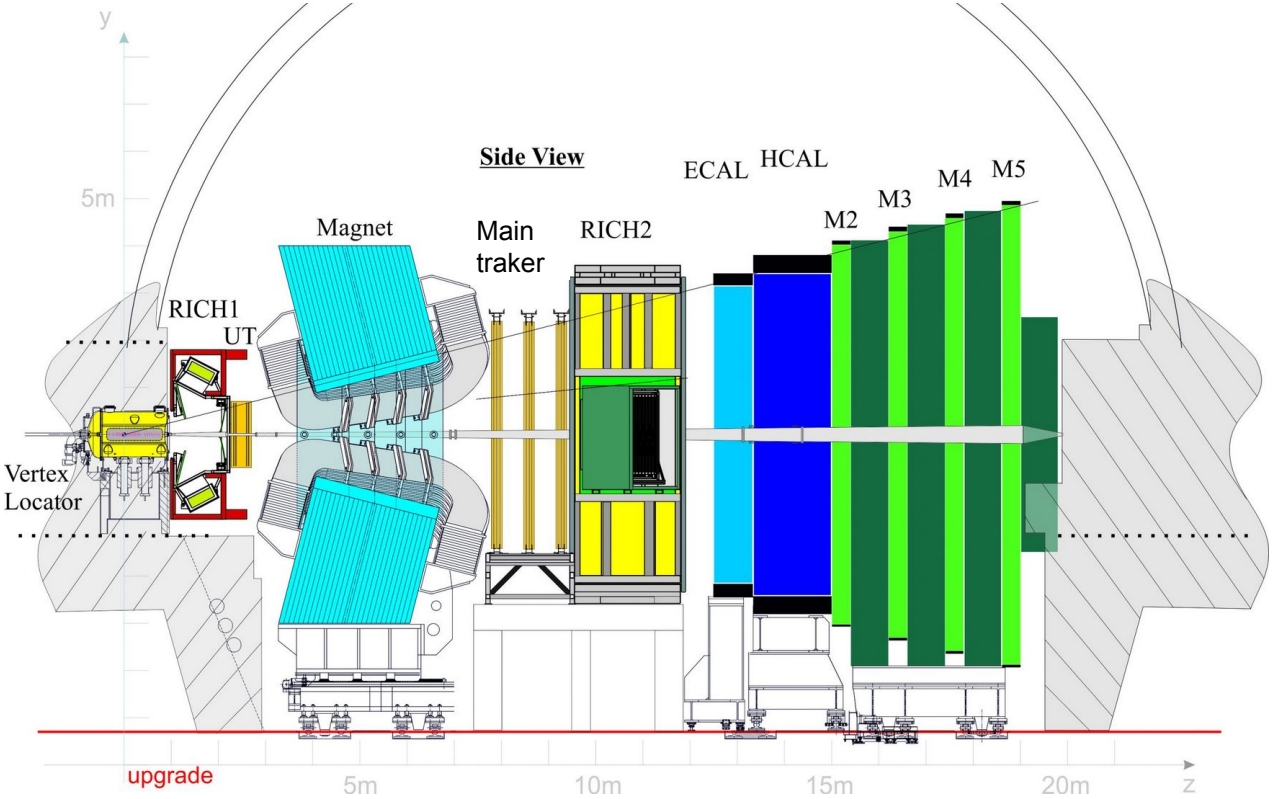
The LHCb VELO Detector

design, operation, and first results

Alice Biolchini
on behalf of the LHCb VELO group

EPS-HEP23, Hamburg *2023 August 21th*

The LHCb detector



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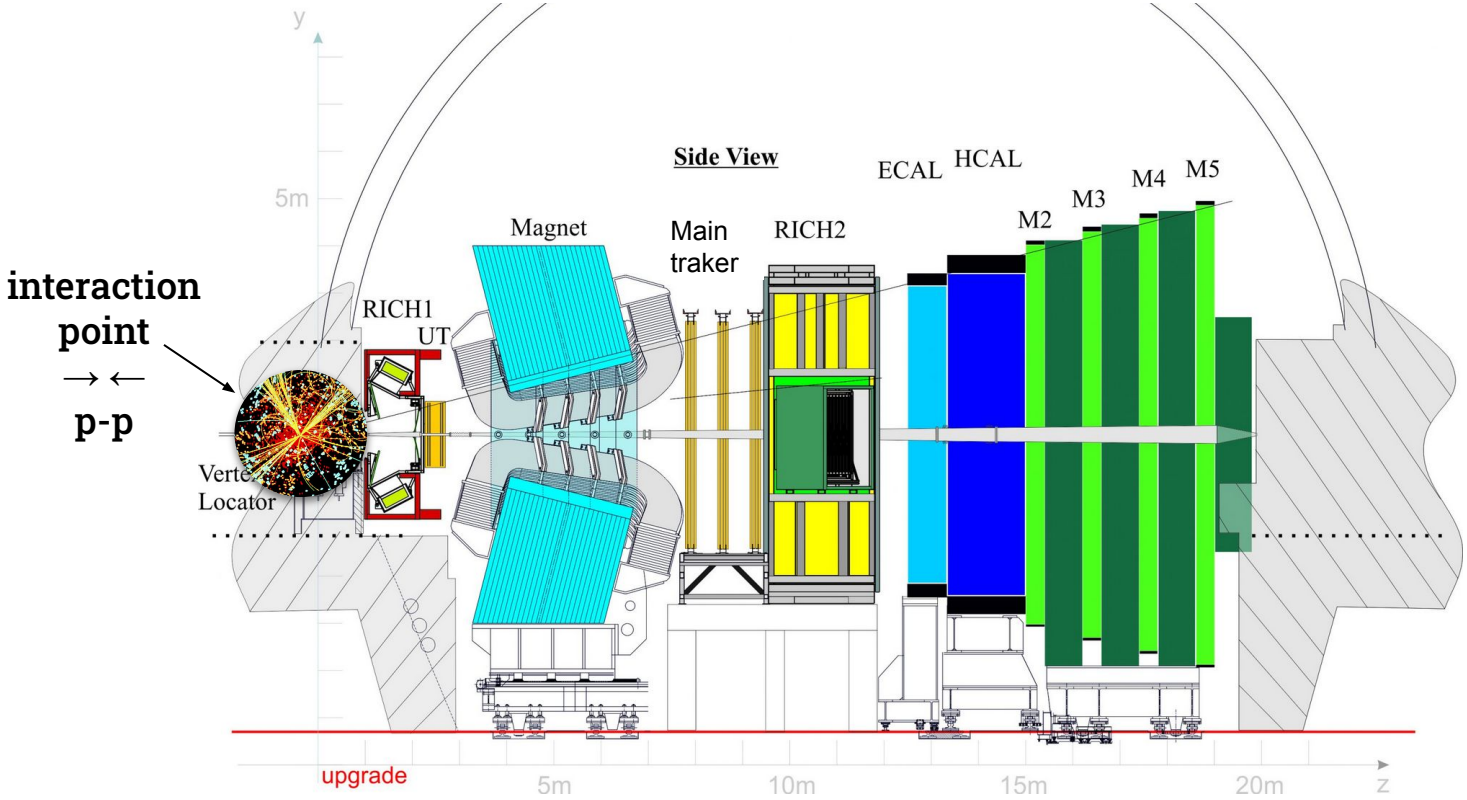
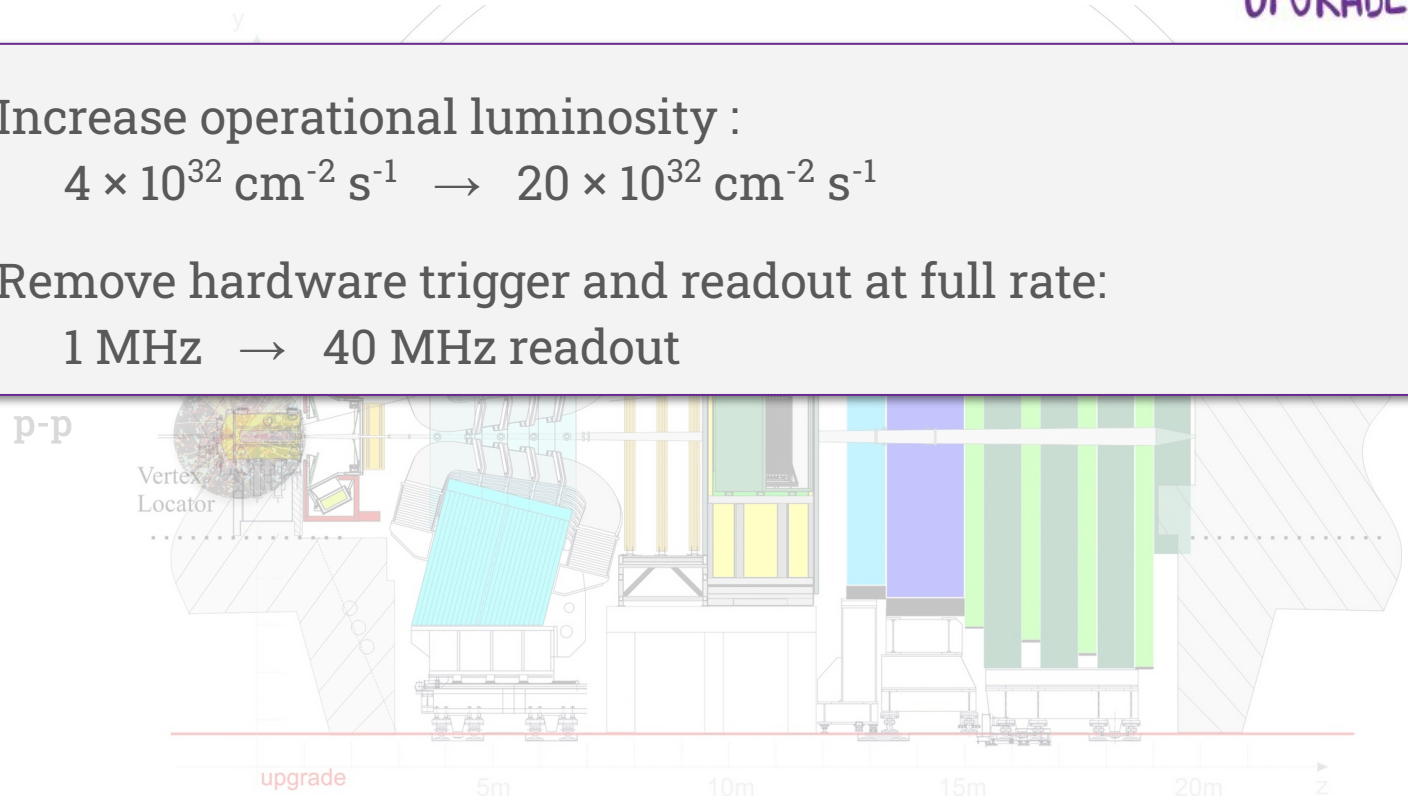


The LHCb detector

UPGRADE 1

- Increase operational luminosity :
  $4 \times 10^{32}\ cm^{-2}\ s^{-1} \rightarrow 20 \times 10^{32}\ cm^{-2}\ s^{-1}$
- Remove hardware trigger and readout at full rate:
  1 MHz → 40 MHz readout



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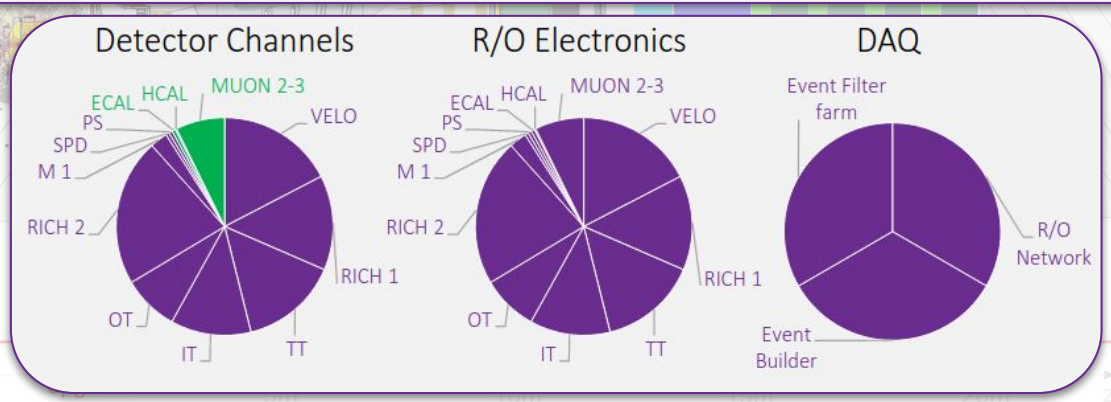
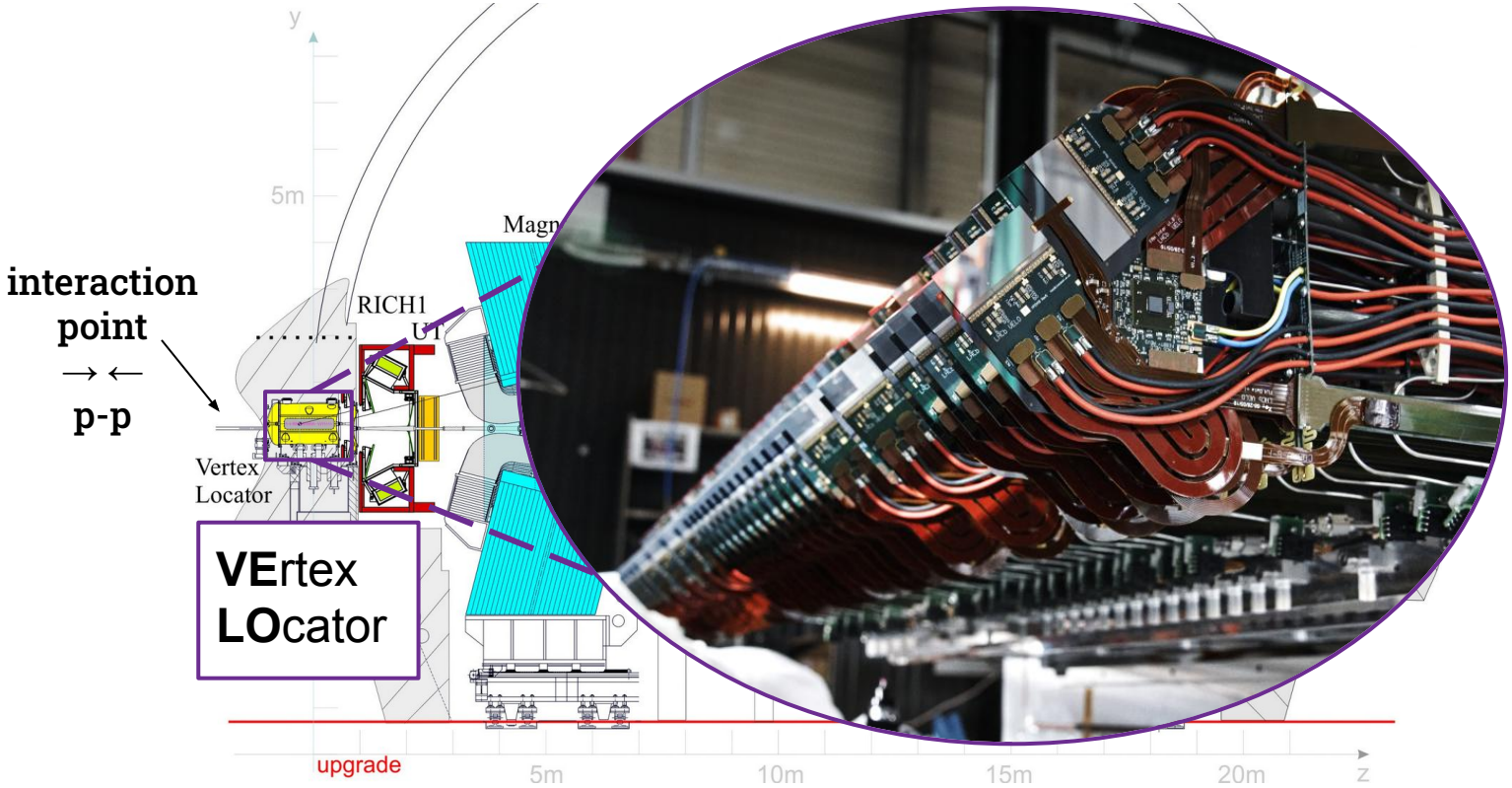
Kept

