# TFPX-TBPX adjustable mechanical connection tests for the Phase II integration of the CMS Inner Tracker

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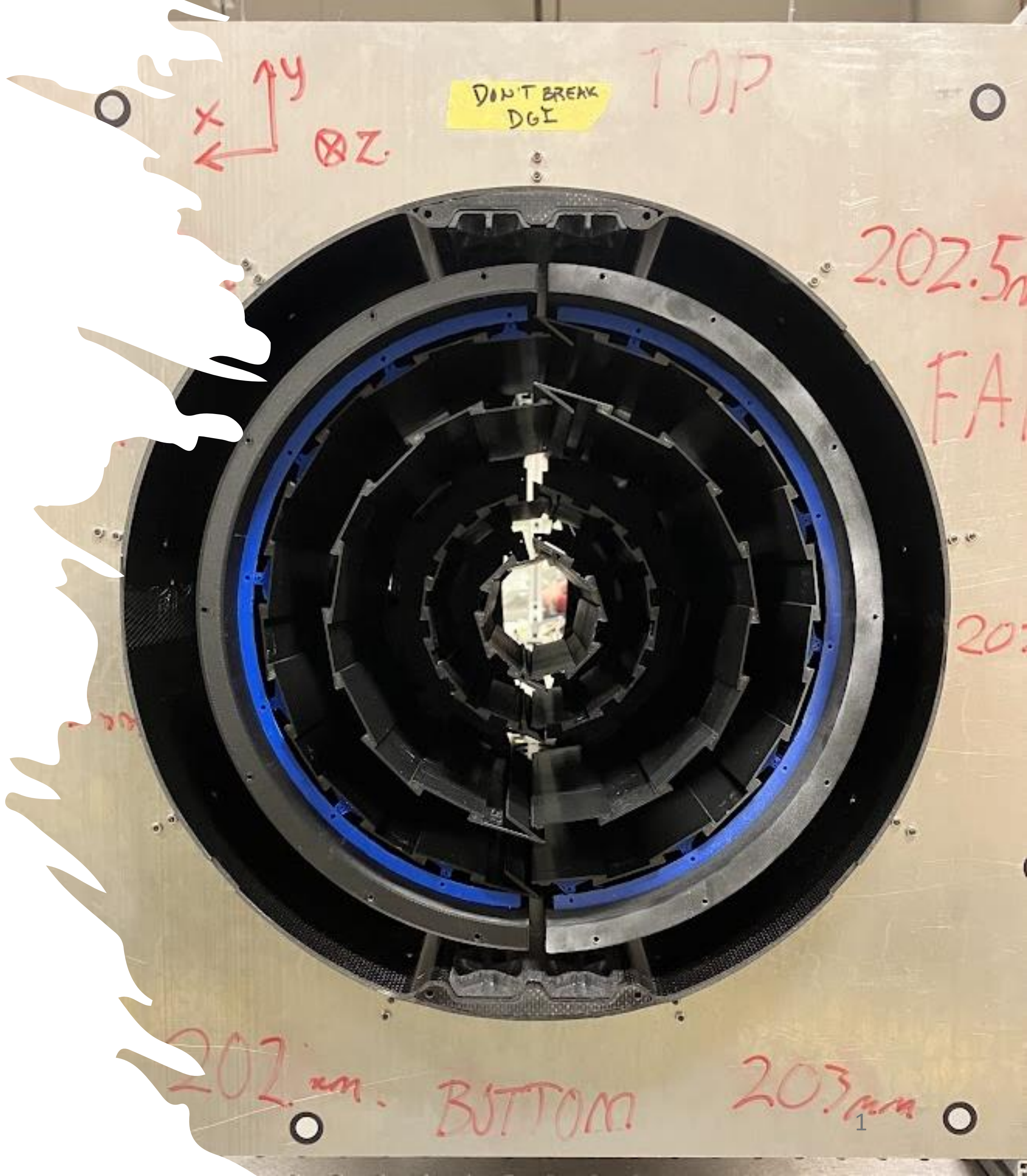
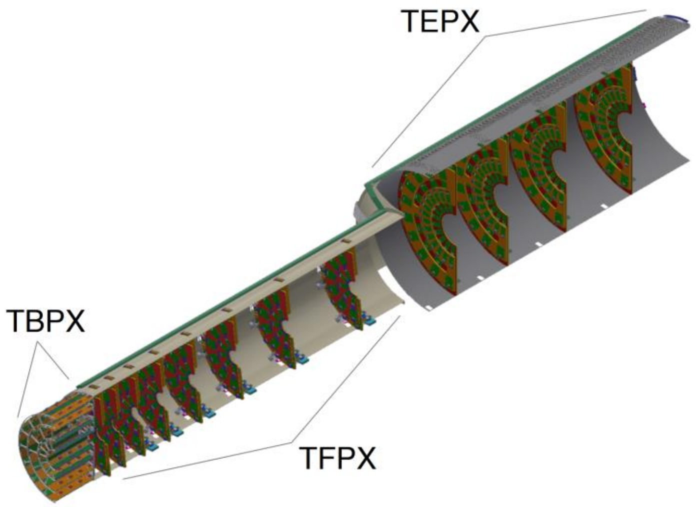
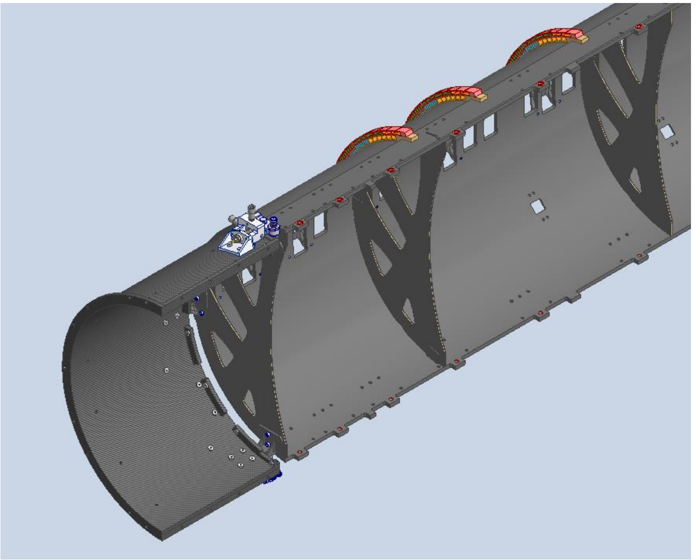
On behalf of CMS Tracker group

