High precision TFPX-TBPX adjustable mechanical connection for Phase II installation in the CMS Inner Tracker

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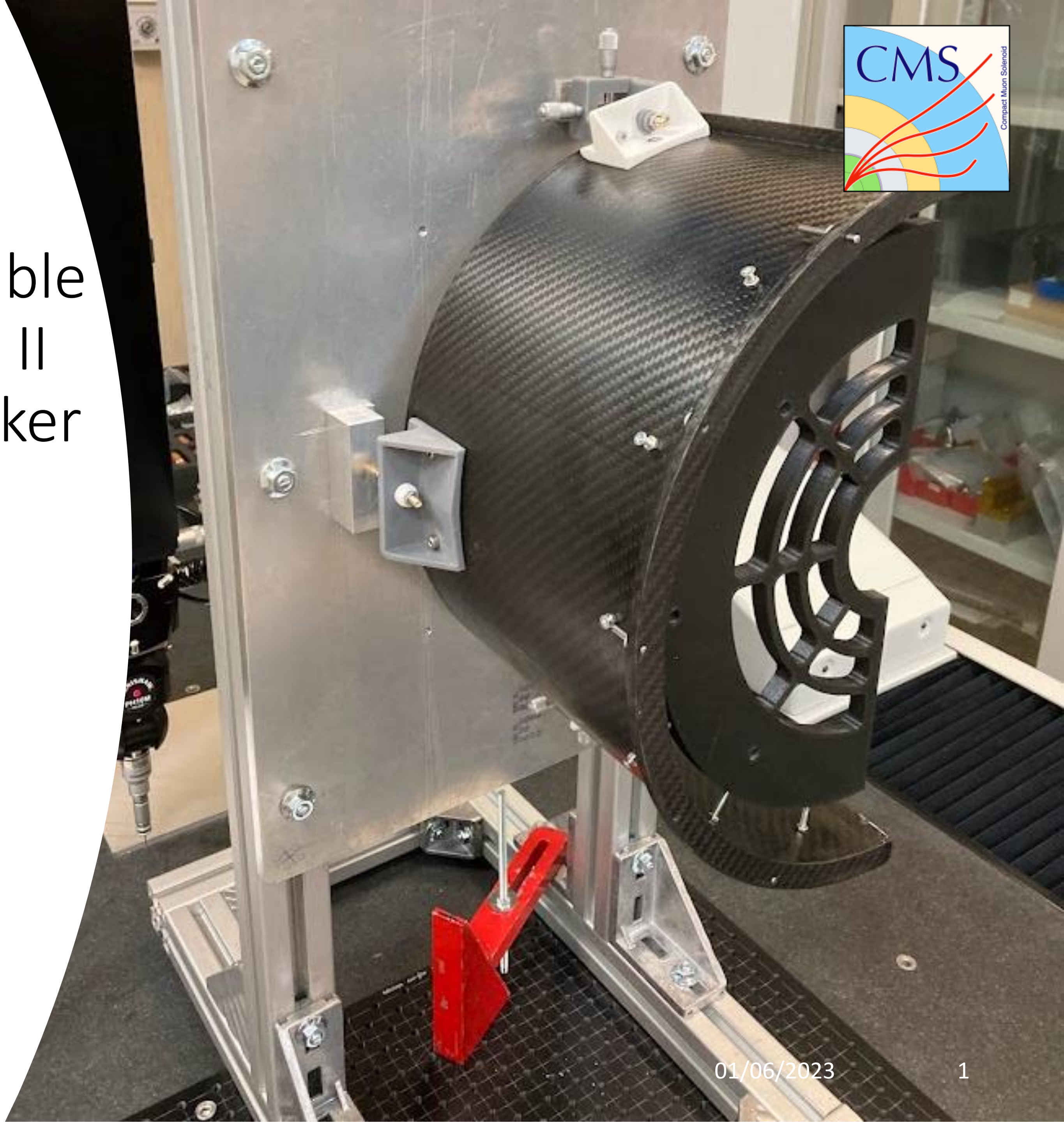
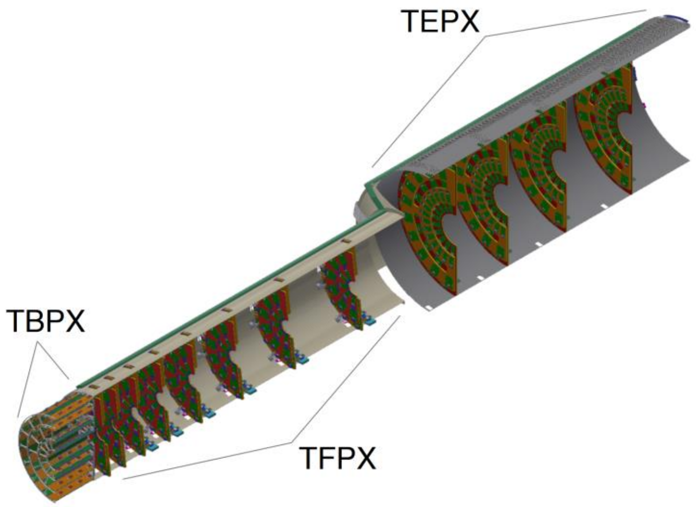
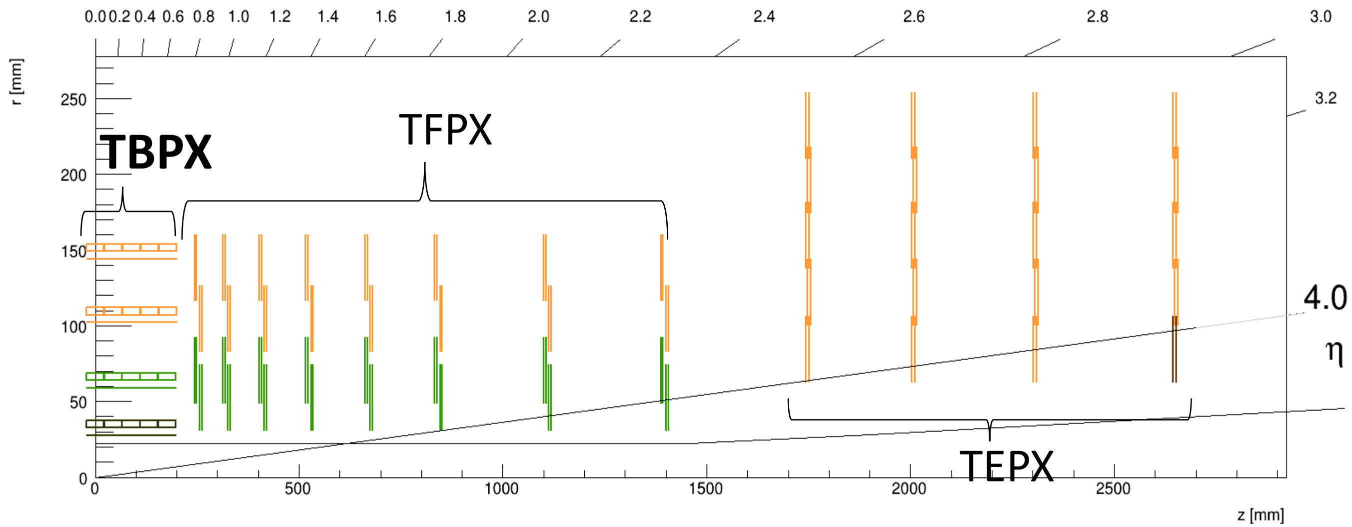
On behalf of CMS Tracker group

