The CMS Outer Tracker endcaps

All the tools needed

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Forum on Tracking Detector Mechanics
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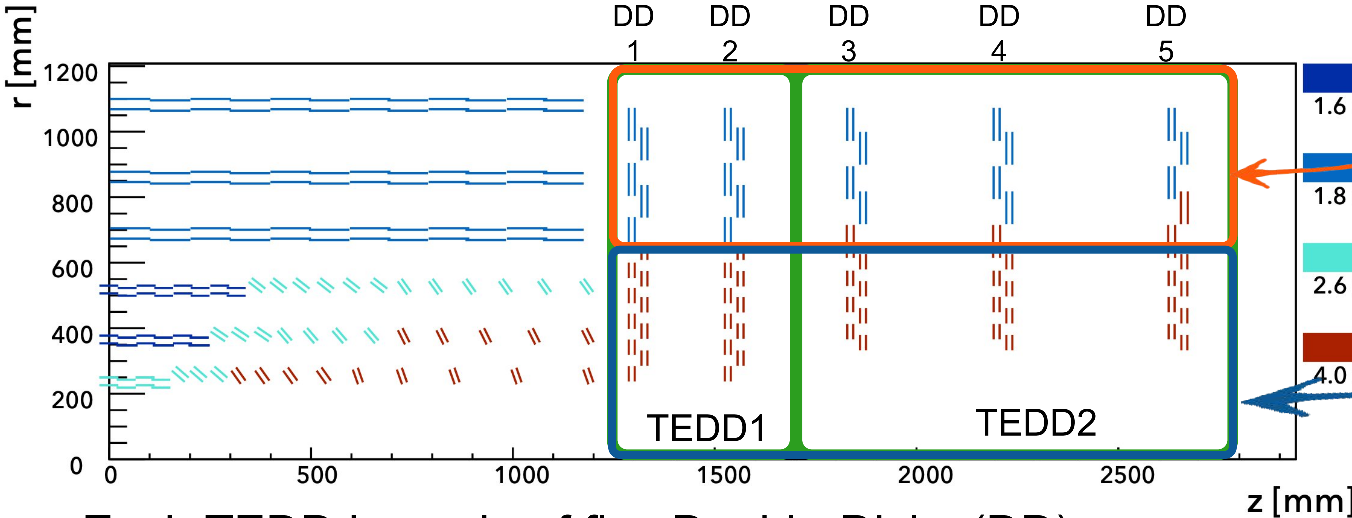
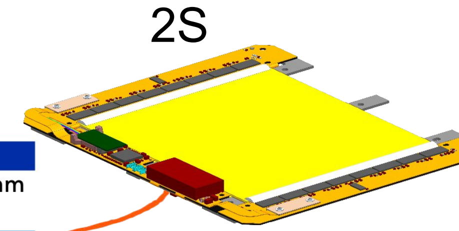
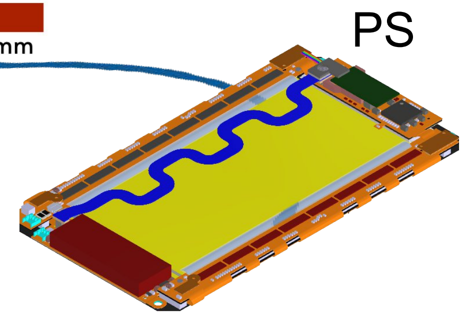
HELMHOLTZ

DESY.

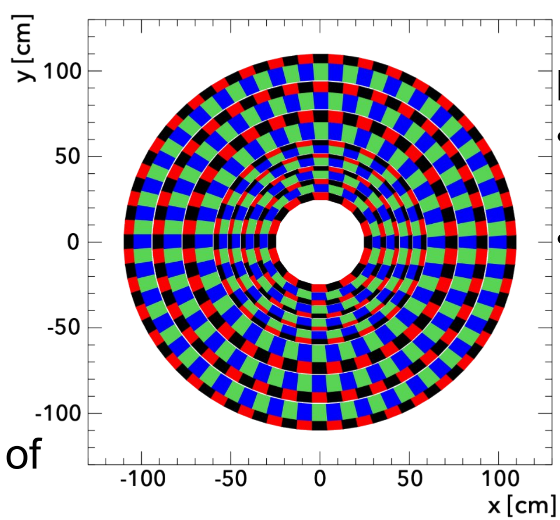
TEDD overview







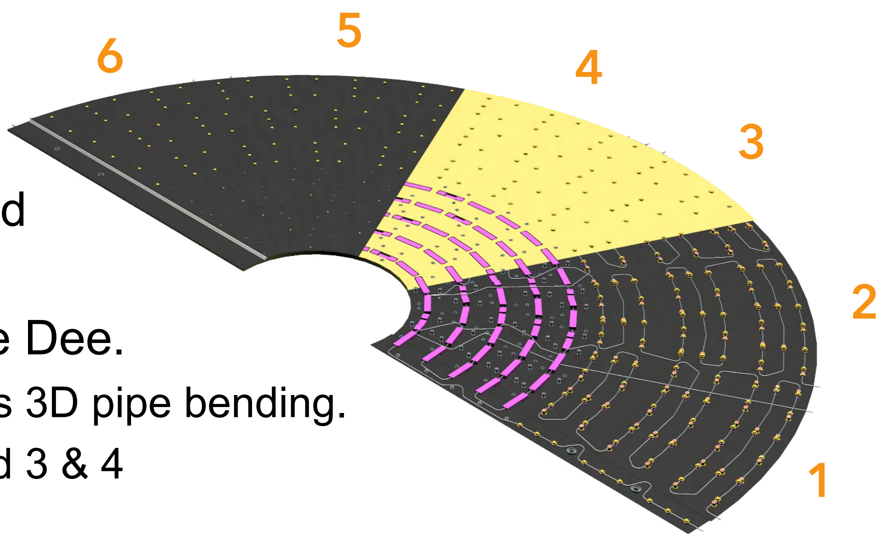
- Each TEDD is made of five Double-Disks (DD)
  - TEDD1: DD1 & DD2
  - TEDD2: DD3, DD4 & DD5
    - TEDD2 has larger radius inner bore
- Modules are arranged in rings, numbered from inner to outer per DD.
- A DD comprises an even and an odd Disk, given by which rings have modules.
- Each disk is made of two half-disks (Dees).
  - Dee is the largest feasible structure, backbone of the mechanical structure.

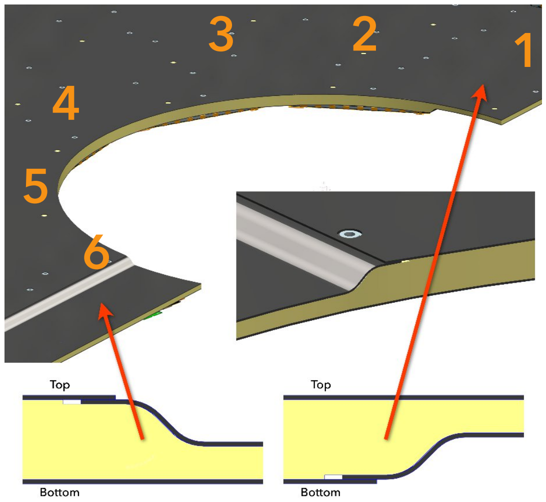


Modules on
- odd disk front/back
- even disk front/back

Dee Design

- Highly embedded 10 mm thick Sandwich
  - Airex foam core
  - CFRP facings
- Symmetries as much as possible exploited in the design.
- 6 cooling sectors routed in two tiers inside Dee.
  - Allows cooling sectors to overlap and avoids 3D pipe bending.
  - Identical design for sectors 1 & 6, 2 & 5, and 3 & 4
- Step at straight edge of Dee
  - Pipe routing requires step to be on opposite sides.
- Modules are positioned with Al inserts.
- Additional inserts for
  - Definition of Dee coordinate system for metrology.
  - Dee-to-Dee and Disk-to-Disk assembly.
  - Patch panel support ring and global TEDD mechanics mounting.