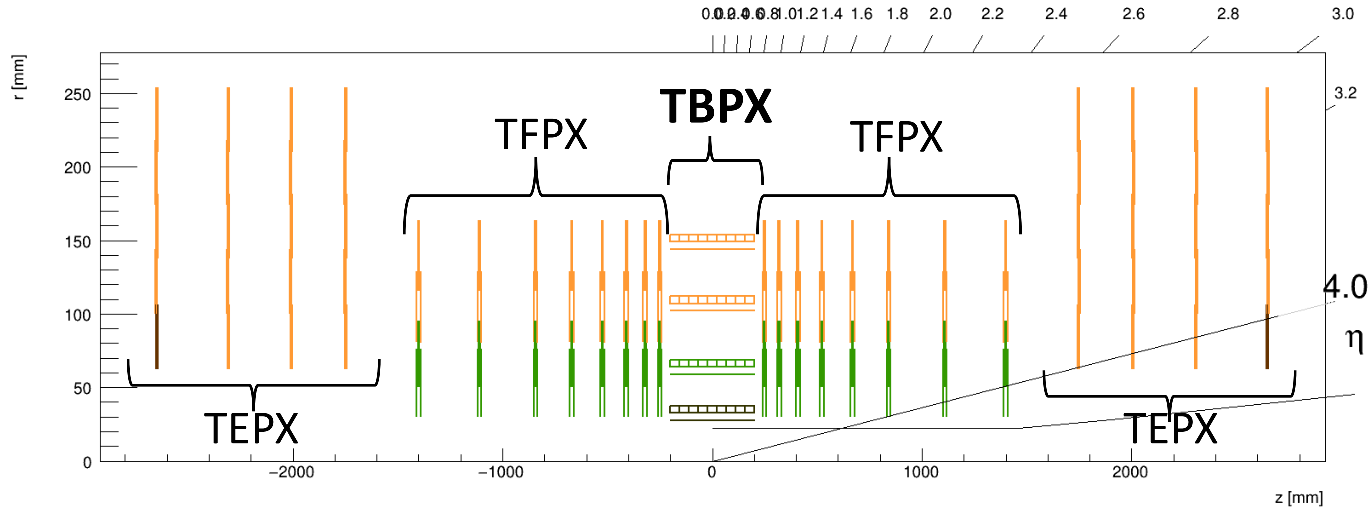


# The Phase-2 Inner Tracker

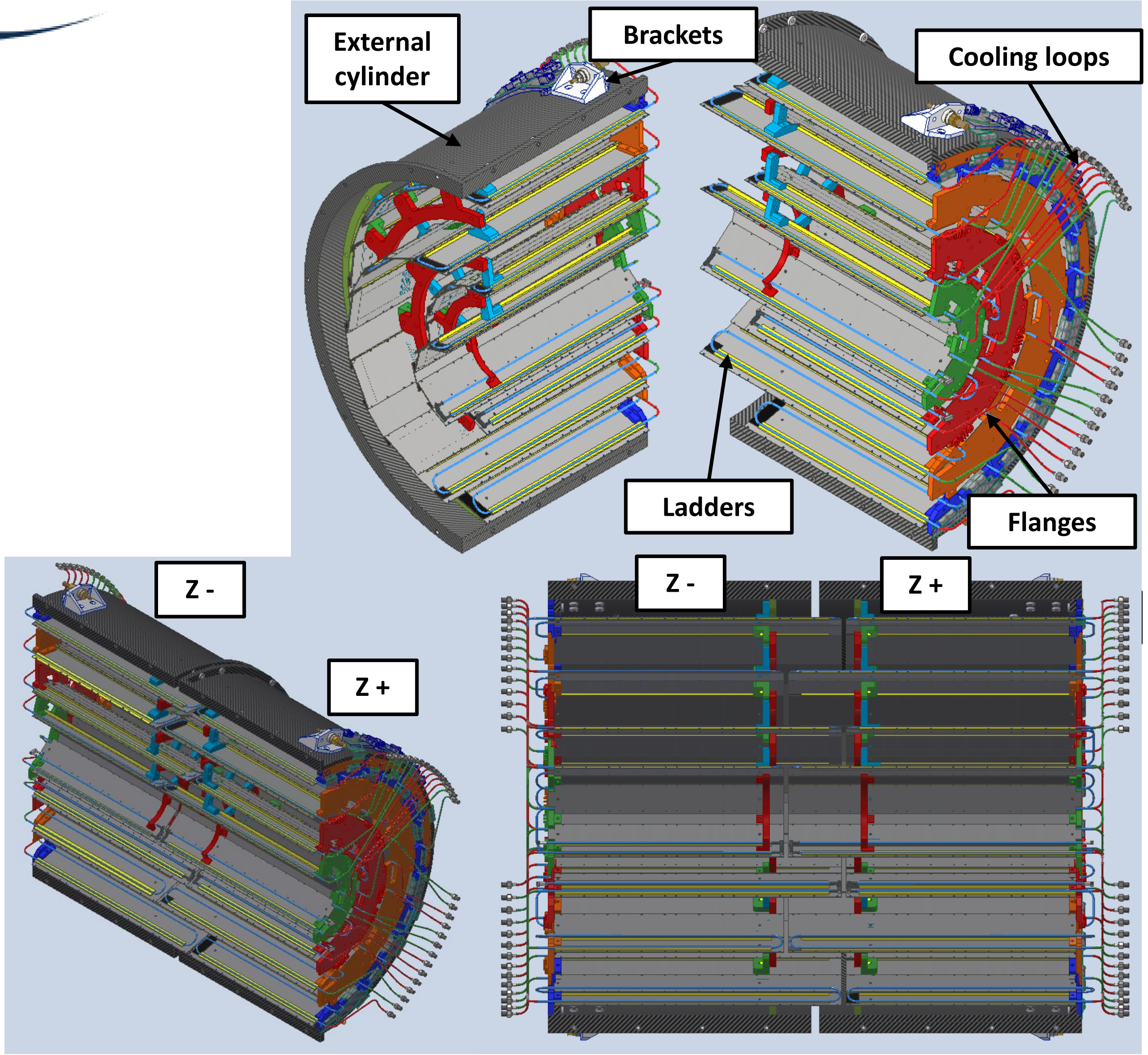
- During LHC Phase II, the CMS Inner tracker will be updated. The goal of this upgrade is to maintain or even **improve the tracking performance** compared to the Phase I detector. The main improvements are the **increase of the tracker coverage** and the **increase of detector resolution**
- Made of barrel part with four layers (Tracker Barrel Pixel Detector, ***TBPX***), eight small double-discs per side (Tracker Forward Pixel Detector, ***TFPX***) and four large double-disks per side (Tracker Endcap Pixel Detector, ***TEPX***). The whole Inner tracker slides inside **ITST** rails (Inner Tracker Support Tube)
- Placed all around the beam pipe, it is installed inside the Outer Tracker → possibility to replace innermost degraded parts over an Extended Technical Stop





# TBPX design

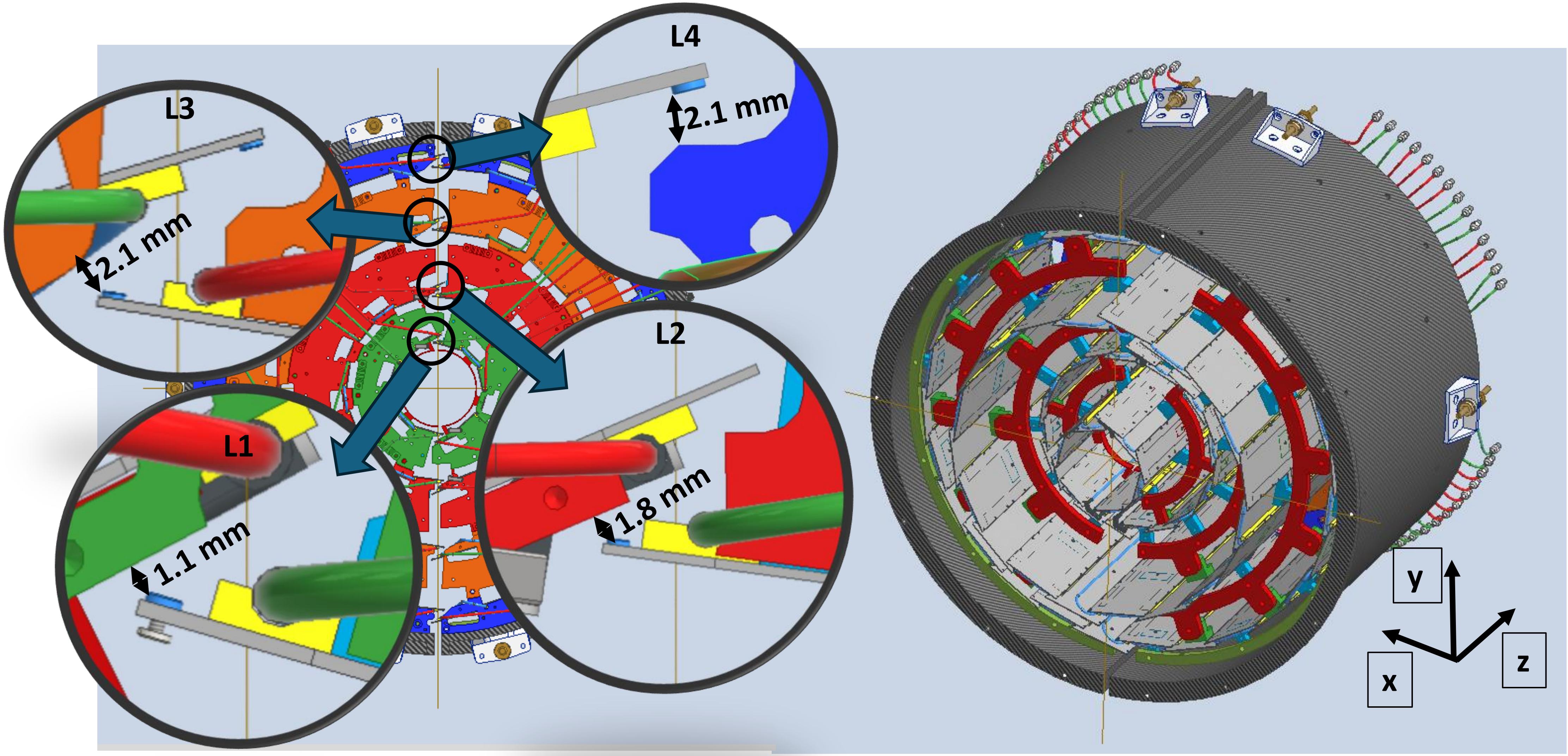



- The TBPX detector is made of four quarters, each quarter is made of four Layers. To increase the Tracker coverage **the ladders of each layer of the two halves are staggered** around the interaction point. In the intersection of the quarters the ladders are skewed to increase the gap

- TBPX is composed by an external carbon fiber shell, the External cylinder, which holds all the TBPX load and allows the connection with TFPX. Inside ladder are connected one by one to the External cylinder by some mechanical flanges, which connect one layer to the other.

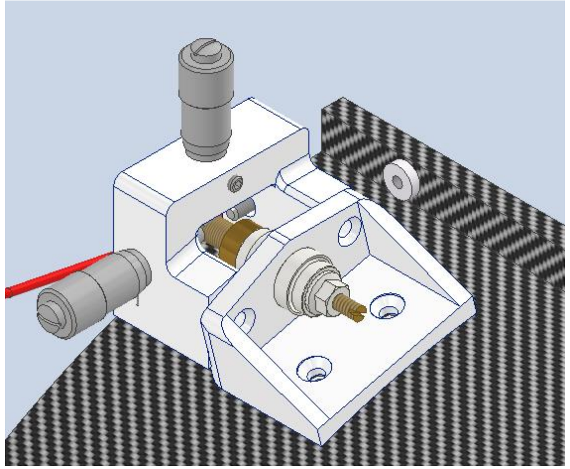
- Since the parts are connected one by one from the External cylinder up to the innermost layer, this **propagate their positioning error**, that might cause collision between the two halves during the installation.