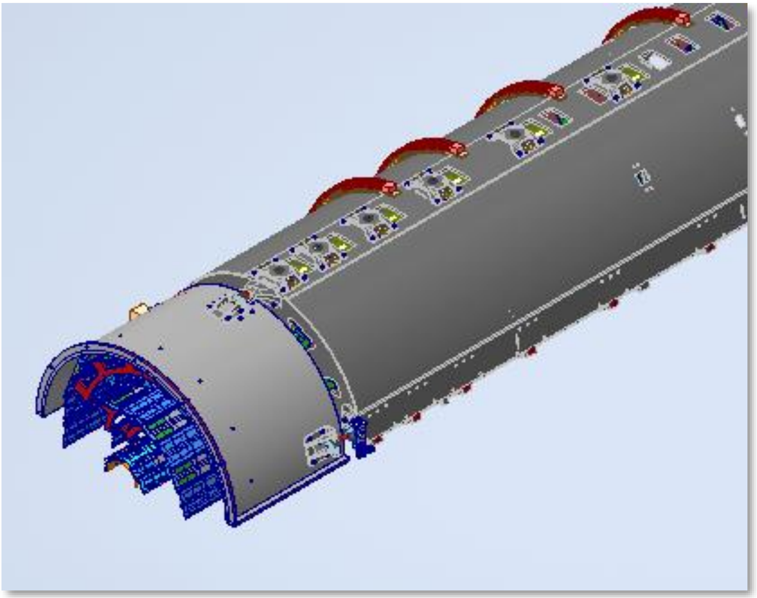


The Phase-2 Inner Tracker

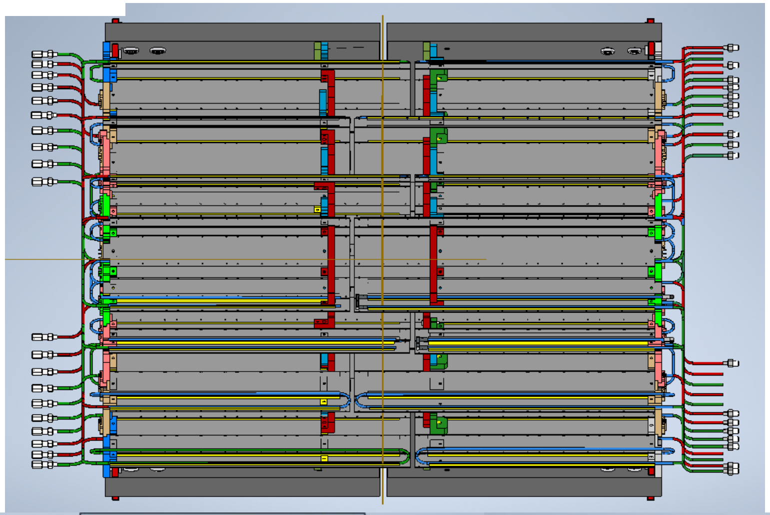
- During LHC Phase II, the CMS Inner tracker will be updated. The goal of this upgrade is to mantain or even **improve the tracking performance** compared to the Phase I detector. The main improvements are the **increase of the tracker coverage** and the **increase of detector resolution**
- Made of 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***)
- Placed all around the beam pipe, it is installed inside the Outer Tracker and the beampipe → possibility to replace degraded parts over an Extended Technical Stop

