The CLIC Module Studies - recent progress and results

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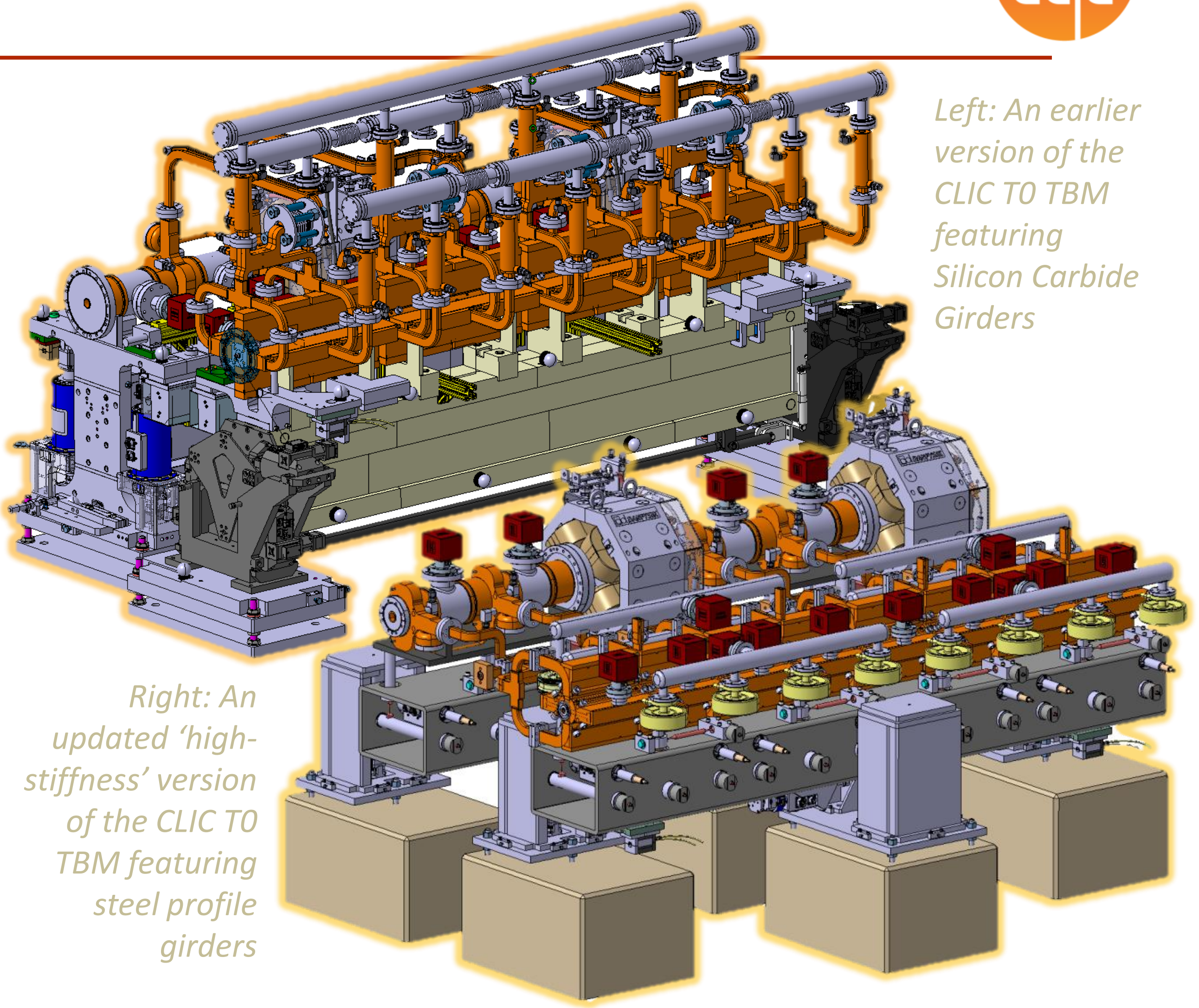
With thanks to:
Mateusz Sosin, Hélène Durand, Kurt Artoos

Contents

Two Beam Module Introduction

This presentation will cover:

- Recent developments to prealignment and active positioning systems for the CLIC module
    - Applicable to both the main beam, drive beam, and K-mode modules
- Justification behind some of the changes and choices we have made
- Demonstrate that the system proposed could meet the alignment and stability requirements of the CLIC modules
- Highlight some points for future work

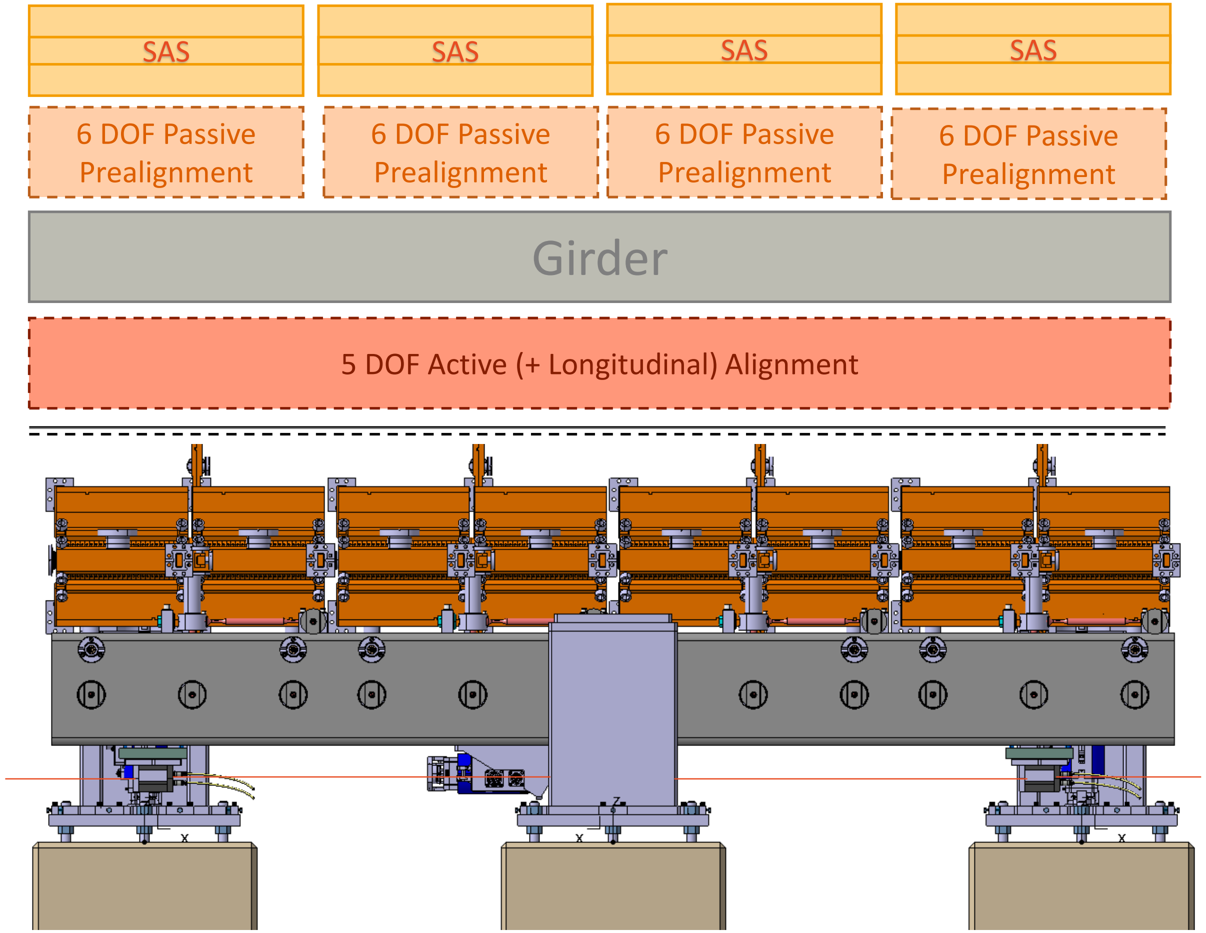


Left: An earlier version of the CLIC T0 TBM featuring Silicon Carbide Girders

Right: An updated 'high-stiffness' version of the CLIC T0 TBM featuring steel profile girders

Alignment Philosophy the of SAS and Girder

- The Super Acceleration Structures (SAS) are individually prealigned relative to the girder to within 14µm
    - Positioned using 6 flexures, each designed to be stiff in one axis and flexible in all others
        - Either manually or automatically adjusted
- The girder is actively aligned using the same methodology
    - Positioned using 6 flexures, each constraining a single degree of freedom
        - Vertically and laterally adjusted automatically using linear actuators
        - Longitudinal axis can be active or passive as required. Currently there is no proposed feedback mechanism
        - Girder position monitored using WPS (Wire Position Sensors)



SAS | SAS | SAS | SAS

6 DOF Passive Prealignment | 6 DOF Passive Prealignment | 6 DOF Passive Prealignment | 6 DOF Passive Prealignment

Girder

5 DOF Active (+ Longitudinal) Alignment

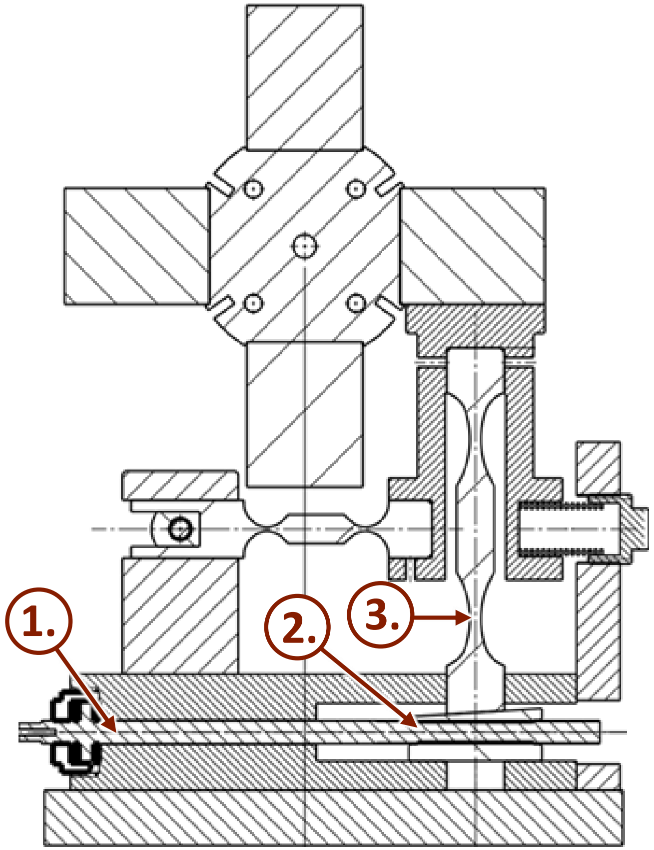
Top: Main beam girder alignment schematic. Bottom: profile view of a main beam girder design