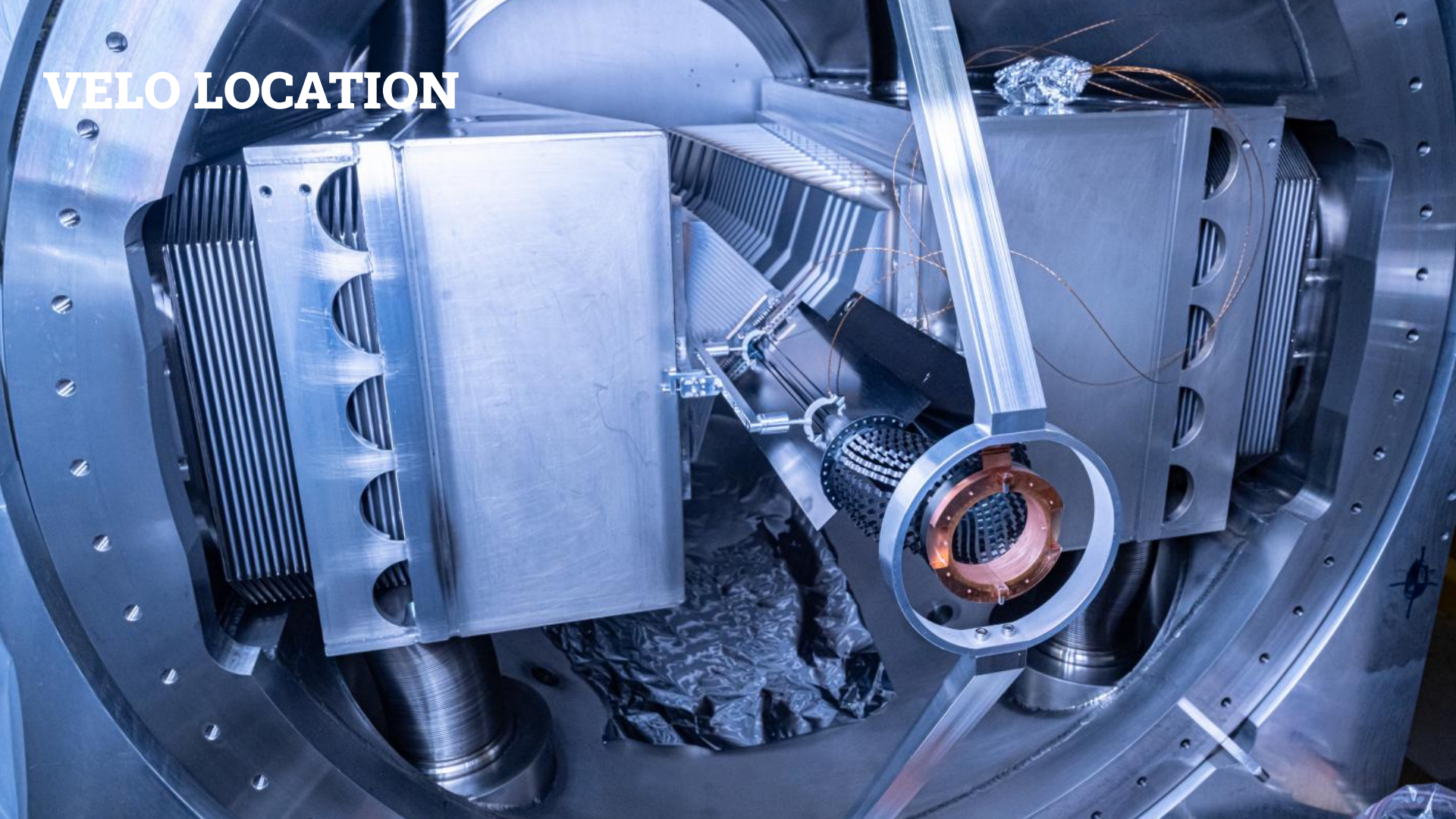
Upgraded

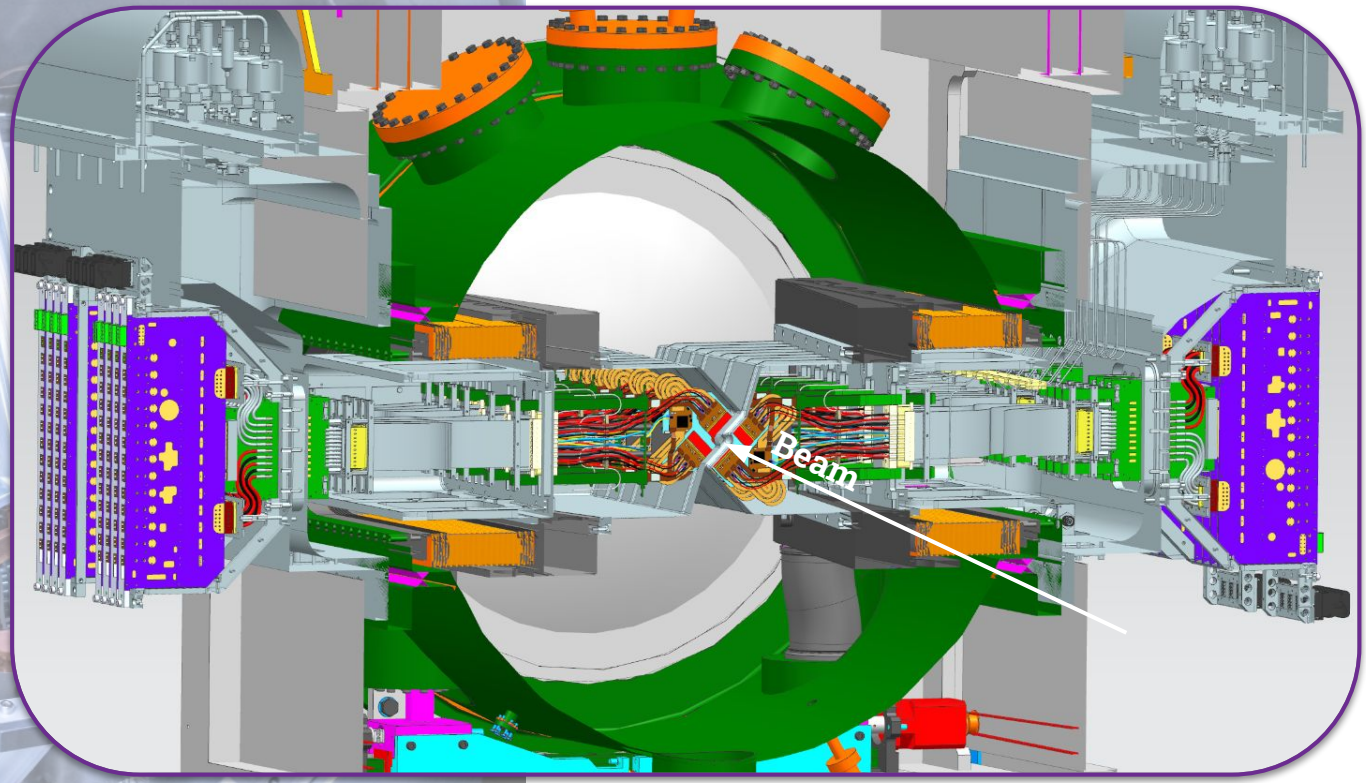


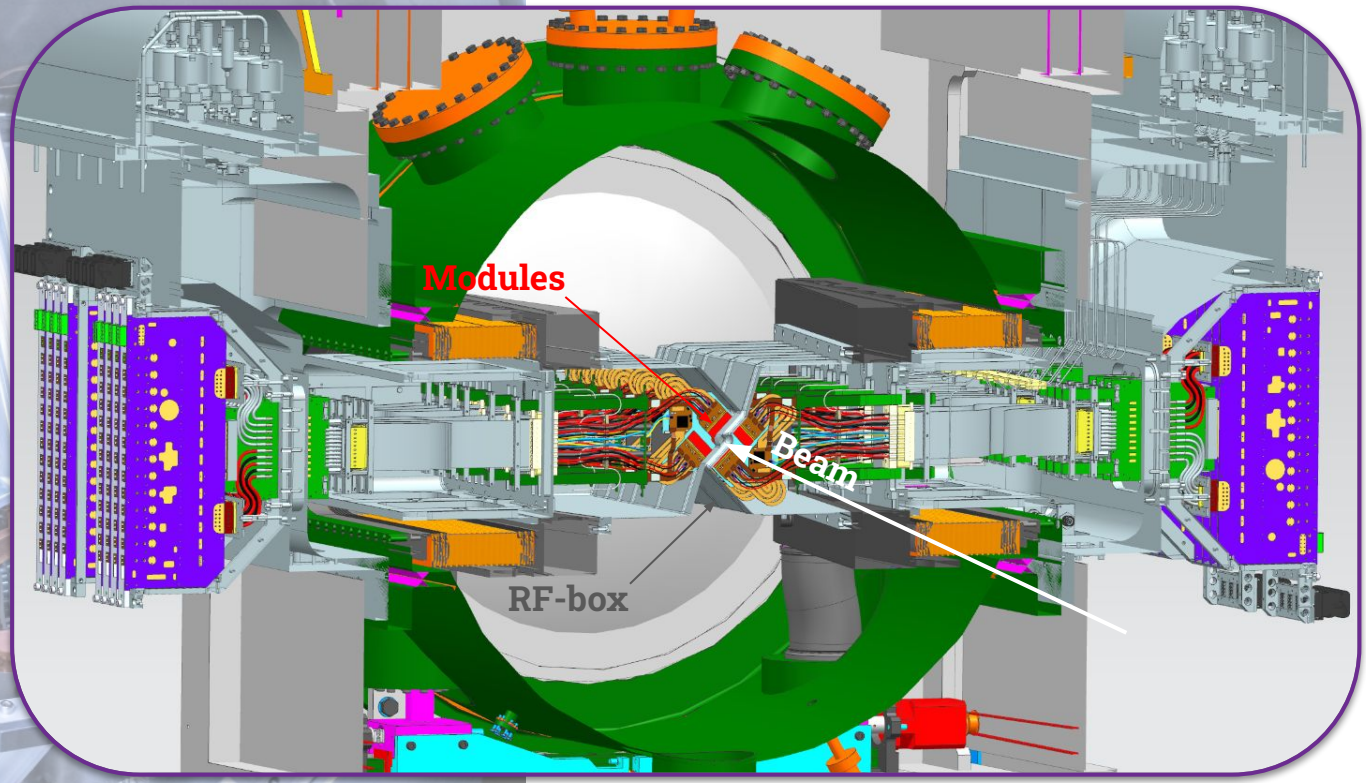
The LHCb detector

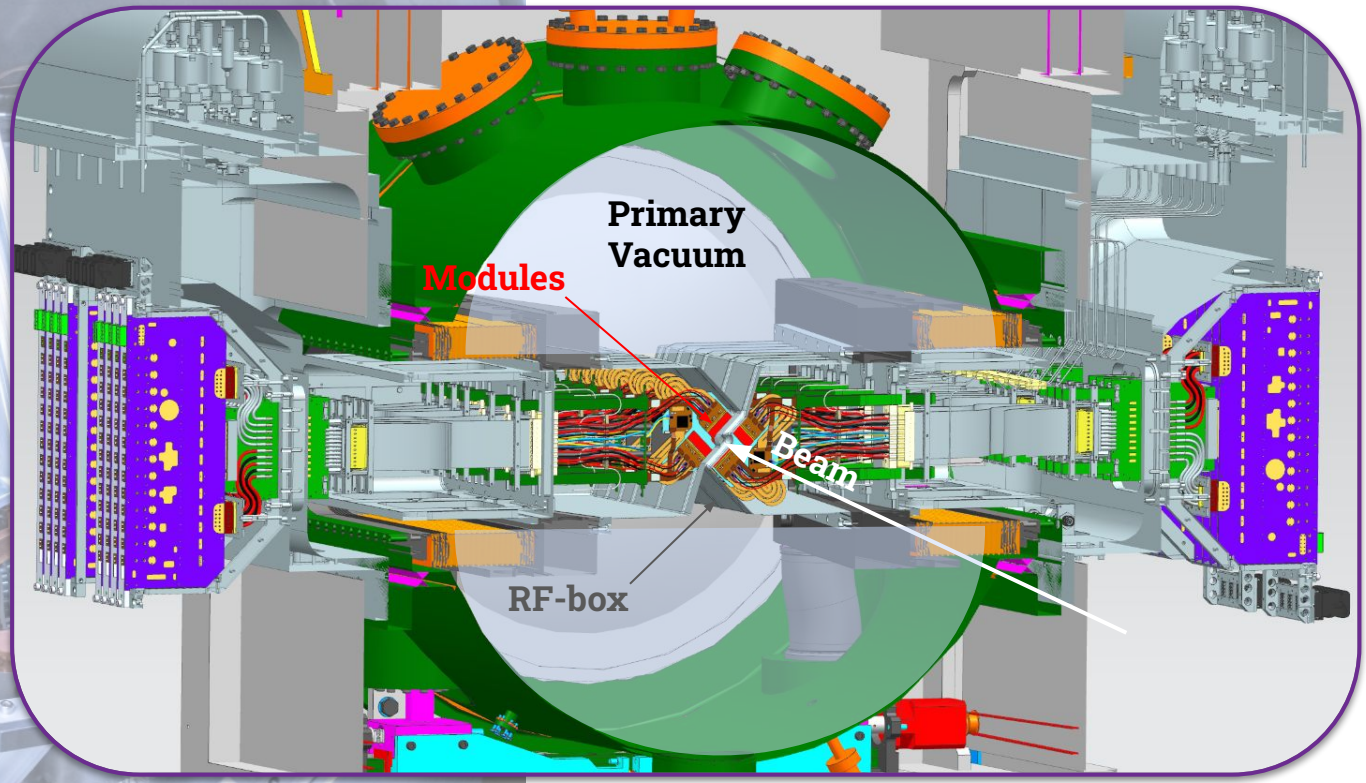


VELO LOCATION




Beam


Modules
Beam
RF-box


Primary
Vacuum
Modules
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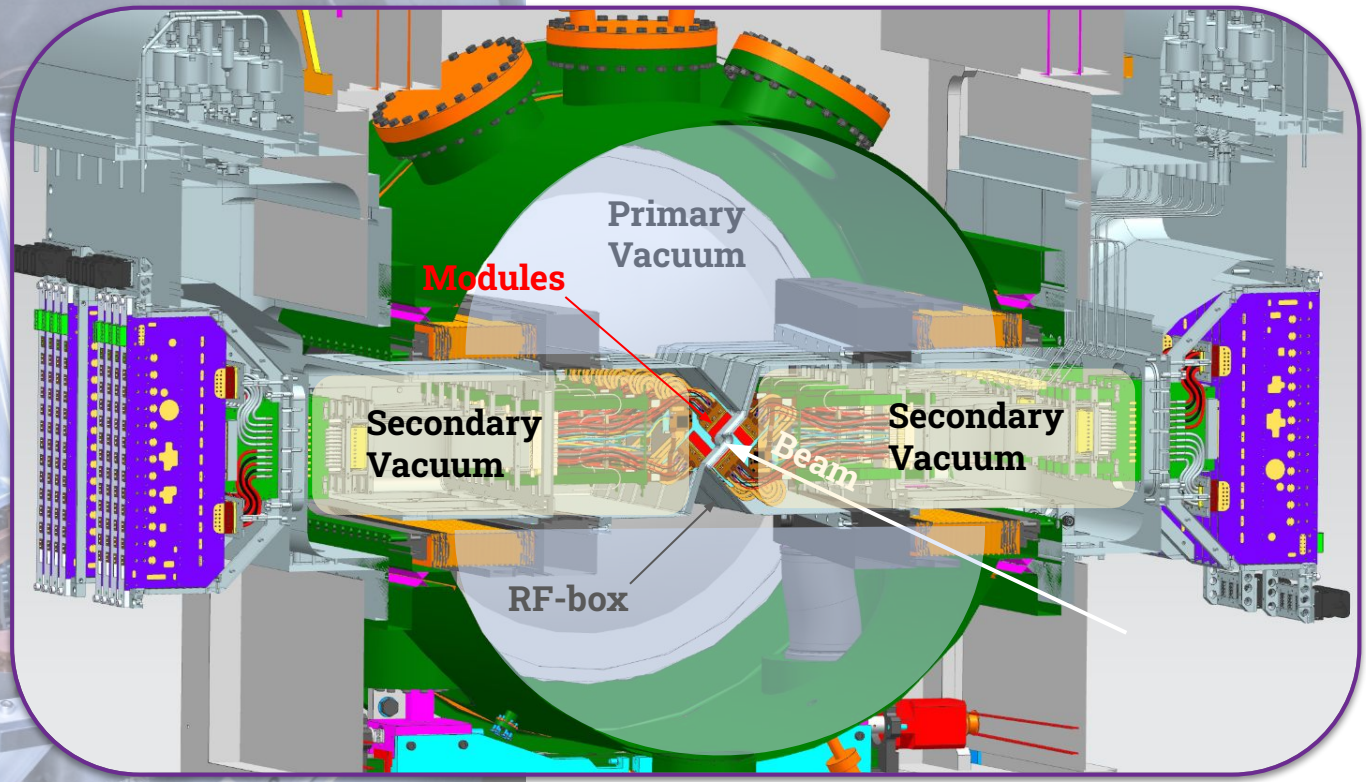
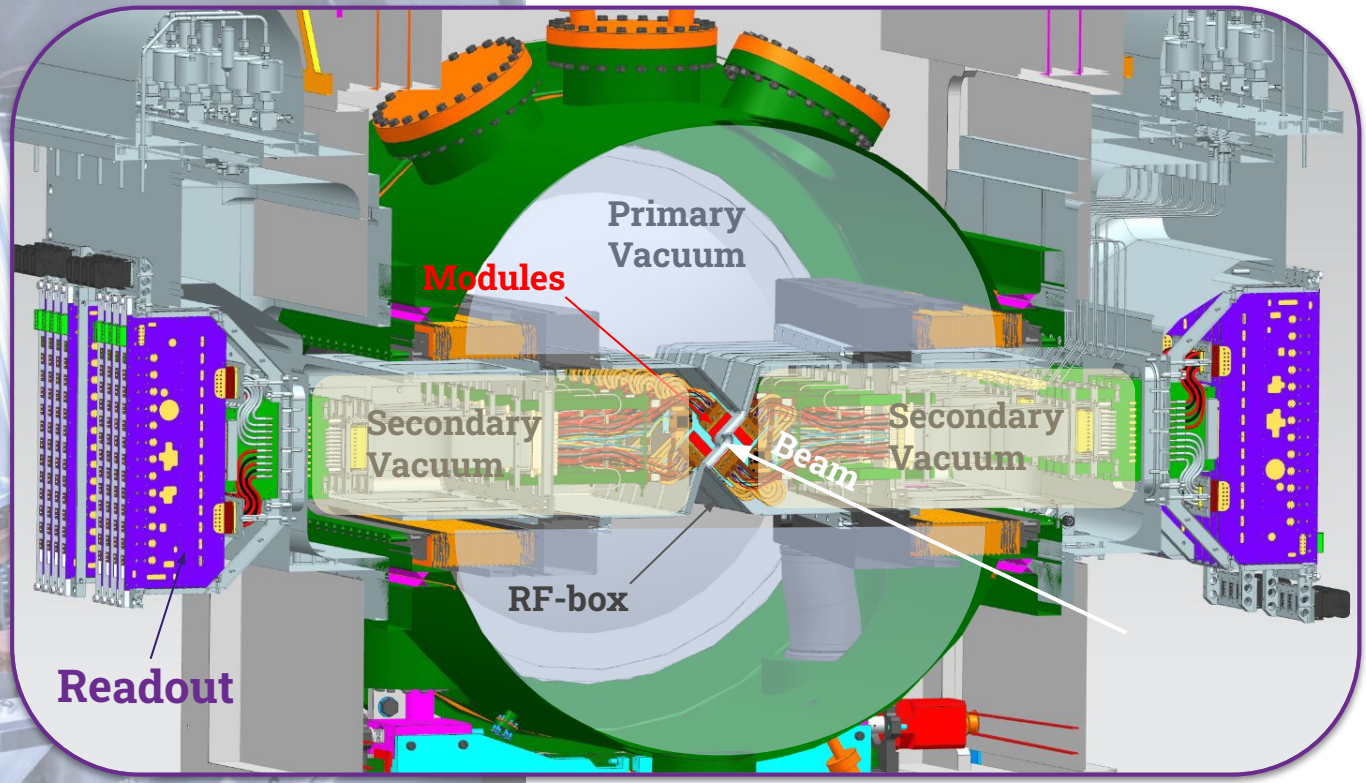
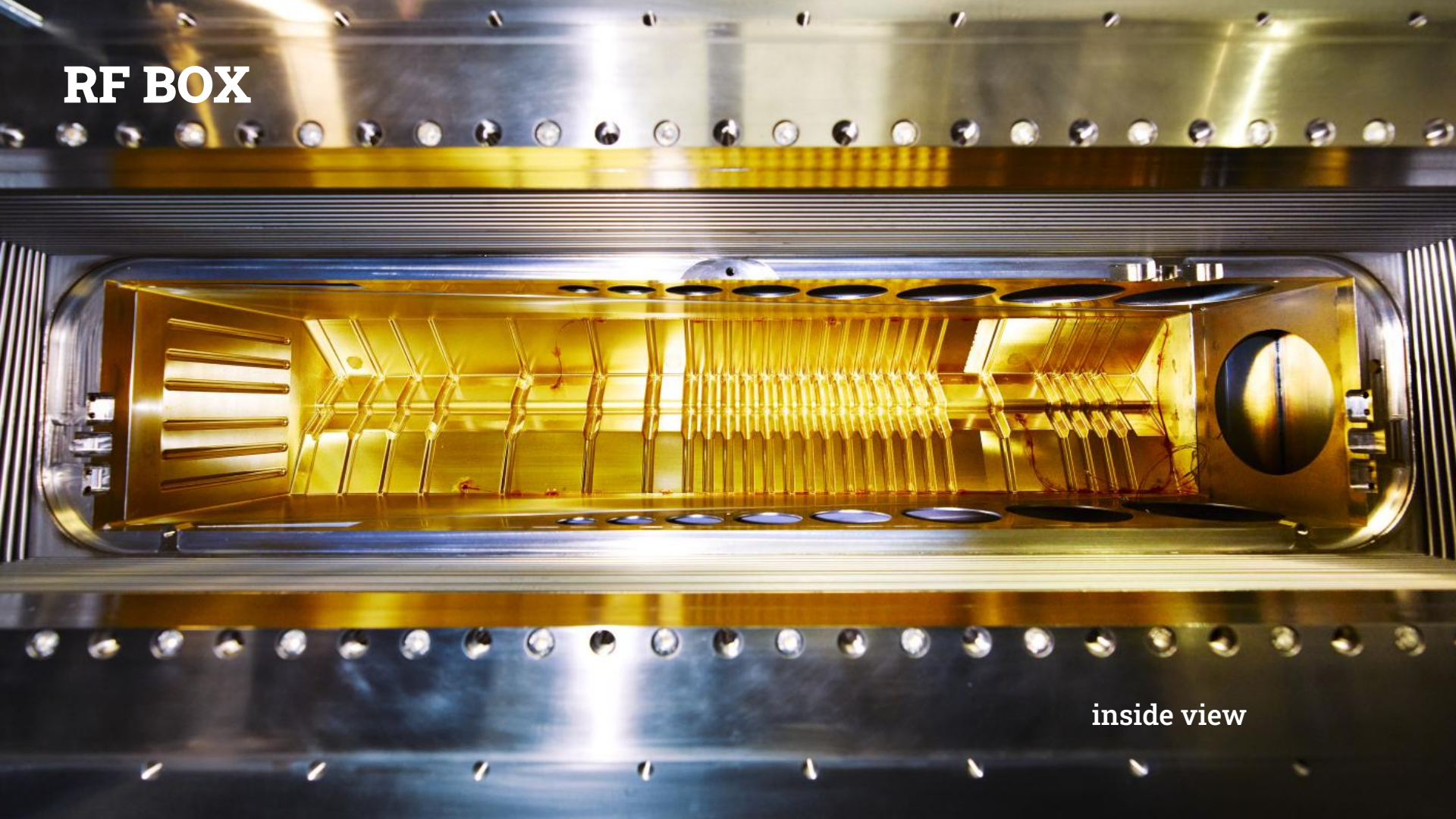