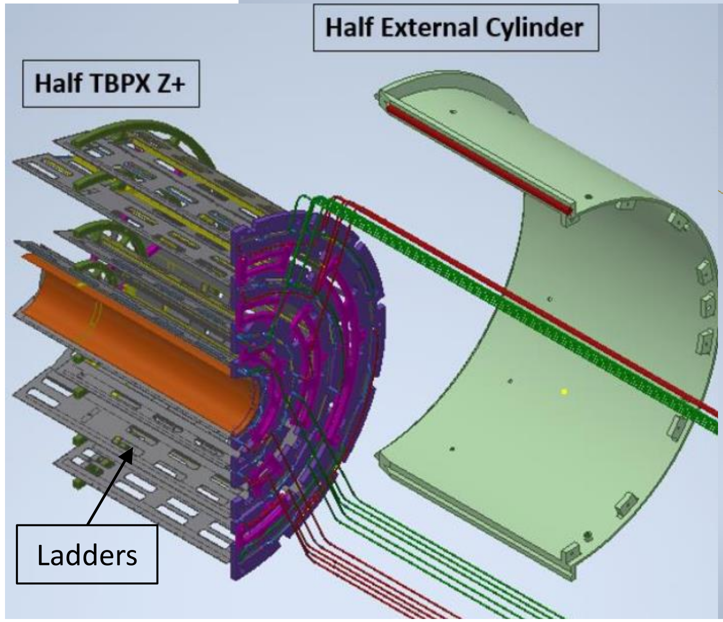


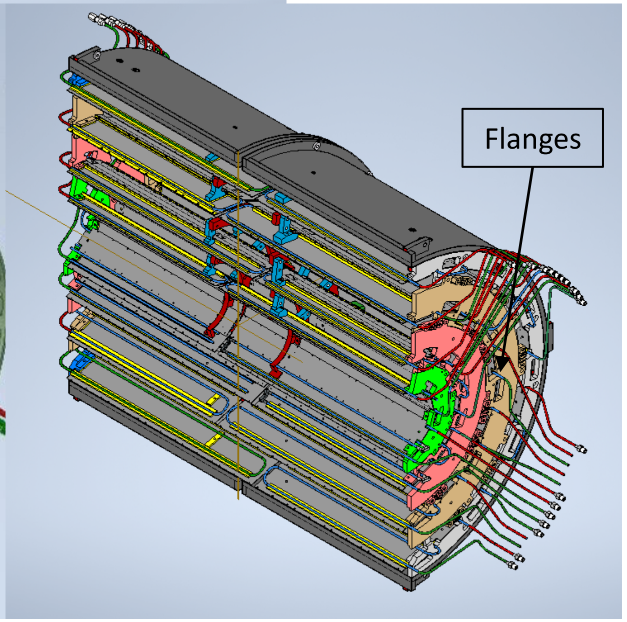




TBPX design

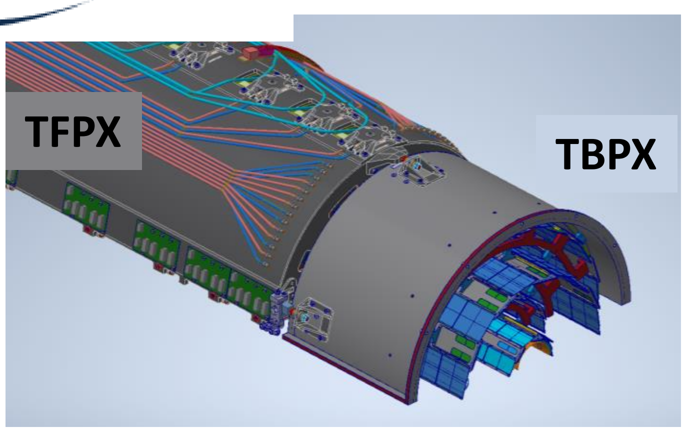






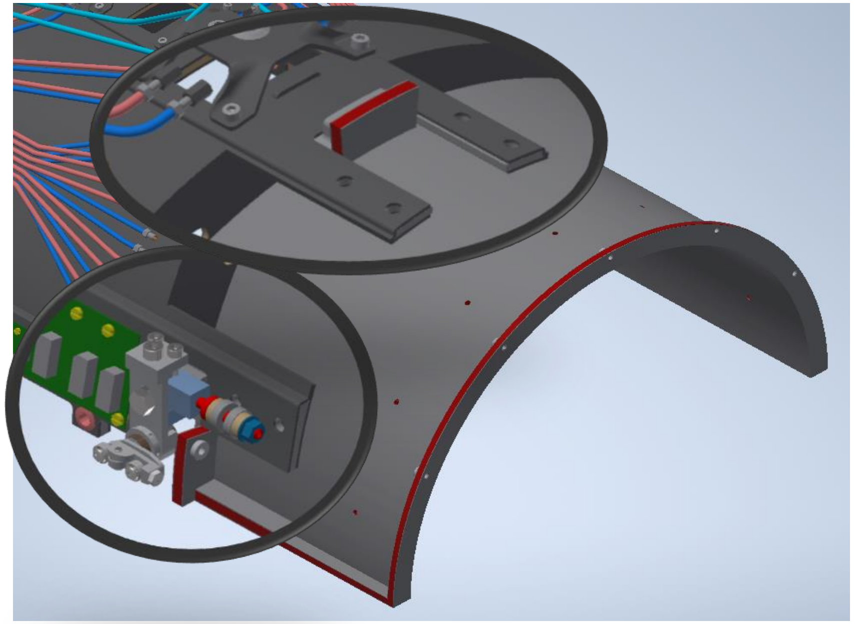
- To increase the Tracker coverage **the ladders of the two halves are staggered** around the interaction point.
- TBPX is composed by an external carbon fiber half cylinder, the External cylinder, which holds all the TBPX load and allows the connection with TFPX. Inside ladder are connected one by one 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 last layer, this **propagate their positioning error**, that might cause collision between the two halves during the installation.

TFPX- TBPX connection

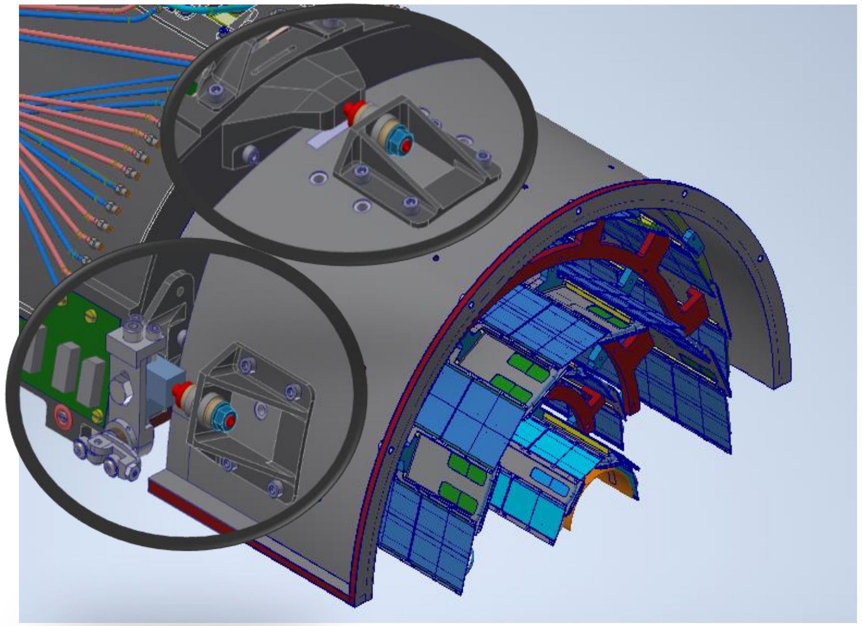


- TBPX, Tracker Barrel PiXel detector, is connected in a cantilevered way to TFPX, Tracker Forward PiXel detector. The connection between the two becomes critical for TBPX positioning, since it's required a high concentricity precision between the two parts
- In order **to reduce the position tolerance and to decouple TBPX and TFPX**, the connection between the two has been changed **from a rigid connection to an adjustable one**. The goal of such a connection is to position the External cylinder in all the three directions and to regulate the orientation

