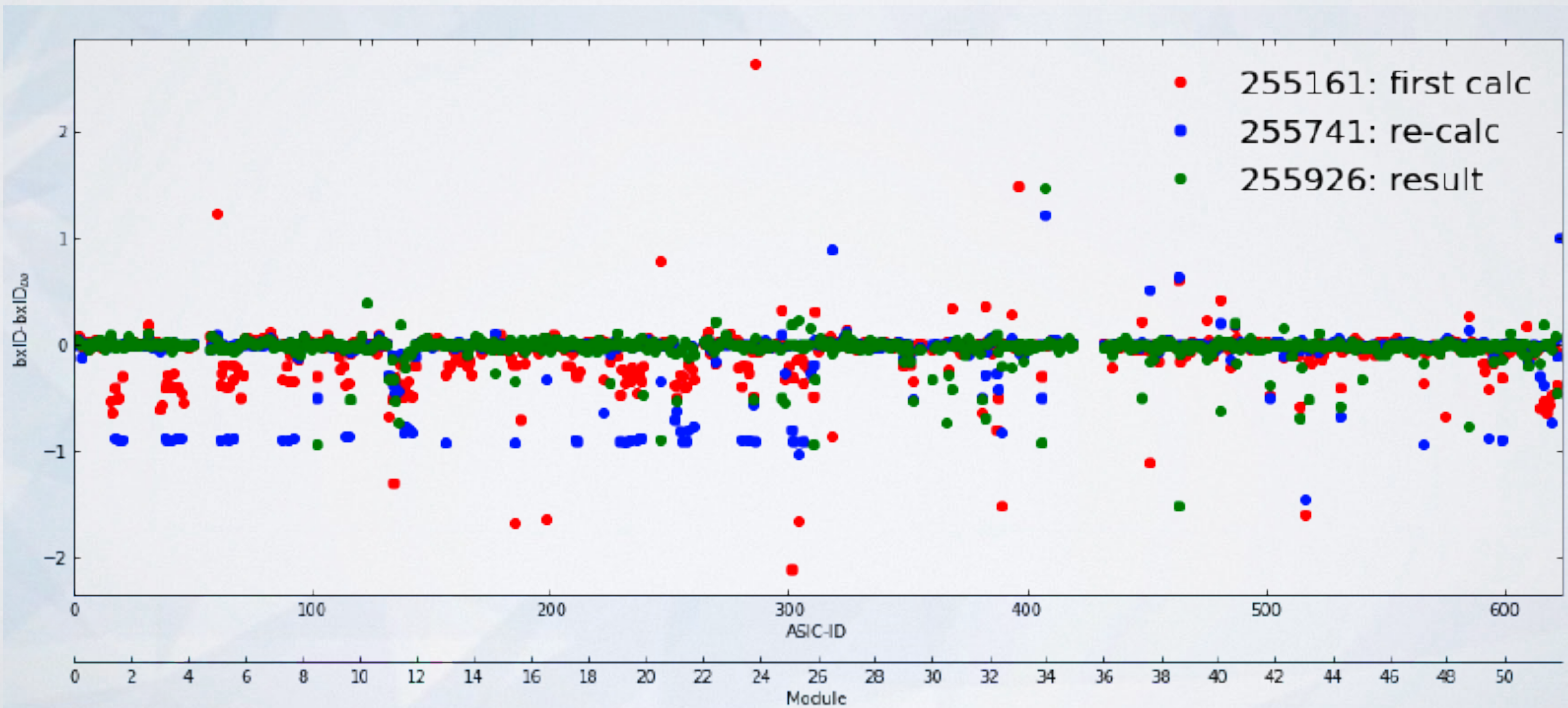




Commissioning: time alignment

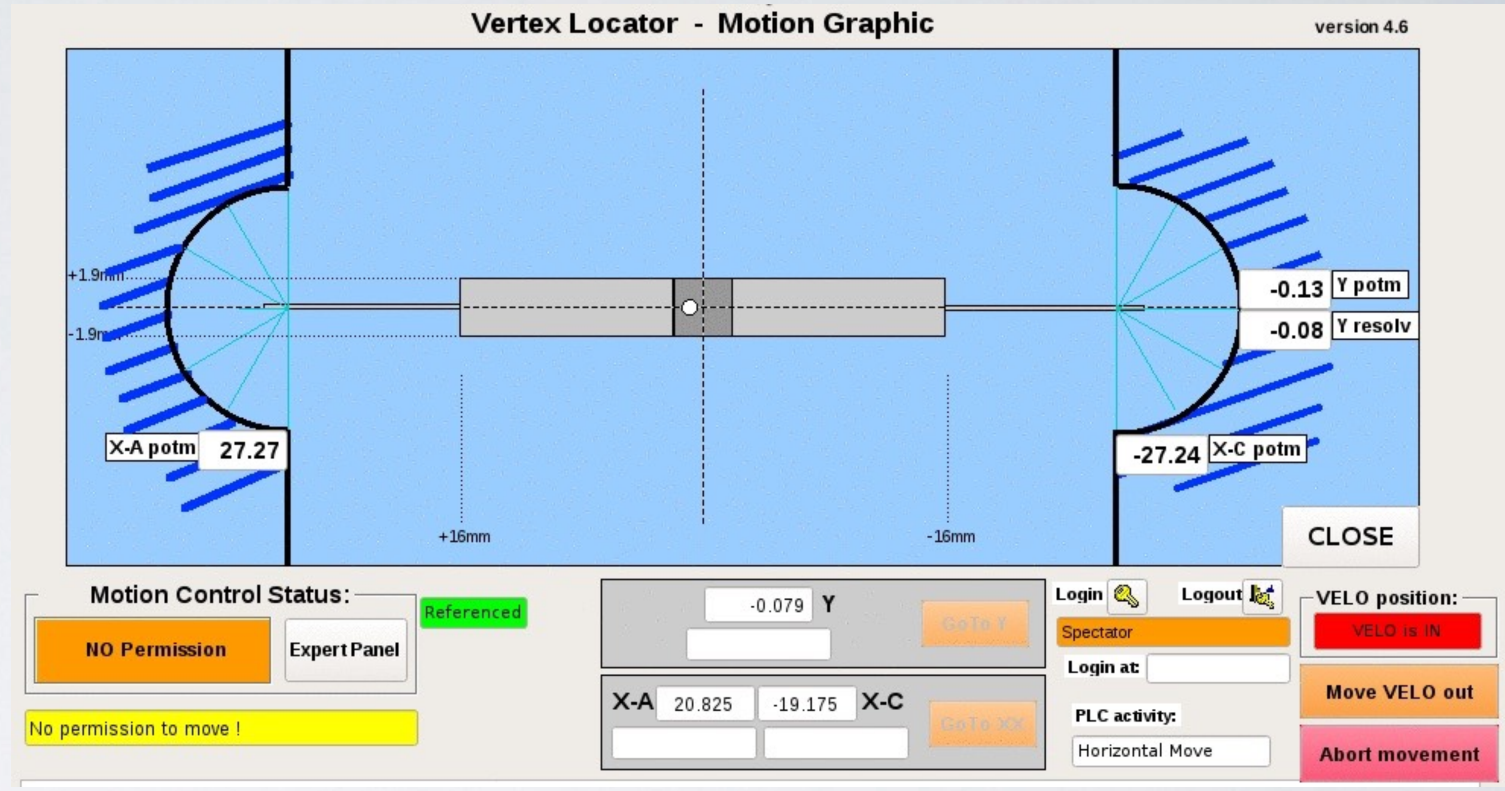
- Time-align the response from all ASICs
  - Differences in cable lengths, Front-End configuration, thresholds, etc.
  - Multiple interconnected latencies/delays
  - Iterative process
- Currently 2.7% of misaligned ASICs