Super Accelerating Structure Alignment

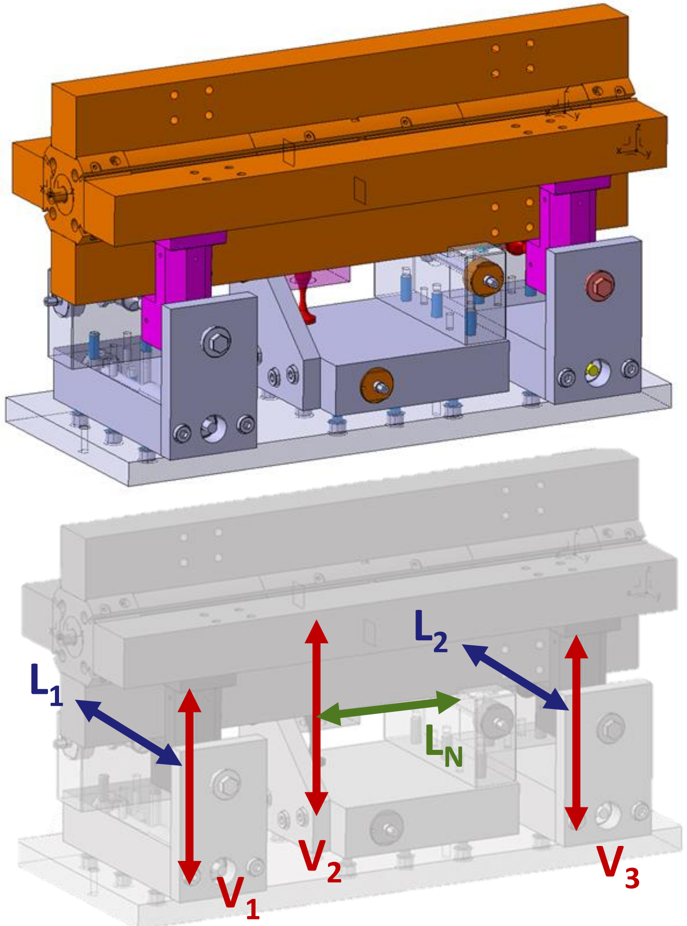
SAS alignment methodology, prototype system design and testing results, and future design.

SAS Alignment Prototype

- A test bench prototype of the SAS flexure adjustment system has been designed by **Jukka Vainola,** manufactured, and tested, with help from the Helsinki Institute of Physics
    1. Threaded rods are used to translate a wedge back and forth
    2. The wedge pushes against the base of the flexure
    3. Due to the angle of the wedge, the flexure is pushed in the direction of adjustment
    4. The flexures are designed to be stiff in one axis and flexible in all others
    5. By using three vertical, two lateral, and one longitudinal flexure, all six degrees of freedom are constrained
- **Designed to achieve a resolution of 90µm/revolution over ±0.75mm**



Above: A cross section of the SAS alignment platform showing 1 vertical and 1 lateral flexure



Above: The 6 flexures and their location within the SAS alignment platform

SAS Alignment Prototype Testing

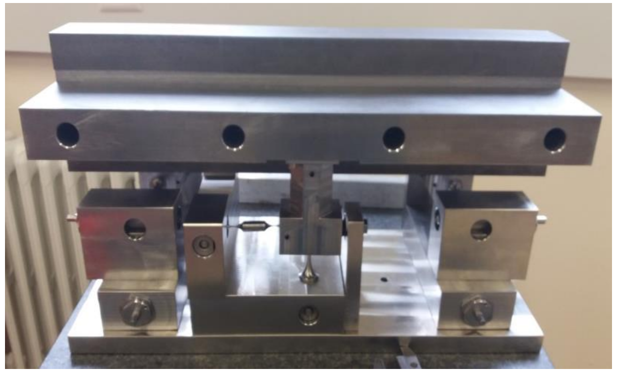
Two prototype Accelerating Structure (AS) pre-alignment adjustment stands have been manufactured and tested in collaboration with the CERN Engineering Survey, Mechatronics, and Measurements (SMM) group.

Prototype Test Results:

- The Accelerating Structures can be to positioned within 1µm when measured directly.
  - To less than the 15µm resolution of the AT401 laser tracker when measured from 2m. Reliant on a reliable datum between the fiducial and beam tube irises.
- Performance of the Adjustment Supports is 90µm/revolution, as designed.
- Backlash is less than 45µm (half a resolution).
  - Backlash can be largely avoided through correct procedure: i.e. always adjusting from the same side
- Stability is dependent on spring preload. Displacements of 50µm measured in several axes across multiple transportation tests.

Demonstrated to meet the CLIC SAS prealignment tolerances

Right: Prototype 1 (Including Dumb Test Mass)



Above: Prototype 2 (Including Thermal Test AS)

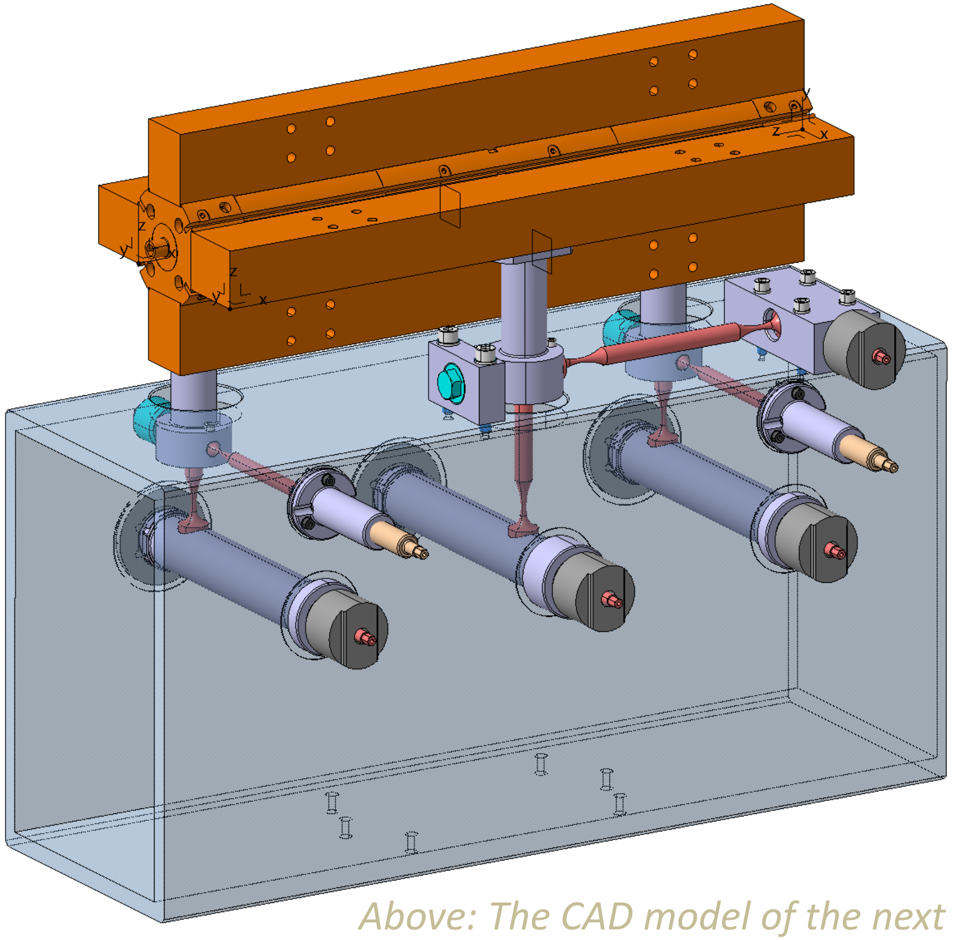
Next Generation Prototype

- A new version of the SAS adjustment platform has been designed and manufactured* with help from **Jukka Vainola,** the Helsinki Institute of Physics, and the CERN Mechanical and Materials Engineering (MME) Group.

Changes based on the feedback from the first version

- Technical changes:
  - The resolution is improved to 40µm/revolution based on the same methodology
  - Linear range is increased to ±1.5mm in all axis
  - Angular range is increased to ±4mrad in pitch and yaw and ±12mrad in roll
- Integration changes:
  - The system can be integrated into a standard steel ‘box section’ profile girder
  - All the adjustment points are on the same side, allow quick manual, or automated adjustments

*expecting delivery any day now



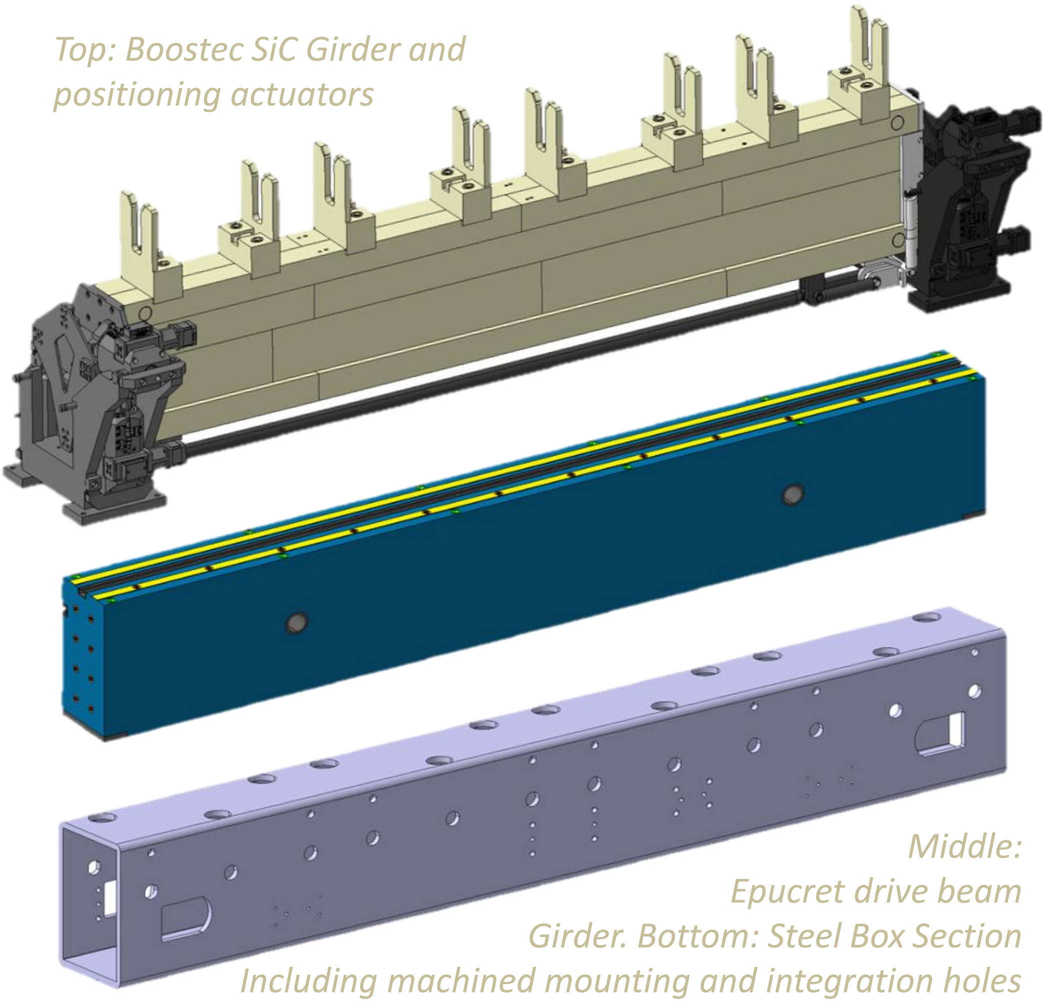
Above: The CAD model of the next generation (V3) SAS alignment system prototype

