

Measurement of the LHCb VELO length scale using material interaction vertices

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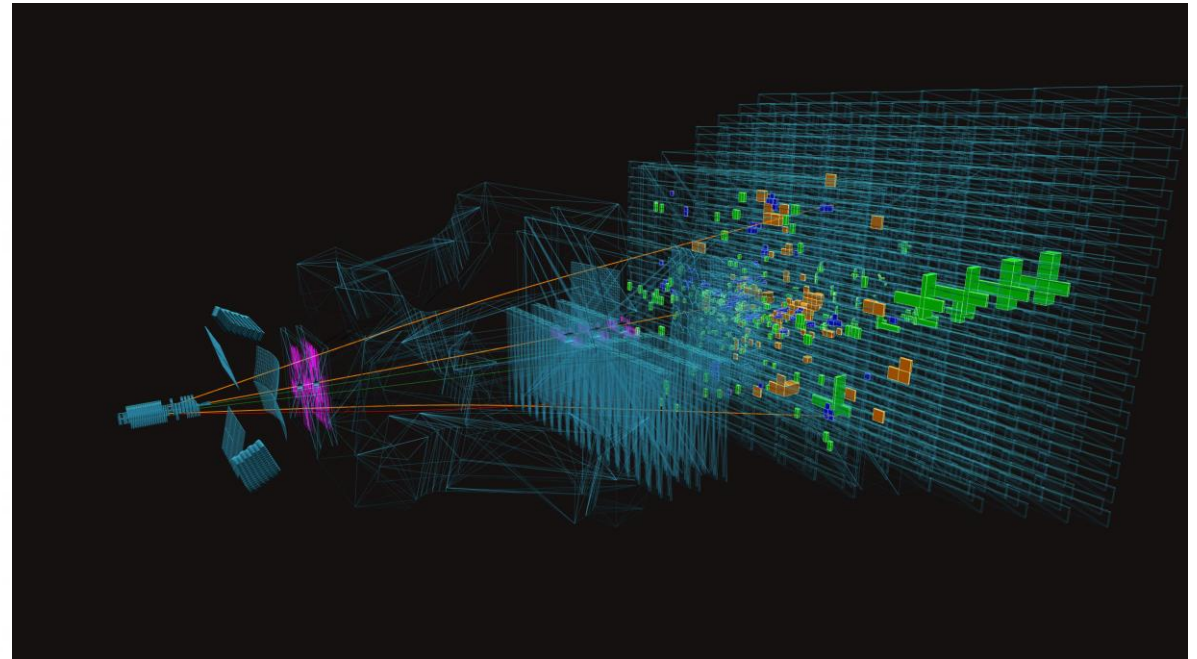
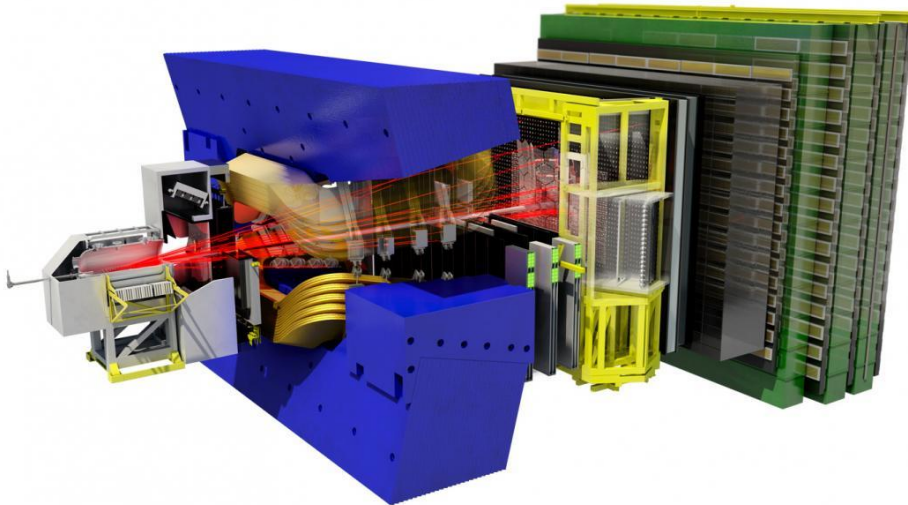
18th. June. 2026

Transfer Symposium



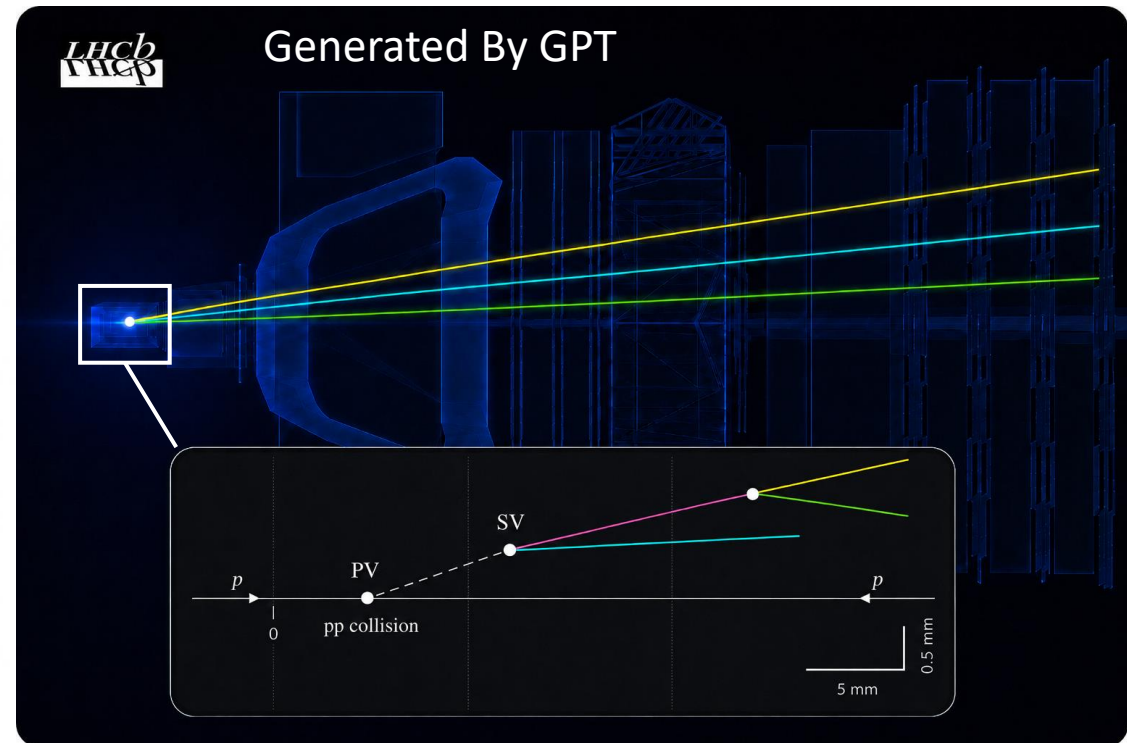
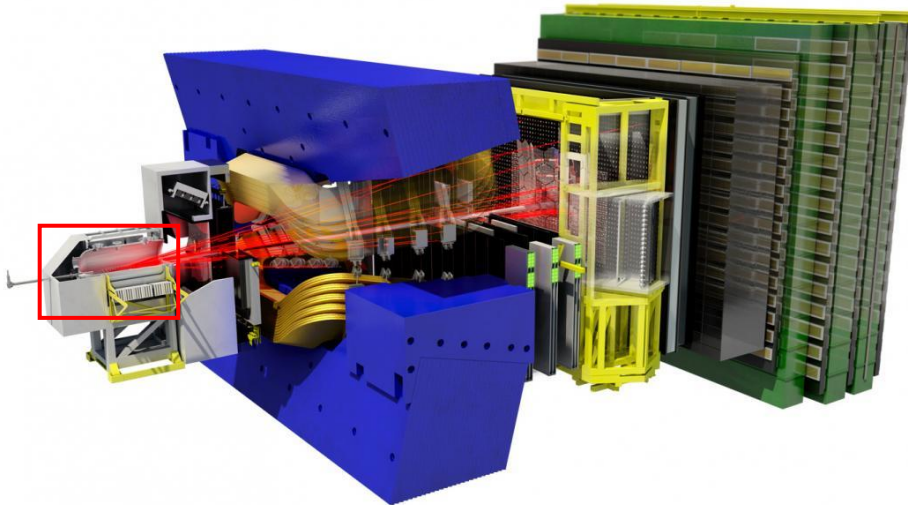
LHCb:

- LHCb is one of the major experiments at the Large Hadron Collider (LHC).
- A forward detector for heavy-flavour physics, designed to study beauty and charm hadrons.
- These particles often decay a measurable distance away from the collision point.
- Therefore, LHCb needs extremely precise vertex reconstruction.



