



# The CLIC Module Studies - recent progress and results

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*With thanks to:*

*Mateusz Sosin, Hélène Durand, Kurt Artoos*

# Contents



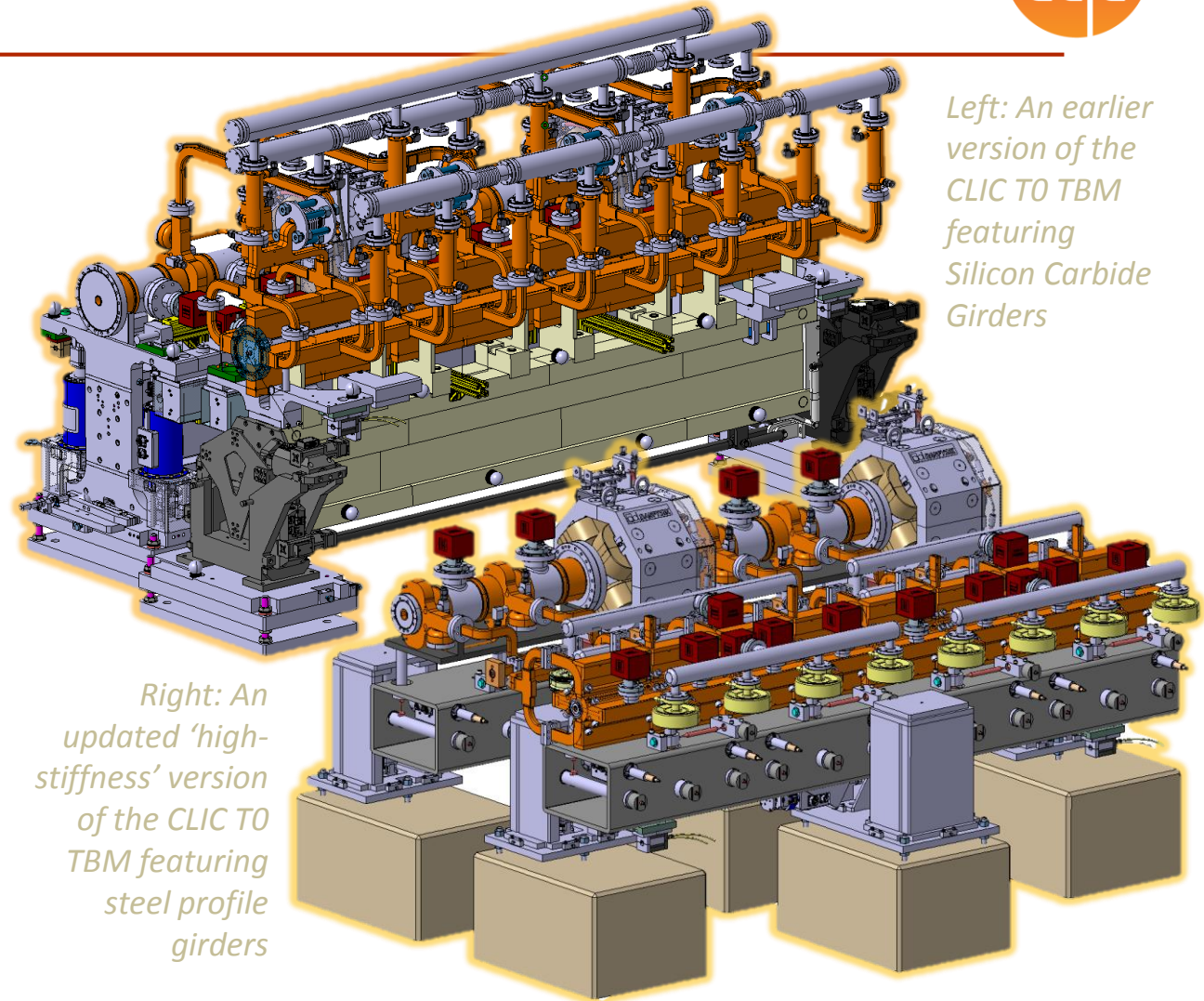
<b>Two Beam Module</b>	2
<i>Two Beam Module Introduction</i>	3
<i>Alignment Philosophy the of SAS and Girder</i>	4
<b>Super Accelerating Structure Alignment</b>	5
<i>SAS Alignment Prototype</i>	6
<i>SAS Alignment Prototype Testing</i>	7
<i>Next Generation Prototype</i>	8
<b>Next Generation Prototype</b>	9
<i>Girder Design and Material</i>	10
<i>Box-Profile Main Beam Summary</i>	11
<b>Module Stability</b>	12
<i>Stability: Harmonic Modes</i>	13
<i>'Universal Adjustment Platform' Technology Collaboration</i>	14
<i>Stiffness Optimisation</i>	15
<i>Ground Noise</i>	17
<i>Ground Noise – Flexure Stiffness</i>	18
<i>Stability Study Summary</i>	21
<i>Module Variations</i>	22
<b>Current and Future Work</b>	23