Girder Material Section and Design

Details and justification of the selection of the support girder material and profile

Girder Material and Design

- Previous girder designs:
  - Silicon Carbide (SiC)
    - Sintered Silicon Carbide provides the <10µm static deformation, and thermal stability
    - Micrometric final machining of v-support surfaces achieves the alignment tolerance
      - Requires equal tolerances on surfaces on the SAS, adjustments require re-machining
      - Is kinematically over-constrained with 4 ‘line-contacts’ per SAS
      - Testing showed v-supports slide during thermal cycles
  - Epucret (Mineral Casting)
    - Epoxy based resin, additives and reinforcement provided similar deformation and thermal stability
    - Reference surfaces and fixings were inserted and machined
- Current girder philosophy:
  - Steel Box Section
    - Raw manufacturing tolerances are quite poor
    - Mounting holes can be machined to <50µm relatively easily
      - Inclusion of adjustment between the girder and the SAS removes the need for micrometric machining and allows readjustment before/after transportation into tunnel
      - Accommodates the 6DOF SAS adjustment systems
    - Significantly reduced cost

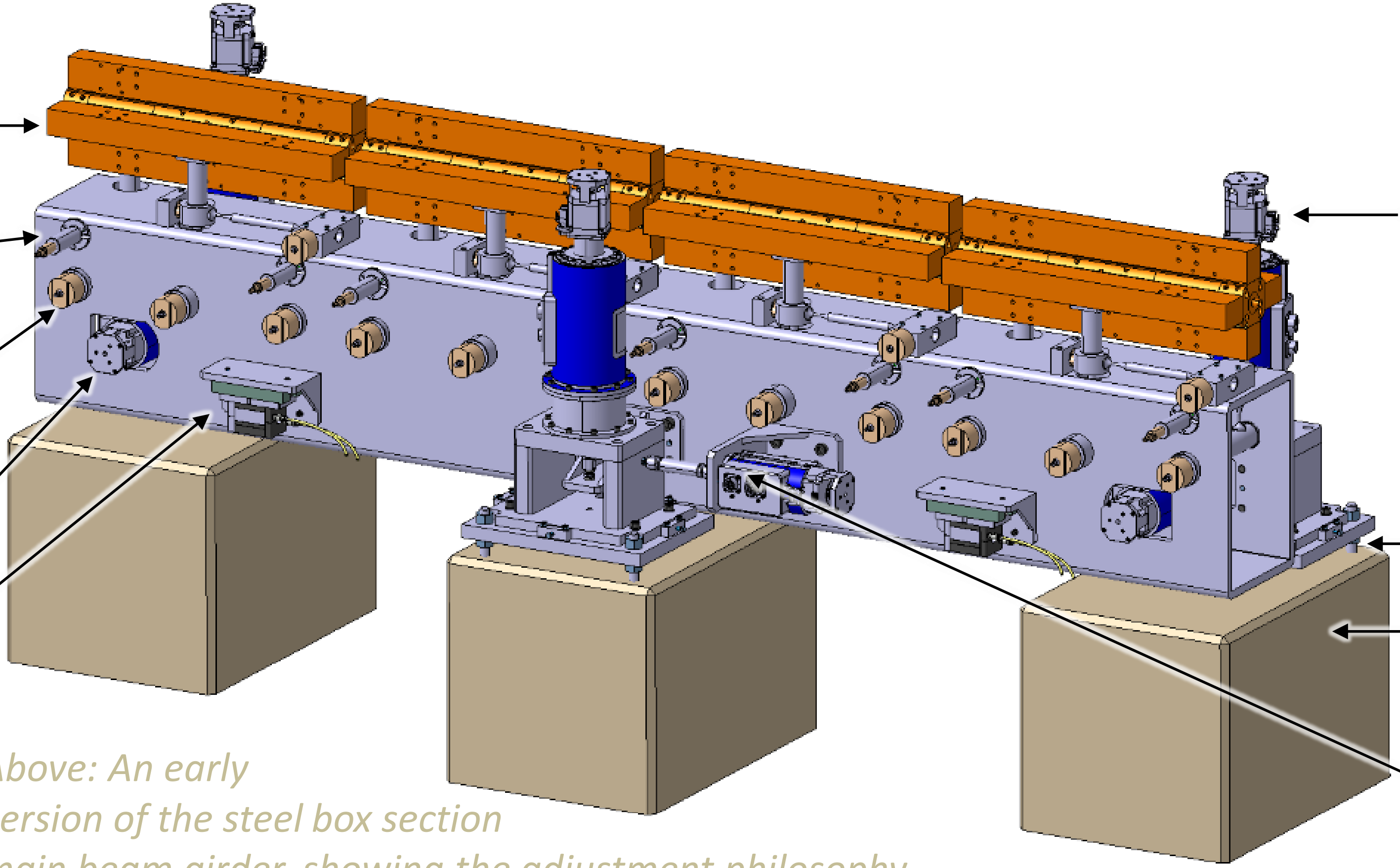


Top: Boostec SiC Girder and positioning actuators

Middle: Epucret drive beam Girder. Bottom: Steel Box Section Including machined mounting and integration holes

Box-Profile Main Beam Summary

Summary of the current module support philosophy. Specifics of the design have scope to change.



SAS

Steel box section girder

Prealignment adjustment points

Lateral adjustment actuators

Wire Position Sensors

Vertical adjustment actuator

Longitudinal adjustment actuator

Course manual adjustment

Bulk supports

Longitudinal flexure (shown with adjustment actuator here)

Above: An early version of the steel box section main beam girder, showing the adjustment philosophy

Module Stability

Module vibration modal analysis, ground noise induced random vibration analysis, and design changes

Stability: Harmonic Modes

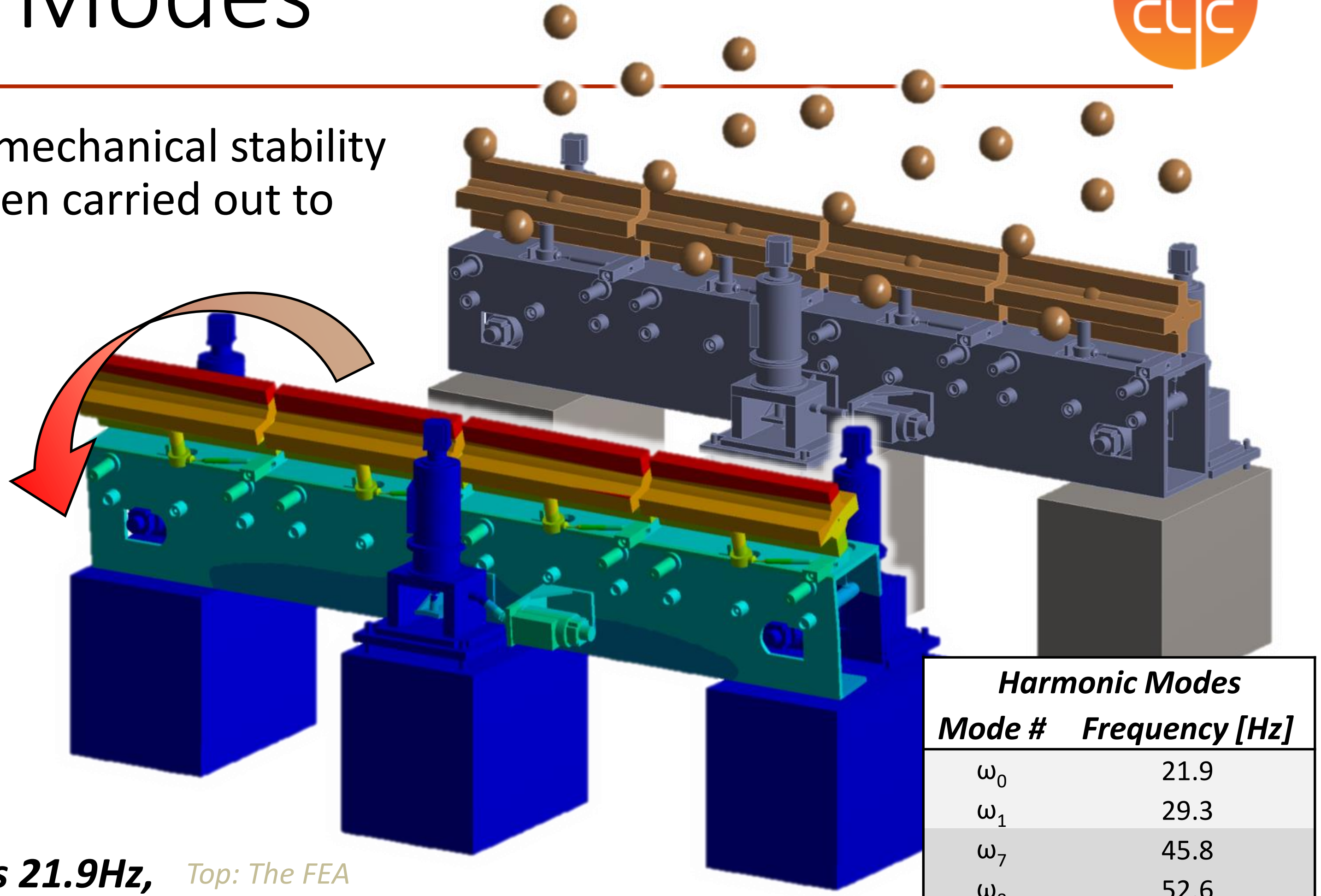
A primary concern with this design is the mechanical stability of the structures. Modal analyses have been carried out to determine the harmonic frequencies.