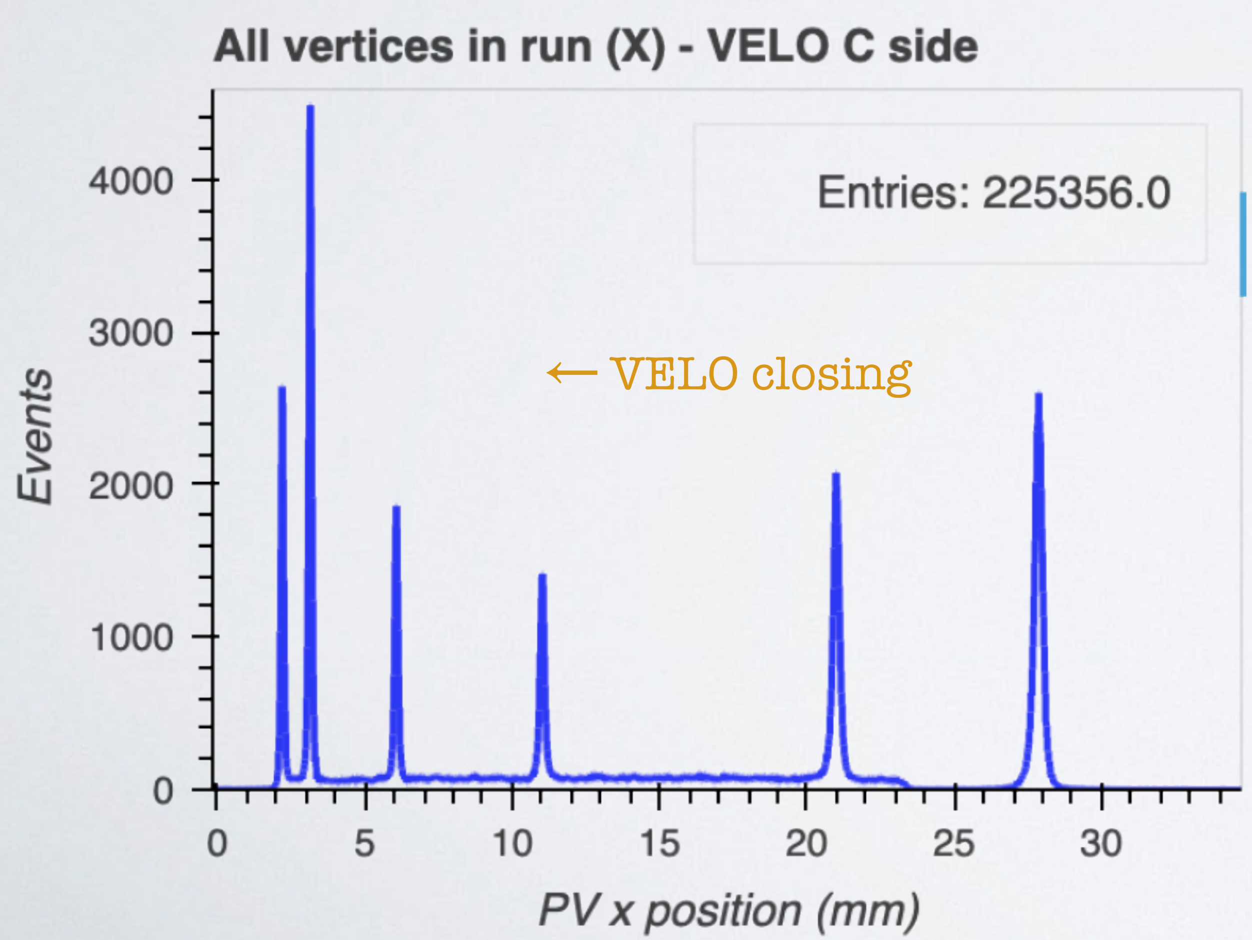


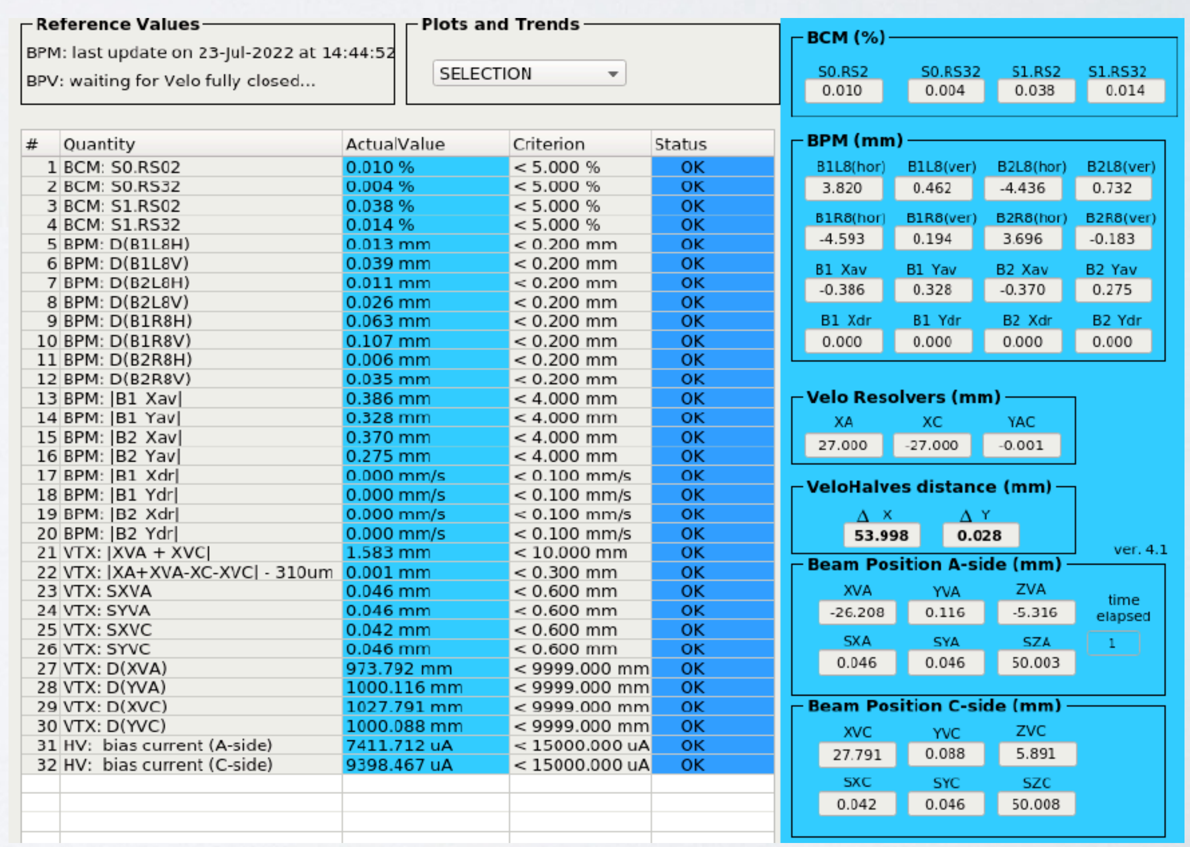


Commissioning: closing procedure

- VELO is in open position during beam injection to protect the detector
- For each fill, the VELO is closed around the beam line
  - Nominal clearance only 3.5 mm
- The two halves move independently in X (horizontal) and together in Y (vertical)
- The closing is carried out in a few steps
- Safety criteria to allow/forbid movement
- Vertices reconstructed to determine beam position

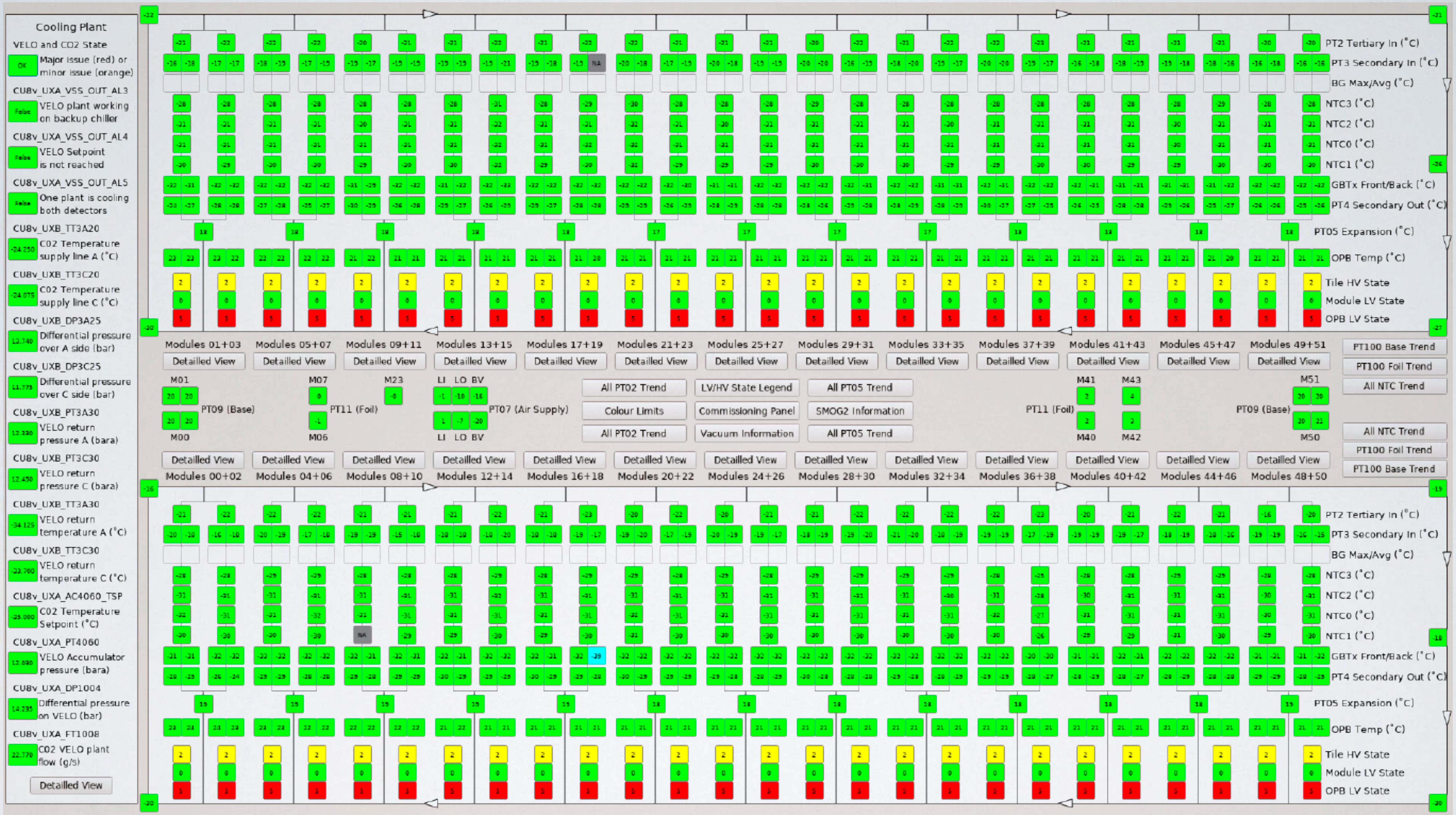






#	Quantity	ActualValue	Criterion	Status
1	BCM: S0.RS02	0.010 %	< 5.000 %	OK
2	BCM: S0.RS32	0.004 %	< 5.000 %	OK
3	BCM: S1.RS02	0.038 %	< 5.000 %	OK
4	BCM: S1.RS32	0.014 %	< 5.000 %	OK
5	BPM: D(B1L8H)	0.013 mm	< 0.200 mm	OK
6	BPM: D(B1L8V)	0.039 mm	< 0.200 mm	OK
7	BPM: D(B2L8H)	0.011 mm	< 0.200 mm	OK
8	BPM: D(B2L8V)	0.026 mm	< 0.200 mm	OK
9	BPM: D(B1R8H)	0.063 mm	< 0.200 mm	OK
10	BPM: D(B1R8V)	0.107 mm	< 0.200 mm	OK
11	BPM: D(B2R8H)	0.006 mm	< 0.200 mm	OK
12	BPM: D(B2R8V)	0.035 mm	< 0.200 mm	OK
13	BPM: |B1 Xav|	0.386 mm	< 4.000 mm	OK
14	BPM: |B1 Yav|	0.328 mm	< 4.000 mm	OK
15	BPM: |B2 Xav|	0.370 mm	< 4.000 mm	OK
16	BPM: |B2 Yav|	0.275 mm	< 4.000 mm	OK
17	BPM: |B1 Xdr|	0.000 mm/s	< 0.100 mm/s	OK
18	BPM: |B1 Ydr|	0.000 mm/s	< 0.100 mm/s	OK
19	BPM: |B2 Xdr|	0.000 mm/s	< 0.100 mm/s	OK
20	BPM: |B2 Ydr|	0.000 mm/s	< 0.100 mm/s	OK
21	VTX: |XVA + XVC|	1.583 mm	< 10.000 mm	OK
22	VTX: |XA+XVA-XC-XVC| - 310um	0.001 mm	< 0.300 mm	OK
23	VTX: SXVA	0.046 mm	< 0.600 mm	OK
24	VTX: SYVA	0.046 mm	< 0.600 mm	OK
25	VTX: SXVC	0.042 mm	< 0.600 mm	OK
26	VTX: SYVC	0.046 mm	< 0.600 mm	OK
27	VTX: D(XVA)	973.792 mm	< 9999.000 mm	OK
28	VTX: D(YVA)	1000.116 mm	< 9999.000 mm	OK
29	VTX: D(XVC)	1027.791 mm	< 9999.000 mm	OK
30	VTX: D(YVC)	1000.088 mm	< 9999.000 mm	OK
31	HV: bias current (A-side)	7411.712 uA	< 15000.000 uA	OK
32	HV: bias current (C-side)	9398.467 uA	< 15000.000 uA	OK