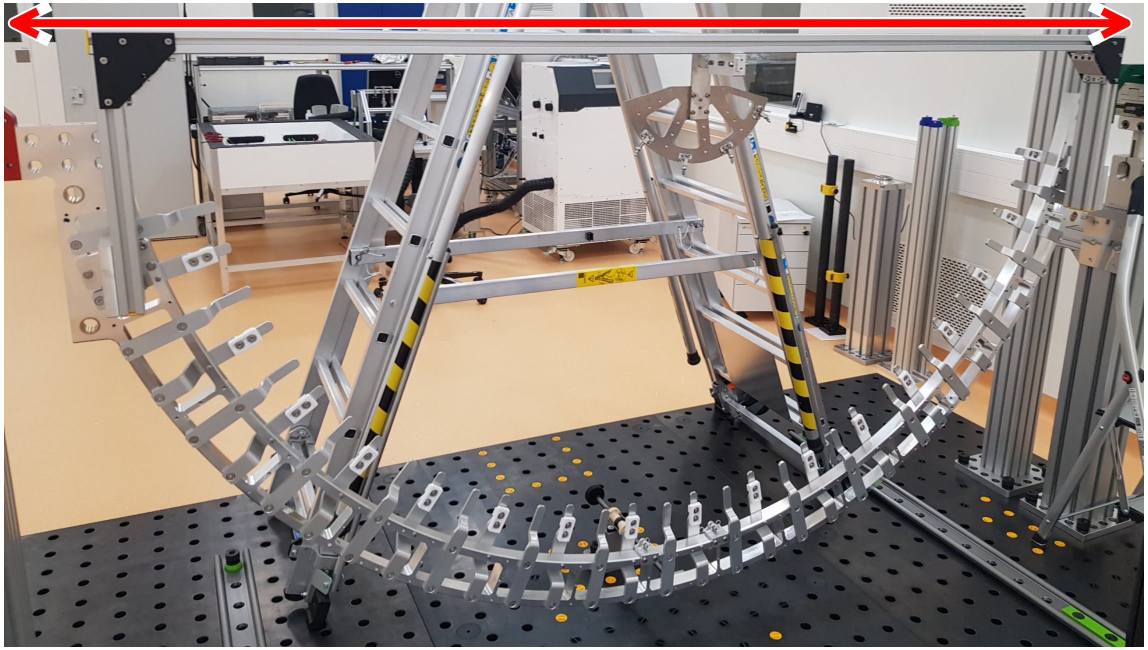




Arc frame

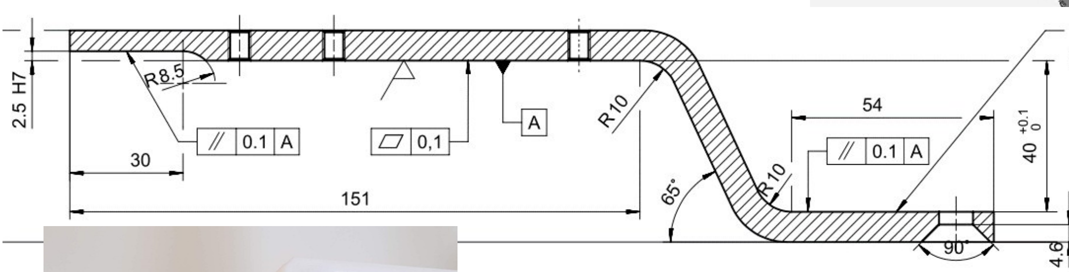
- Dee with modules can't be handled manually. Dedicated holding structure - Arc frame - was designed. Each Dee will rest in its own Arc frame up to almost the last integration step.
- The Arc frame is equipped with support fingers that clamp and hold the Dee.
  - Fingers are equipped with radial constraint sliders.
- A cross bar with inner edge support provides additional support for some integration steps and during transport.
- Interfaces to all toolings (fixations, transport box, stages etc.)
- Arc frames can form a ring in disk assembly and two rings can be connected in the DD assembly.

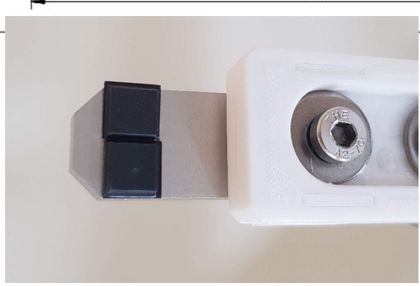
2.7 m

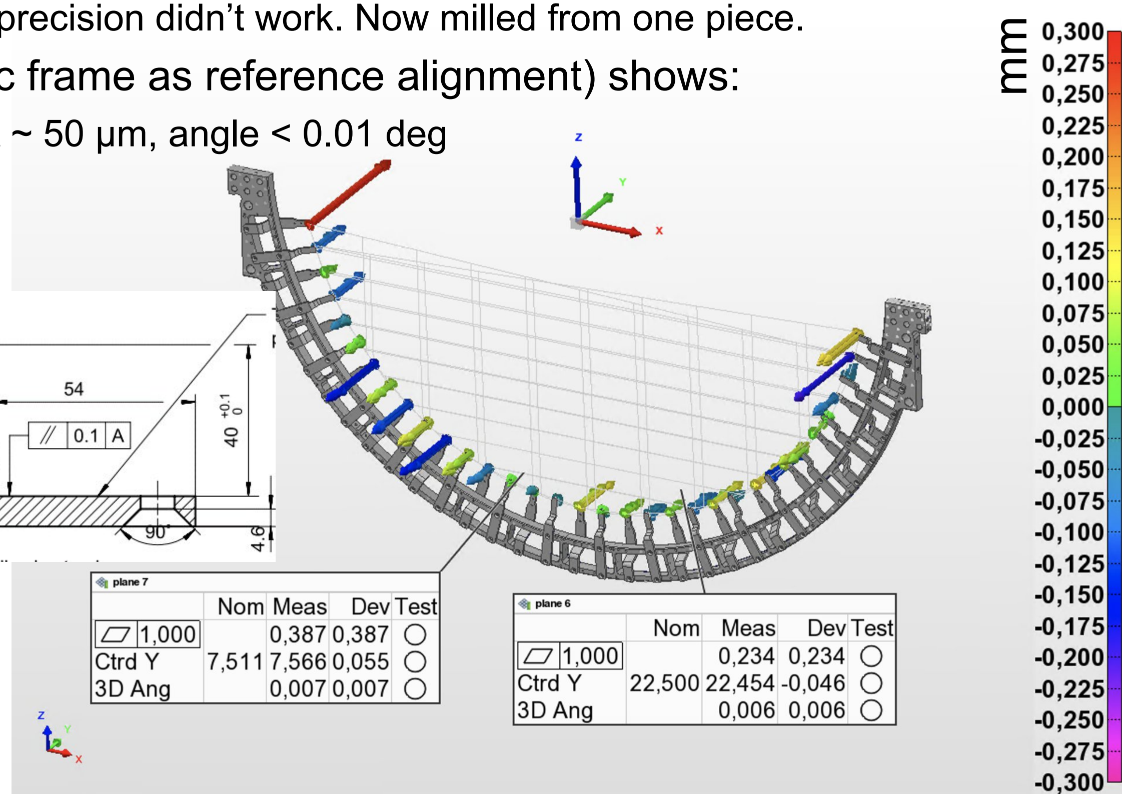


Arc frame precision

- Dee flatness specified to 1 mm. —> Arc frame, other toolings and the integration procedure must not deteriorate the flatness of the Dees.
- Arc is machined from one plate of cast Aluminum with the surface milled flat.
  - Raw material flatness 0.1 mm per m.
- Top and bottom fingers form a plane that must hold the Dee flat and accurately relative to the Arc frame itself.
  - Fingers are tightly toleranced.
  - Bent sheets milled over to achieve precision didn't work. Now milled from one piece.
- Measurement of finger planes (Arc frame as reference alignment) shows:
  - Flatness < 0.5 mm, centeroid offset ~ 50 µm, angle < 0.01 deg
- Rubber pads on the fingers compensate some deformation.







plane 7

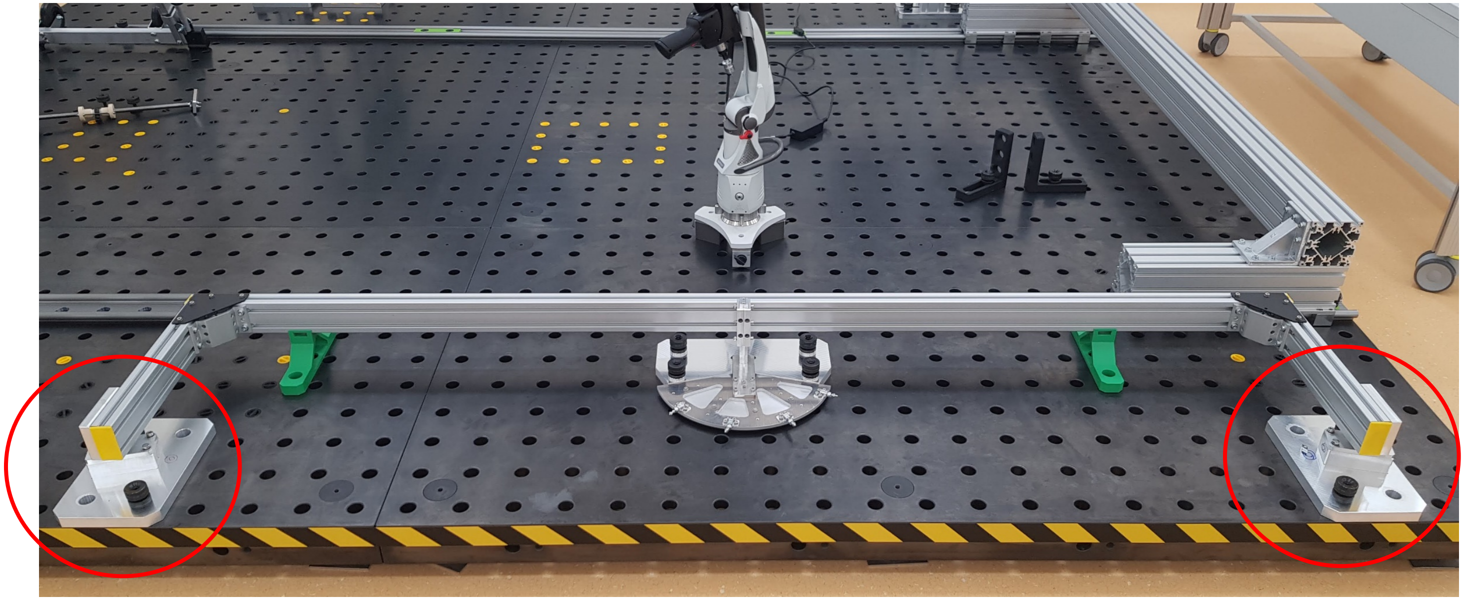
	Nom	Meas	Dev	Test
▱ 1,000		0,387	0,387	○
Ctrd Y	7,511	7,566	0,055	○
3D Ang		0,007	0,007	○

plane 6

	Nom	Meas	Dev	Test
▱ 1,000		0,234	0,234	○
Ctrd Y	22,500	22,454	-0,046	○
3D Ang		0,006	0,006	○