# 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



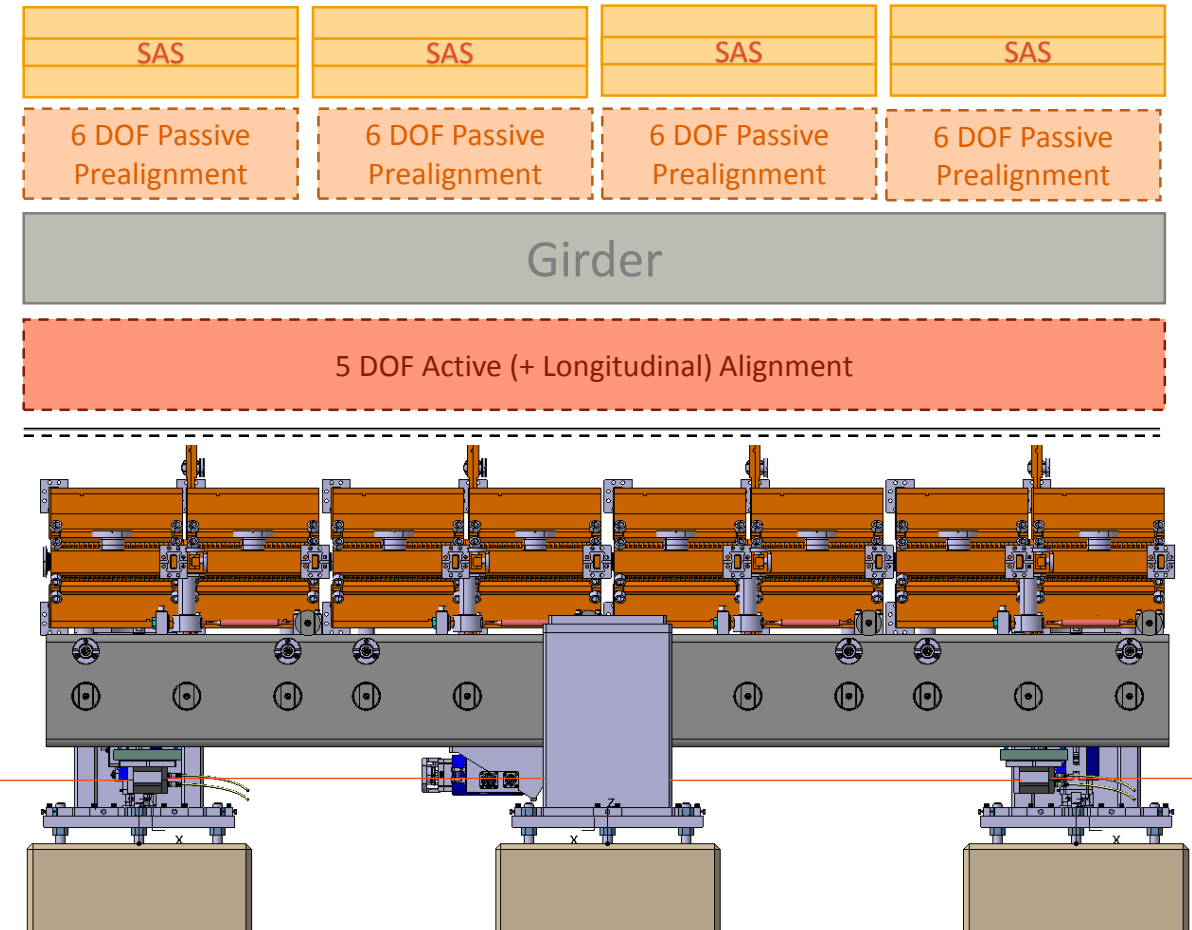
*Left: An earlier version of the CLIC TO TBM featuring Silicon Carbide Girders*

*Right: An updated 'high-stiffness' version of the CLIC TO 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  $14\mu\text{m}$ 
  - 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)