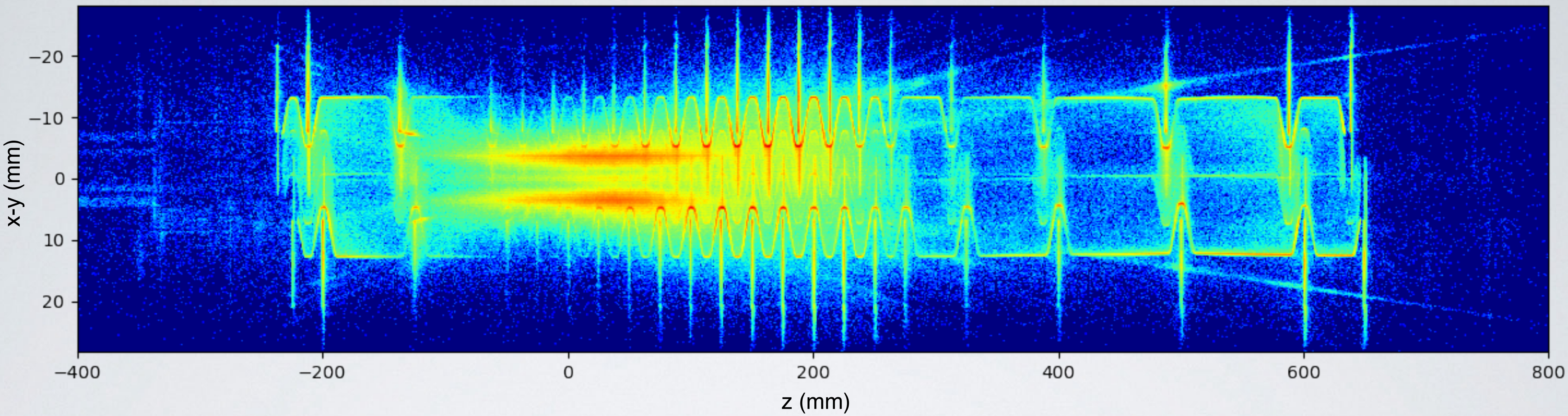
Commissioning: temperature monitoring

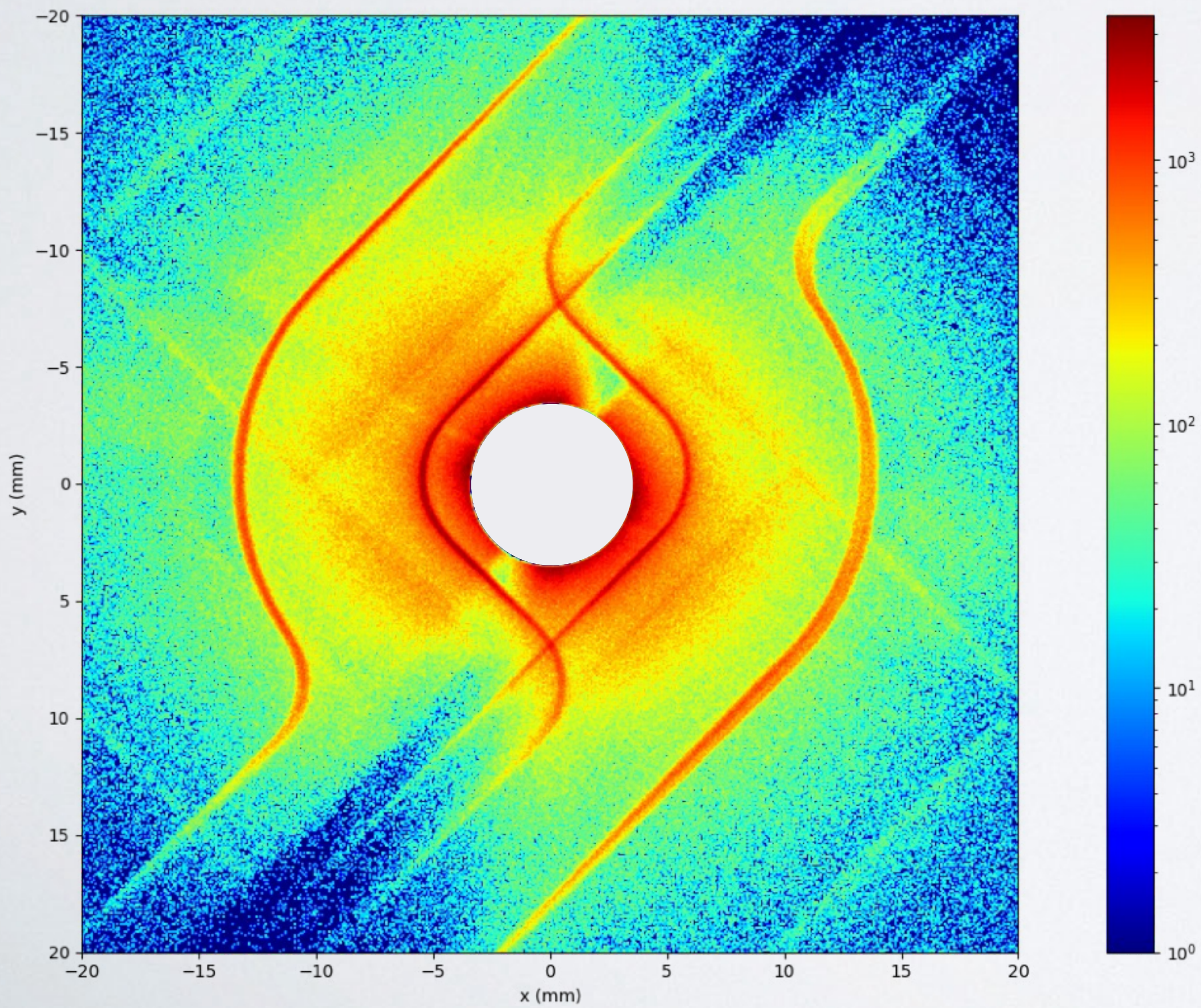


- 6 NTC probes per module
- 3 PT100 probes on cooling capillaries
- Temperature probes on OPB's, tertiary vacuum, RF Foil, VELO base, ...
- LV/HV state, cooling plant info, vacuum state, trending functionalities, ...

1894 readings in total!

Commissioning: vertex reconstruction

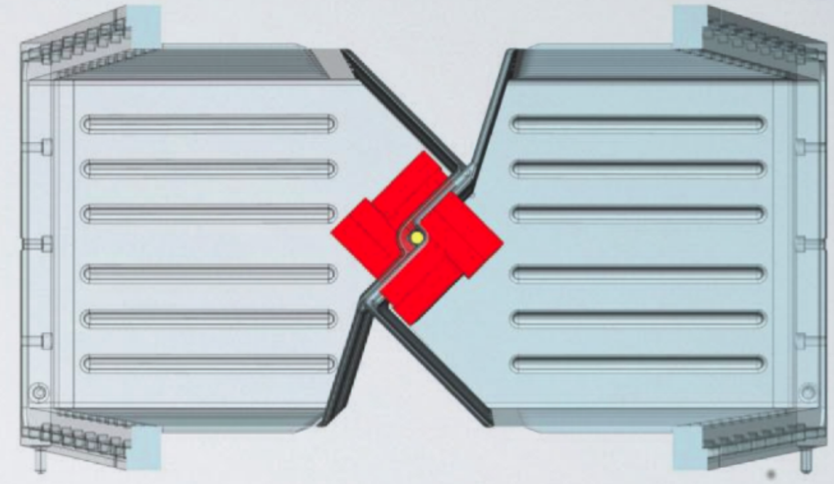


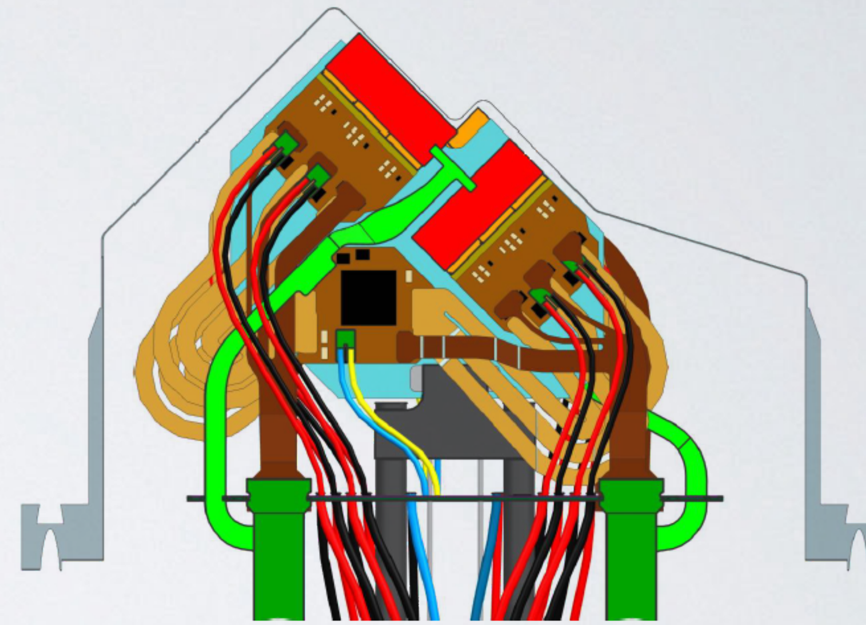


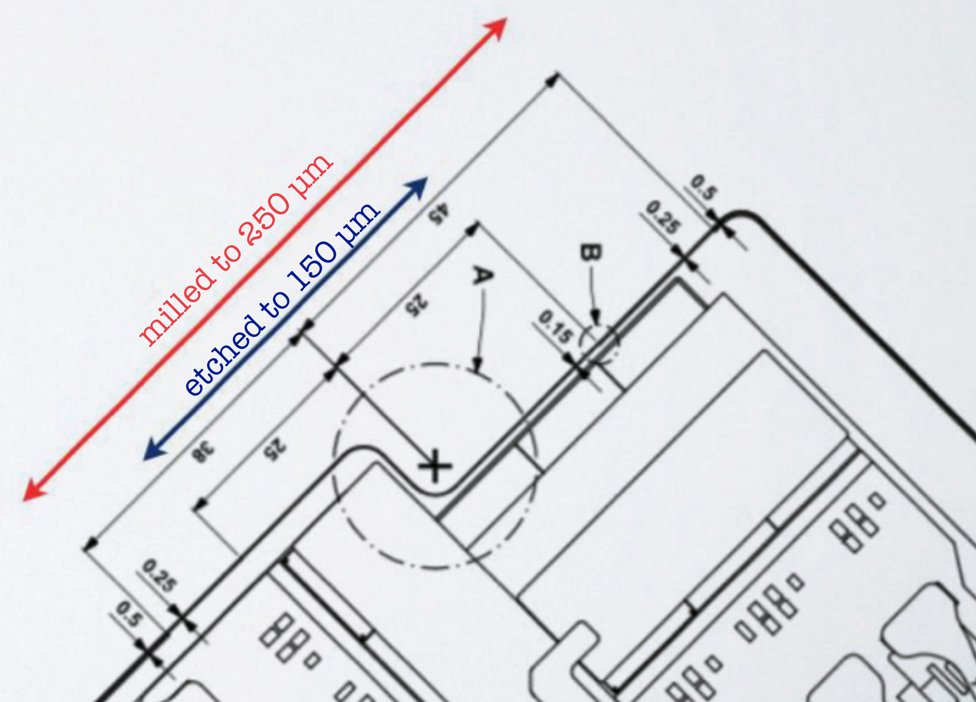
- Vertex reconstruction is a powerful tool to precisely measure the modules and foil position
- Material scans by hadronic interactions provide a tomography of the VELO
- Currently spacers keep the modules 1 mm further away from the foil
- Used during first closing to measure aperture
- Allows to measure relative position of modules to foil, relative z position of modules

RF Foil: design

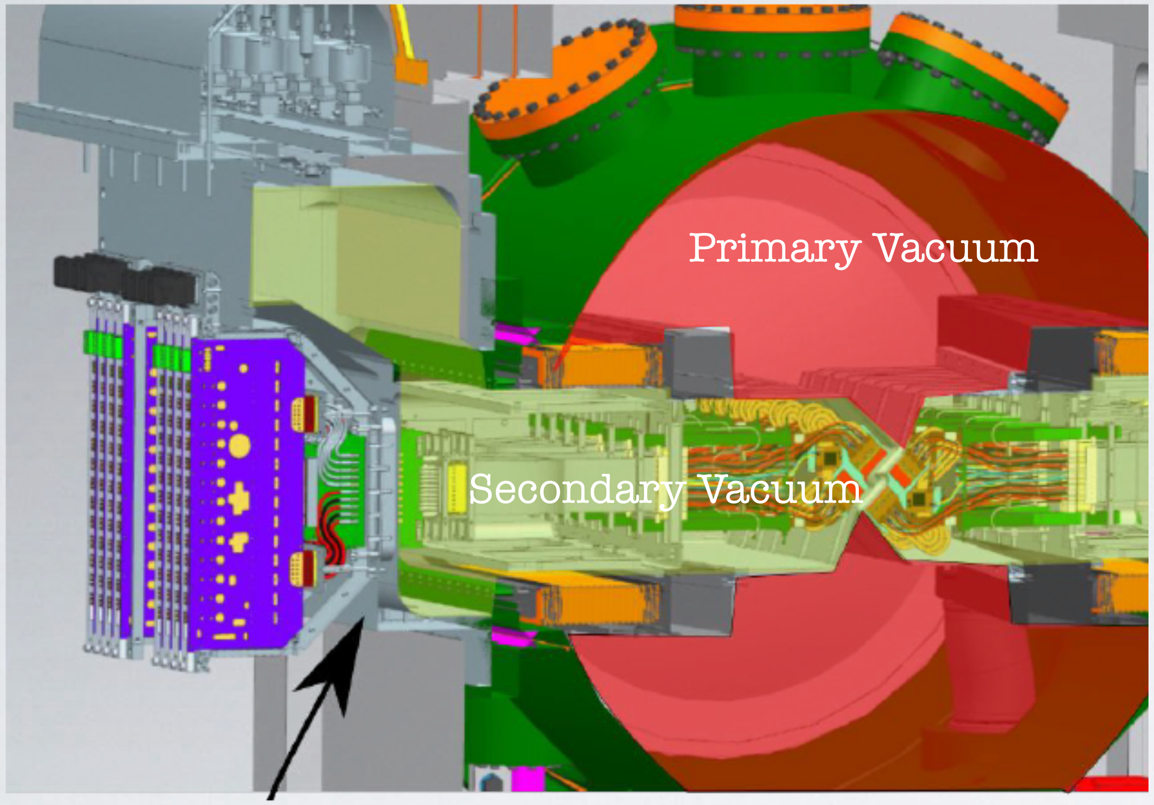
- accommodate modules (~1 m long)
- separate primary/secondary vacua
- shield against RF pick-up from the LHC beams
- light 250 µm (150 µm inner region)
- withstand ΔP = 10 mbar
- corrugated, thermally stable, vacuum tight, rad-hard







RF Foil: Vacuum Safety System



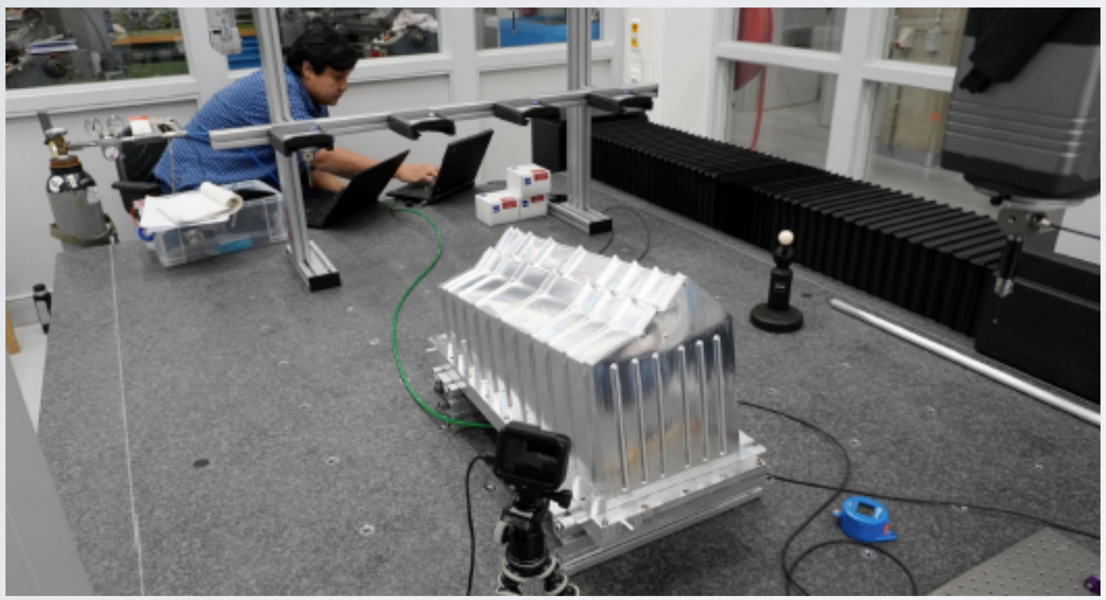
The LHC vacuum control system protects against pressure differentials, both during vacuum operation and during technical stops, when all volumes are sometimes filled with neon.