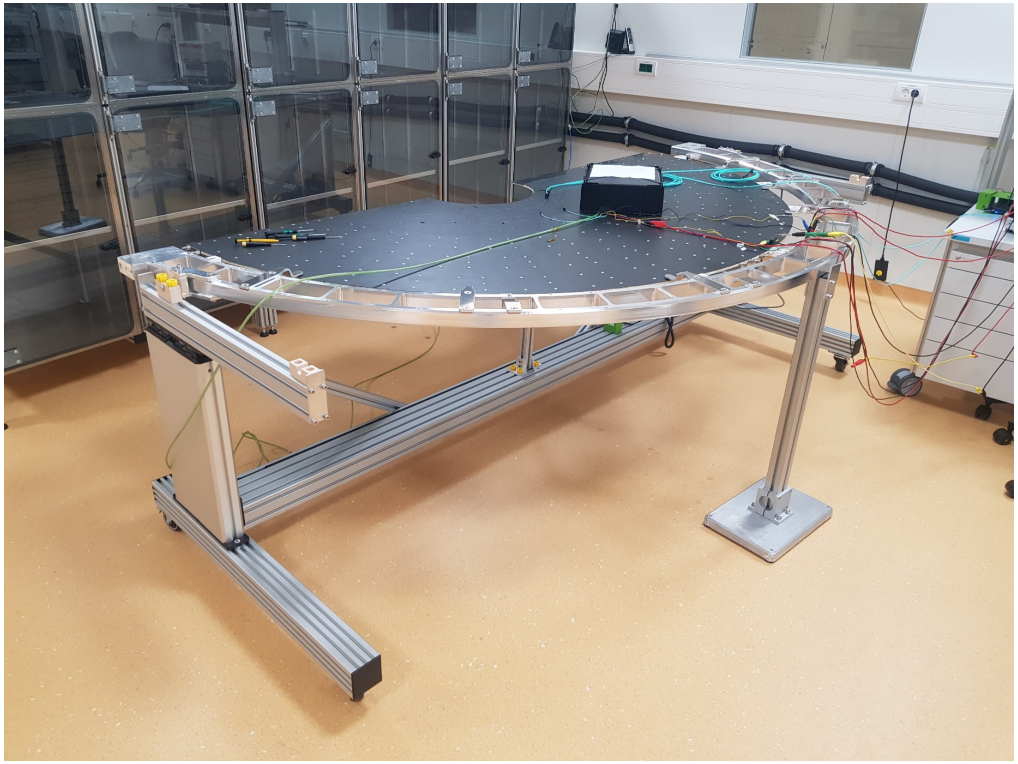
Cross bar

- Dees need support in the center when horizontally or turned upside down.
- To assemble the cross bar as precise as possible, a construction jig was built on our assembly platform.
  - 3D position and orientation of the attachment points were measured with metrology and re-machined to form a flat surface.
- When Dees are finally installed, the central support needs to be adjusted to maintain the flatness of the Dee based on metrology measurements.



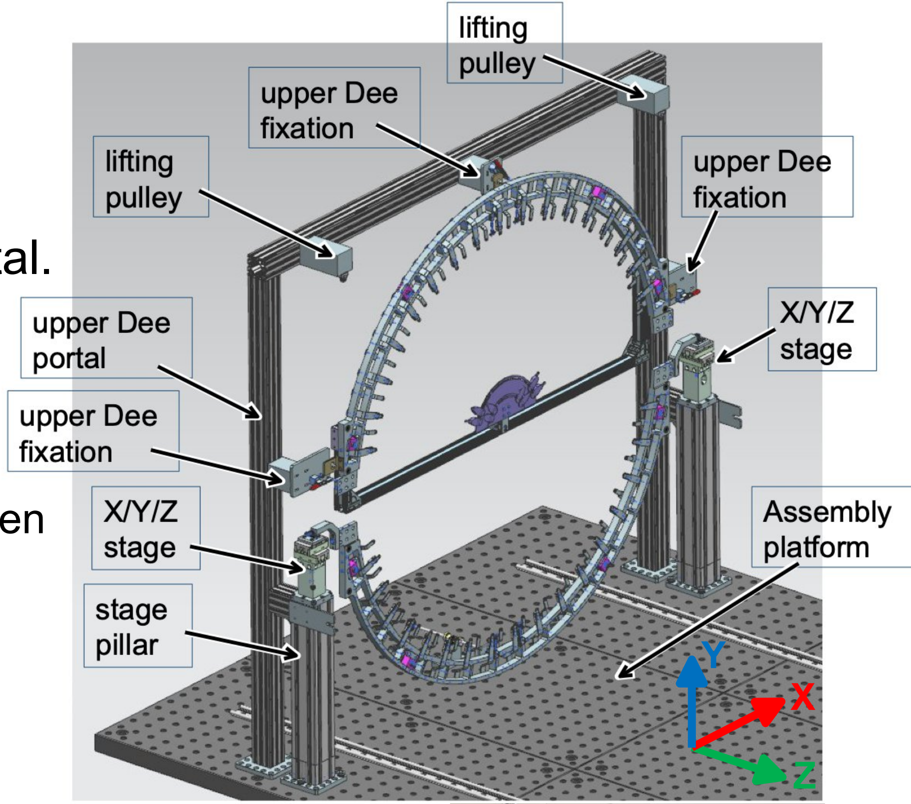
Dee integration trolley

- Tooling to hold and position the Arc frames during module integration.
- Rotates freely with 3rd support locking the rotation.
- Designed to have an as comfortable as possible working height.



Disk assembly

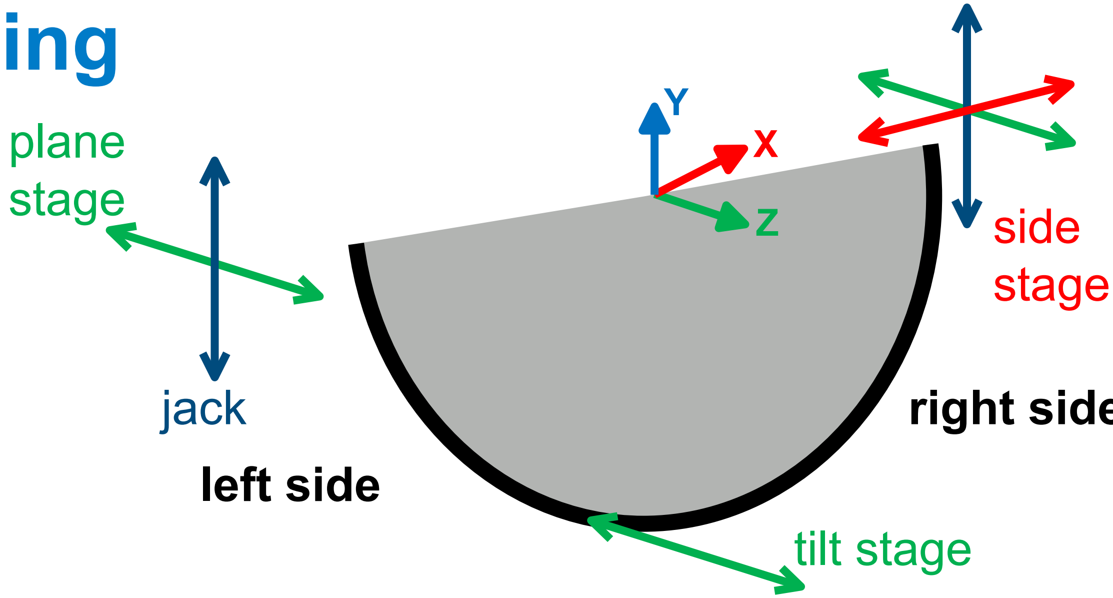
- Upper Dee is mounted on upper Dee portal.
- Lower Dee is placed on x/y/z stages.
- Position of lower Dee wrt. upper Dee is measured with a metrology arm.
  - Iterative process with measurements between movements.
- Lower Dee is
  - rotated out of plane (around y)
  - moved upwards
  - rotated back into the Disk plane
- When both Dees are align they are connect by bolts through the Dee-to-Dee inserts.
  - Mainly serves to fix the relative positioning. The connection is not structurally strong.
- Upper and lower Arc frames are mechanically connected.