Primary
Vacuum
Modules
Secondary
Vacuum
Beam
Secondary
Vacuum
RF-box

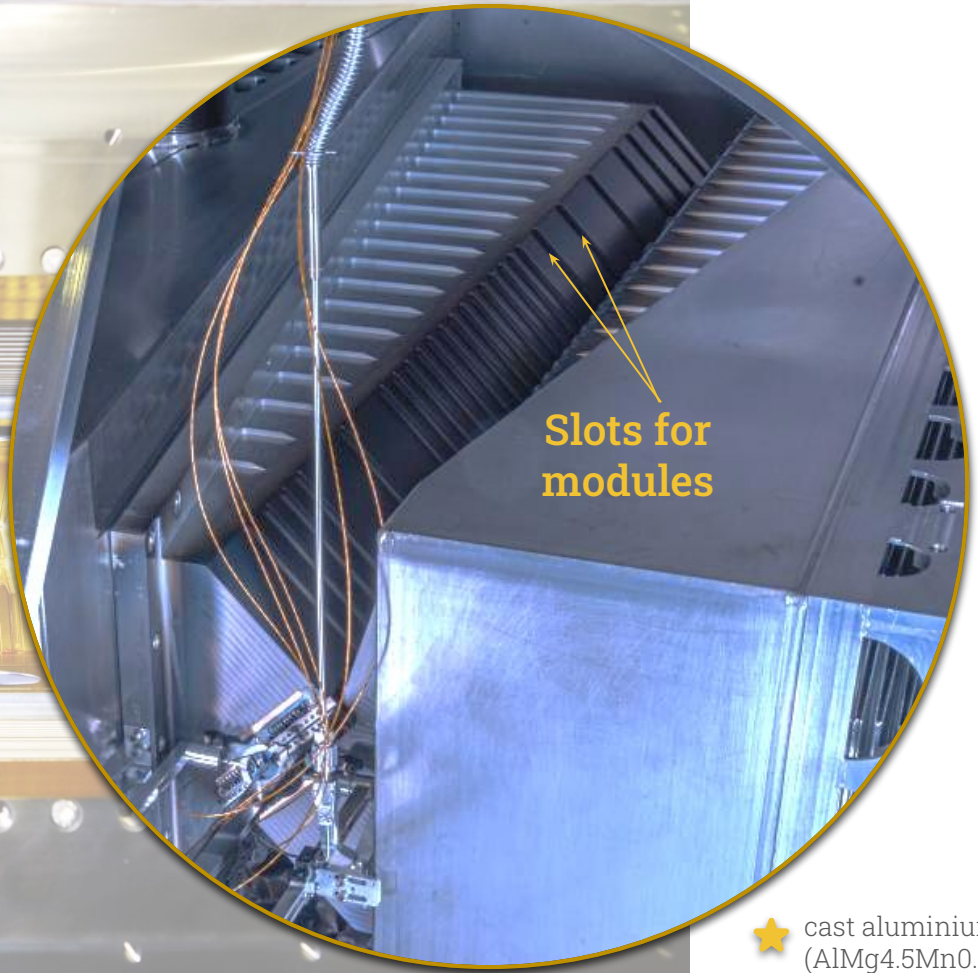

Primary
Vacuum
Modules
Secondary
Vacuum
Beam
Secondary
Vacuum
RF-box
Readout

RF BOX



inside view

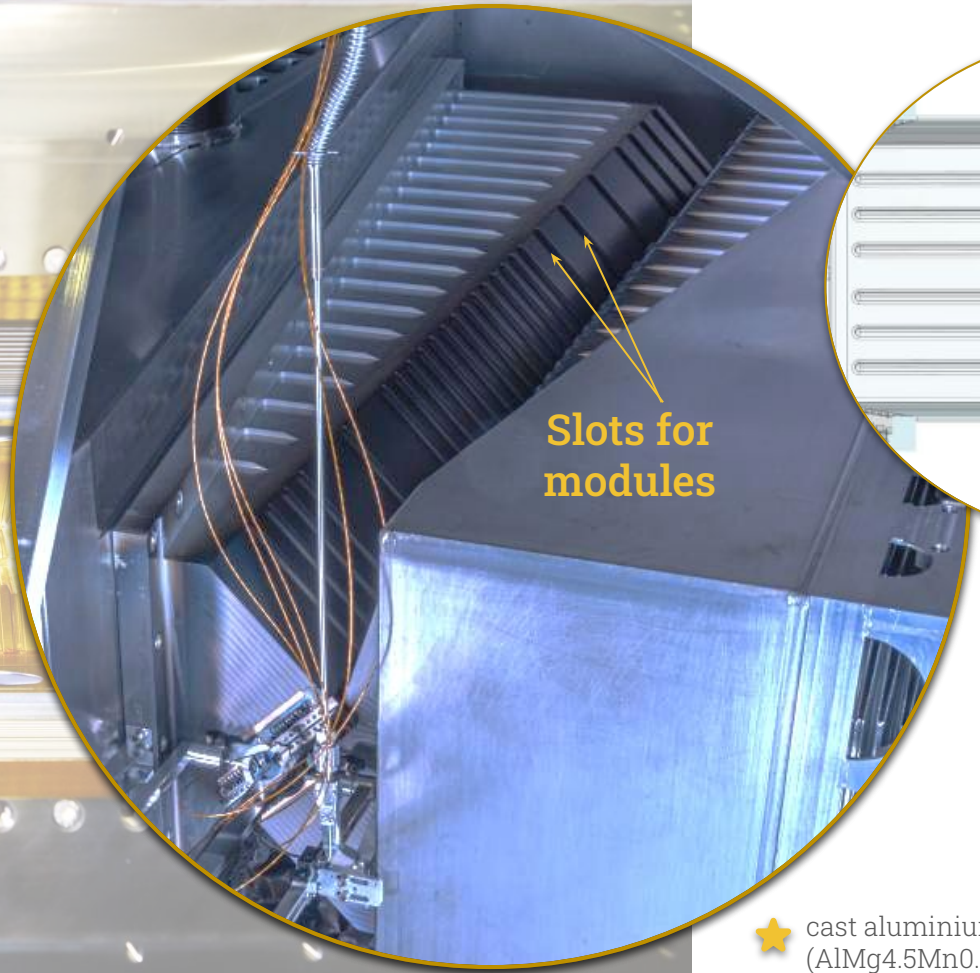
RF BOX

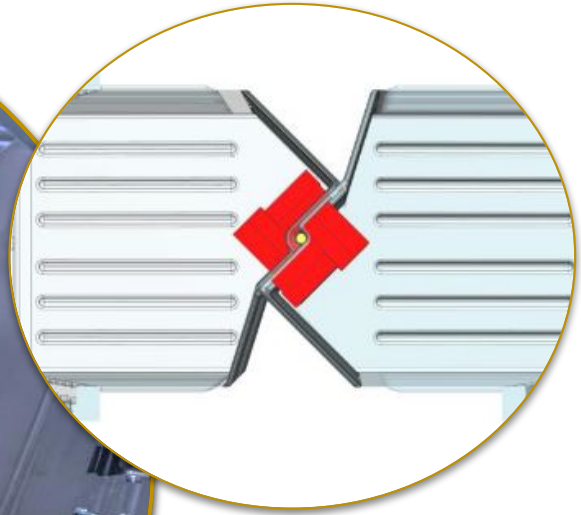


13 26,981
Al
Aluminium
1,61 2,70

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

RF BOX





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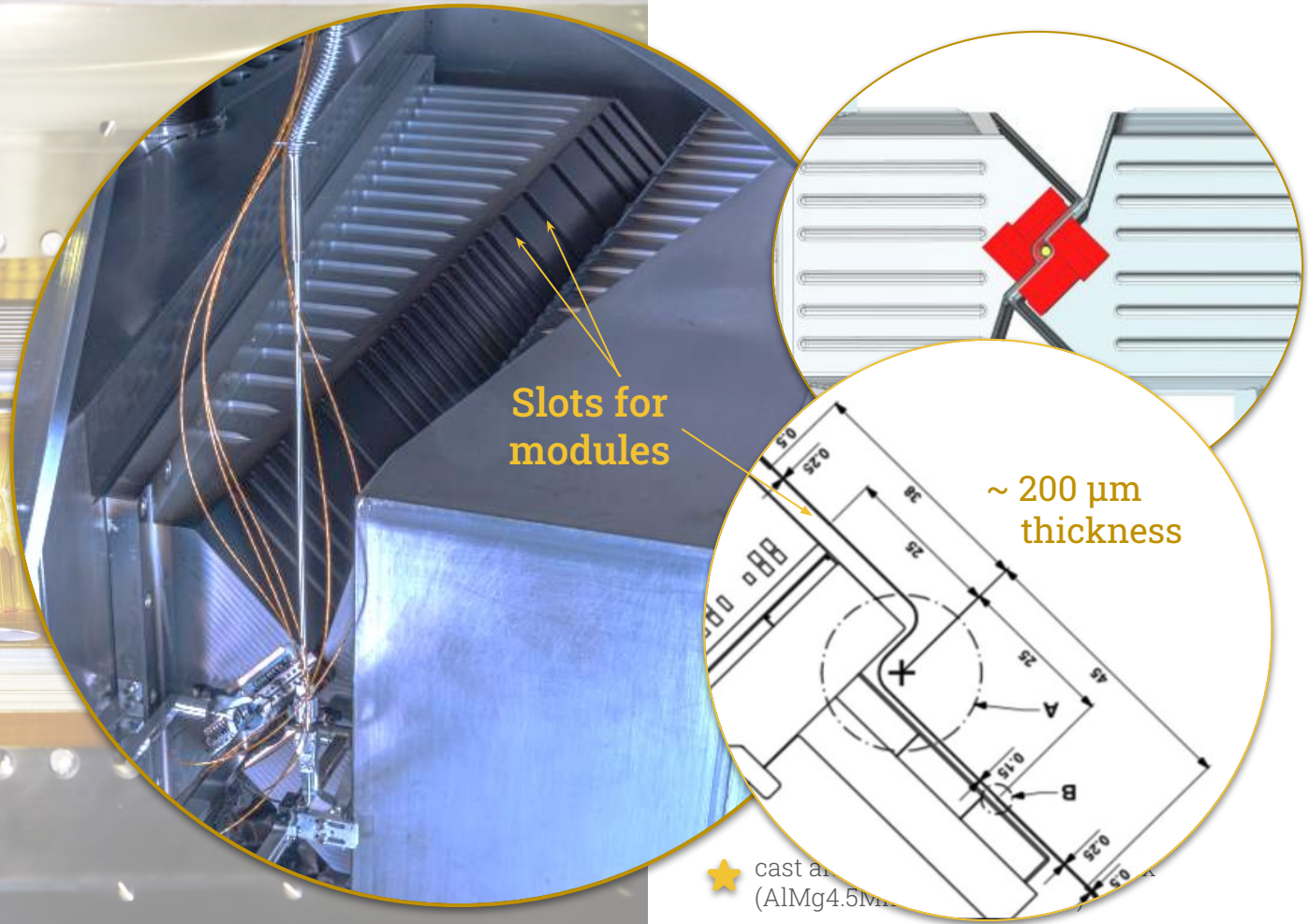

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Aluminium
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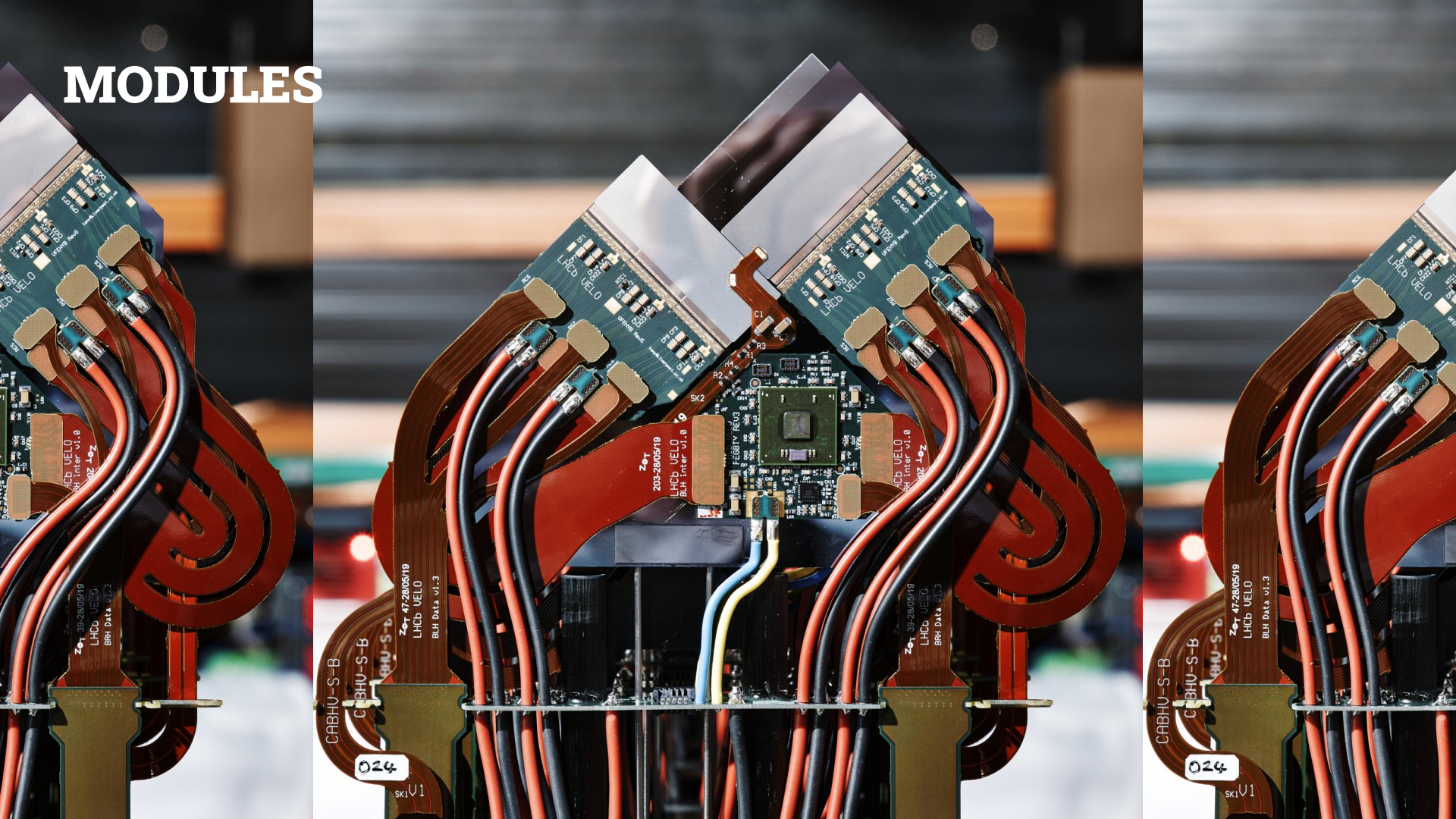
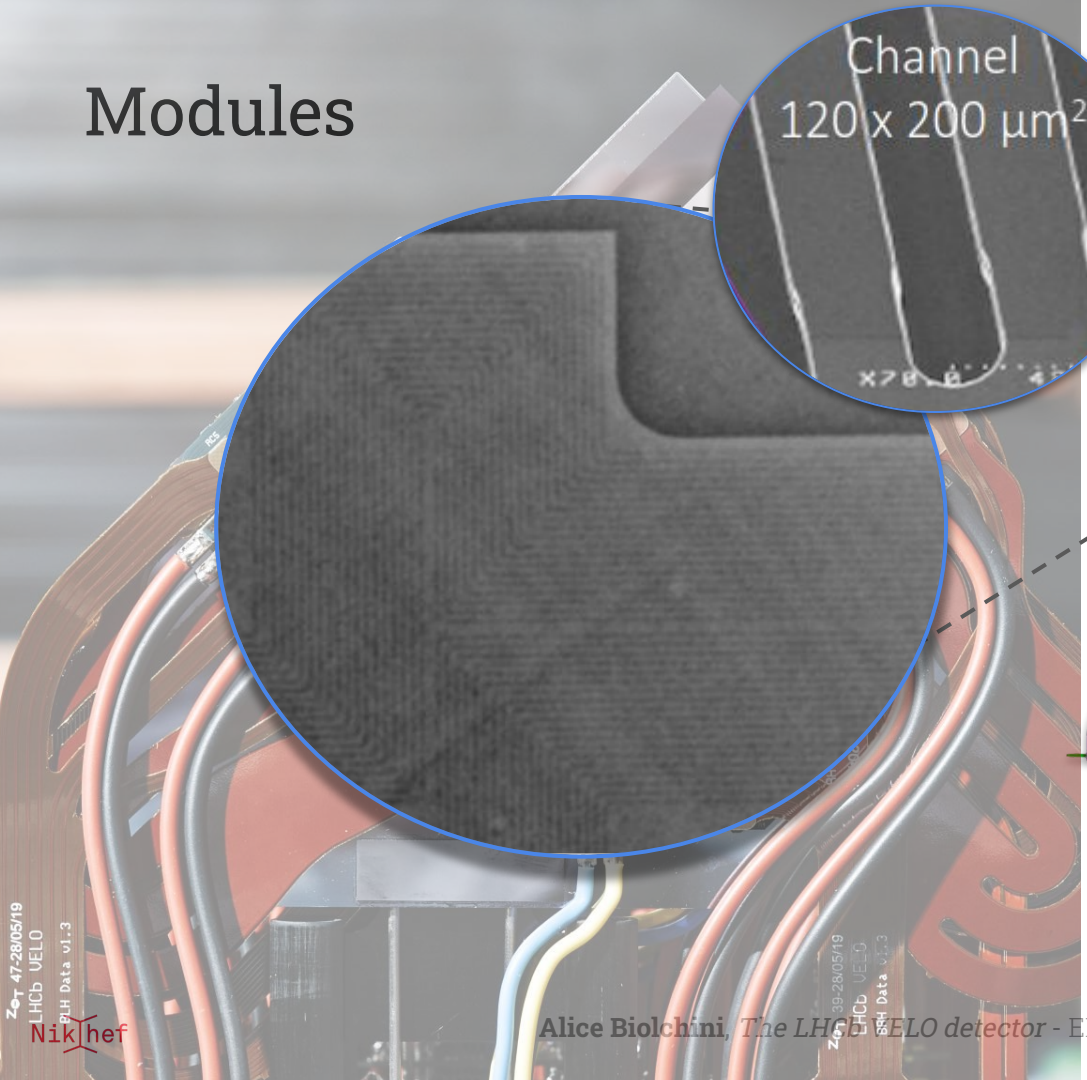
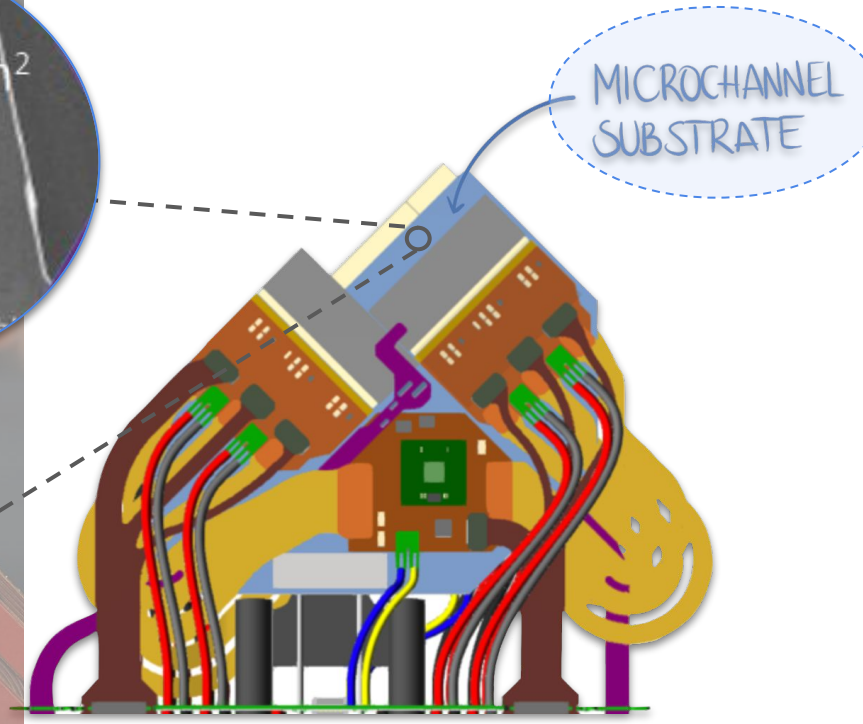
★ cast al
(AlMg4.5M

MODULES


CABHV-S-B
024
SK1
V1
LHCb VELO
BLH Data v1.3
LHCb VELO
BLH inter v1.0
FEGBTY REV3
SK2
C1
R1
R2
R3
R4