Vertex Locator (VELO) in LHCb:

- Sits closest to the proton-proton collision point.
- Measures charged-particle tracks very precisely near the interaction region.
- Provide precise reconstruction of primary and secondary vertices, which are essential for heavy-flavour physics.



What is a Velo length scale (bias), δ_z ?

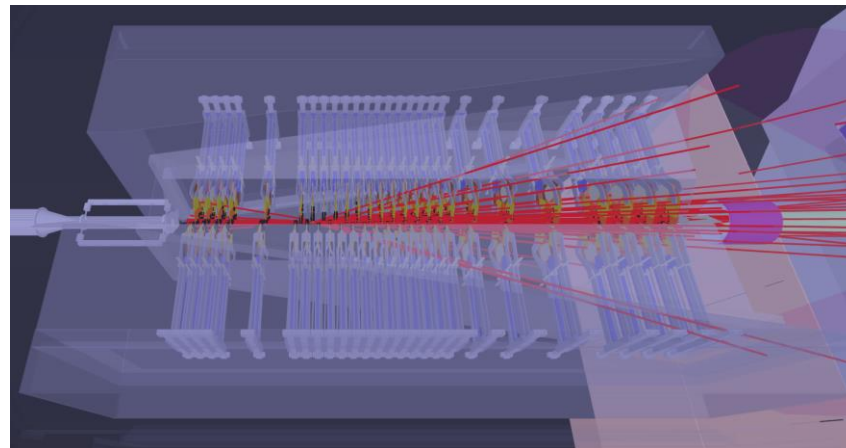
- LHCb jargon 😊: “length scale” (in LHCb) mis-use as scale bias on reconstructed distances, rather than physical size of the detector.
 - Here I focus on the VELO z-scale bias, δ_z .
- This δ_z is a residual z-scale bias rescales the reconstructed flight distance.

$$L_{\text{reco}} = (1 + \delta_z)L_{\text{true}}$$

- Since the decay time is computed from the flight distance, this gives a common scale uncertainty on decay time and other time dependent measurements.
 - For example, mixing frequency Δm_s .

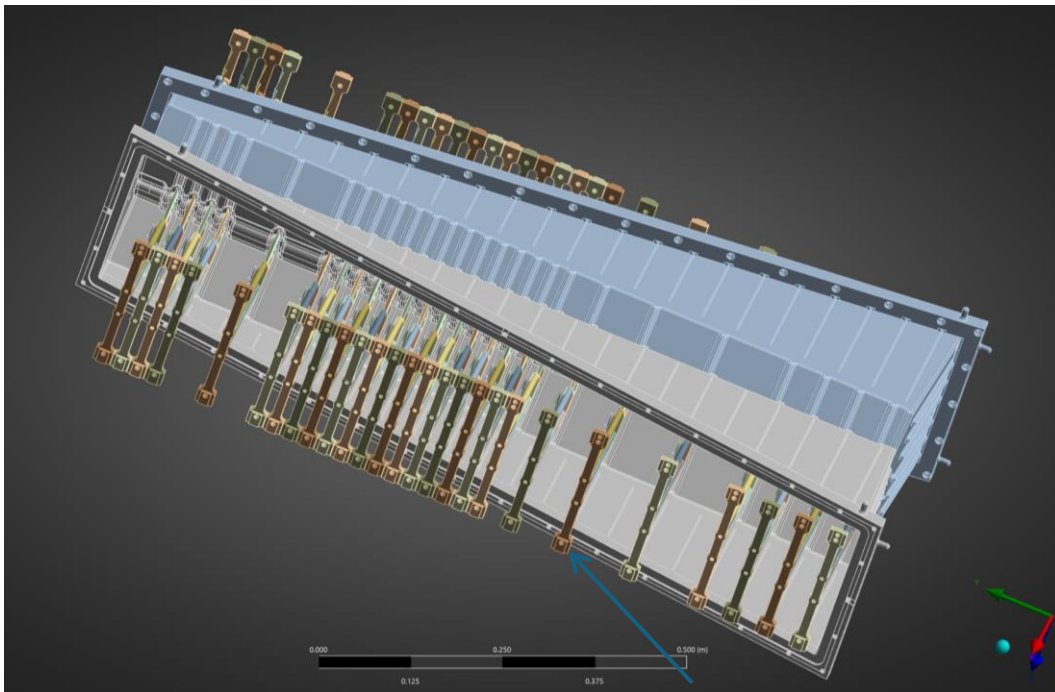
Where does the z-scale bias come from?

- Track-based alignment works by moving detector elements until reconstructed tracks fit the measured hits as well as possible.
 - This is very powerful for relative misalignments: for example, if one sensor is shifted, tracks will show clear residuals.
- In the VELO geometry, the sensors are approximately planes perpendicular to the beam direction. If **all** planes transform coherently ($z \rightarrow a + bz$), this has little effect on track-fit quality.
 - Track-based alignment algorithm could not sensor this change.
 - This leads to a z-scale uncertainty/bias.

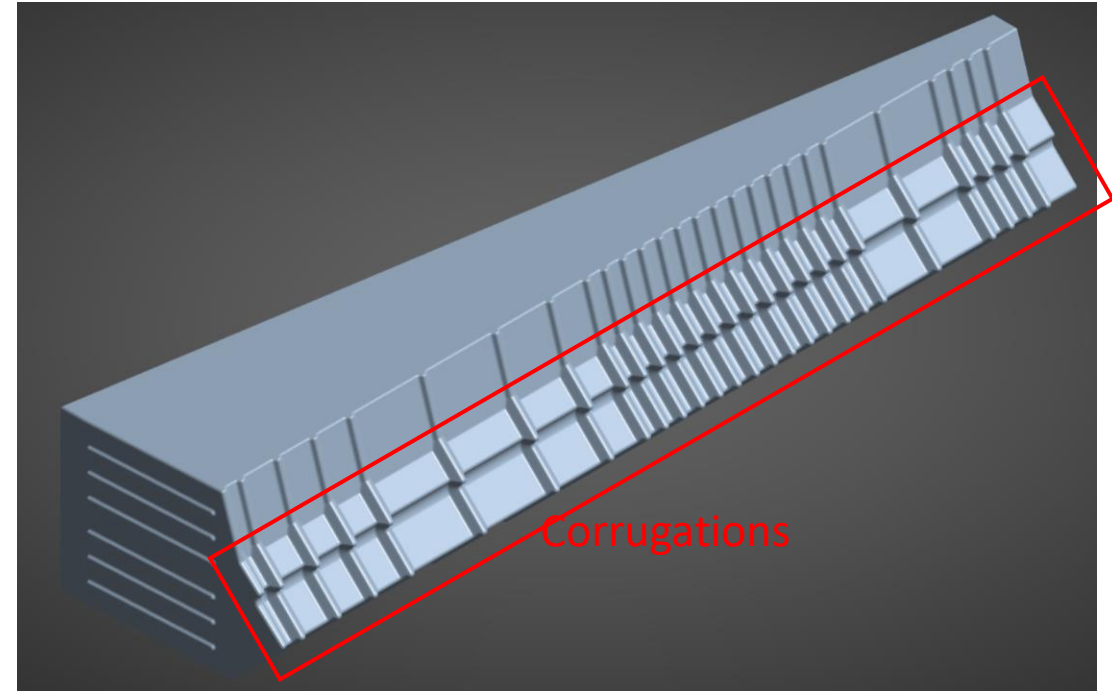


The RF Box provides built-in tick marks:

- Luckily, the VELO sensors are surrounded by thin aluminium RF boxes. The box has repeated corrugations along z.
- These corrugations act like reference marks inside the detector.