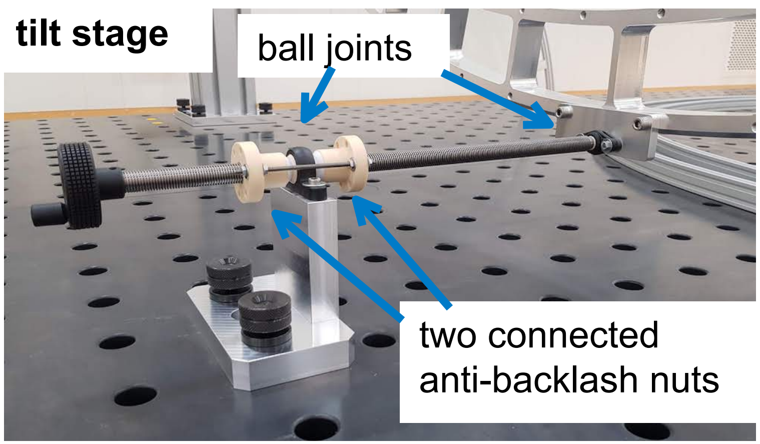
Disk assembly tooling

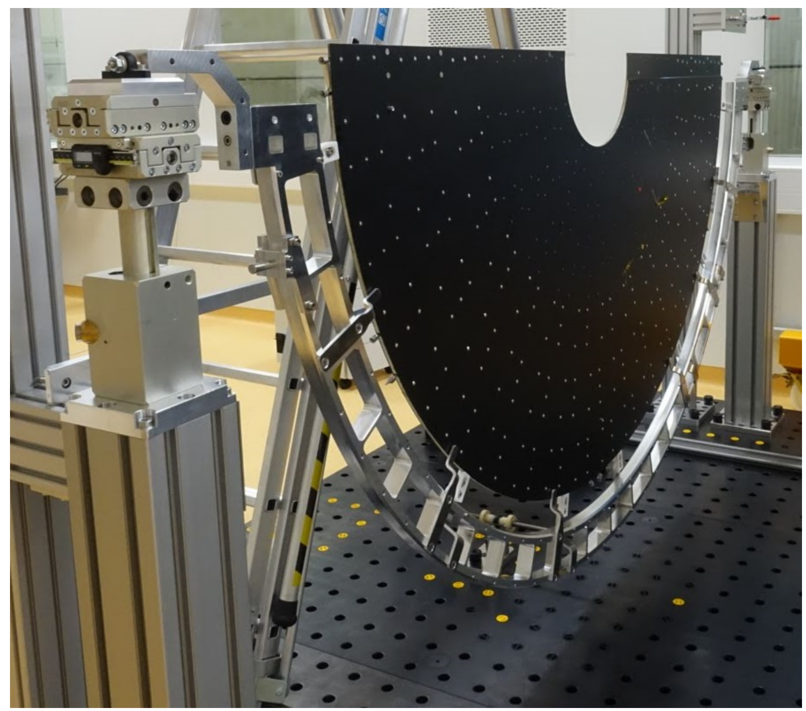
Lower Dee on stages

- Six stages allow 3 translations and 3 rotations.
- Side stage on the left is freely moving along X.
- Tilt stage freely moves in X/Y.



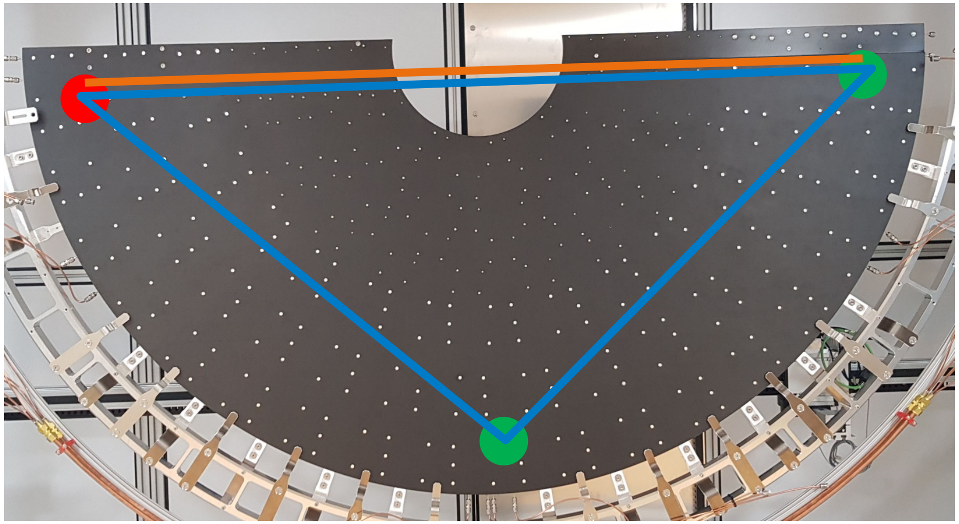
tilt stage





Basic metrology concept

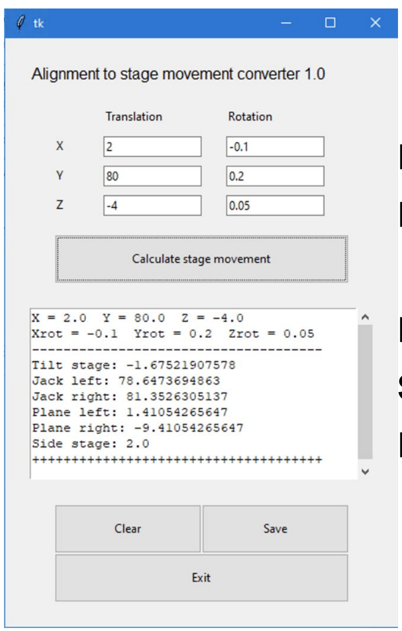
- Different “features” (plane, point, line, cylinder etc) are measured and compared to their nominal values.
- CAD model gives ideal shape from which the nominal features are extracted.
- The coordinate systems of the CAD model and the metrology arm must be aligned.
  - Certain measured features are defined as ideal: Plane-line-point alignment, three orthogonal planes, fit of point cloud.
  - Measurement results can depend heavily on the chosen alignment.



- Three reference inserts form a plane, a line and give a point.
- Alignment results change depending on selection of points.
- Additional reference inserts are available including on the outer and inner edges.
- Relative position differences of the various reference inserts will need to be measured.

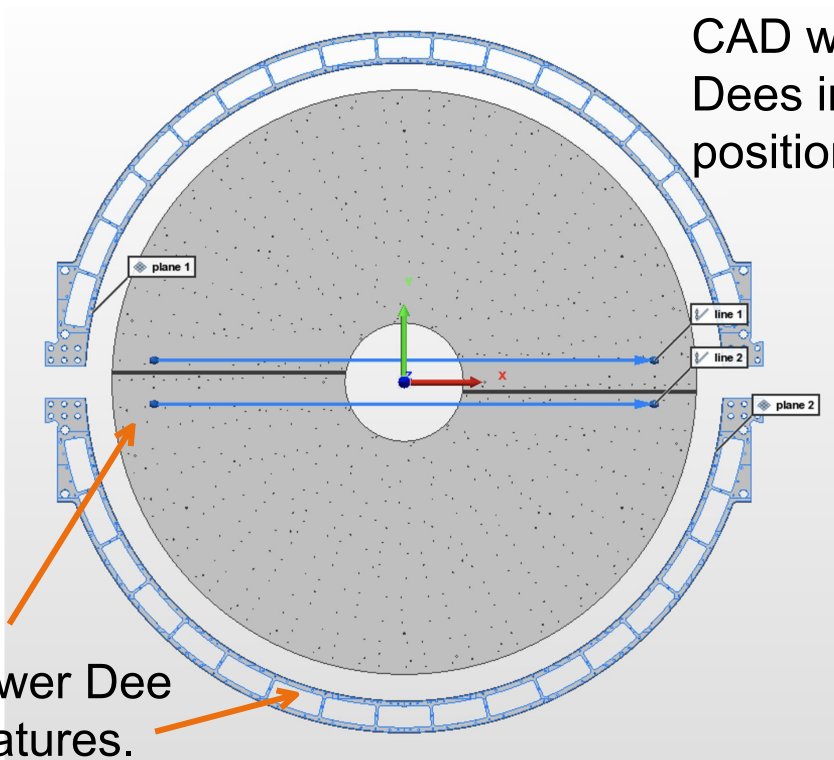
Alignment procedure

- Make separate alignment for upper and lower Dee.
  - Primary alignment plane uses the Arc frame surface.
  - Two reference inserts (forming a line and a point) to define the position in the X/Y plane.
- Obtain relative difference between both alignments (Software feature)
- Custom tool to convert relative alignment to stage movements needed for optimal alignment.