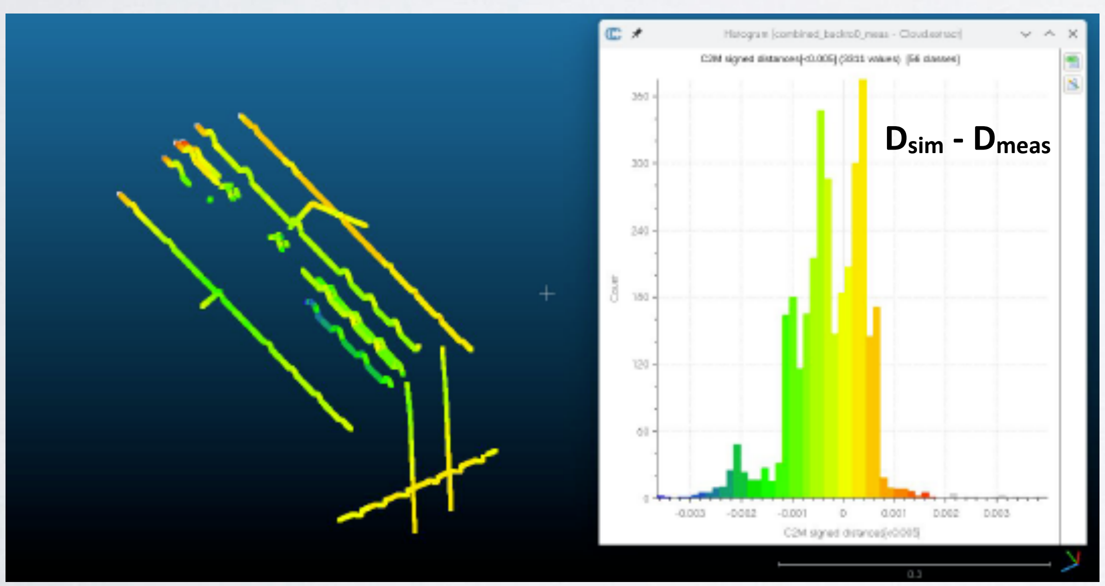
- On 10th January 2023, during a VELO warm up in neon, there was a loss of control of the protection system.
- A relay failed and damaged a power supply, leading to multiple equipment failures and a pumping action on the primary volume.
- A pressure differential of 200 mbar built up between the two volumes.
- The system has been returned to safe conditions and initial investigations show no damage to the VELO modules.
- More details available in Machine Committee and VELO internal meetings.

RF Foil: aftermath

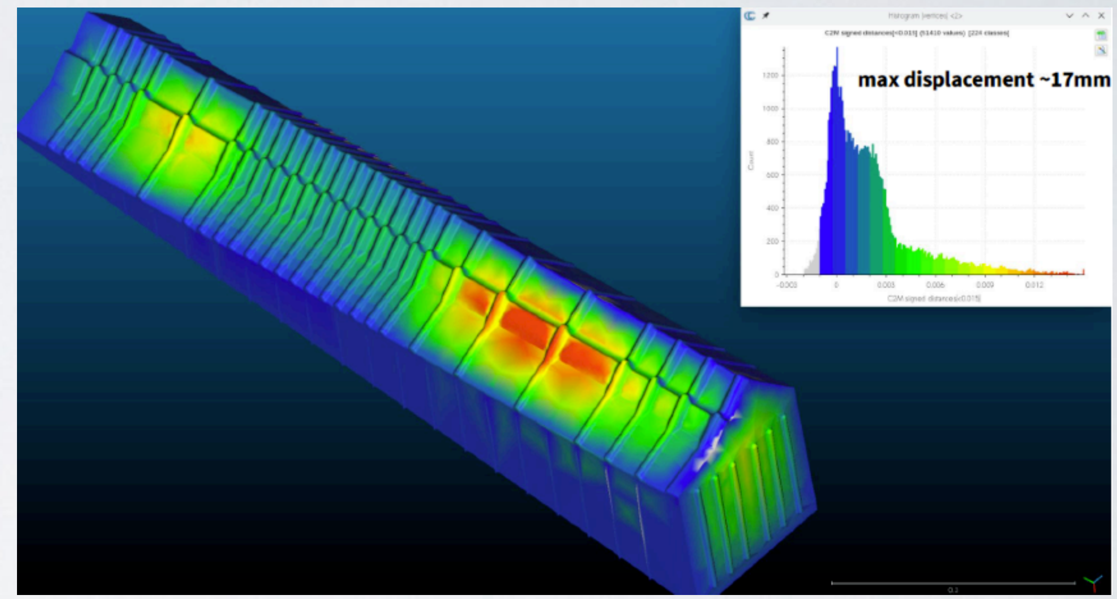
- RF foil has suffered a plastic deformation
  - Intensive programme of measurements and simulations to assess size of deformation

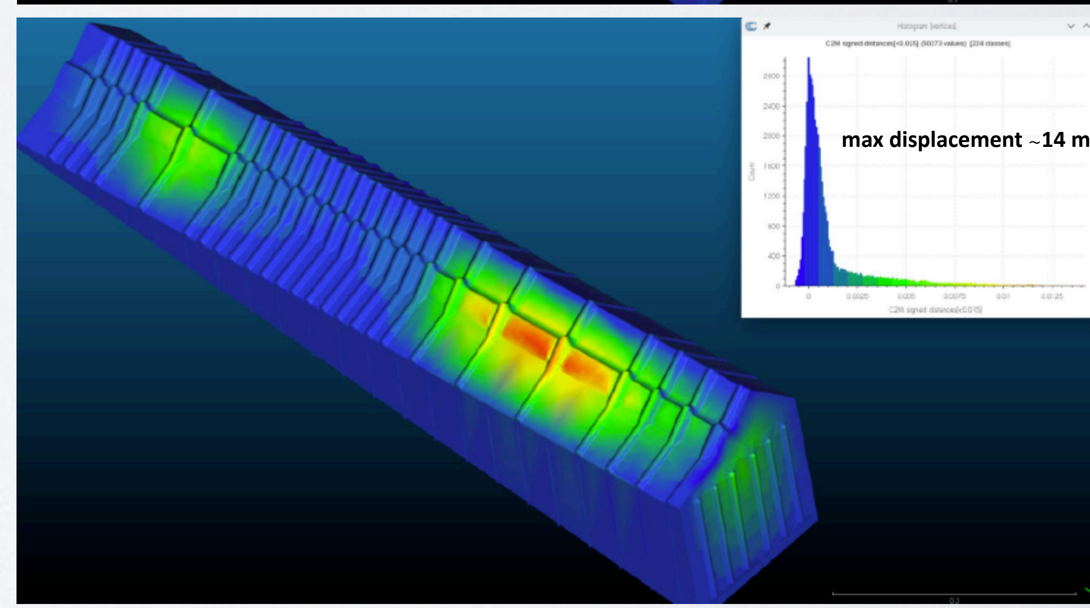
Test at Nikhef on RF half-box prototype
ΔP = 0 mbar → 200 mbar → 0 mbar
Max residual displacement D ~ 12 mm





Simulation of full RF box
ΔP = 0 mbar → 200 mbar → 0 mbar
Max residual displacement D ~ 14 mm





RF Foil: recovery

Actions 11th - 16th of January:

- Pressure difference reduced to 100 mbar in two 50 mbar steps, then to 20 mbar
  - Faulty parts replaced and system made more robust against hardware failure
- Now back within the safety range (-5, +2 mbar) and safety system reactivated
  - Pumping/venting up
  - Further checks of detector functionalities
- LHCb wish to thank TE-VSC for their full commitment in the recovery process and EN-MME for their support and advices

- Detector is unharmed as far as we can test (micro-channels, sensors)
- RF foil has suffered a plastic deformation

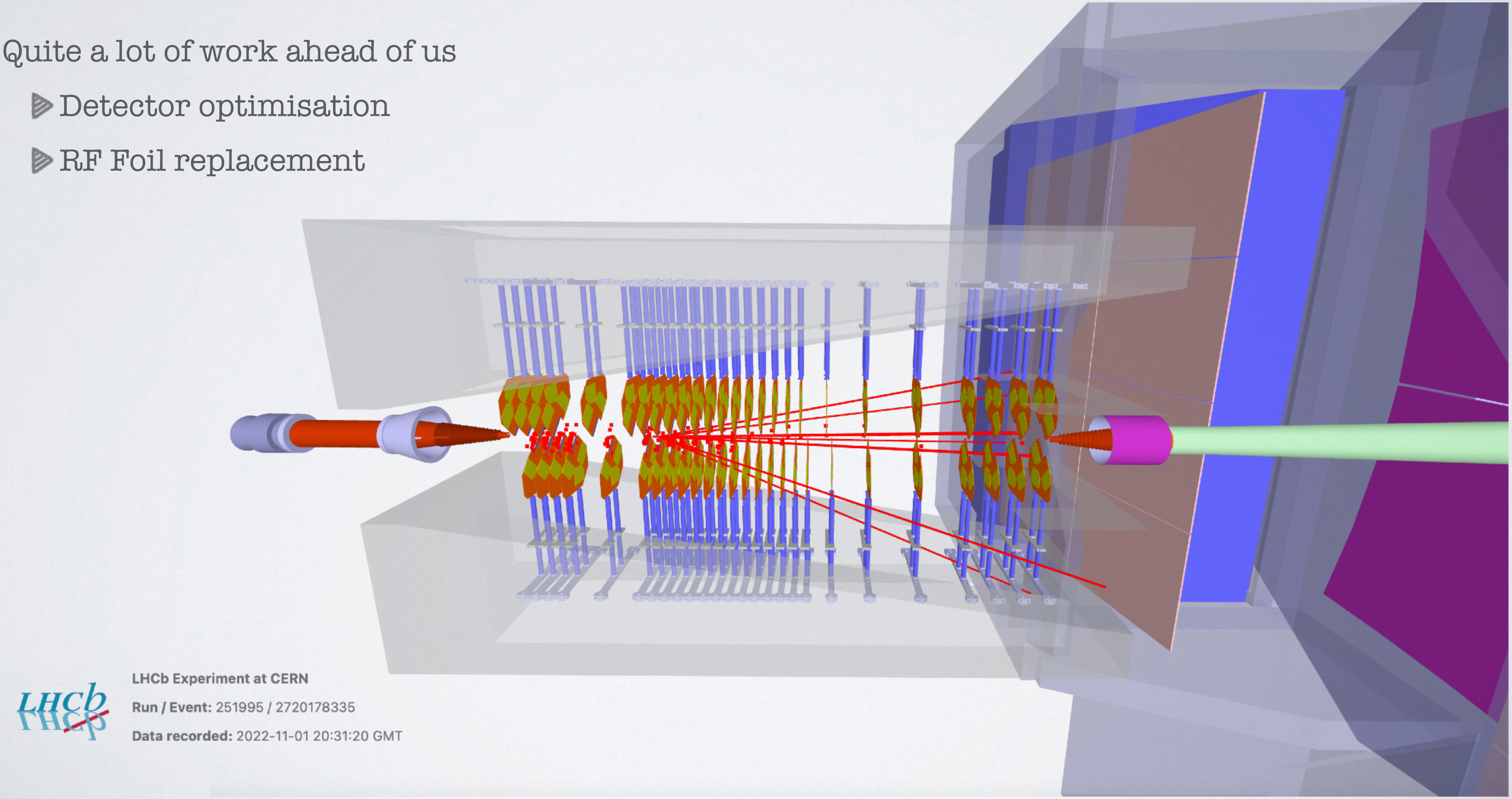
The RF foil will require replacement. After discussions with the EP-DH and RD, the recommendation is to schedule the replacement in autumn 2023, and this advice has been endorsed by the machine, although a few more checks are required. This would imply running the VELO partially open, with a significant impact on the 2023 physics programme.