Modules





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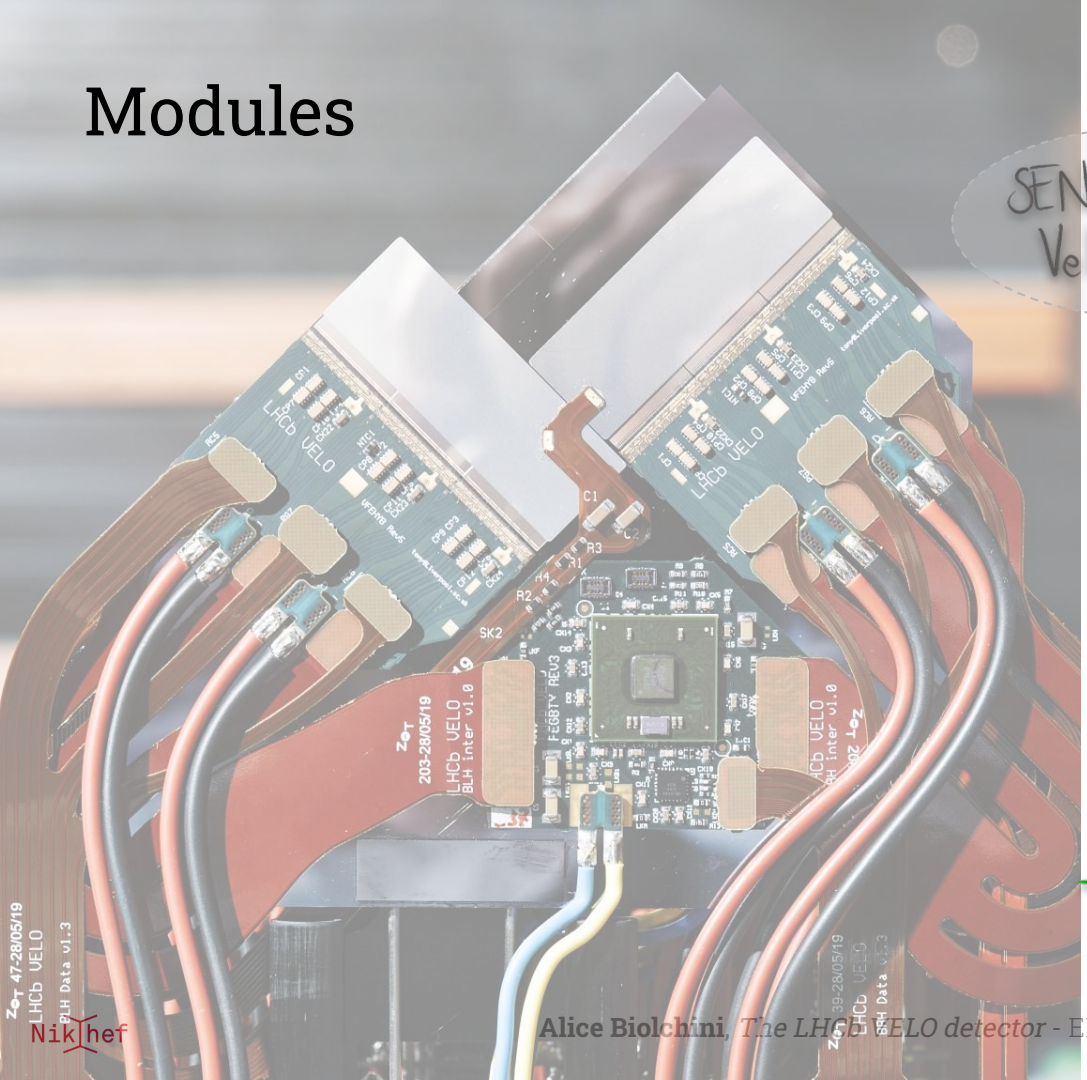
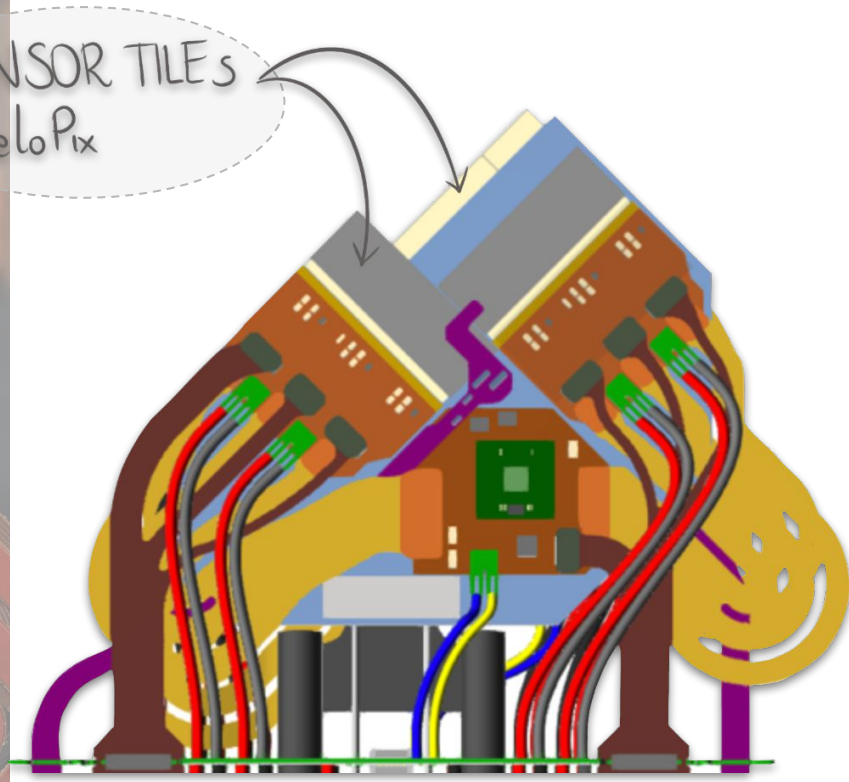
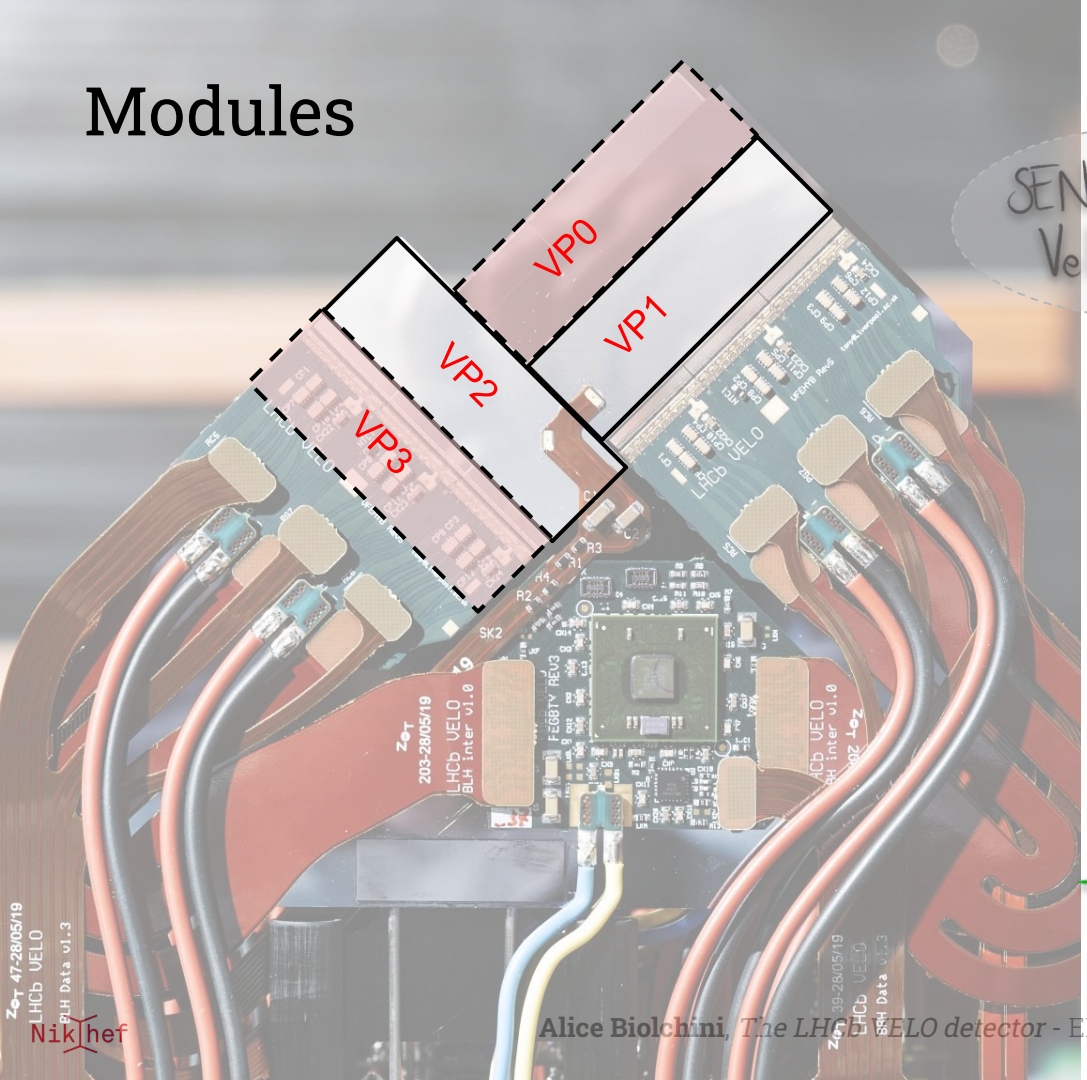
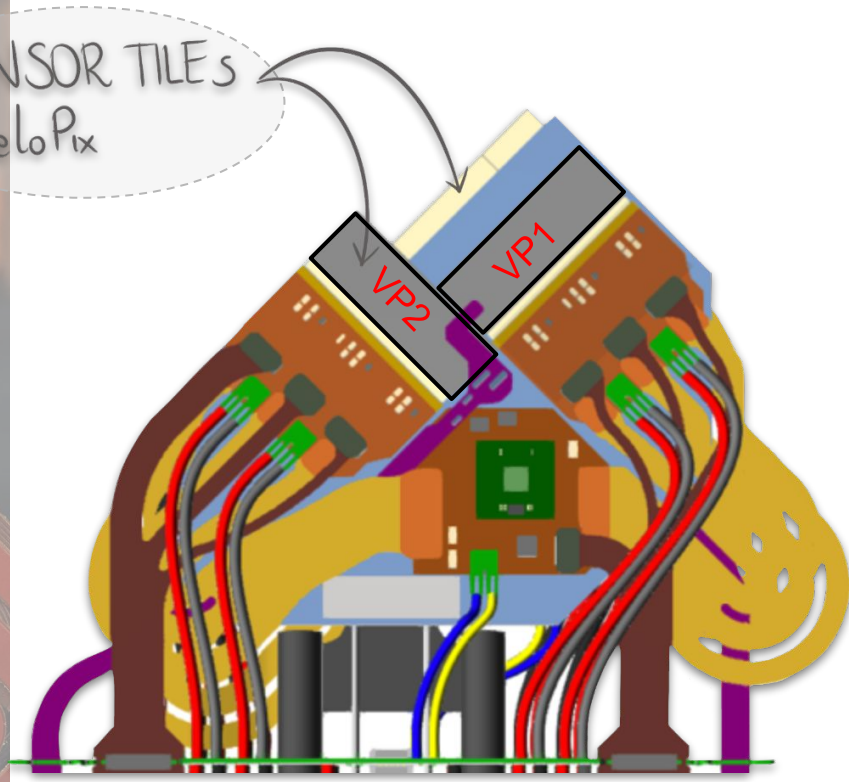


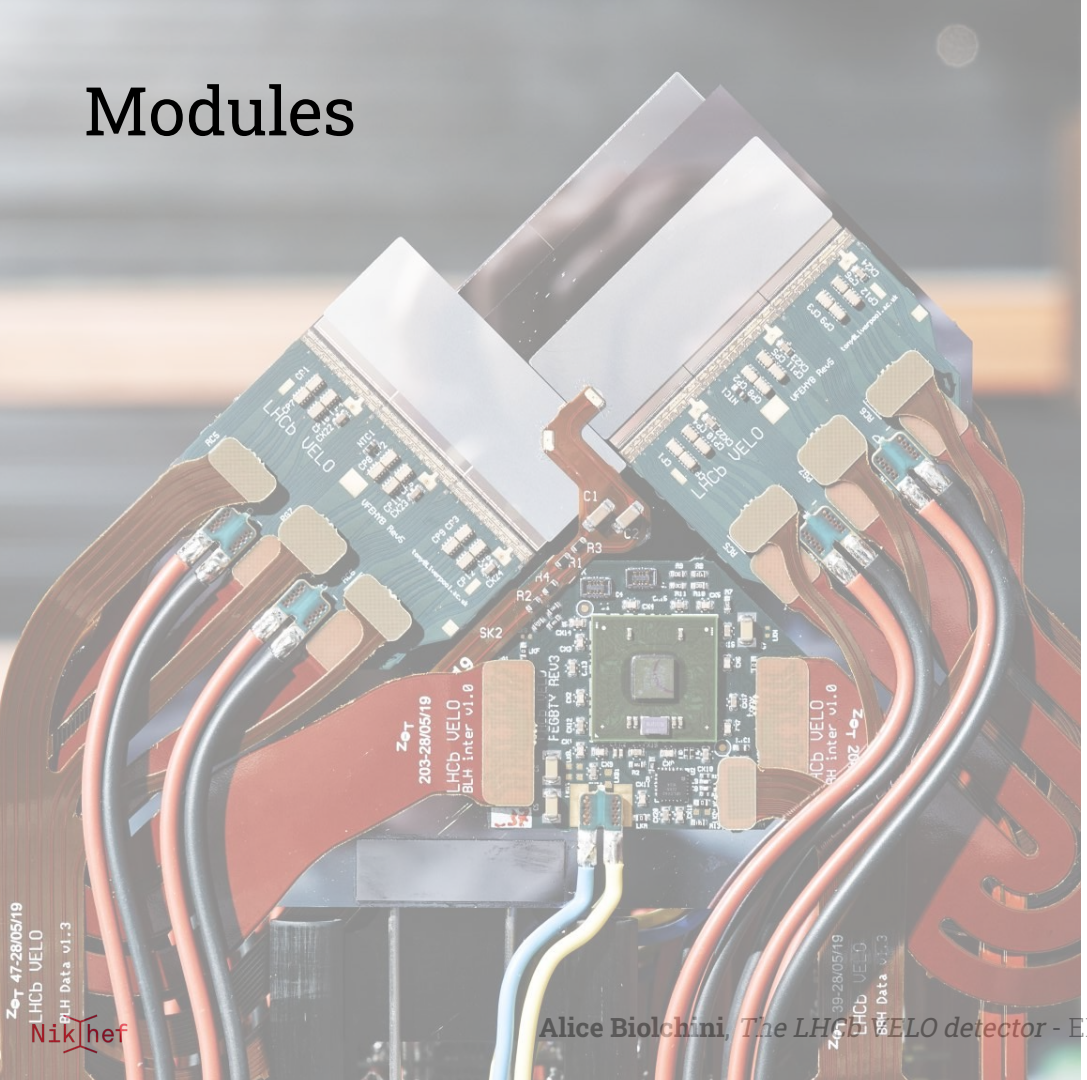


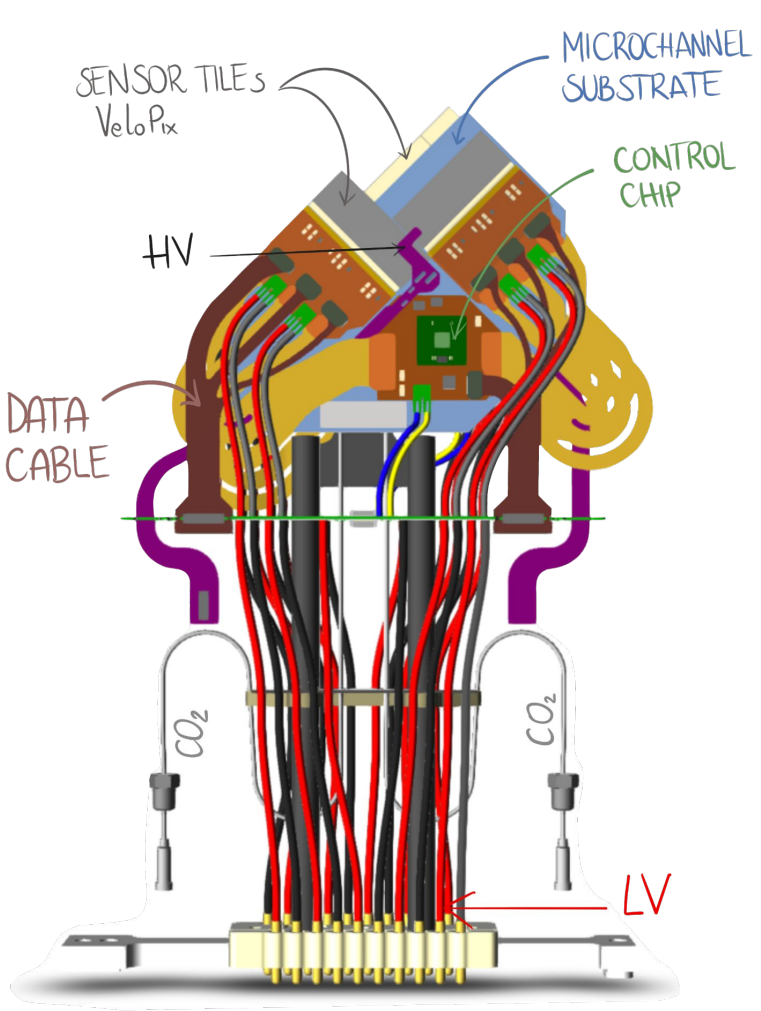
Modules



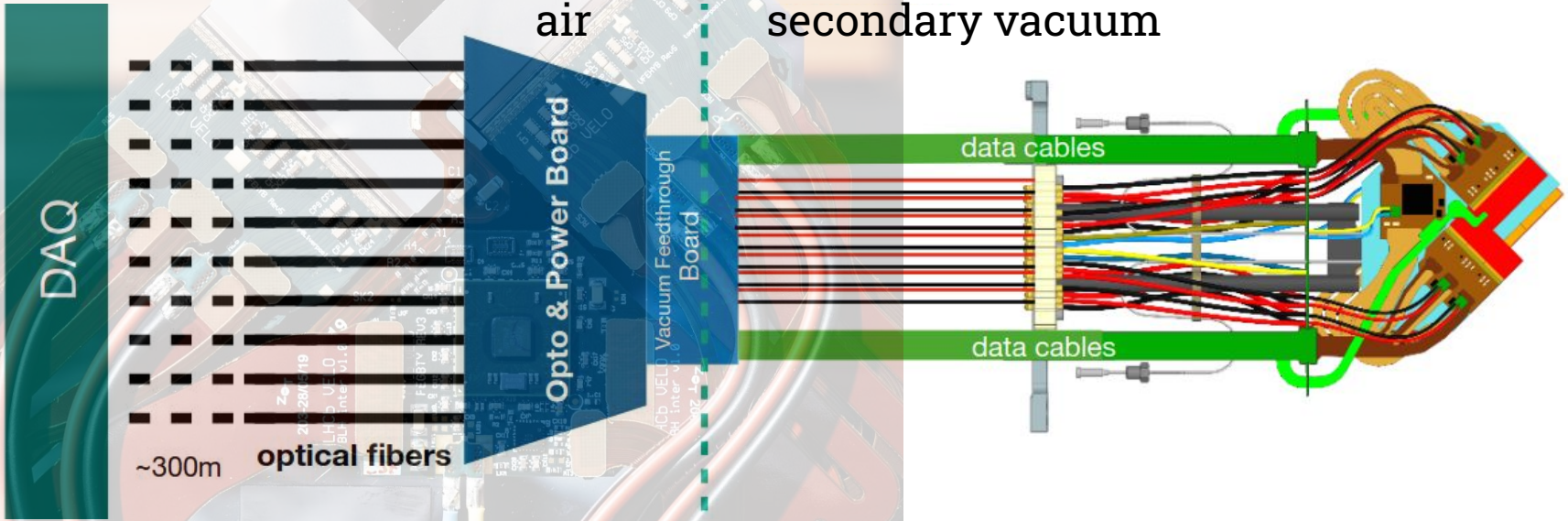


Modules

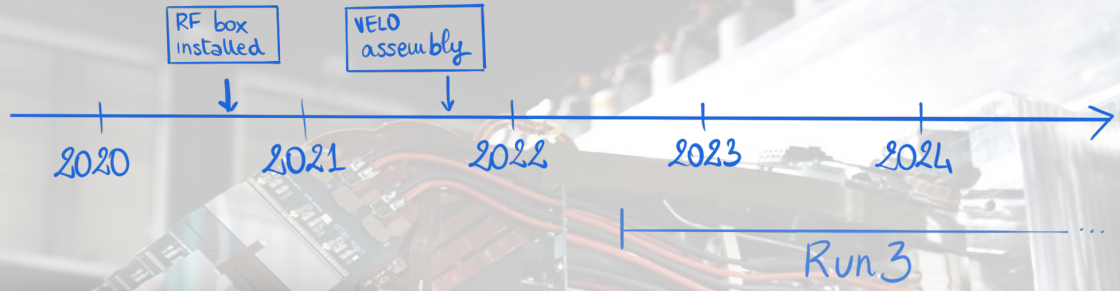


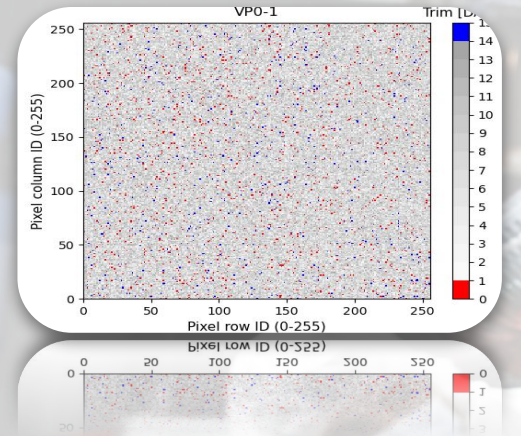

SENSOR TILES
VeloPix
MICROCHANNEL
SUBSTRATE
CONTROL
CHIP
HV
DATA
CABLE
CO_2
CO_2
LV

Readout

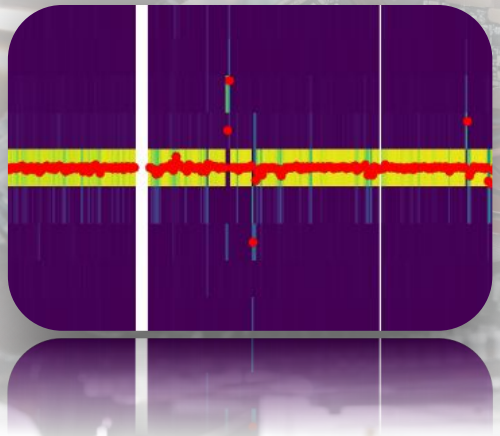

air
secondary vacuum
DAQ
~300m
optical fibers
Opto & Power Board
Vacuum Feedthrough Board
data cables
data cables

COMMISSIONING

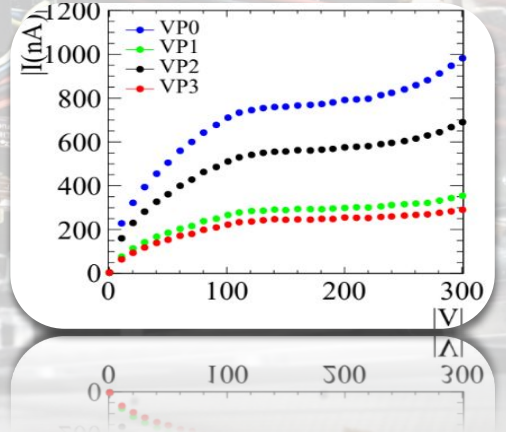




Equalisation



Time alignment



IV scans

EQUALISATION

Goal: Pixels respond the same.