# TBPX Z+ Nominal gaps

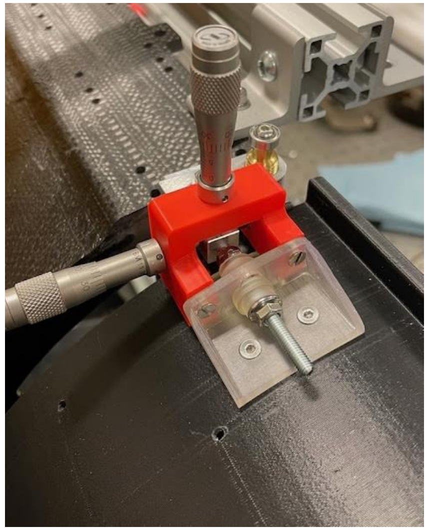


# TFPX-TBPX connection design first test

## Definitive design



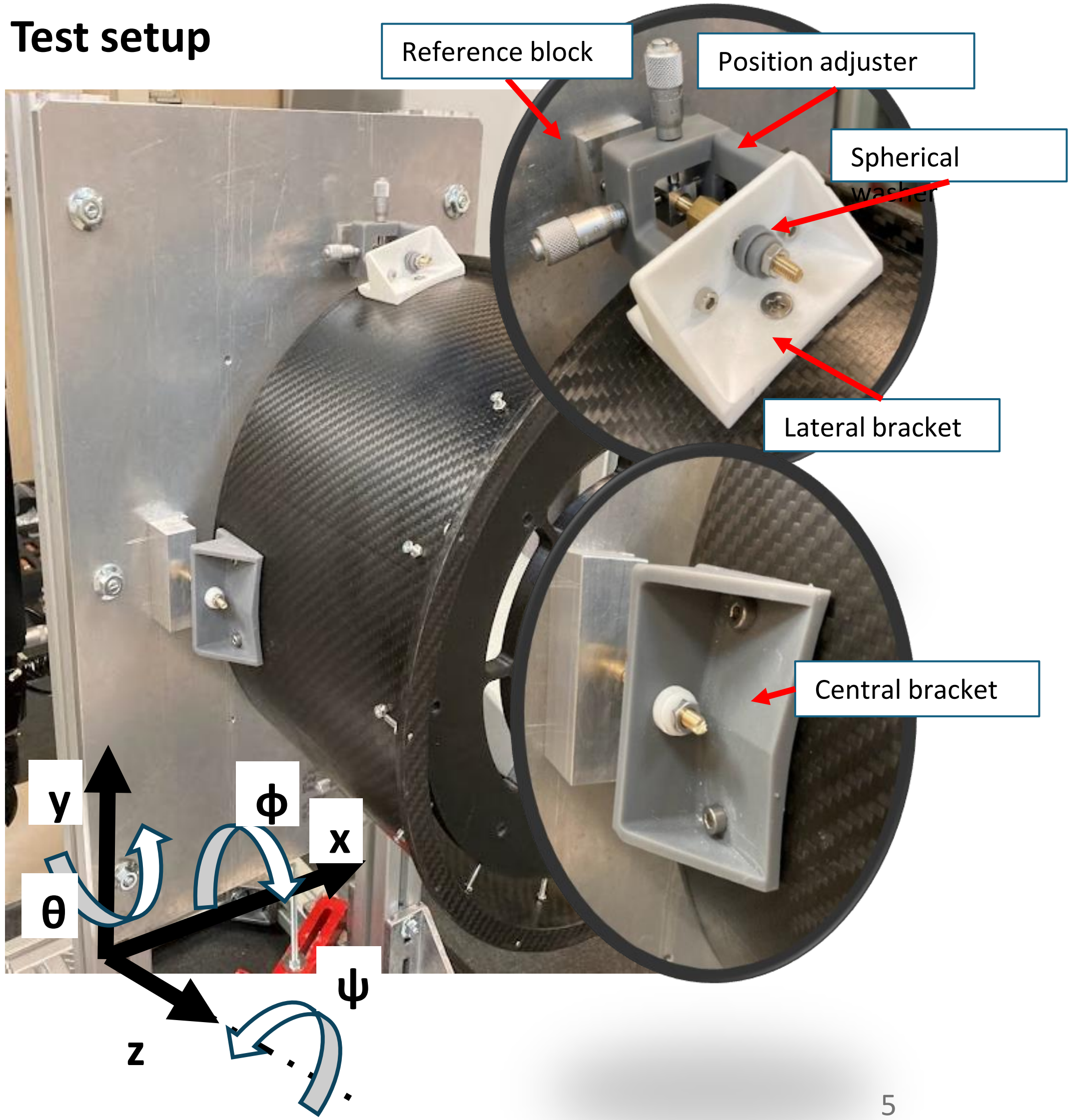
The first accuracy test consisted into adjusting TBPX to two reference blocks simulating TFPX wheels references. The goal was to check and fine tune the precision of the connection and the accuracy of the adjusting tool. During the alignment, the TBPX position is defined by two pinned holes placed on the rear flange of the External Cylinder, which are referred to the global Barrel Pixel reference system



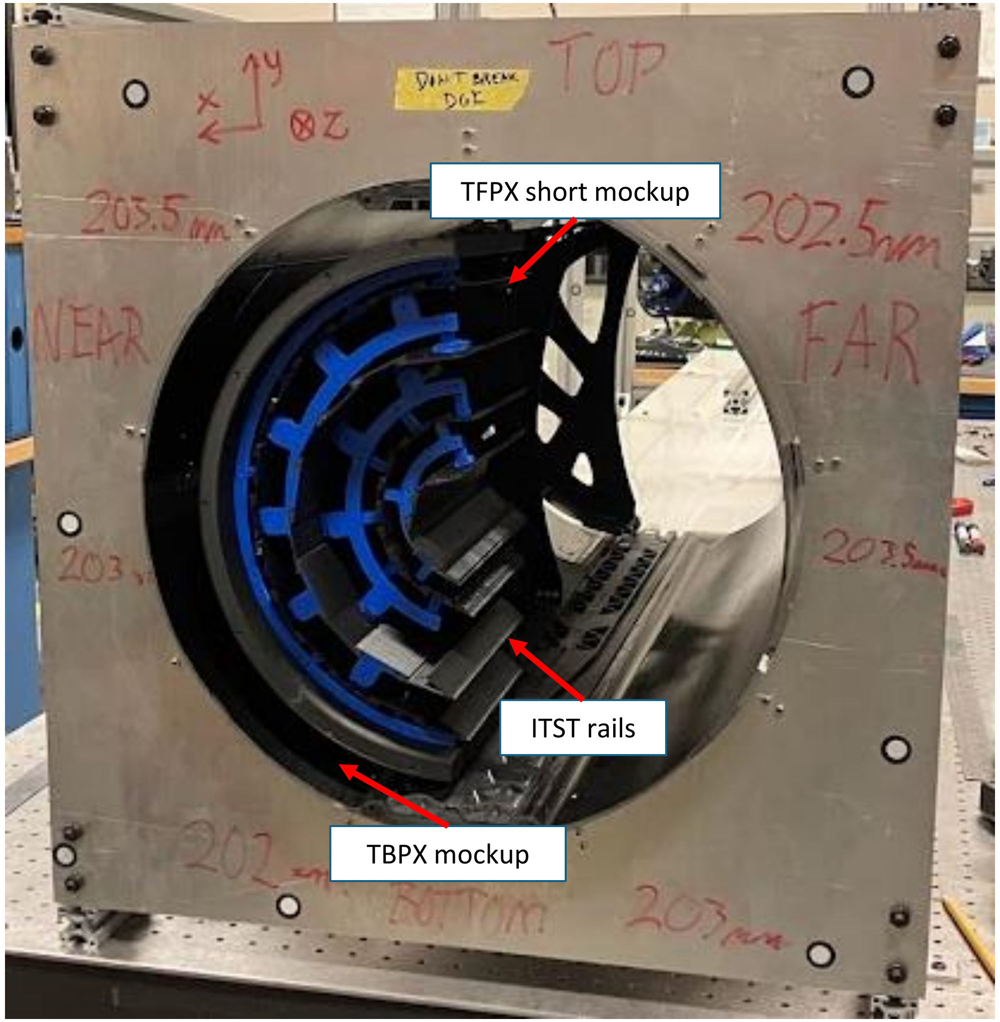
**The tooling is attached to the TBPX brackets with two bolts**
- Self aligning against the TBPX external cylinder
- The tool has 2x micrometric screws and one M3 set-screw, allowing precise adjustments
- The adjuster is removable after the regulation

| Relative precision | x [mm] | y [mm] | z [mm] |
|---|---|---|---|
| After adjustments | 0.050 | 0.050 | 0.050 |
| Locked | 0.100 | 0.100 | 0.100 |
| **Relative angle precision** | **θ [°]** | **ψ [°]** | **ϕ [°]** |
| After adjustments | 0.02 | 0.01 | 0.02 |
| Locked | 0.100 | 0.01 | 0.100 |

## Test setup



# Integration test setup in Purdue



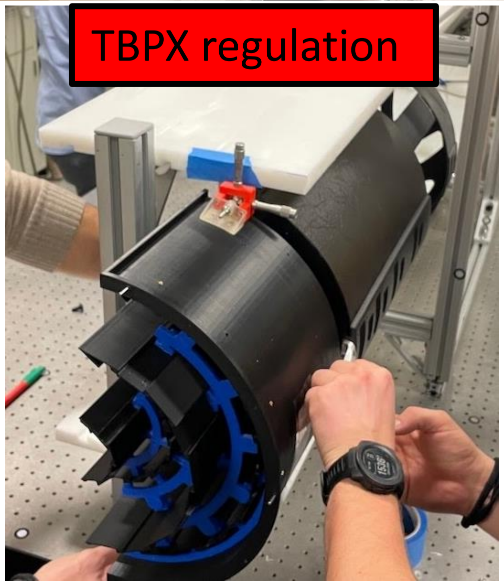

The test setup is composed by:

- ITST carbon fiber mockup
- TFPX short carbon fiber mockup
- TBPX plastic mockup

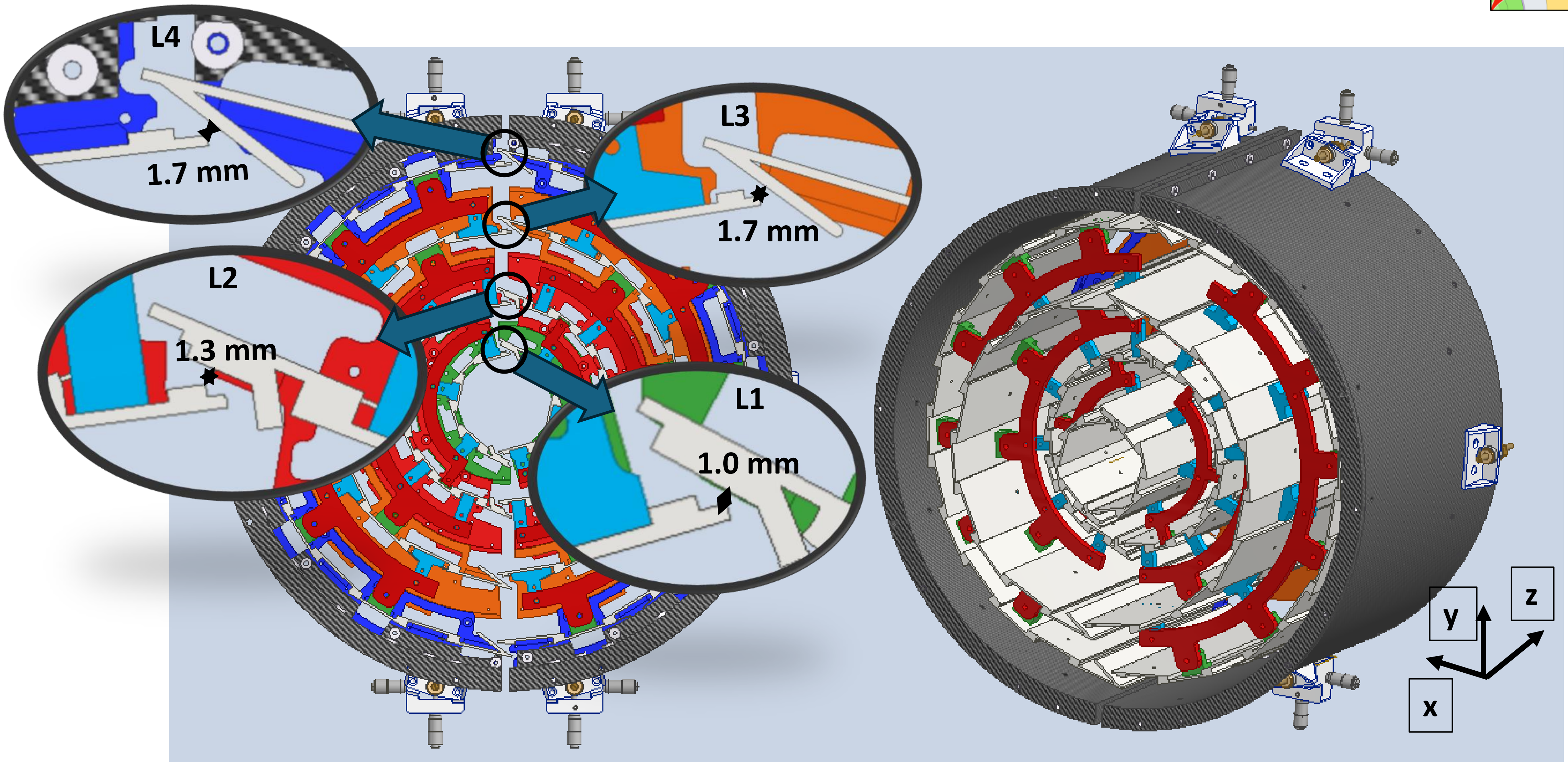
The regulation for TFPX was done directly on the ITST rails, meanwhile for TBPX it was necessary to take out the Service cylinder and to regulate it supported by a Bosch structure

