Design and Testing of the CLIC Two Beam Module Alignment Systems

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With thanks to Steffen Doebert, Carlo Rossi, and the rest of the module integration team

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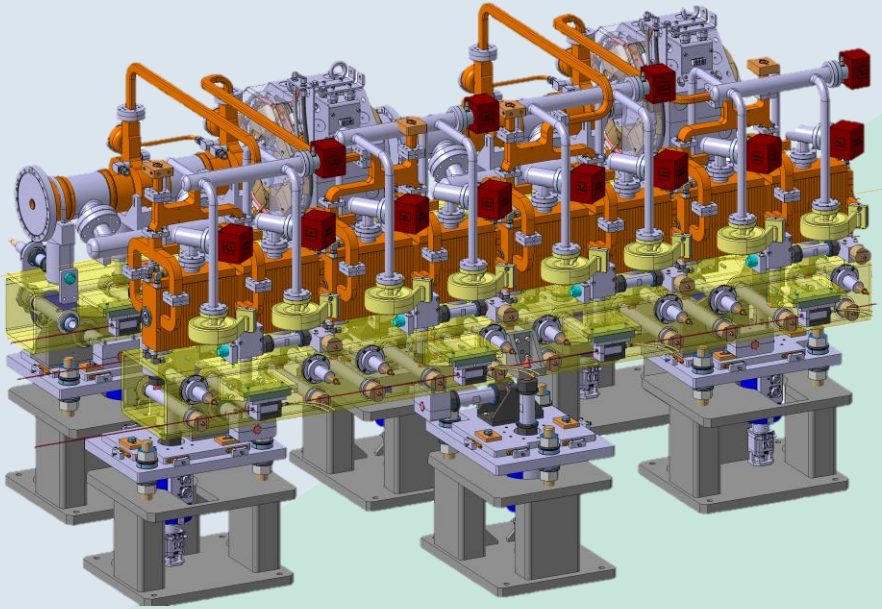
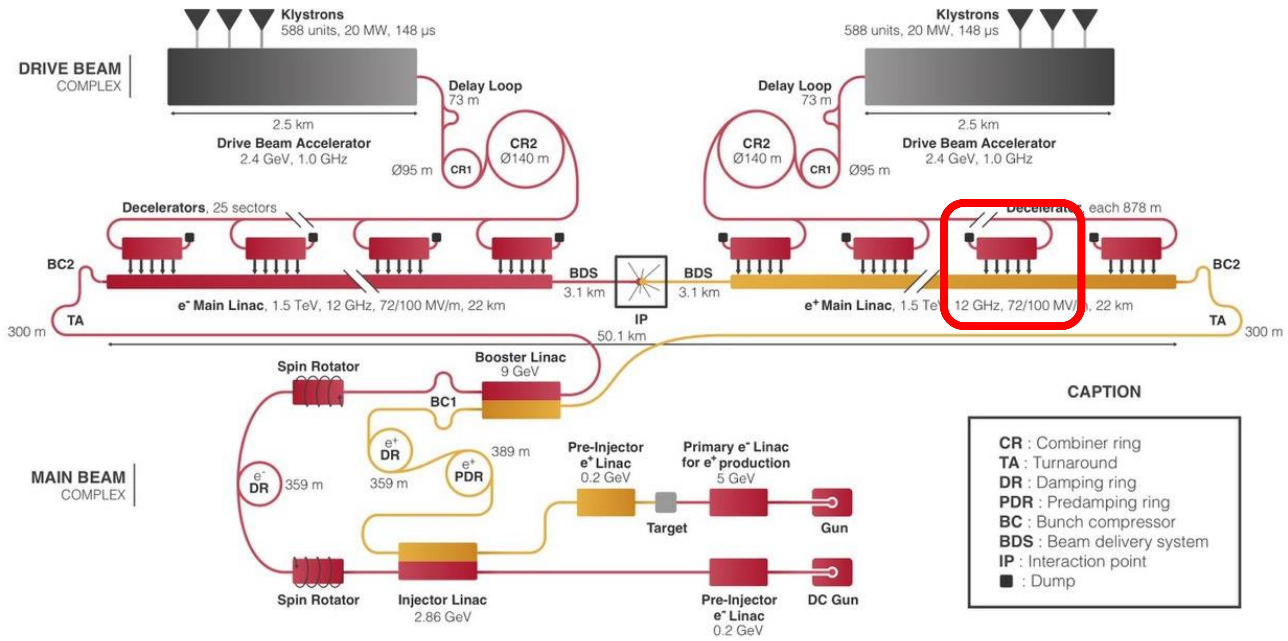


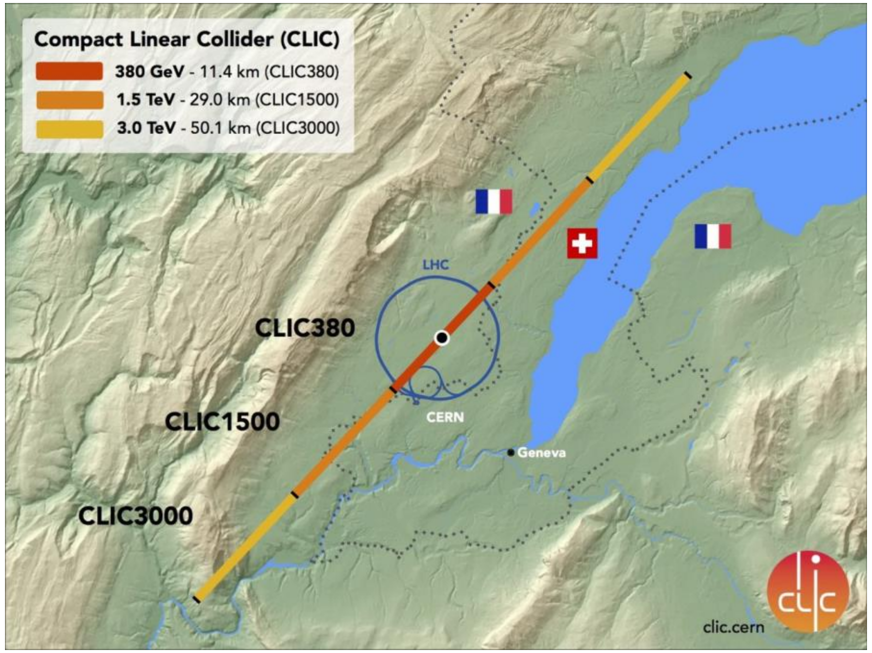
JAI Fest
December 4th 2023

The Compact Linear Collider

- Electron – Position linear collider
- One of the proposed future colliders at CERN
- ‘Compact’ due to a very high acceleration gradient ~100MV/m
- Built in stages, starting at 380GeV (11km) and going up to 3TeV (50km)

- Use ‘two-beam’ acceleration where RF power is extracted from a drive-beam and used to accelerate the main beam.
  - This takes place with Two Beam Modules
- A high luminosity of 1.5 × 1034 cm−2 s−1 which requires a normalised vertical emittance of 20nm.
  - Requires tight alignment and stability constraints.





Two Beam Module

The components which make up the Main LINACs, along with the main beam quadrupoles.

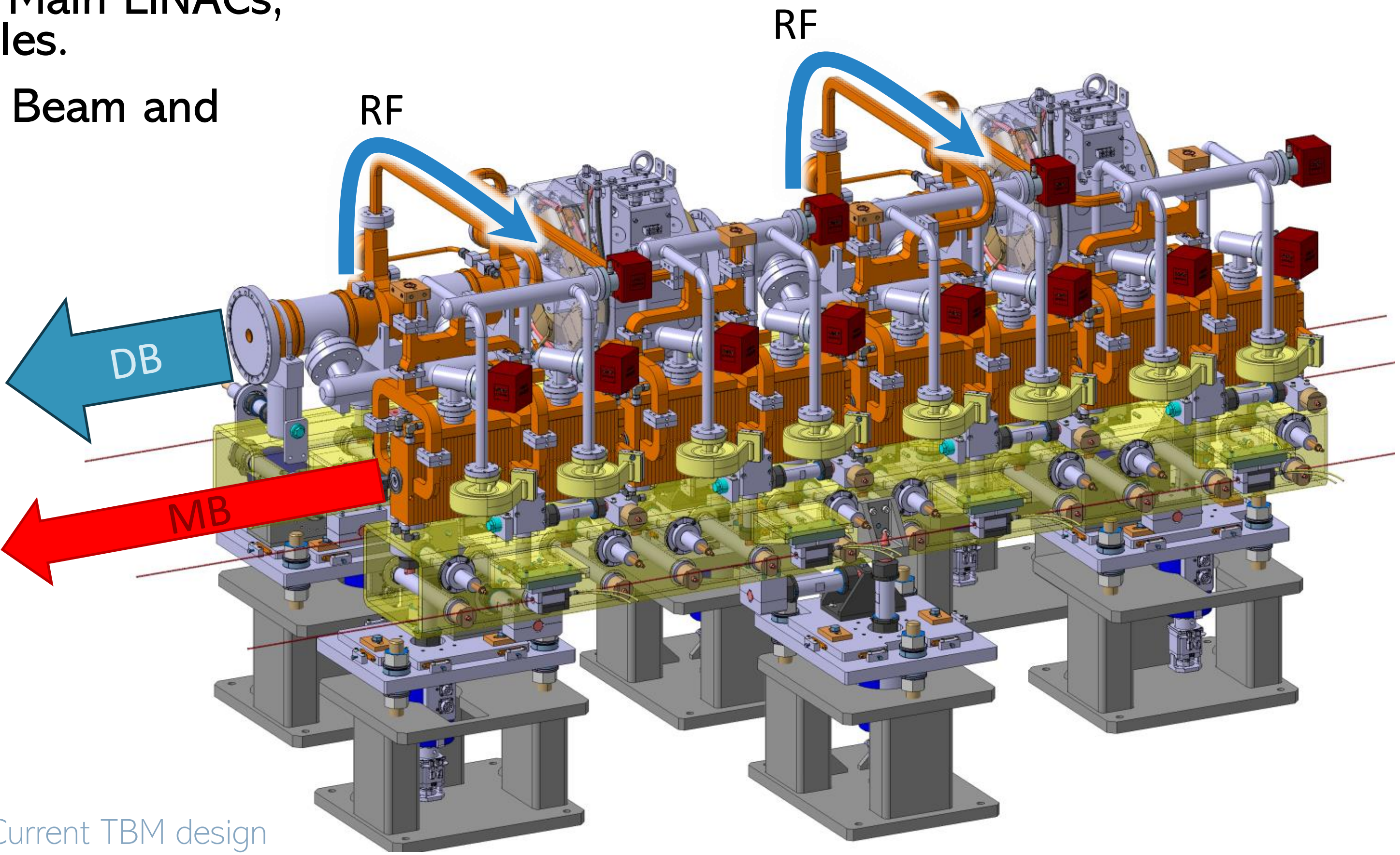
A closely integrated section of Drive Beam and Main Beam components:

Drive Beam:
- Quadrupoles
- Power extraction and transfer structures (PETS)

Main Beam:
- 4 Super Accelerating Structures SAS (8 accelerating structures)

The module contains all the positioning and alignment systems for the accelerating structures:

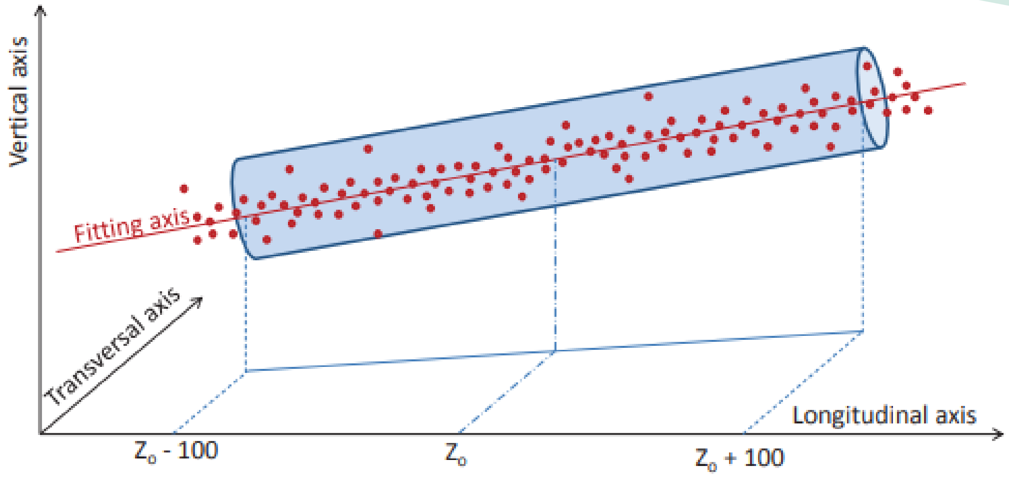
- Passive prealignment
- Active positioning
- Stabilisation

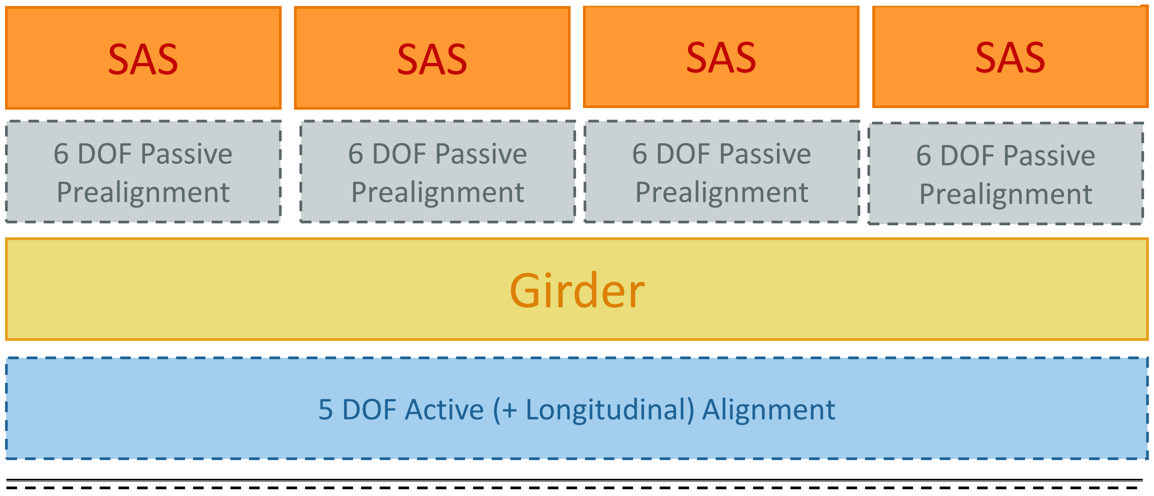


Current TBM design

Alignment Methods & Requirements

- **The Super Acceleration Structures (SAS) are individually prealigned to within 14µm**
  - Relative to each other, and the girder CS
  - Before installation in the tunnel, using CMM
- **The girder is installed on active adjustment supports within the tunnel**
- **Stretched wires within the tunnel define the machine reference network.**
  - Overlapping 200m stretches
- **Active positioning system propagates the 14µm prealignment along the LINACs**
- **Beam-based alignment using wakefield monitors achieves greater alignment**

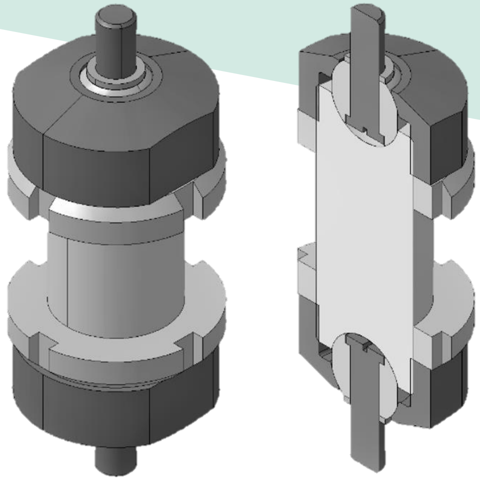




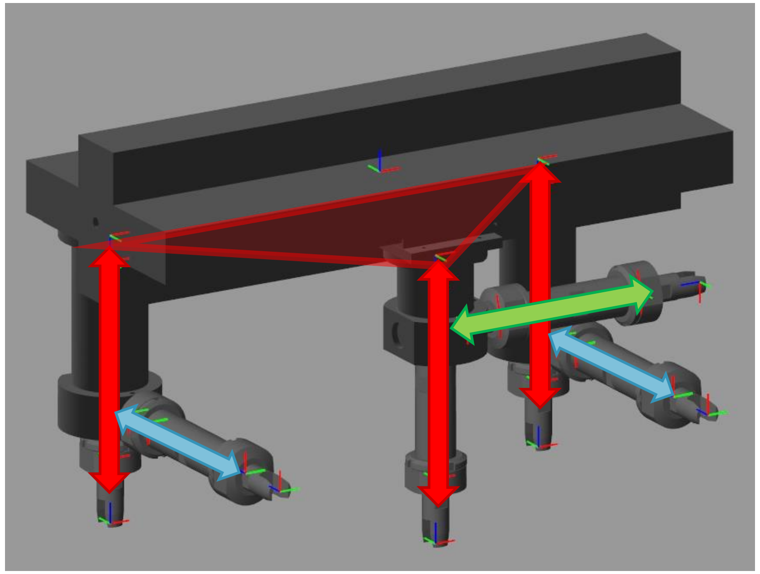
Schematic of the CLIC module alignment systems

Structure Prealignment

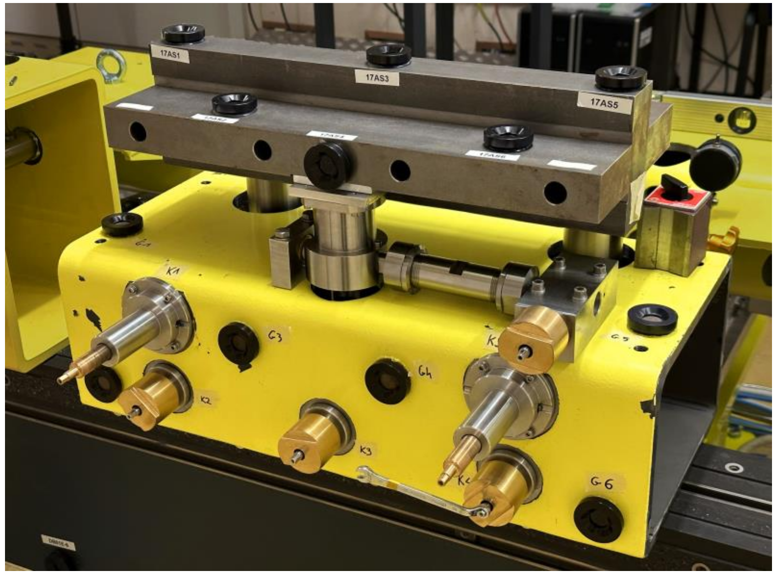
- 6 Axis precision adjustment system
- Uses ‘universal joints’: stiff in one axis but allow movement in all other axes.
- 3 Vertical joints (red), 2 lateral joints (blue), and a single longitudinal joint (green)
- Uses two adjustment mechanisms to achieve sub-micron adjustment over +-1.5mm.
  - Wedge mechanism = 30μm/turn
  - Differential thread = 40μm/turn
- Support accommodates thermal expansion of the structure.