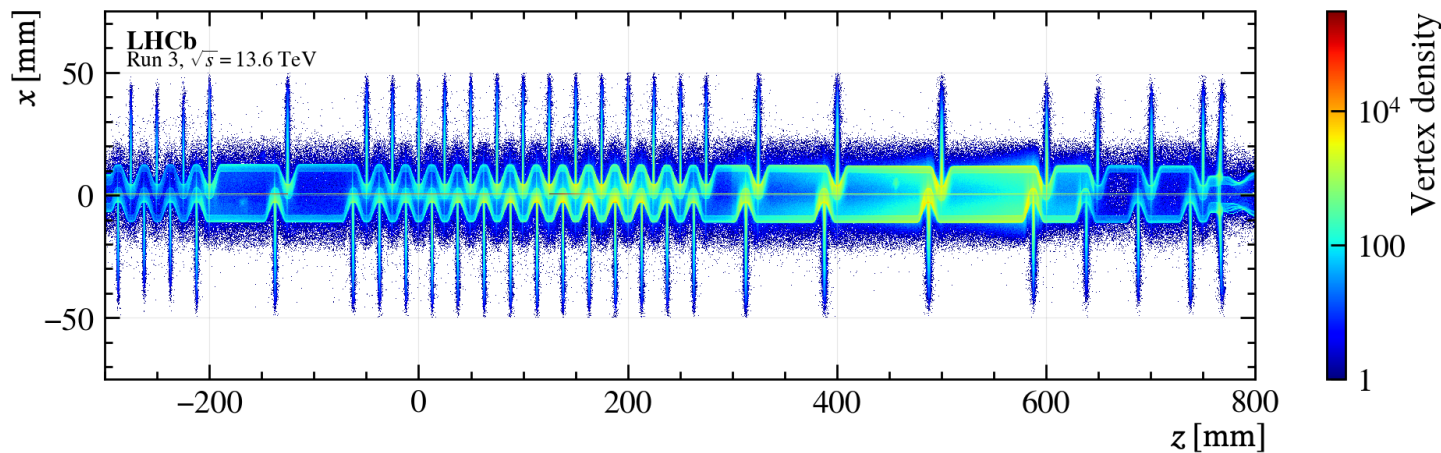


VELO Sensor



How RF-Box could be used in VELO Z-bias:

- Tomography data (reconstructed vertices):
 - As particles pass through detector, they undergo hadronic interactions with the material of the RF box and VELO modules
 - Treat as 'effective' geometry as seen by the LHCb reconstruction algorithms.
 - This heavily relies on the VELO internal alignment.
- Metrology data (high precision scan) of RF-Box.
 - Treat as the 'physical reference'.



Tomography

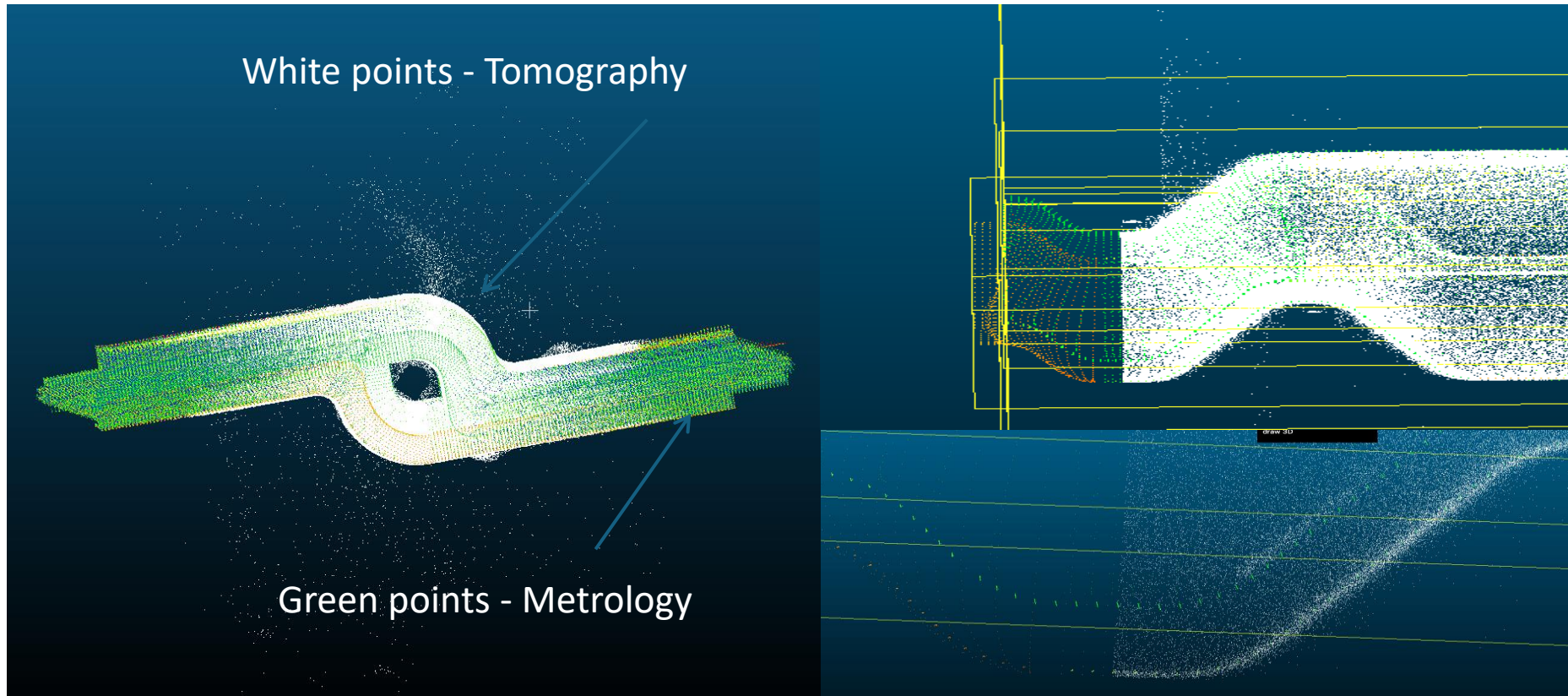


Metrology

Alignment

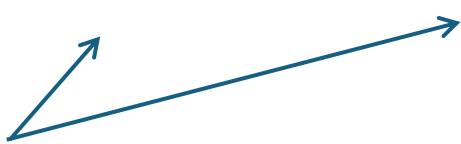


- The Metrology data is not aligned in LHCb Reference system.
- We use software “CloudCompare” and python to do the alignment iteratively.



How RF-Box could be used in VELO Z-bias:

- We have tomography data (reconstructed vertices) and metrology (high precision scan) of RF-Foil.
- We will use differences between metrology and tomography to estimate the z-scale bias.

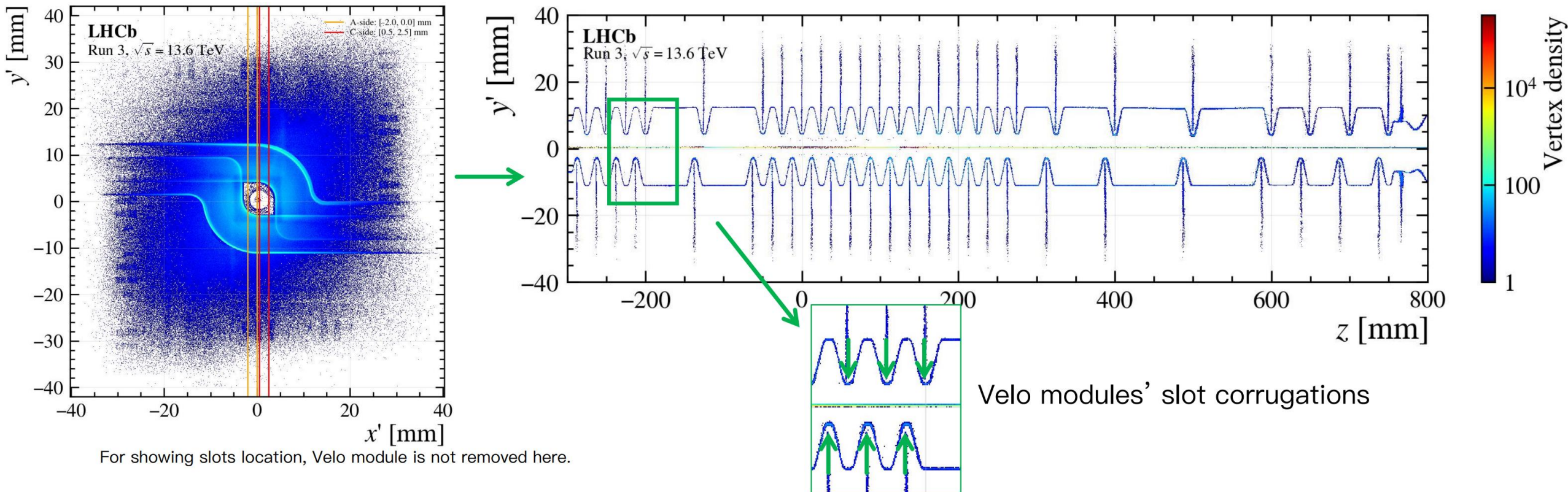
$$\delta_z = \frac{z_{\text{Tomo}} - z_{\text{Metro}}}{z_{\text{Metro}}} = \frac{\Delta z}{z_{\text{Metro}}}$$


Physical reference

$$z_{\text{Tomo}} = (1 + \delta_z) \cdot z_{\text{Metro}}$$

How RF-Box could be used in VELO Z-bias:

- We obtain these differences by precise determination of the center of corrugations.
- We first cut both data into a y' - z slice, and then fit the slot corrugation.



For showing slots location, Velo module is not removed here.

y' : rotate y axis 45 degree.