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



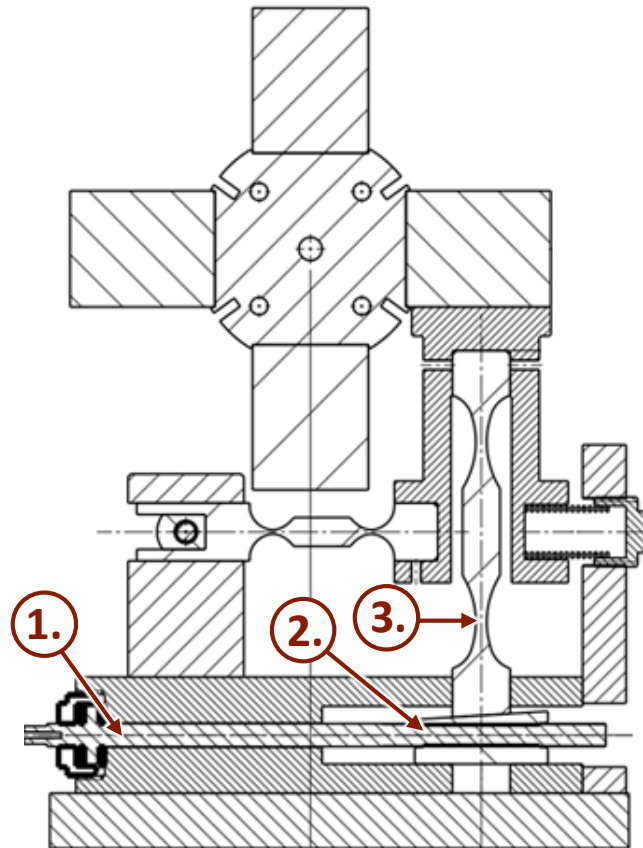
# Super Accelerating Structure Alignment

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

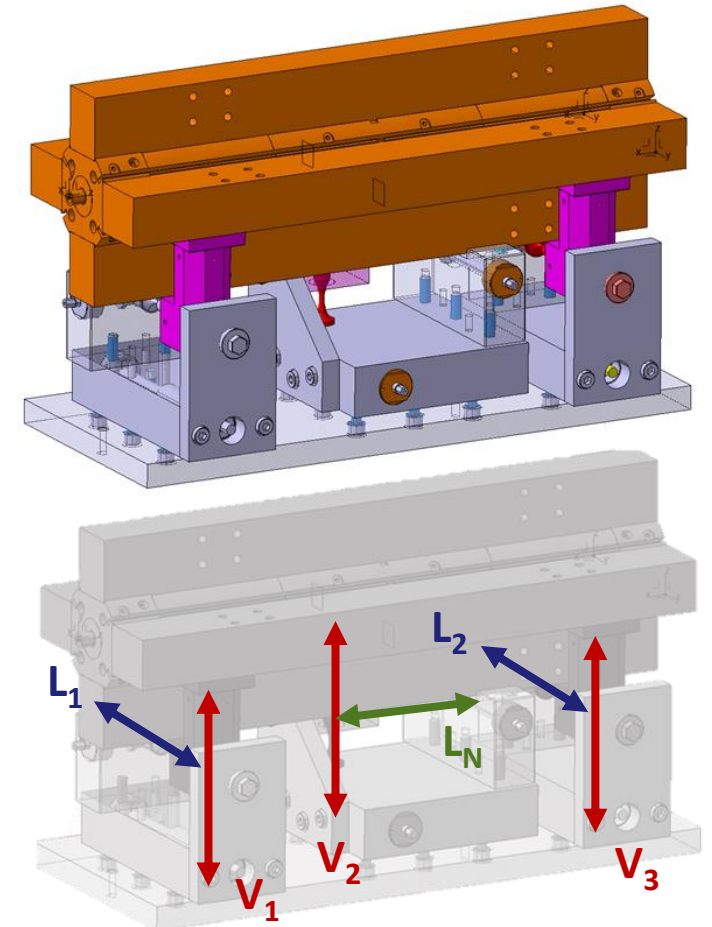
# SAS Alignment Prototype



- 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  $90\mu\text{m}/\text{revolution}$  over  $\pm 0.75\text{mm}$**