measured misalignment

required stage movements

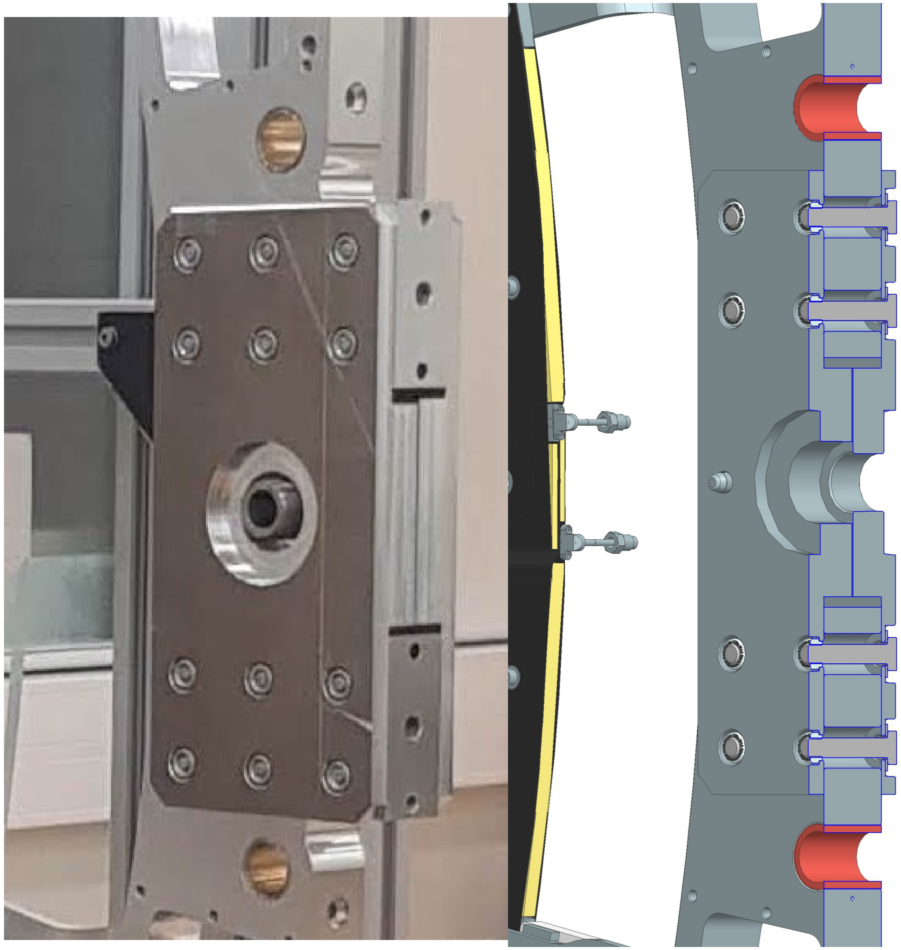


CAD with both Dees in final position.

upper and lower Dee alignment features.

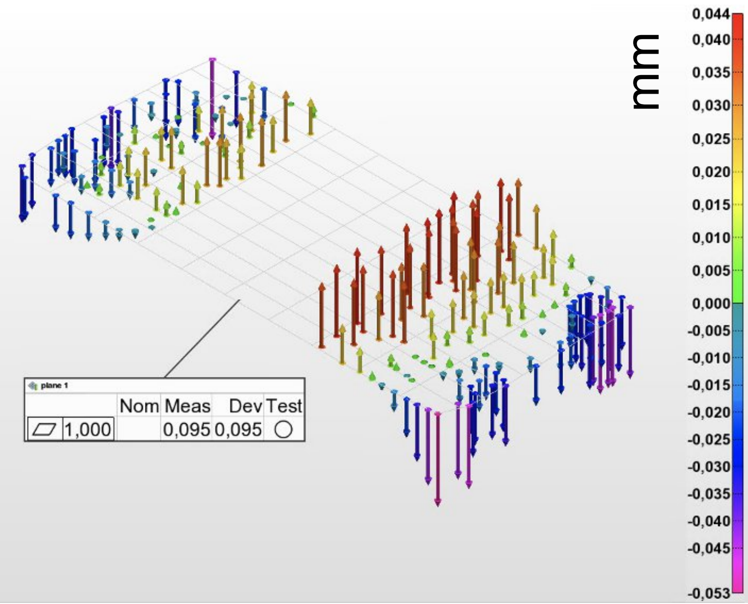
Ring connection

- Merging of two arc frames to a ring must maintain the position and create a rigid connection.
- The two arc frames are sandwiched between plates.
  - Requires the Arc frame surfaces to be perfectly aligned.
  - The Dee out-of-plane position has to be exact relative to the Arc frame.
- Within the plane, the Dee positions are used for alignment, hence Arc frames are never well aligned.
  - Large play in the screw holes
- Due to the limited space, Al plates have press in nuts.

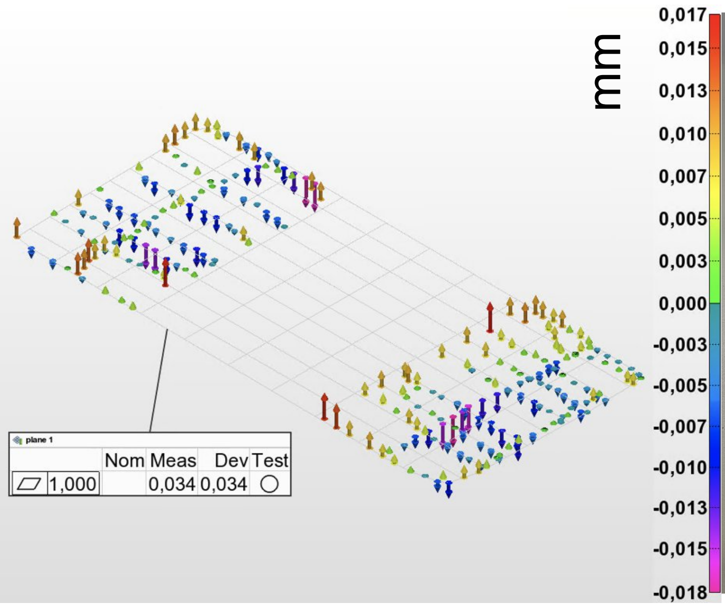


Ring connection performance

- Connection plates must be very flat to not have a kink in the circle.
- After pressing the nuts, plates are deformed and need to be re-machined
- Final machining is done with workpiece glued to a support to avoid clamping forces. Target flatness 25 µm.
  - Test of flatness limited by accuracy of our measurement arm.



after pressing nuts

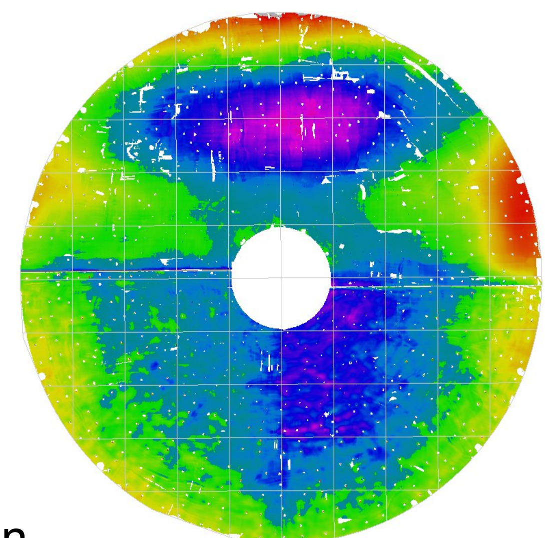


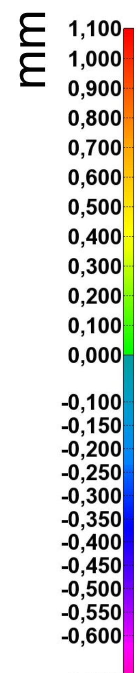
after re-machining

glue on support

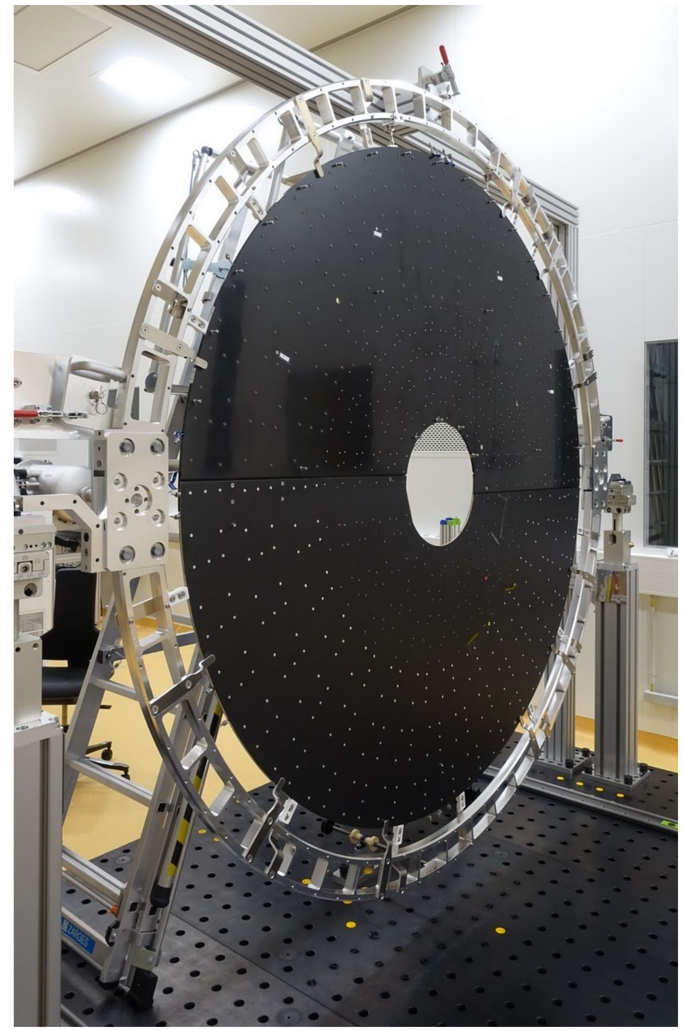
Prototype Disk

- Disk assembly procedure was validated using Dee prototypes.
- Flatness of final disk < 1.5 mm
  - Flatness driven by the shape of the upper Dee.
- Alignment withing the plane better than 0.1 mm (taken from the last iteration of the alignment measurement)





