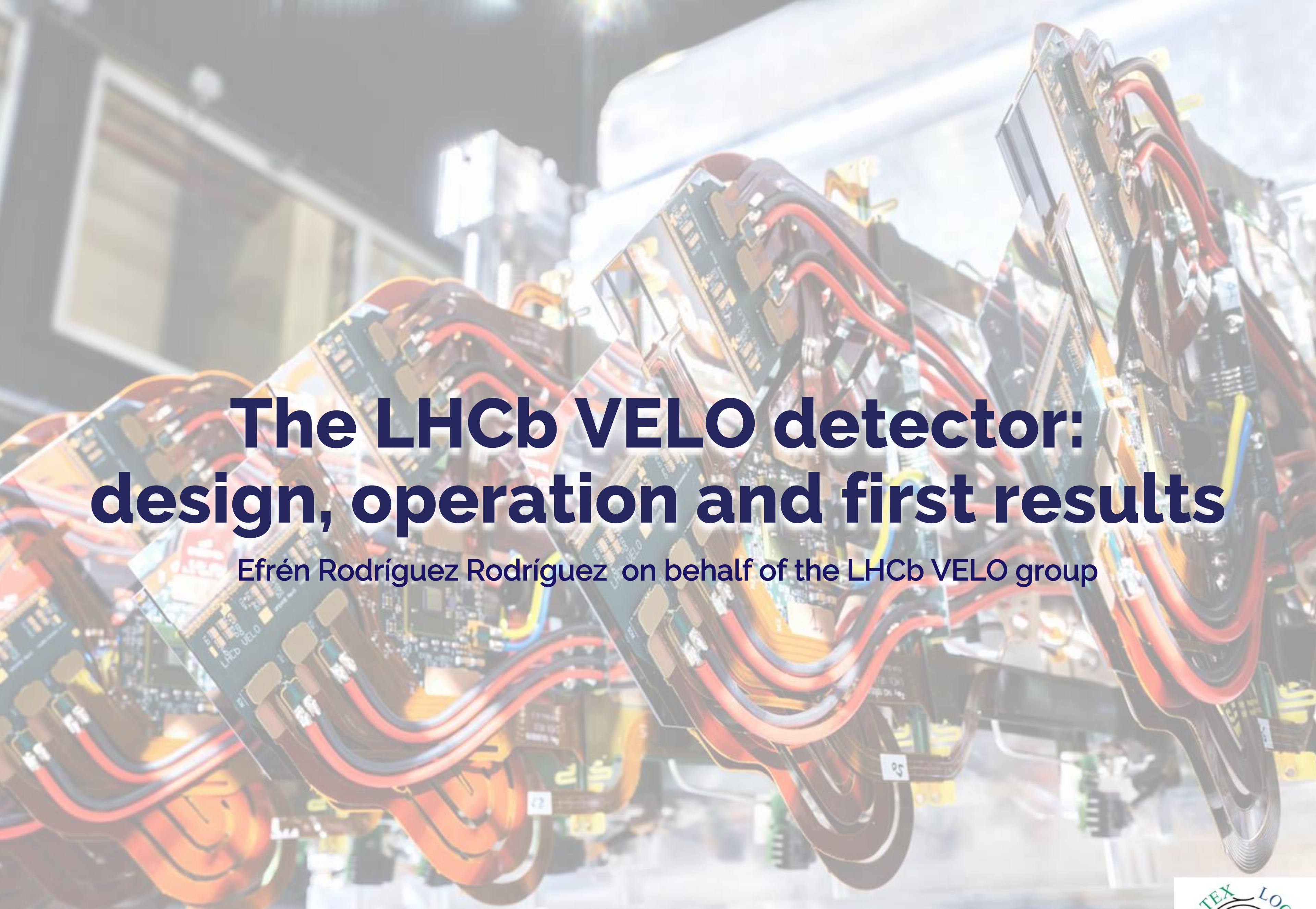


The LHCb VELO detector: design, operation and first results

Efrén Rodríguez Rodríguez on behalf of the LHCb VELO group

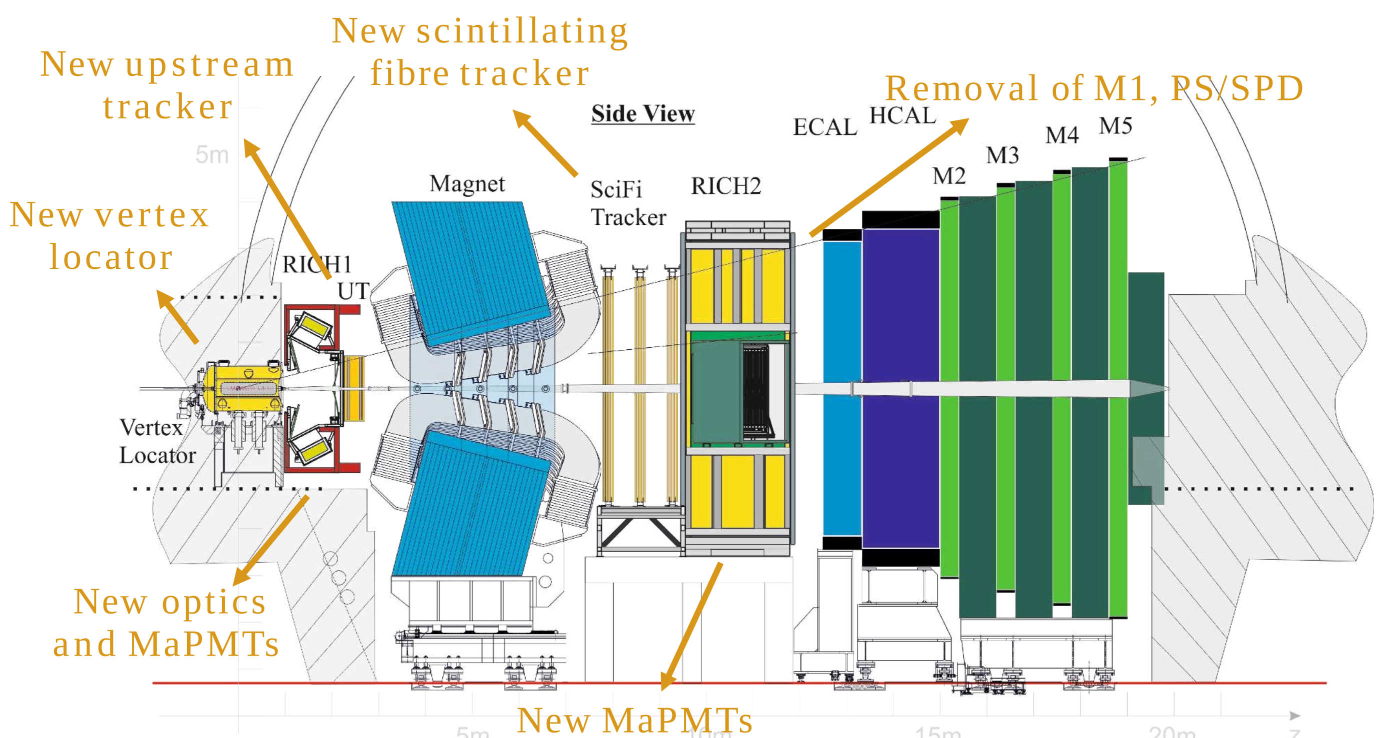
LHCb

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

For this, good secondary vertex identification needed ->
Good Impact parameter resolution needed

Upgrade I:

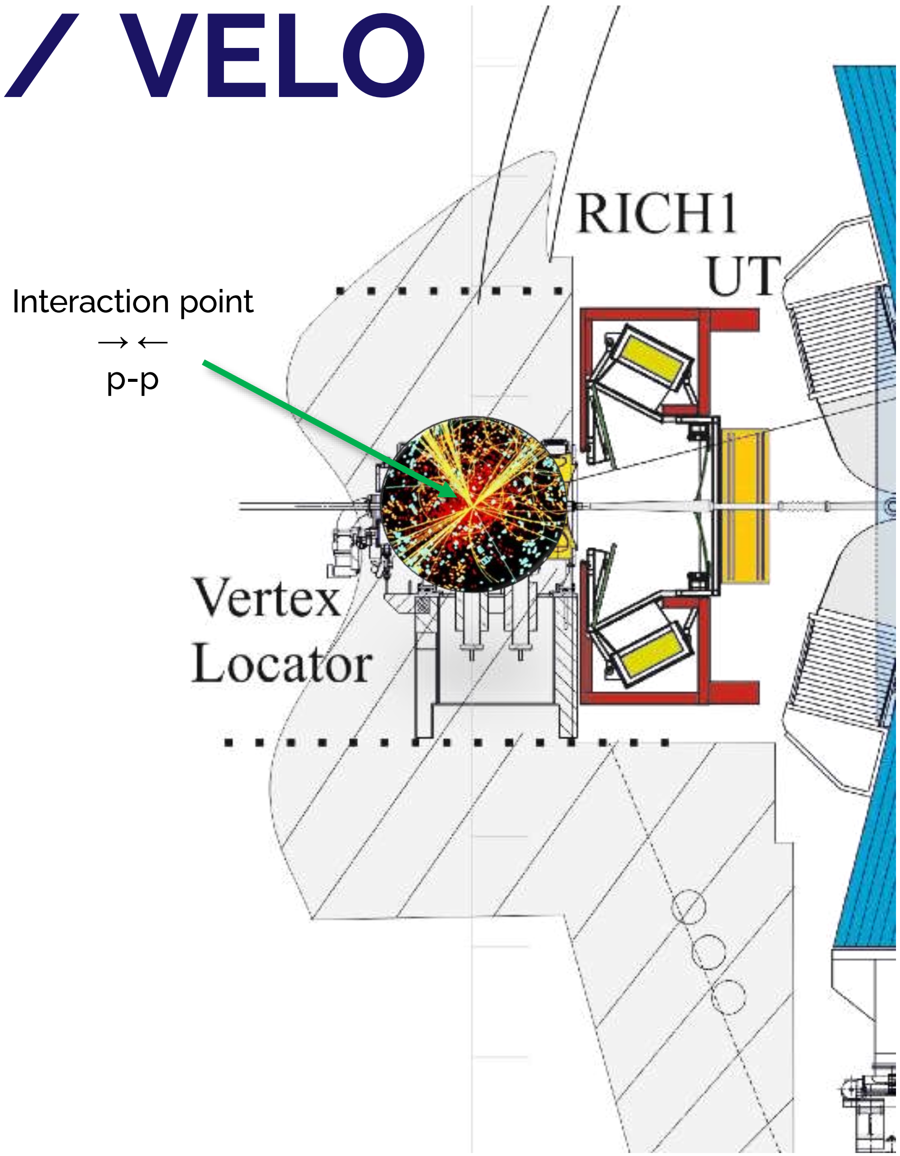
- Increase luminosity to boost statistics: $4x10^{32}$ $cm^{-2}s^{-1}$ ➔ $2x10^{33}$ $cm^{-2}s^{-1}$
- 50 fb^{-1} expected after LS2



LHCb / VELO

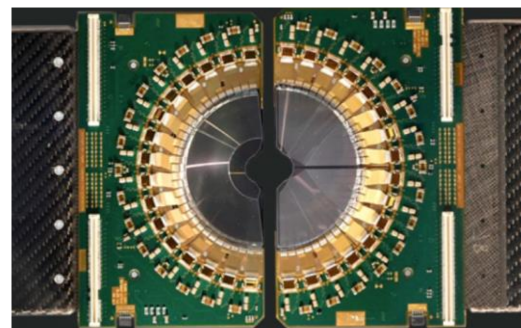
VErtex LOcator is a silicon detector surrounding the collision region providing excellent:

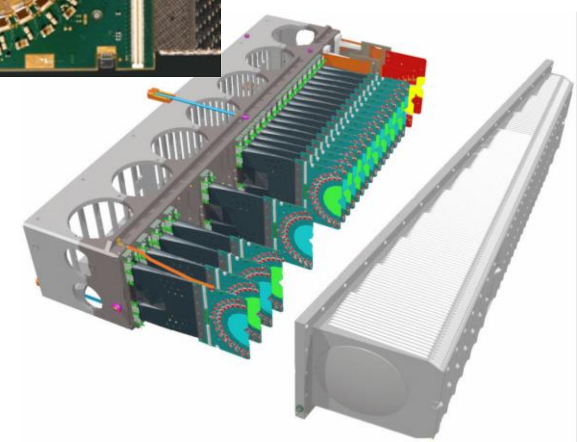
- Impact parameter resolution
- Identification of secondary vertices



Original **VELO**, great spatial resolution:

- Silicon microstrips
- Two halves retracted during injection
- Readout at 1MHz
- Innermost radius 8.2 mm from the beam



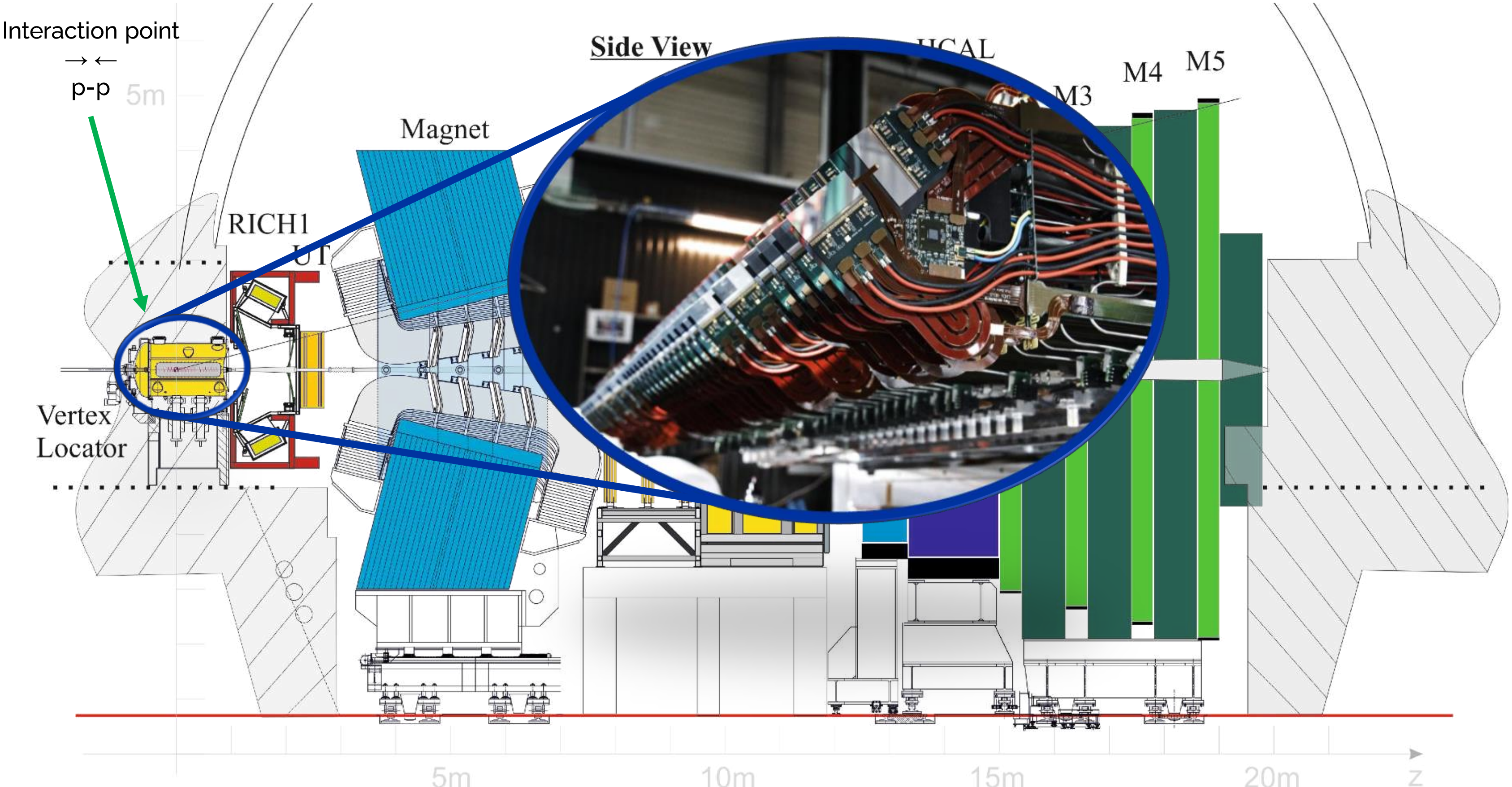


LHCb / VELO

A pixel detector for tracking and vertex reconstruction.

New VELO to improve even more impact parameter resolution and stand higher luminosity:

- Higher irradiation -> **New radiation hard detectors**
- Higher hit rates -> **Remove hardware trigger** and **increase readout speed**
- **Improve impact parameter and spatial resolutions**
- **Less material budget**

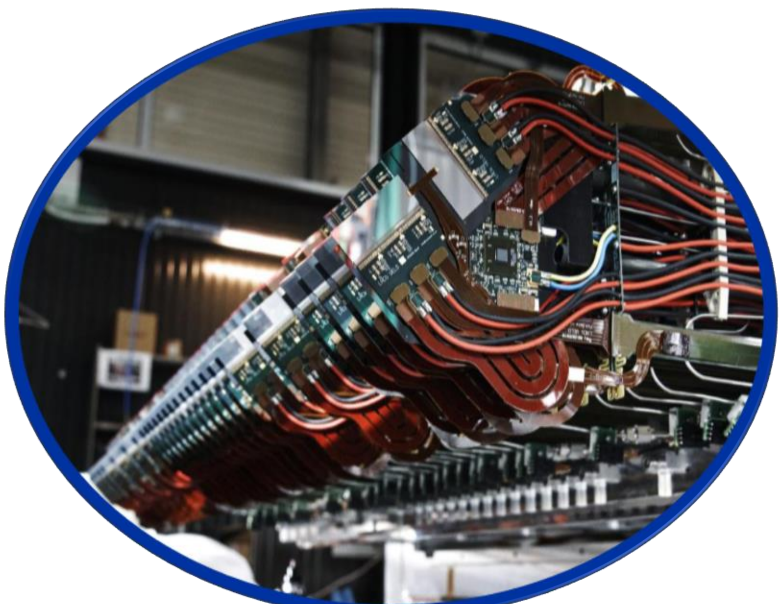


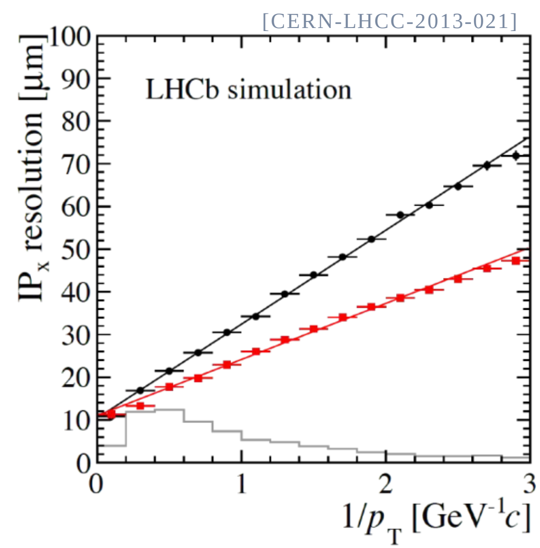
LHCb / VELO

- New pixel detector:
  - No ghost tracks
  - Faster reconstruction algorithm
- New front-end electronics
- Thinner RF-foil
- More efficient cooling interface