Conclusion

- Huge amount of work behind us
  - Module production
  - Mechanics, cooling, safety system, ...
  - Installation, integration, commissioning

2023 will be as busy as all previous years!

- Quite a lot of work ahead of us
  - Detector optimisation
  - RF Foil replacement

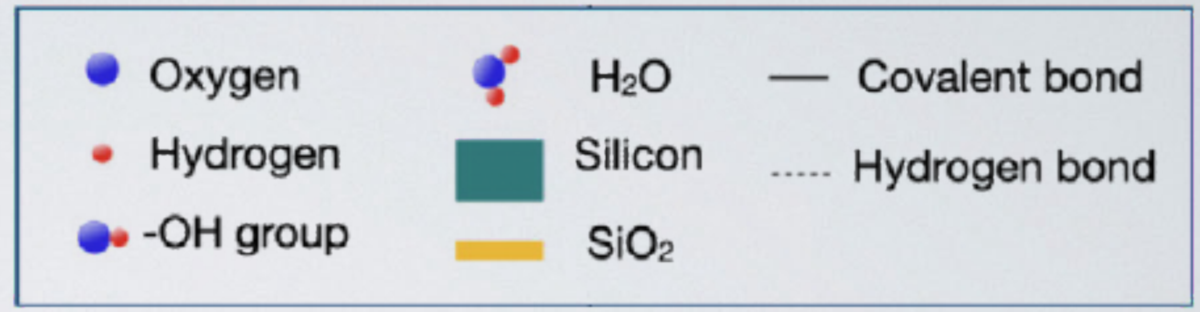


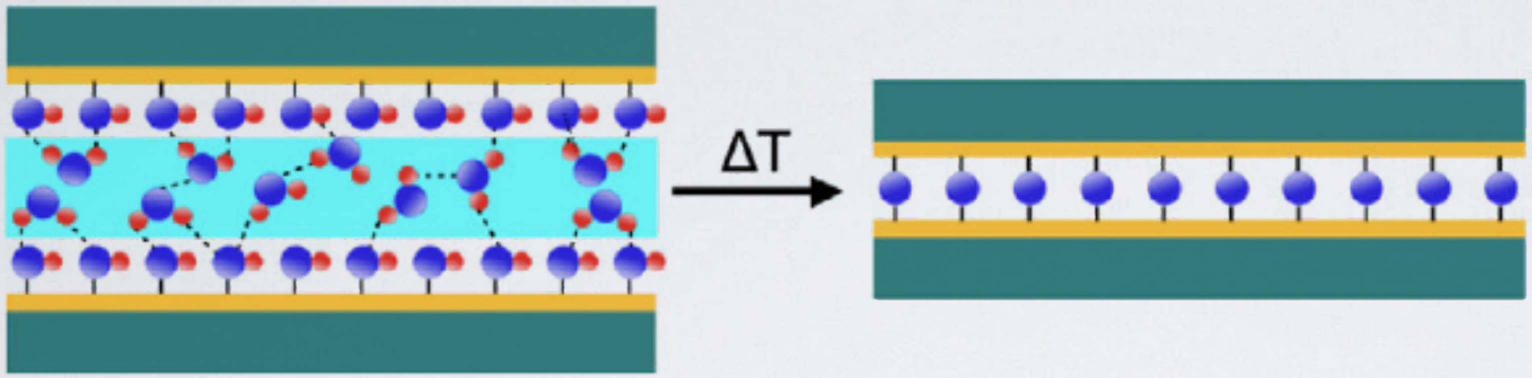
Thanks for listening !

VELO Vs. VELO Upgrade

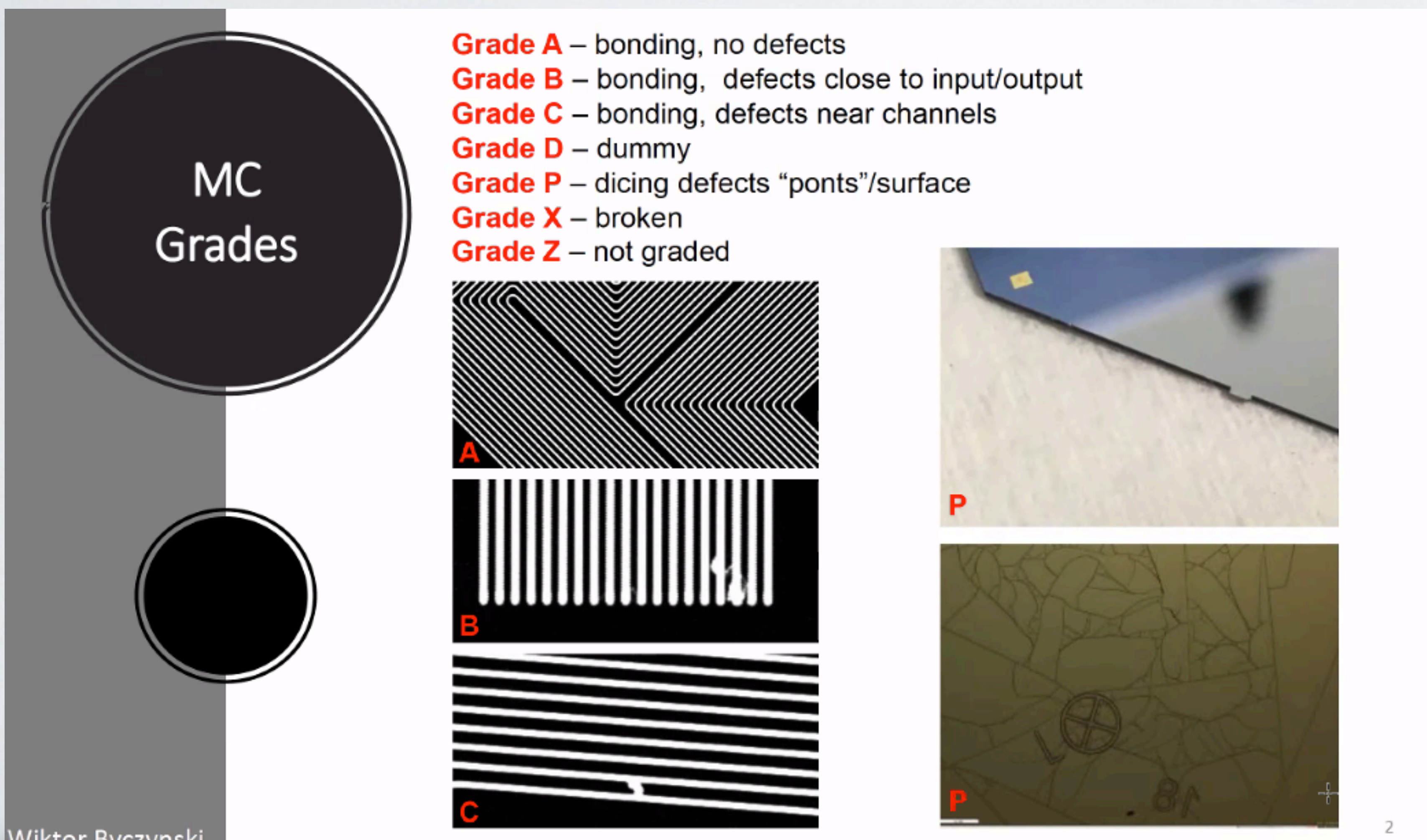
Feature	VELO	Upgrade
Sensors	R & φ strips 0.22 m^2 172,032 strips electron collecting 300 µm thick 40-100 µm pitch	Pixels 0.12 m^2 **41 M pixels** electron collecting **200 µm thick** 55 µm pitch
# of modules	42	52
Max fluence	4.3×10^{14} MeV n_{eq} cm^{-2}	**8×10^{15}** 1 MeV n_{eq} cm^{-2}
HV tolerance	500 V	**1000 V**
ASIC readout rate	1 MHz	40 MHz
Total data rate	analog (eq. to 150 Gb/s)	2.8 Tb/s
Total Power consumption	1 kW	**1.6 kW** (30 W/module)

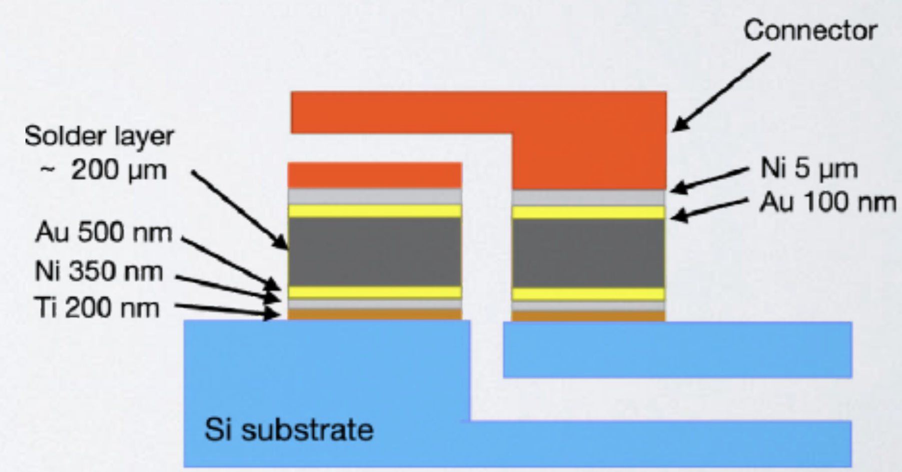
Hydrophilic Bonding Process



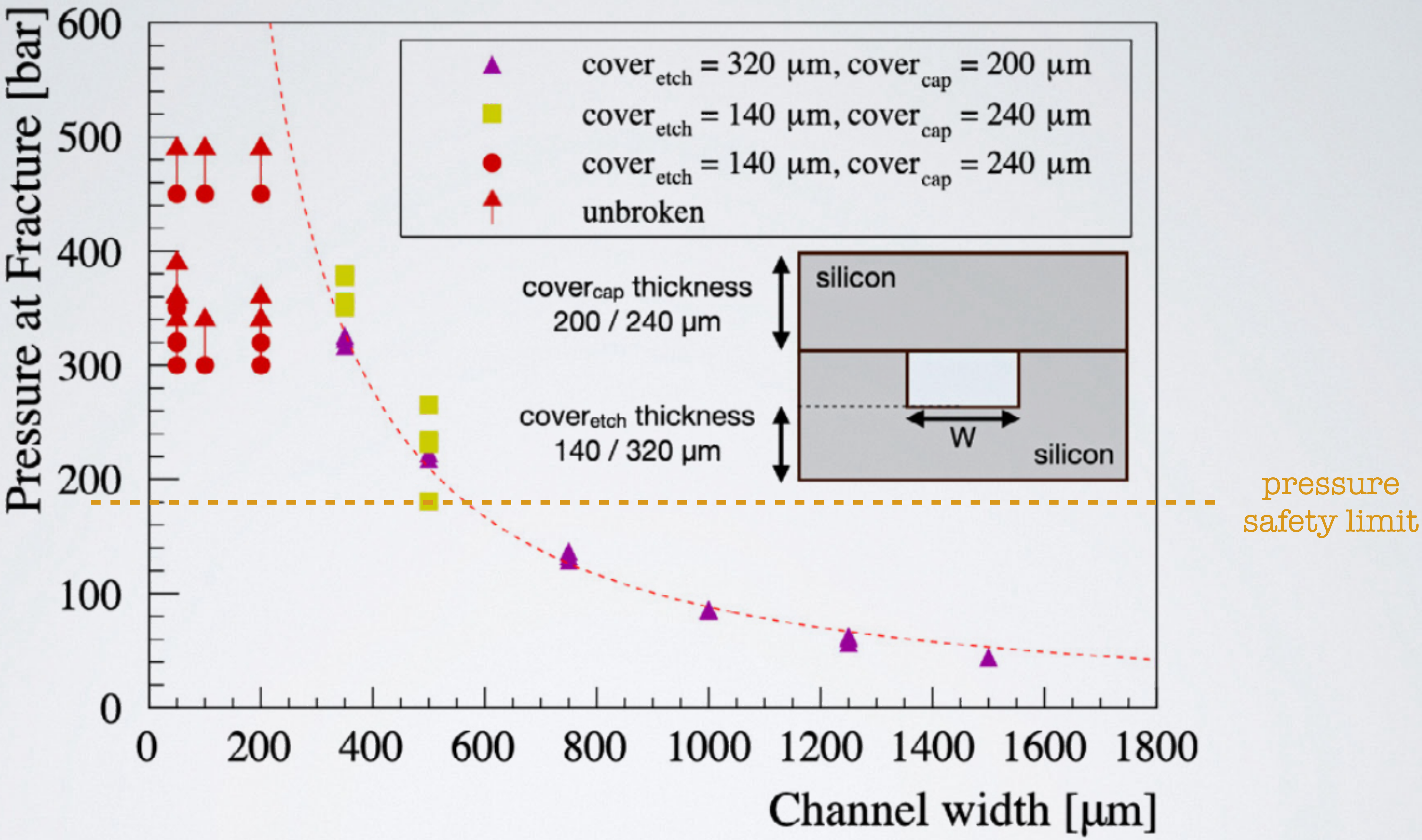


- A wet chemical treatment decontaminates the surfaces and promotes the formation of silanol groups (Si–OH), covered with a few monolayers of water.
- As two wafers are pressed together they spontaneously bind to each other via hydrogen bonds, capillarity and van der Waals forces.
- The final bonding is achieved by condensation of silanol groups to give strong covalent Si–O–Si siloxane bonds





Pressure tests



None of the LHCb samples with nominal channel width broke.
Max testing pressure: 450 bar.