Rigid connection system

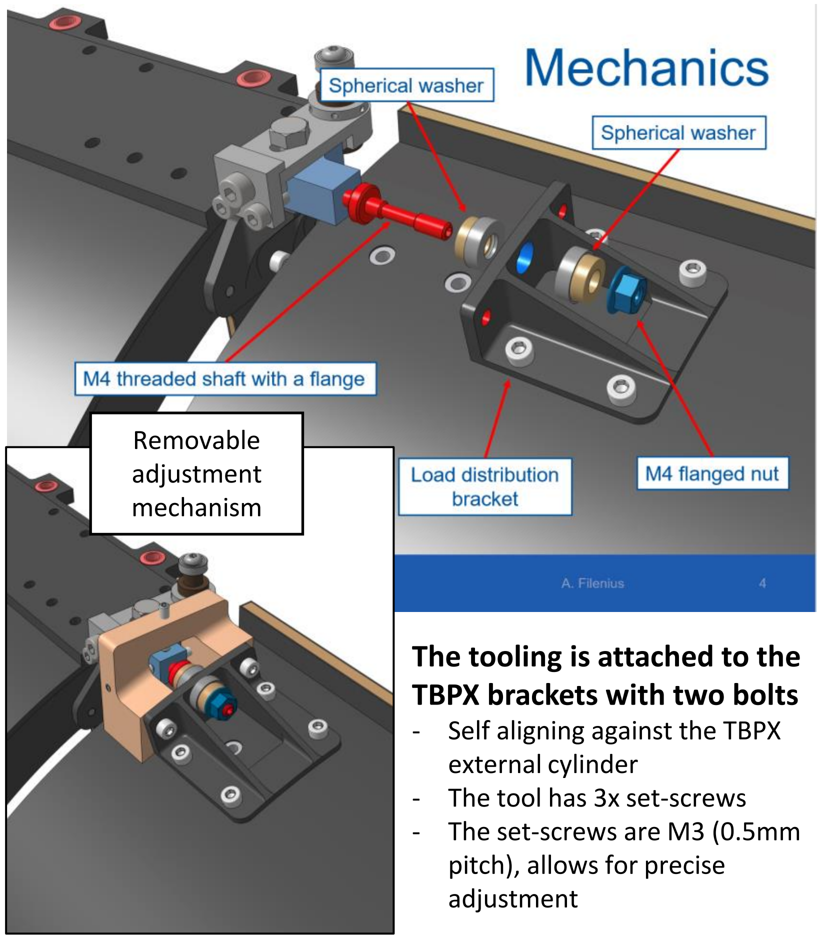


Adjustable connection system



TFPX-TBPX connection design

Current definitive design



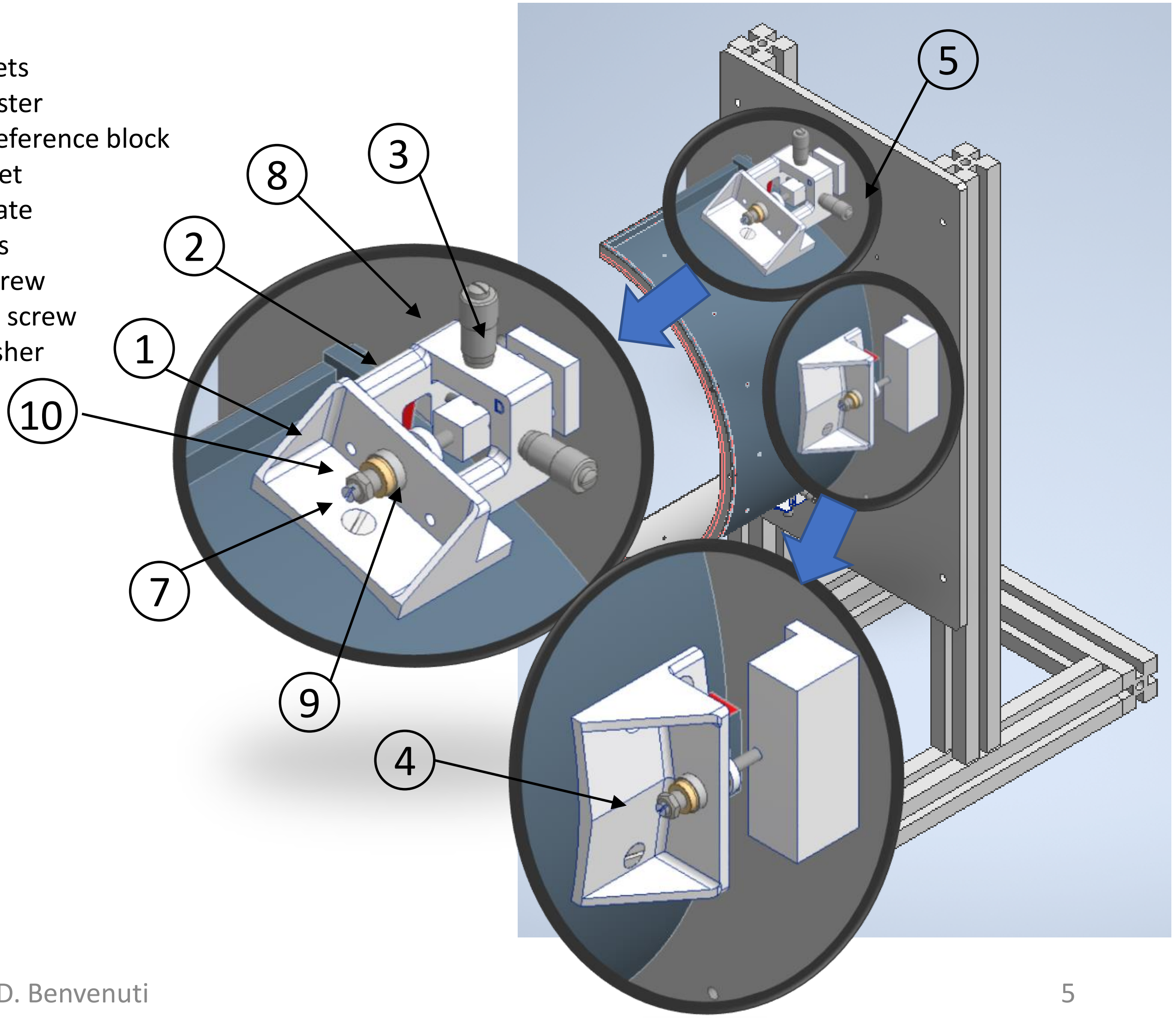
The tooling is attached to the TBPX brackets with two bolts

- Self aligning against the TBPX external cylinder
- The tool has 3x set-screws
- The set-screws are M3 (0.5mm pitch), allows for precise adjustment

Test setup

Components:

1. Lateral brackets
2. Position adjuster
3. Fine thread reference block
4. Central bracket
5. Aluminum plate
6. Bosch profiles
7. Regulation screw
8. Micrometrics screw
9. Spherical washer
10. Locking nut



Material choice

Environmental constraints:

- **Low mass**
  To reduce the interaction with particles
- **Radiation hard material**
  TBPX is subject to a high level of radiations
- **Highest rigidity possible**
  The deflection of the parts change the effective position from the nominal, causing misalignments and collisions
- **Low thermal expansion materials**
  The expected operating temperature is -20 °C, this might create thermal stress between materials with big difference in thermal expansion coefficient



Definitive material

Screws → aluminum/titanium
Brackets → High Temp resin/ CF PPS/ Aluminum
Spherical washers → High Temp resin/Stainless steel
Position adjuster → Aluminum

The usage of PPS CF for brackets is under tests. That would allow to maintain the advantages of the High temp resin, increasing the stiffness of the part

High Temp resin properties

	Green[2]	Post-Cured[3]
Mechanical Properties		
Ultimate Tensile Strength	33 MPa	51.1 MPa
Tensile Modulus	1.5 GPa	3.6 GPa
Thermal Properties		
Heat Deflection Temp. @ 1.8 MPa	42.3 °C	130 °C
Heat Deflection Temp. @ 0.45 MPa	55.9 °C	289 °C
Thermal Expansion (0 – 150 °C)	120.9 μm/m/°C	87.5 μm/m/°C

Reference system and measure procedure

Reference system definition:

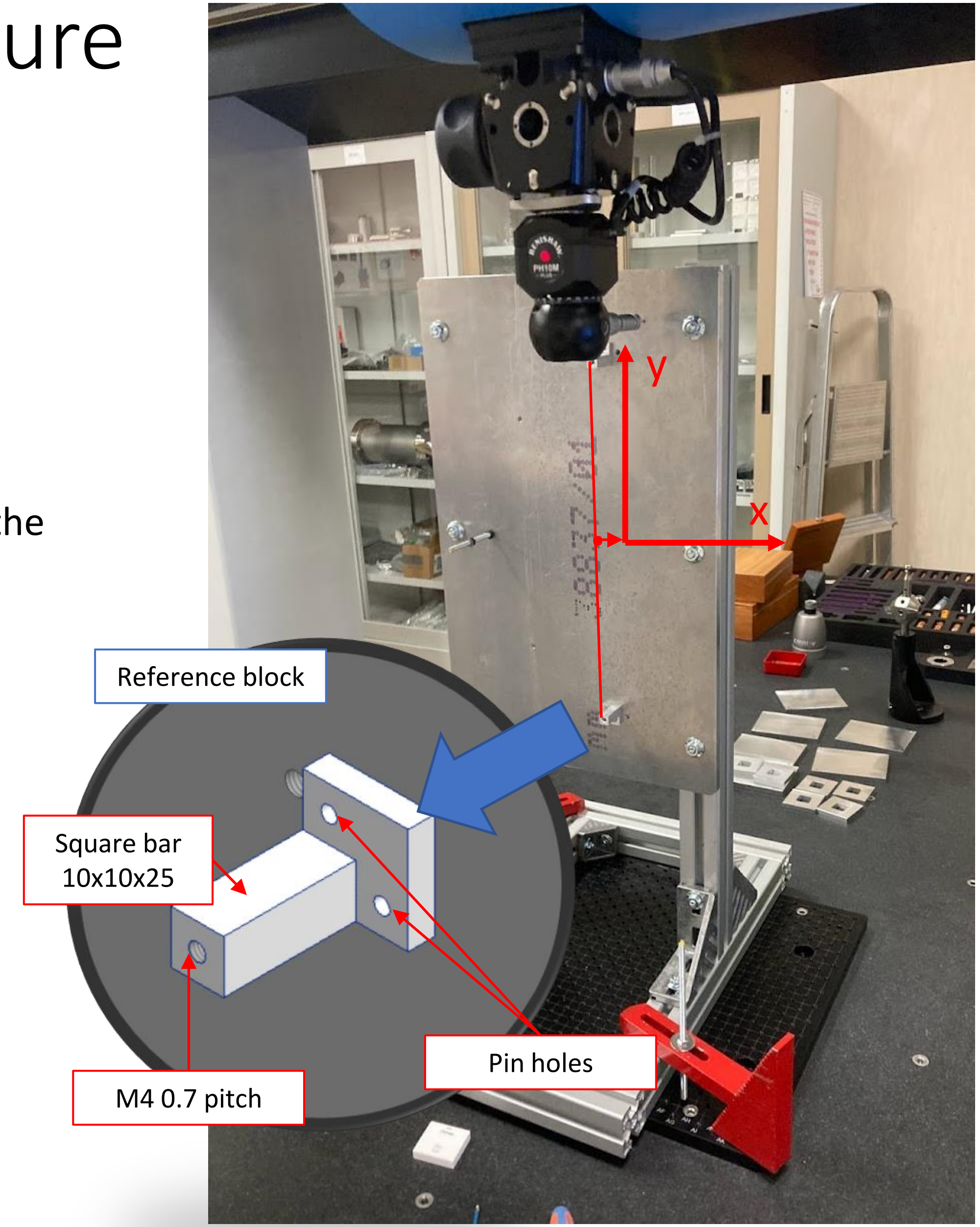
- Measure the aluminum plate to **set the plane z**
- **Measure the reference blocks** position to define their axis
- **Extrapolate the center position**

Procedure:

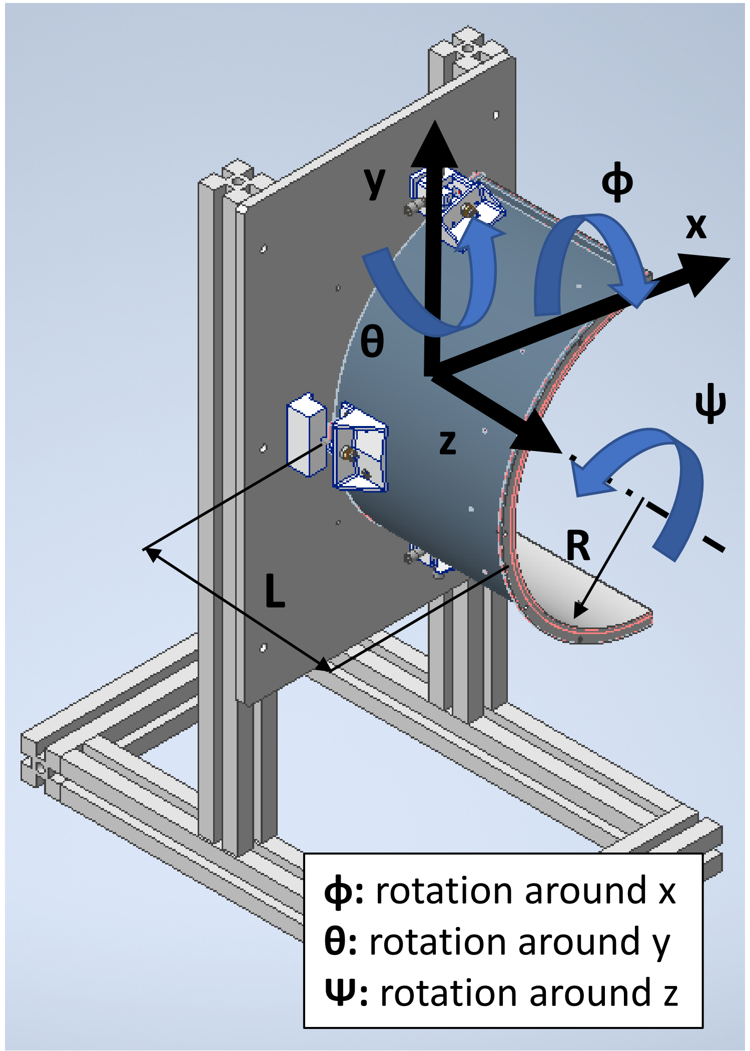
- **Mount the External cylinder**
- **Connect the position adjuster** into the brackets and lock their headless screws to the reference block
- **Measure** the position of **the axis of the External cylinder**, taking as reference the external surface and the flange plane
- **Calculate and apply the adjustments** to take the external cylinder into the correct position and orientation
- Re-measure the position and **re-iterate this procedure** until it reaches the final position with the correct precision

Goal:

- **Position the cylinder axis into x=y=0 ± 0.050 mm**
- **Position the cylinder axis into zp=226.5 ± 0.050 mm**
- **Orientation misalignment = 0 ± 0.1 °**



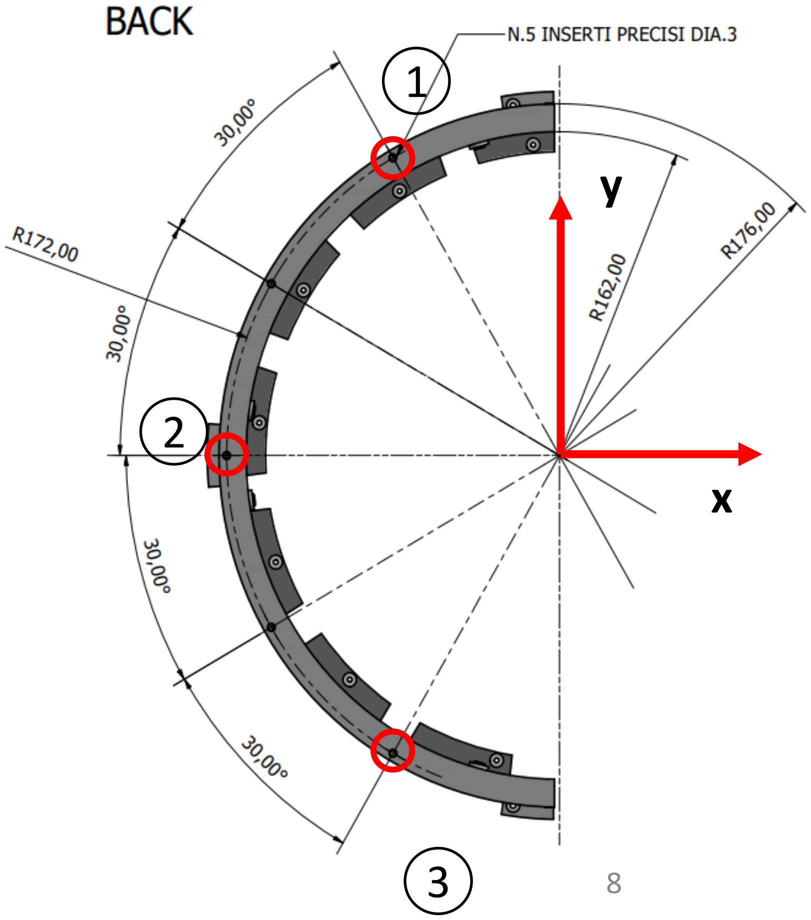
Posture estimation



- **External cylinder measure**
  Measure all the relevant External cylinder features
- **External cylinder mounting and measuring**
  Mount the cylinder and measure the previous features. Compare their position relative to a new given reference system
- **Center position calculation**
  By measuring the external surface of the cylinder and projecting the axis on the front flange plane
- **Orientation calculation**
  By measuring the position of three holes on the front flange and comparing them with their exact position, we estimate its orientation. The result is given by solving a linear equation system coming out from the trigonometry study of a rigid body affected by small rotations along three axis

The assumption of rigid body was validated by a load test on the external cylinder.