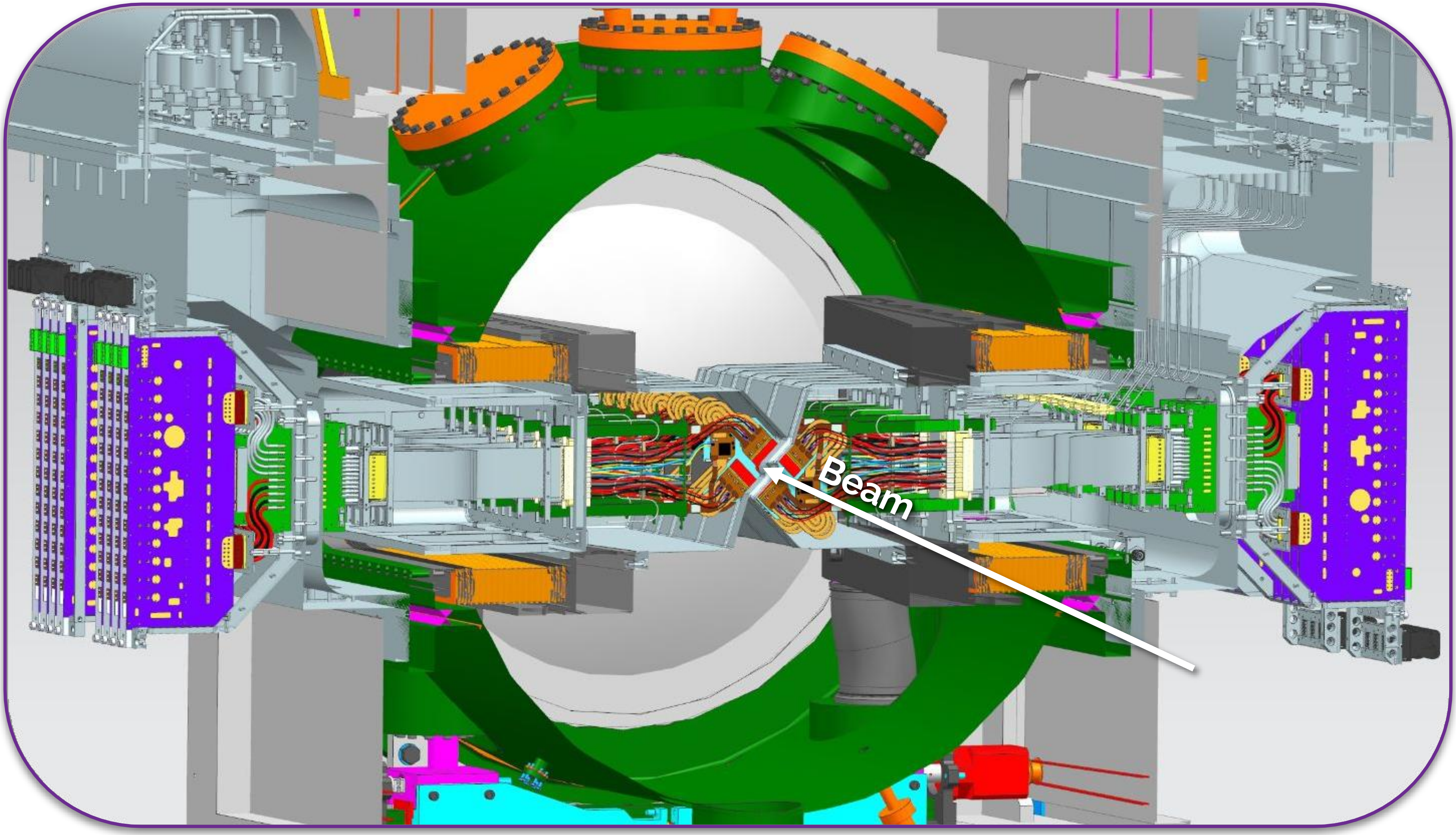
- Operated @40 MHz and 2×10^{33} $cm^{-2}s^{-1}$ at only 5.1 mm from the beams
  - 2.8 Tb/s data rates
  - 8 $\times 10^{15}$ 1MeV n_{eq} cm^{-2} max fluence
  - Sensors to be kept <-20 °C

- Increase hit resolution
- Increase number of visible interactions
- Increase impact parameter resolution
- Reduced ghost tracks

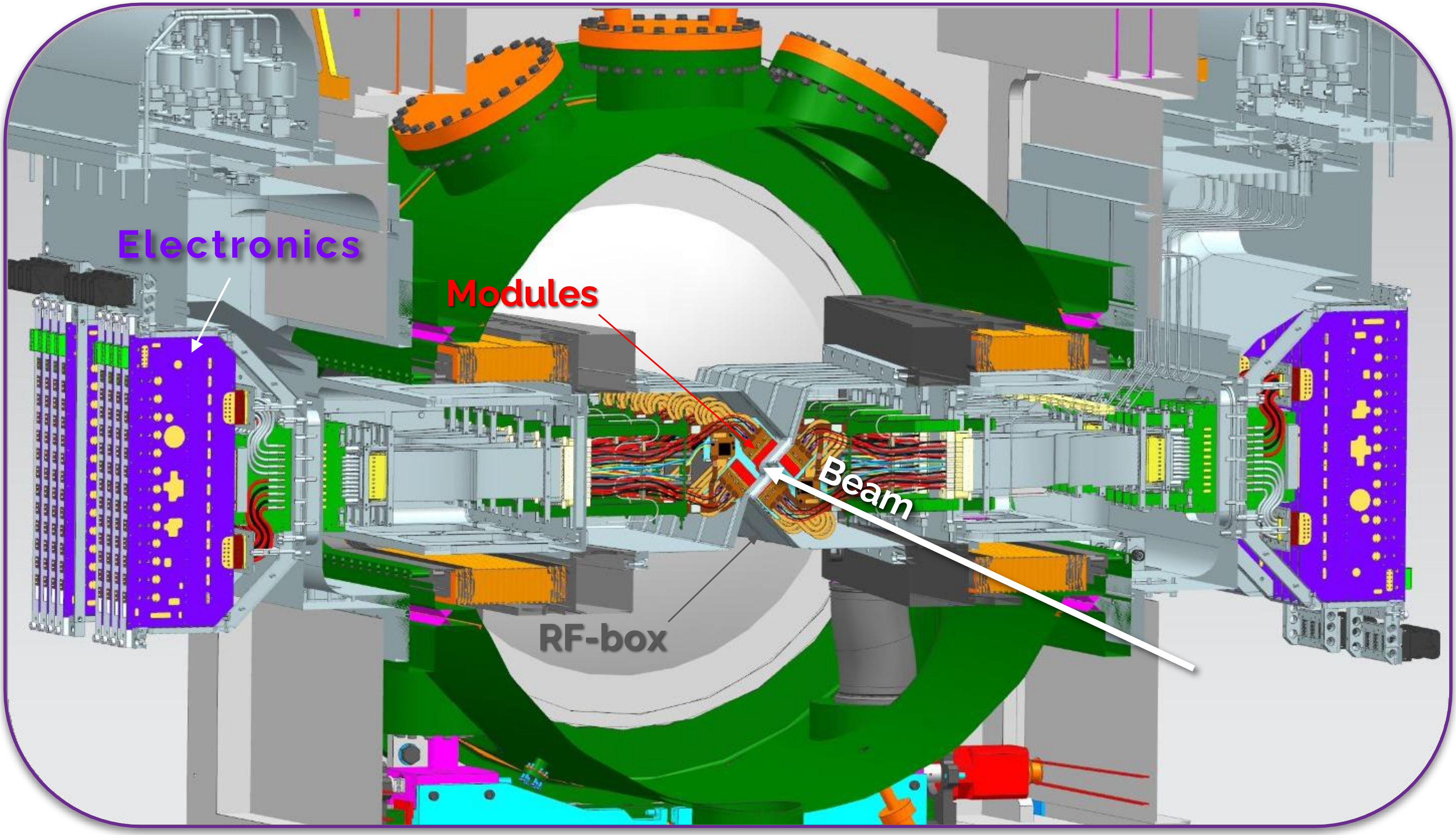




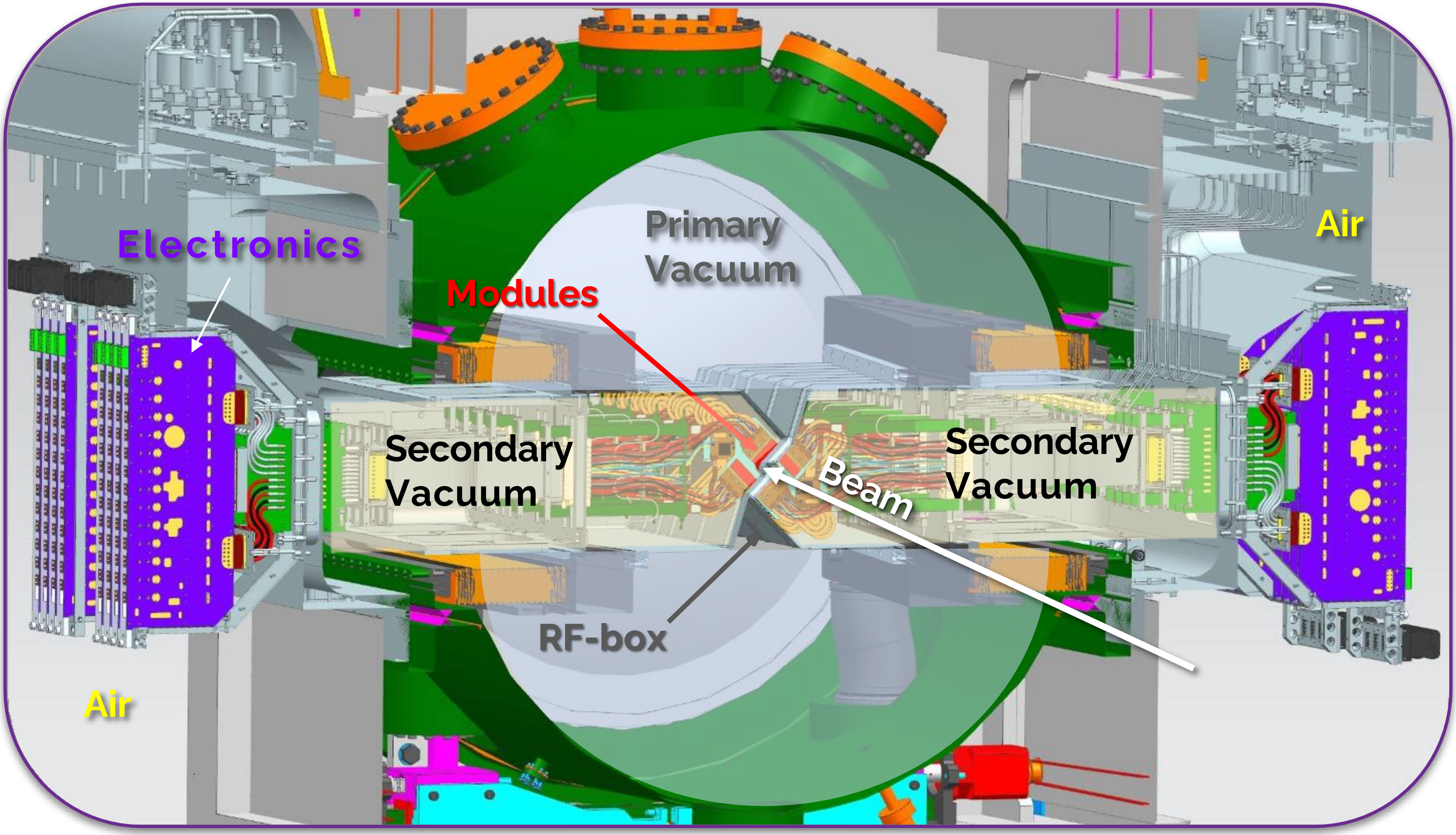
LHCb / VELO

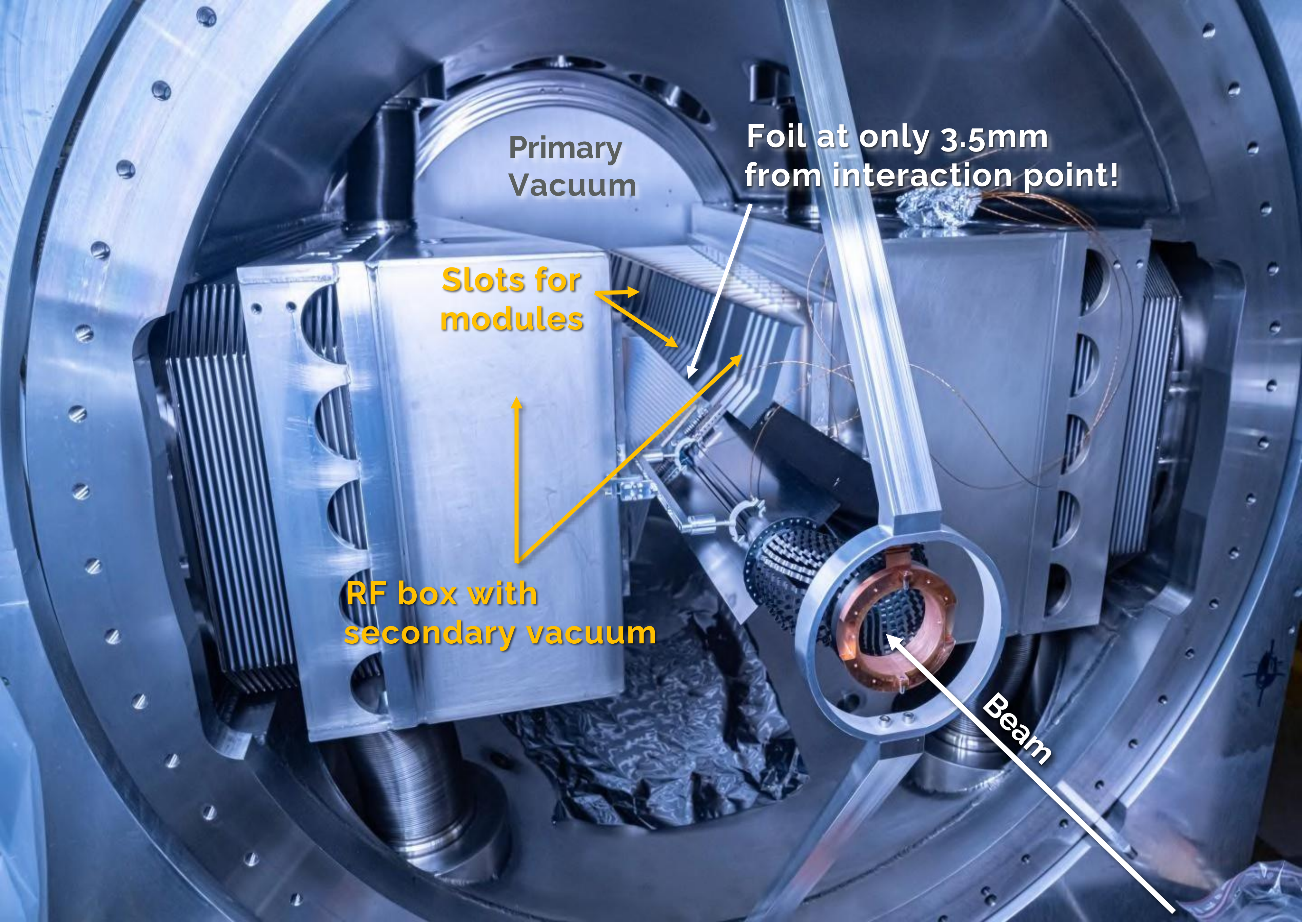


LHCb / VELO

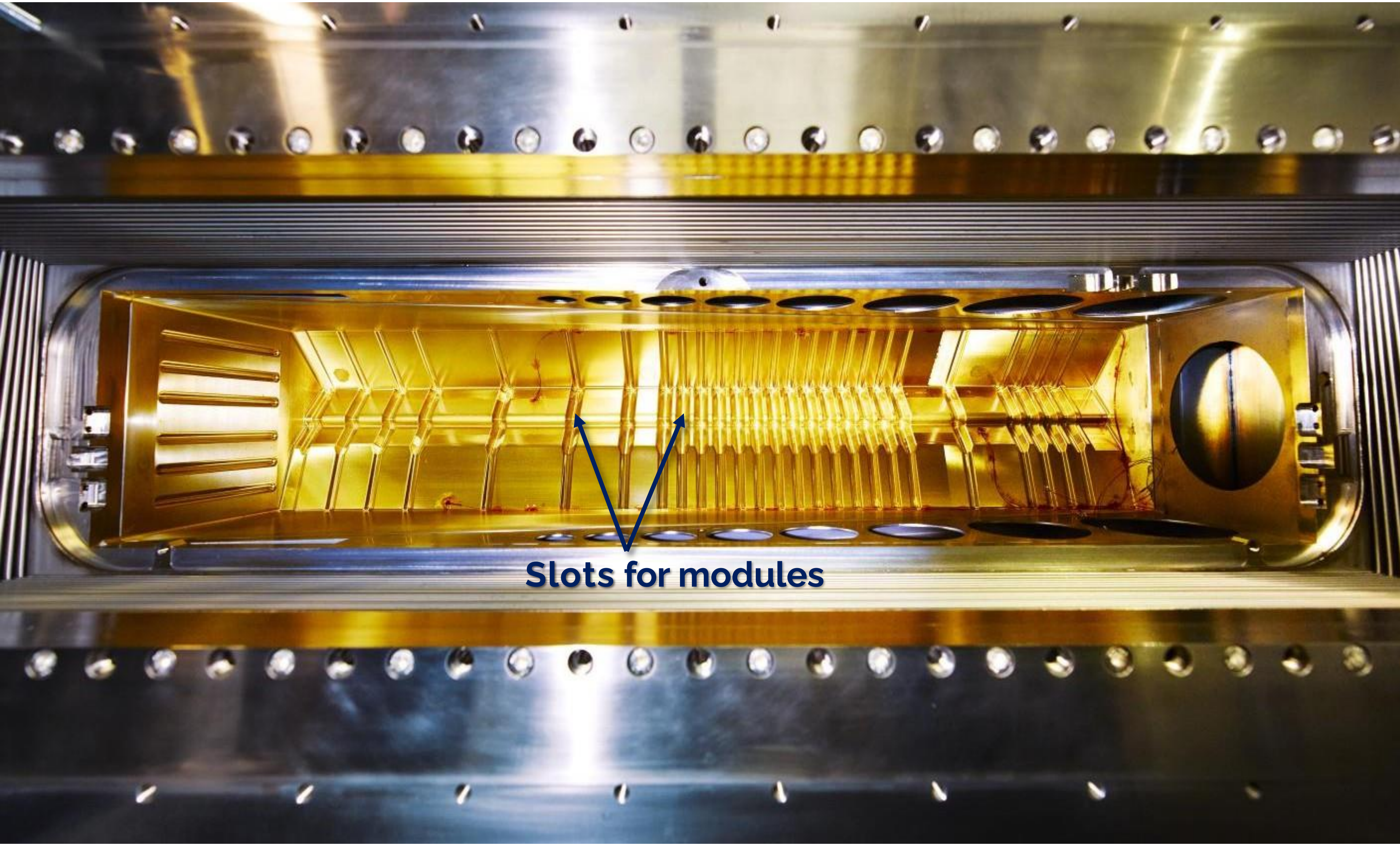


LHCb / VELO

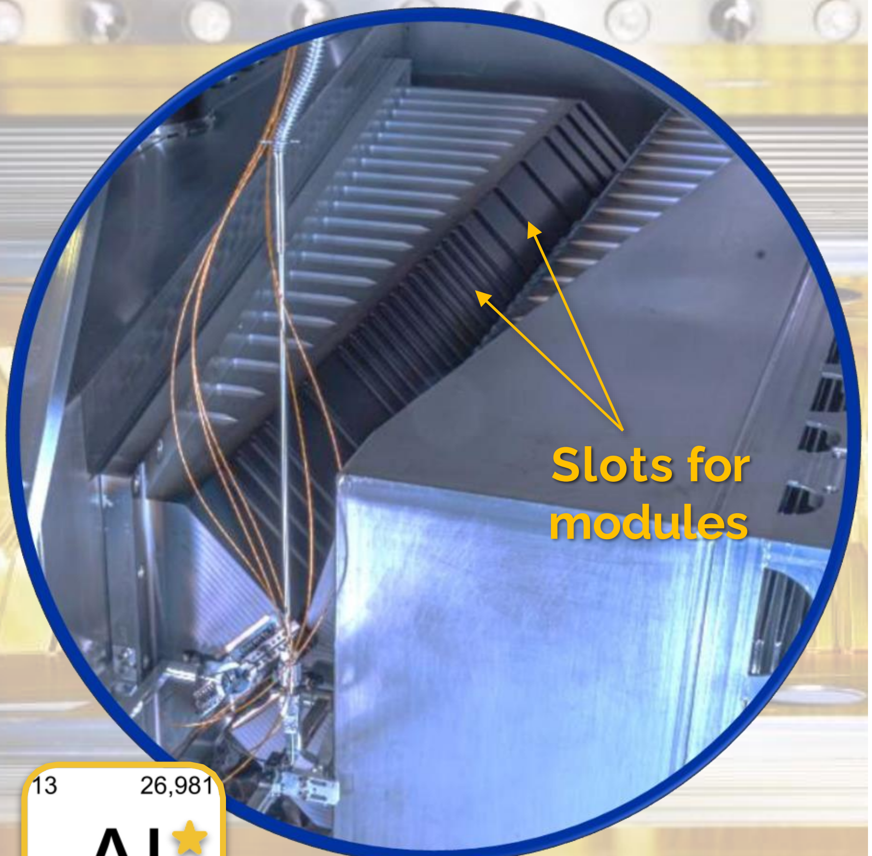

Electronics
Modules
Primary Vacuum
Air
Secondary Vacuum
Secondary Vacuum
Beam
RF-box
Air