Known Sources of Vibration

- CLIC operational frequency:
  - 50Hz (or 100Hz)
  - The ground noise
- Other sources of vibrations:
  - Water cooling circuits
  - Tunnel air flow
  - Other, unquantified sources of mechanical vibration

The natural frequency (ω_0) of the MB girder is 21.9Hz, with several harmonic modes around 50Hz.

- ***Concerning for the alignment and stability***



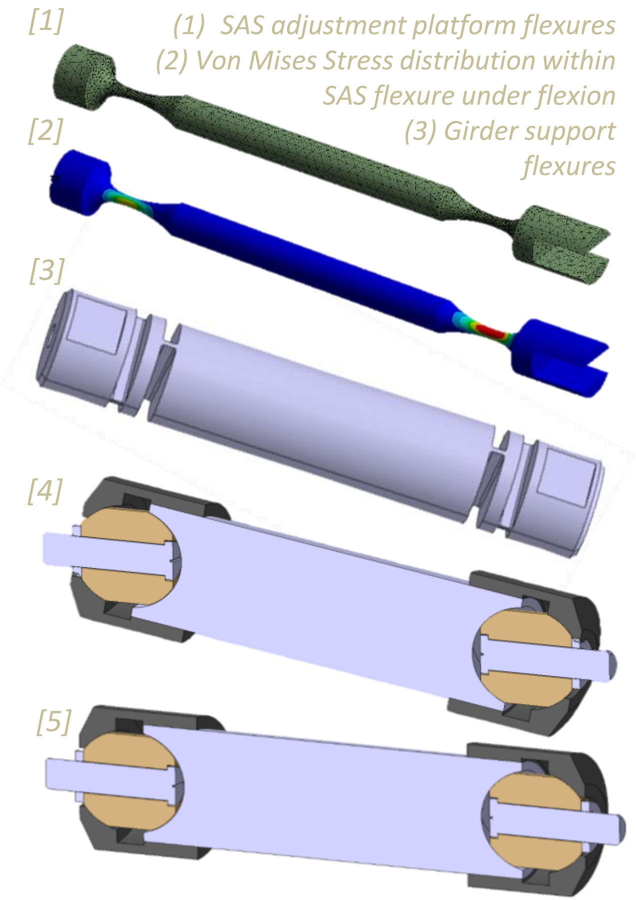
Top: The FEA model used for the modal analysis, including 'point mass' representation of the waveguide & vacuum network. Bottom: A contour plot of the primary mode. Right: Table of modal frequencies

Harmonic Modes	
Mode #	***Frequency [Hz]***
ω_0	21.9
ω_1	29.3
ω_7	45.8
ω_8	52.6
ω_9	58.4
ω_{17}	87.6
ω_{18}	117.3

‘Universal Adjustment Platform’ Technology Collaboration

- The lowest stiffness components within the assembly are the flexures:
  - The on-axis stiffness is determined by the cross-sectional area. This should be *maximised* to improve stiffness.
  - The off-axis stiffness is determined by the cross-sectional area. This should be *minimised* to increase the adjustment range.
- Options:
  - Find a compromise between the two stiffness values
  - Find an alternative to the flexures: *“Universal Adjustment Platform Zero Backlash Joints”* Designed by **Mateusz Sosin (EN-SMM-HPA)**

- ***“Universal Adjustment Platform Zero Backlash Joints” for HL-LHC***
  - The design consists of two sintered bronze ball bearings connected in series, providing the same kinematics as the original flexure
  - Mostly decouples the adjustment range and the axial stiffness
  - Analysis shows that the axial stiffness can exceed that of single-component flexures, if a ball bearing of sufficient diameter is selected
    - Testing: To be carried out shortly by **Mateusz Sosin (EN-SMM-HPA)**



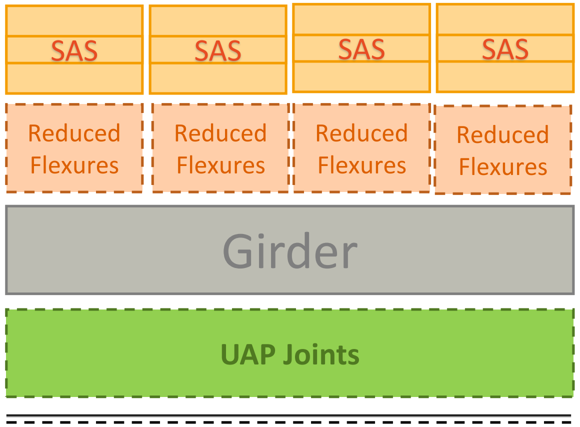
(1) SAS adjustment platform flexures
(2) Von Mises Stress distribution within SAS flexure under flexion
(3) Girder support flexures

(4) A cross section of a ‘Universal Adjustment Platform’ style joint showing off-axis displacement
(5) The ‘UAP’ Joint, un-deformed

Stiffness Optimisation

- In order to increase the fundamental frequency the following alterations have been made:
    - The active-alignment of the girder is achieved using UAP joints rather than flexures
        - The diameter of the UAP joints is increased to 50mm
    - The stiffness of the passive-alignment flexures for the SAS is increased
        - Reducing the range from ±1.5mm to ±0.5mm
    - The height of the centre-of-mass of the waveguide network, vacuum manifolds, and RF loads is lowered

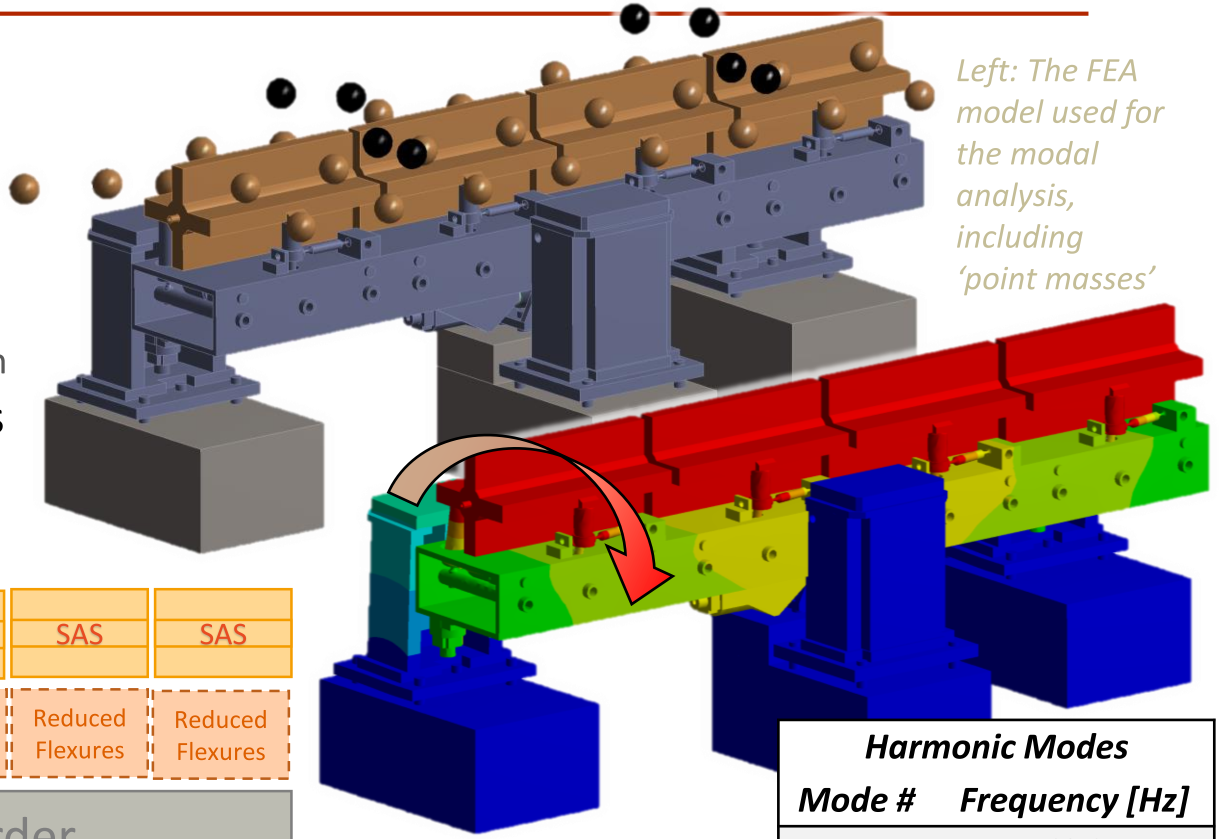
The natural frequency (ω_0) of this MB girder is 60.6Hz.


SAS SAS SAS SAS

Reduced Flexures Reduced Flexures Reduced Flexures Reduced Flexures

Girder

UAP Joints


Left: The FEA model used for the modal analysis, including 'point masses'

(Above) A contour plot of the primary mode. (Left) Girder alignment schematic. (Right) Table of the modal frequencies

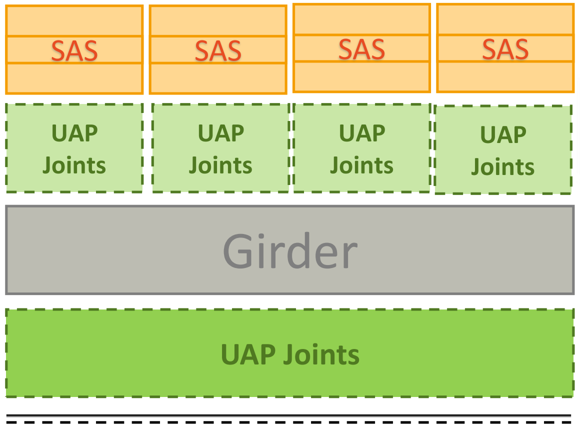
Harmonic Modes	
Mode #	***Frequency [Hz]***
ω_0	60.6
ω_1	61.5
ω_2	98.9
ω_3	158.7
ω_4	169.5