Laser scan
Deviation from fitted plane



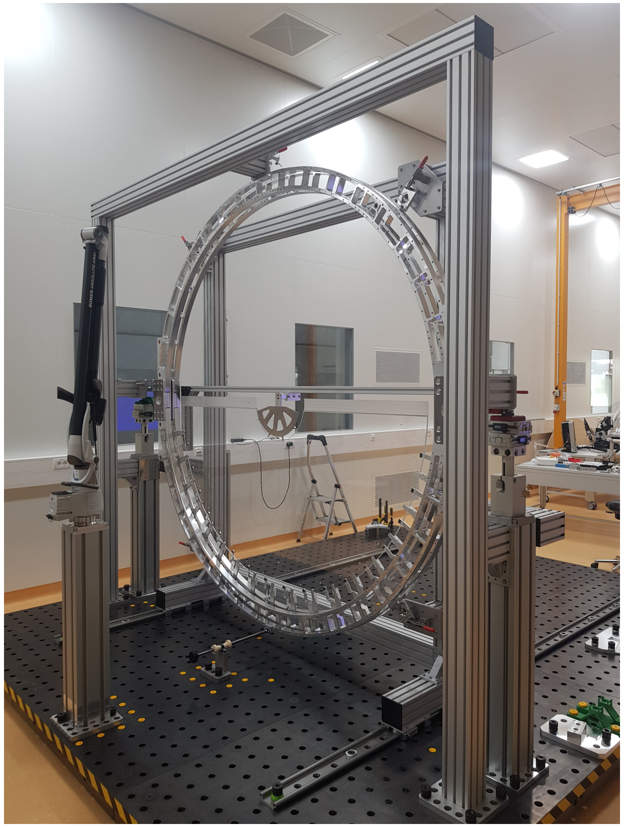
DD assembly

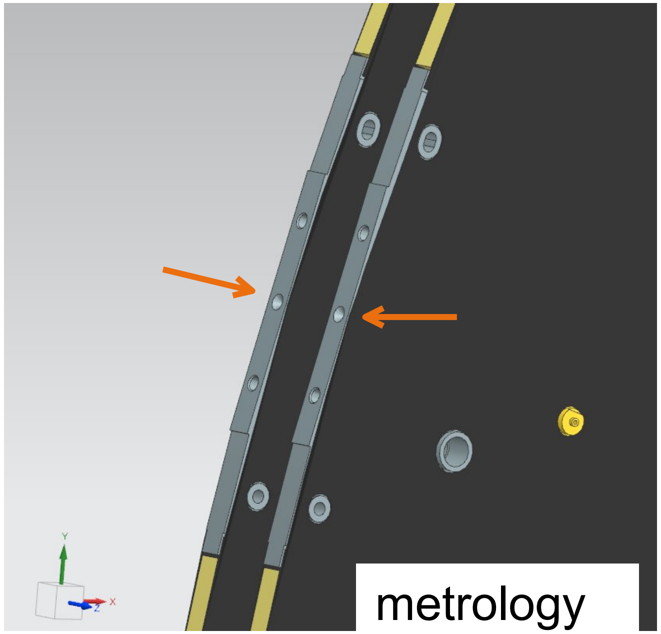
- Rail frame can hold a disk at four fixations (45°)
- Three positions:
  - Parking (away from the disk assembly)
  - Pickup position:
  - Assembly position: Close to nominal distance
- Removable spacer defines pickup and assembly position.
- In assembly position the rail frame is locked to the stage pillar.

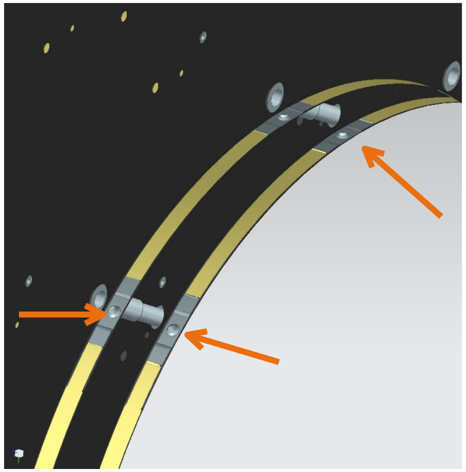
Rail frame in parking

spacer

Disk to disk alignment







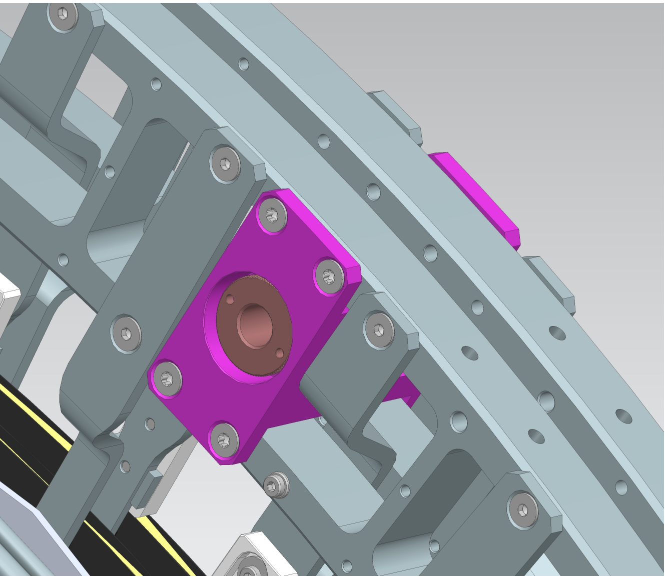
- First disk is brought into nominal distance to second disk.
- Second disk can be positioned with the stages

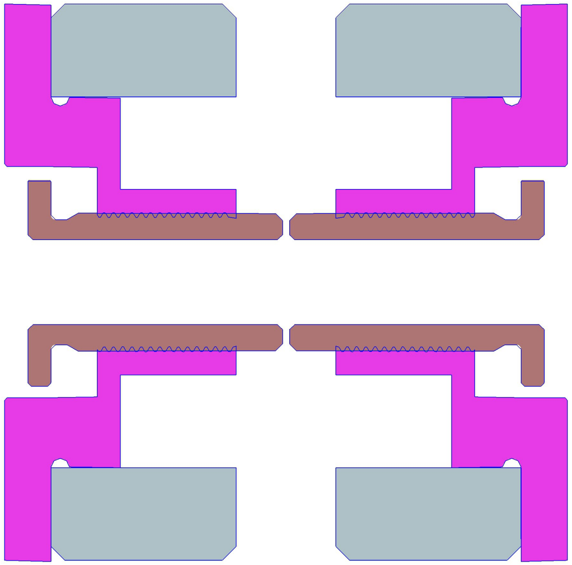
Metrology to align both disks

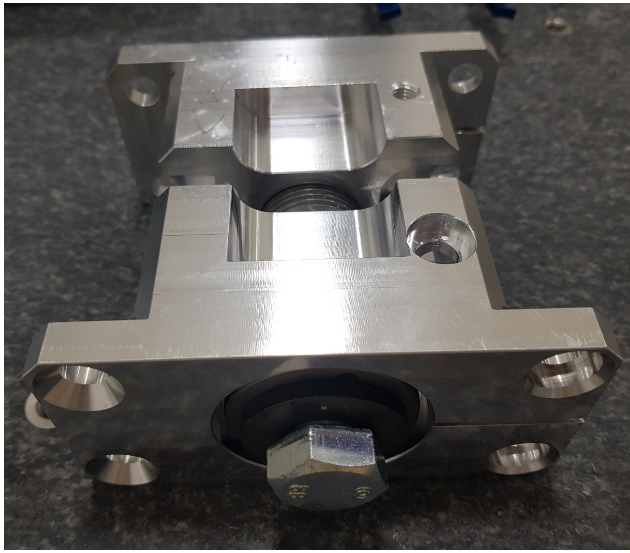
- Will use outer and inner edge inserts, which can be reached from one side.
- Will be exercised once four final Dees are available

Arc rings merging

- Adjustable threaded cylinder as spacer.
  - Technique: adjust until a sheet of paper (0.1 mm) in between moves with resistance. Then engage by another 18° (thread is 2 mm per rotation).
  - A locking screw is used to prevent moving while clamping together.
- Large bolt to clamp both together.