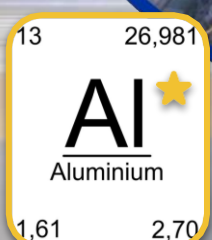

Primary
Vacuum
Foil at only 3.5mm
from interaction point!
Slots for
modules
RF box with
secondary vacuum
Beam

RF BOX (inside view)



RF BOX



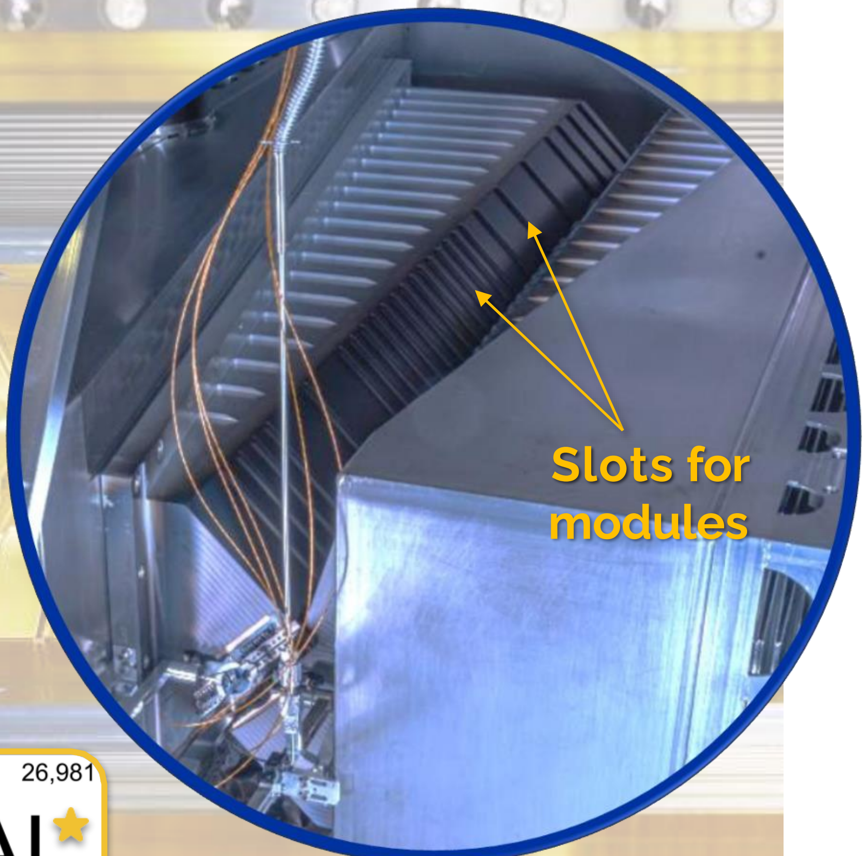


★ cast aluminium alloy from Alimex (AlMg4.5Mn0.7 EN-AW5083)

RF Foil design:

- Accommodate modules (~1 m long)
- Separate primary/secondary vacuum
- Shield against RF pick-up from the LHC beams
- Withstand **ΔP = 10 mbar**
- Corrugated, thermally stable, vacuum tight, rad-hard
- Light:
  - Aluminum: light and not contaminant for LHC vacuum
  - 250 µm (**150 µm** inner region)

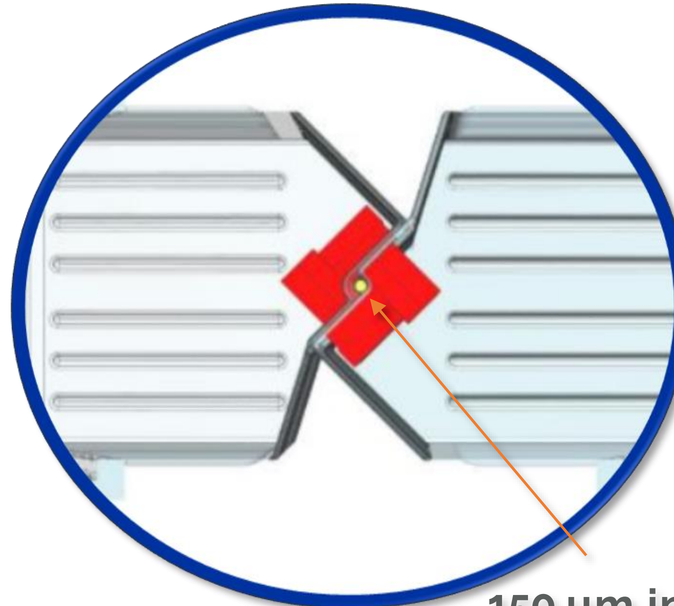
RF BOX



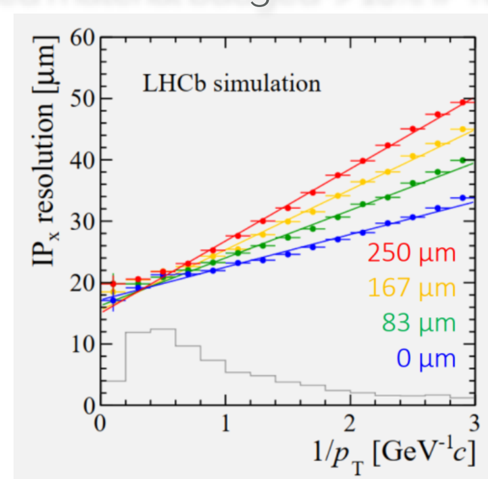
13 26,981
Al
Aluminium
1,61 2,70

★ cast aluminium alloy from Alimex (AlMg4.5Mn0.7 EN-AW5083)

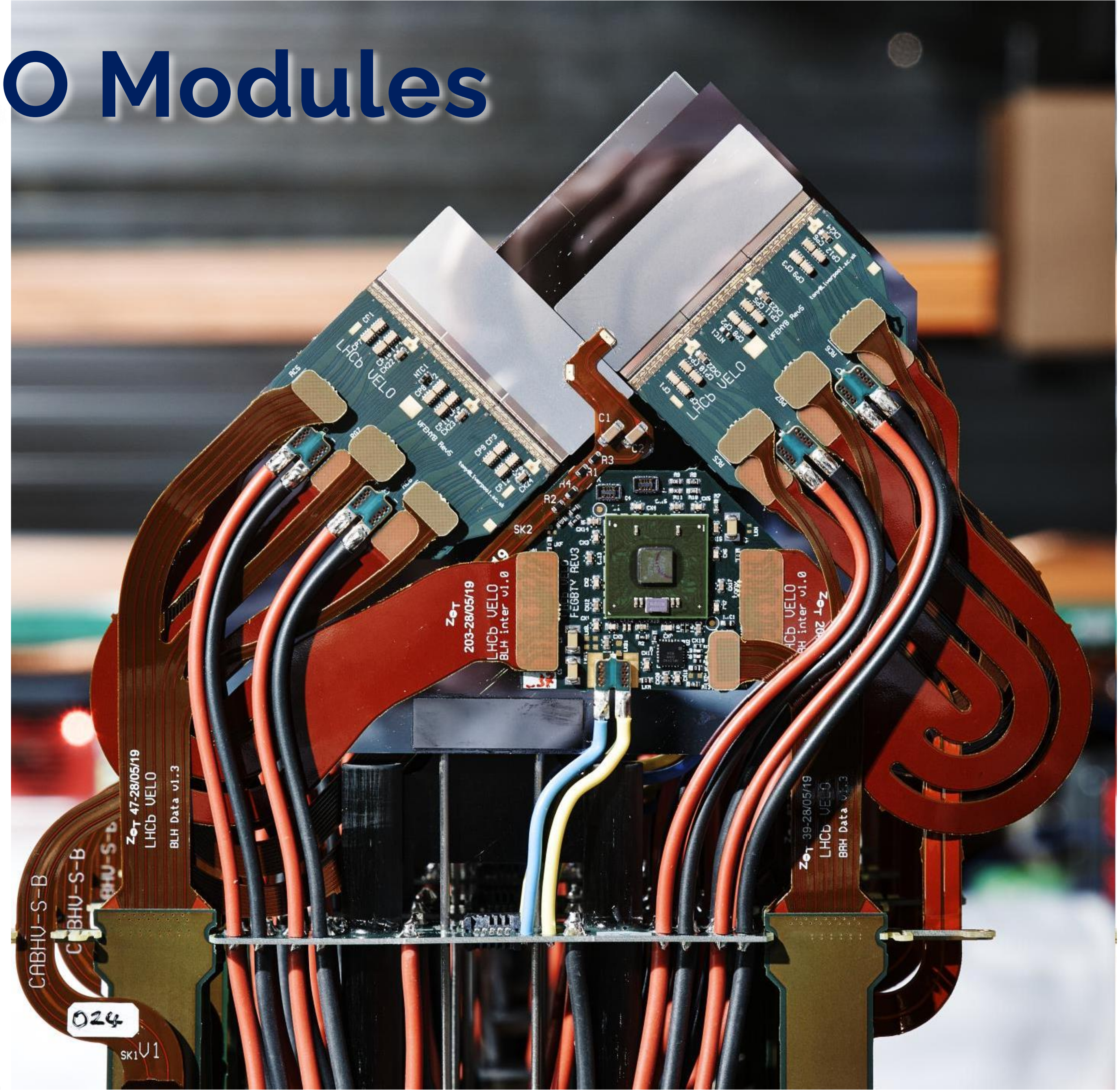
Vertical section



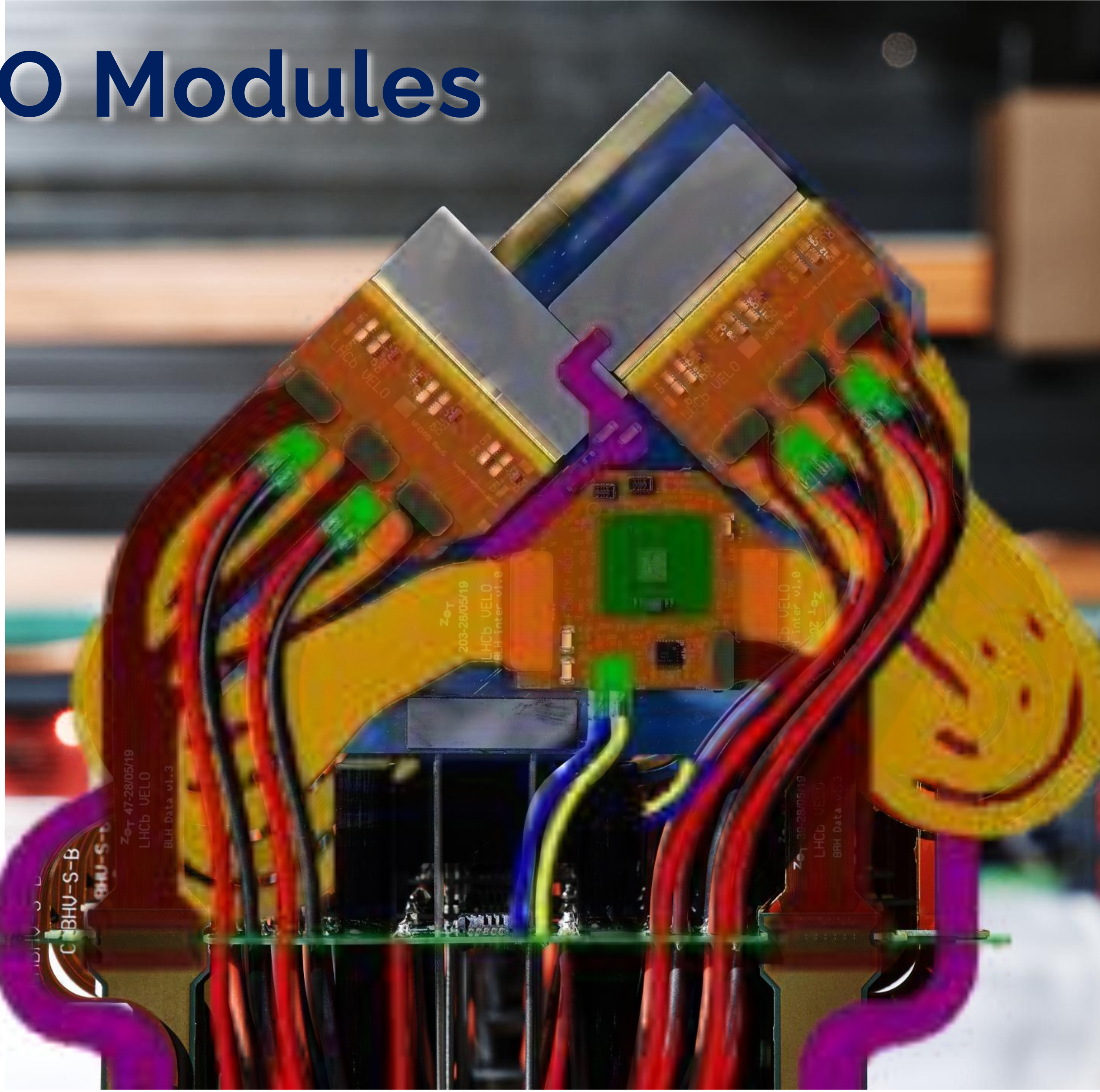
Reduced material budged-> 10% IP resolution