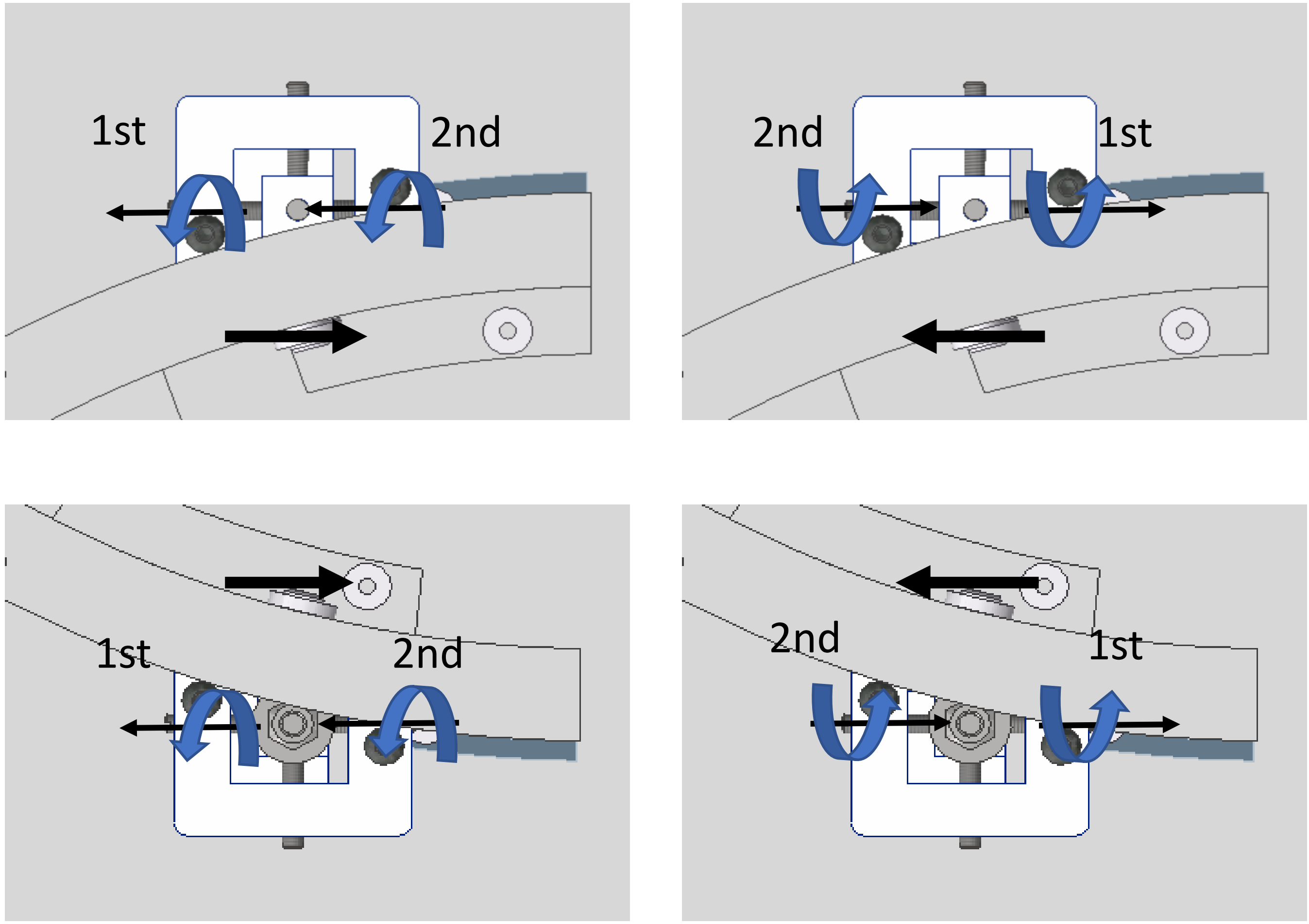
	Nominal		Measured	
	x [mm]	y [mm]	x [mm]	y [mm]
Point 1	-86,000	148,956	-86,361	148,957
Point 2	-172,000	0,000	-172,553	-0,285
Point 3	-86,000	-148,956	-86,399	-149,512