TFPX regulation

TBPX regulation

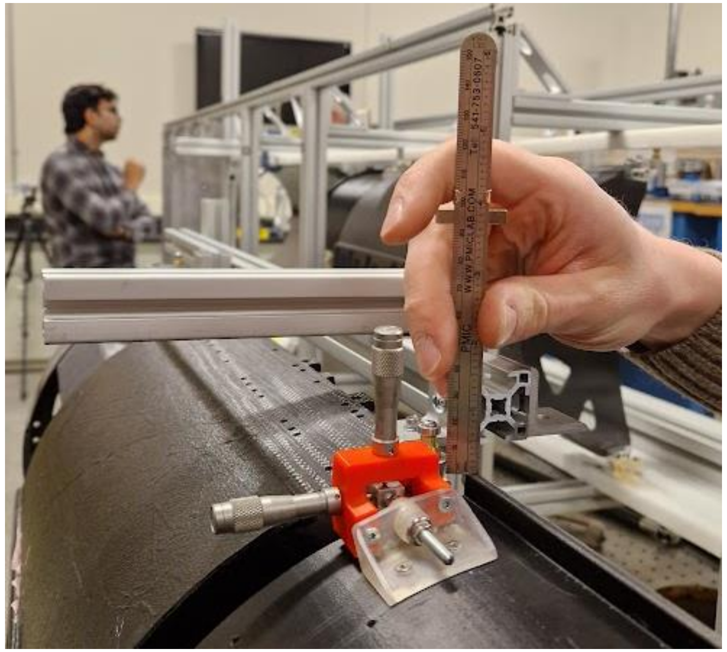


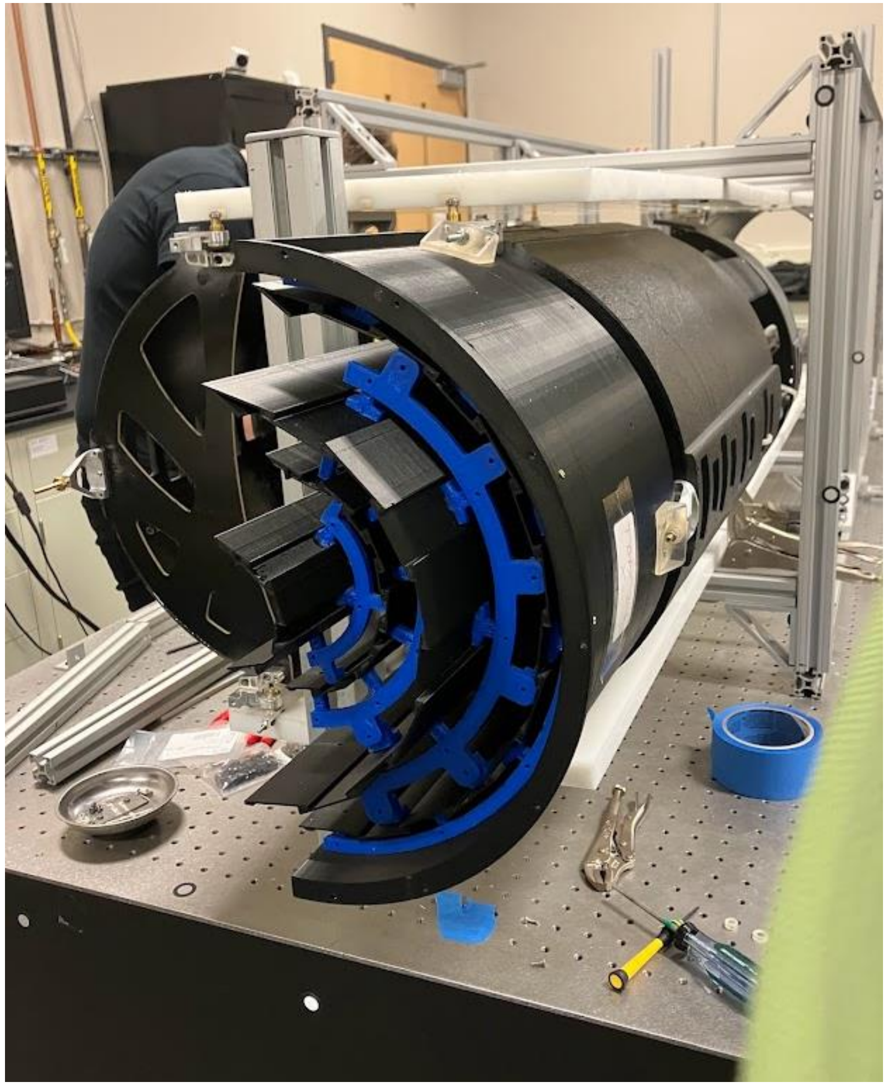
# Mockup gaps

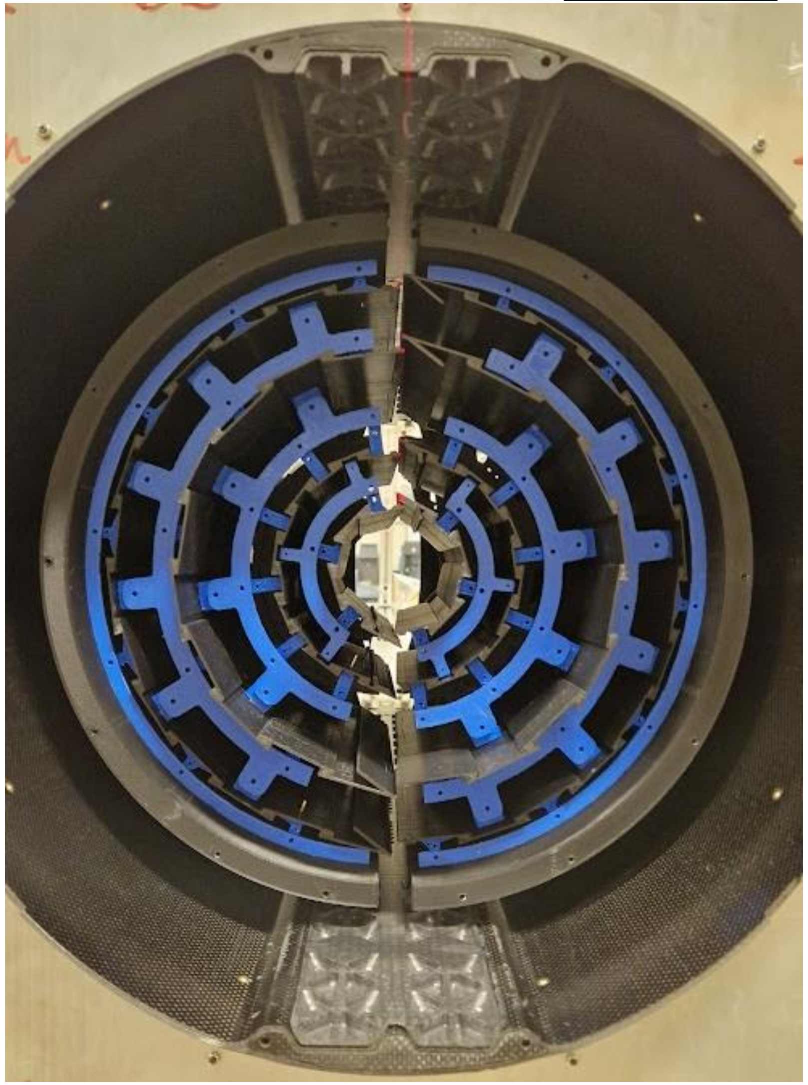


# First assembly and insertion

First insertion, without applying the proper adjustments by scanning but by using a ruler. The goal of this first insertion was to check any collision o issues during the insertion of the final assembly. We didn't find any issues on rails, but we had collision for L1 and L2 layers, pointing out that the internal layers were tilted to the center by the internal rings. We took them off for the next insertion







# First regulation and problematics

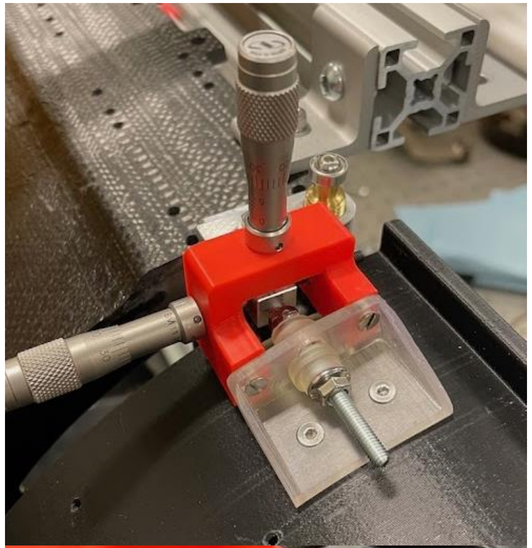
| Target | 0.000 | 0.000 | 194.500 | 0.000 | 0.000 | 0.000 |
|---|---|---|---|---|---|---|
| 1st trial | xc | yc | zp | theta | psi | phi |
| Position | -0.890 | 0.402 | 193.450 | 0.000 rad | -0.011 rad | -0.001 rad |
| | | | | 0.000 ° | -0.642 ° | -0.045 ° |
| Adjustments | xt | xd | yt=yd | zt | zc | zd |
| | -1.109 | 2.888 | -0.402 | 1.313 | 1.051 | 0.786 |

| 2nd trial | xc | yc | zp | theta | psi | phi |
|---|---|---|---|---|---|---|
| Position | -4.492 | -0.801 | 194.480 | 0.000 rad | -0.005 rad | -0.001 rad |
| | | | | 0.000 ° | -0.258 ° | -0.083 ° |
| Adjustments | xt | xd | yt=yd | zt | zc | zd |
| | 3.687 | 5.297 | 0.801 | 0.511 | 0.020 | -0.472 |

Where: xc and yc are the position of the center of TBPX quarter and zp is the position of the External cylinder rear plane

We went out of regulation for the x direction. It was due to sums of errors into the prototypes position, which was out of the ± 1.75 mm that the position adjuster can compensate.
Indeed, trying to force the system we crack a High temp resin bracket, pointing out the fragility of such a material. It was substituted by more resistant carbon fiber pps bracket.

We decided so to change the set point to $xc = -2.5\ mm$ to validate the regulation and to make a proper insertion



# Regulation

### TBPX z+ x+

| Target | -2.500 | 0.000 | 194.500 | 0.000 | 0.000 | 0.000 |
|---|---|---|---|---|---|---|
| 1st trial | xc | yc | zp | theta | psi | phi |
| Position | -2.759 | -0.782 | 194.525 | 0.000 rad | 0.002 rad | 0.000 rad |
| | | | | 0.000 ° | 0.099 ° | 0.017 ° |
| Adjustments | xt | xd | yt=yd | zt | zc | zd |
| | 0.566 | -0.049 | 0.782 | -0.124 | -0.025 | 0.074 |

| 4th trial | xc | yc | zp | theta | psi | phi |
|---|---|---|---|---|---|---|
| Position | **-2.306** | **-0.447** | **194.662** | 0.000 rad | 0.001 rad | 0.000 rad |
| | | | | **0.000 °** | **0.065 °** | **0.019 °** |
| Adjustments | xt | xd | yt=yd | zt | zc | zd |
| | 0.007 | -0.396 | 0.447 | -0.276 | -0.161 | -0.047 |

### TBPX z+ x-

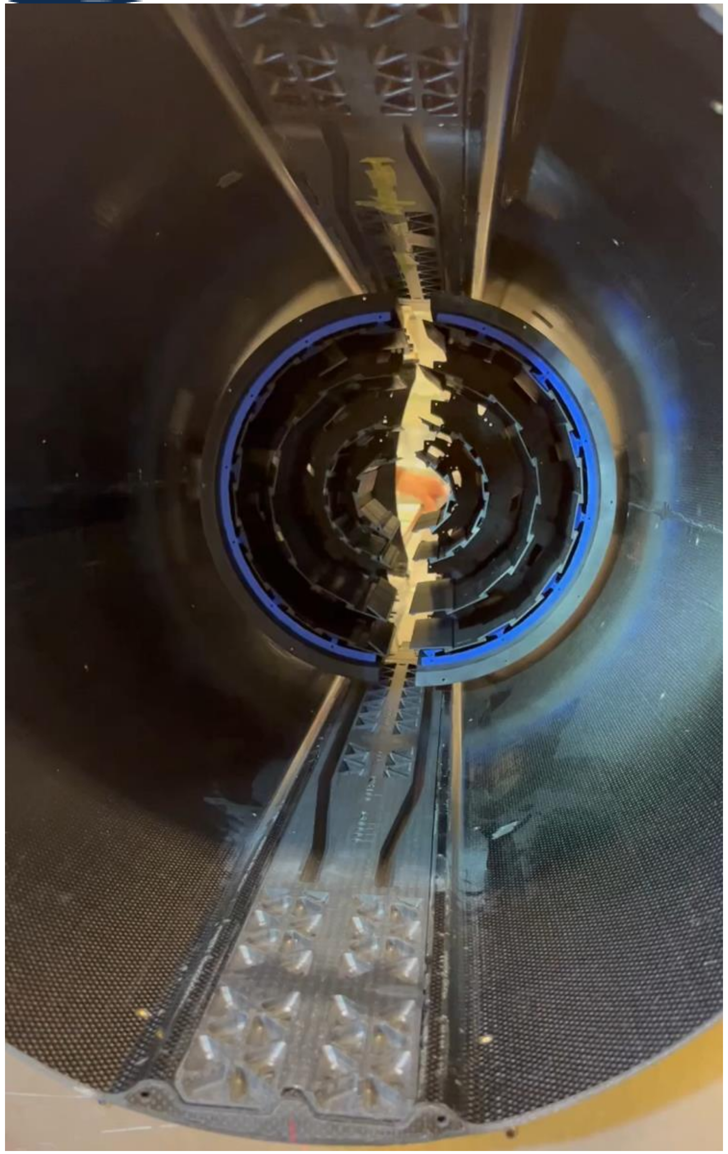
| Target | -2.500 | 0.000 | 194.500 | 0.000 | 0.000 | 0.000 |
|---|---|---|---|---|---|---|
| 1st trial | xc | yc | zp | theta | psi | phi |
| Position | -2.984 | -0.272 | 193.727 | 0.000 rad | 0.000 rad | 0.005 rad |
| | | | | 0.000 ° | -0.009 ° | 0.274 ° |
| Adjustments | xt | xd | yt=yd | zt | zc | zd |
| | 0.454 | 0.454 | 0.272 | -0.848 | 0.773 | 2.394 |