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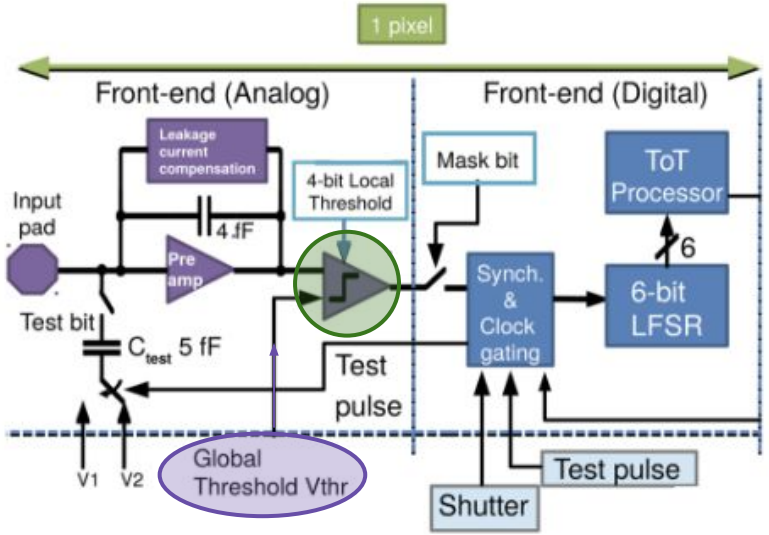
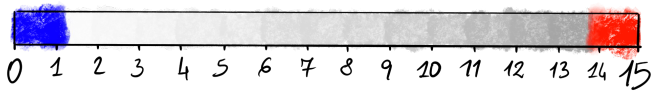
Th_{local} = trim + Th_{global}



- global threshold (Th_{global}) defined per ASIC
- trim defined per pixel



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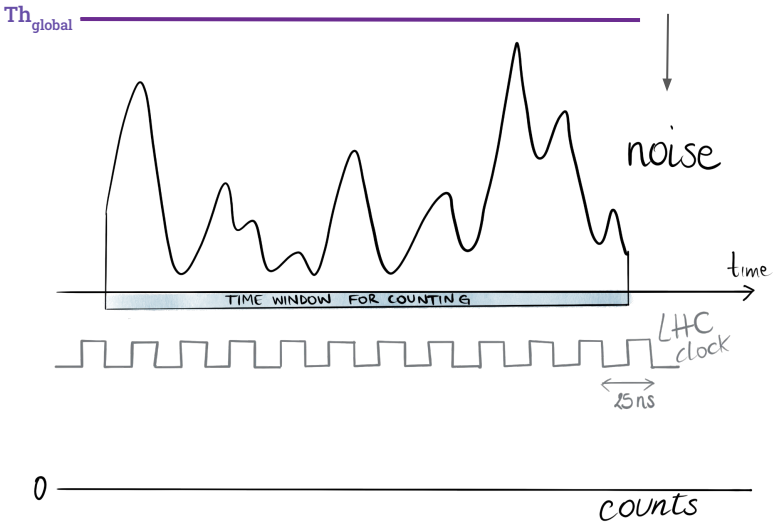

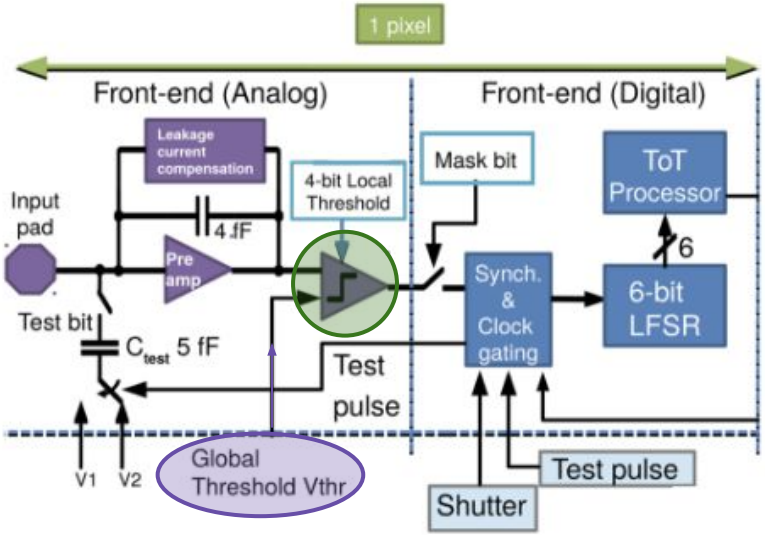

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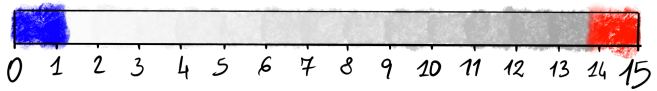

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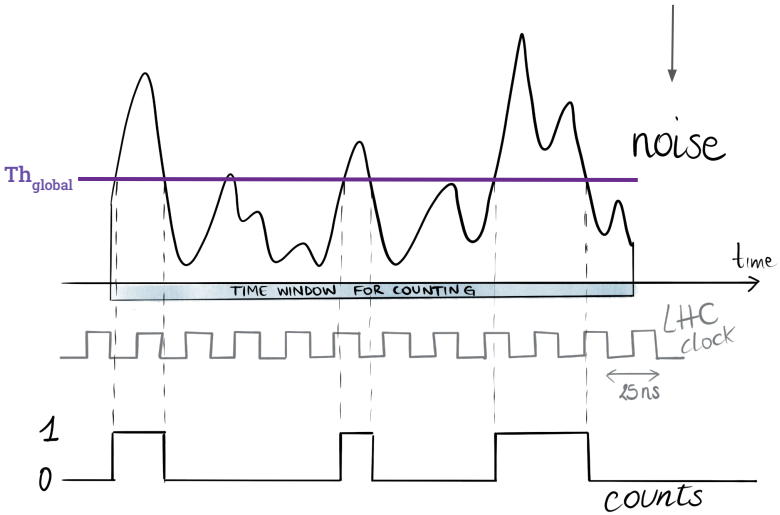

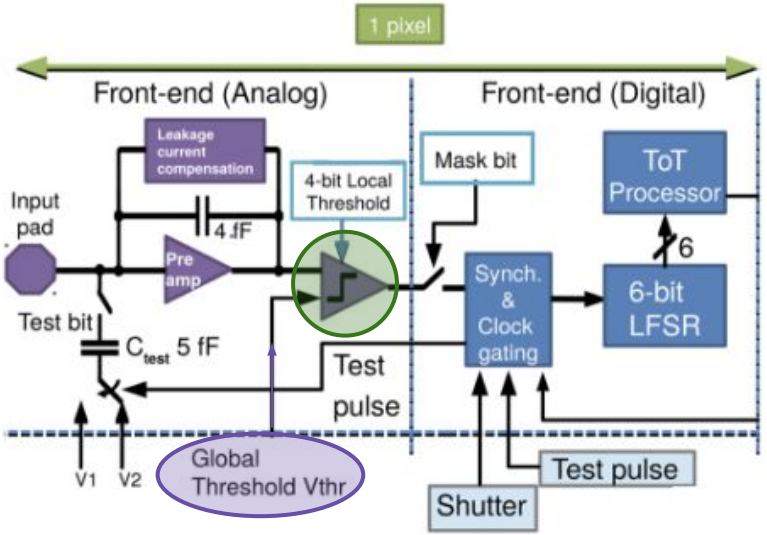

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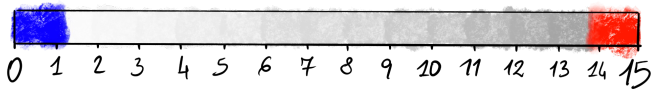

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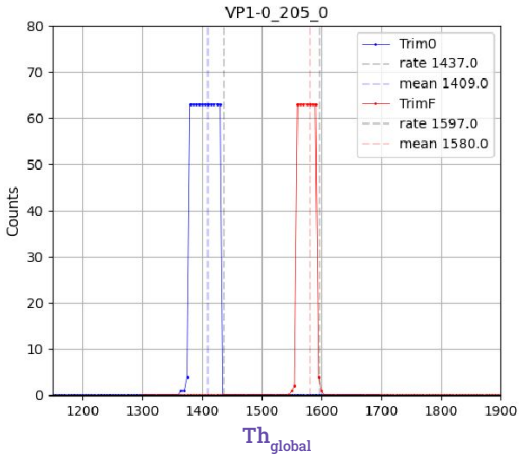

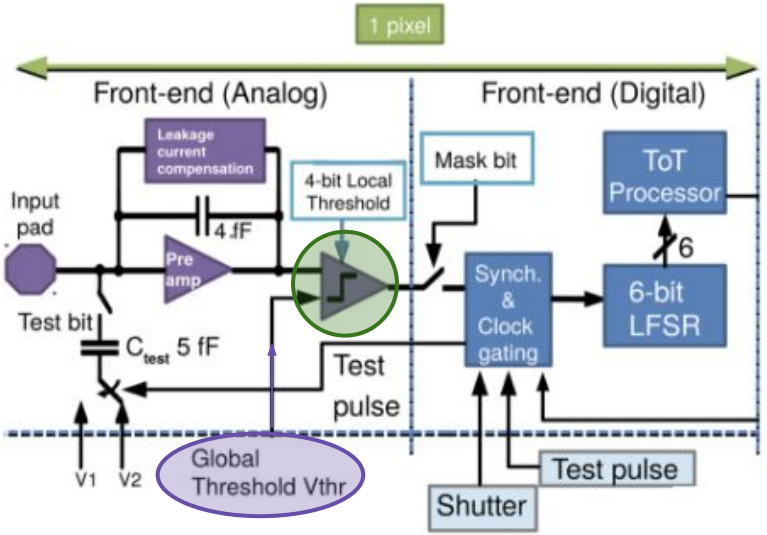

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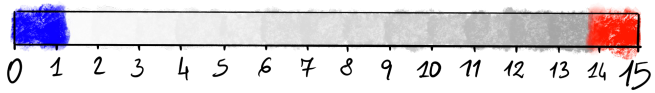

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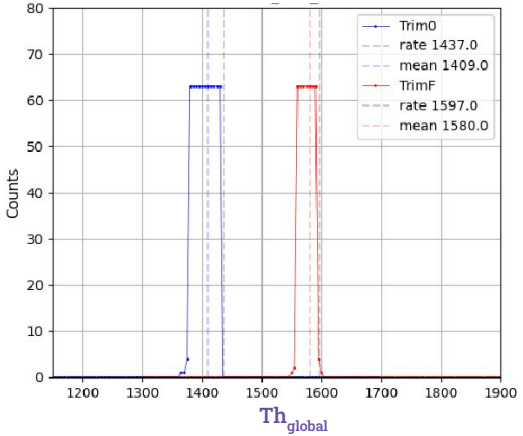
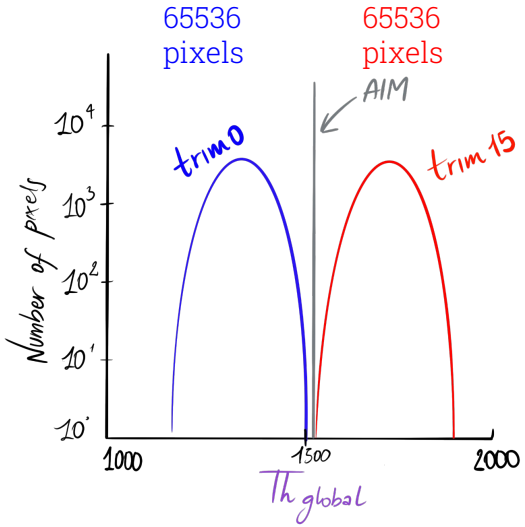
1 pixel



1 ASIC (256x256 pixels)



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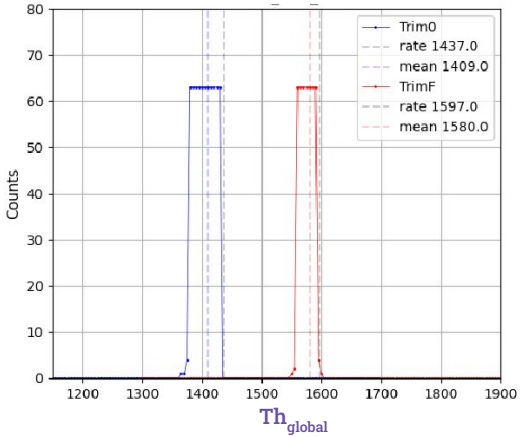

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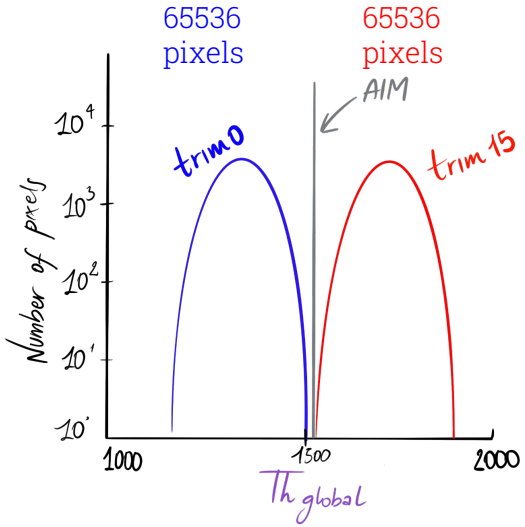

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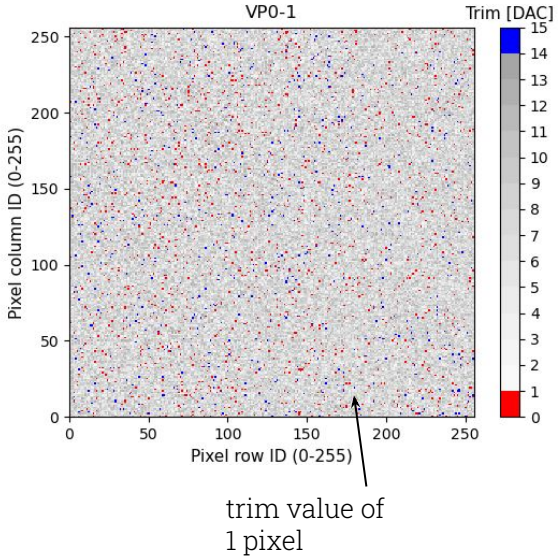

trim value of 1 pixel

EQUALISATION

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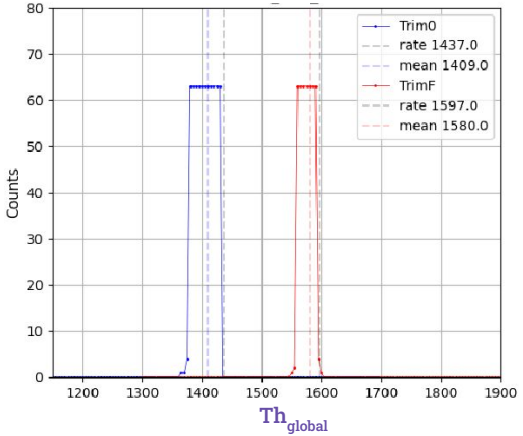
The equalized matrix defines *operational local thresholds* per pixel

1 pixel



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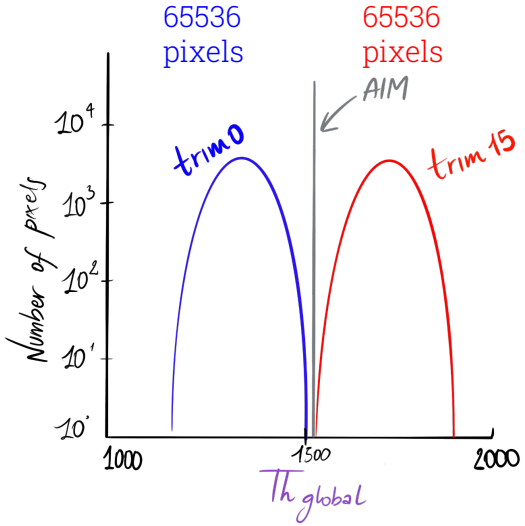

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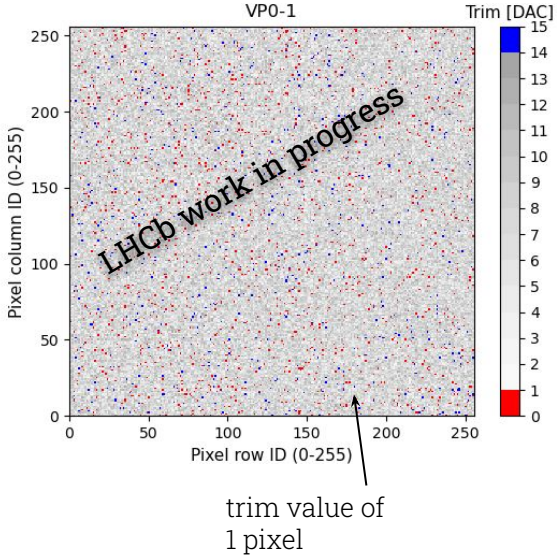
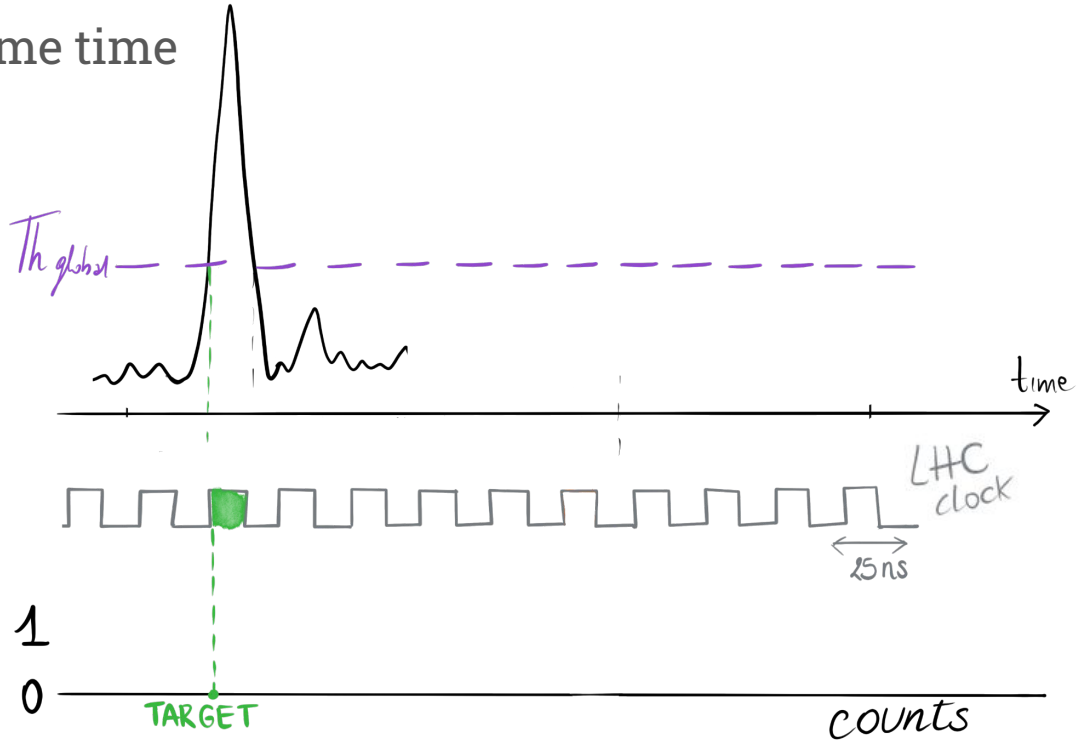


trim value of 1 pixel

TIME ALIGNMENT

Goal: ASICs responding at the same time

1. Synchronise with LHC clock



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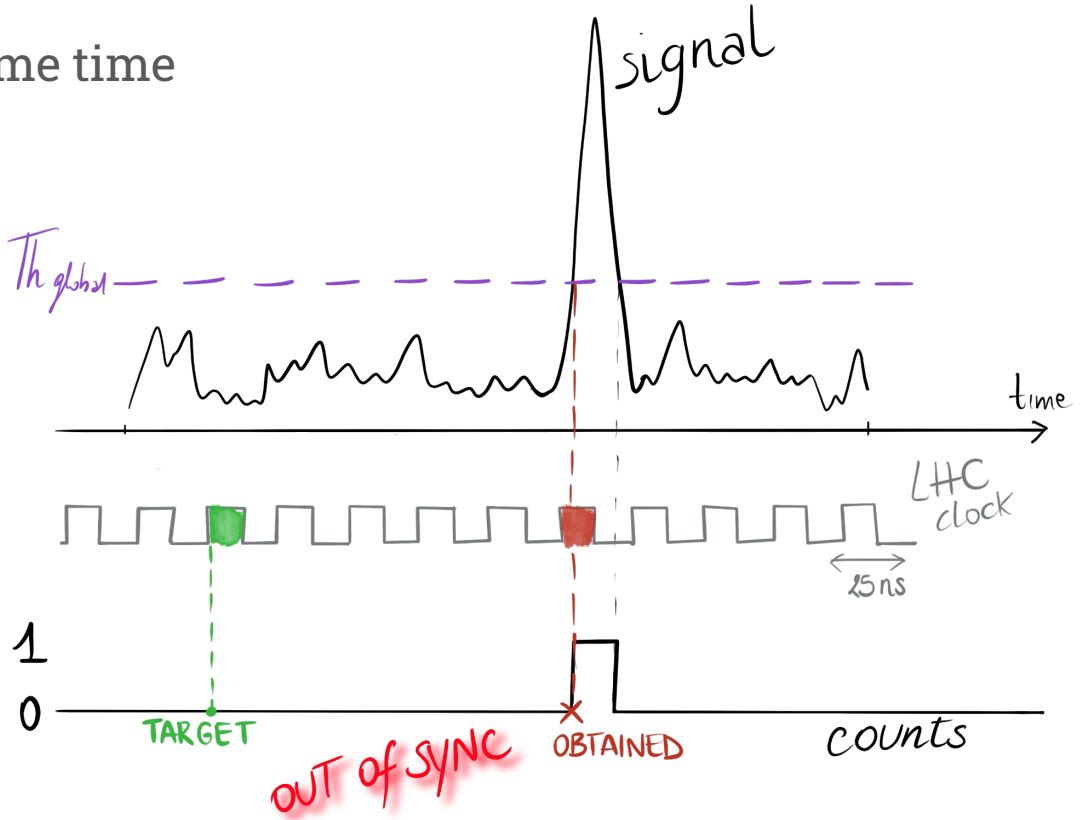