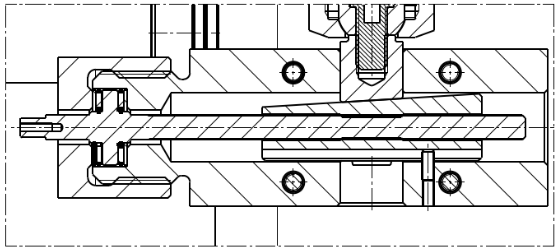
Universal Joint



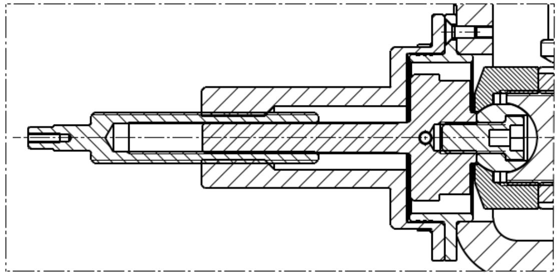
Simulink Prealignment Platform Model



Prealignment Platform Prototype



Wedge Mechanism



Differential Threads

Structure Prealignment Testing

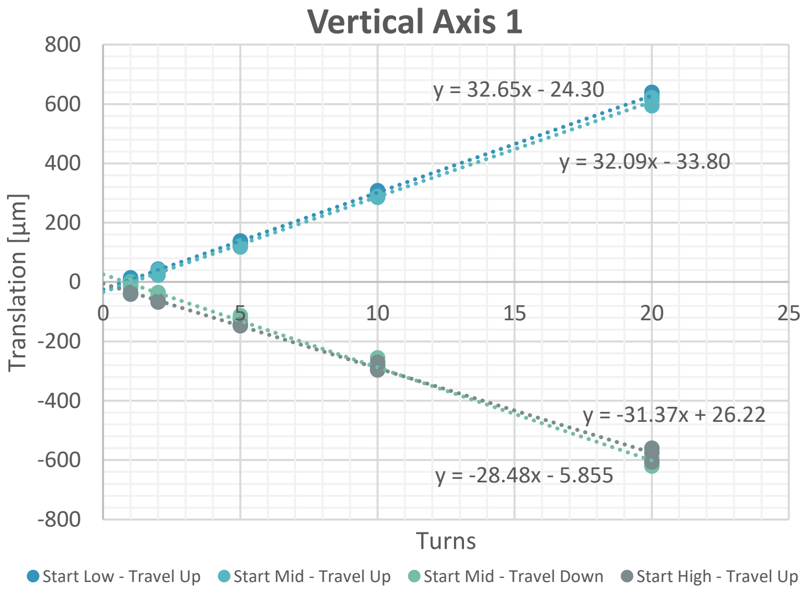
Testing procedure:

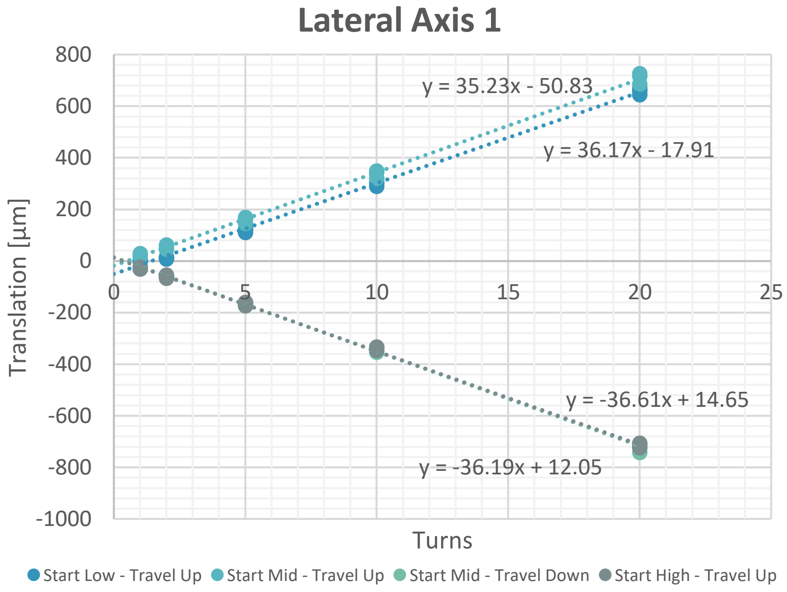
- Each axis was adjusted and the displacement per revolution was measured using a laser tracker

Testing results:

- Sub-micron resolution in all axes
- Average range 2.85mm
  - Sufficient to accommodate tolerances on the girder/structures
- Adjustment rate close to design
- Backlash <30µm
  - Current design does not attempt to eliminate backlash, but it can be avoided through correct operation

Met all requirements





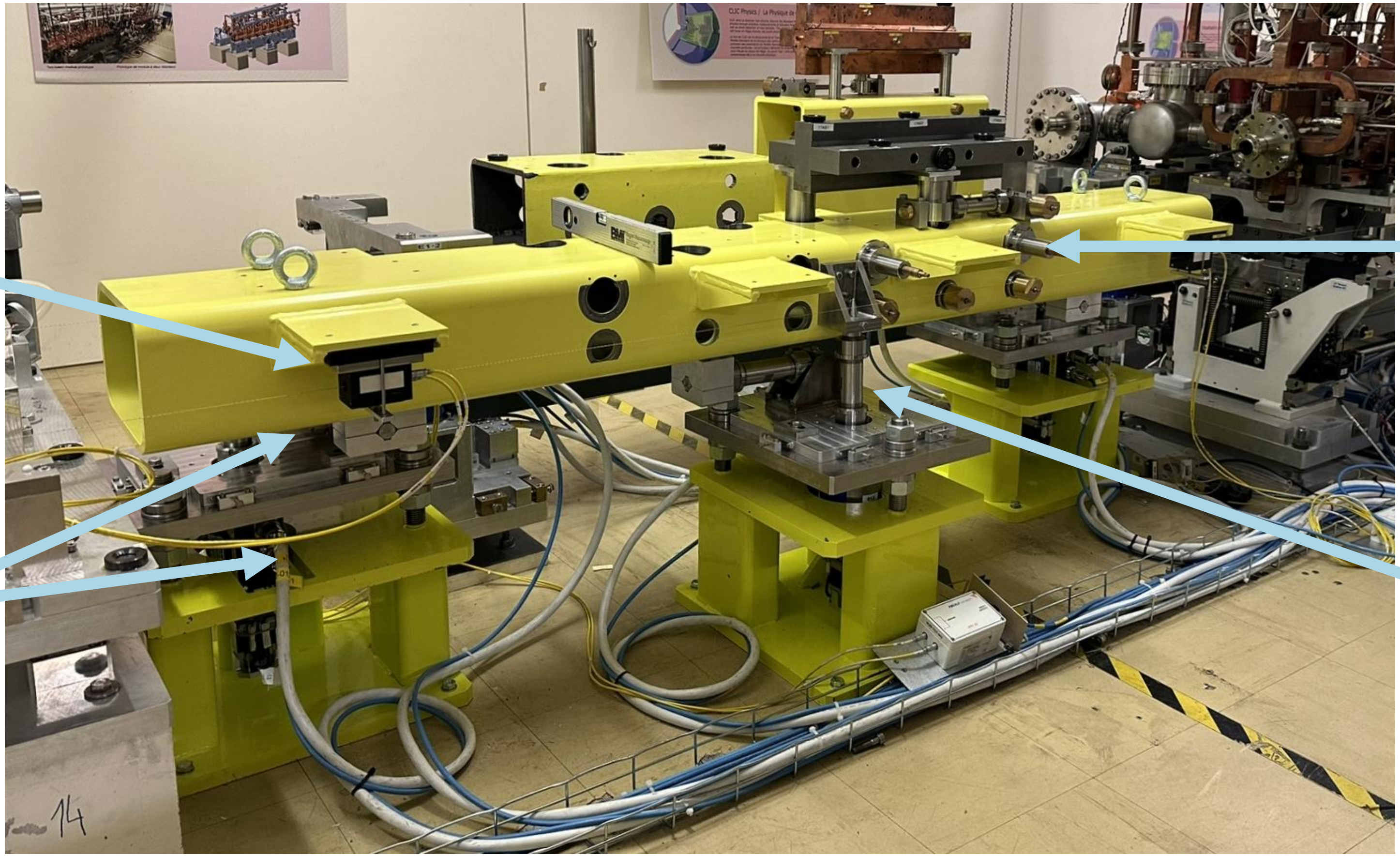
Axis	Axis Type	Measured Rate [µm]	Design Rate [µm]	Backlash [µm]	Backlash [turns]
Vertical 1	Wedge	31.147	30	22.544	0.724
Vertical 2	Wedge	31.162	30	19.830	0.636
Vertical 3	Wedge	29.370	30	8.099	0.276
Lateral 1	Differential Thread	36.052	40	23.863	0.662
Lateral 2	Differential Thread	35.591	40	27.722	0.779
Longitudinal	Wedge	32.409	30	17.578	0.542

Module Support Prototype

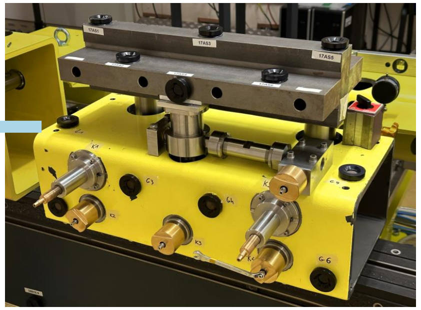
The current CLIC module support prototype in Bld169 at CERN