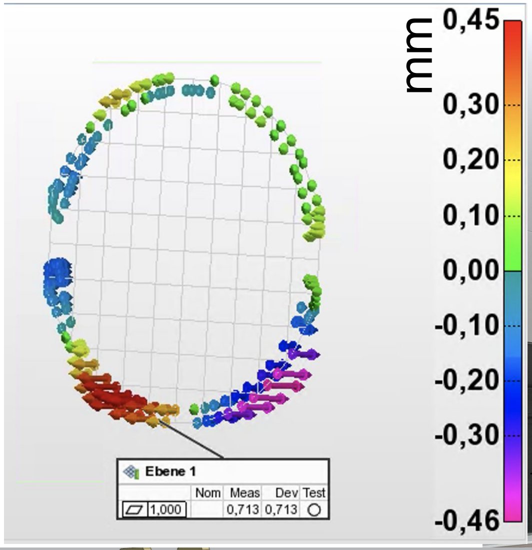


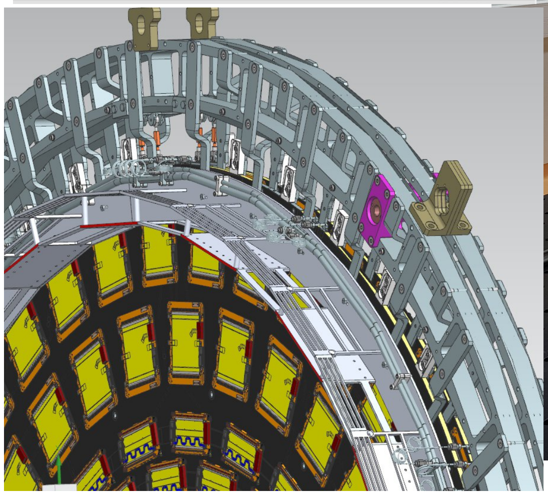


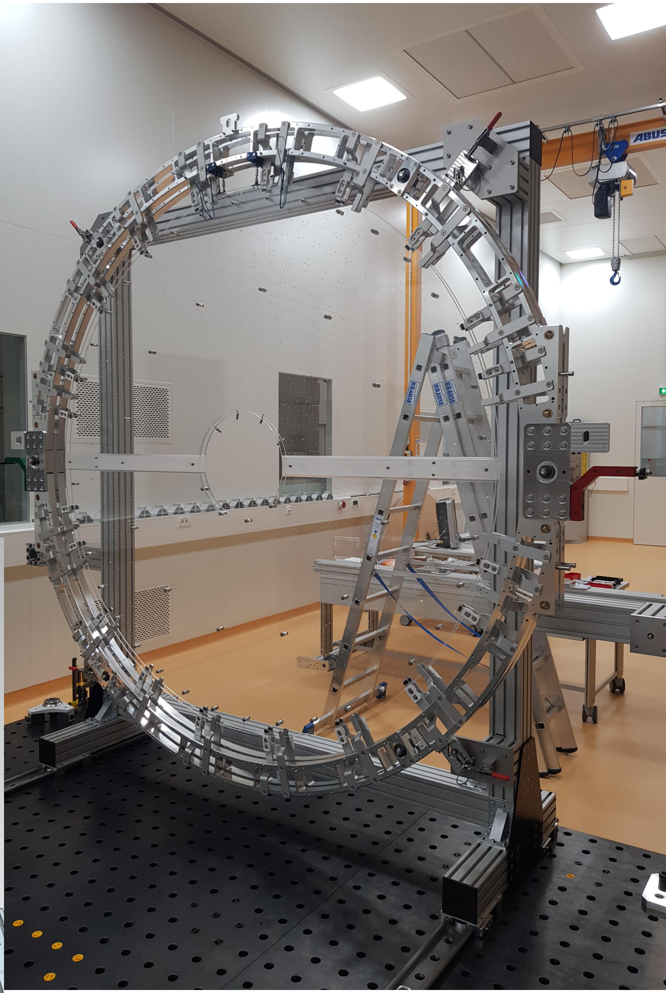


Finalisation of the DD

- After the arc rings are merged the DD is disconnected from the stages and kept on the rail frame.
  - DD kept on the stages showed significant deformation
  - On the rail frame the flatness is conserved.
  - In recent tests: ~0.7 mm flatness.
- In parking position the DD is finalised, e.g. Patch panels are installed.

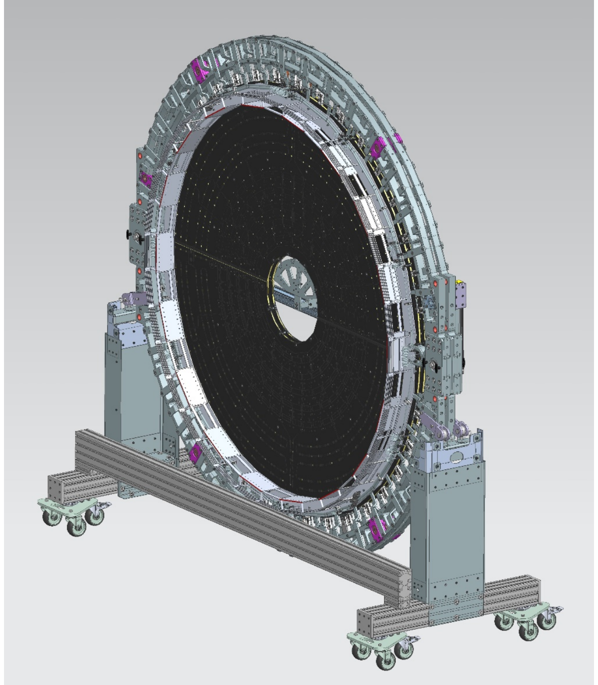


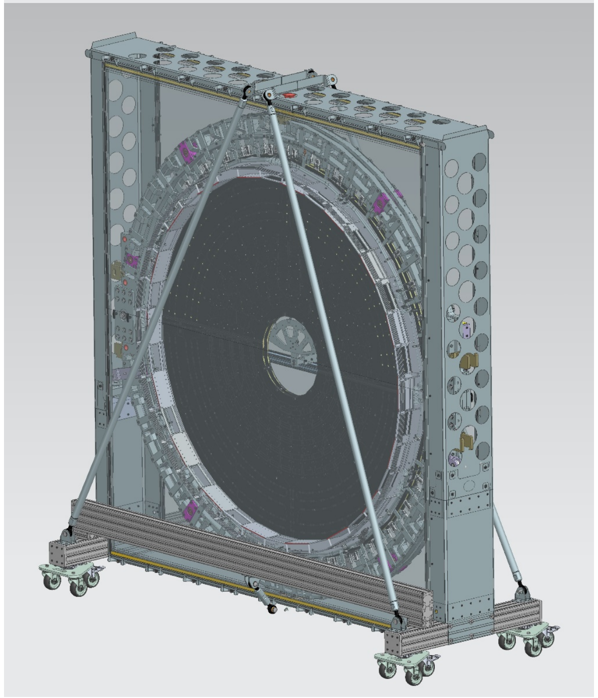




DD storage and transport

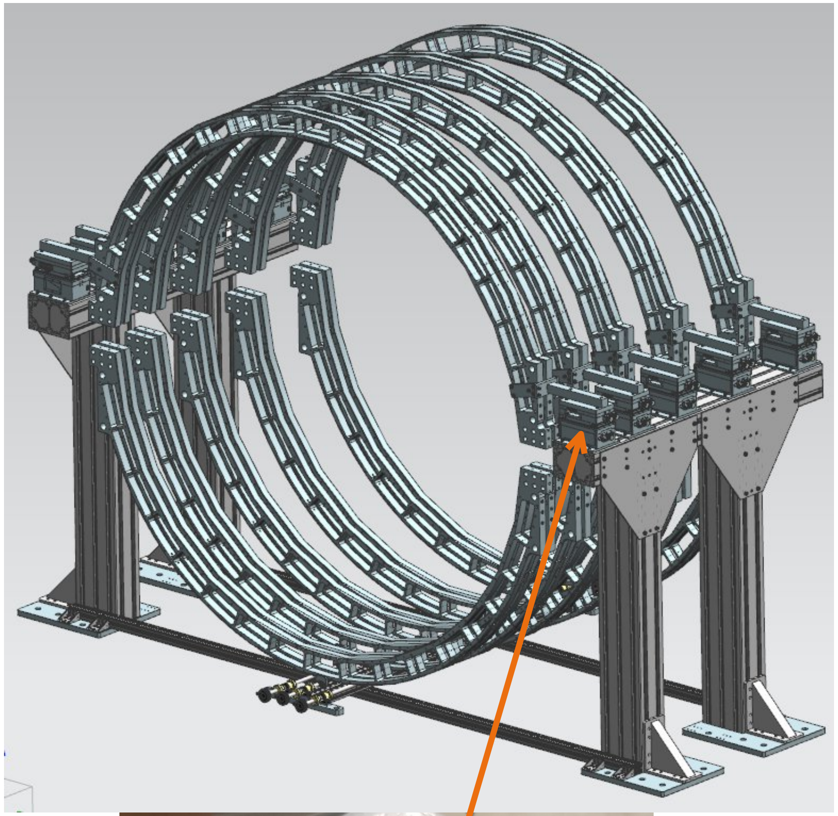
- After DDs have been finalised it needs to be transported and stored for an extended period.
- Feet with rollers are installed.
  - Can be installed while DD is on rail frame.
- For storage a frame is built on it with the faces being covered with foil to allow storage in dry environment
- Additional bars connect to top and bottom for additional rigidity.
- Road transport will require additional protection and vibration dampening.
- Prototype now being built.