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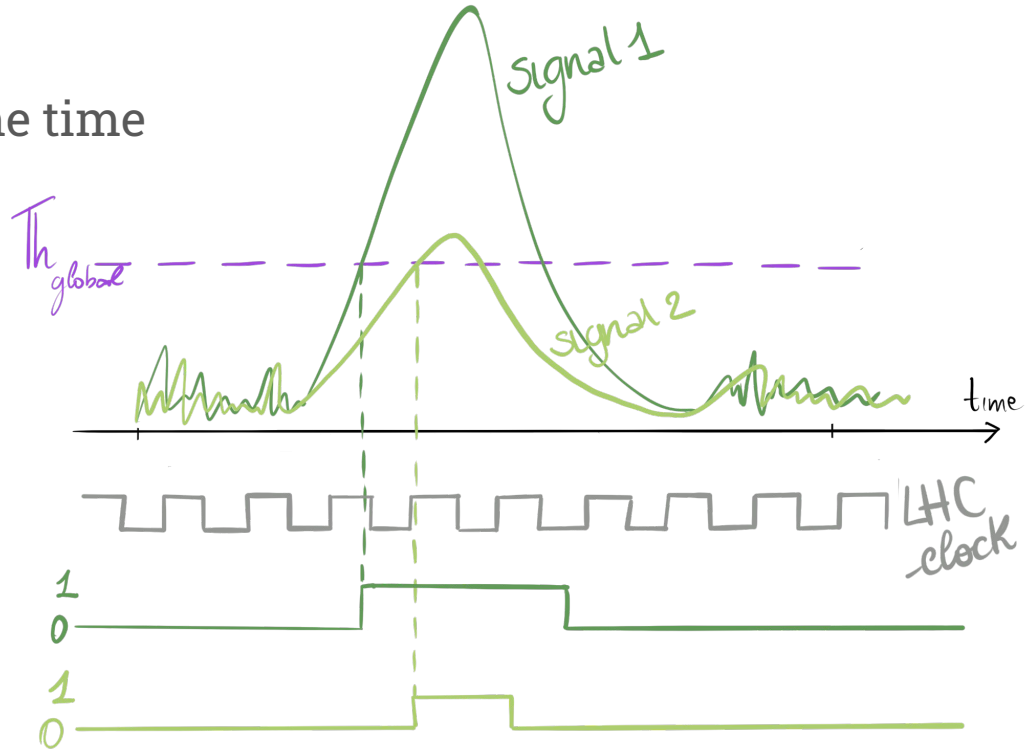
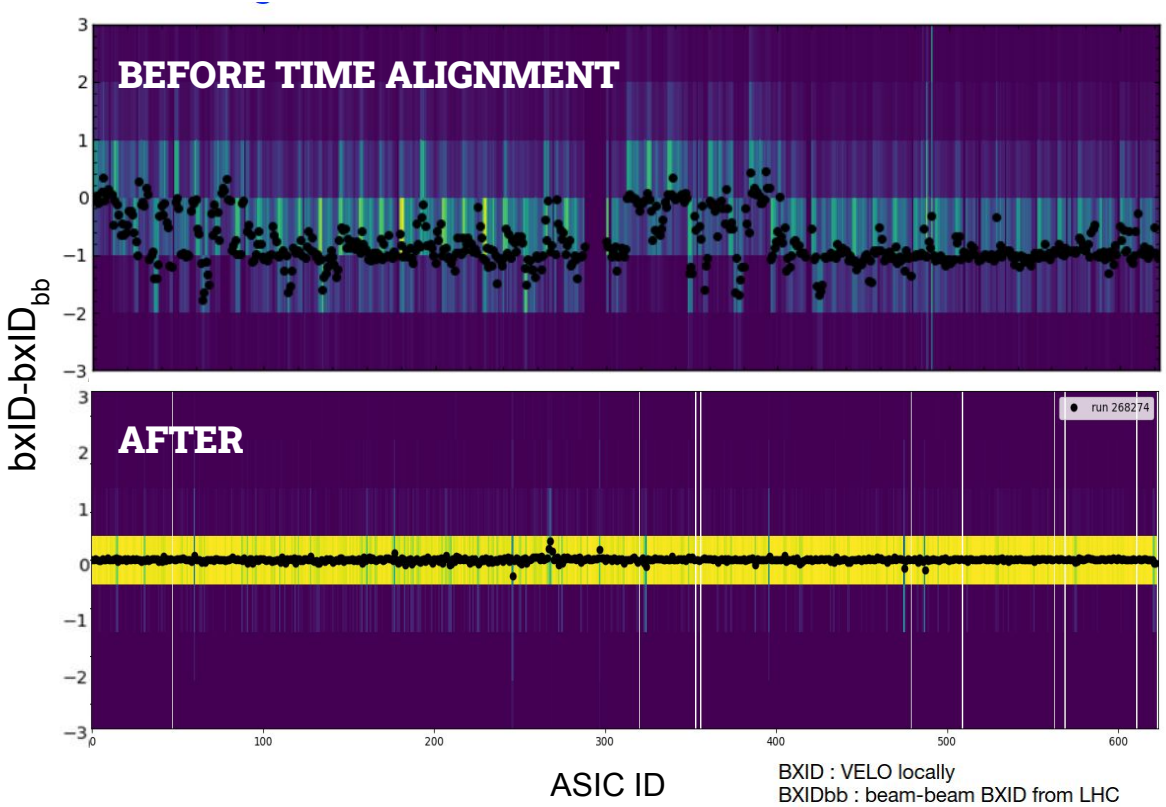
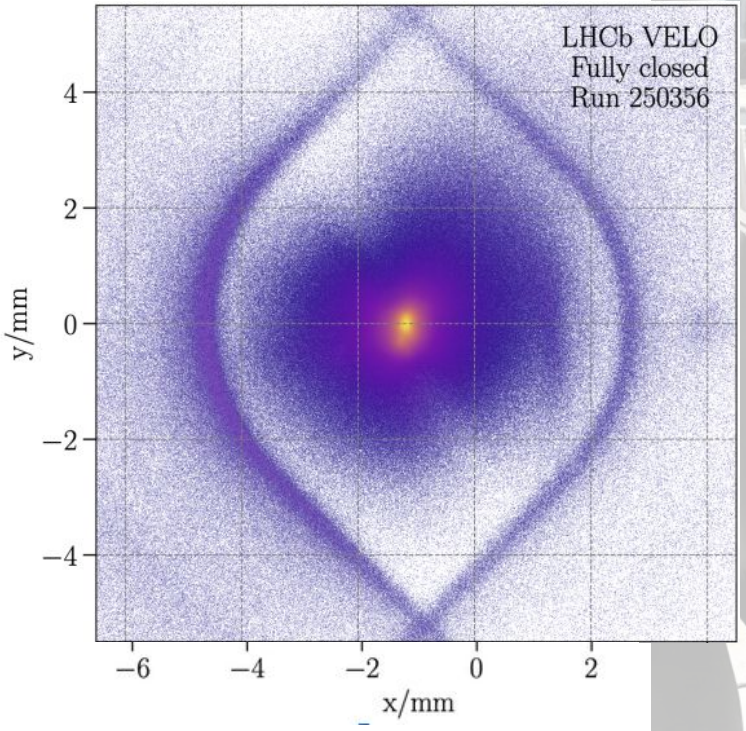


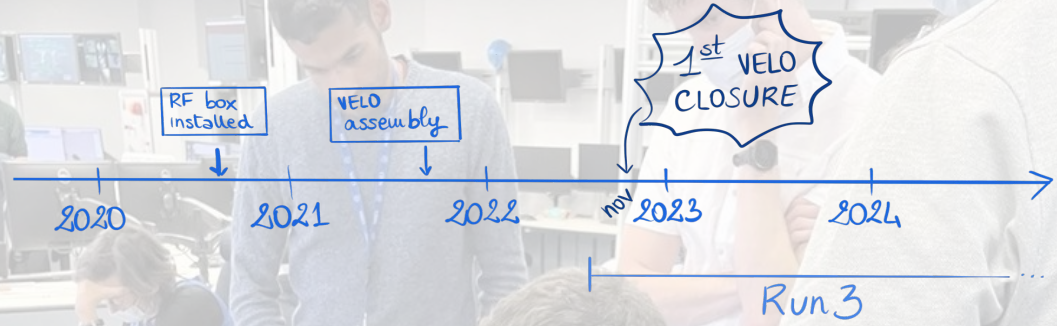
TIME ALIGNMENT

- Tune the phases of the electronic to regulate the delay on the clock
- Time alignment procedure in place



FIRST RESULTS





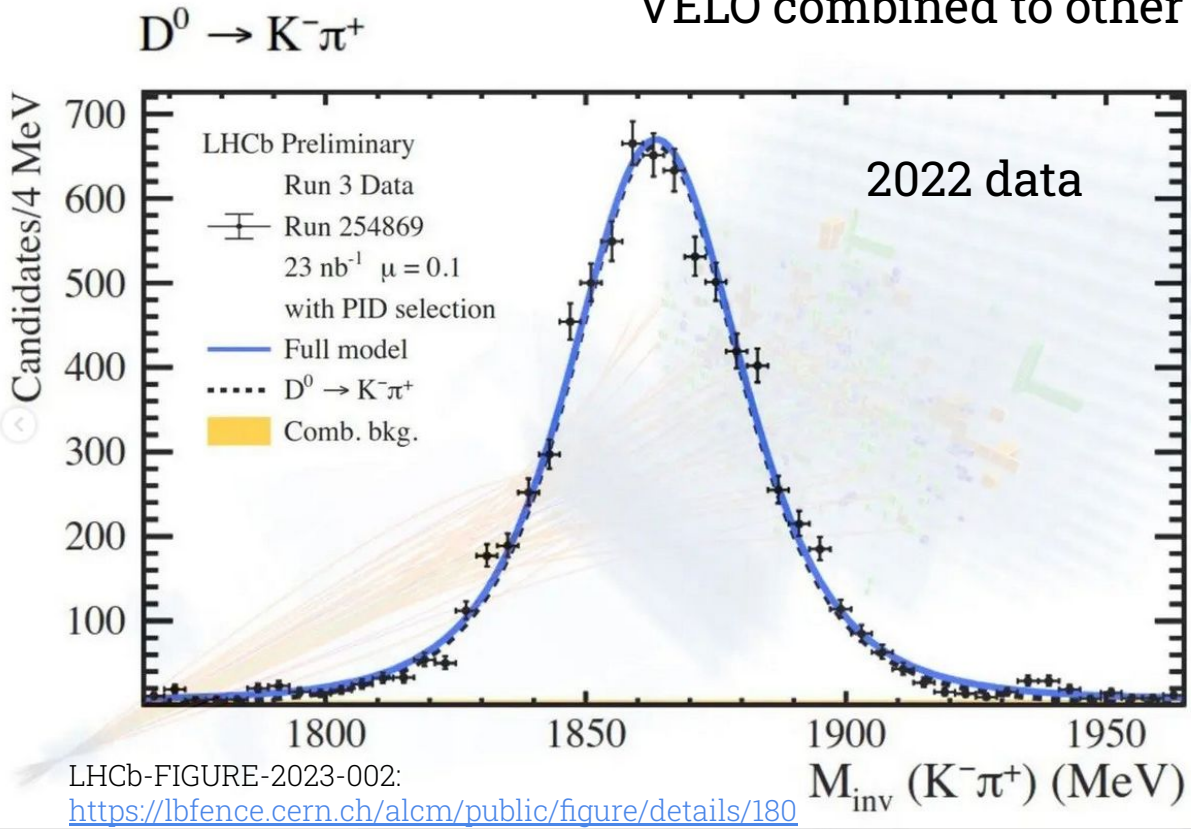
First version of equalisation and time alignment allowed to reconstruct tracks and do spatial alignment

First tracks allowed reconstructing PV in real time and close the VELO to nominal position

VELO tomography: online vertex reconstruction with at least 3 tracks

FIRST RESULTS

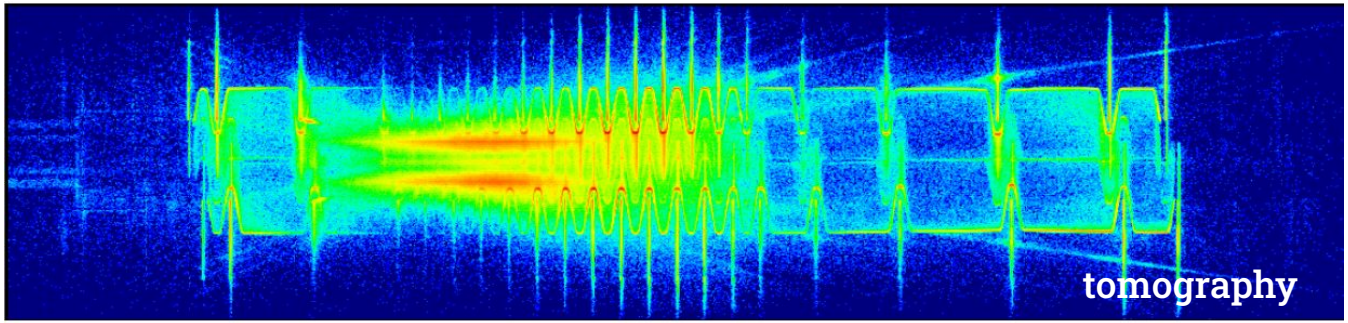
VELO combined to other detectors



LHCb-FIGURE-2023-002:
https://lbfence.cern.ch/alcm/public/figure/details/180

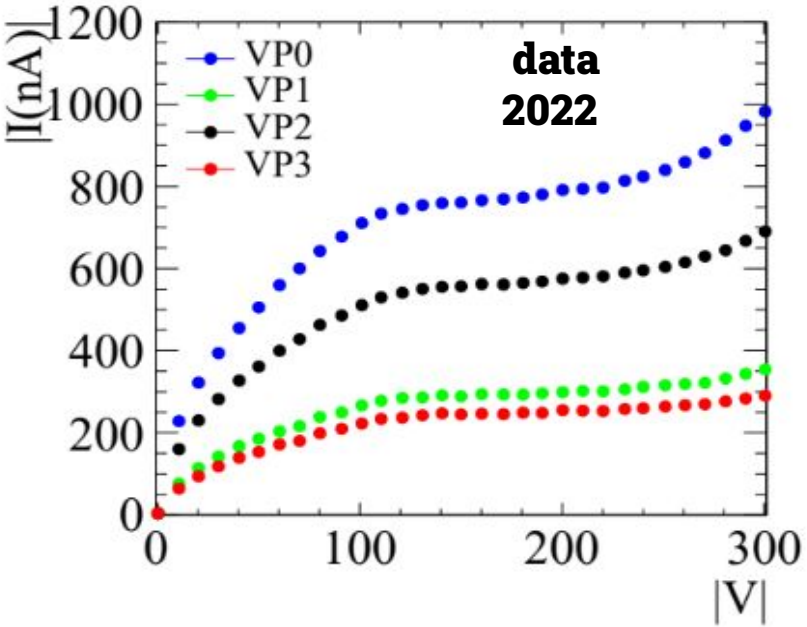
IV SCANS: RADIATION DAMAGE

- Irradiation profile strongly depends on distance from interaction point

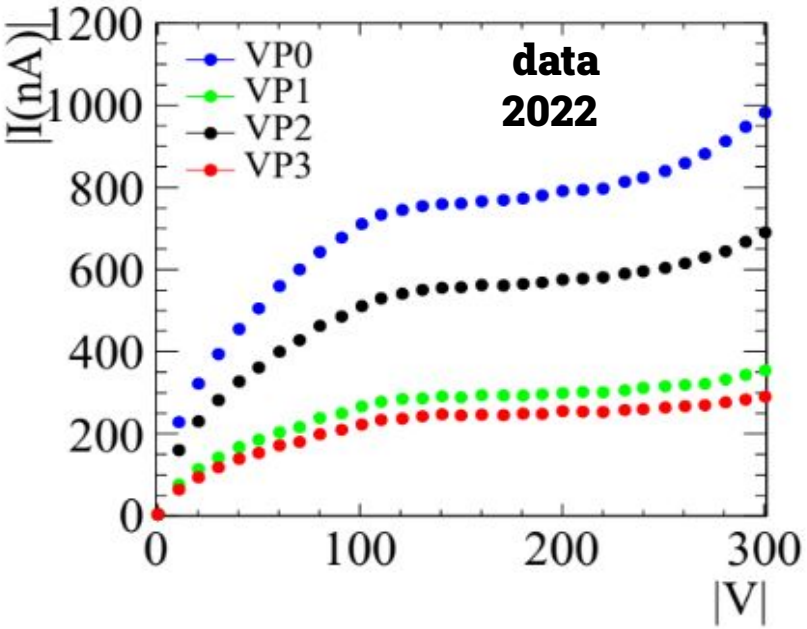


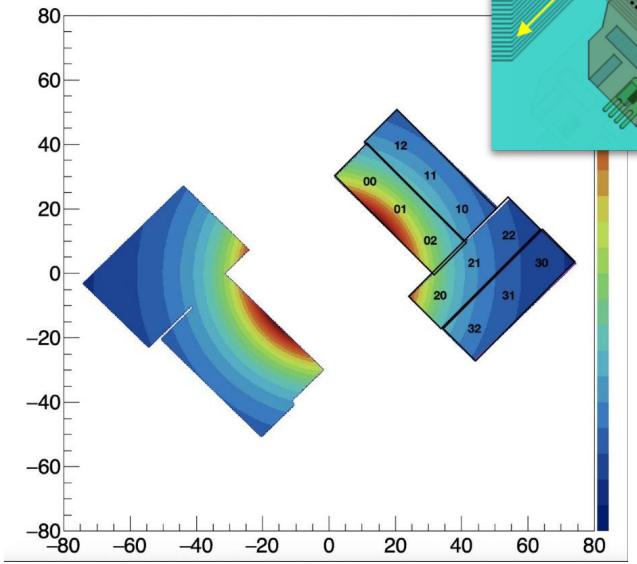
- Current vs voltage (IV) scans are a fundamental tool to monitor the evolution of radiation damage with fluence.

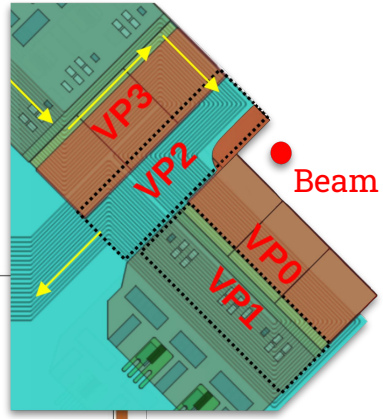
IV SCANS: RADIATION DAMAGE



IV SCANS: RADIATION DAMAGE

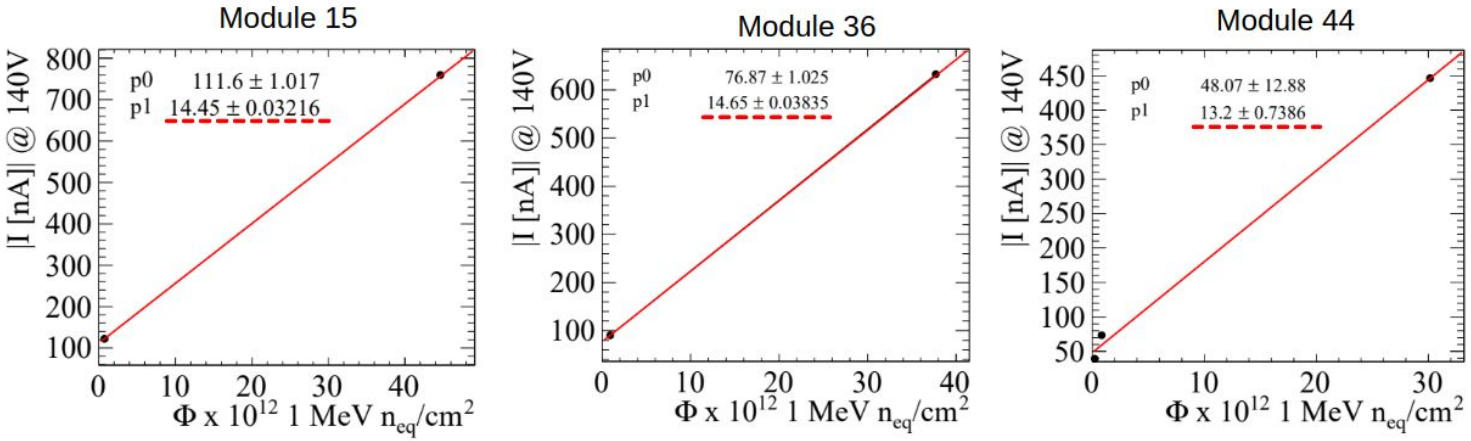






IV SCANS: RADIATION DAMAGE

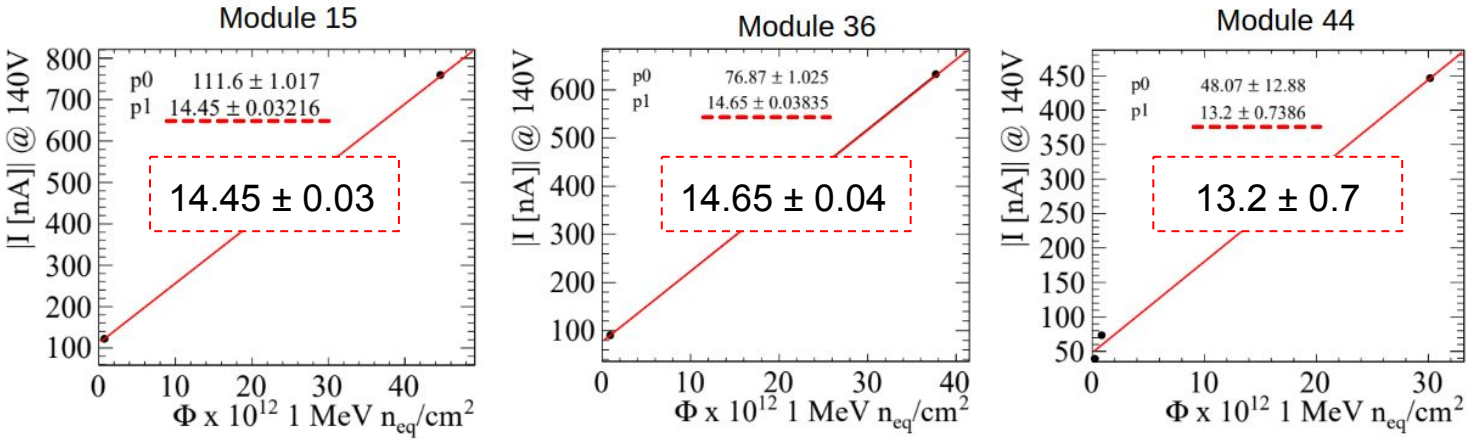
Leakage current vs fluence to estimate the radiation damage



Radiation damage (slope) is consistent across the whole detector

IV SCANS: RADIATION DAMAGE

Leakage current vs fluence to estimate the radiation damage

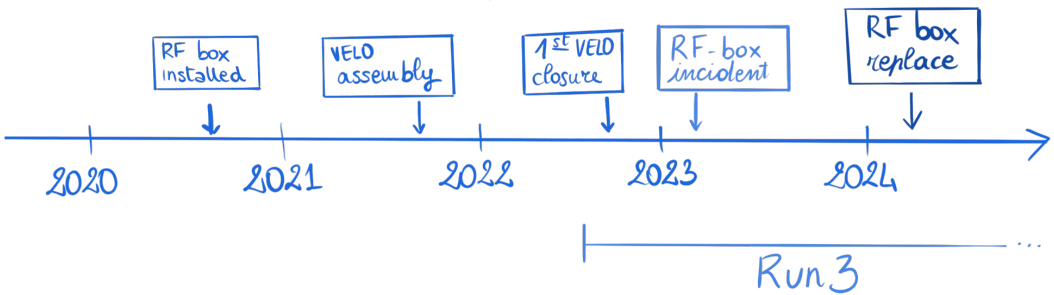


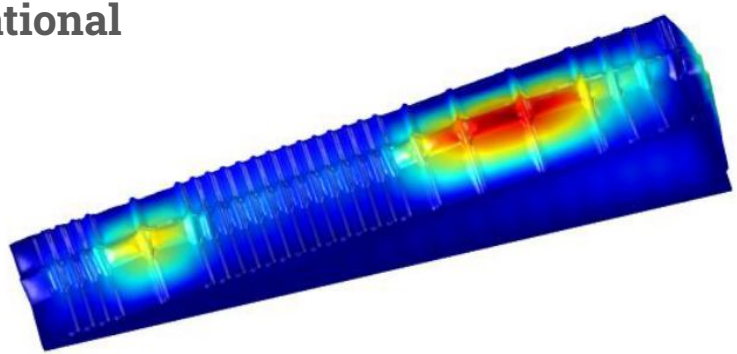
Radiation damage (slope) is consistent across the whole detector