Capacitive WPS on girder, Kevlar/Carbon wire

Linear actuator, 0.26µm/step, 6mm range, 162N/µm stiffness



SAS prealignment platform integrated into girder

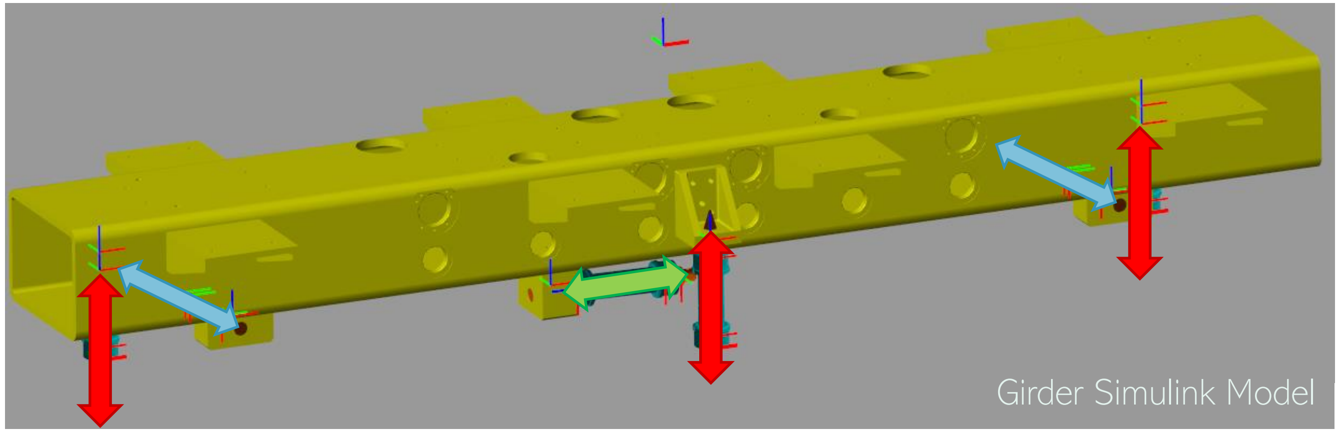


Girder Support Joint

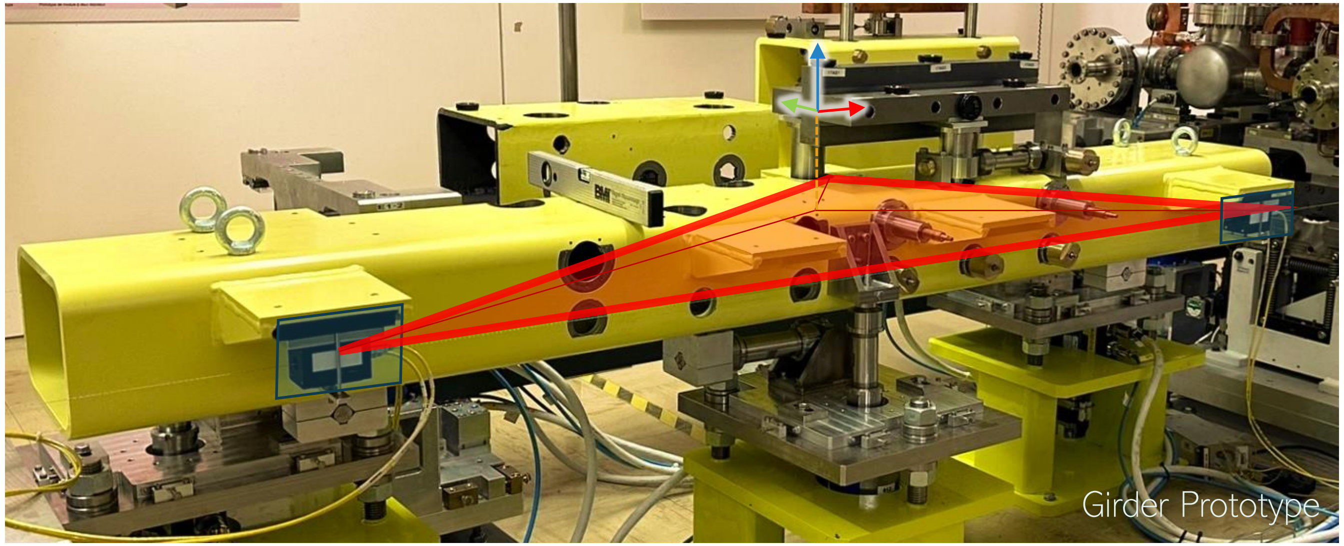
Active Alignment

Kinematically similar to the SAS support platform:

- **Girder supported by 6 high stiffness universal joints**
  - The joints are larger to accommodate the increased mass
- **5 Joints are actuated to provide the active alignment**
  - 3 vertical actuators (red)
  - 2 lateral actuators (blue)
  - The longitudinal joint is fixed
- **Three Wire Position Sensors provide the positional feedback**
  - 2 on one side, 1 on the other
  - Provide point coordinates, which can be used to determine a plane, from which the girder coordinate system can be found
- **Comparable to the kinematically ideal model created in Simulink (top right)**



Girder Simulink Model



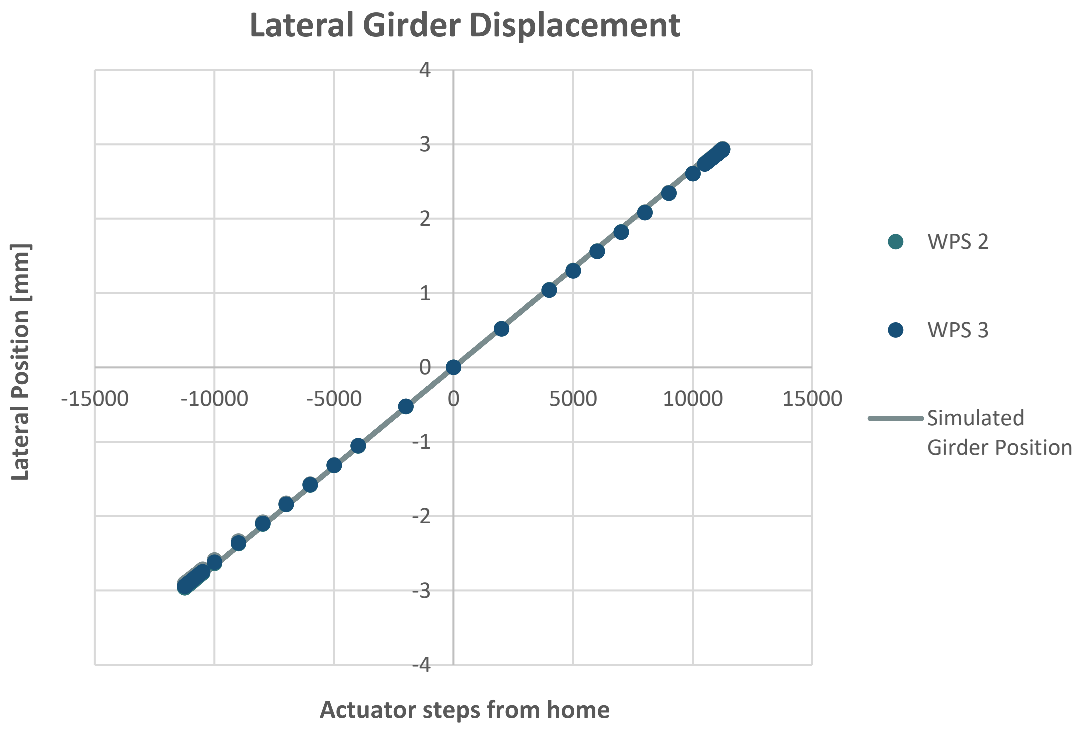
Girder Prototype

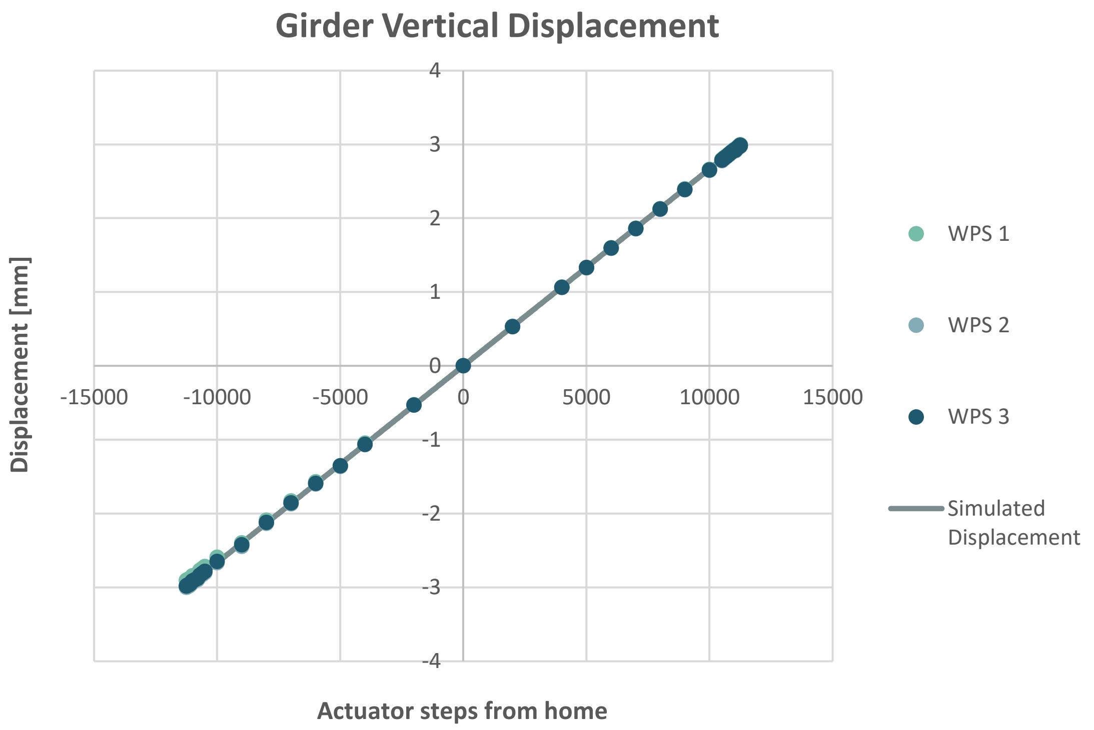
Active Alignment Testing

Initial 'dead reckoning' tests:

- Translation over the full length of travel
- Position measured from WPS
- Compared to the Simulink model
- Expected sources of error (parasitic motion)*

Parameter	Design	Average Measured	Max Deviation
Rate [µm/step]	0.26	0.2635	0.05
Range [mm]	5.999*	5.91	0.13
Position error at EOT [µm]	-	49	73
Position error at 1mm [µm]	-	16	26



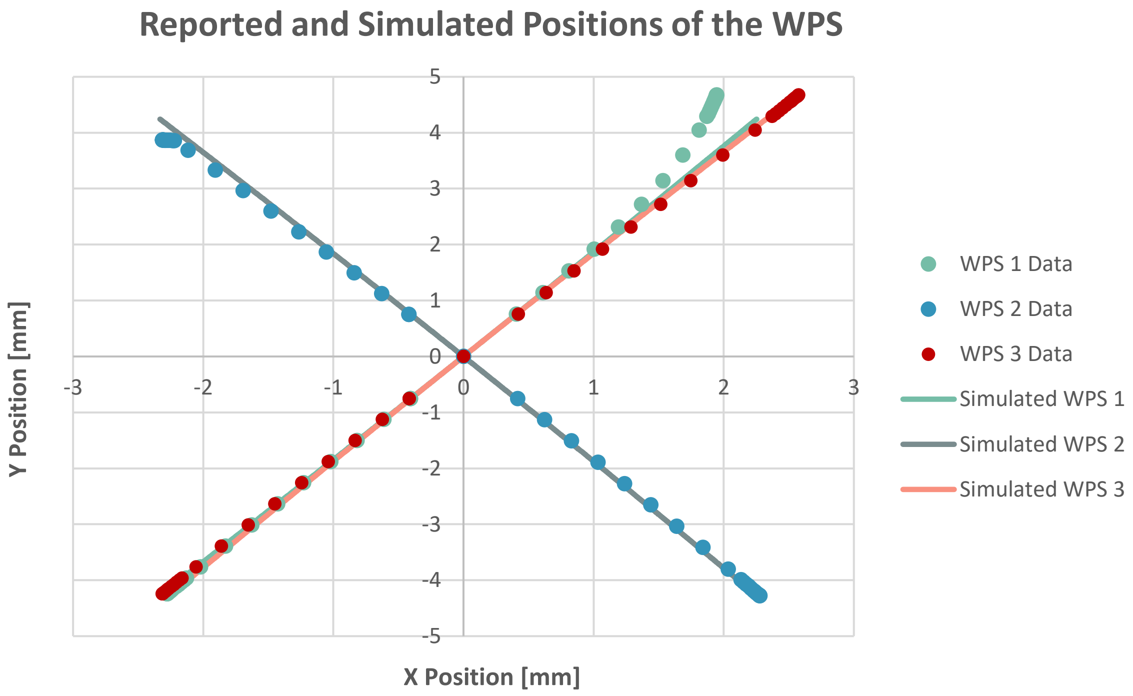


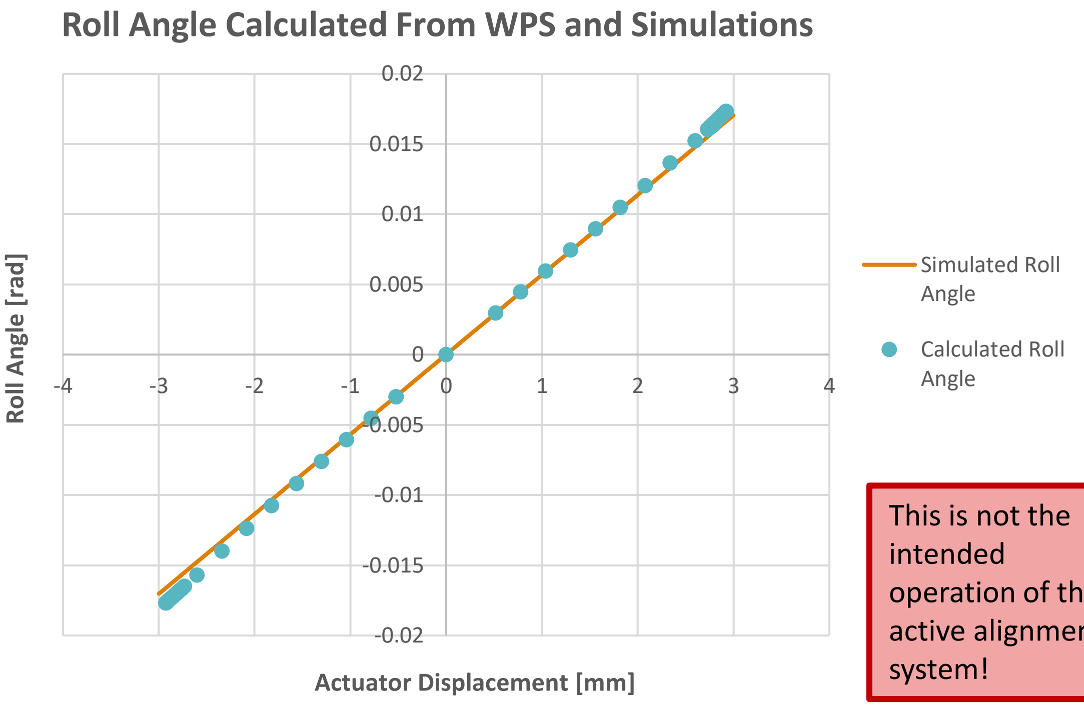
Active Alignment Testing

Pure rotation tests:

- Example roll:
  - -3mm to 3mm V1 & V3, 3mm to -3mm V2
- Position measured from WPS & compared
- Increases the total displacement
- Noticeable kinematic error during roll tests

Parameter	Pitch/Yaw			Roll		
	Design	Average	Max Error	Design	Average	Max Error
Rate [µrad/step]	0.31	0.32	0.01	1.52	1.55	0.05
Range [mrad]	6.89	7.00	0.24	32.3	34.1	3.56
Error at EOT [mrad]	-	0.12	0.17	-	0.64	1.01
Error at 1mm [µrad]	-	0.04	0.08	-	0.08	0.19





This is not the intended operation of the active alignment system!

Active Alignment Testing

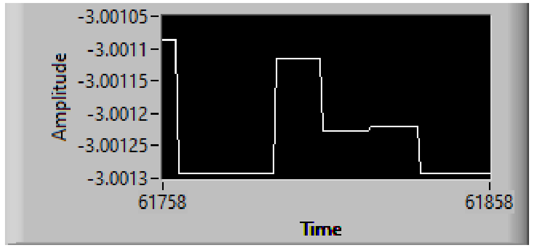
The active alignment system will always rely upon feedback from the WPS.

These charts show manual readjustment to an arbitrary position using the feedback.

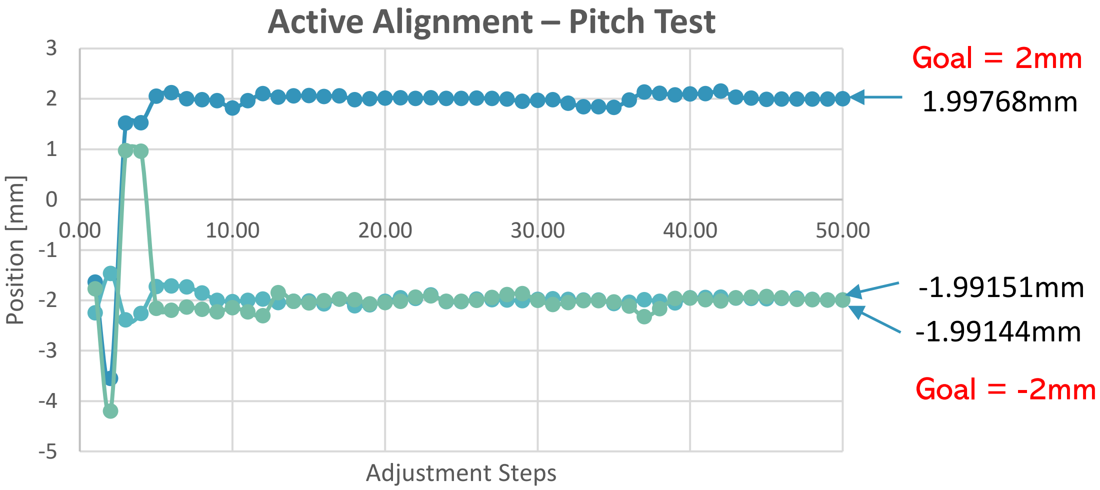
- Top: pitching to ±2mm
- Bottom: yawing to ±3mm