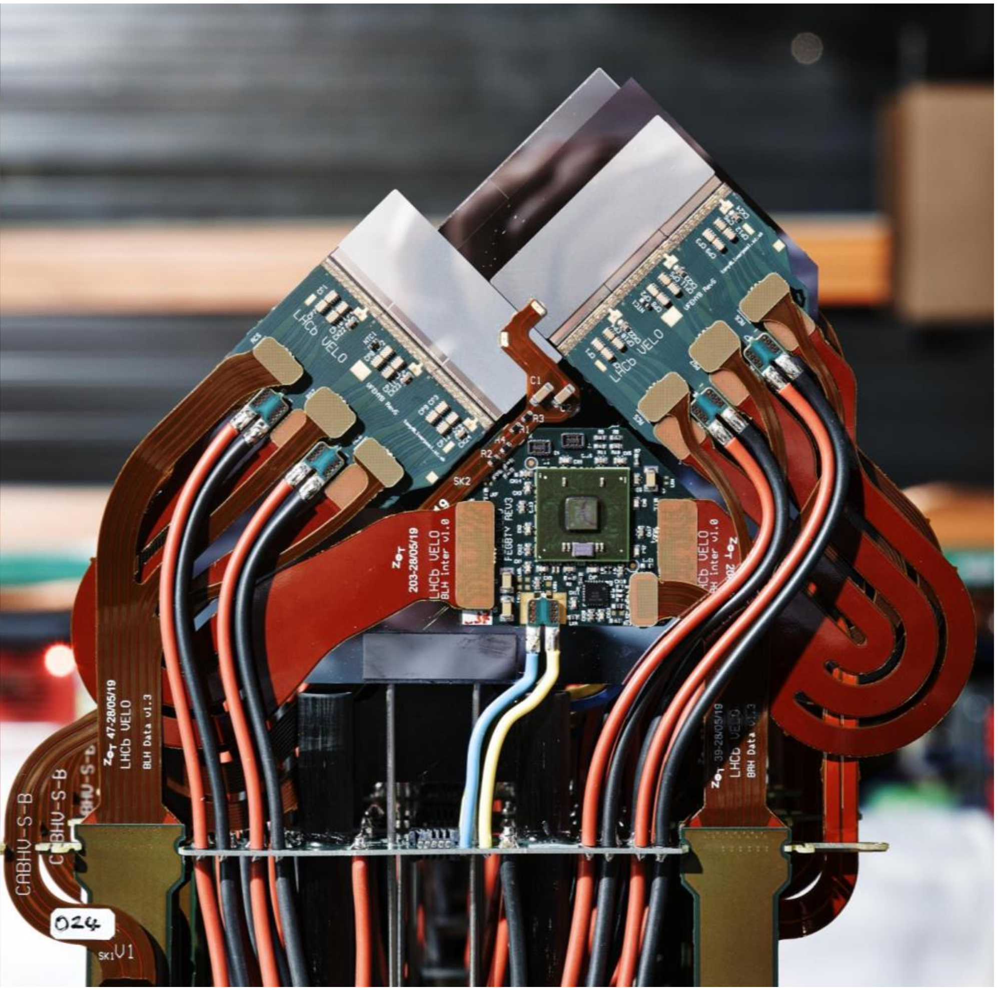
VELO Modules

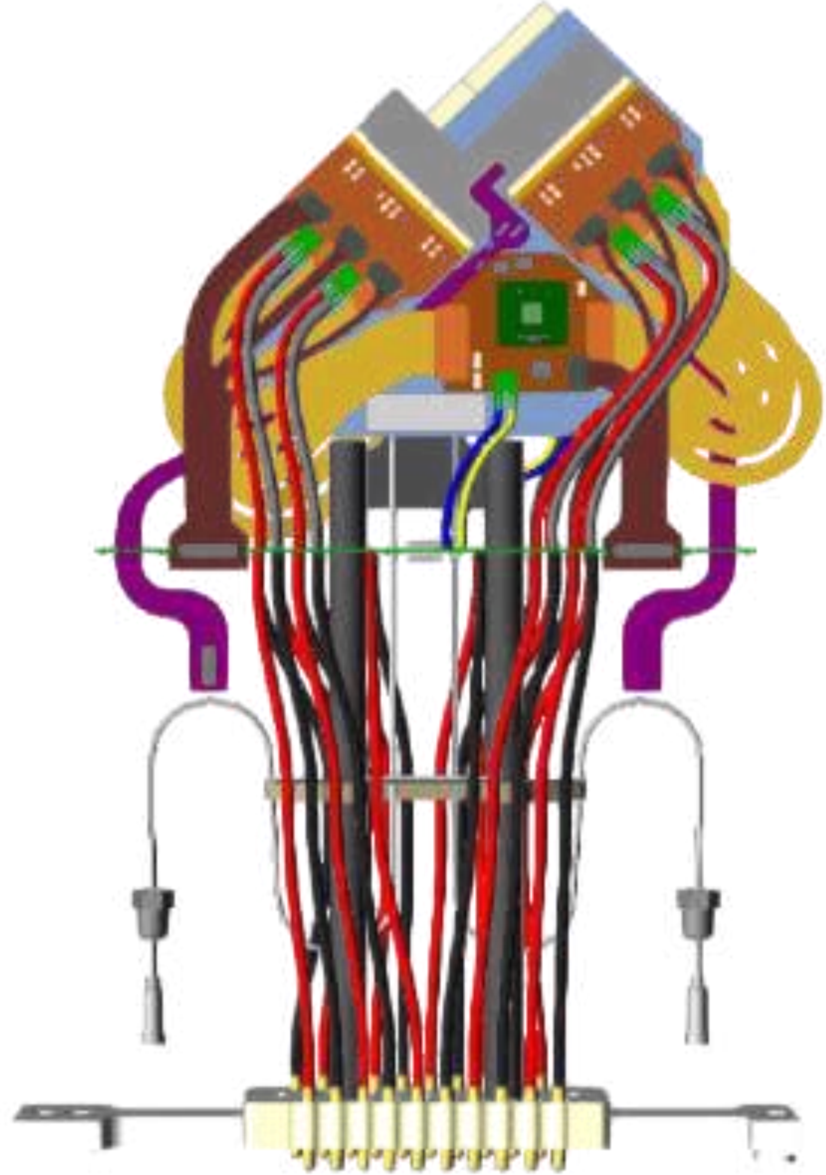


VELO Modules



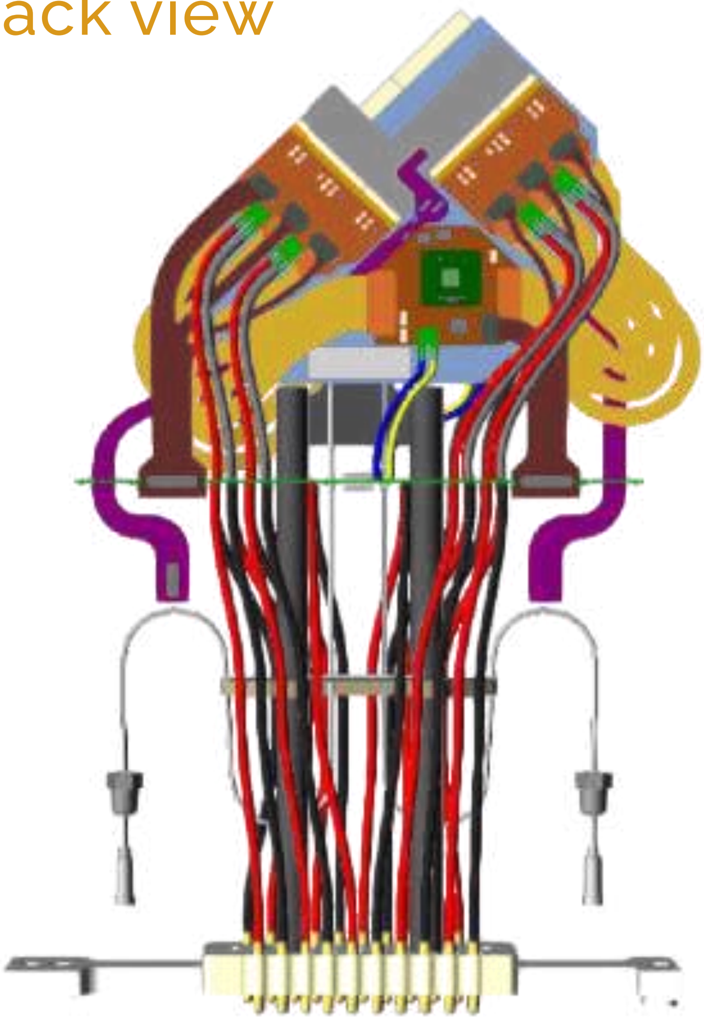
VELO Modules



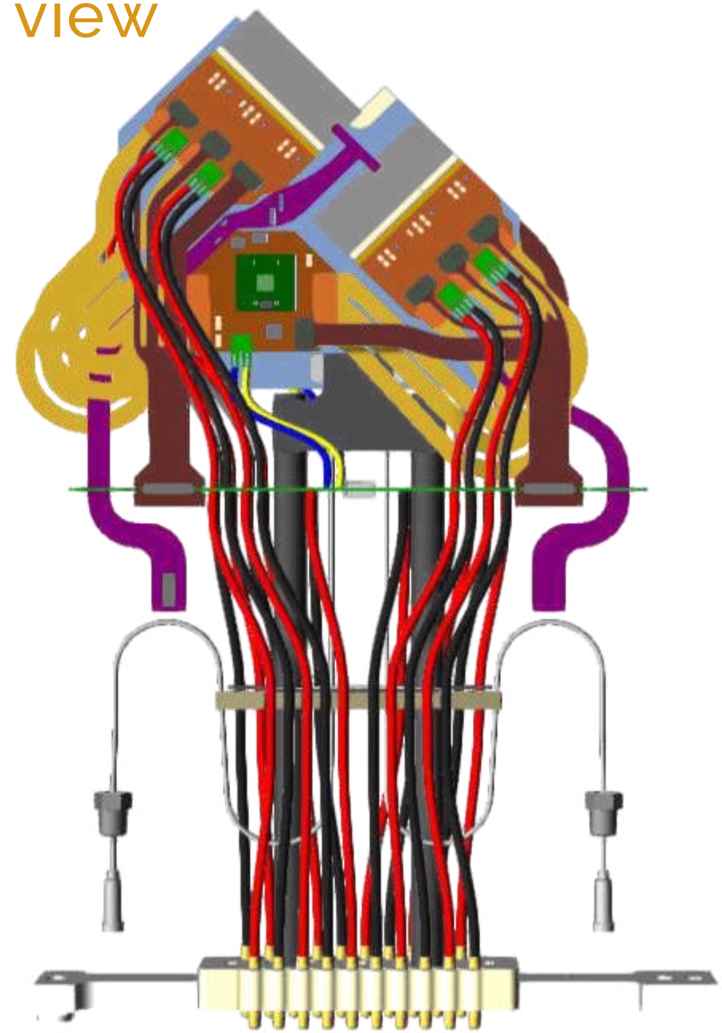


VELO Module design

back view

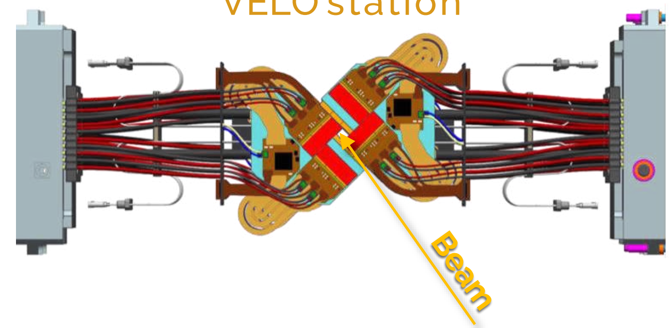


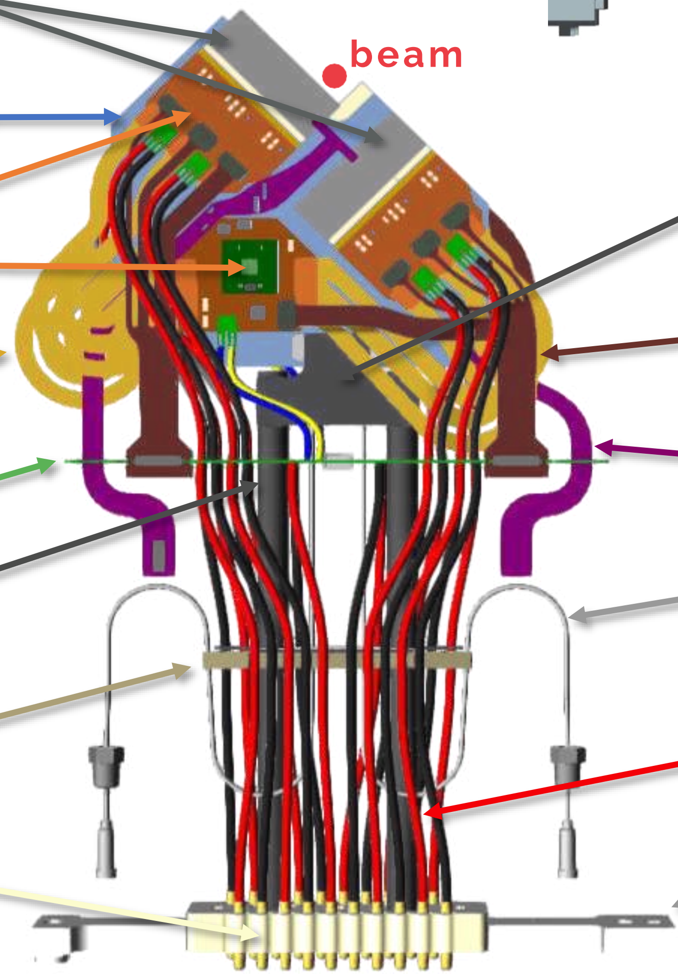
front view



VELO Module design

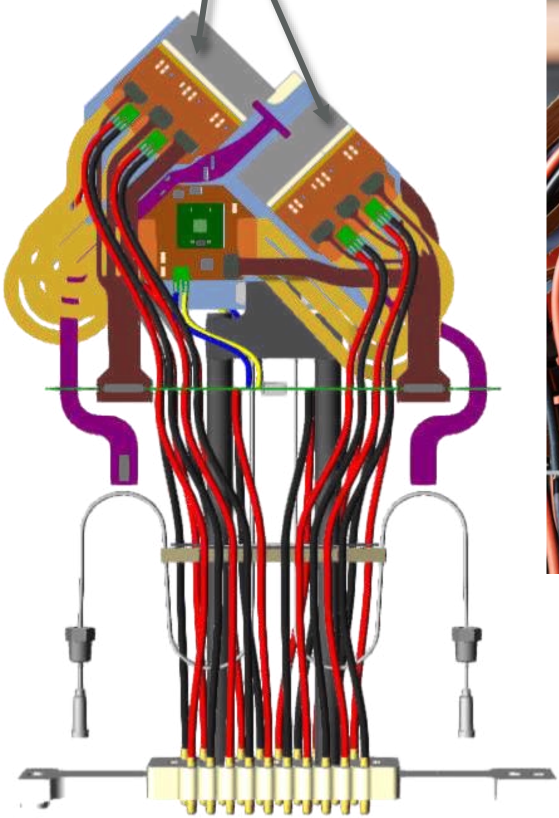
Different materials brought together into a module

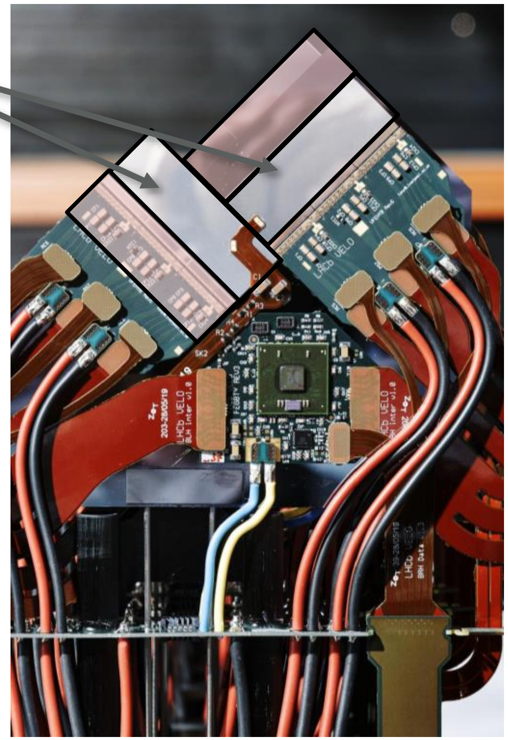




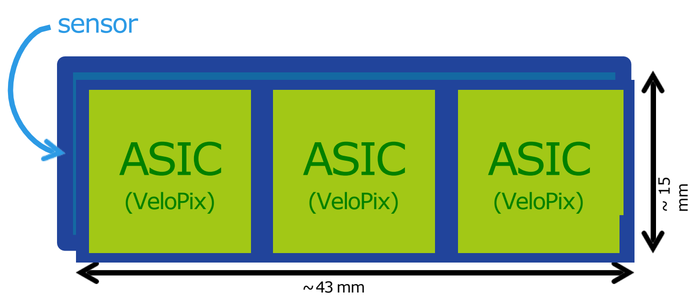
Sensors

Tiles (Silicon sensors bump-bonded to 3 ASICs)





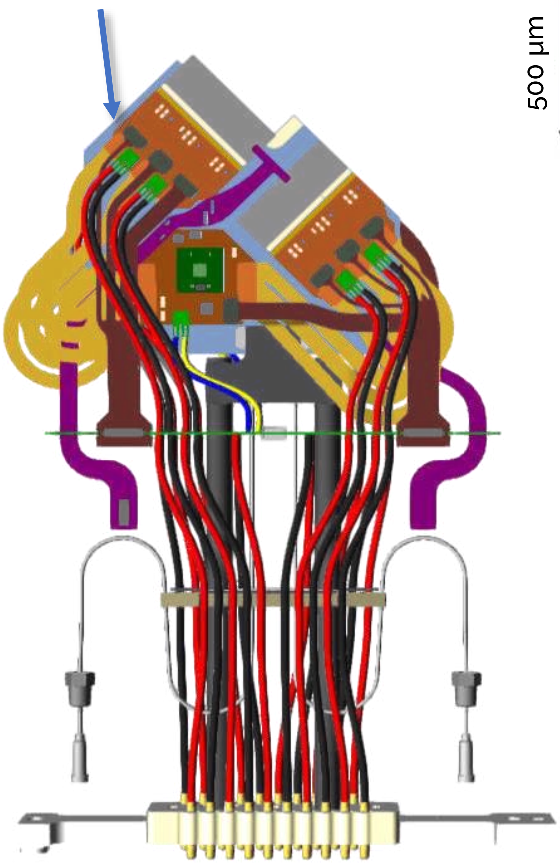
Feature	Upgrade
Sensor	Pixels 55 µm pitch 0.12 m^2 - 41 M pixels electron collecting 200 µm thick
ASIC	200 µm thick for material budget
# of modules	52
Max fluence	8×10^{15} 1 MeV neq cm^{-2}
HV tolerance	1000 V due to high irradiation gradient
Hit rate	800 Mhits/s/ASIC
ASIC readout	Binary data driven
Total data rate	2,8 Tb/s
Power consumption	1.6 kW (30 W/module)
Radiation hard	Technology 130nm TSMC-> Up to 400 Mrad

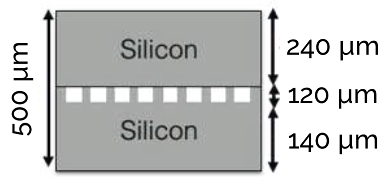


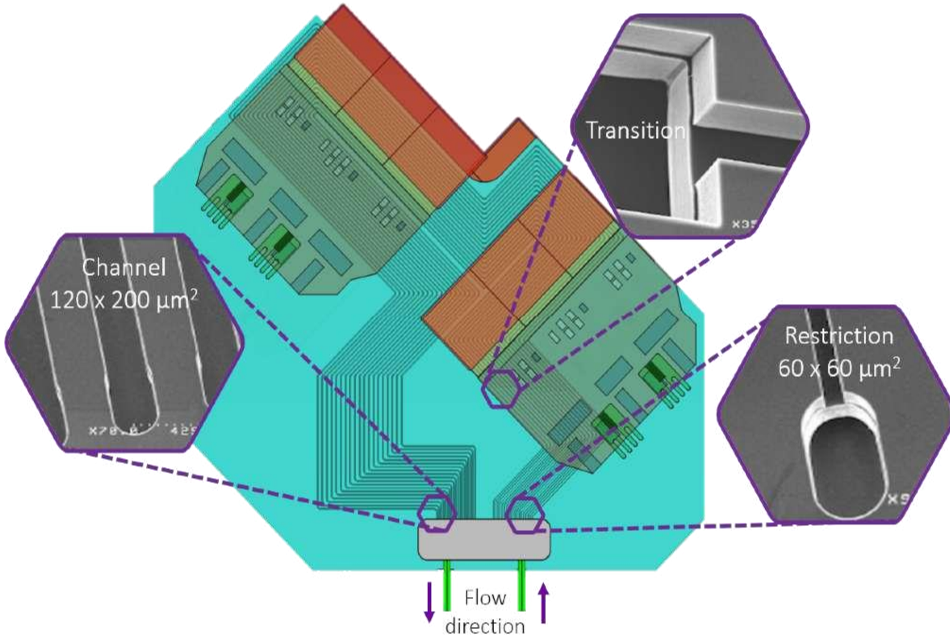
Cooling

Two phase evaporative CO_2 cooling

Silicon micro-channel substrate





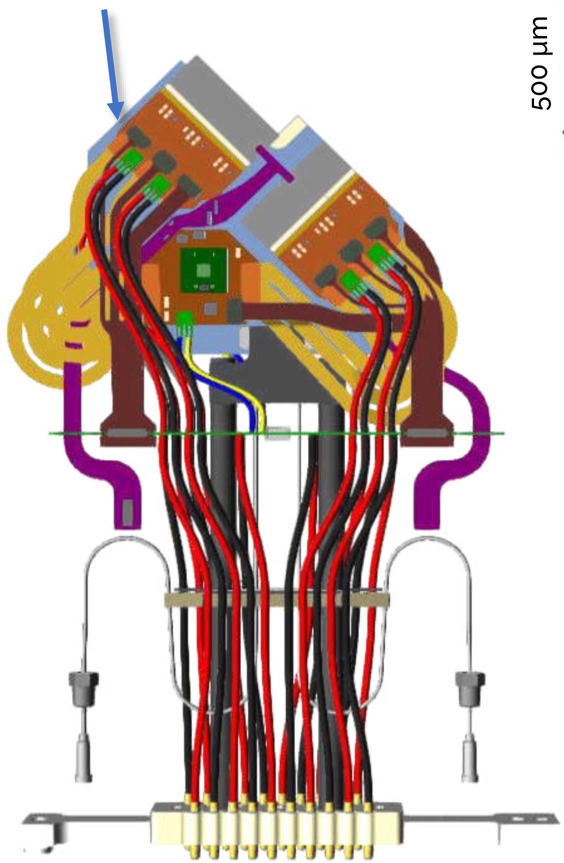


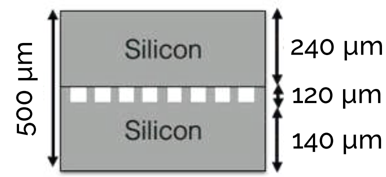
- 500 µm thick silicon substrate with integrated micro-channels.
  - Same CTE as sensors + low material budget
- Routing of channels customisable
  - 120 × 200 µm micro-channels (19×)
  - 60 × 60 µm high impedance restrictions
- Pressure: 14 bar @ -30 °C, 60 bar @ 22 °C
- High thermal efficiency. Cooling power up to 40 W at -30 °C