How RF-Box could be used in VELO Z-bias:

- We first cut both data into a y' (rotate 45 degree)- z slice, and then fit the slot corrugation.
- We create a function called Double Super-Gauss to describe corrugation

$$y'(z) = A_1 \exp\left(-\left|\frac{z - z_0}{w_1}\right|^{n_1}\right) + A_2 \exp\left(-\left|\frac{z - z_0}{w_2}\right|^{n_2}\right) + y'_0,$$

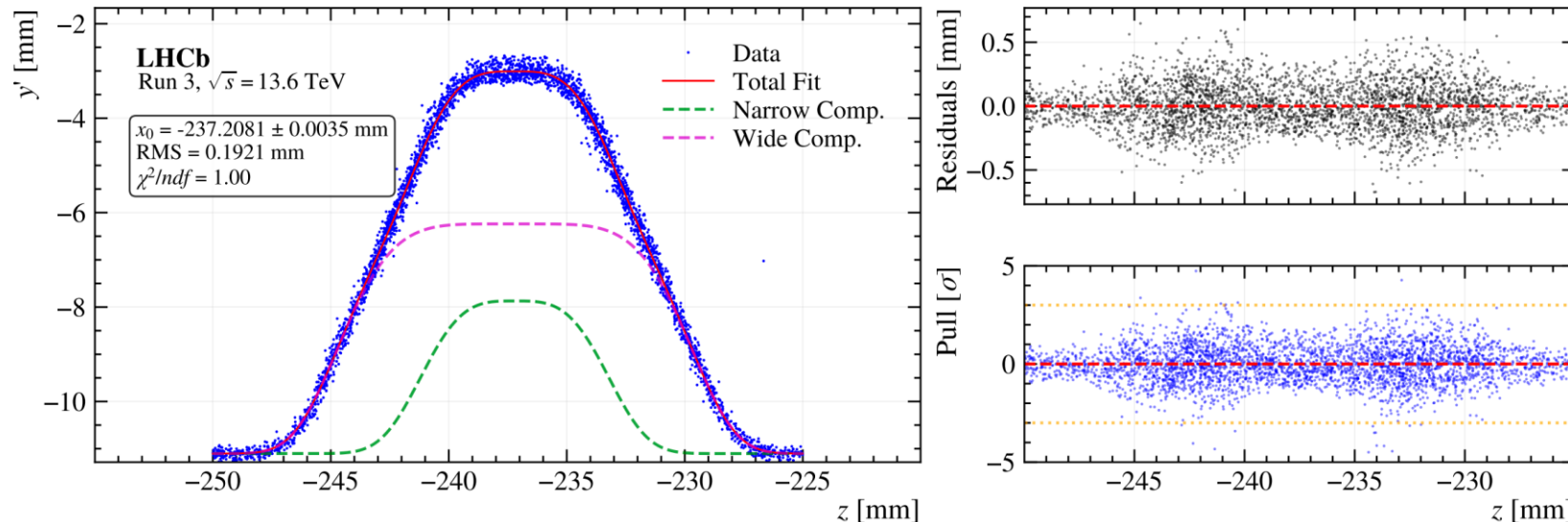
z_0 - Center of corrugation

y'_0 - overall shift of the data relative to $y = 0$ (beam)

$w_{\{1,2\}}$ - width

$A_{\{1,2\}}$ - Amplitude

$n_{\{1,2\}}$ - Shape exponent



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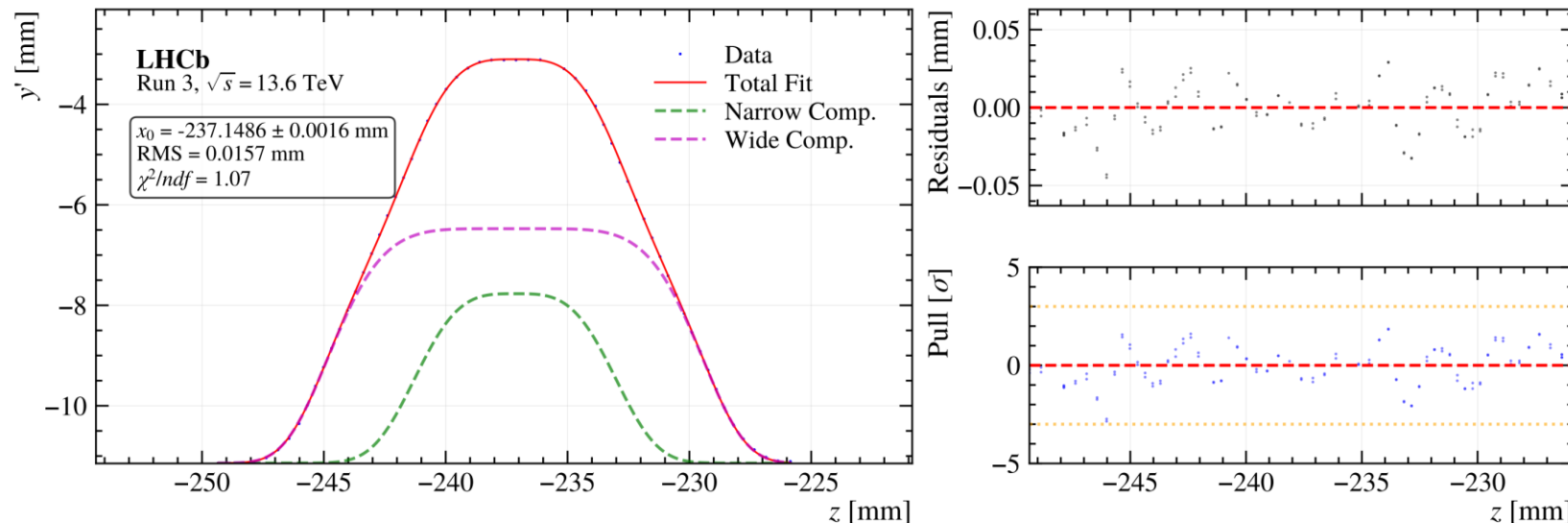
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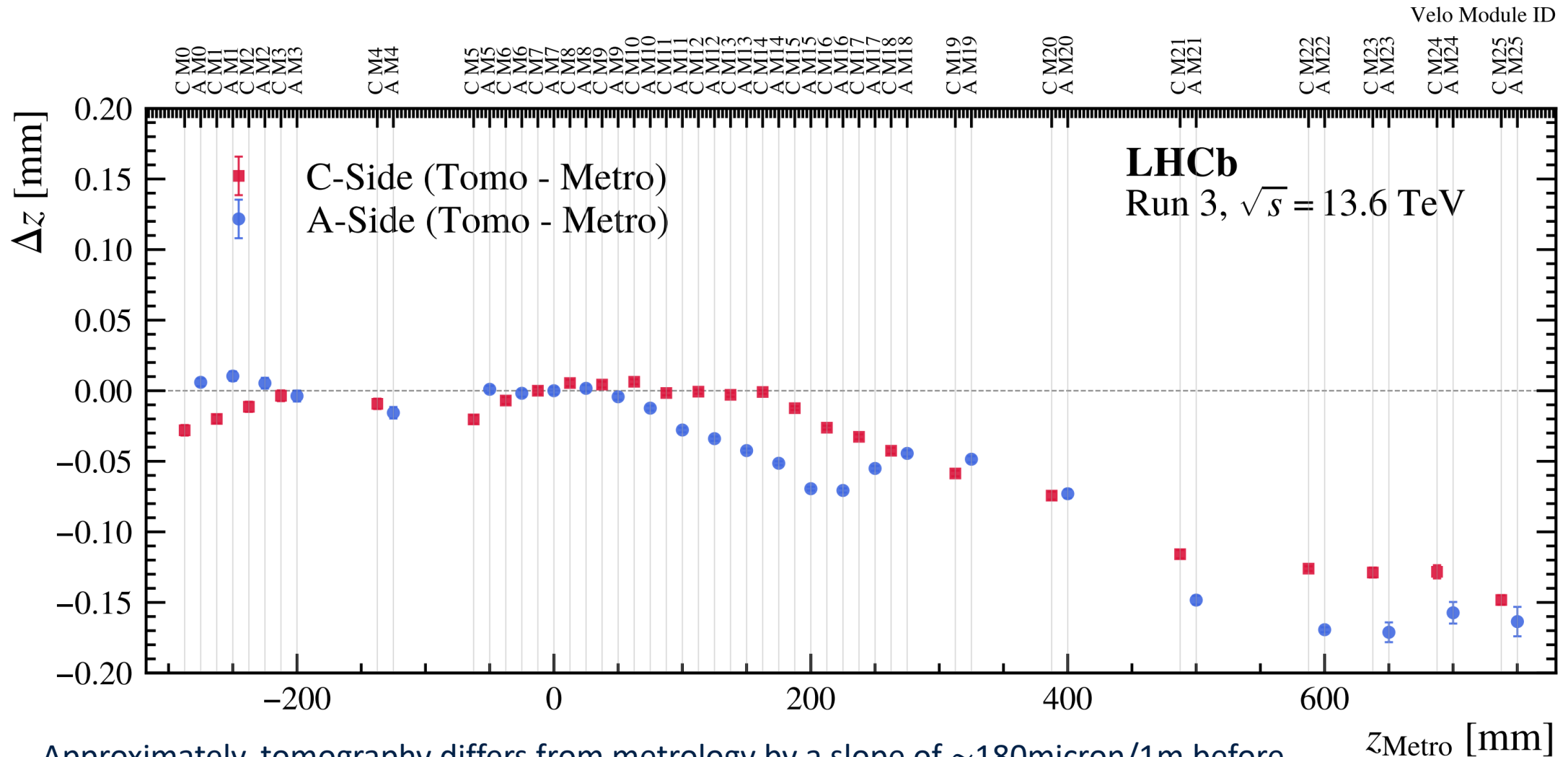
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$\Delta Z(\text{Tomo.} - \text{Metro.}) \text{ VS } Z_{\text{Metro}}$:



Approximately, tomography differs from metrology by a slope of $\sim 180 \mu\text{m}/1\text{m}$ before applying the any correction.