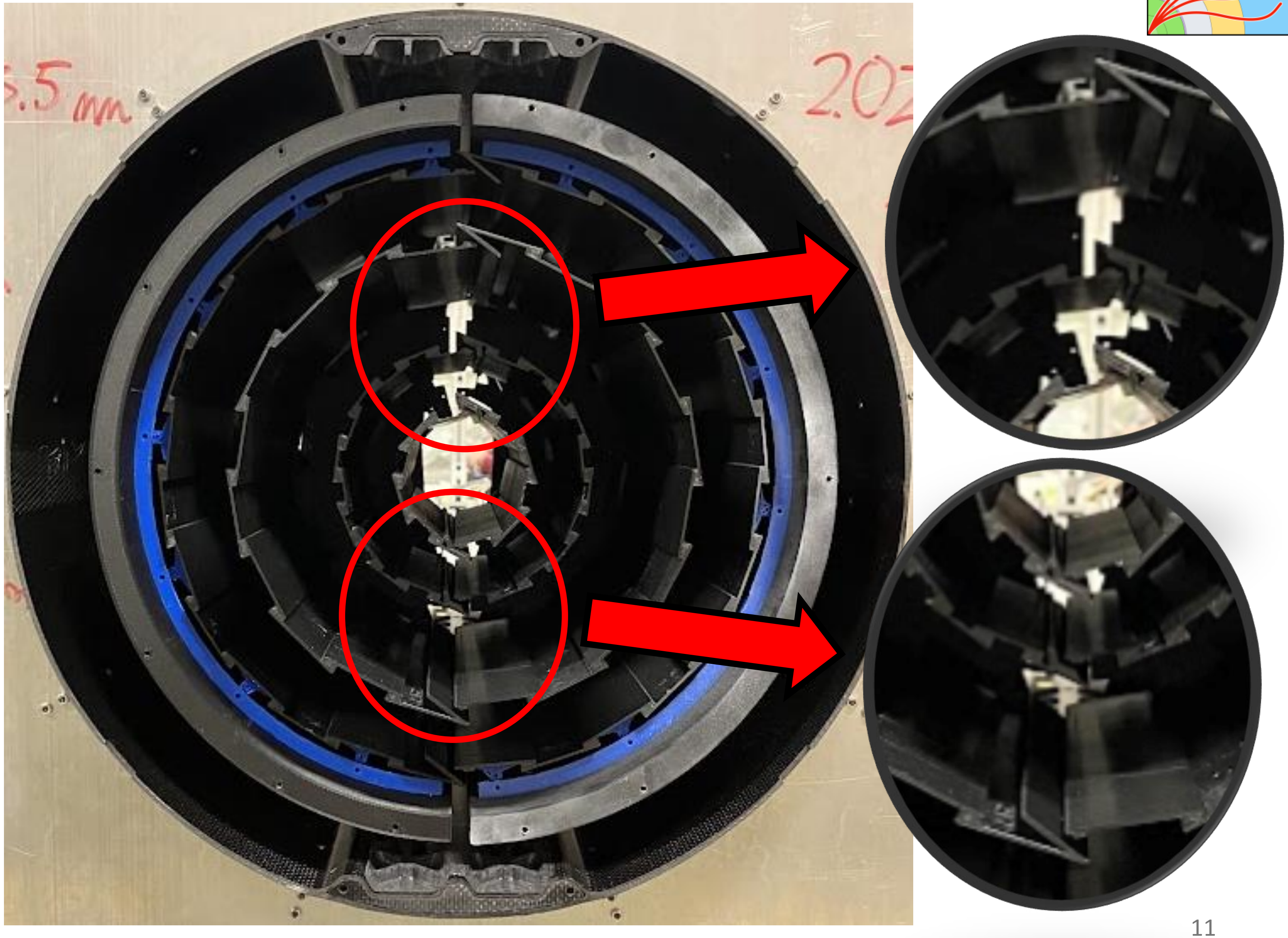
| 6th trial | xc | yc | zp | theta | psi | phi |
|---|---|---|---|---|---|---|
| Position | **-3.078** | **-0.888** | **194.340** | 0.000 rad | -0.001 rad | -0.003 rad |
| | | | | **0.000 °** | **-0.032 °** | **-0.152 °** |
| Adjustments | xt | xd | yt=yd | zt | zc | zd |
| | 0.477 | 0.679 | 0.888 | 1.060 | 0.160 | -0.740 |

From this two positioning tests it was pointed out:

- The precision of the connection is quite far from the one expected from previous test run in Pisa
- The regulation of x and y is accurate and simple till we stay inside the regulation range, otherwise the adjustments applied are not effective as they should.
- The z positioning it's accurate and stable. In case we go outside of the regulation range for the x and y, the z system get blocked, allowing adjustments in just one direction.

# The insertion





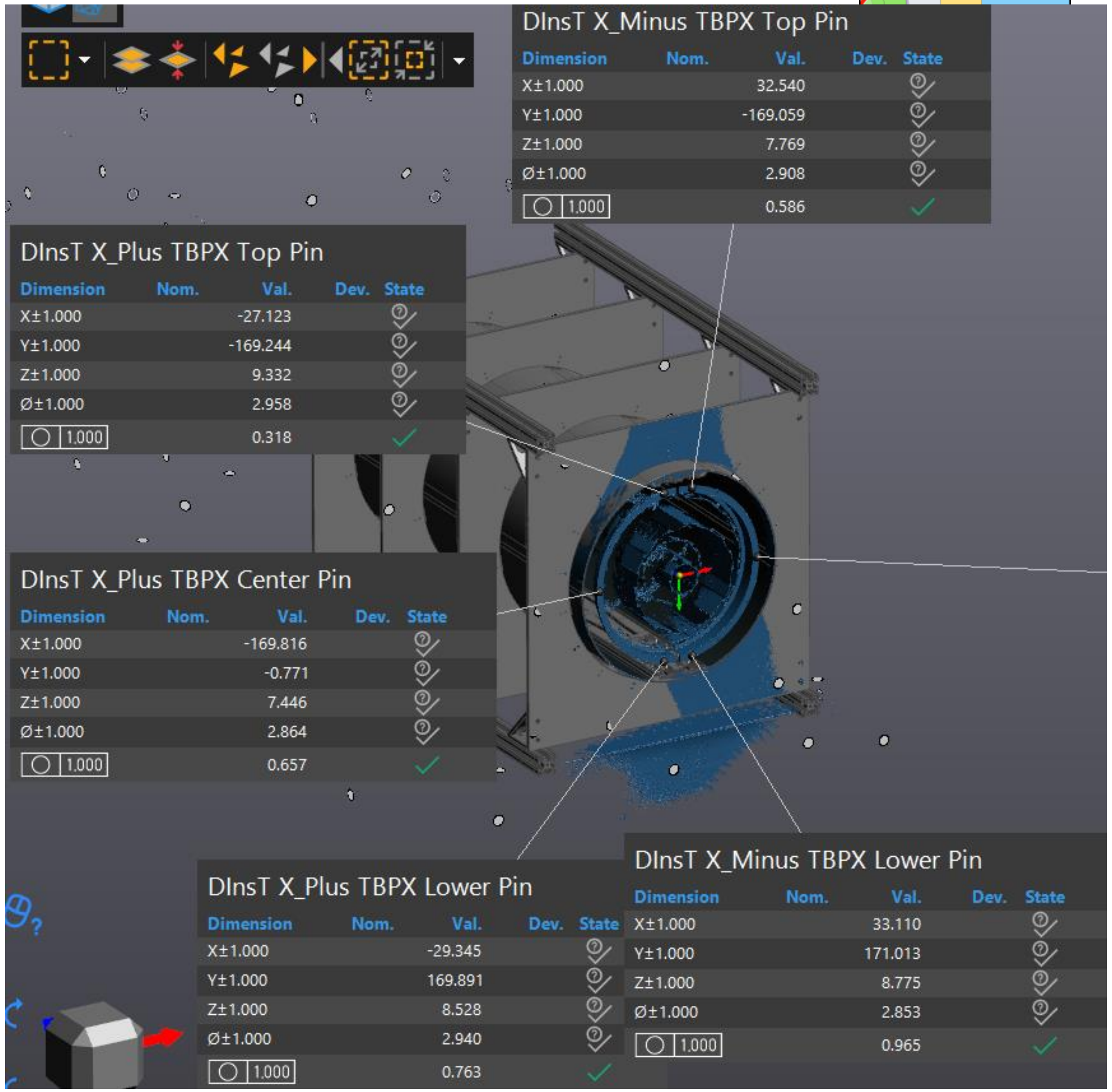
# Precision after the insertion

### TBPX z+ x+

| Target | -2.500 | 0.000 | 194.500 | 0.000 | 0.000 | 0.000 |
|---|---|---|---|---|---|---|
| | xc | yc | zp | theta | psi | phi |
| Before insertion | -2.306 | -0.447 | 194.662 | 0.000 rad | 0.001 rad | 0.000 rad |
| | | | | 0.000 ° | 0.065 ° | 0.019 ° |
| After insertion | xc | yc | zp | theta | psi | phi |
| | -2.553 | -0.445 | 193.415 | 0.000 rad | 0.005 rad | 0.000 rad |
| | | | | 0.000 ° | 0.291 ° | 0.016 ° |