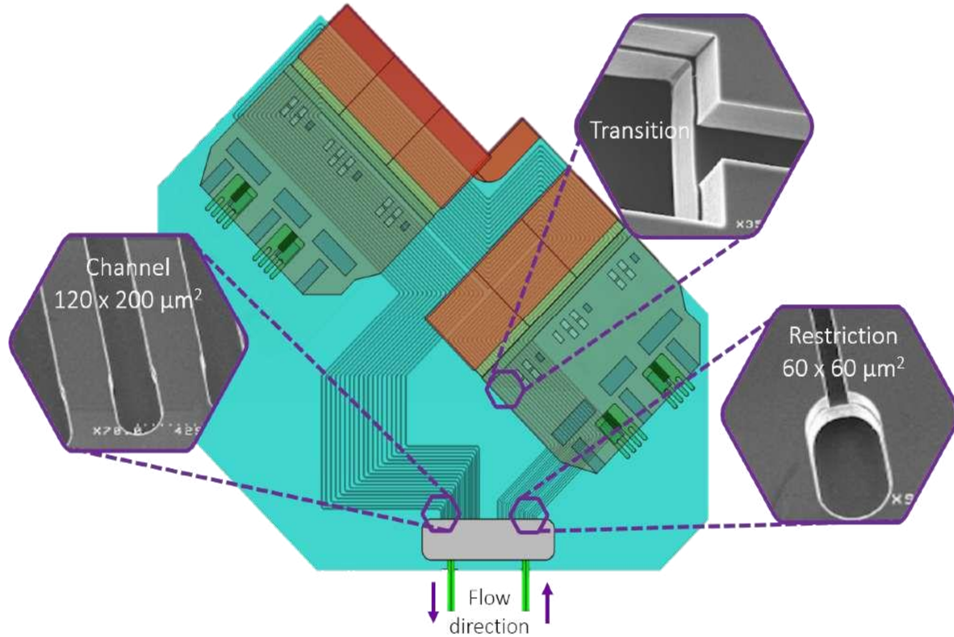
Cooling

Two phase evaporative CO_2 cooling

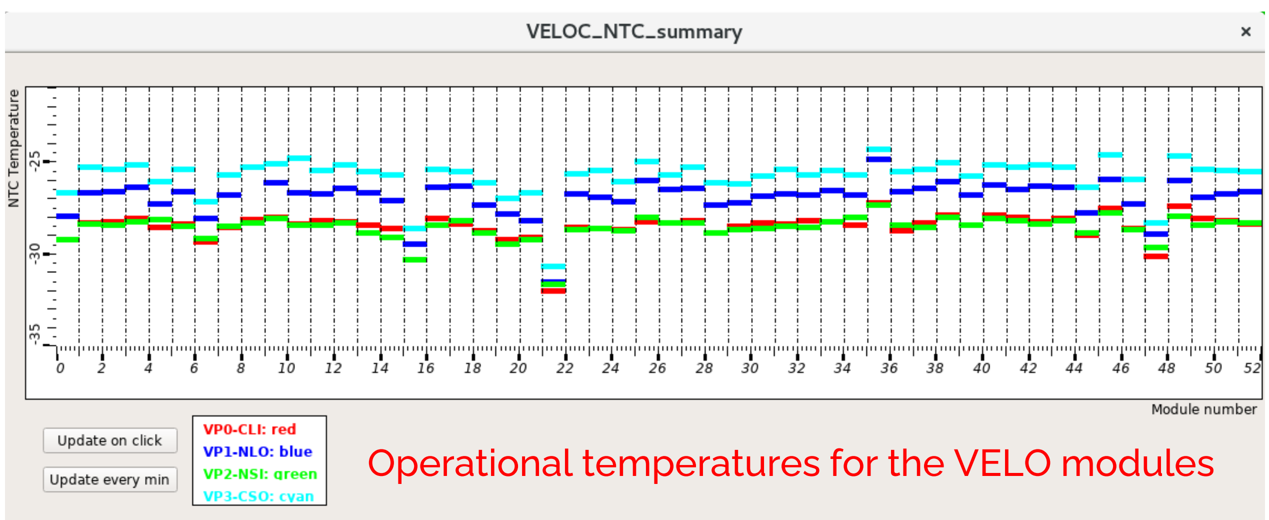
Silicon micro-channel substrate







- High thermal efficiency. Cooling power up to 40 W at -30 ºC

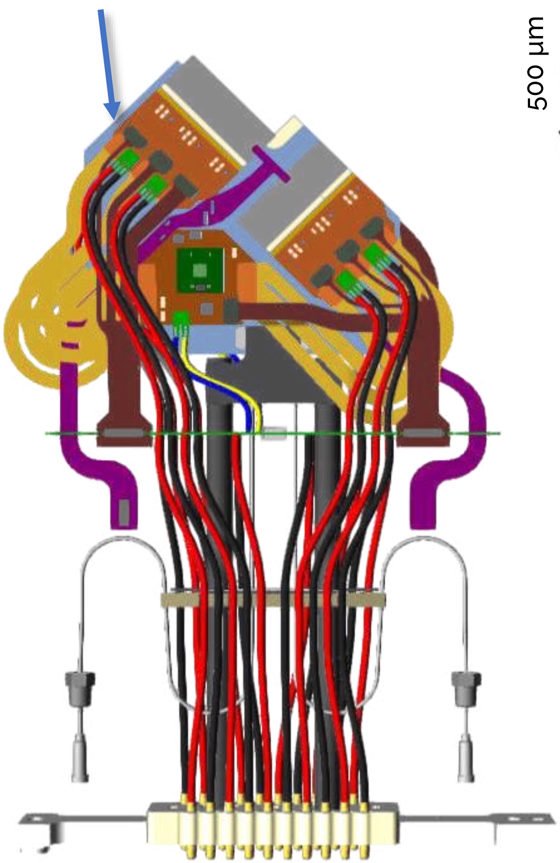


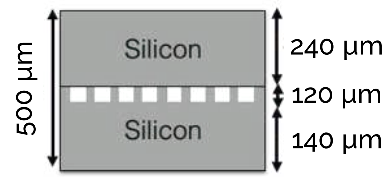
Operational temperatures for the VELO modules

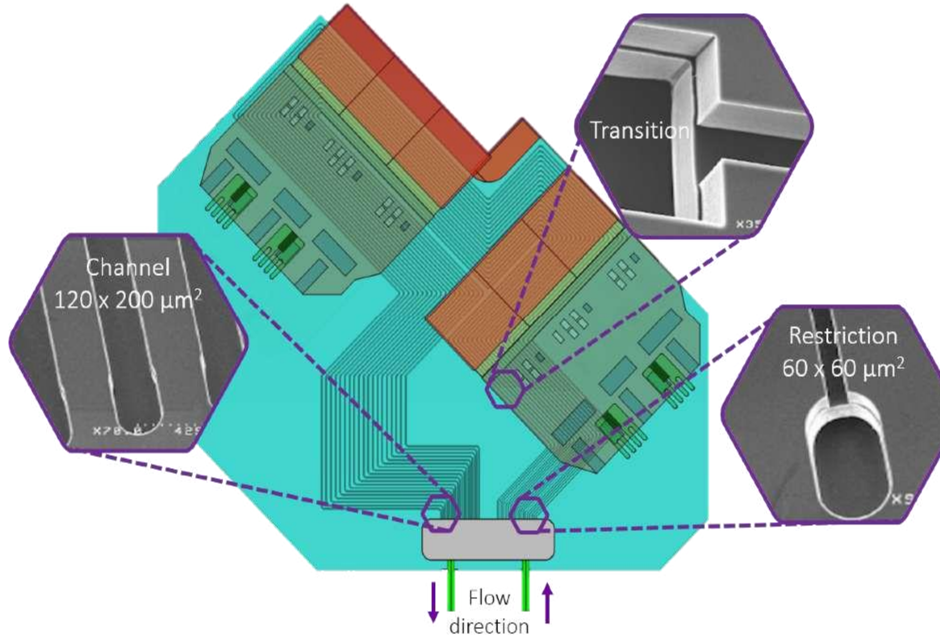
Cooling

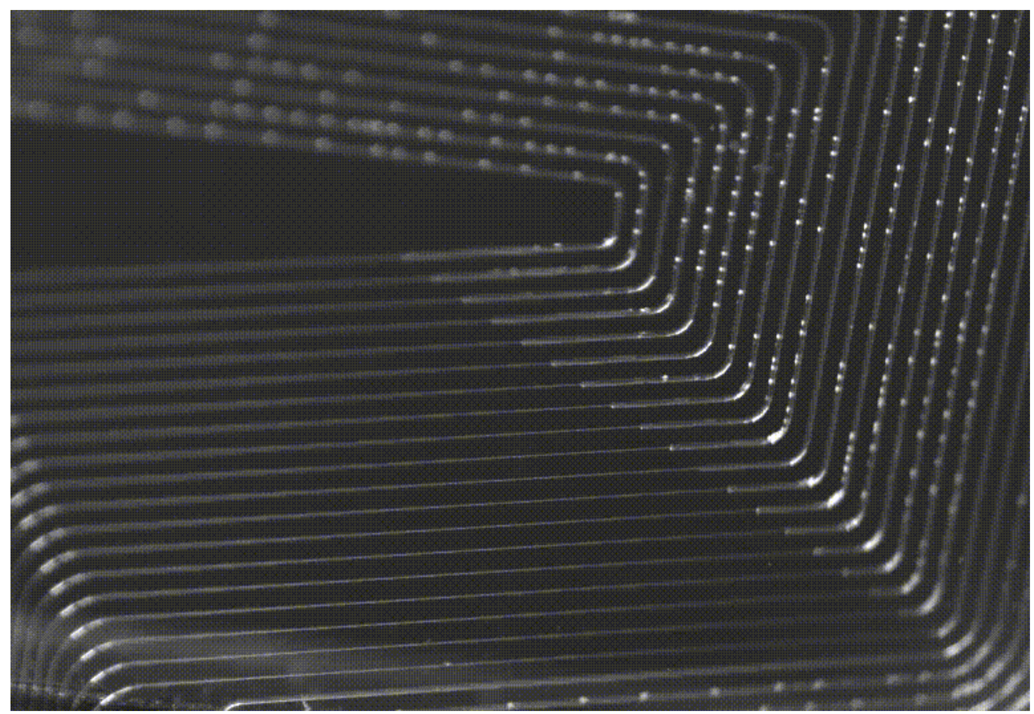
Two phase evaporative CO_2 cooling

Silicon micro-channel substrate

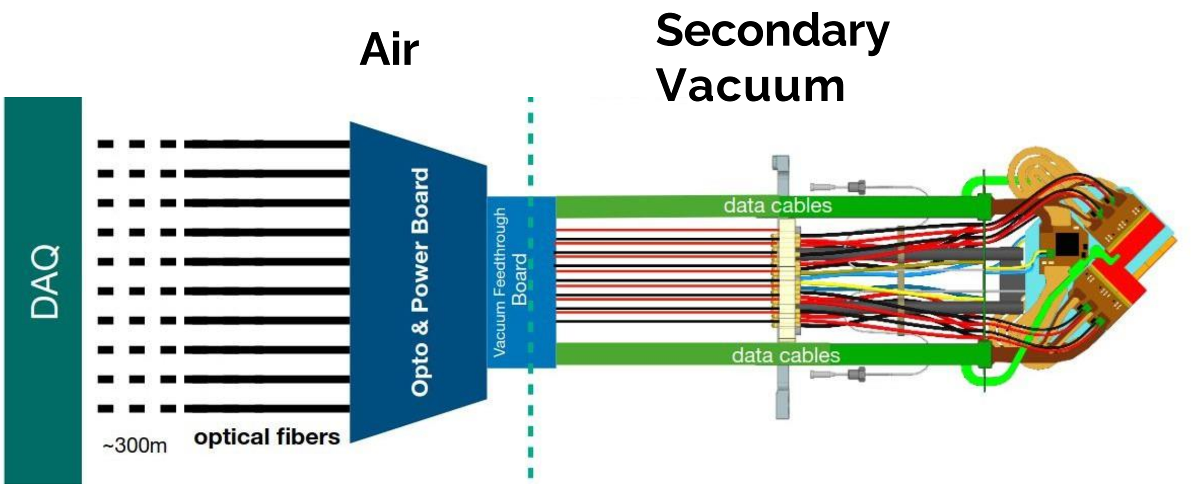








Readout

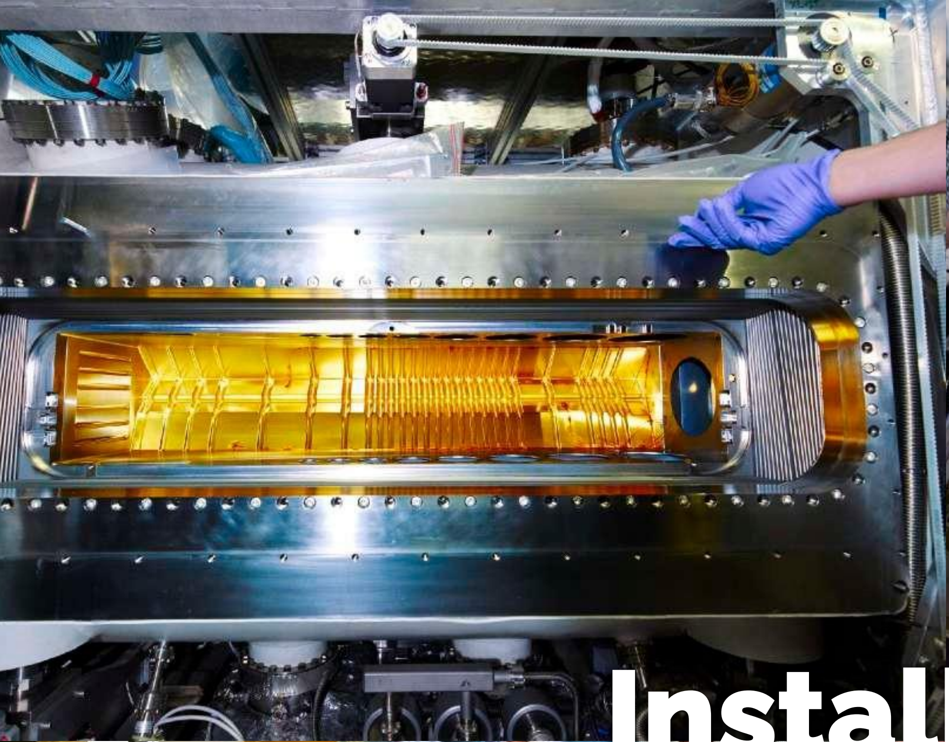


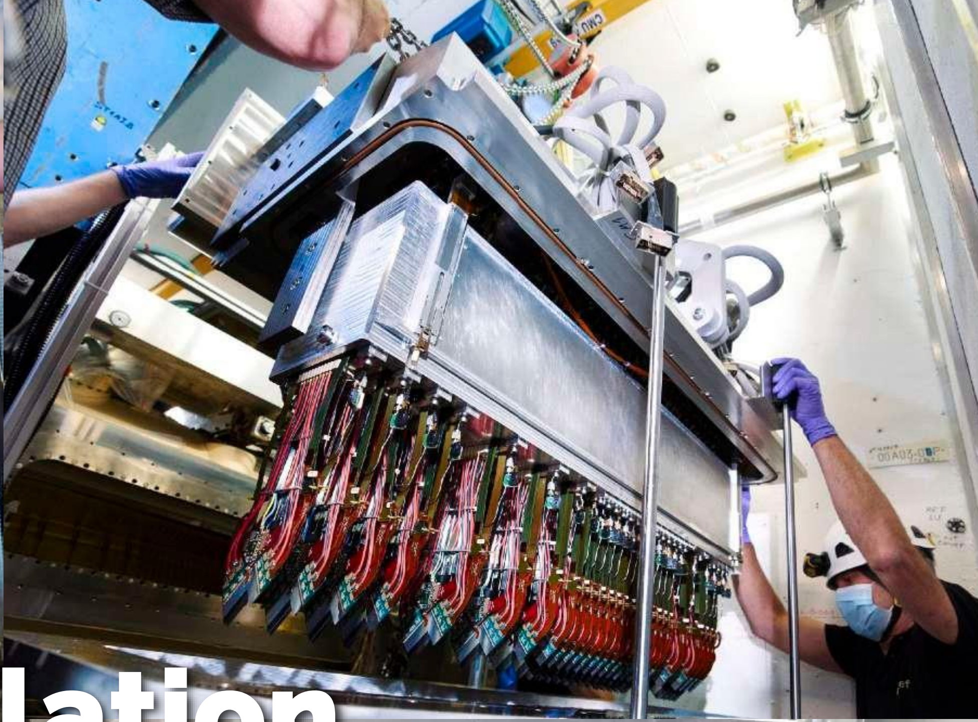
- VELO DAQ: 20 readout links at 5 Gb/s per module
- Integrating the clustering in the FPGA

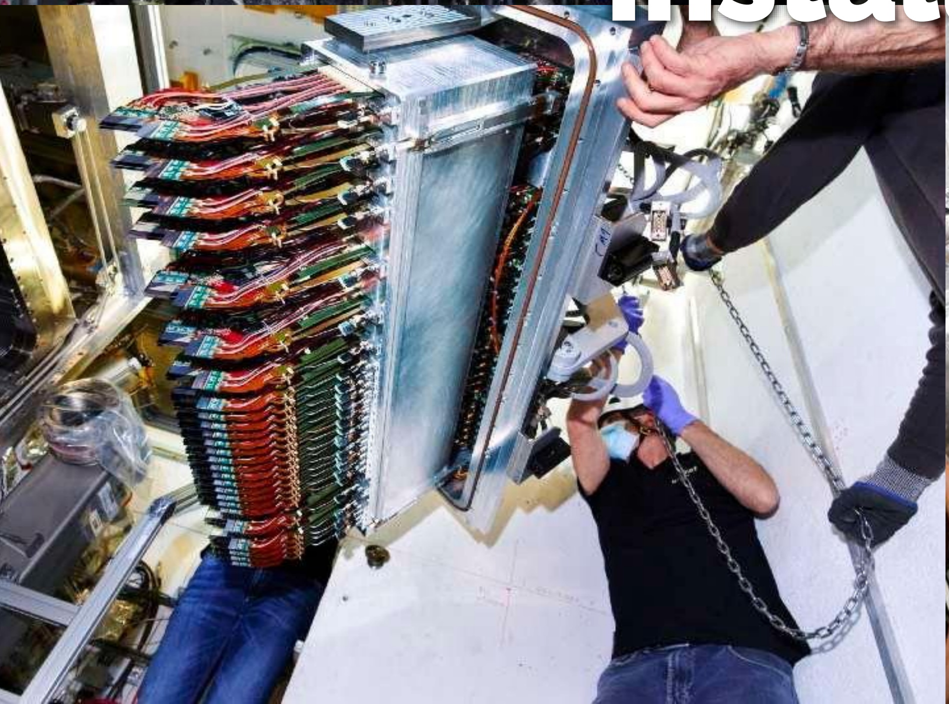
  11% reduction of HLT1 reconstruction sequence