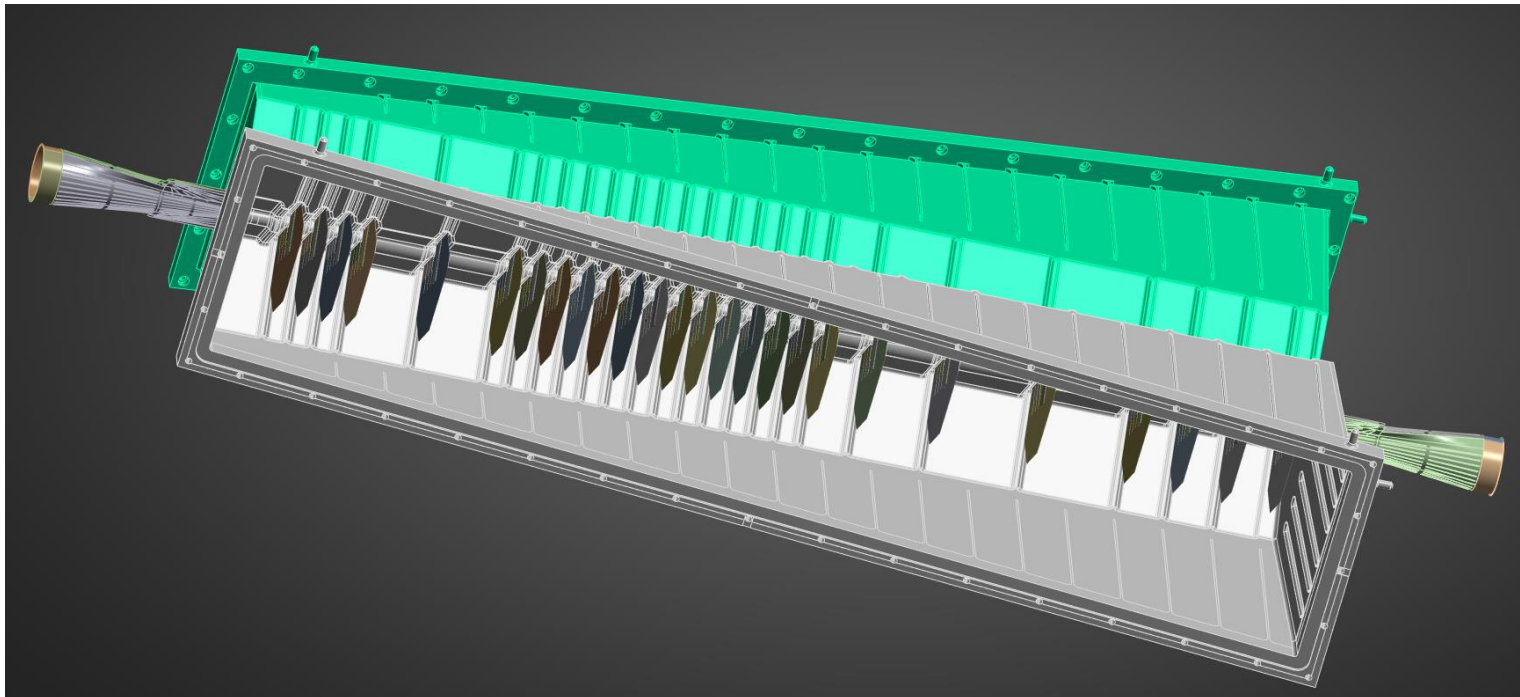
Thermal contraction

- The Metrology data was collected at 20 degrees, while the tomography data fluctuated around 4 degrees.
 - --> Need to “Remove” this thermal contraction.
- There are two ways to do that:
 - 1. simple homogeneous thermal-contraction correction, based on $\Delta T = 16^{\circ}\text{C}$ and the CTE of aluminium (CTE $\cdot\Delta T\cdot z \sim 390$ micron metre).
 - 390 micron metre correction is too large. The real thermal contraction is not that large.
 - 2. Finite Element (FEM) Simulation.

Thermal contraction



- We then perform our own FEM simulation using Ansys.
 - We only include VELO substrates in simulation.
 - The screws of flange is fixed (no deformation will occur).
 - The base is constantly heat at 20 degree.
 - VELO substrates is set to -30 degree and cooling RF box via radiation (RF box --> cold VELO)