RF-BOX INCIDENT:

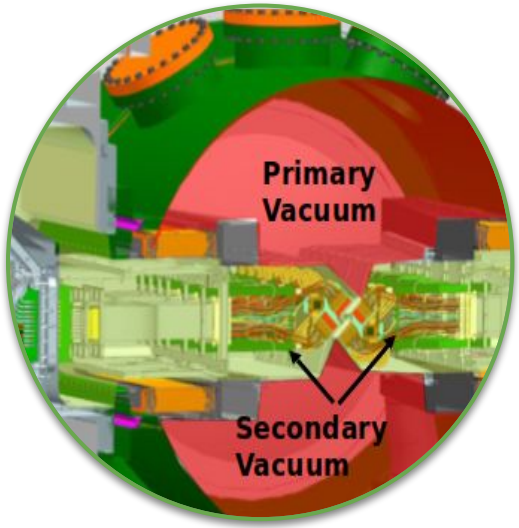
- Loss of control of the protection system, lead to a *pumping action on the primary volume*
- A differential pressure beyond the specification limits built up between the two volumes
- The RF box has suffered a plastic (permanent) deformation

- **Modules sensor not damaged, VELO still operational**
- **RF box will be replaced in 2024**

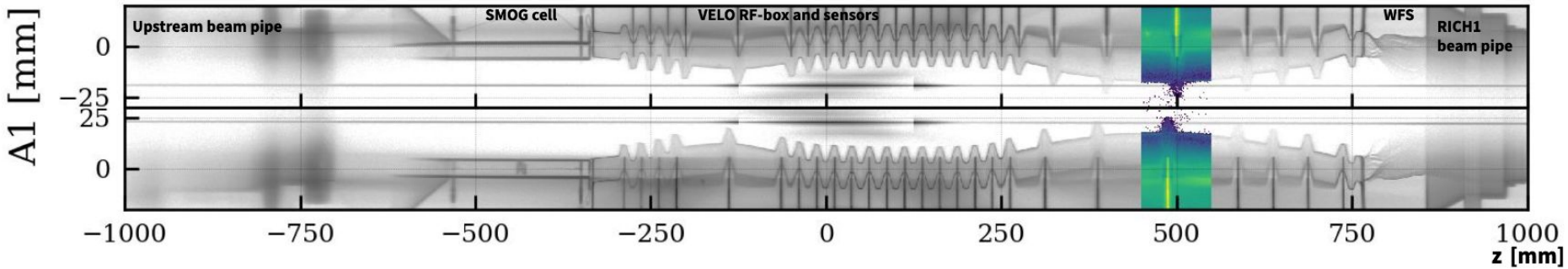




RF-BOX INCIDENT:



- Detector inside secondary vacuum
- Leakage current measurements and ASICs response, confirmed that the VELO was undamaged
- Tomography → *see* the damage to the RF box
  → define limits of VELO movements



Conclusions

2022: Commissioning

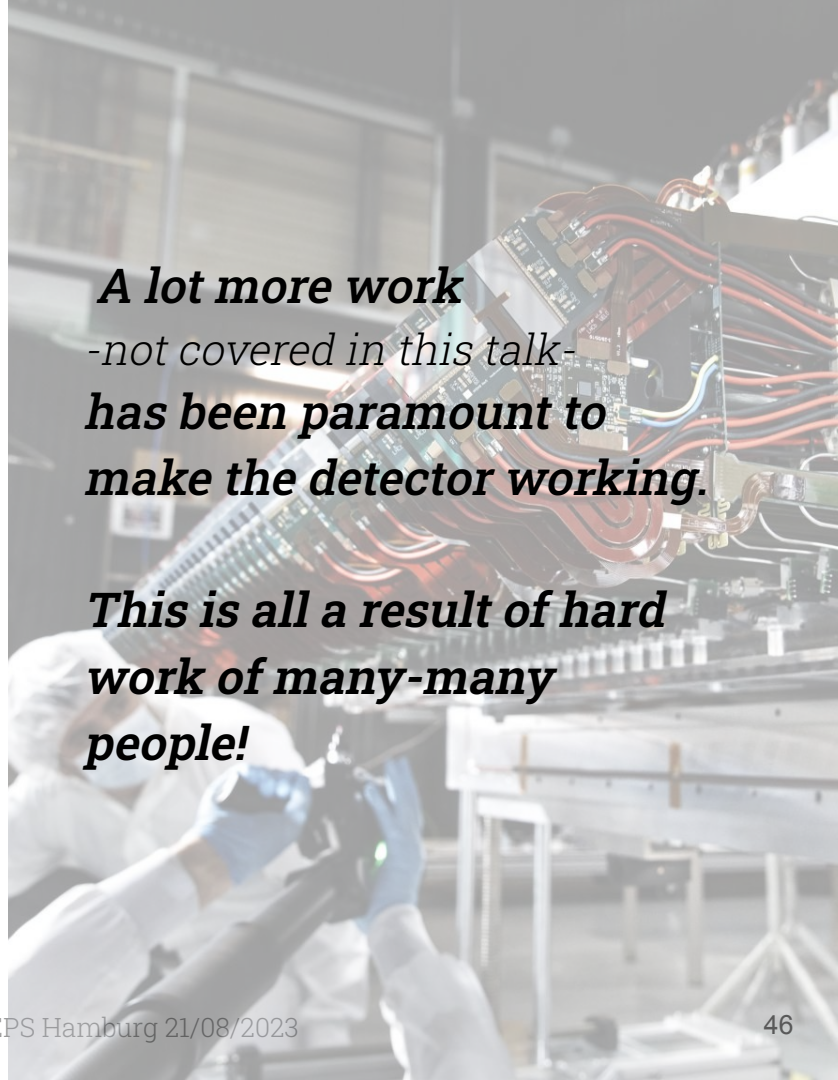
- July 2022 → starts Run3
- VELO fully closed in November 2022

RF-box incident:

- Plastic deformation of RF-box
- RF-box replaced in 2024
- 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!

Thanks for your attention.
Any questions?

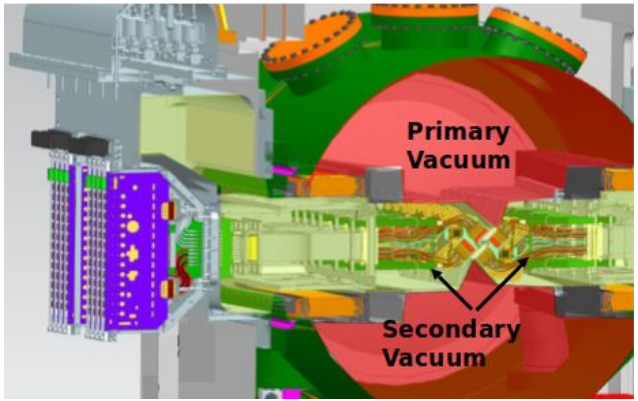
abiolchi@nikhef.nl alice.biolchini@cern.ch

REFERENCES

LHCb VELO Upgrade Technical Design Report - LHCB-TDR-013

BACKUP SLIDES

RF-box incident



The VELO detector is installed in a secondary vacuum inside the LHC primary vacuum. The primary and secondary volumes are separated by two thin walled Aluminium boxes, the RF foils.

On 10th January 2023, during a VELO warm up in neon, there was a loss of control of the protection system. A pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only Initial investigations show no damage to the VELO modules; sensors show correct leakage currents, microchannels show no leaks RF foils have suffered plastic deformation up to 14 mm and have to be replaced. Major intervention, planning under study.

Replace at the end of the year. Physics programme of 2023 is significantly affected, commissioning of Upgrade I systems can proceed as planned

After the RF-box incident

After the incident, it was confirmed with leakage current measurements and by checking the response of the ASICs that the VELO modules were completely undamaged.

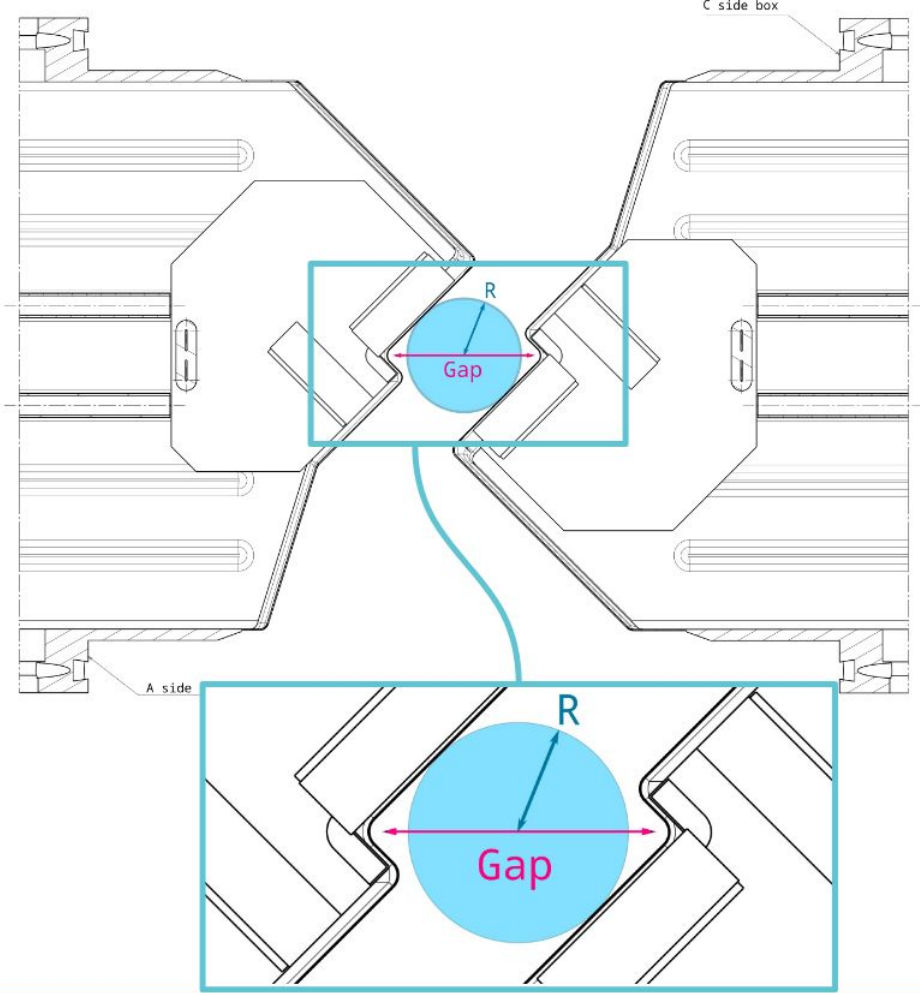
However, the mechanical shape of the foil had been changed. Because of this, in 2023, it was not possible to fully close the VELO as had been done in 2022. As the VELO was fully efficient for tracking, it was possible to measure the shape of the mechanics by reconstructing hadronic vertices in the material (“tomography”).

This enabled us to define the limit of the VELO movement, both for LHC injection and for stable running.

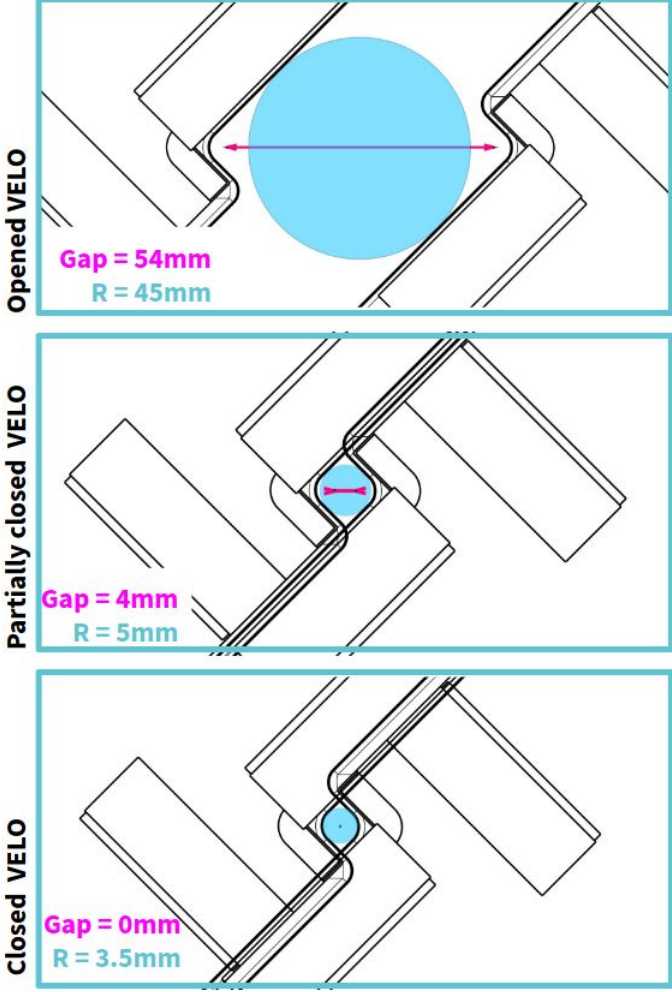
Closing vocabulary

- **Half position is the distance of the half wrt. the beam position**
  - in garage position centered over reference orbit
  - while moving centered on reconstructed beam
- **The Gap is the sum of A and C side positions**

- **The minimal radial aperture R, is the minimal aperture seen by the beam when the VELO is centered on the interaction point**



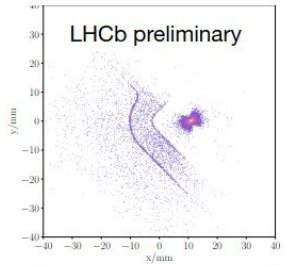
Slide from Victor Coco

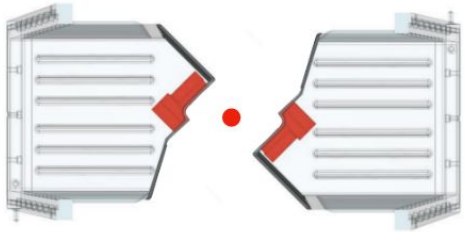


Slide from Victor Coco

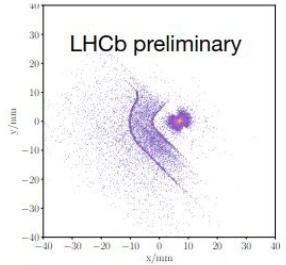
VELO CLOSURE

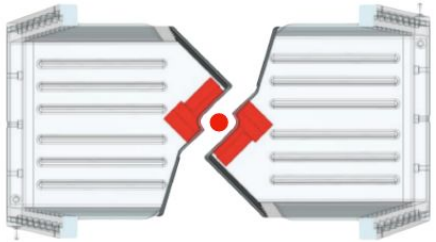
gap 20 mm



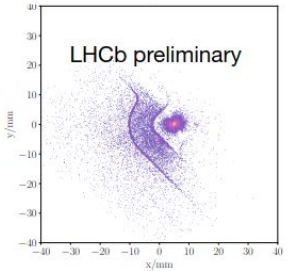


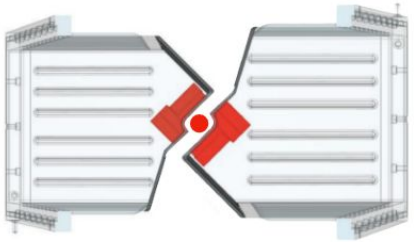
gap 12 mm





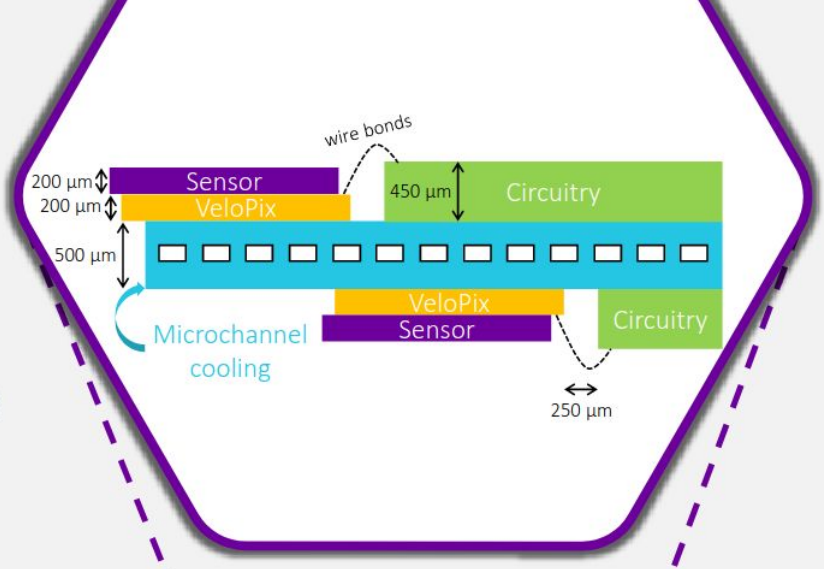
gap 8 mm

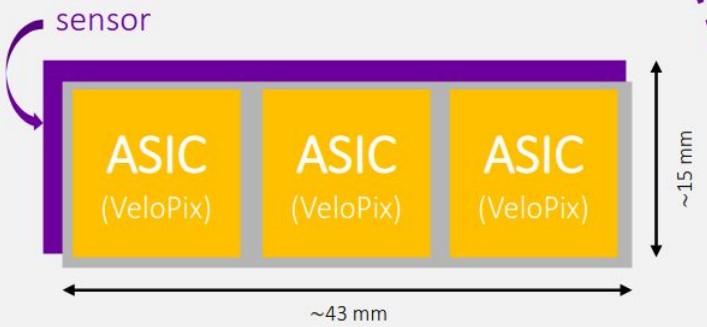


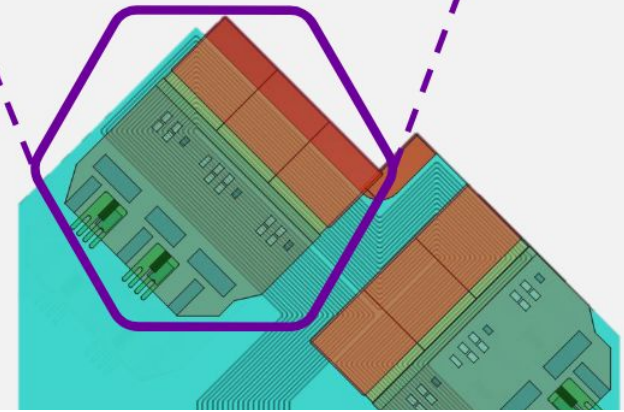


Module

- Sensors
  - 55 × 55 μm² pixels
  - 4 sensors, thickness 200 um
- VeloPix ASICs based on Timepix3
  - 256x256 pixels
  - Data driven readout
  - Up to 800 Mhits/s/ASIC

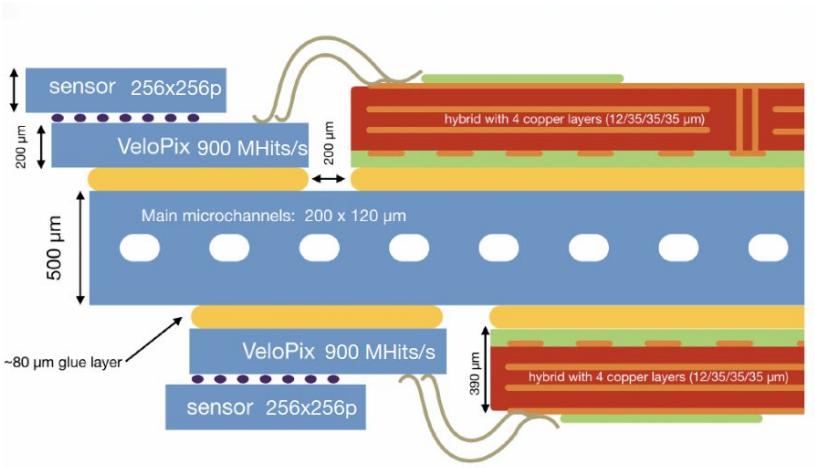




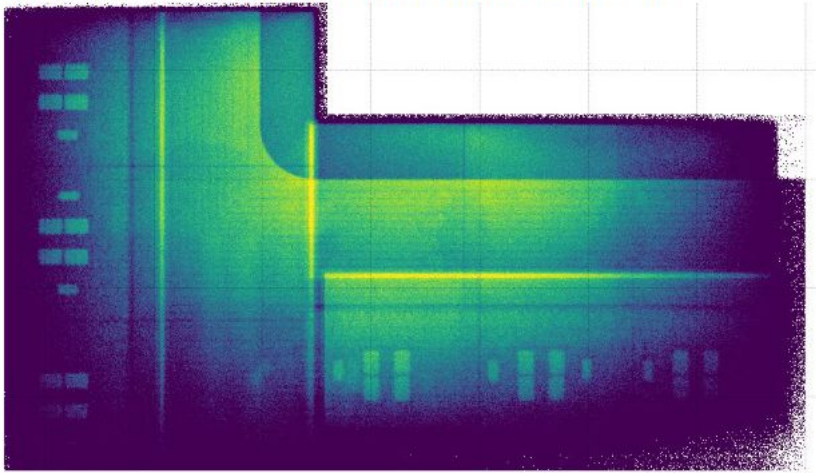


Slide from Peter Svihra, ICHEP2020 (pdf)