  O(50) less power consumption in the FPGA compare with the GPU

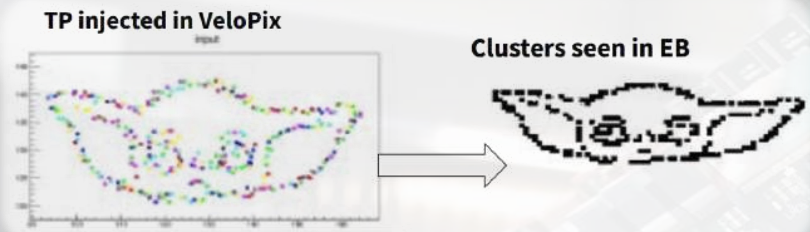
Installation



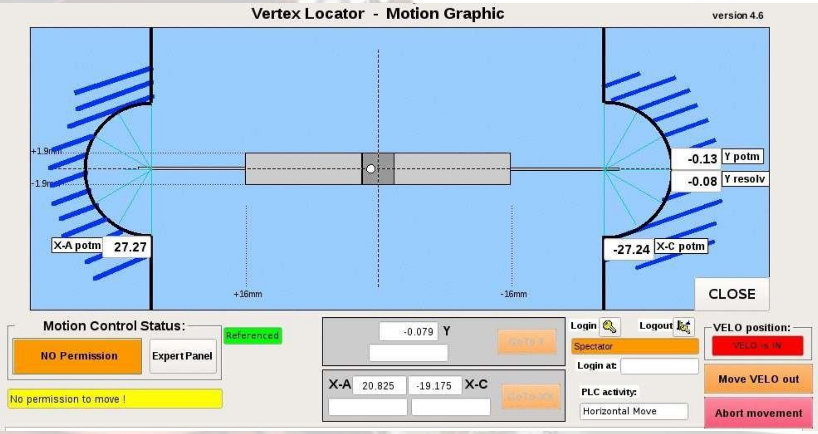




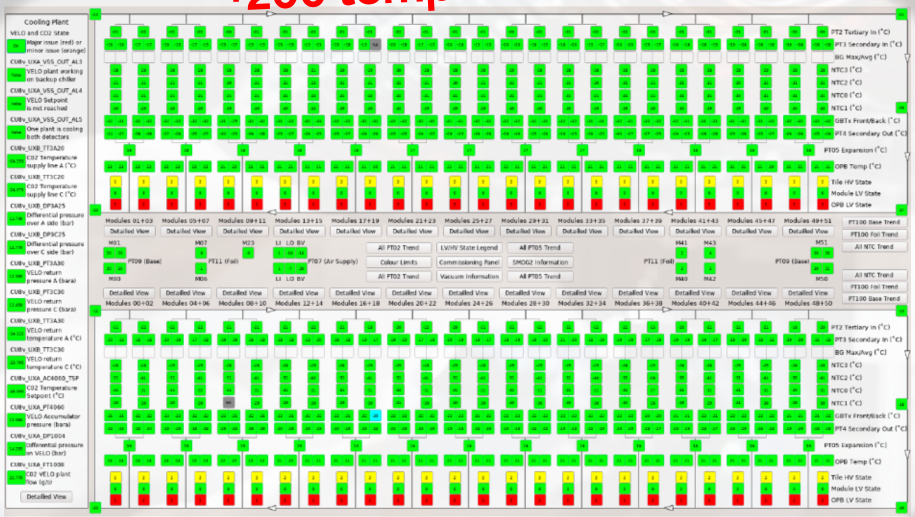
Commissioning



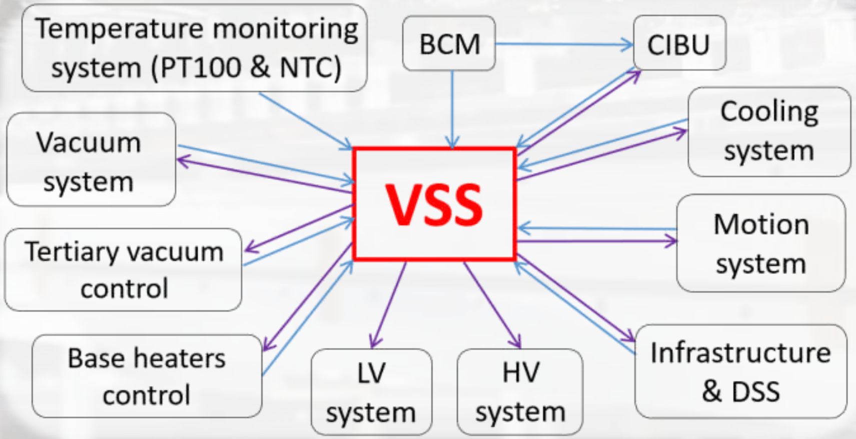
VELO motion control panel



+200 temp monitoring!

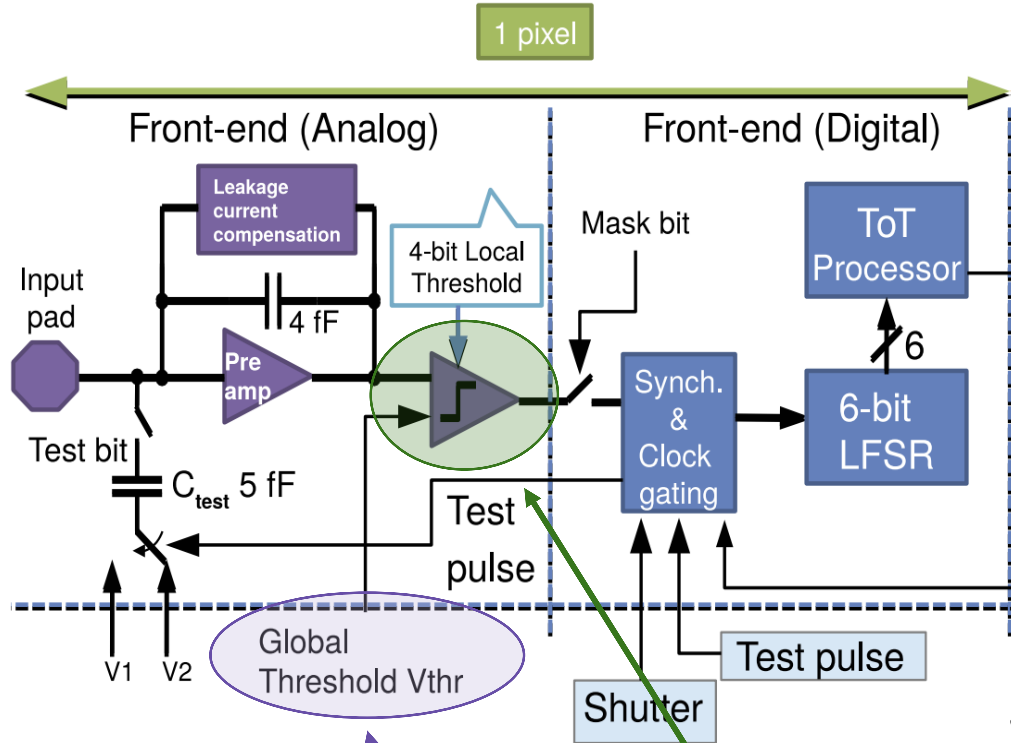


Complex control matrix for all the systems!



Equalisation

Goal: fine tune the threshold per pixel to get a uniform ASIC response

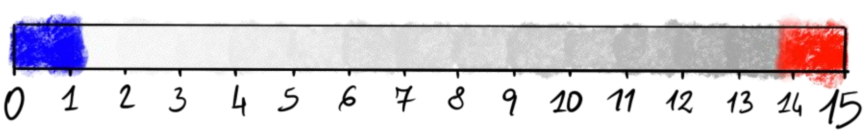


Th_{local} = trim + Th_{global}

trim defined per pixel

Global threshold (Th_{global}) defined per ASIC

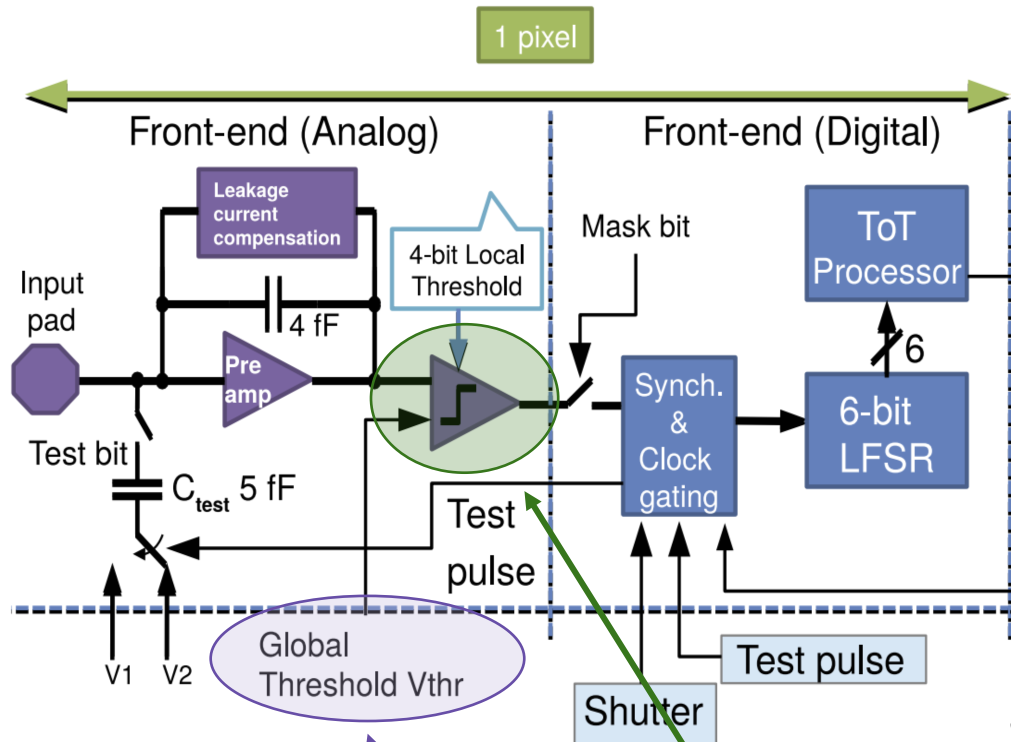
4-bit local trim



Equalisation

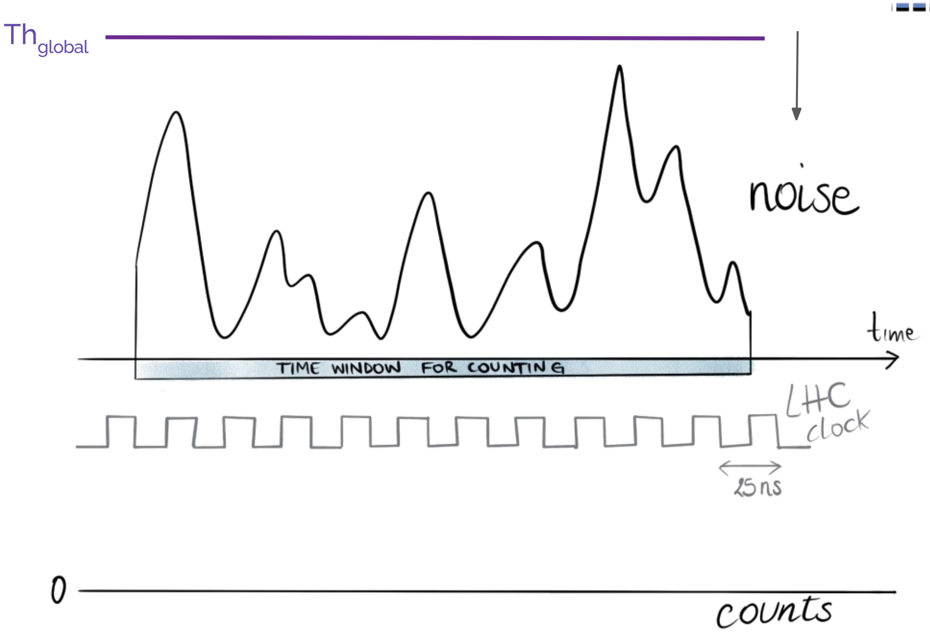
Goal: fine tune the threshold per pixel to get a uniform ASIC response