### TBPX z+ x-

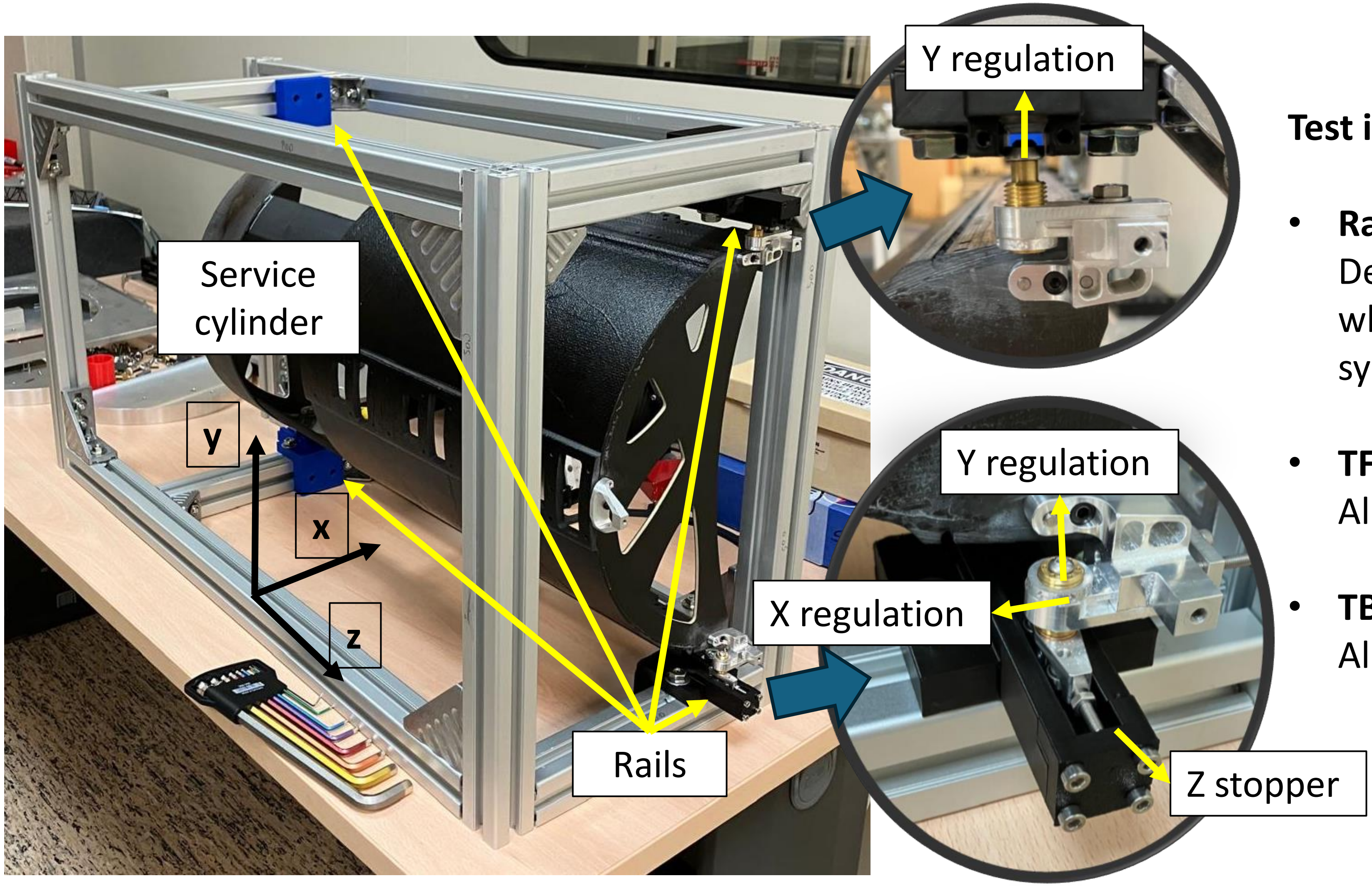
| Target | -2.500 | 0.000 | 194.500 | 0.000 | 0.000 | 0.000 |
|---|---|---|---|---|---|---|
| | xc | yc | zp | theta | psi | phi |
| Before insertion | -3.078 | -0.888 | 194.340 | 0.000 rad | -0.001 rad | -0.003 rad |
| | | | | 0.000 ° | -0.032 ° | -0.152 ° |
| After insertion | xc | yc | zp | theta | psi | phi |
| | -3.301 | -0.868 | 194.412 | 0.000 rad | -0.002 rad | -0.003 rad |
| | | | | 0.000 ° | -0.132 ° | -0.152 ° |




After the insertion

- The precision in y direction was steady
- The precision in z was expected to be steady, but for TBPX z+ x+ we lost 1mm
- The position in x wasn't steady. That might have been caused by a rotation of the whole mockup in ψ (perpendicular to z). The reason behind that could be the fact that TFPX wheels were touching just one side of the rails, while the adjustments were applied with the mockup locked on the service cylinder.
- θ and ϕ resulted steady after the insertion

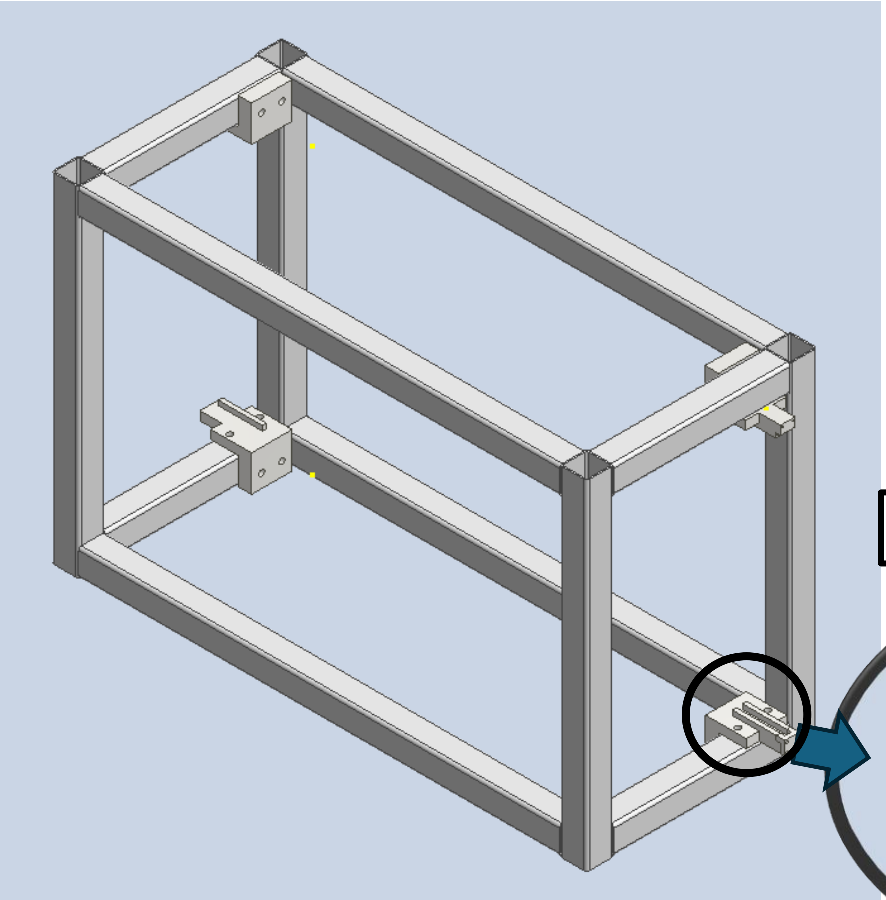
# Future Test in Pisa setup and procedure




**Test in Pisa mounting schedule**

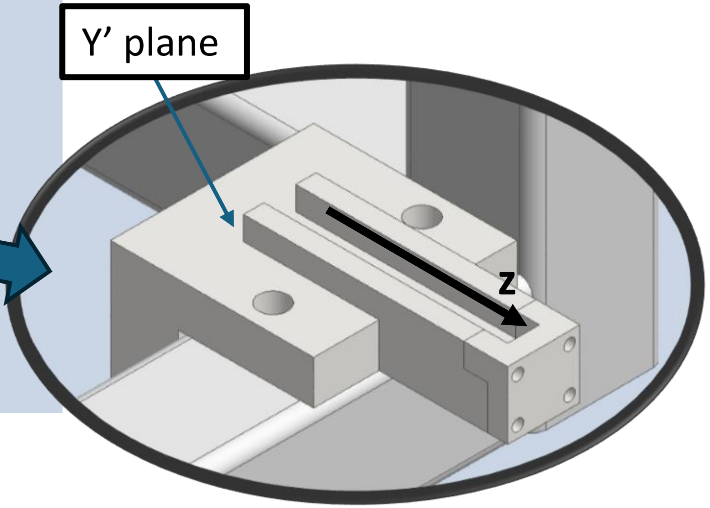
- **Rail alignment**
  Define a reference system from one rail, which is going to be a global reference system, and align the other 3 rails to it
- **TFPX alignment**
  Align TFPX to the global reference system
- **TBPX alignment**
  Align TBPX to the global reference system