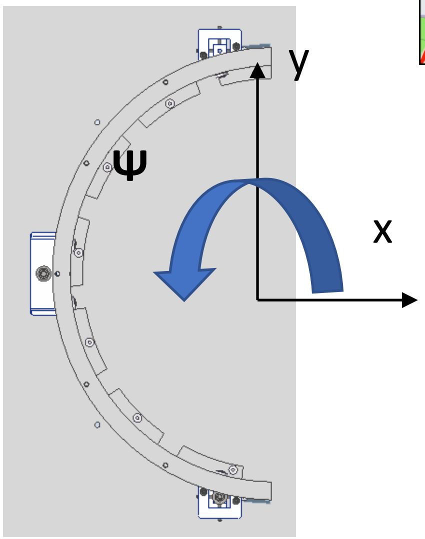


Movement criteria

x +

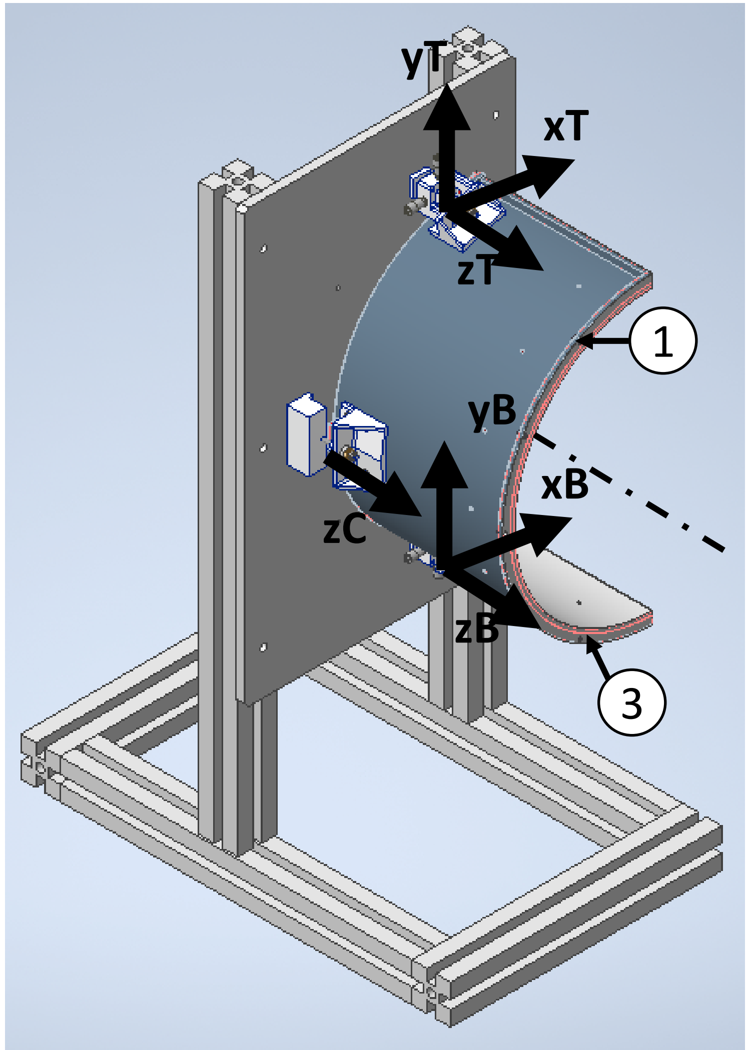
x -





Example for direction x

Adjustments calculation



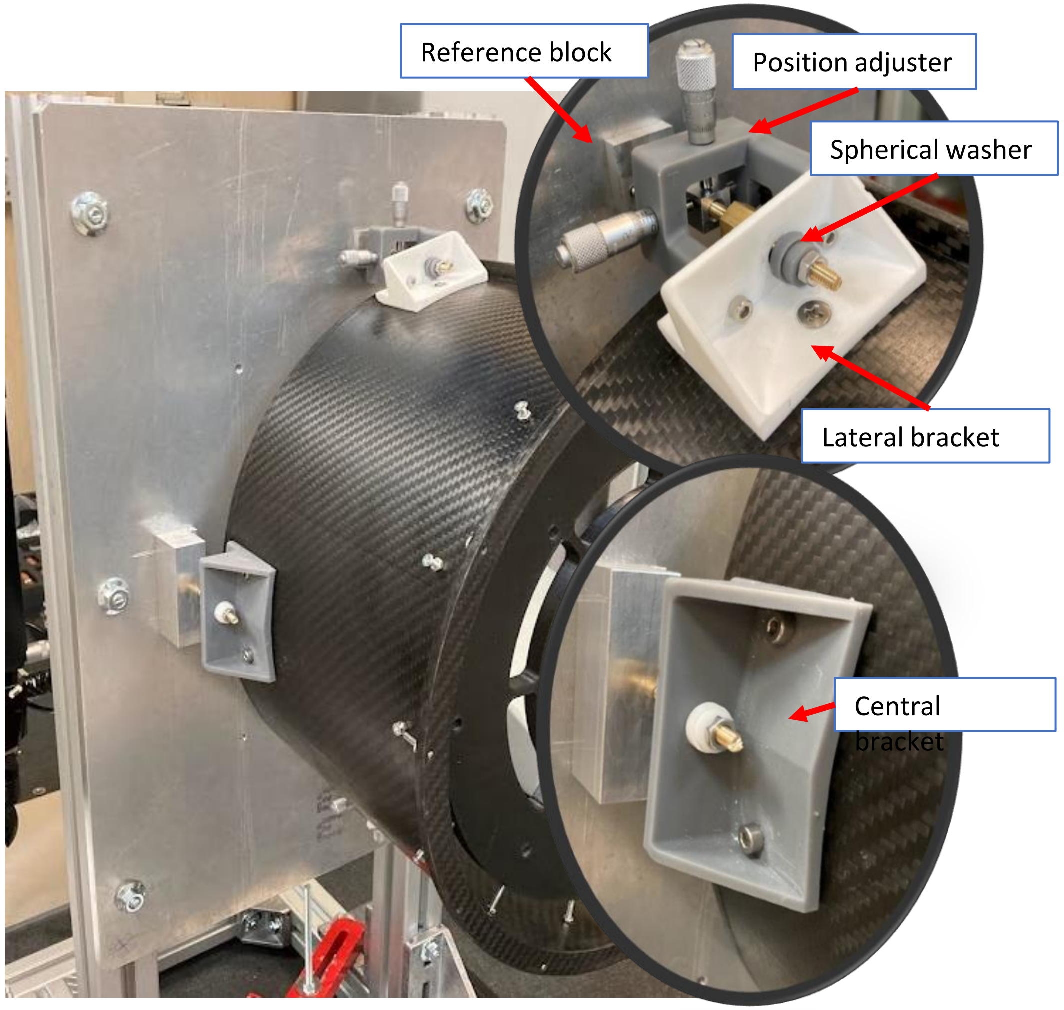
A program was developed to calculate the adjustments required by the connector based on the measure taken on the cylinder. The goal of the program is to take:

- θ,ψ, ϕ, xc, yc → 0
- zp → 226.5 mm

Input:
xc, yc, x1, y1, x3, y3, zp

Estimated parameters:
θ,ψ, ϕ

Output:
xT, xB, yT, yB, zT, zC, zB



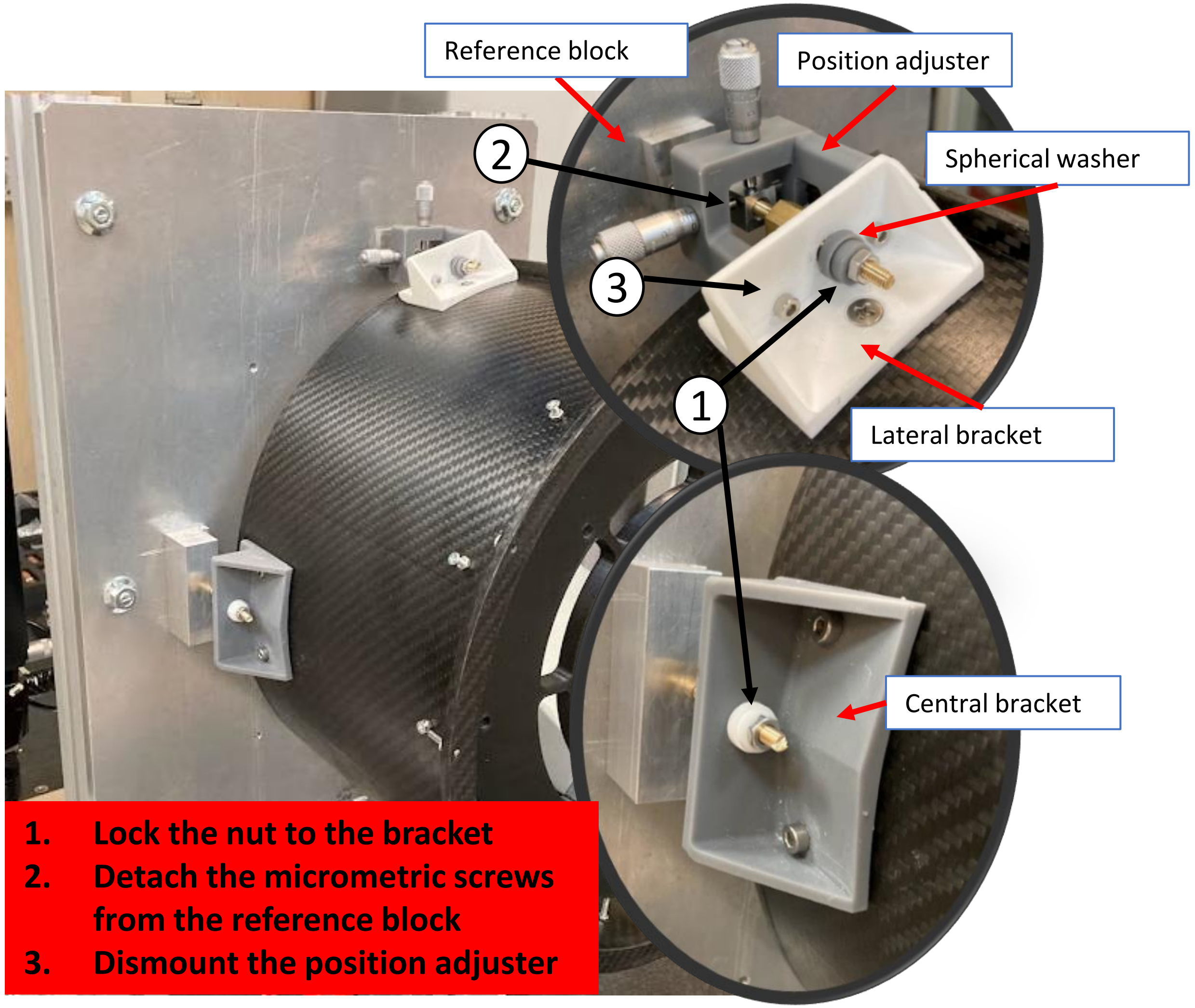
Final fixing

The locking steps are:

1. Lock the nut to the bracket
2. Detach the micrometric screws from the reference block
3. Dismount the position adjuster

The main problematics of all this procedure are:

- **Friction between screws and reference block**
  It causes difficulties during the regulation since the cylinder stucked into position and it doesn't slide
- **Internal forces**
  Due to hyperstaticity some internal forces are created, which causes friction and displacements. It is possible to avoid them by not overtight the connections



Regulation example

Measure 1	x [mm]	y [mm]	z [mm]	xT [mm]	yT [mm]	xB [mm]	yB [mm]
1	-0.272	-0.317	227.179	-84.074	148.750	-87.412	-149.650
4	0.018	0.021	226.571	-85.686	149.222	-85.717	-149.229
4 locking the counter nuts	-0.037	0.123	226.685	-85.883	149.300	-85.579	-149.151
4 dismounting the adaptor	-0.193	0.067	226.696	-85.948	149.251	-85.665	-149.280

	Nominal		Measured	
	x [mm]	y [mm]	x [mm]	y [mm]
Point 1	-86,000	148,956	-86,361	148,957
Point 2	-172,000	0,000	-172,553	-0,285
Point 3	-86,000	-148,956	-86,399	-149,512

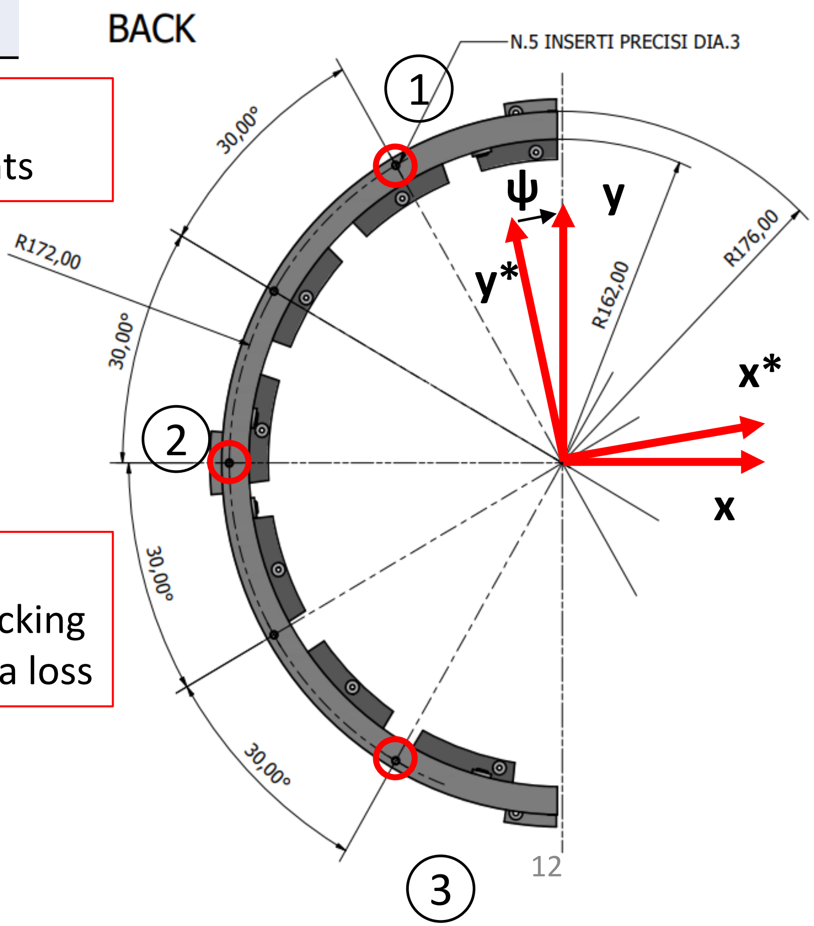
ψ ≈ 0 , ϕ≠0, θ≠0

ϕ, θ is more difficult since it's regulated by regulating the z position of the connection points

Measure 2	x [mm]	y [mm]	z [mm]	θ [°]	ψ [°]	ϕ [°]
1	0.417	-0.089	226.511	0.70	0.04	0.41
5	0.074	0.054	226.491	0.10	0.04	0.10
5 locking the counter nuts	0.034	0.142	226.482	0.12	-0.01	0.13
5 dismounting the adaptor	-0.130	0.151	226.505	0.13	0.005	0.10

ψ ≈ 0.01 ° , ϕ ≈ 0.1 °, θ ≈ 0.1 °

It's obtained a good precision for the cylinder orientation, but the precision loss due to the locking can still be reduced. Further tests are planned to simplify the locking system and reduce such a loss



Results

Relative precision	x [mm]	y [mm]	z [mm]
After adjustments	**0.050**	**0.050**	**0.050**
Locked	**0.200**	**0.200**	**0.100**

Current system evaluated precision

Tolerance in z direction:
100 µm

Tolerance in x and y directions:
200 µm

This is just the precision of the connection between TFPX and the External cylinder, for the total evaluated precision we need to take into account also the rest of TBPX components

Conclusion

- The main result of this system is the capability of controlling and regulating a 3D system by a simple manual system. Indeed, in our case we reached a precision into the positioning below 50 µm for each direction and below 0.1 °
- Even if we reach a good precision into the positioning and the regulation, the system still must be performed by reducing the precision loss due to the final locking
- Furthermore, this connection decouple the cumulative error given by connecting multiples parts, being able to mount the External cylinder referred to a given reference system.
- This system has been tested under a Coordinate Measuring Machine (CMM) with a touch probe in a clean room. It will be tested also with the condition of the final installation, with a portable CMM or laser tracker

Backup slides

Movement criteria