$$Th_{local} = trim + Th_{global}$$

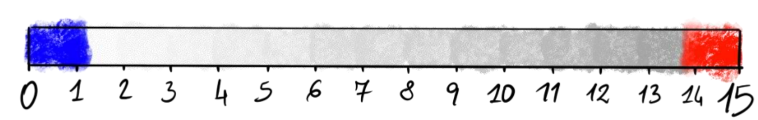


Global threshold (Th_{global}) defined per ASIC

trim defined per pixel



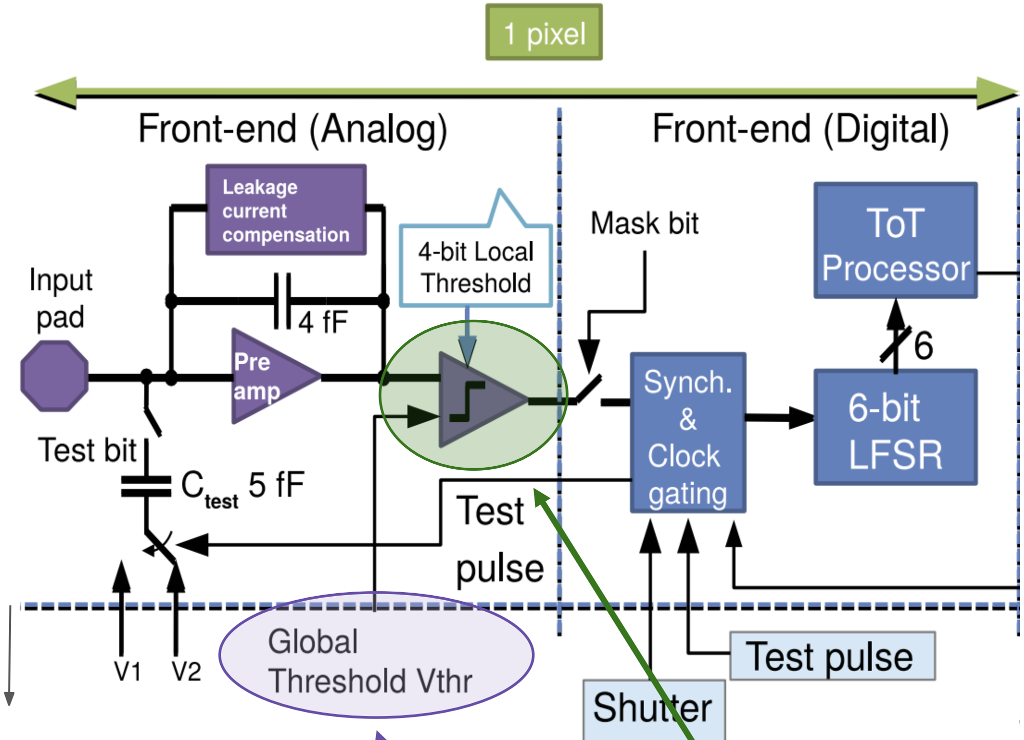
4-bit local trim

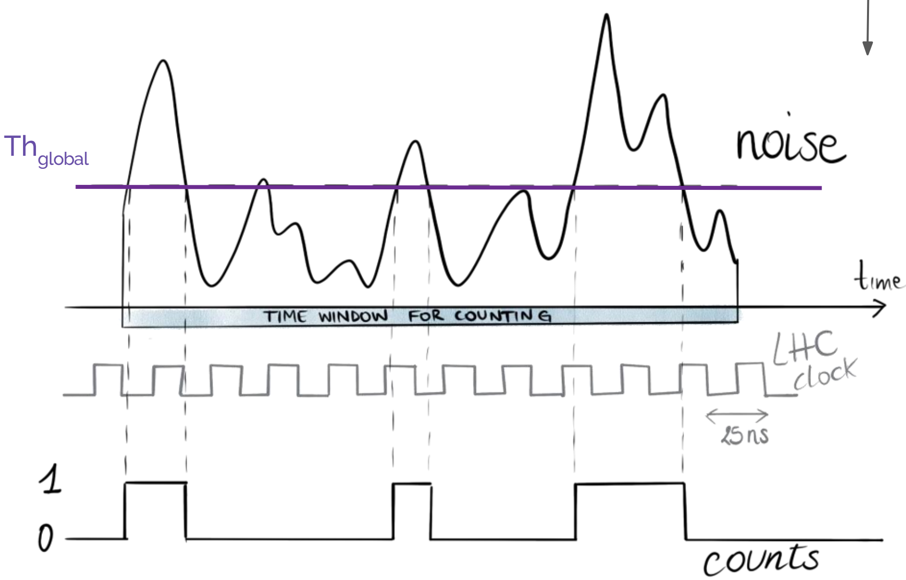


Equalisation

Goal: fine tune the threshold per pixel to get a uniform ASIC response

$$Th_{local} = trim + Th_{global}$$

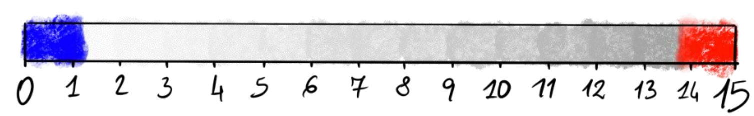




Global threshold (Th_{global}) defined per ASIC

trim defined per pixel

4-bit local trim

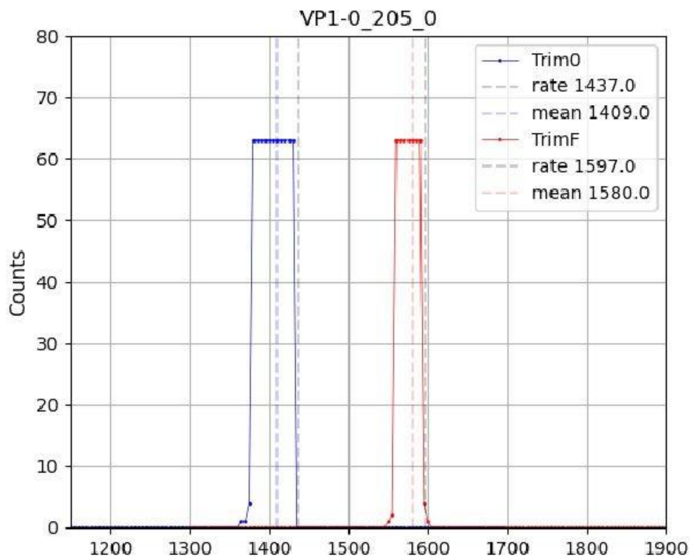


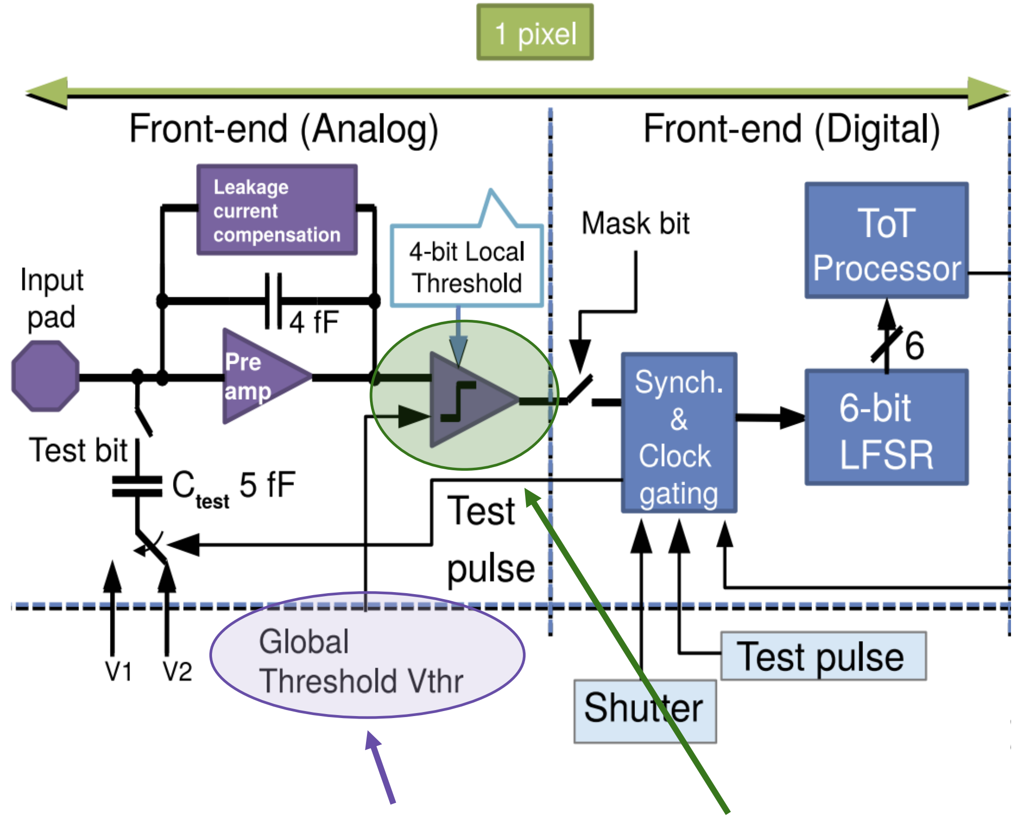
Equalisation

Goal: fine tune the threshold per pixel to get a uniform ASIC response

$$Th_{local} = trim + Th_{global}$$

Single pixel distribution

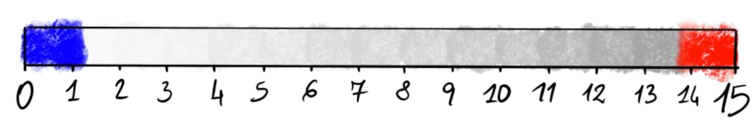




Global threshold (Th_{global}) defined per ASIC

trim defined per pixel

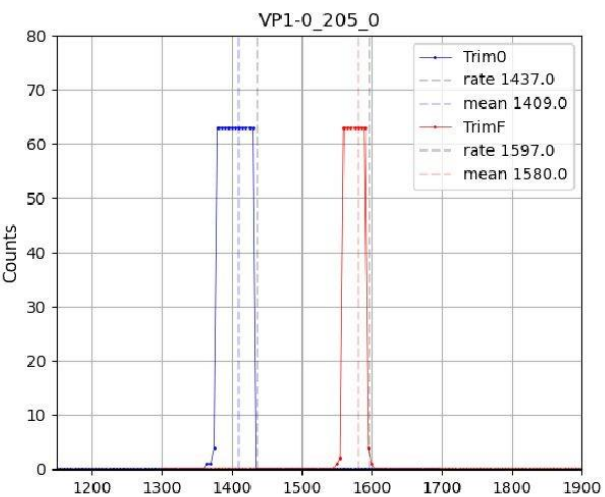
4-bit local trim



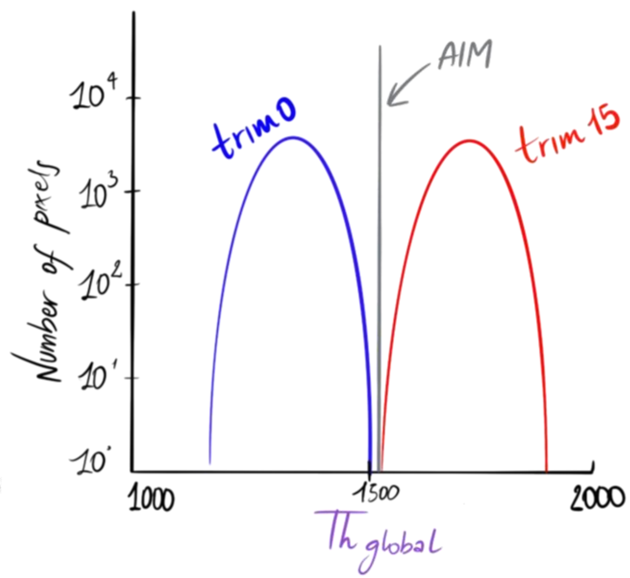
Equalisation

Do a threshold scan and analyse result to find optimal configuration for uniform response across pixels

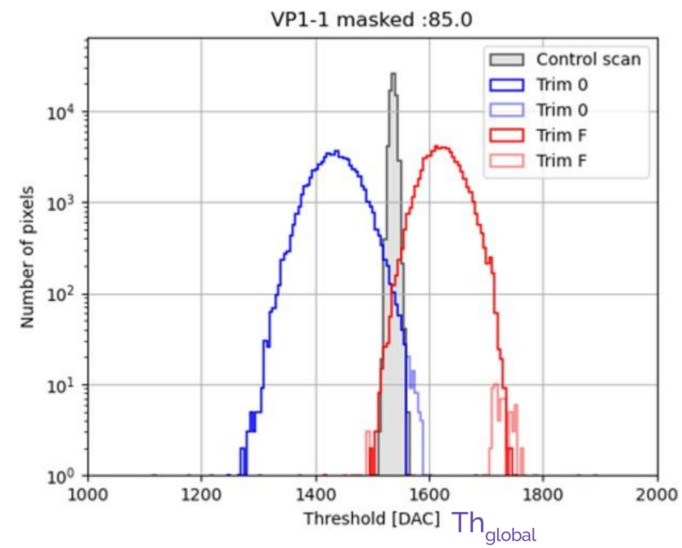
Single pixel distribution



Full ASIC goal representation



Full ASIC (256x256 pixels)

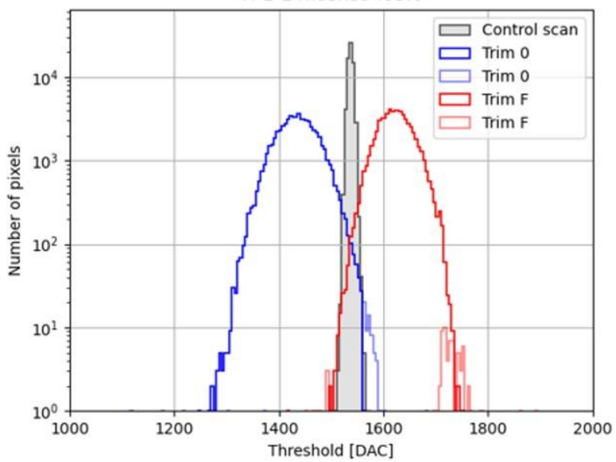


Lengthy procedure through slow control (~ 30 min), further optimisation by moving scan to FPGA.

Equalisation

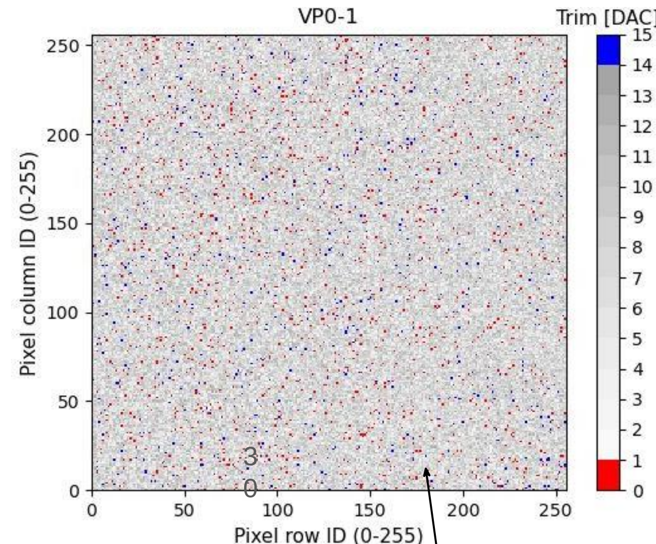
Do a threshold scan and analyse result to find optimal configuration for uniform response across pixels

Single pixel distribution



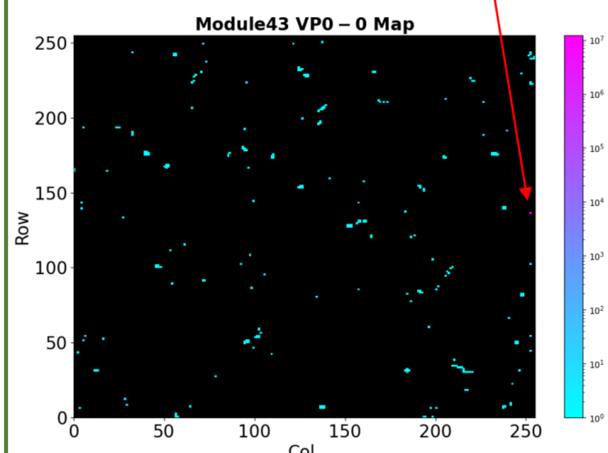
Over 40 Million pixels equalized in the whole VELO!!

The equalised matrix defines operational local thresholds *(trim)* per pixel



trim value of single pixel

Noisy pixel



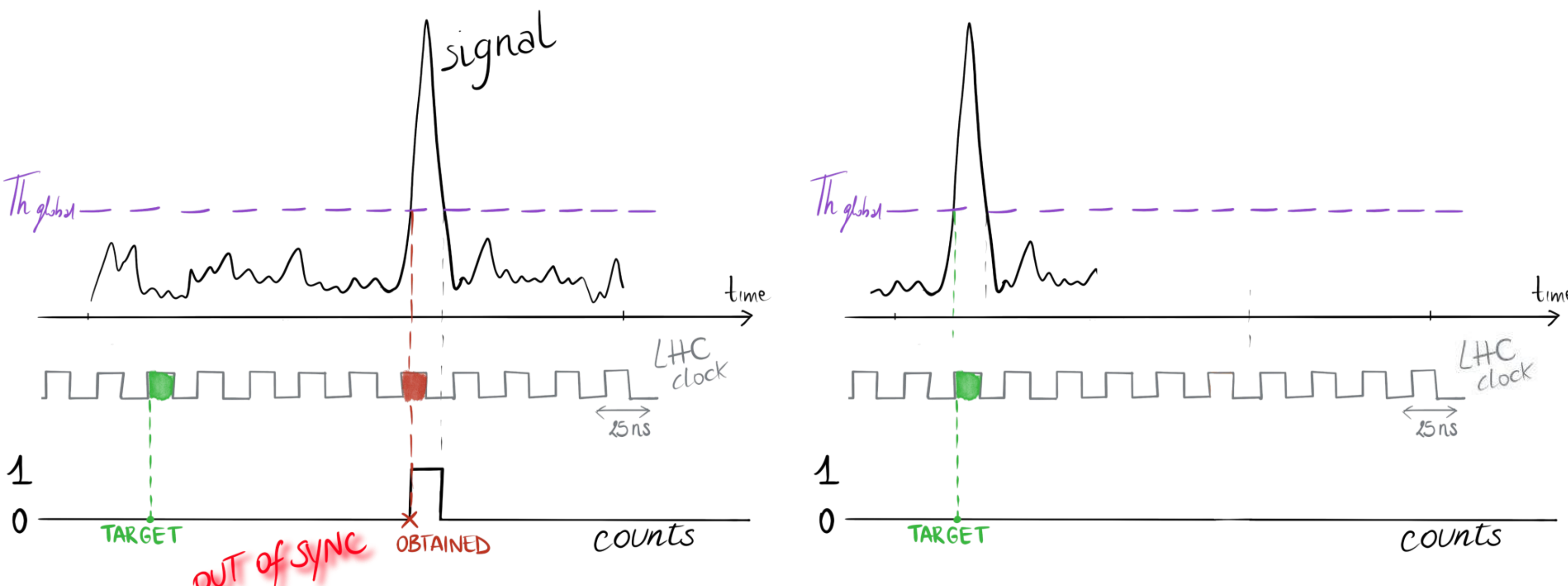
“Noisy” pixels are masked during the equalisation procedure

Time alignment

Goal: signal response for all ASICs at the same time

1. Possible miss alignment:
   - Large latency shift: signal appears in a different BXID (25 ns step)

   Synchronise with LHC clock



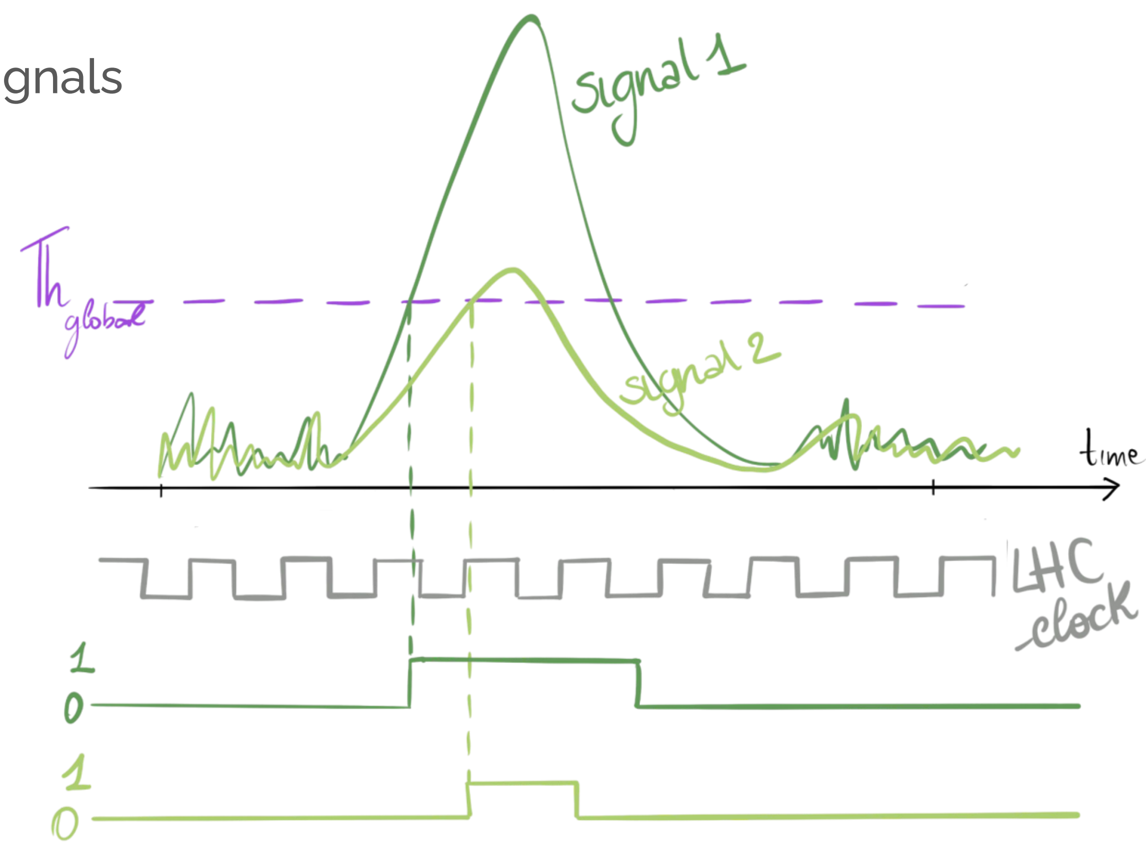
Time alignment

Goal: signal response for all ASICs at the same time

1. Possible miss alignment:
   - Large latency shift: signal appears in a different BXID (25 ns step)

Synchronise with LHC clock
Align high and low amplitude signals

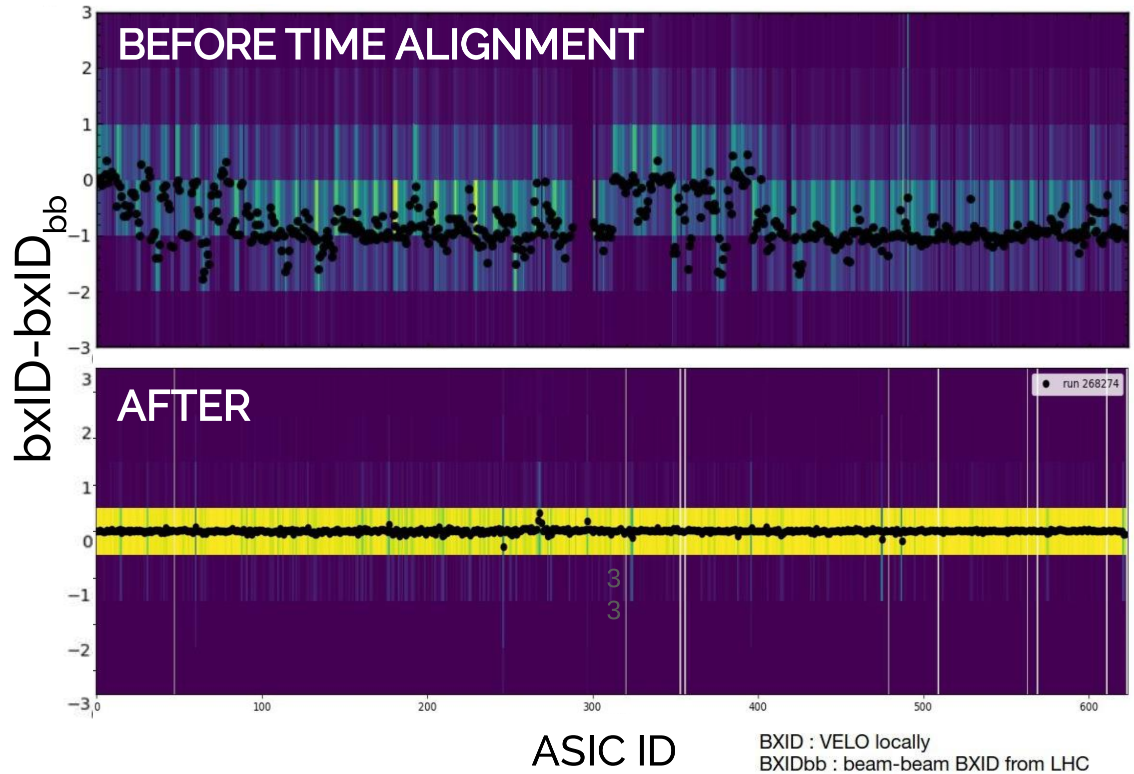
2. Possible miss alignment:
   - Small latency shift: difference within the same BXID (781.25 ps step)



Time alignment

Goal: signal response for all ASICs at the same time

- Use isolate BXID* to find timing of different ASICs
- SOL40** delay to correct the latency
- Use GBTx*** phase-shifter channel to correct the clock difference
- BXID spread for pixels within one ASIC
- Solution: DAC and signal threshold adjustment