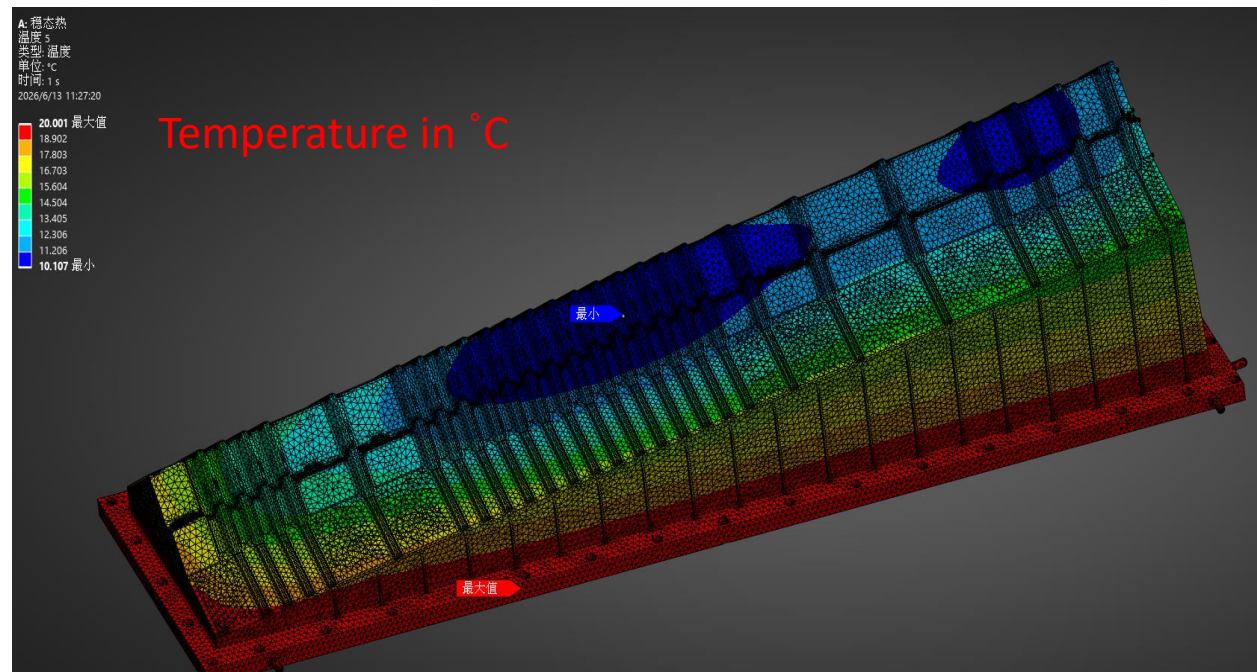


Thermal contraction

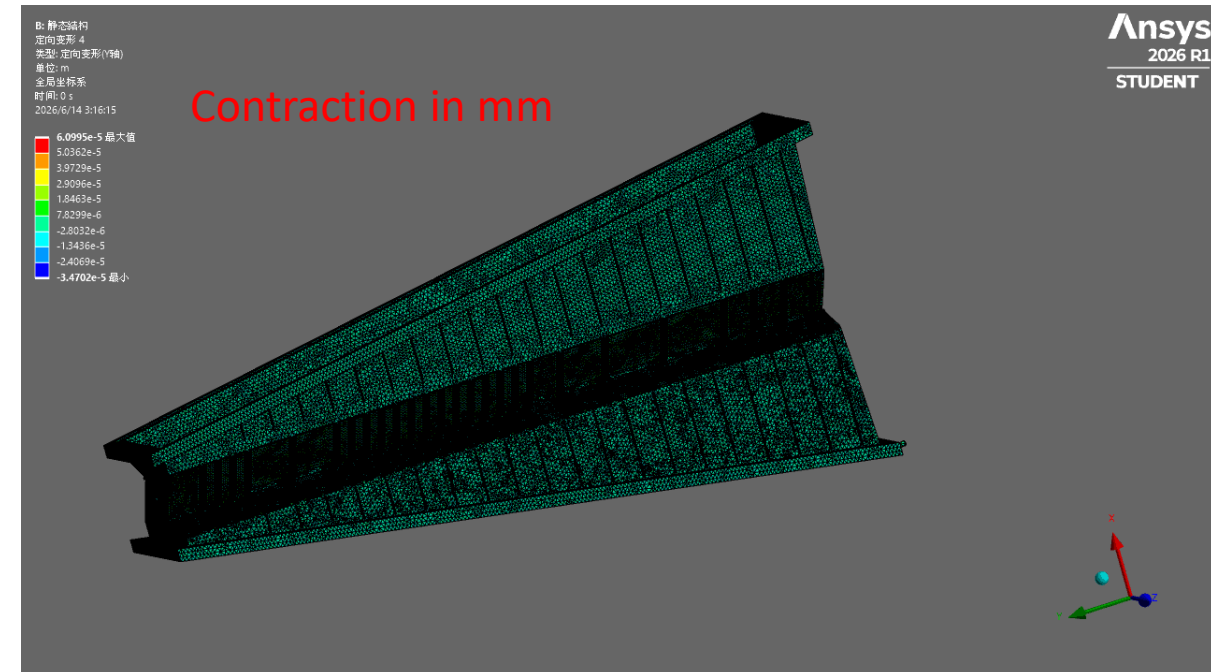
- We perform then perform our own FEM simulation using Ansys.

Notice: the deformation in animation is exaggerated for visual purposes..

y-axis in FEM = z-axis in LHCb



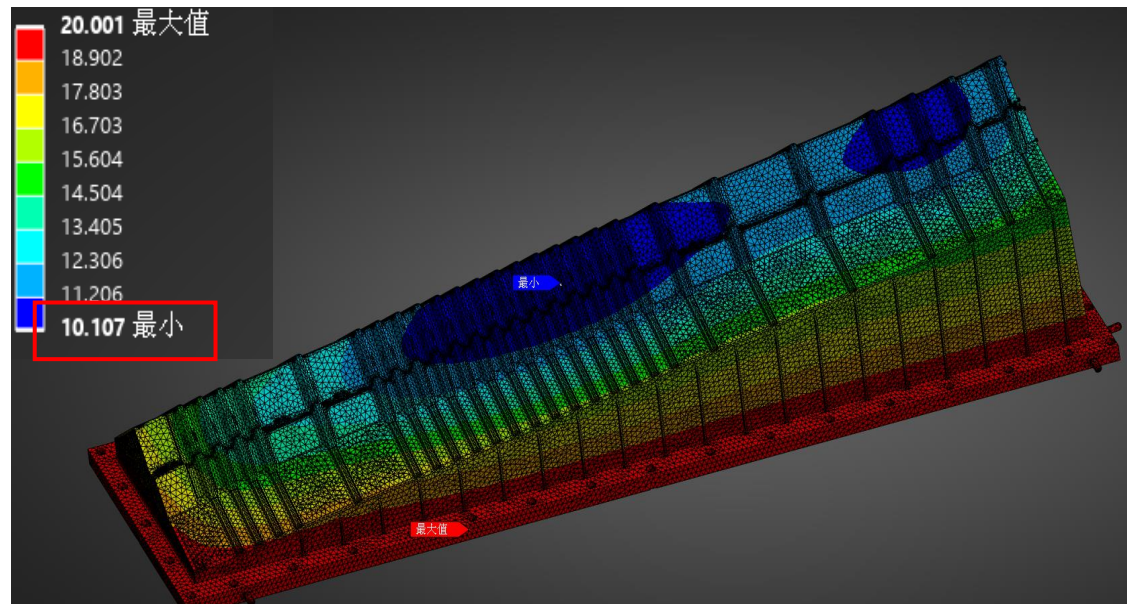
Temperature distribution



Displacement along FEM y (= LHCb z)

Thermal contraction

- We perform then perform our own FEM simulation using Ansys.
 - The thermal deformation in the z-direction is small compare with 390 micron.
- This FEM simulation is not finalised, Because our FEM readings for temperature don't match the actual temperature.
 - Perhaps we have overlooked certain part of materials.
 - Perhaps we have entered incorrect material parameters.



Conclusion:

- Currently, since we are still trying to work out the "corrected" thermal contribution.
- At this stage, we could only provide results based on **homogeneous thermal** contraction, which is too simplistic.

Detector region	Module range	$\delta_{\text{VELO}} (\times 10^{-4})$
A-side	0–25	$1.62 \pm 0.19 \pm 0.93$
C-side	0–25	$2.07 \pm 0.22 \pm 0.93$
A-side	5–18	$1.19 \pm 0.34 \pm 0.93$
C-side	5–18	$2.61 \pm 0.36 \pm 0.93$

Conclusion:

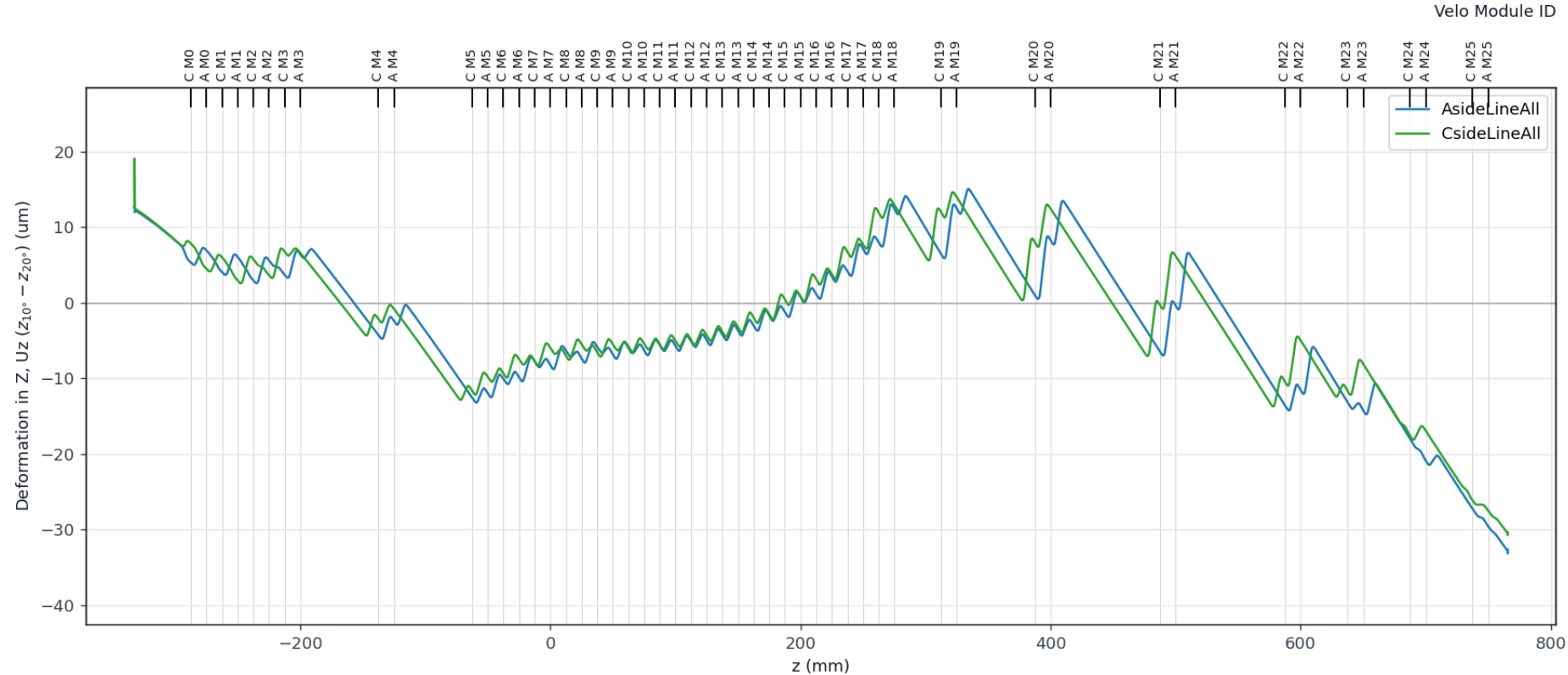
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For the central module range, the average value ($\delta_{\text{VELO}} \approx 1.9 \times 10^{-4}$) would correspond to a relative decay-time bias of about 0.019%. For a typical B_s^0 lifetime of about 1.5 ps, this is an absolute shift of approximately 0.3 fs. For oscillation measurements ($\Delta m_s \approx 17.8 \text{ ps}^{-1}$), this gives an estimated shift of about $3 \times 10^{-3} \text{ ps}^{-1}$.