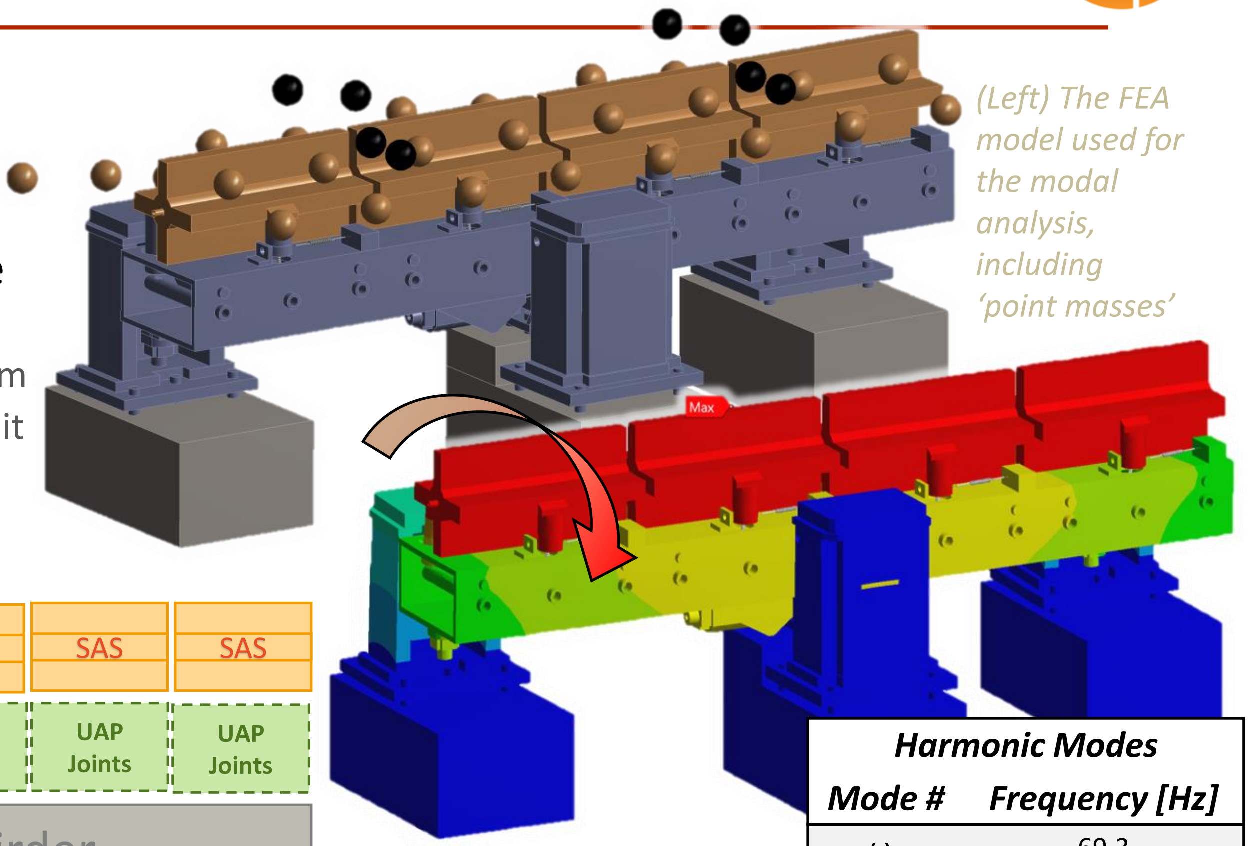
Stiffness Optimisation

- In order to further increase the fundamental frequency the following alterations been made:
  - All flexures within the alignment system have been replaced with UAP joints
    - The diameter of the UAP joints is increased to 50mm
    - For integration purposes it may be necessary to limit the diameter of the SAS UAP joints to <40mm
    - The adjustment range is no-longer limited
  - The height of the centre-of-mass of the waveguide network, vacuum manifolds, and RF loads is lowered

The natural frequency (ω_0) of this MB girder is increased 69.3Hz.

The range of the adjustment is not limited.





(Left) The FEA model used for the modal analysis, including 'point masses'

(Above) A contour plot of the primary mode. (Left) Girder alignment schematic. (Right) Table of the modal frequencies

Harmonic Modes

Mode #	***Frequency [Hz]***
ω_0	69.3
ω_1	72.2
ω_2	110.6
ω_3	153.1
ω_4	171.4

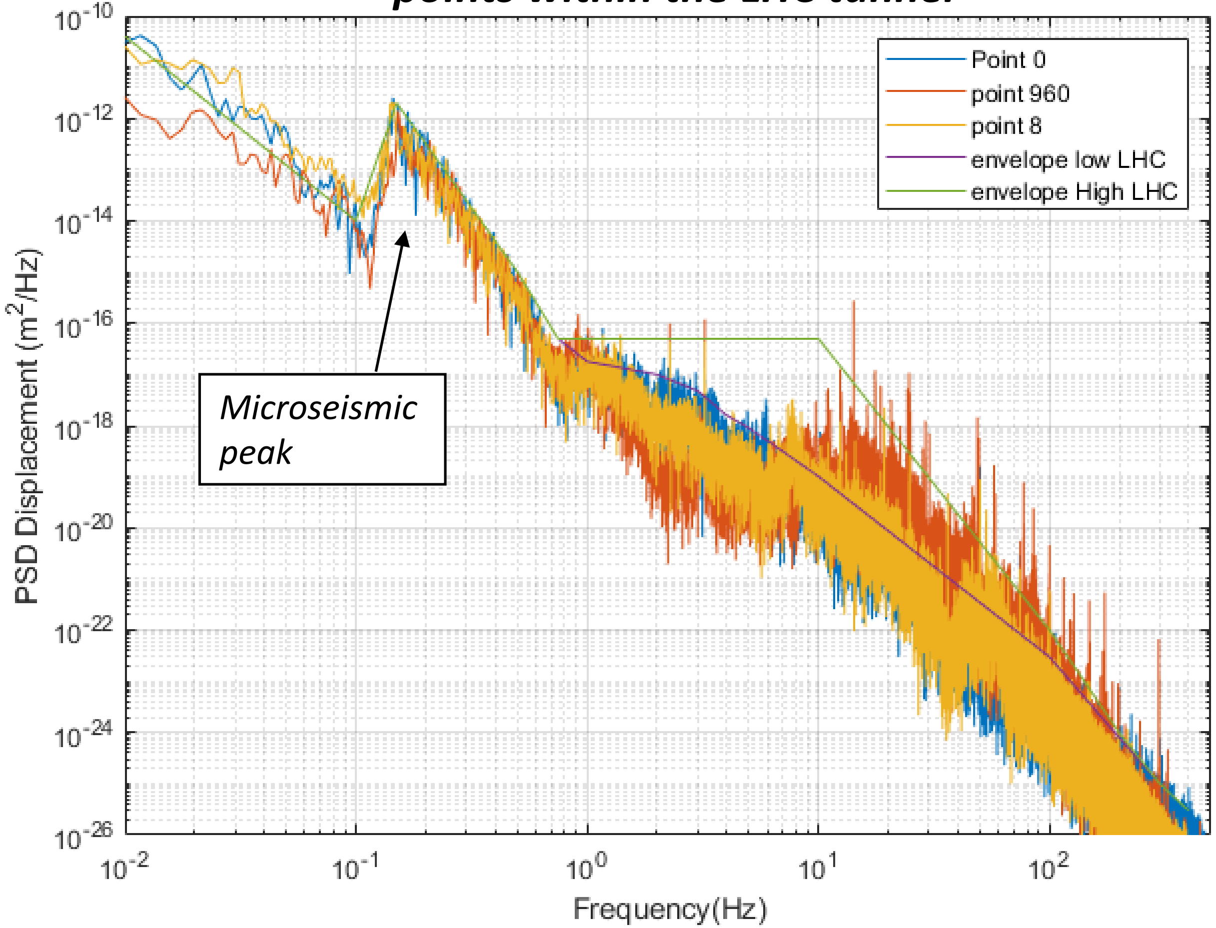
Ground Noise

- The harmonic frequencies are interesting, but difficult to quantify without an excitation frequency
- We have ground noise data recorded from several points within the LHC tunnel
  - Measured with seismometers at several locations between point 0 (the furthest & quietest) and point 960 (noisiest)
  - Each measurement was taken over 20 minutes
  - The frequency domain results of these measurements are shown right

Thank you to Kurt Artoos (EN-MME-EDM) who provided and processed the data

Produce the high and low envelopes, and advised me on the following analysis

Displacement Power Spectral Density from several points within the LHC tunnel



Ground Noise – Flexure Stiffness

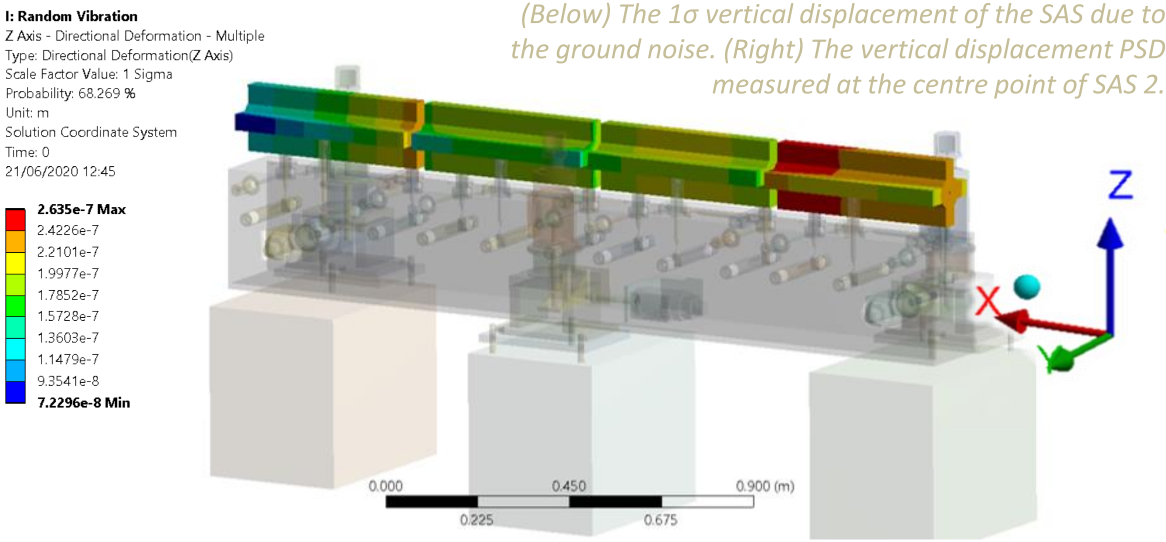
- The displacement PSD data can be used as a direct input into Ansys ‘Random Noise’ analysis
  - The excitation is assumed to be the same in X, Y, and Z directions
  - Used to determine the probability of displacements on a gaussian distribution