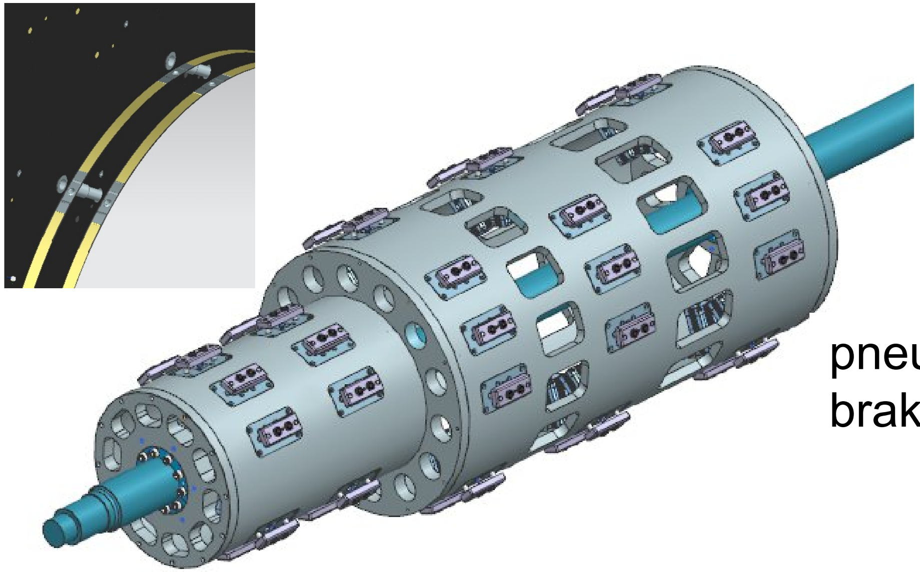
TEDD assembly: DD alignment

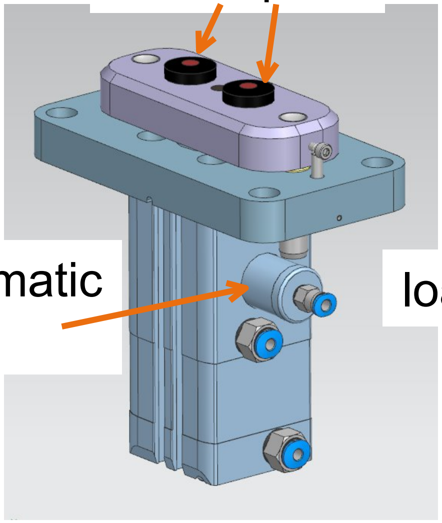
- Same positioning mechanics as in disk assembly, same tilt stage design.
- Each DD is supported by DESY designed EASy stages.
  - +/- 12 mm in X, Y and Z
  - 250kg load capacity.
  - All stages have been delivered.
- DDs can be rolled in and picked up by the stages.
- After all DDs are installed they can be positioned relative to each other.
- Longitudinal beams and inner tube can be installed to mechanically connect all DDs.
- Except stages, only CAD design available. A prototype is planned.

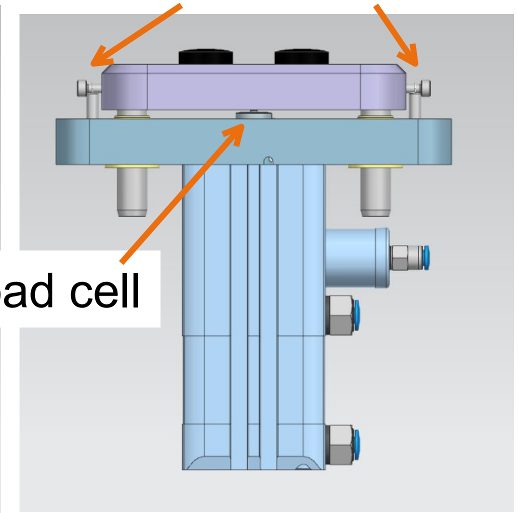


TEDD assembly: rotation tool

- For services installation, the Arc frames have to be removed.
- TEDD will be supported from the inner bore on a tooling that allows rotation around central axis.
- A support axle has been designed with pneumatic cylinders pressing on the inserts at the Dee inner edge
- Load cells included to configure the appropriate force and monitor it during load transfer and rotation.

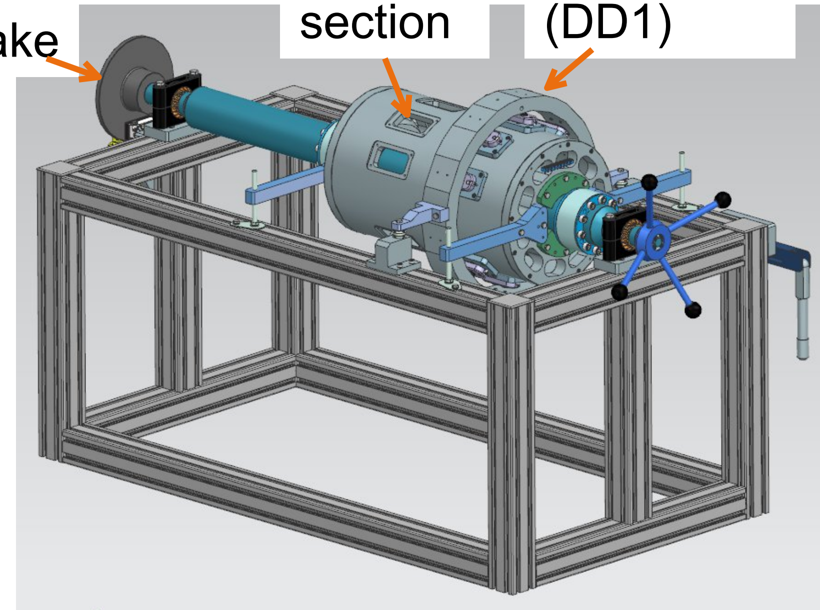


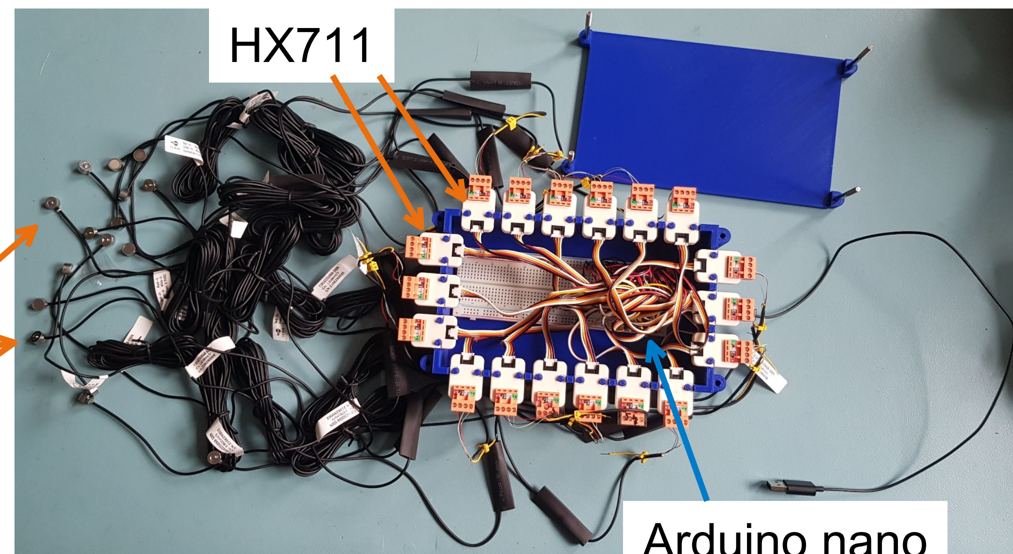




Rotation tool developments

- A prototype tooling (only TEDD1 section) and dedicated testing station has been designed and will be constructed now.
  - Can simulate load transfer and different load conditions to establish procedures and evaluate needed pressures.
- A load cell readout system has been developed.
  - Arduino based readout of 18 load cell measurement ADCs (HX711).
  - Python GUI for visualization and applying calibration.
  - Final system will be implemented on a dedicated PCB.





Concluding remarks

- TEDD design is not only about its mechanics, but also about assembly procedures and the needed tooling, which requires substantial amount of development.
- Integration and assembly is challenging and if not considered during detector design can lead to difficulties.
  - Tooling needs attachment points, metrology targets, methods to handle the detector.
- The devil is in the detail !
  - The full assembly process needs to be carefully planned for and exercised.
- All toolings need to be prototyped and tested.
  - If there is an assembly step that can’t be tested, there is a high risk of failure.
- Tooling can get complicated and expensive.
  - The complication of how to assemble must be considered in early design and included in the costing.

BACKUP

Metrology

- Mechanical assembly and testing of tooling relies heavily on our Hexagon Romer metrology arm 7735 (1.75m) with laser scanner, volumetric accuracy 80 µm.
- Several probes available:
  - 1.5 and 2 mm probes are mainly for Dee QA.
  - 6 mm extended rod (reference inserts and outer edge inserts).
  - 8 mm (inner edge inserts)
  - Auto trigger with 3 mm sphere: Ideal for surface measurements.
  - SiN (grey) tips are better for Aluminium, as Al over time sticks to ruby (red).
  - Probes are encoded and system loads the corresponding calibration.

Craning of the DD

- Dedicated craning hooks can hold the DD and carry them off the assembly platform.

Overview

- Introduction to the CMS Phase-2 Tracker Endcap Double Disk (TEDD)
- How to hold the Dees, or the tool at the heart of it all: ***The Arc Frame and its features***.
- Working on the Dee for module installation: **Positioning the Dee with the trolley**
- ***Disk assembly and Double Disk assembly***: The tool to make big and precise objects.
- ***Double Disk storage and transport***. More tools needed.
- Building the endcap: The tools get bigger
  - ***DD alignment***
  - ***TEDD rotation***

Summary

All the toolings

- The Arc frame design is final and production of the full quantity has started.
- The Dee integration trolley is already in regular use.
- Double disk assembly has been fully developed and tested with dummy Dees. Final verification possible with the first four pre-production Dees.
  - The DD assembly process validation also implied the validation of the Arc frames.
- The DD storage and transport tool has been designed. The additional requirements for the road transport are now being evaluated.
- The DD alignment tool for TEDD assembly has been designed.
- The TEDD rotation tool for services installation with a pneumatically controlled inner support has a preliminary design.
- The concept of moving the TEDD from the rotation tool to the TB2S/TEDD insertion tool has to be established as final step in the workflow.