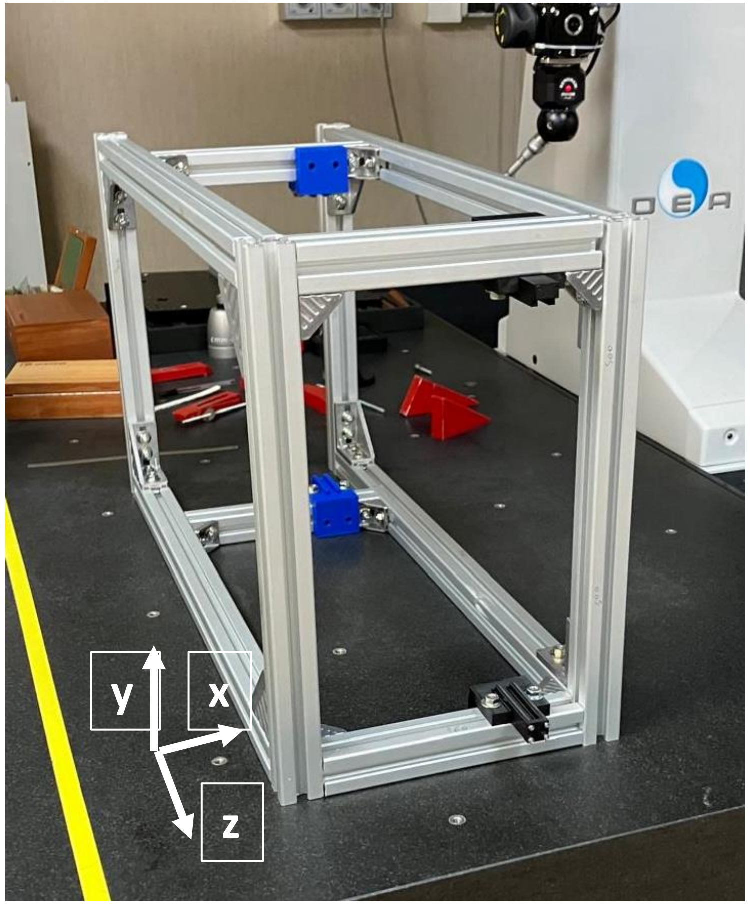
# Rails pre alignment



**Reference system definition:**
- Y plane offset by 197 mm from Y’ plane
- Z direction given by the bottom right edge

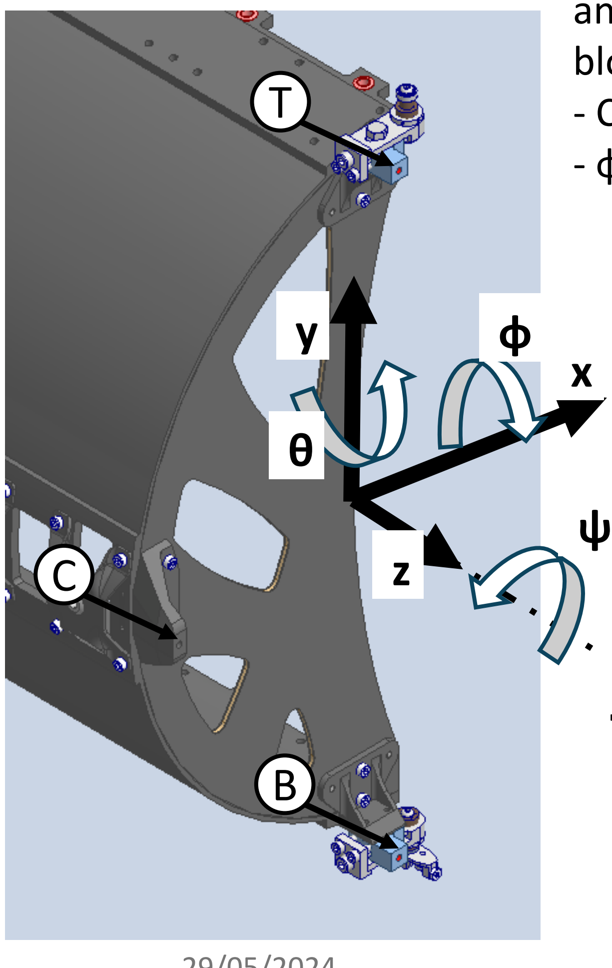
Align the other 3 rails with a 0.1 mm precision



# TFPX posture estimation and regulation

## TFPX posture estimation



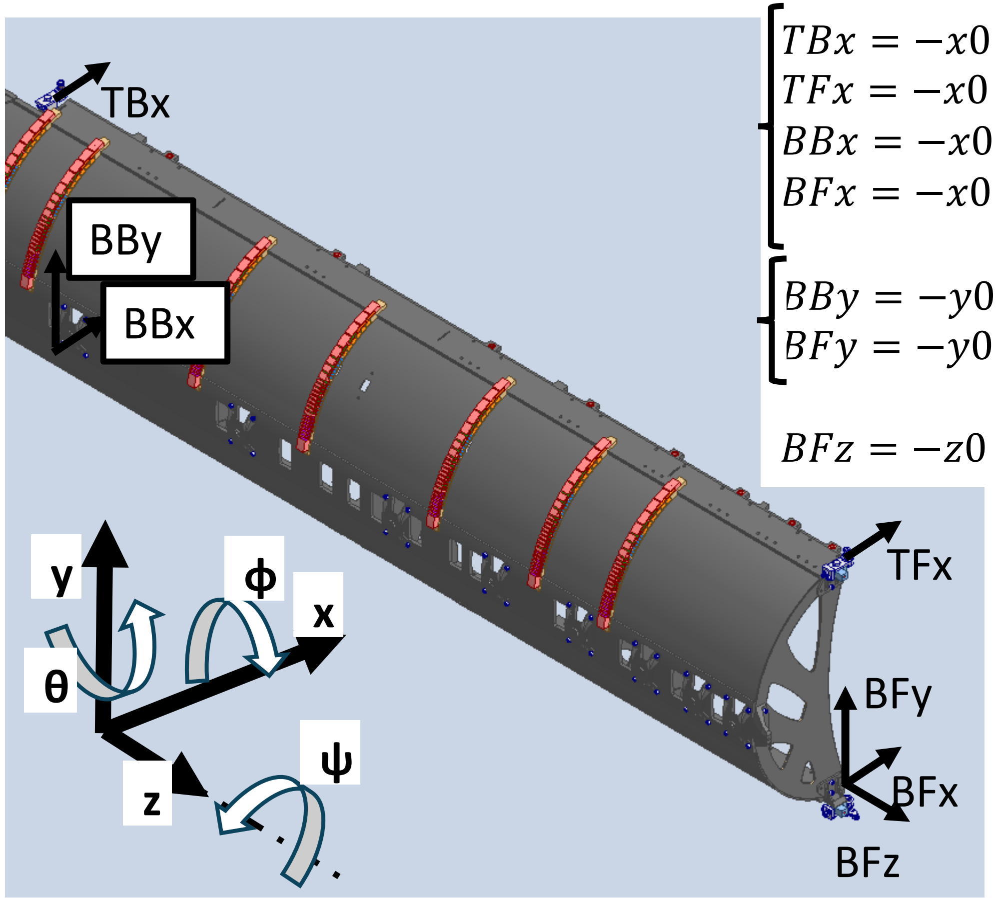

By giving the position in x, y and z of the three reference blocks it tells you:
- Center misalignment
- ϕ, θ, ψ

$$
\begin{cases}
x0 = \dfrac{xT + xC + xB}{3} \\
y0 = \dfrac{yT + yC + yB}{3} \\
z0 = \dfrac{zT + zC + zB}{3}
\end{cases}
$$

$$
\begin{cases}
\varphi = \dfrac{zT - zB}{2L} \\
\theta = \dfrac{zC - \dfrac{zT + zB}{2}}{xC - xT} \\
\psi = \dfrac{xT - xB - x0}{2 \cdot yT}
\end{cases}
$$

## TFPX regulation

It tells you how to regulate the wheels in x and y, and the stopper in z to compensate misalignments and rotations




$$
\begin{cases}
TBx = -x0 + L \cdot \theta + yT \cdot \psi \\
TFx = -x0 + yT \cdot \psi \\
BBx = -x0 - L \cdot \theta + yB \cdot \psi \\
BFx = -x0 - yB \cdot \psi
\end{cases}
$$

$$
\begin{cases}
BBy = -y0 - L \cdot \varphi \\
BFy = -y0
\end{cases}
$$

$$BFz = -z0 - yT \cdot \theta$$

| Input | xt | yt | zt | xc | yc | zc |
|---|---|---|---|---|---|---|
| Target | 42.5 | 173.4 | 197 | 174 | 0 | 197 |
| Measured | 44.673 | 171.243 | 203.773 | 175.335 | 2.692 | 202.253 |
| Δ | 2.173 | -2.157 | 6.773 | 1.335 | 2.692 | 5.253 |

| Output | x0 | y0 | z0 | ϕ | θ | ψ |
|---|---|---|---|---|---|---|
| Target | 0 | 0 | 0 | 0 | 0 | 0 |
| Measured | 1.156667 | -0.03433 | 5.545667 | 0.006234 | -0.00335 | 0.00304 |
| | | | | 0.35719 | -0.19215 | 0.174189 |

| Adjustments | TBx | TFx | BBx | BFx | TBy | TFy |
|---|---|---|---|---|---|---|
| | -3.31246 | -0.6295 | -3.31246 | -0.6295 | -4.95298 | 0.034333 |

# Conclusion

- The insertion test run in Purdue has been useful, for the first time ITST, TFPX and TBPX mockups were mounted and tested together. This test pointed out many criticalities to solve, procedure to define and correction to the designs.
- The system was proved to be adjustable and precise. It has been proved the possibility to align with a center offset in case of necessity. Nevertheless, the alignment precision and assembly components needs to be improved to have more margin from collision
- Some criticalities of the system were pointed out, making necessary:
  - a precise pre-alignment of the connection reference blocks, to avoid to run out of the regulation
  - a bigger regulation range, to better compensate misalignments
  - rigid connection components, to reduce elastic deflections or cracks
  - define the metrology system to the final alignment to freeze mounting criteria to improve the precision and reduce the amount of time needed
  - tools and structures to lock TFPX while the adjustments are applied on TBPX
- Further tests are foreseen in Pisa to improve TFPX and TBPX regulation, based on a trigonometry-based system to take the parts to the nominal position