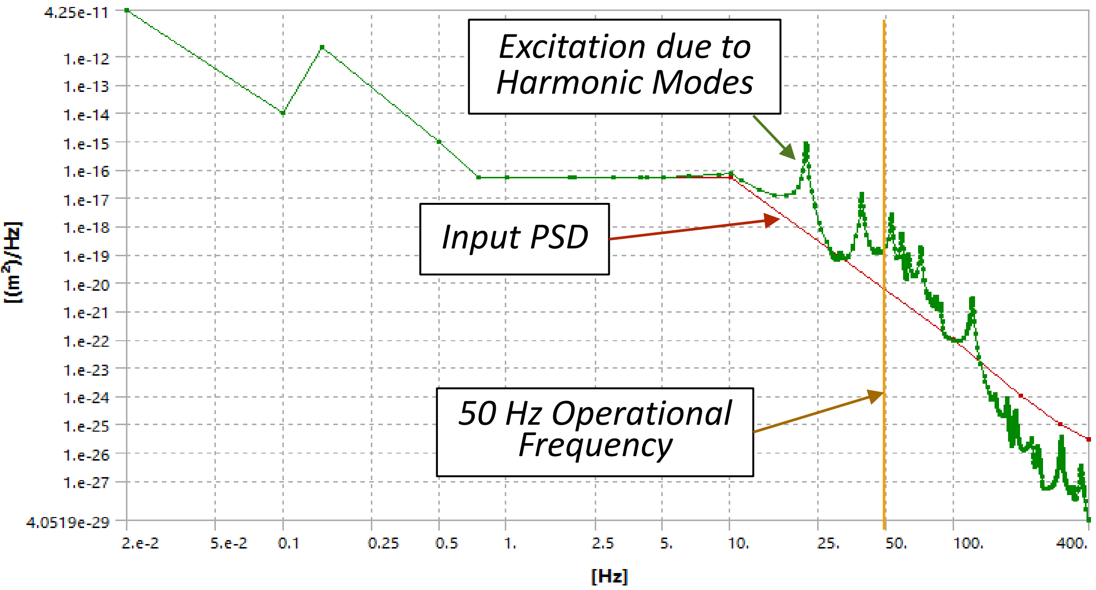
Results for Box Section Flexure Supported Girder:

- 3σ vertical displacement of the SAS due to ground noise is 0.8μm
- The PSD shows the excitation due to the harmonic modes

Normal Distribution	Maximum Displacement [μm]		
	X Axis	Y Axis	Z Axis
1σ (66.27%)	0.1254	0.1256	0.2635
2σ (95.45%)	0.2508	0.2512	0.527
3σ (99.73%)	0.3762	0.3768	0.7905
4σ (99.99%)	0.5016	0.5024	1.054

(Below) The 1σ vertical displacement of the SAS due to the ground noise. (Right) The vertical displacement PSD measured at the centre point of SAS 2.





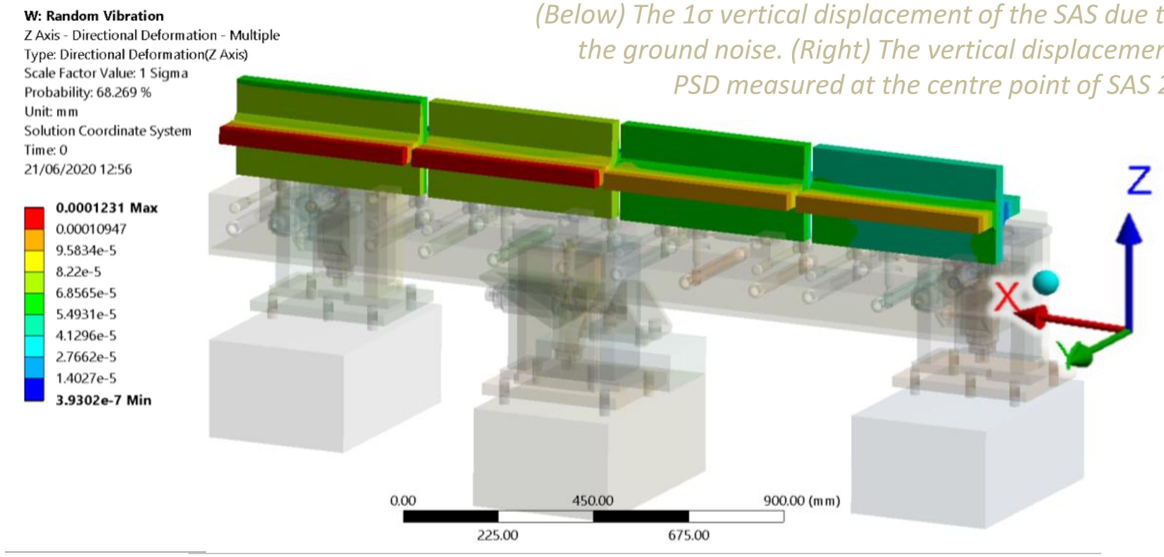
Ground Noise – Flexure Stiffness

The same analysis performed when the girder is supported by the UAP (50mm) joints, and the SAS are supported by the limited range flexures.

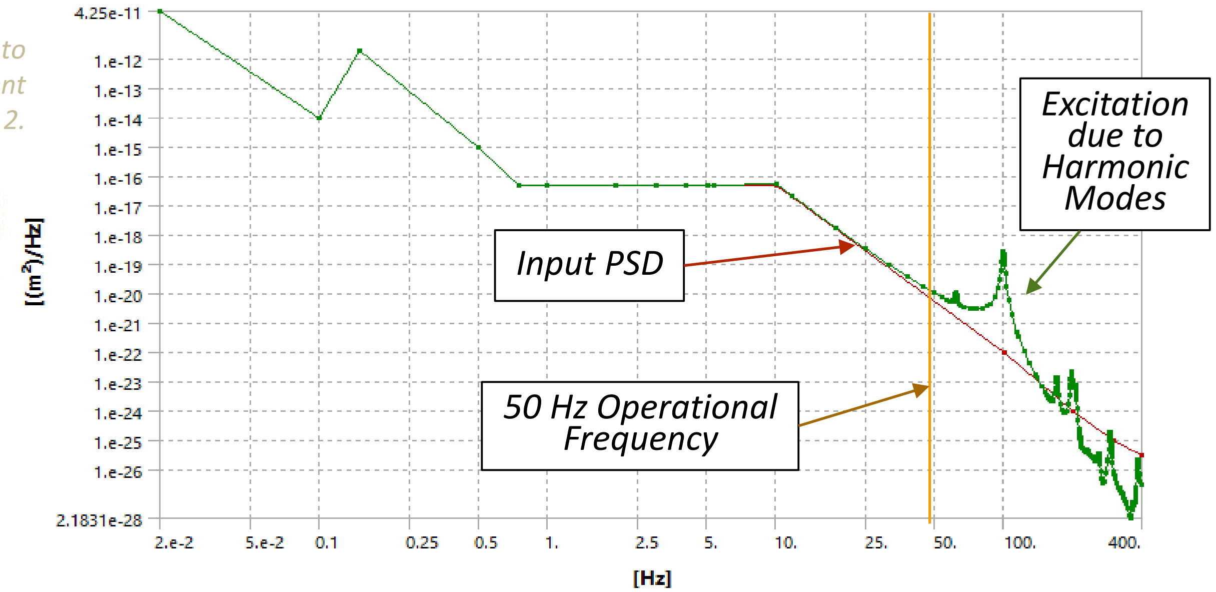
Results for Box Section Joint Supported Girder:

- 3σ vertical displacement of the SAS due to ground noise is 0.4µm
- The PSD shows the excitation due to the harmonic modes
  - The natural frequency is now above the 50Hz operational frequency of CLIC.
  - At frequencies below ω_0 the SAS follow the ground displacement

Normal Distribution	Maximum Displacement [µm]		
	X Axis	Y Axis	Z Axis
1σ (66.27%)	0.1254	0.1371	0.1348
2σ (95.45%)	0.2508	0.2742	0.2696
3σ (99.73%)	0.3762	0.4113	0.4044
4σ (99.99%)	0.5016	0.5484	0.5392



(Below) The 1σ vertical displacement of the SAS due to the ground noise. (Right) The vertical displacement PSD measured at the centre point of SAS 2.



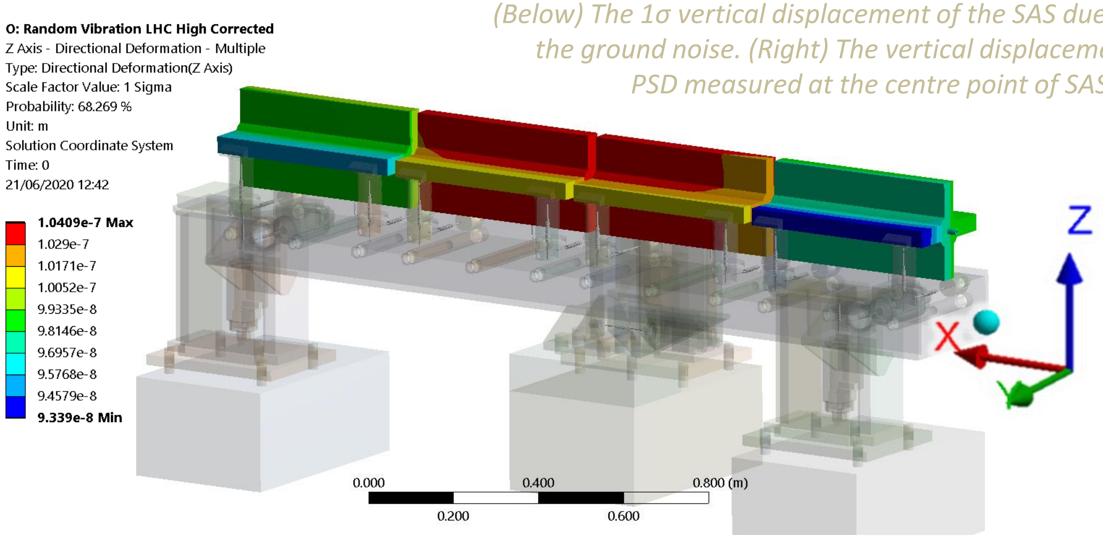
Ground Noise – Flexure Stiffness

The same analysis performed when the girder and all of the SAS are supported by the UAP (50mm) joints.