Glue candidates

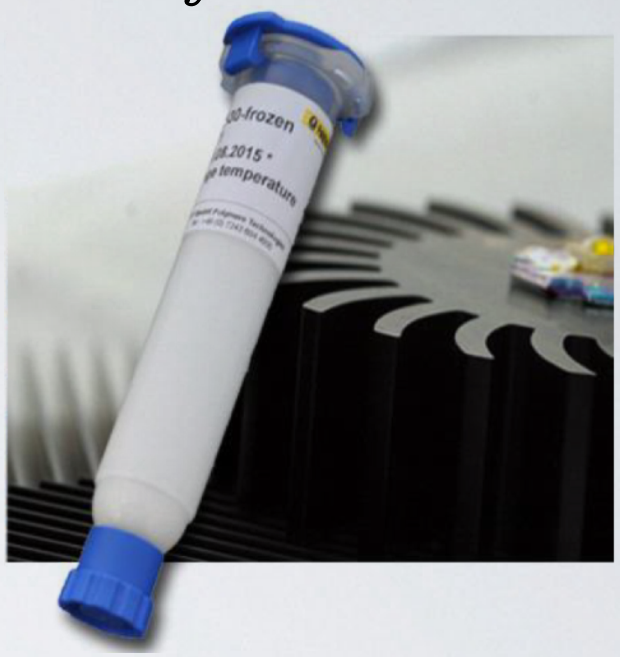
Stycast 2850FT

- Current solution: tiles glueing jigs designed around it.
- Excellent thermal conductivity.
- Reasonable working time.
- Reasonable curing time.
- Good viscosity (ease of deposition).
- Two catalyst to choose from: catalyst 9 and 23LV*.
- Glue preparation might become very complicated to ensure good adhesion.

Araldite 2011

- Well known epoxy in our community.
- Fair thermal conductivity.
- Reasonable working time.
- Reasonable curing time.
- Low viscosity (less easy to deposit).
- No glue preparation.
- Comes in cartridges that can be mixed manually with dedicated gun.
- Might require jigs redesign.

Polytec TC 418

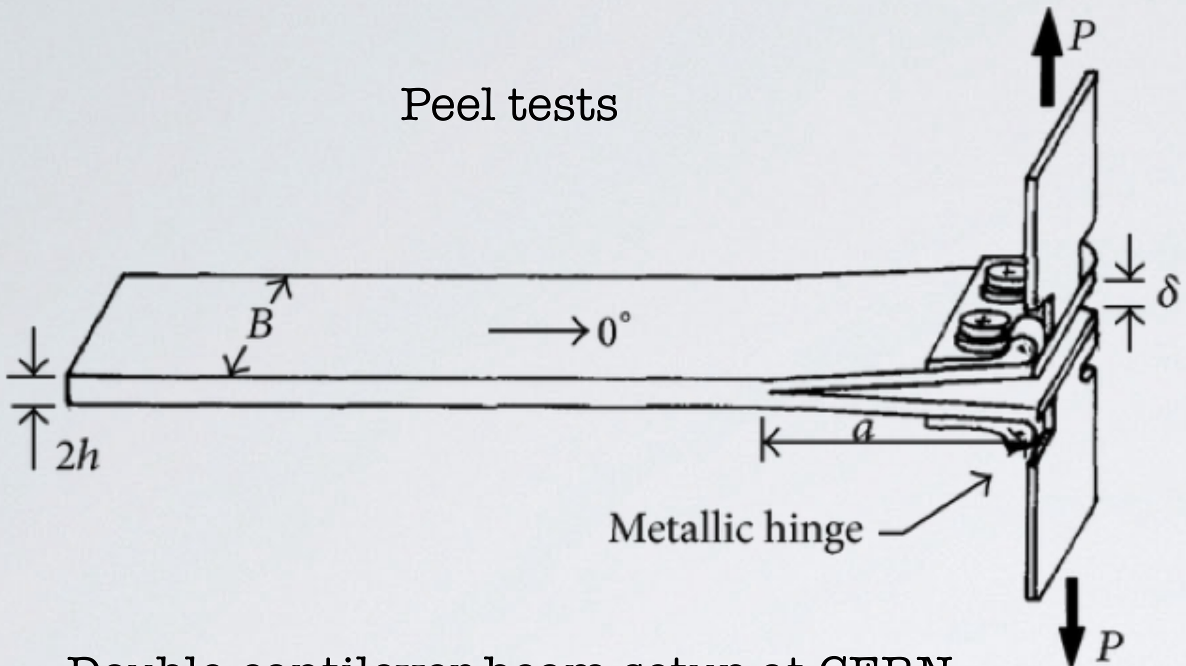


- Advised by CERN DT.
- Excellent thermal performance.
- Excellent working time.
- Good viscosity.
- Long curing time.
- No internal (VELO) experience.
- Discontinued - buy all glue needed in 1 batch.

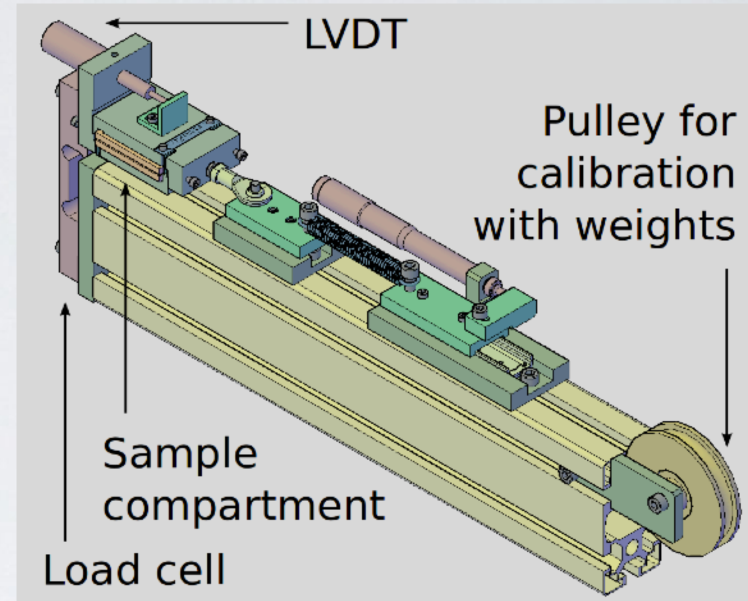
*23LV:
✔ longer working time, larger ratio to main part, less brittle, stronger adhesion
✗ lower thermal conductivity, less viscous, no rad-hard data, less experience