BXID : VELO locally
BXIDbb : beam-beam BXID from LHC

(*) BXID: Bunch Cross ID
(**) SOL40: board responsible of distributing all the control and timing signals to the front-ends
(***) GBTx: radiation tolerant chip used to implement multipurpose high speed bidirectional optical links

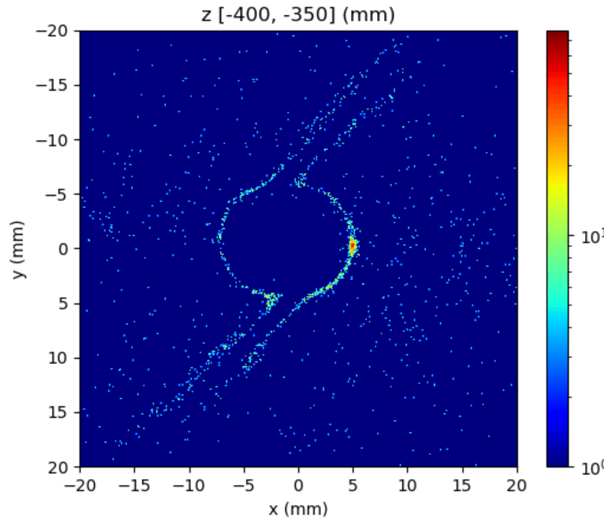
Vertex reconstruction

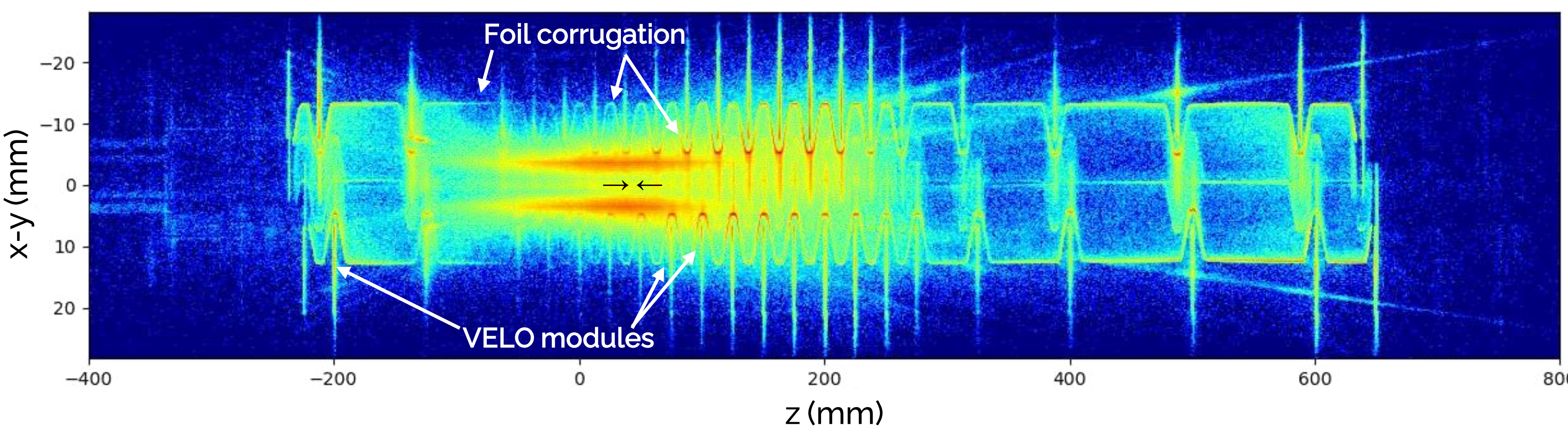
Equalisation and time alignment allowed to reconstruct tracks and do spatial alignment

First tracks allowed reconstructing PV in real time and close the VELO to 5.1mm from the beam

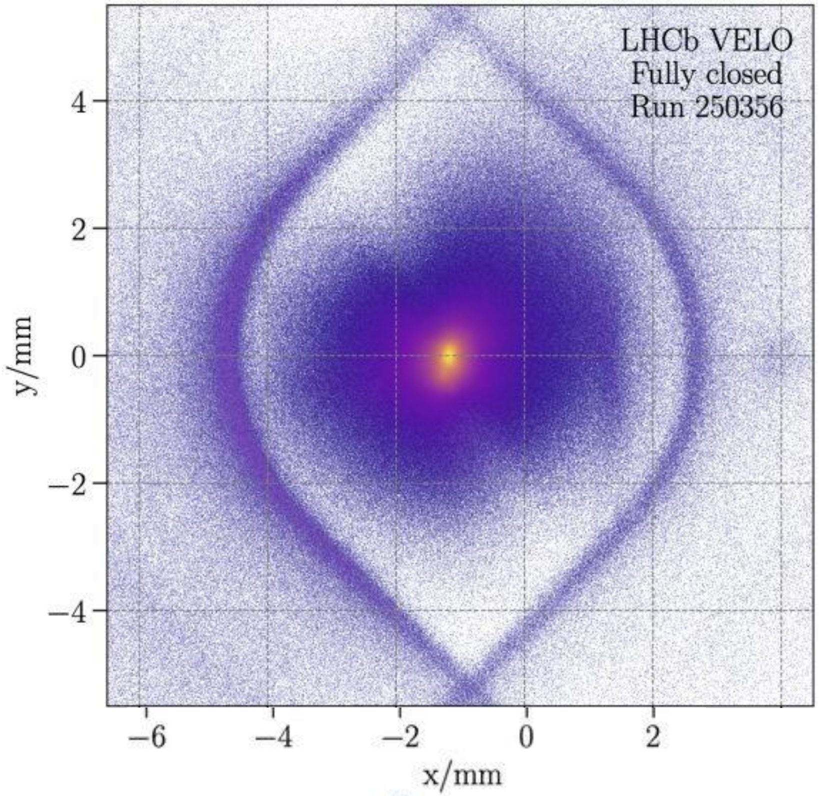
VELO tomography:

- Reconstruction of material interaction vertexes
- Online vertex reconstruction with at least 3 tracks

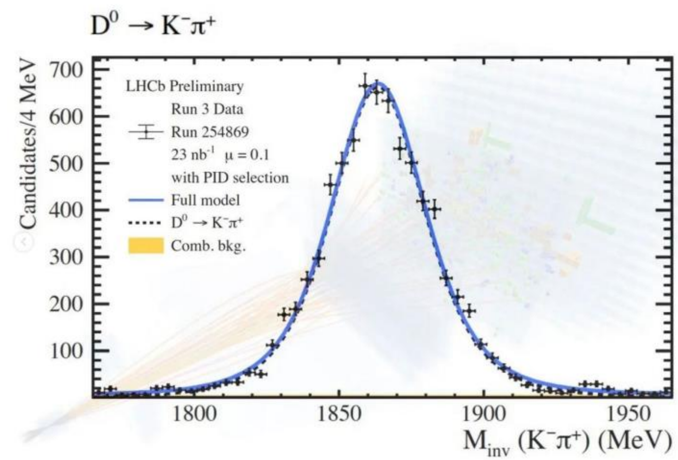




First results



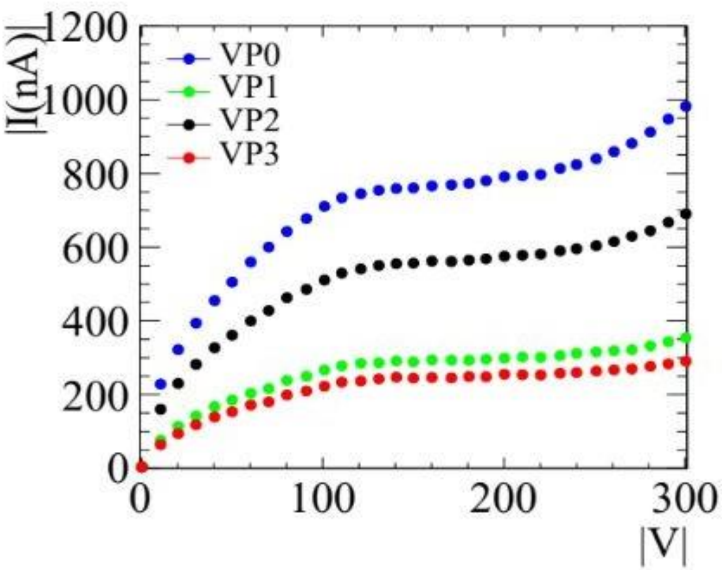
- Closing based on primary vertex reconstruction
- Can only be done once beams are stable
- Closing is done in steps, final closing after foil reconstruction



2022 data: VELO combined to other detectors

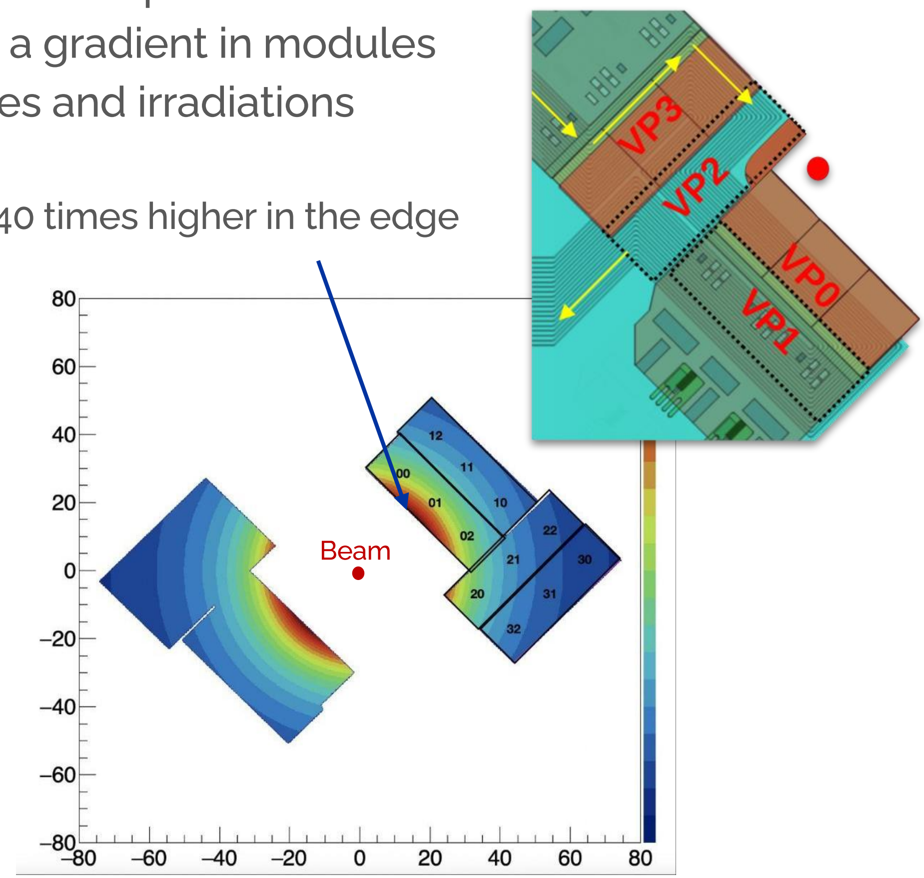
IV Scans: Radiation damage

Current vs voltage (IV) scans are a fundamental tool to monitor the evolution of radiation damage with fluence.



Even more important for VELO due to a gradient in modules fluences and irradiations

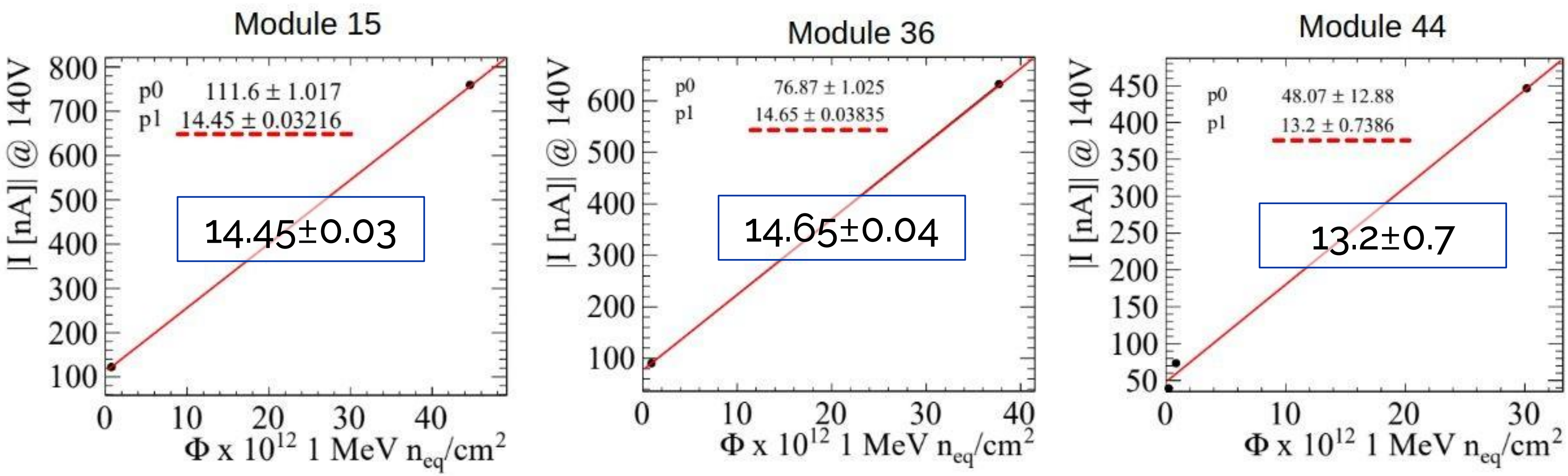
Up to 140 times higher in the edge

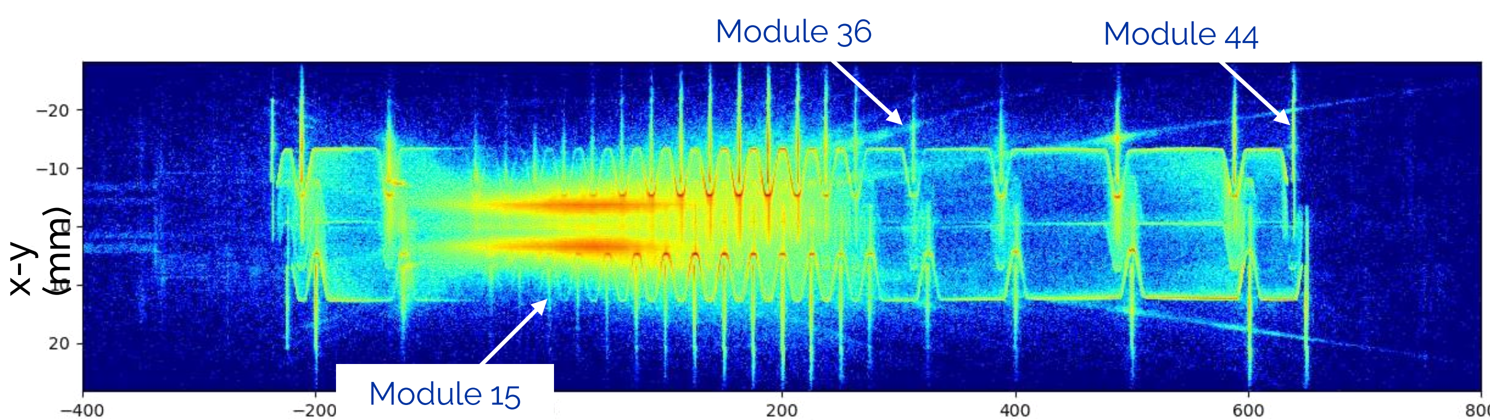


IV Scans: Radiation damage

Leakage current vs fluence to estimate the radiation damage

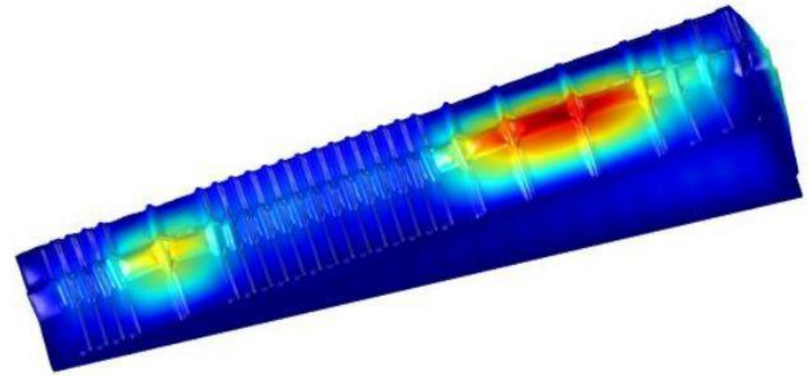
Radiation damage (slope) is consistent across the whole detector





RF Foil incident

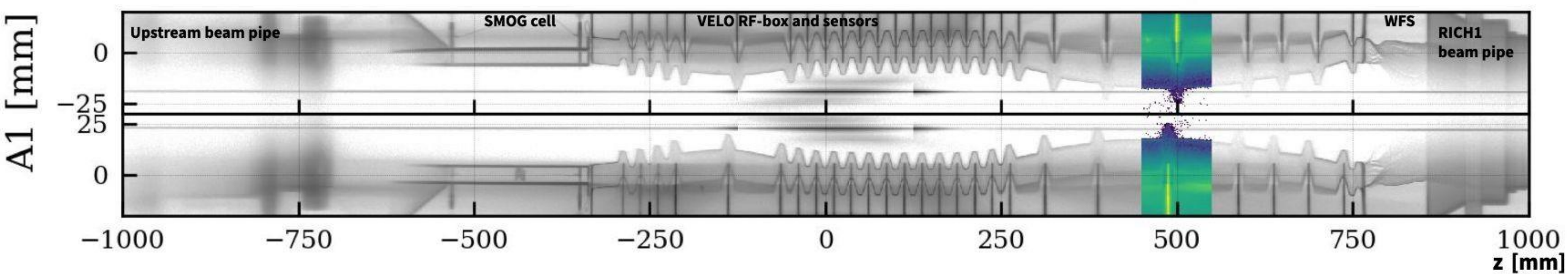
- Loss of control in the LHC vacuum protection system, lead to a pumping action on the primary volume…
- Differential pressure beyond the specification limits built up between the two volumes
- The RF box has suffered a plastic (permanent) deformation
- Deformation assessed with tomography



Simulation of plastic deformation, confirmed accuracy after inspection during replacement

Sensor modules not damaged, VELO still operational in "open" position

RF box being replaced during the winter stop of LHC



Conclusions

2022: Commissioning

- July 2022 → starts Run3
- VELO fully closed in November 2022
- Robust calibration & configuration established

RF-box incident:

- Plastic deformation of RF-box
- VELO is working (perfectly preserved)

2023: Commissioning and physics

- VELO kept open

A lot more work -not covered in this talk- has been paramount to make the detector working.

This is all a result of hard work of many-many people!

Quite a lot of work ahead in 2024!

- RF Foil replacement commissioning
- Detector optimisation

Thanks for your attention.
Questions?

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References:

LHCb VELO Upgrade Technical Design Report - LHCB-TDR-013
The LHCb VELO detector: design, operation and first results -TIPP 2023
The LHCb VELO Upgrade detector: design, construction and installation – CERN Detector Seminar
The LHCb VELO detector: design, operation and first results – EPS-HEP2023
First radiation damage studies on the LHCb VELO upgrade – TREDI 2023
All drawings credit: Alice Biolchini