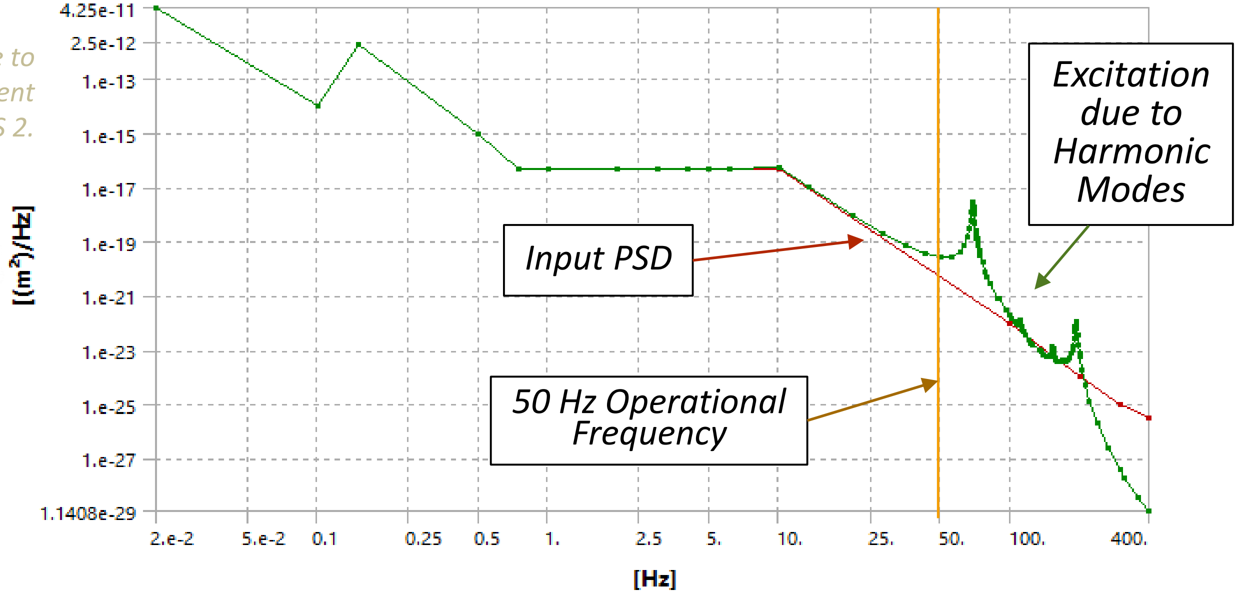
Results for Joint Supported Box Section Girder and SAS:

- 3σ vertical displacement of the SAS due to ground noise is 0.3µm
- The PSD shows the excitation due to the harmonic modes
  - The natural frequency is now above the 50Hz operational frequency of CLIC.
  - At frequencies below ω_0 the SAS follow the ground displacement

Normal Distribution	**Maximum Displacement [µm]**		
	X Axis	**Y Axis**	**Z Axis**
1σ (66.27%)	0.11	0.0677	0.1041
2σ (95.45%)	0.22	0.1354	0.2082
3σ (99.73%)	0.33	0.2031	0.3123
4σ (99.99%)	0.44	0.2708	0.4164



(Below) The 1σ vertical displacement of the SAS due to the ground noise. (Right) The vertical displacement PSD measured at the centre point of SAS 2.



Excitation due to Harmonic Modes

Input PSD

50 Hz Operational Frequency

Stability Study Summary

Summary of the results of the stability studies carried out on the 'current' CLIC main beam support girder design:

- The current flexure support system is non-optimised with regards to stability
- By utilising the joints developed for the Universal Adjustment Platform, the same adjustment methodology can be used while improving:
  - The fundamental frequency
  - The statistical ground noise induced displacements
  - The achievable adjustment range
  - Potentially at a lower cost

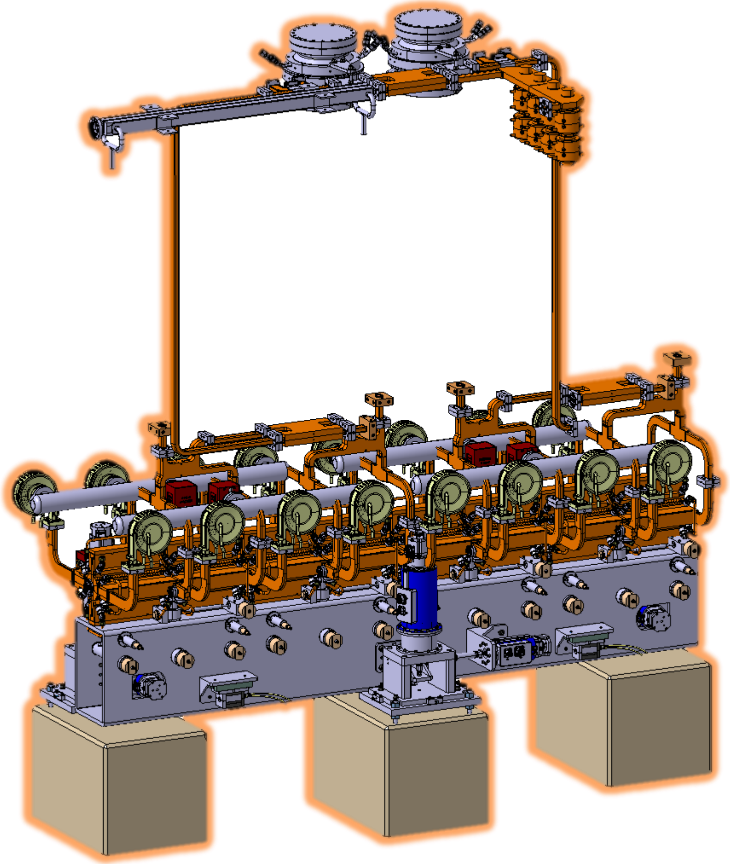
1. *The actually suitability of these designs depends on the stability requirements of the CLIC SAS* ***. To be discussed.***
2. *The numbers presented here are dependent on an assumed optimisation of the waveguide network.* ***Is this achievable?***

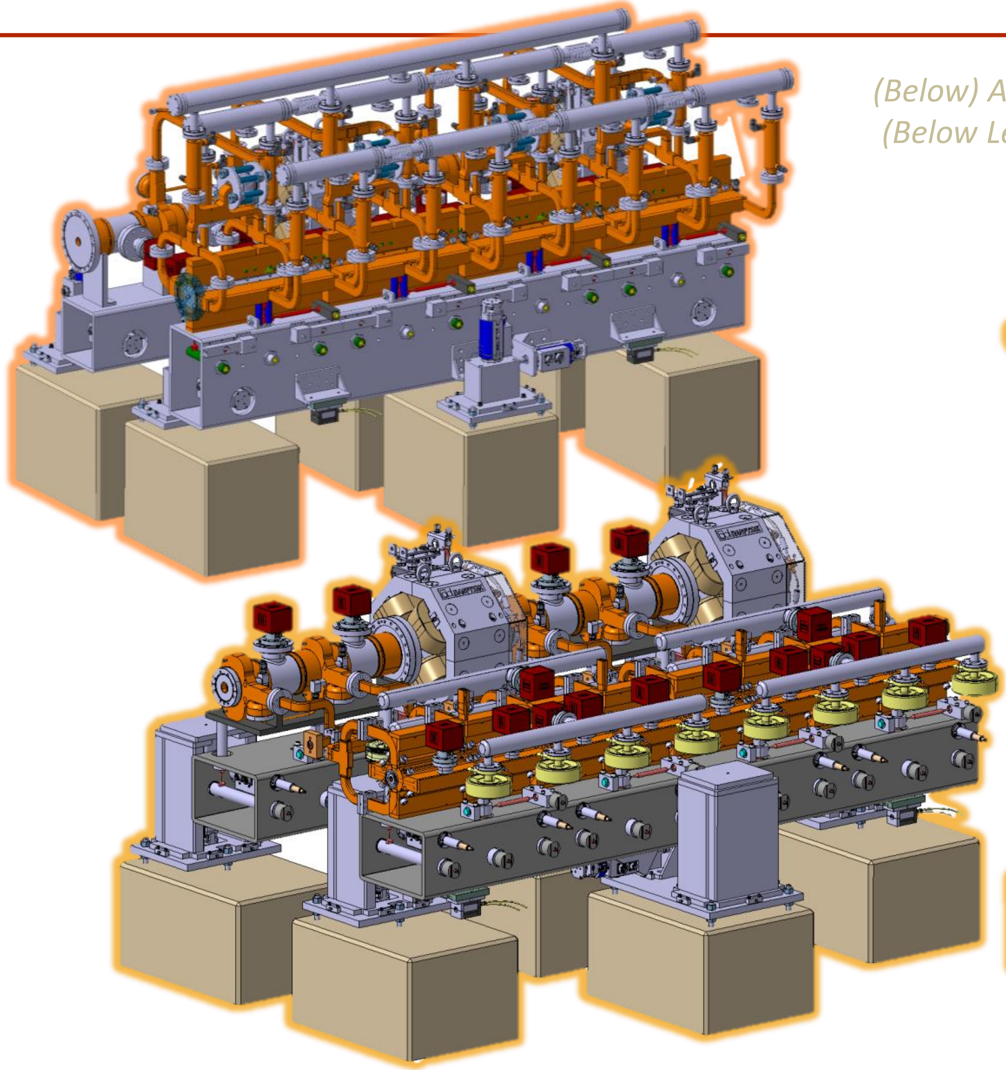
Support Design	**Adjustment Range (Girder, SAS) [mm]**	**Fundamental Frequency ω_0 [Hz]**	**Ground Noise 3σ Vertical Displacement [μm]**	**Ground Noise 3σ Lateral Displacement [μm]**
Box Section: Flexures Supporting Girder	±1.0, ±0.5,	21.9	0.7905	0.3768
Box Section: Joints Supporting Girder	>±1.5,±0.5,	60.6	0.4044	0.4113
Box Section: Joints Supporting Girder and SAS	>±1.5, >±1.5	69.3	0.3123	0.2031