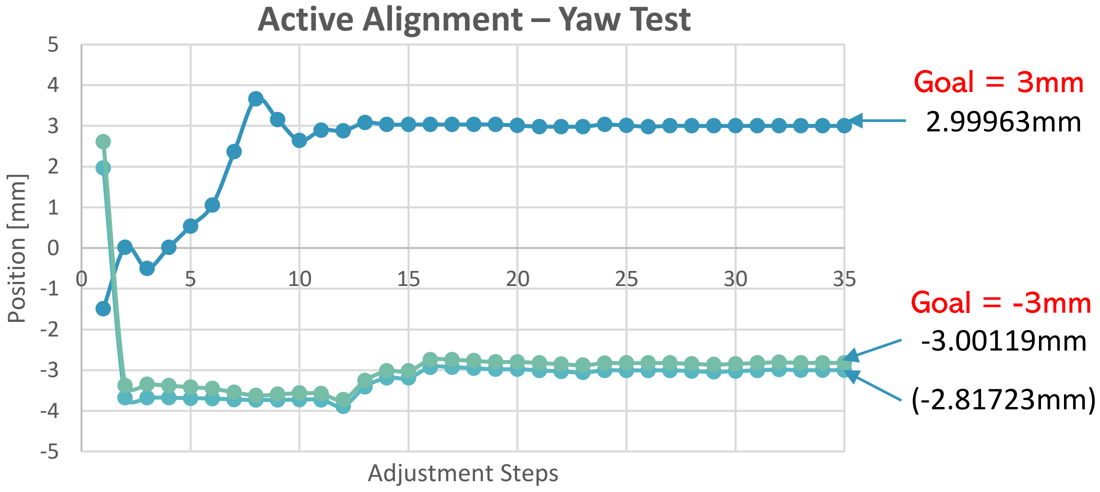
Possible to position down to <5µm manually

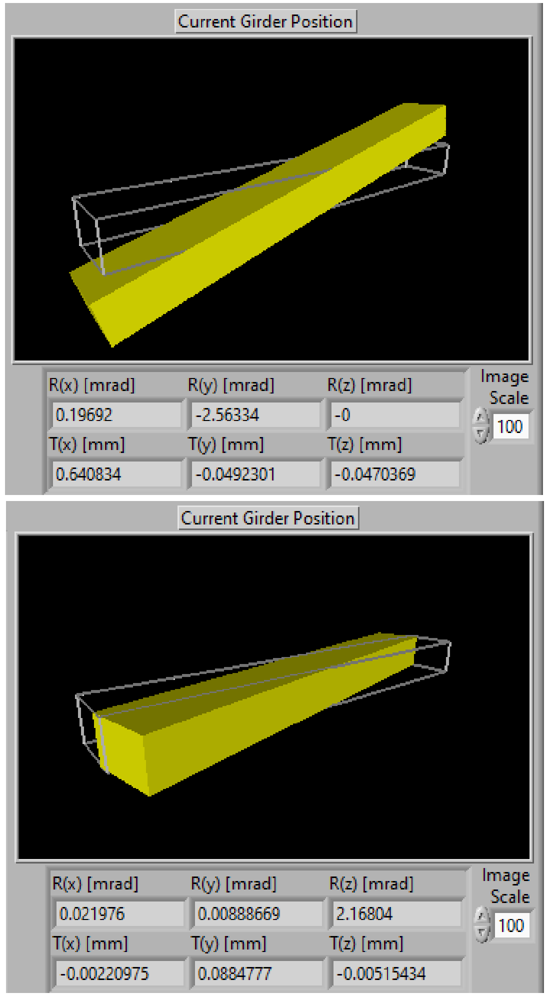
Demonstrates that the automatic alignment process is technically possible



WPS Stability <1µm





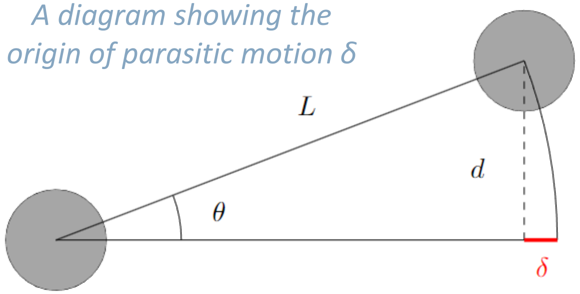


Girder Position GUI

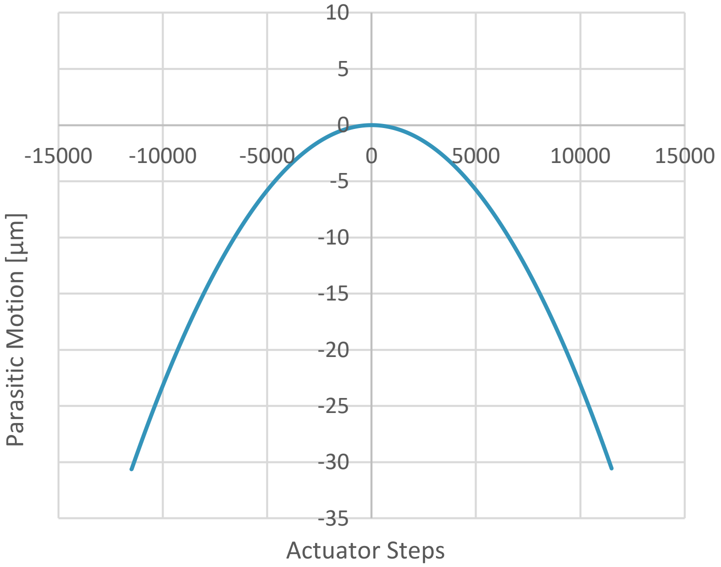
Parasitic Motion

- A source of mechanical error: when the module is moved in one axis, it will experience a small displacement in the perpendicular axes.
- This a known and expected consequence of kinematics of the system.

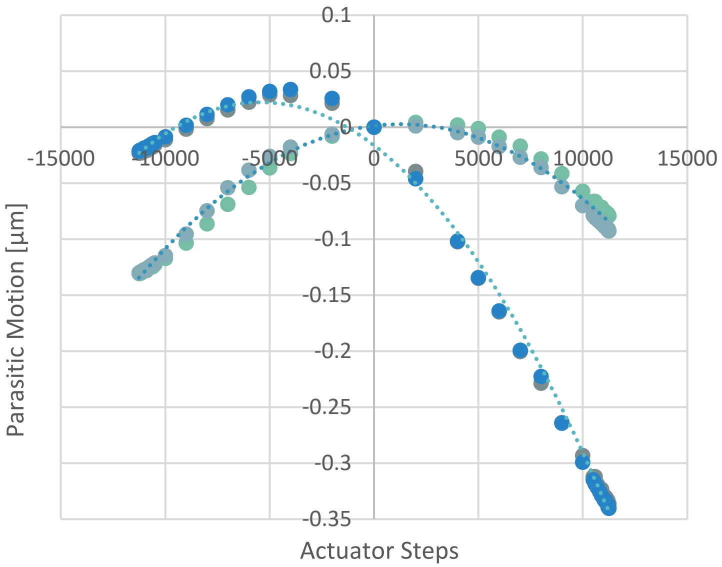
A diagram showing the origin of parasitic motion δ



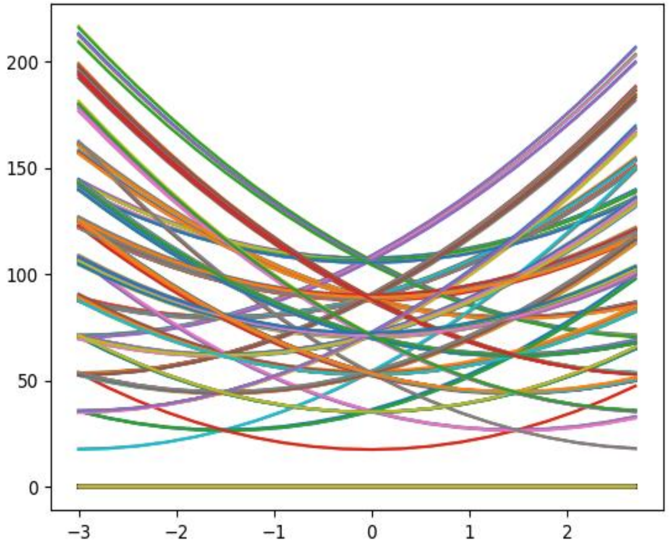
- Misalignments of the base plates will angle the joints in the neutral position.
- This will increase the impact of the parasitic motion at the extremes of travel.