Backup

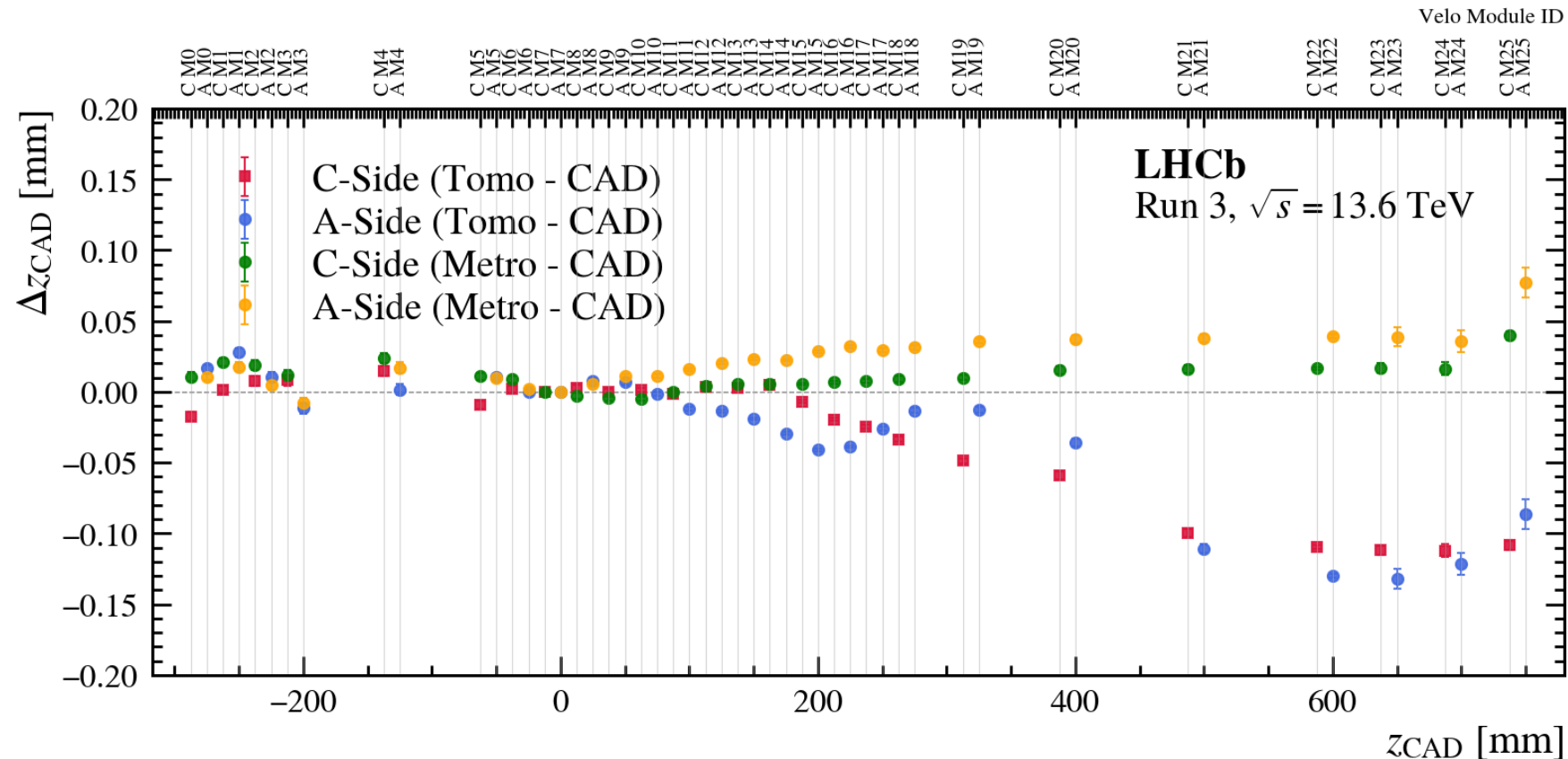
Thermal contraction

- We then perform our own FEM simulation using Ansys.
 - The change in the z-direction is small compare with 390 micron.



Compare with CAD design.

- [Metro - CAD] The built RF boxes deviates from the design by about 40 micron/1m.
- [Tomo - CAD] devaiate 150 micron/1m, which accounts for bias from trackbased alignment, deformation of RF-foil, thermal contraction.



Deformation in Aside.

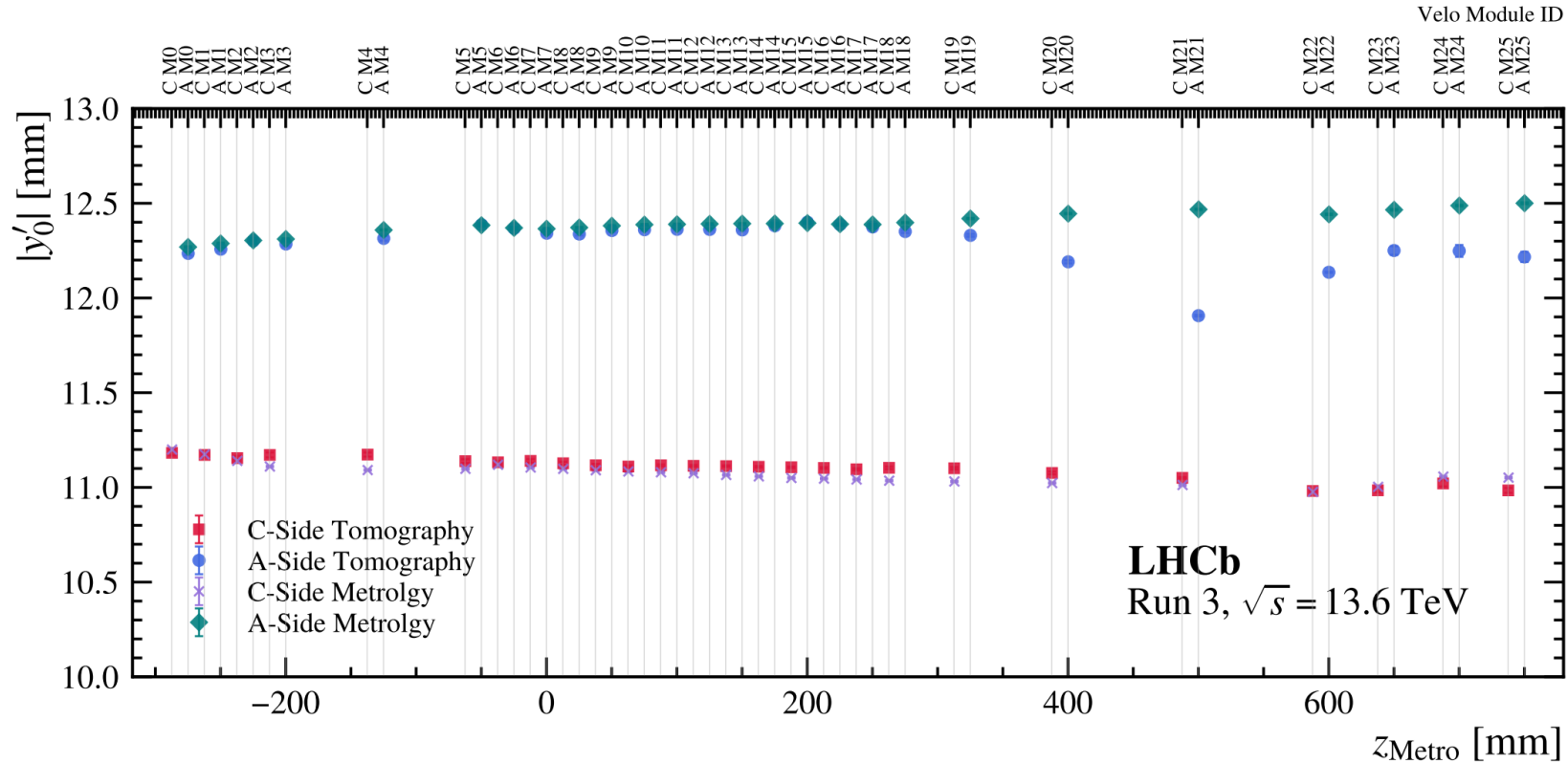


Figure 8: The absolute values of extracted translational offset ($|y'_0|$) as a function of the longitudinal coordinate z in $y'z$ plane.. It should be noted that the baseline trend of this distribution is highly sensitive to the global alignment of the detector.

Deformation in Aside.