(Above) Stability study summary table

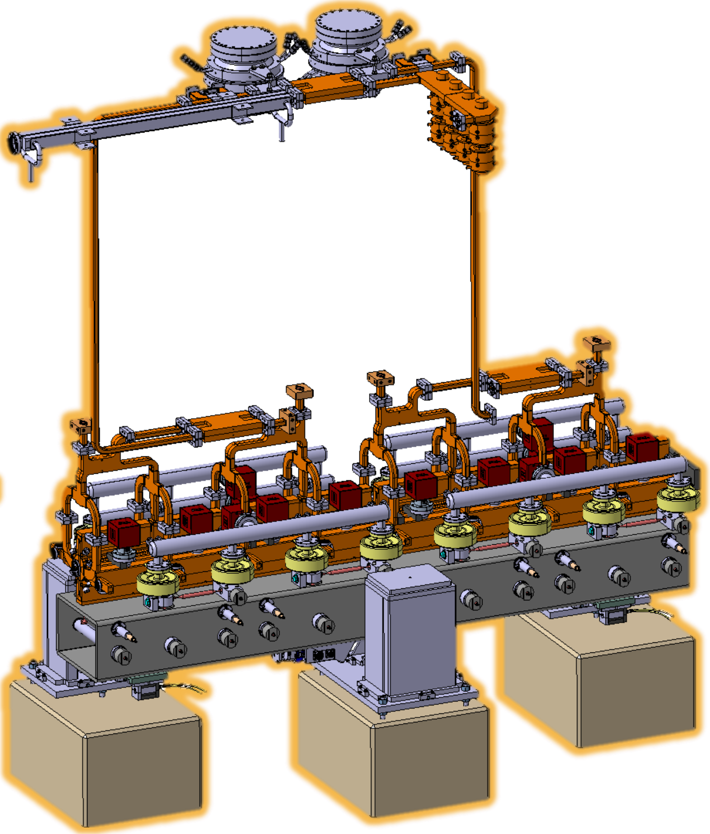
Module Variations

(Below) A flexure based K-CLIC Module
(Right) A flexure based CLIC Two Beam Module



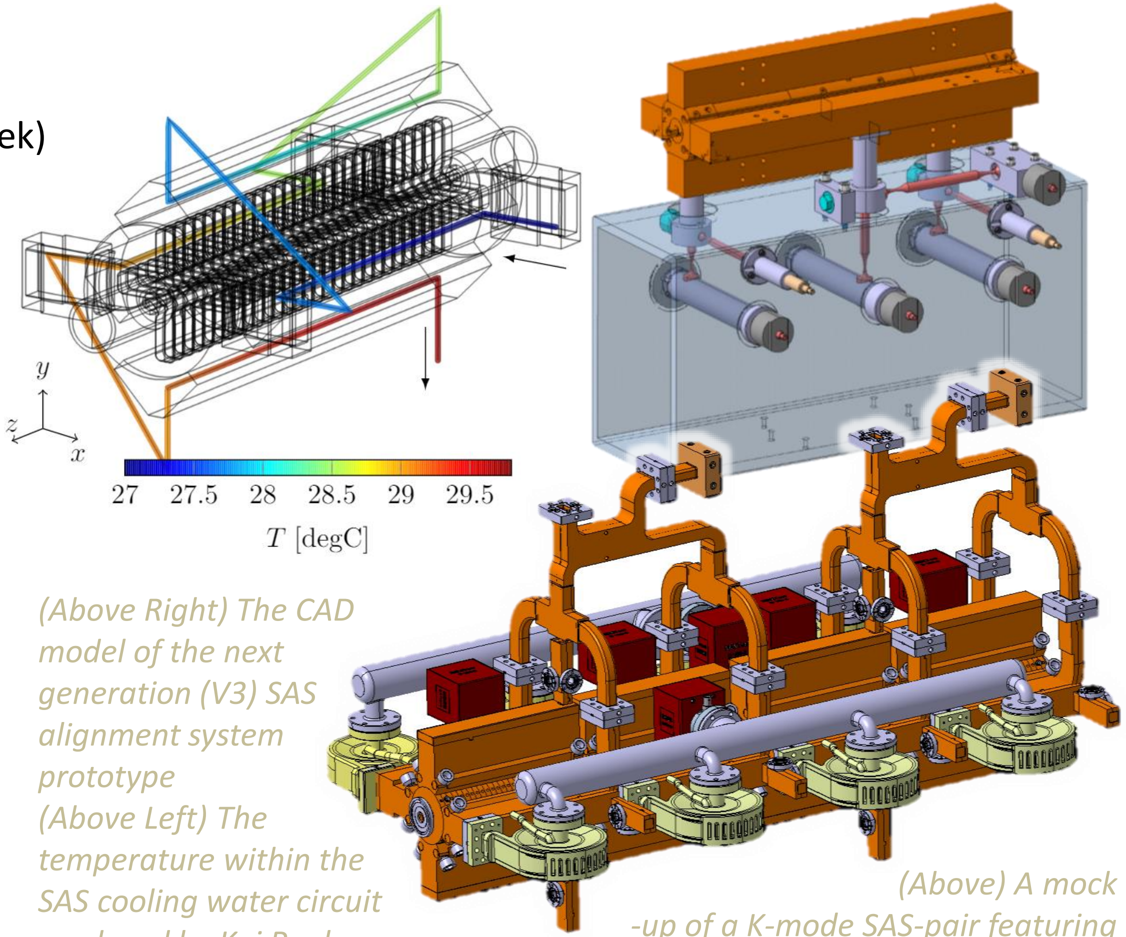


(Below) A joint based 'High-Stiffness' K-CLIC Module
(Below Left) A joint based 'High-Stiffness' CLIC Two Beam Module



Current and Future Work

- Receive the next-generation SAS adjustment platform prototype
  - Test and characterise this system (delivery is expected this week)
- Develop full supporting system utilising UAP joints
  - Probably using UAP joints throughout the module due to high stiffness, greater range, lower cost
    - Define a stability requirement: joint stiffness is related to bearing diameter, which effects integration
  - Optimisations for other module types (e.g. K-CLIC, eSPS,)
    - Separate MB & DB girders
    - Different alignment and stability requirements
  - Assist with the stiffness testing of the UAP joints
    - Use the results to verify the FEA
- Other SAS considerations:
  - Cooling circuit development and optimisation
    - Analysis carried out by **Kai Papke** characterised the impact of different cooling circuit designs
    - Cooling circuit design is significant for integration optimisation
  - Design of waveguide and vacuum networks



(Above Right) The CAD model of the next generation (V3) SAS alignment system prototype

(Above Left) The temperature within the SAS cooling water circuit produced by Kai Papke

(Above) A mock-up of a K-mode SAS-pair featuring compact waveguide and vacuum networks

Thank you for listening

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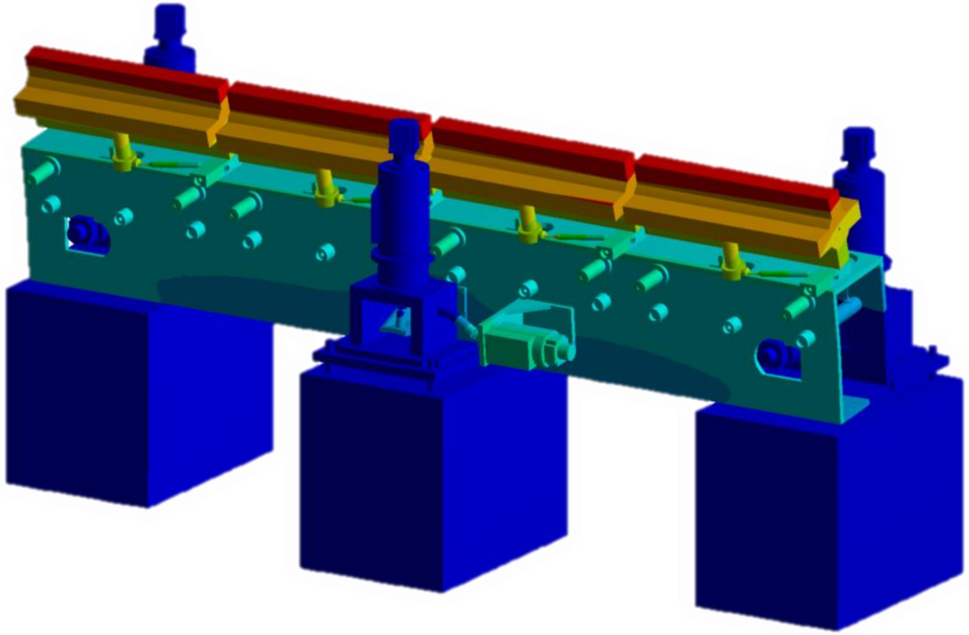
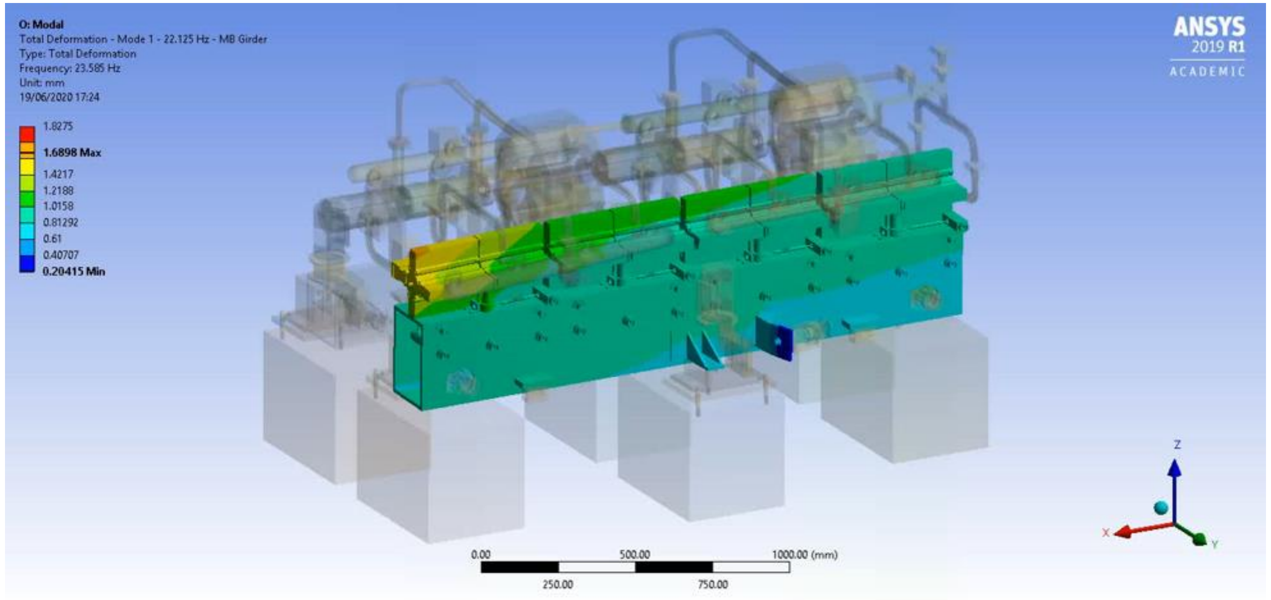
Extra Slide: Full System Analysis





O: Modal
Total Deformation - Mode 1 - 22.125 Hz - MB Girder
Type: Total Deformation
Frequency: 23.585 Hz
Unit: mm
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