The theoretical horizontal parasitic motion due to vertical translation



The measured horizontal parasitic motion due to vertical translation



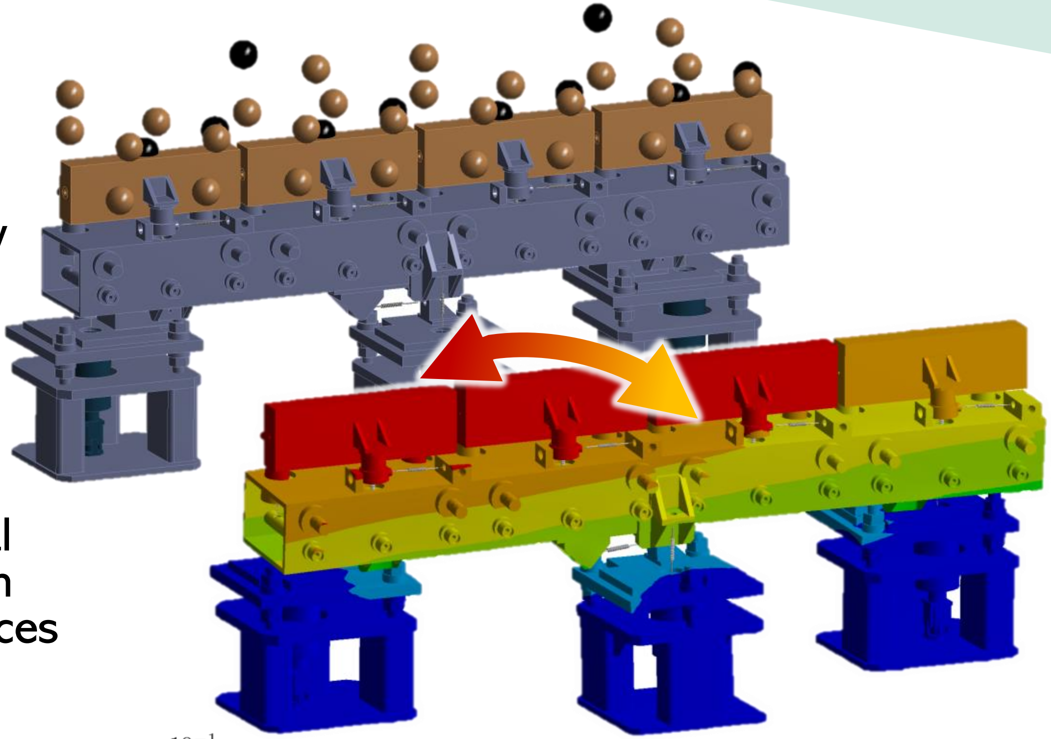
A study into the impact of baseplate misalignment on the magnitude of parasitic motion

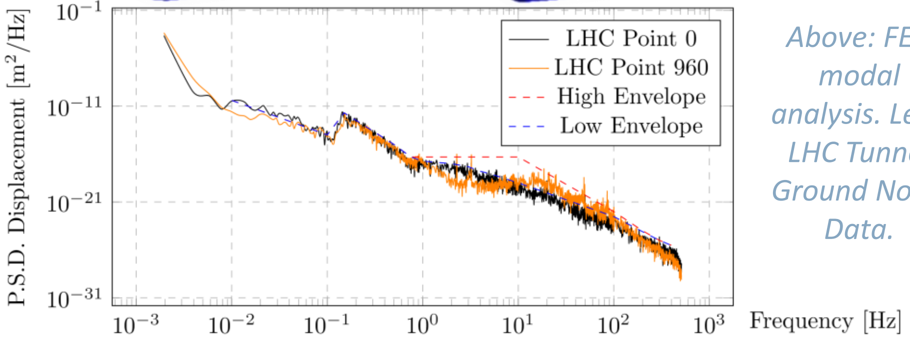
Stability Constraints

Structure Jitter Requirements (CDR)

- RMS jitter tolerance which leads to a 1% luminosity loss
  - Accelerating structure horizontal position = 8μm
  - Accelerating structure vertical position = 1.4μm
  - Accelerating structure horizontal tilt = 6μrad
  - Accelerating structure vertical tilt = 1.1μrad
- These tolerances are tighter (particularly the vertical position), and harder to compare our current design against, and require consideration of the local sources of vibration:
  - Known: e.g. ground motion, technical noise
  - Unknown: e.g. Structure water cooling, tunnel airflow, other equipment

Module design is a 'hard mount' support, where a high stiffness is intended to push the harmonic frequencies above the frequency range of most concern





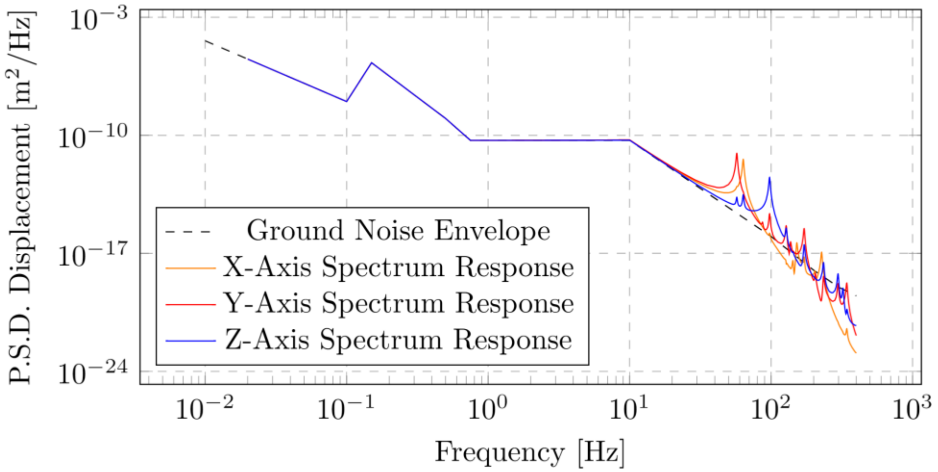
Above: FEA modal analysis. Left: LHC Tunnel Ground Noise Data.

Stability Analysis

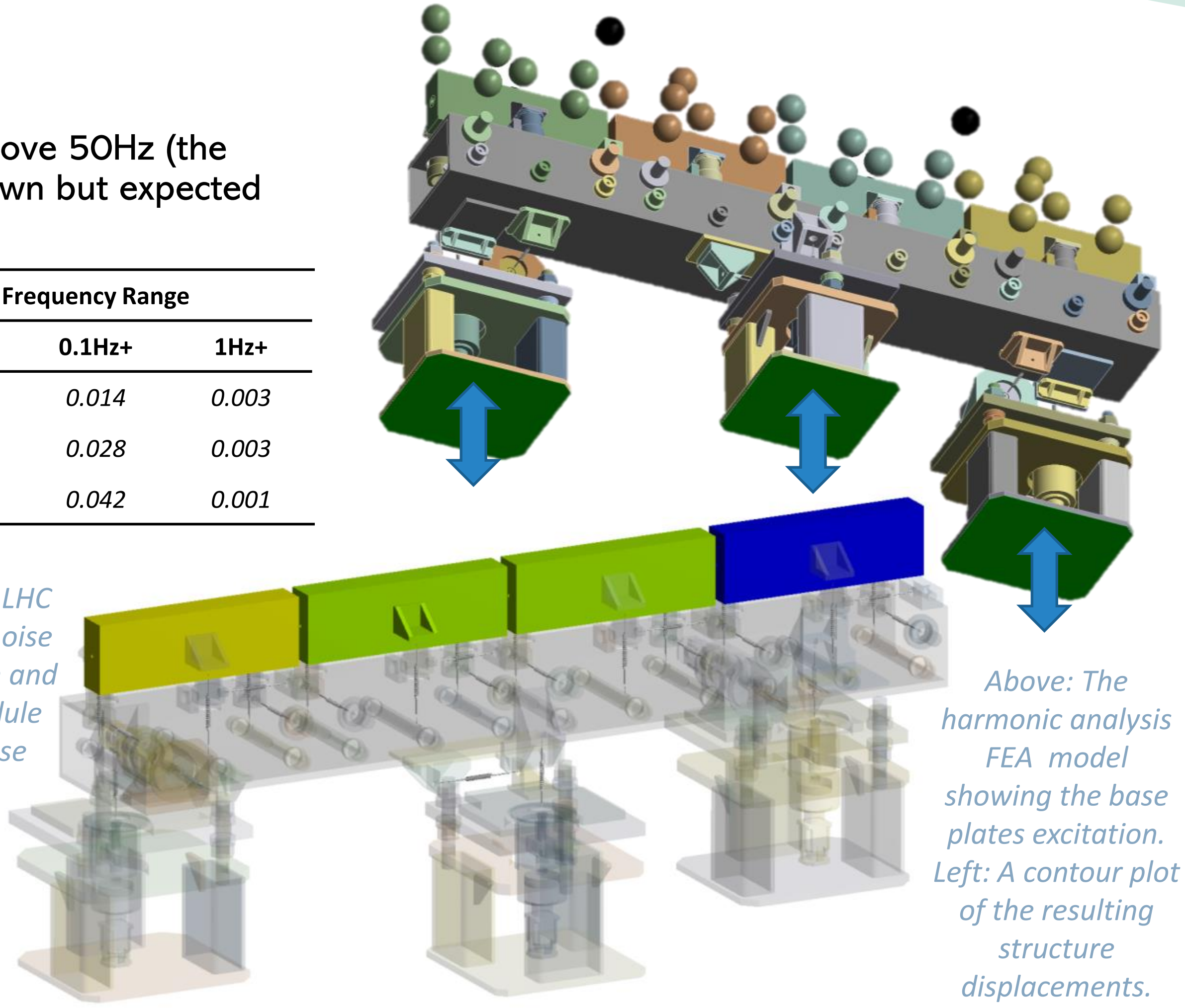
Several types of analysis has been used:

- Modal analysis: to ensure the fundamental frequency is well above 50Hz (the operational frequency of CLIC) & minimise the impact of unknown but expected sources of vibration
- Harmonic analysis: to determine the response to all frequencies
- Random noise analysis: to predict the statistical response to a known source of vibration; i.e. measured ground noise from the LHC tunnel

	Frequency Range		
Axis	0.08Hz+	0.1Hz+	1Hz+
X	*0.445*	*0.014*	*0.003*
Y	*1.375*	*0.028*	*0.003*
Z	*0.905*	*0.042*	*0.001*



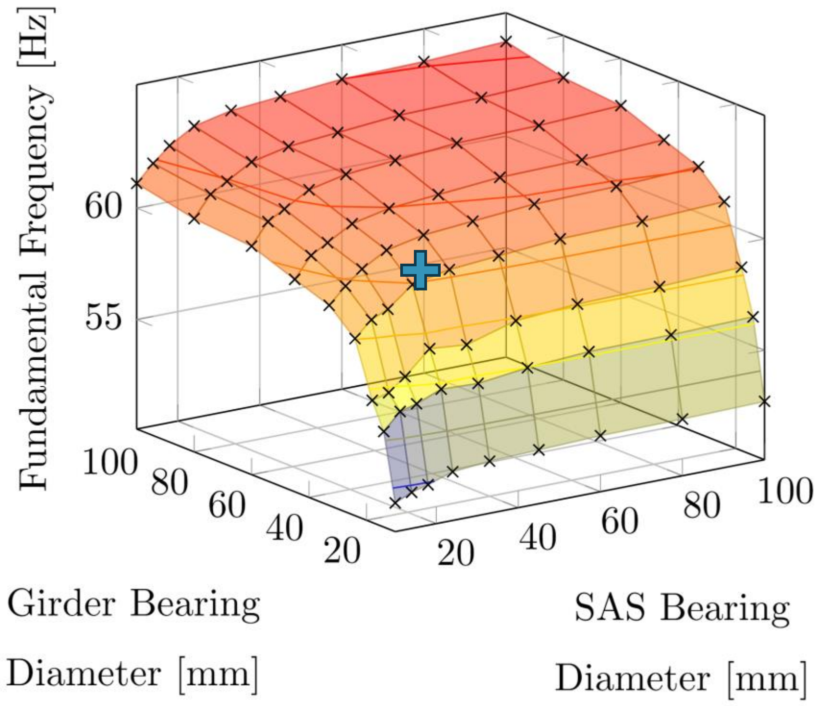
Left: the LHC ground noise spectrum and the module response



Above: The harmonic analysis FEA model showing the base plates excitation. Left: A contour plot of the resulting structure displacements.