Adhesion properties

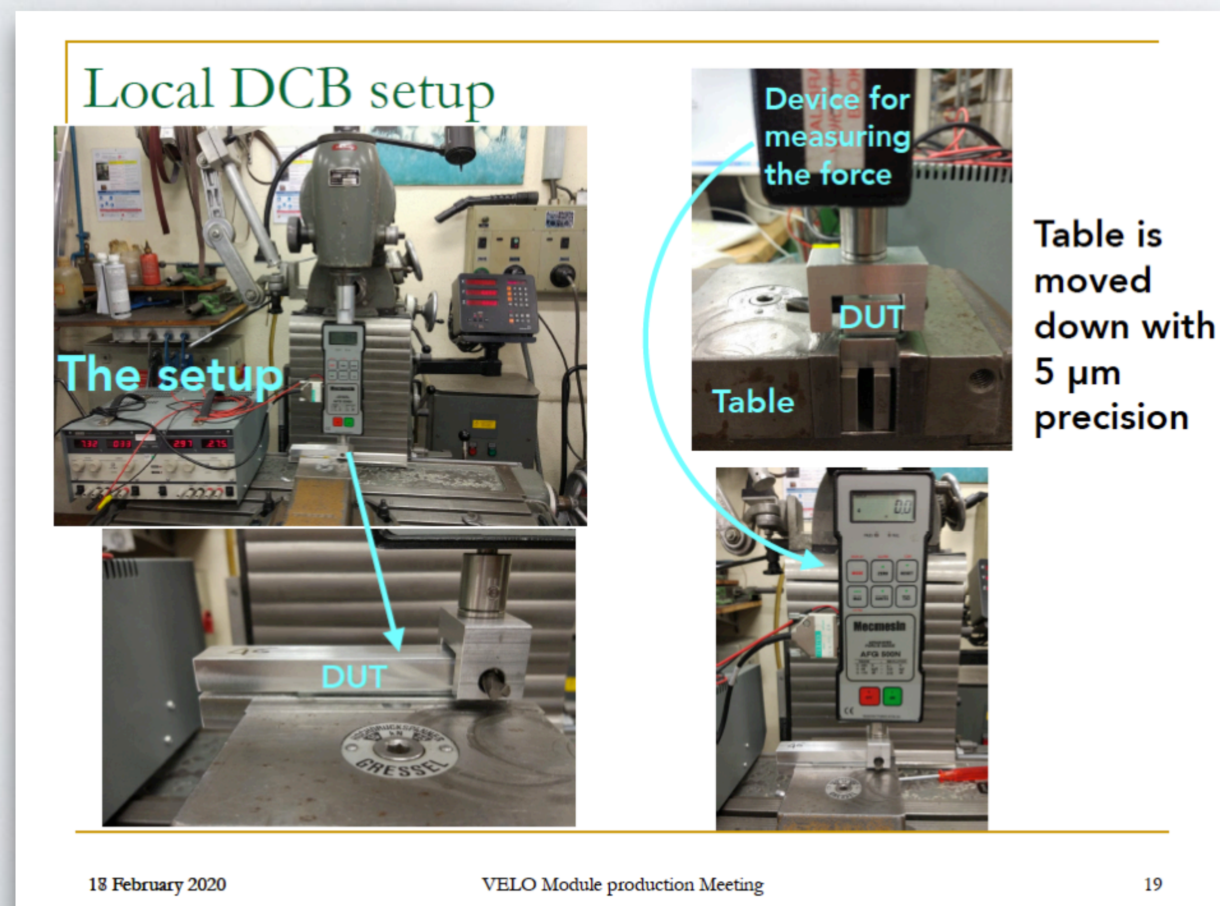
Peel tests

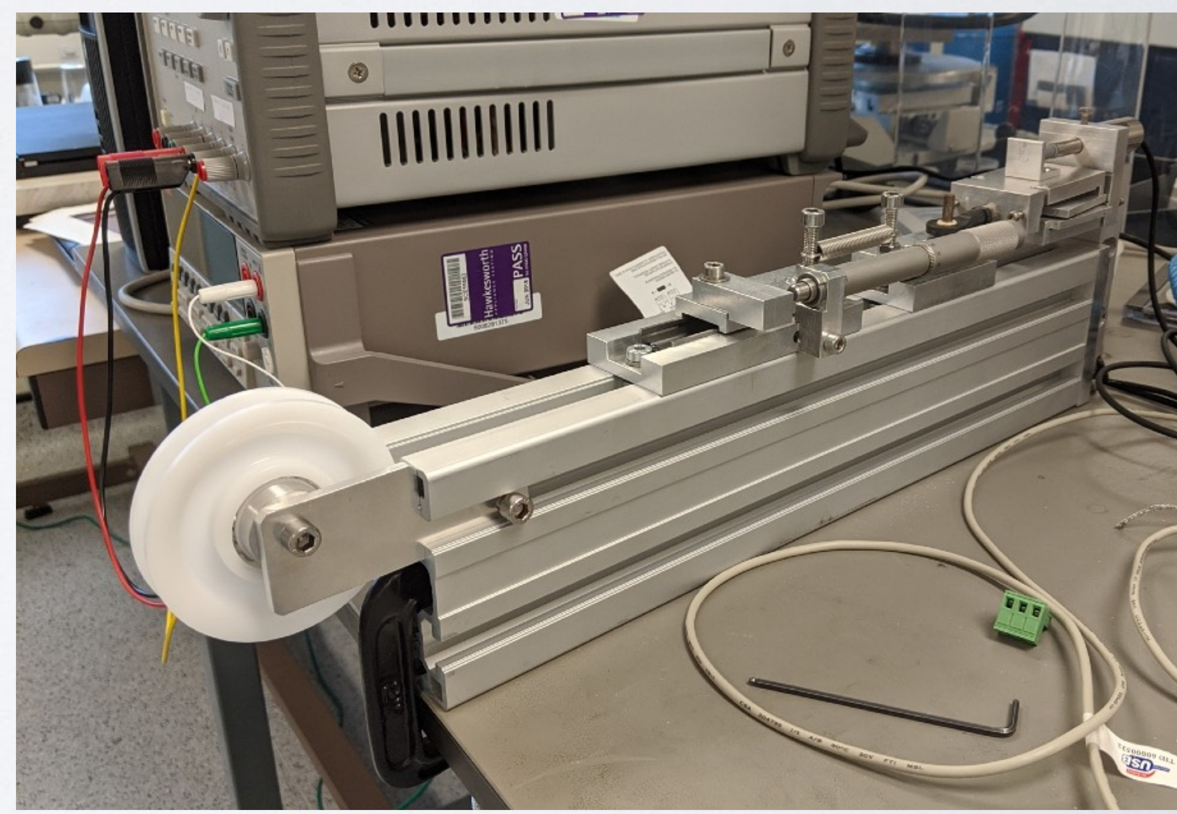


Double-cantilever beam setup at CERN

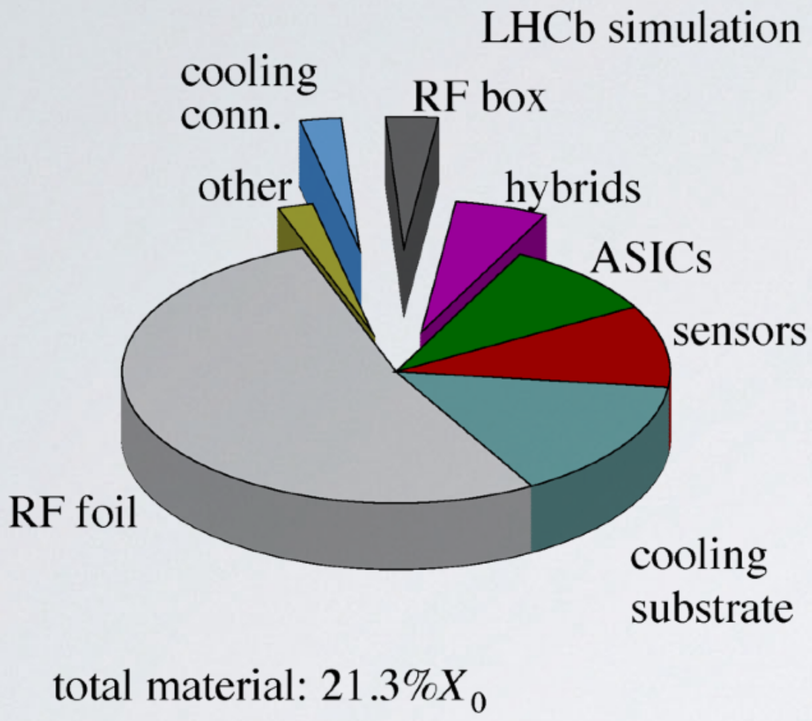


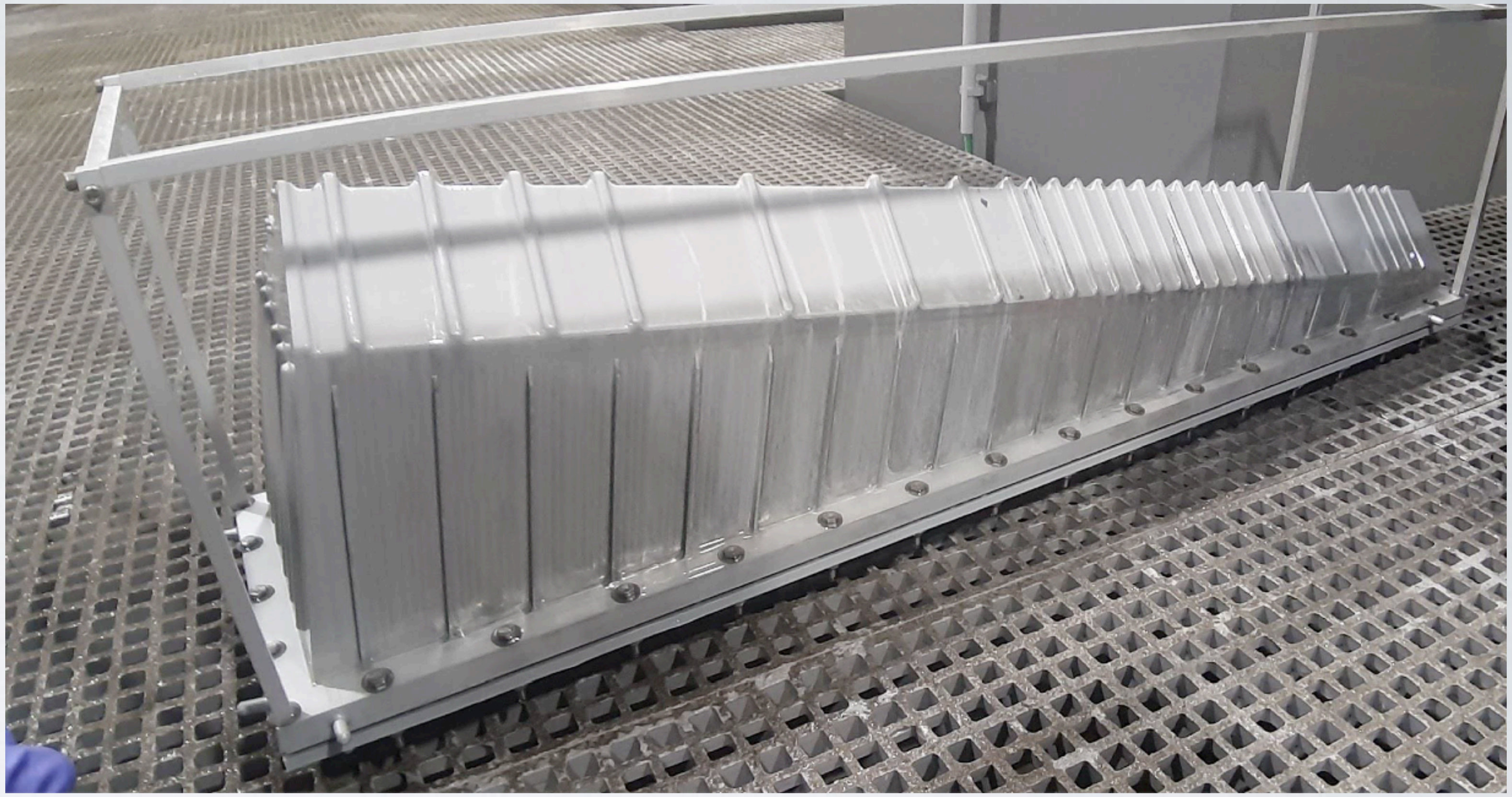
Shear force setup in Manchester



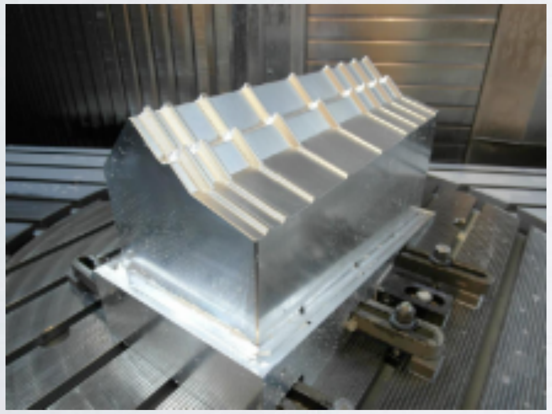


RF Foil

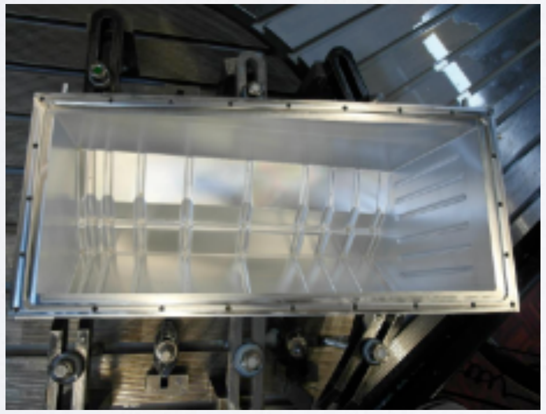




Al mould 1 mm smaller than box

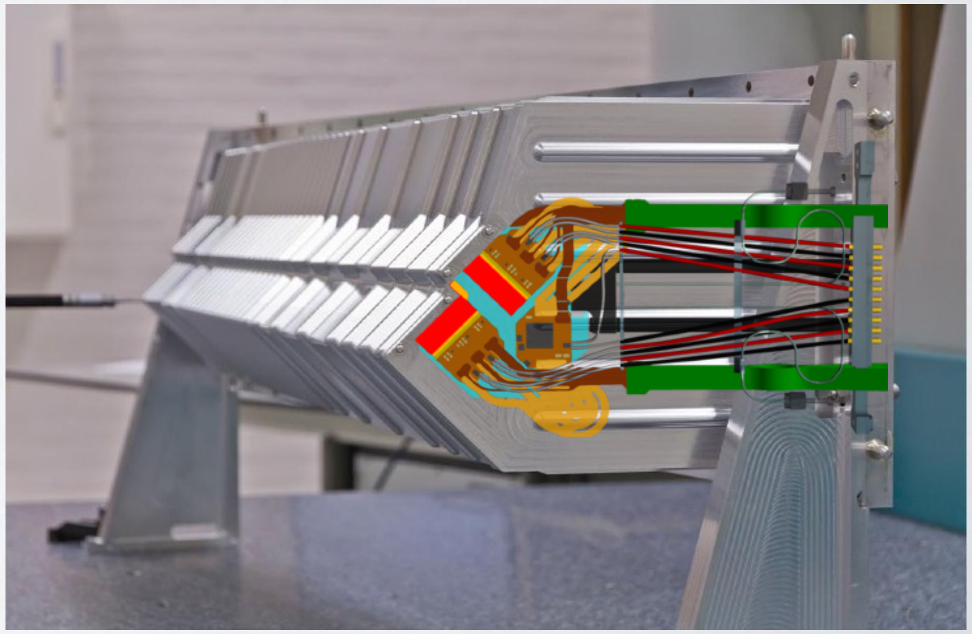


Mill inside of box



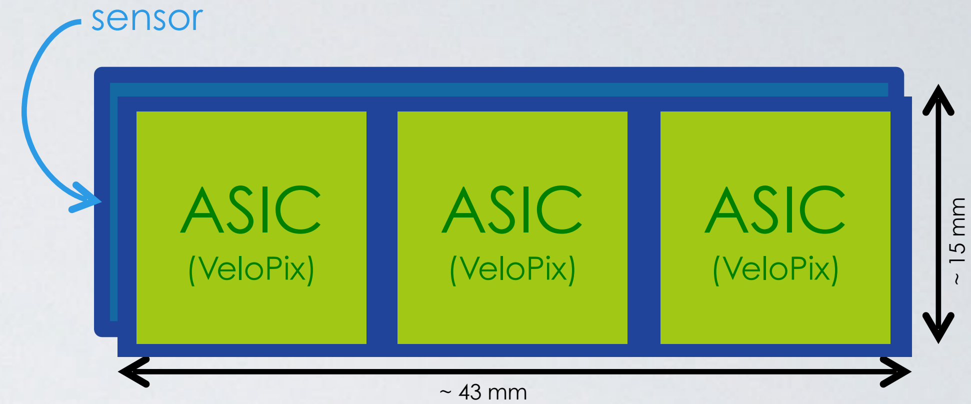
Mill outside of box

Half box prototype



Sensors & ASICs: specifications

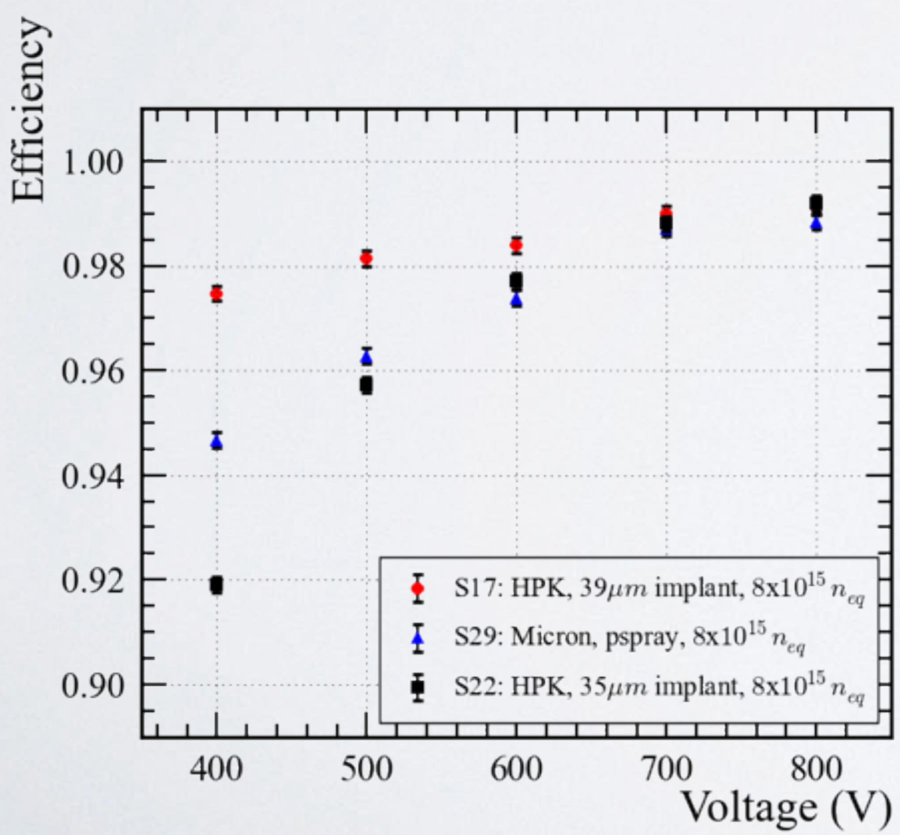
- ASIC derived from TimePix3 (VeloPix)
- 130 nm CMOS technology (TSMC)
- 256 x 256 pixels, 55 x 55 µm pixel size