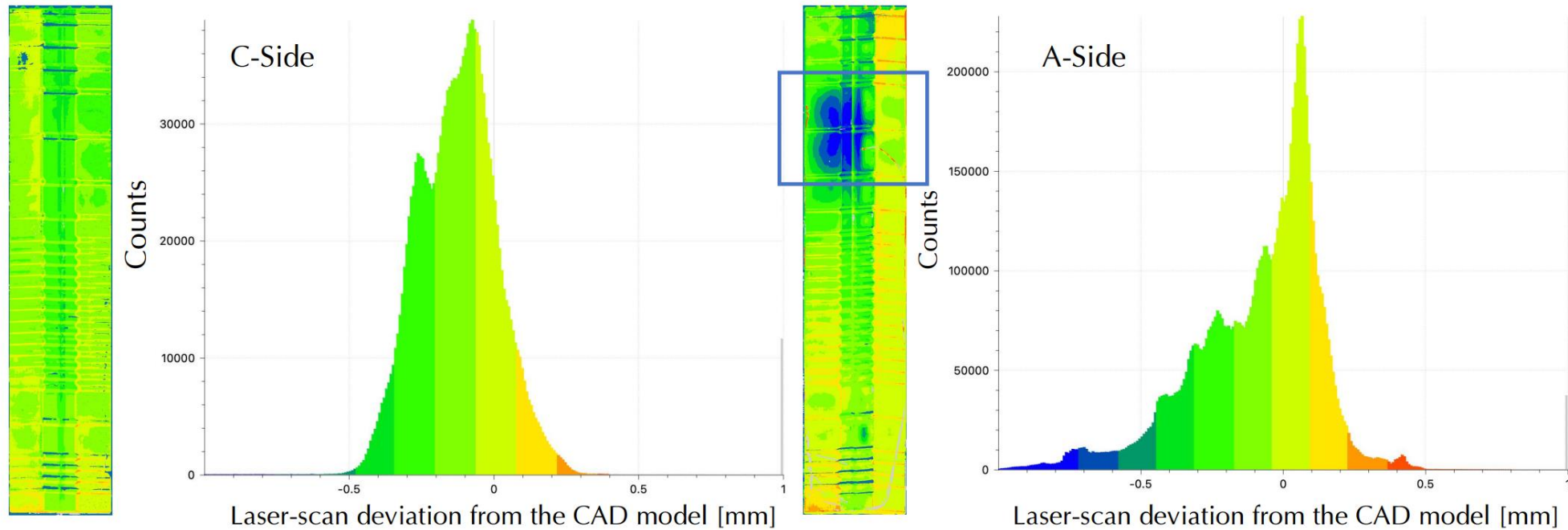


Figure 9: Geometrical deviations between the supplementary 3D laser scan of the RF foil (performed at CERN) and its nominal CAD model. For A-side (Right hand figure), A distinct deformation (dark blue area) is clearly visible at $z \approx 500$ mm.

How are material-interaction vertices reconstructed?

- Online trigger selection
 - HLT1 looks for material-interaction candidates.
 - Uses triplets of tracks displaced from the beamline.
 - Tracks are required to have distance to beamline >3.5 mm and mutual distance <0.5 mm.
- Offline vertex reconstruction
 - Events are processed with an unbiased primary-vertex finder.
 - Vertices are reconstructed without requiring them to be near the beamline.
 - Requires at least 4 tracks per vertex.
- RF-shield vertex selection
 - Keep vertices displaced from the beamline: 2mm away in x and y.
 - This removes most ordinary pp primary vertices.
- Quality selection
 - Require at least 7 tracks per vertex.
 - Require estimated z-position uncertainty < 0.2 mm.

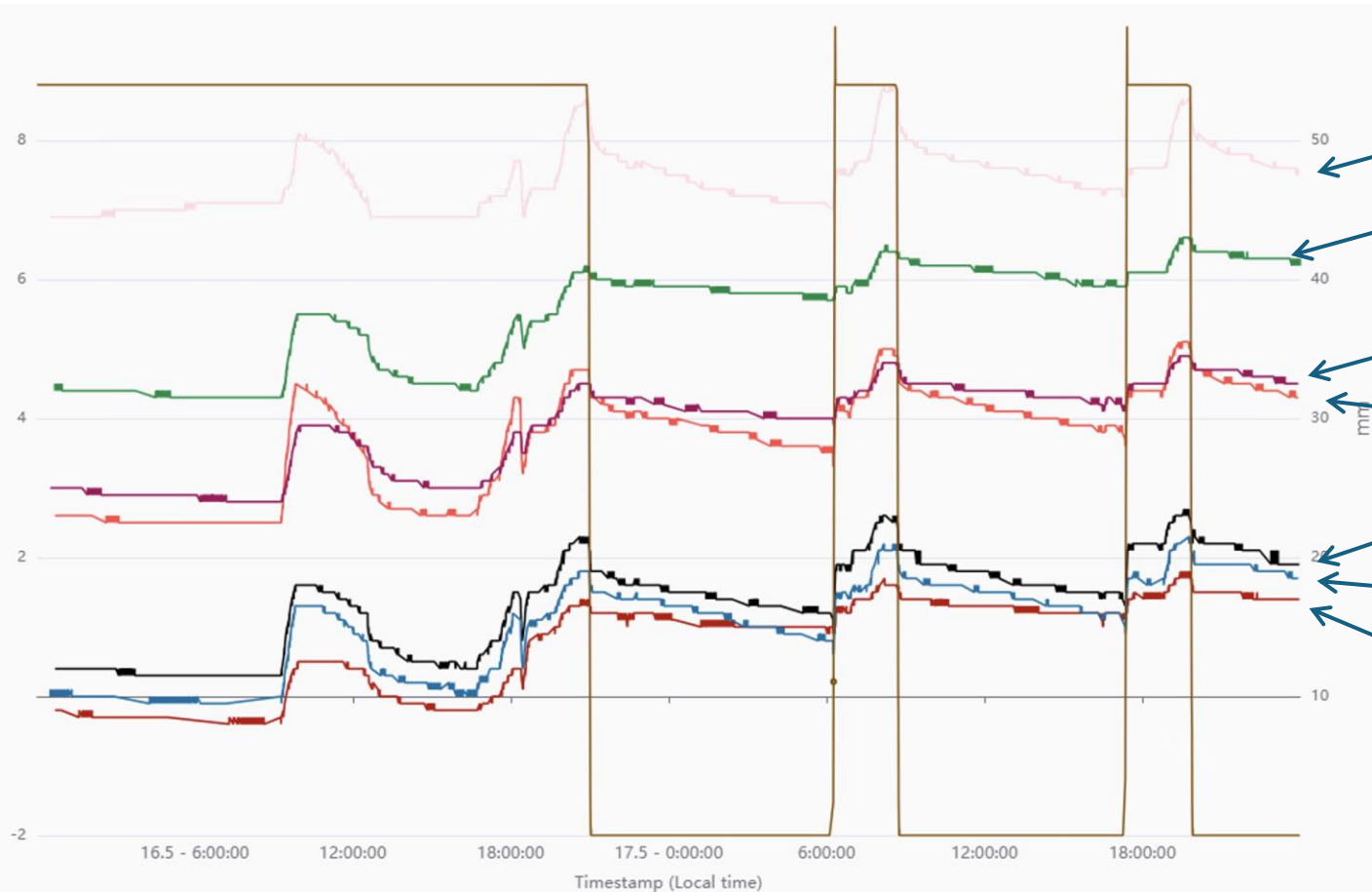
Some caveats:

- This analysis only applies to data taken in March - August 2025.
 - The period between the internal alignment of the velo was updated.
 - There is a known z-scale bias in the 2024 alignment.
 - So, this result (due to tomography) is track-based alignment dependent.
- It is possible that aging affects the hit z-position due to changes in depletion depth, especially if we don't run at sufficient HV.
- This analysis may be repeated for different points in time.

Some Remarks:

- The following effects are not included explicitly:
 - The beam-induced temperature effects.
 - It is expected to be small and can be checked by comparing the pt-100 temperatures under different beam conditions.
 - The larger issue is not that the beam makes the foil warmer, but that the measured foil temperature appears colder than expected when compared with the simulation. This is still under investigation.
 - Average temperature from pt-100 sensor is ~4 degree, but the simulation shows we only cooling to 10 degree.
 - Deformation from Stress effects:
 - For Metrology, the deformations from stress effect are not be very large, because:
 - During machining the box was fixed to a flat surface (hence constrained)
 - During metrology it was free.
 - However, the metrology is very close to the CAD design [40 micron/1m].
 - Deformation from Air Pressure effect:
 - In the detector (tomography), the pressure is approximately balanced on the two sides, the pressure force itself may not be the dominant issue of deformation.

Temperature (deg)



C M42 -> Cside Module 21 (~)

A M43 -> Aside Module 22 (~)

C M40 -> Cside Module 19 (~)

A M41 -> Aside Module 20 (~)

A M07-> Aside Module 3 (~)

C M06 -> Cside Module 3 (~)

A M03 -> Cside Module 11 (~)

Conductivity reduced by 1.5