Stability Optimisation

- The stiffness of the universal joints are closely related to the diameter of the spherical bearings
    - Joint stiffness determined through axisymmetric analysis, validated against test data
- Considering universal joints for both the girder support system, and the structure support systems, we can perform an impact study:
    - Increasing the both bearing diameters increases natural frequency
    - The girder support bearing is more significant
    - Very large bearings show diminishing returns
- Chosen design:
    - 22mm bearings for the SAS supports (commercially available)
    - 35mm bearings for the Girder supports (custom)
    - Increases the fundamental frequency to ~60Hz

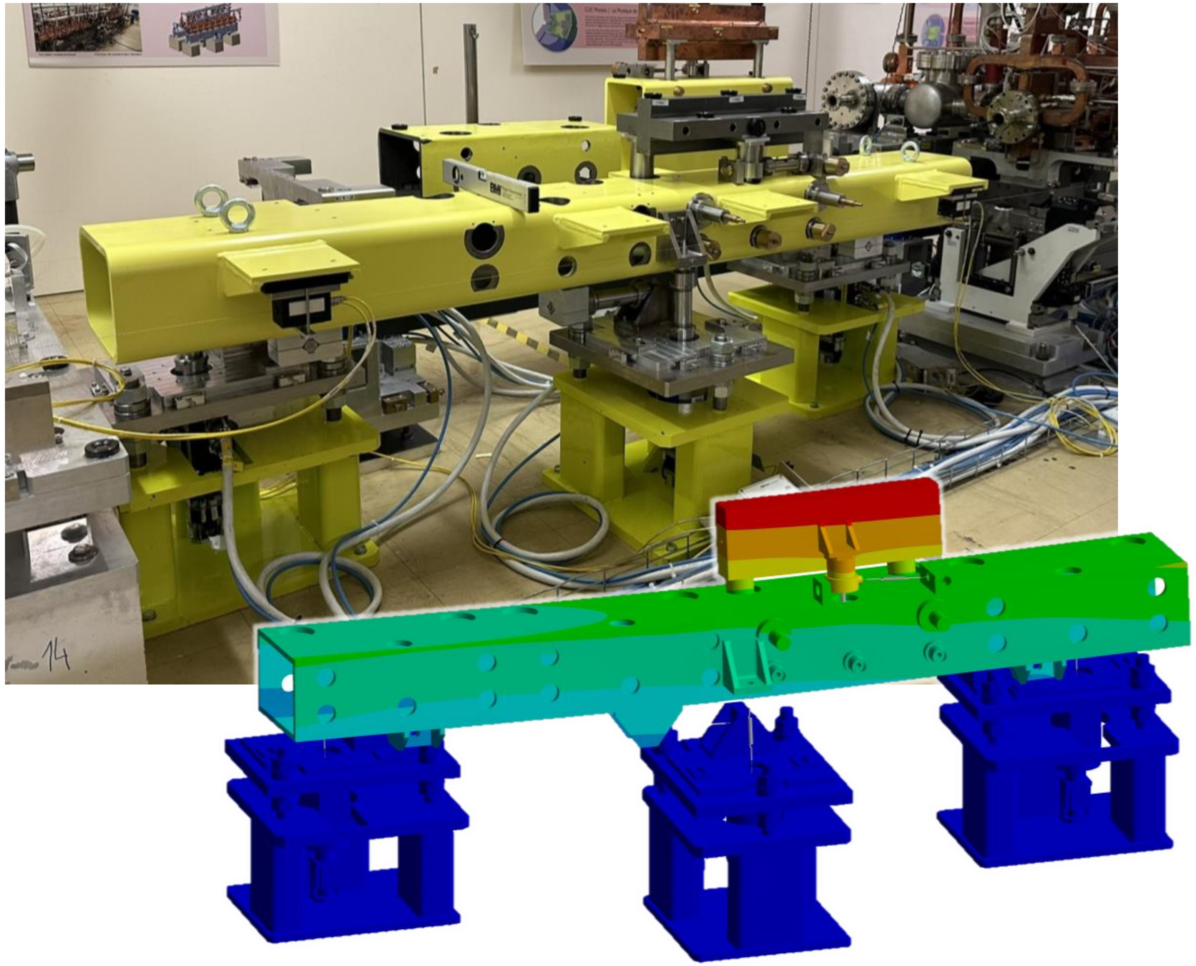


Study into the bearing diameter impact on the module fundamental frequency

Stability Testing

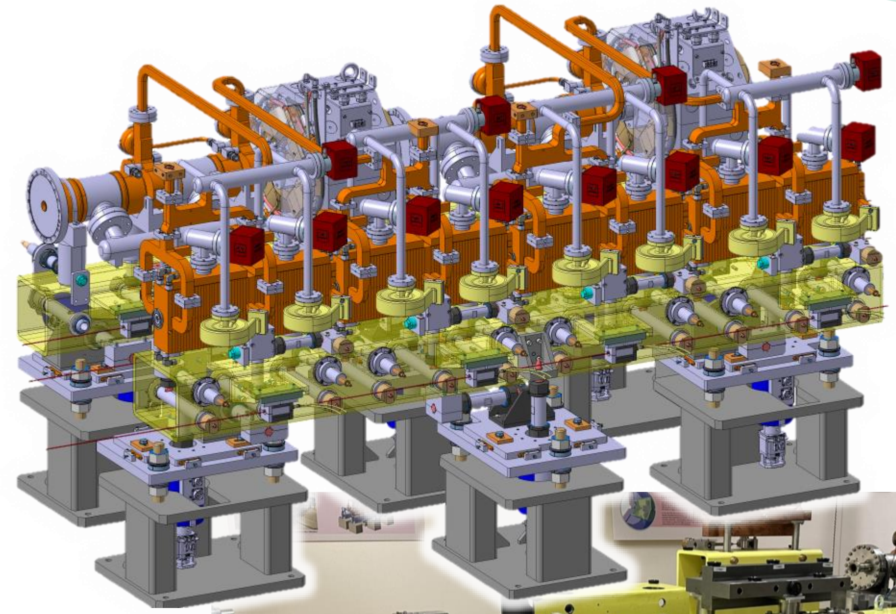
- Experimental modal analysis:
  - Surface mounted accelerometers
  - Non-contact laser vibrometers

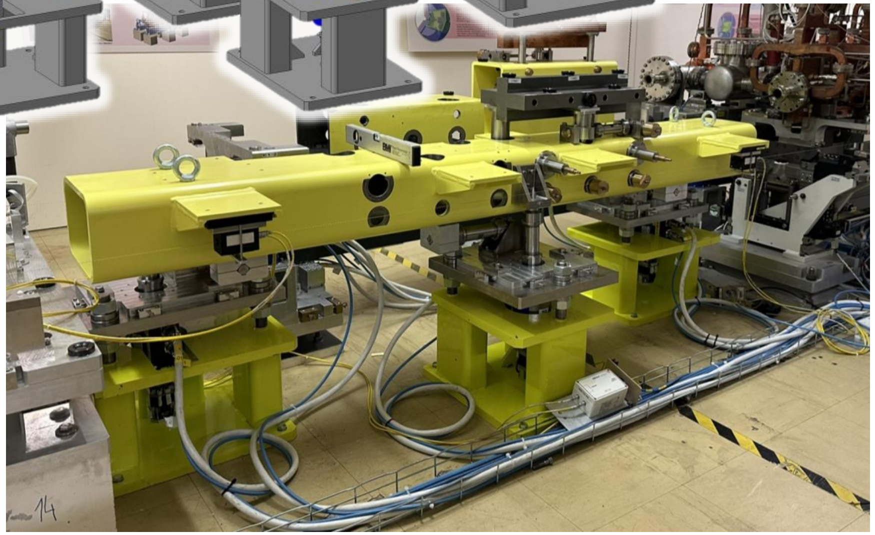
- To be performed early next year…



Summary

1. Design and optimization of the CLIC Two Beam Module based on the technical and scientific requirements has been completed
2. Testing of the structure prealignment system has demonstrated the ability to position the SAS to less that 1μm over ±1.4mm
3. Initial testing of the active alignment system has shown a positional accuracy of <26μm and <1μrad over ±1mm without feedback, and <5μm when using the WPS for positional feedback
4. Stability testing of the system is due to take place early next year.





Thanks for listening

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