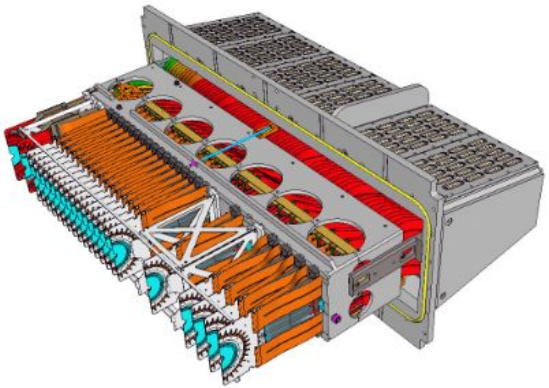
Modules: different PoV

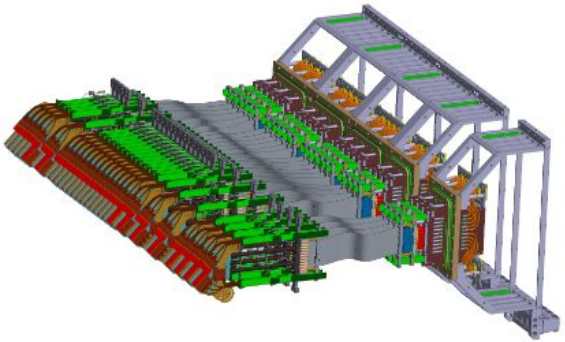


Microchannels seen with tomography of the modules



Slide from Valeriia Lukashenko, Vertex22 (pdf)





	Run 1+2	Run 3+4 Upgrade 1
# modules	42(r,ϕ)+4r modules	52 modules
geometry	r,ϕ	x,y
technology	strips	pixels
pitch	$48 \times 120\mu m$	$55 \times 55\mu m$
distance to beam from the first sensing element	~8 mm	~5 mm
readout rate	70MHits/s	900MHits/s
max fluence	$43 \times 10^{13} 1MeV \cdot n_{eq} \cdot cm^{-2}$	$800 \times 10^{13} 1MeV \cdot n_{eq} \cdot cm^{-2}$
sensor temperature	-8°C	-25°C

TRUE AND RECONSTRUCTED PV POSITION

LHCB-TDR-013

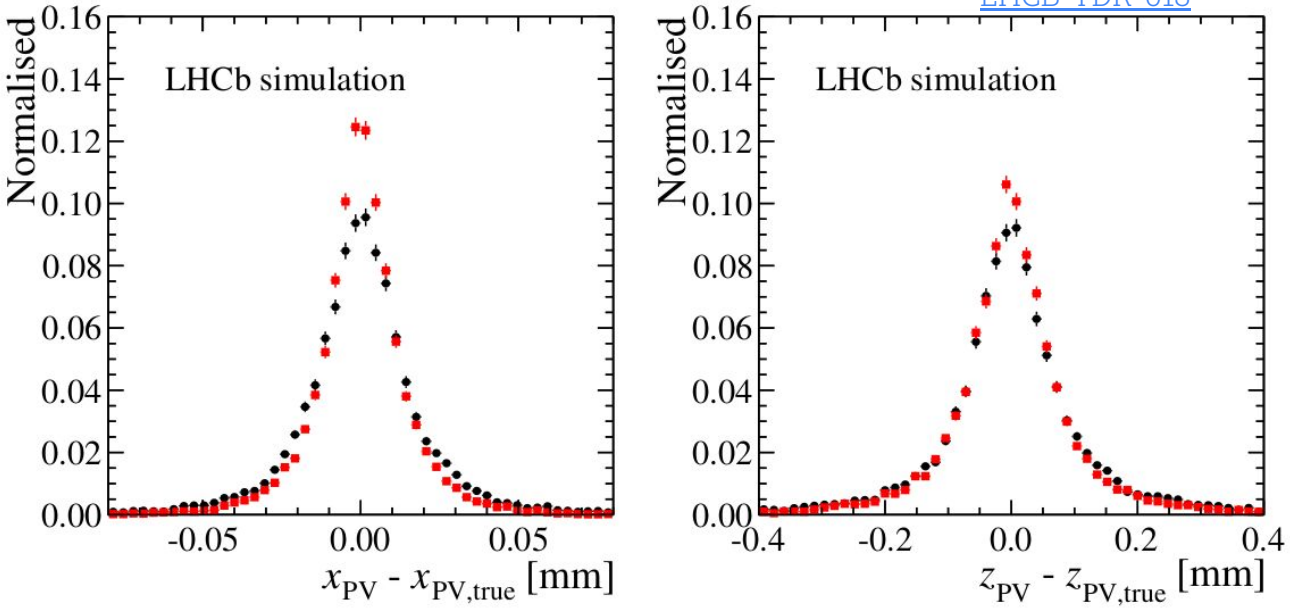
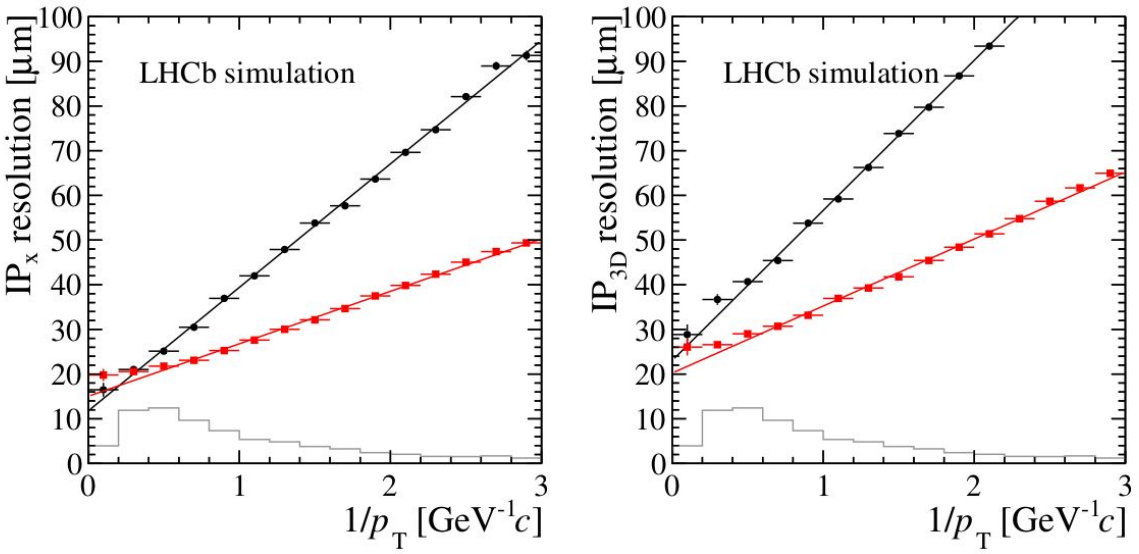


Figure 27: The difference between the true and reconstructed PV position in x and z is shown. The current VELO is shown with black circles and the upgrade VELO with red squares, both are evaluated at $\nu = 7.6$, $\sqrt{s} = 14\,\text{TeV}$. The resolutions in x and y are similar.

IP RESOLUTION (VELO segments)



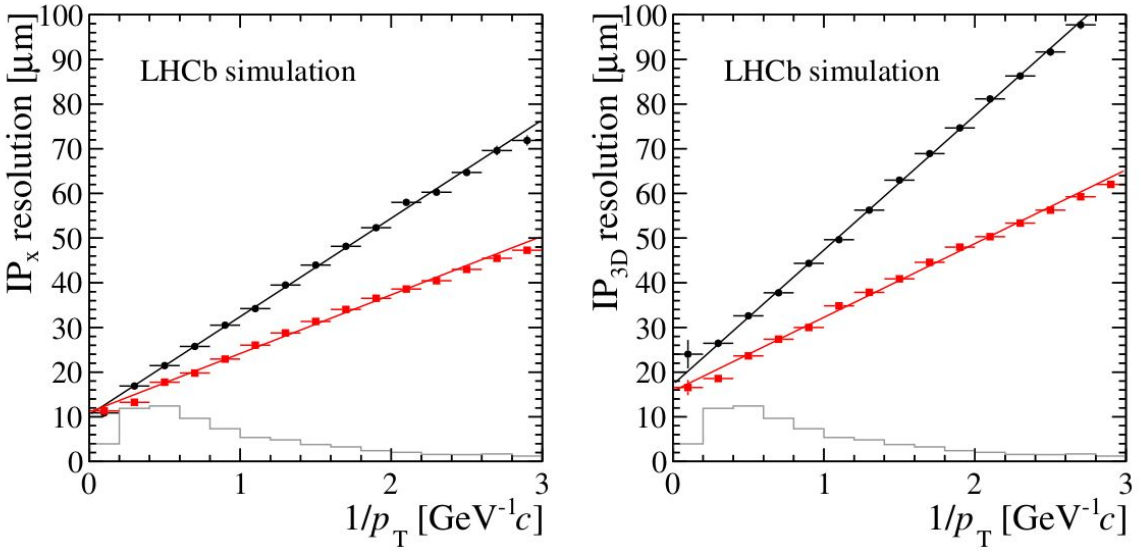
LHCB-TDR-013

	Offset [μm]	Slope [μm GeV/c]
VELO only σ_x	15.0	11.7
VELO only σ_{IP3D}	20.2	15.0
Long track σ_x	11.0	13.1
Long track σ_{IP3D}	15.7	16.5

Slope sensitive mostly to multiple scattering

Figure 30: The left figure shows the x resolution and the right figure shows the 3D resolution of the IP. For both VELO segments with $2 < \eta < 5$ from a primary vertex are used. The segments were fitted with a Kalman filter using an approximation of the amount of scattering at a fixed p_T. The current VELO is shown with black circles and the upgrade VELO with red squares, both are evaluated at $\nu = 7.6$, $\sqrt{s} = 14\,\text{TeV}$. The resolutions in x and y are similar. The light grey histogram shows the relative population of b-hadron daughter tracks in each $1/p_T$ bin.

IP RESOLUTION (Long tracks)



LHCB-TDR-013

	Offset [μm]	Slope [μm GeV/c]
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VELO only σ_{IP3D}	20.2	15.0
Long track σ_x	11.0	13.1
Long track σ_{IP3D}	15.7	16.5

Slope sensitive mostly to multiple scattering

Figure 31: The left figure shows the x resolution and the right figure shows the 3D resolution of the IP. Long tracks with $2 < \eta < 5$ from a primary vertex are used for both. The tracks were fitted with a Kalman filter using the momentum measured in the spectrometer. The current VELO is shown in black circles and the upgrade VELO in red squares, both are evaluated at $\nu = 7.6$, $\sqrt{s} = 14\,\text{TeV}$. The resolutions in x and y are similar. The light grey histogram shows the relative population of b-hadron daughter tracks in each $1/p_T$ bin.

ESTIMATED RADIATION DOSE (TDR)

LHCB-TDR-013

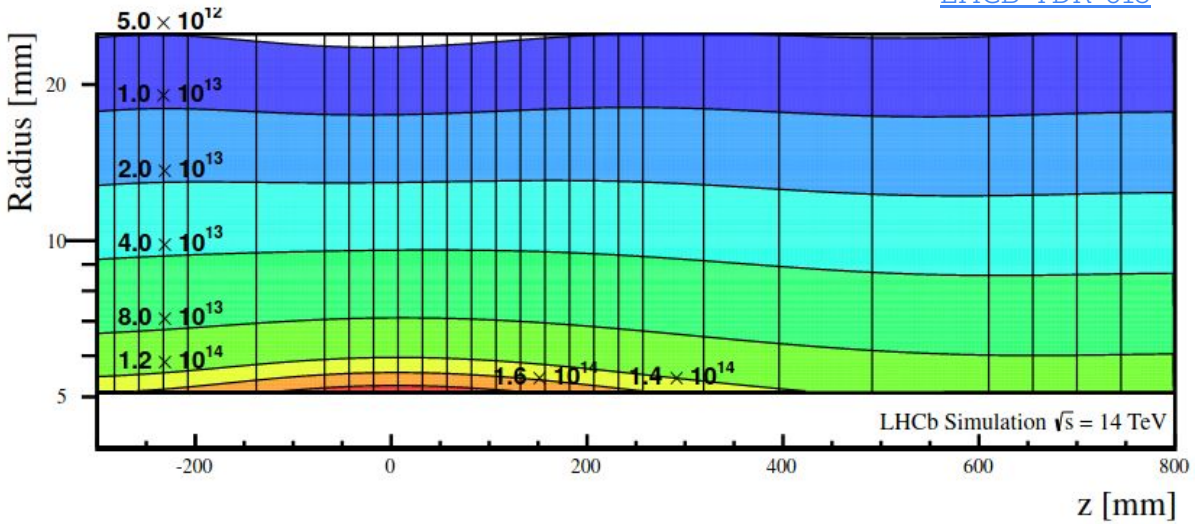
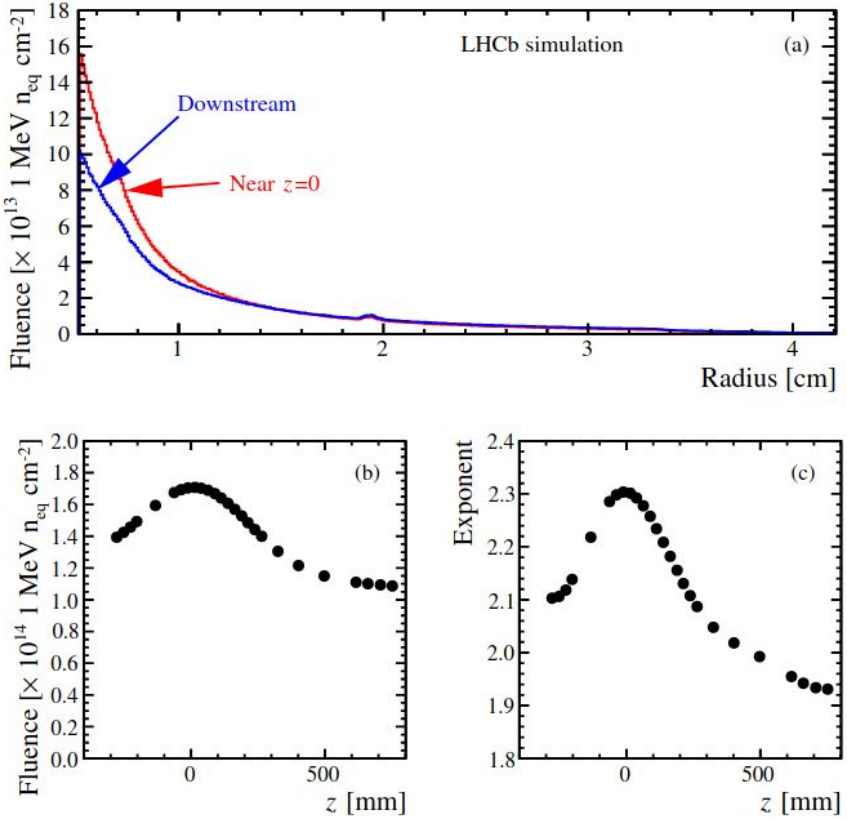


Figure 8: Estimated integrated radiation dose in the $R - z$ plane per fb^{-1} at upgrade conditions expressed in units of 1 MeV $\text{n}_{\text{eq}}/\text{cm}^2$. The radiation damage contours are shown. Note that the vertical axis is logarithmic, in order to highlight the behaviour around the interaction region.

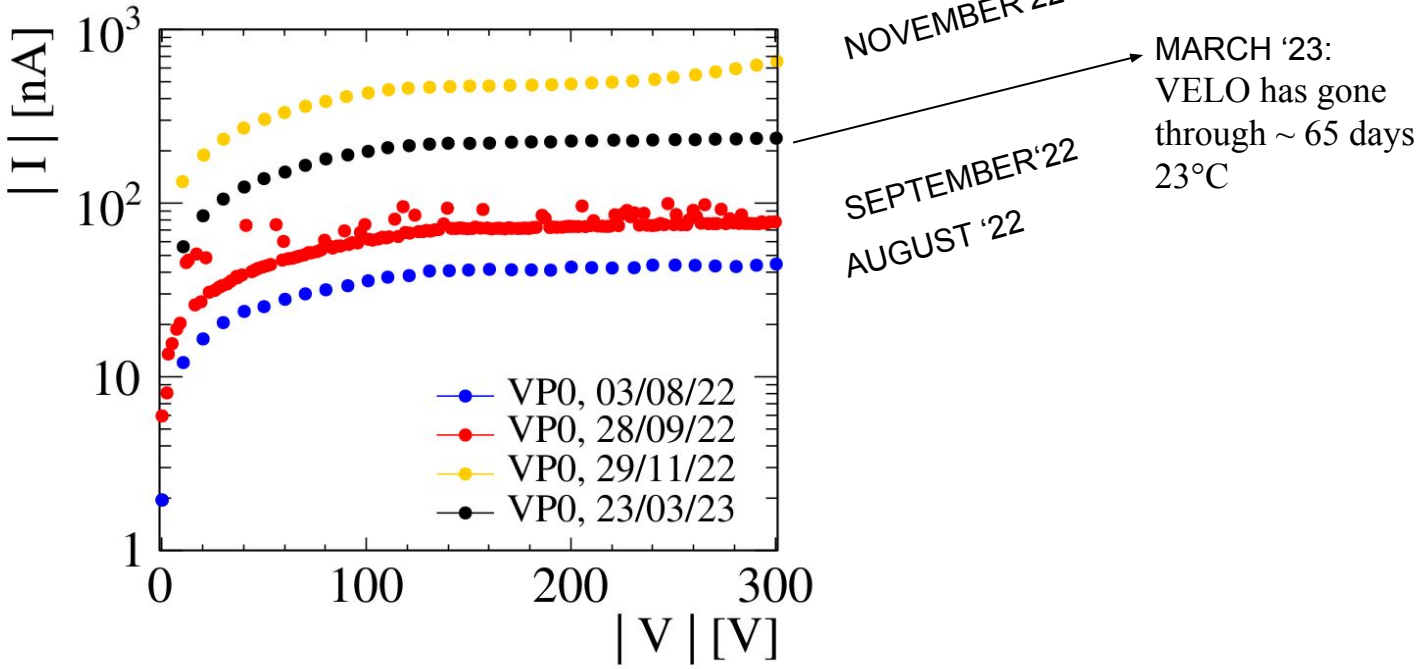
ESTIMATED RADIATION DOSE (TDR)



LHCB-TDR-013

Figure 9: (a) Fluence as a function of radius R per delivered fb^{-1} for the most highly irradiated sensor (above interaction region) and the sensor receiving the smallest dose (downstream). The shape for each sensor is fitted with the expression $A \times R^{-k}$, where R is the radius in cm and the A and k are fitted constants. (b) shows the dose measured at the position of the closest pixel as a function of z position, and (c) shows the value of the exponent k, showing how the radiation map flattens further away from the interaction region.

IV SCANS ON VP0



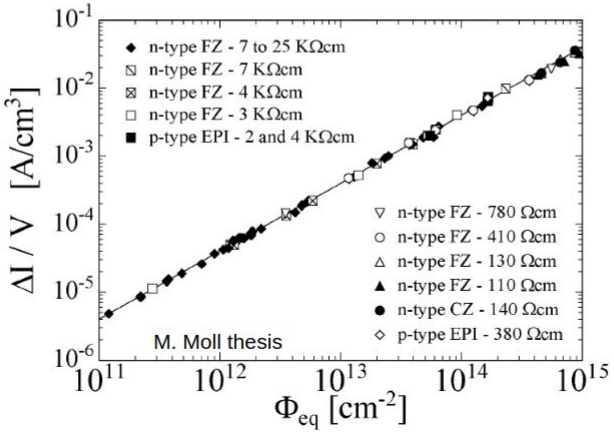
RADIATION DAMAGE

Slide from Gianluca Zunica, TREDI23 (pdf)

Leakage current scales linearly with fluence:

$$\Delta I/V = \alpha\, \phi$$

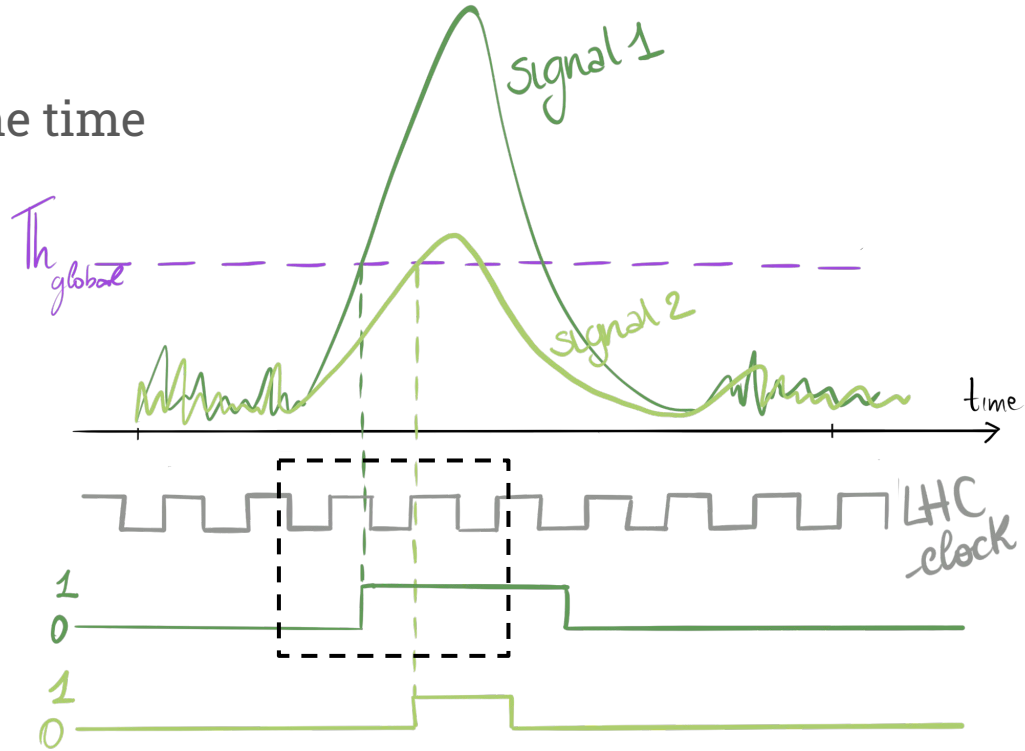
- I = leakage current
- Silicon volume
- Proportionality factor
- fluence



TIME ALIGNMENT

Goal: ASICs responding at the same time

1. Synchronise with LHC clock
2. Both low and high amplitude end up in the same clock cout



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