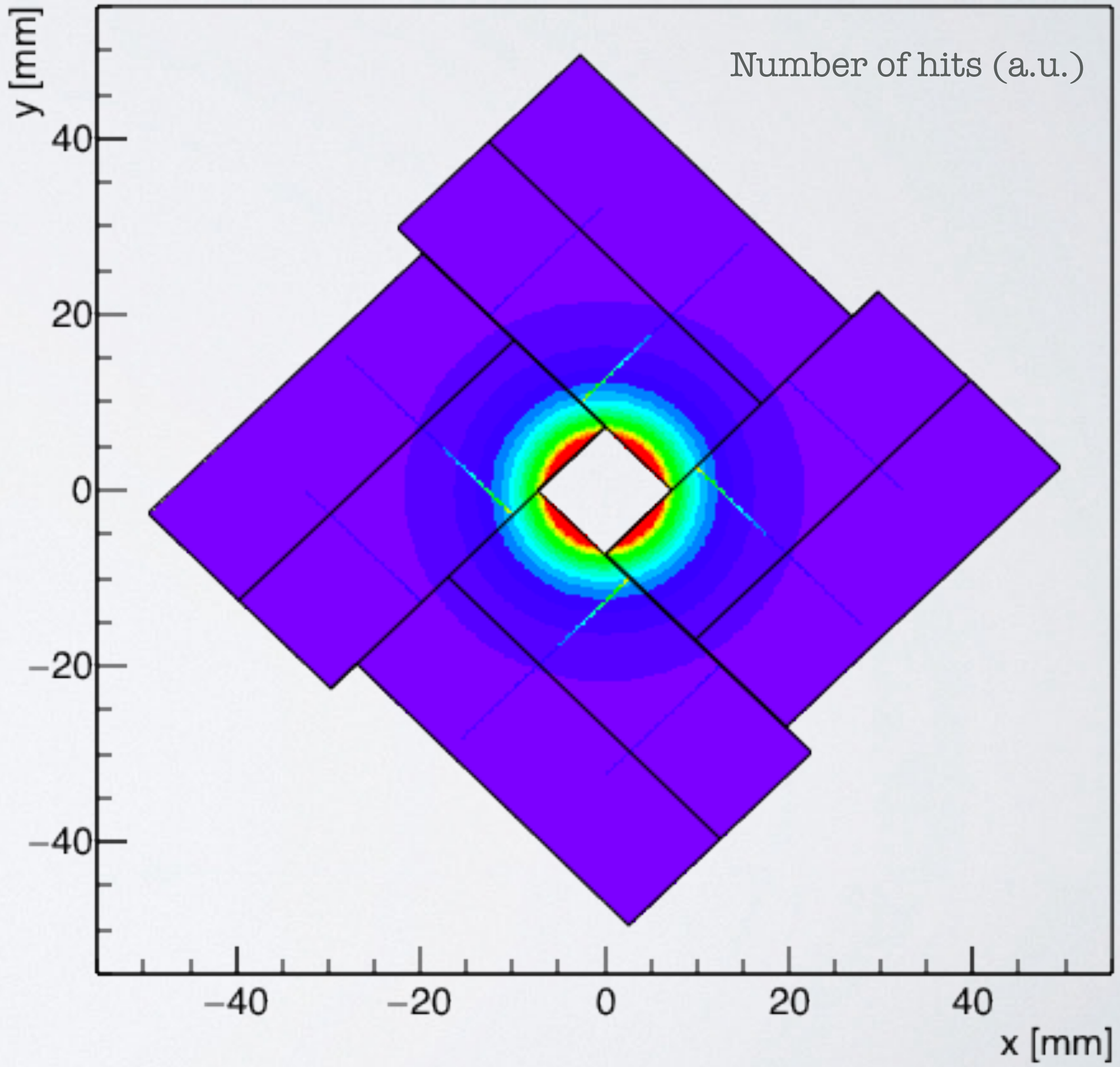


- Sensor is bump-bonded to 3 VeloPix ASICs
- Hamamatsu n-on-p 200 µm thickness
- Elongated pixels (137.5 µm) in the region between ASICs
- 450 µm wide guard ring
- DRIE-etched round corners (foil clearance)

- Triggerless, binary readout (data-driven readout)
- Up to 800 Mhits/s/ASIC
- Highly non-uniform irradiation

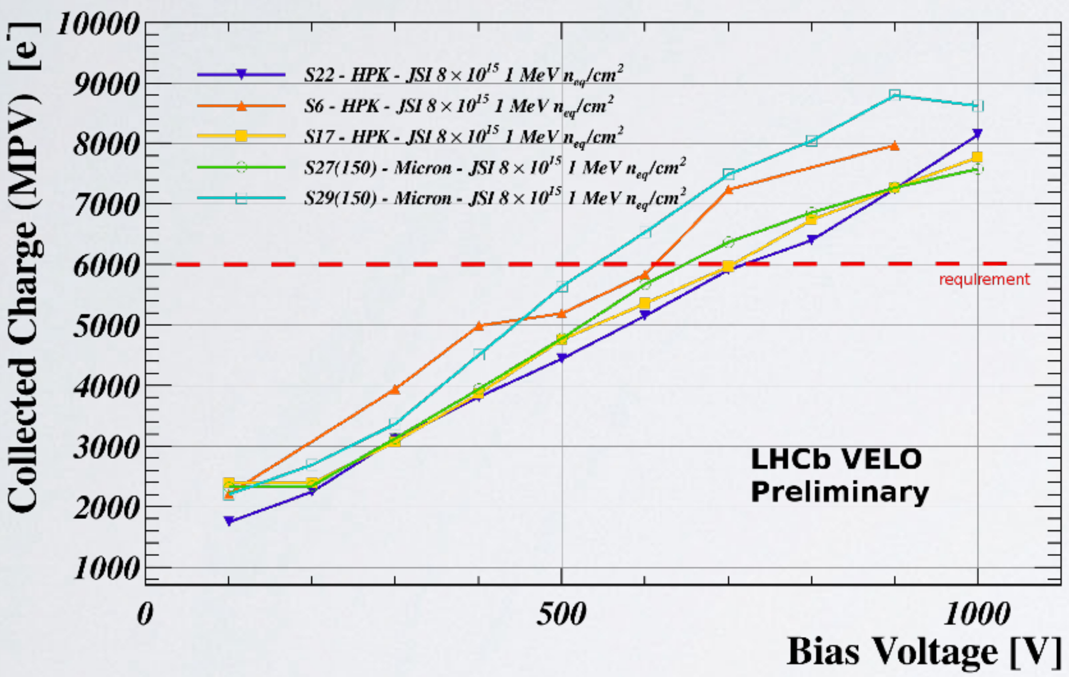
For more info, see here.

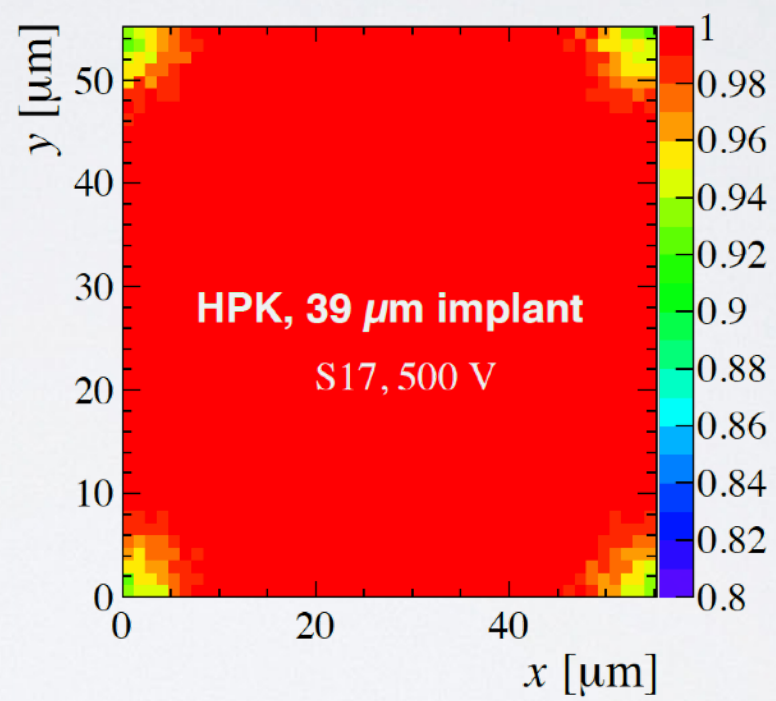


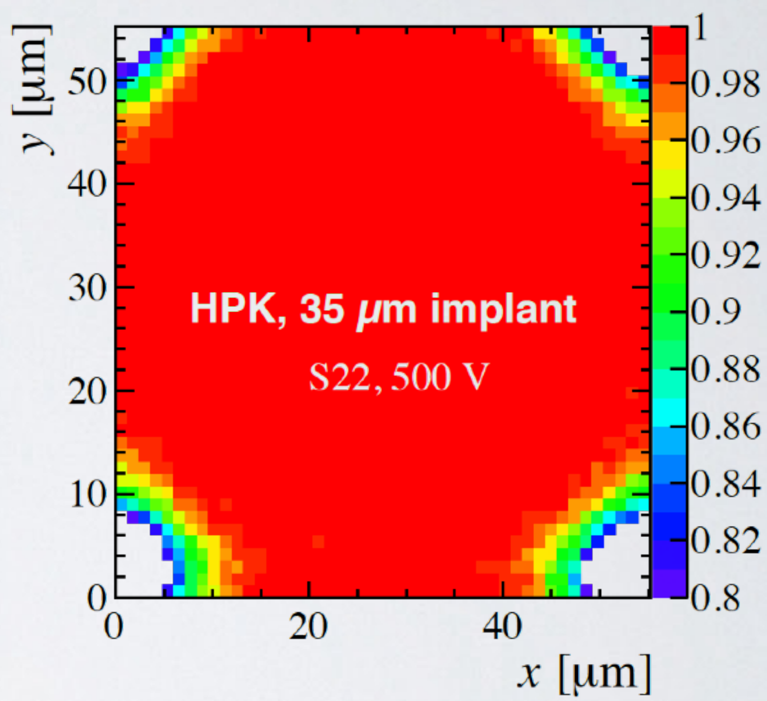


Sensors qualification

- Sensors irradiated (2-8 × 10^{15} MeV n_{eq} cm^{-2}) in 5 different facilities with neutrons (uniform) and protons (non uniform).
- Rigorous series of testbeams to qualify the sensors, using TimePix3 telescope at SPS.
- Velo Sensors must collect at least 6000 e^-/MIP @ 99% efficiency.







- ☑ Results after full fluence irradiation.
- ☑ Collected charge reaches 6000 e^- target with bias voltage < 1000V.

- ☑ Results after full fluence irradiation.
- ☑ Efficiencies reach 99% at 1000V, also in the corners.
- ☑ Production choice: 39 μm implants.