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



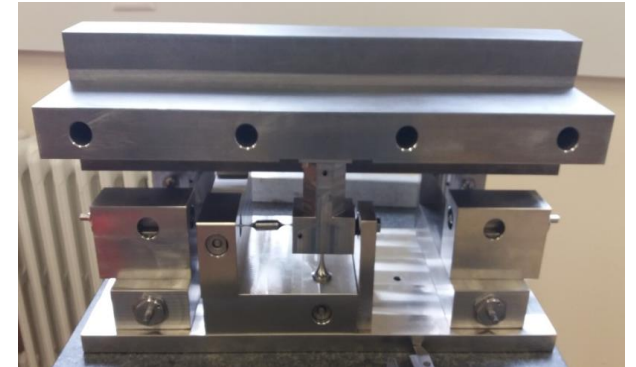
Two prototype Accelerating Structure (AS) pre-alignment adjustment stands have been manufactured and tested in collaboration with the CERN Engineering Survey, Mechatronics, and Measurements (SMM) group.

## Prototype Test Results:

- The Accelerating Structures can be positioned within  $1\mu\text{m}$  when measured directly.
  - To less than the  $15\mu\text{m}$  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  $90\mu\text{m}/\text{revolution}$ , as designed.
- Backlash is less than  $45\mu\text{m}$  (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  $50\mu\text{m}$  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

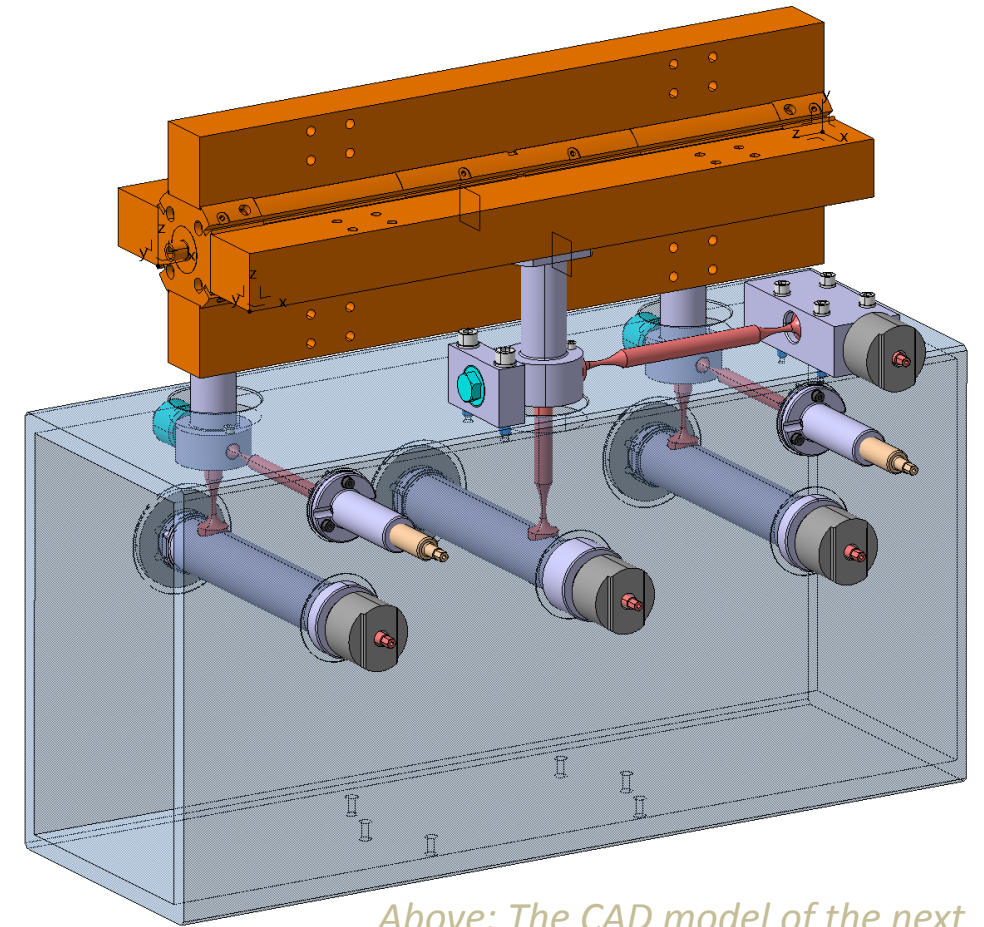


- A new version of the SAS adjustment platform has been designed and manufactured\* with help from **Jukka Vainola**, the Helsinki Institute of Physics, and the CERN Mechanical and Materials Engineering (MME) Group.

## Changes based on the feedback from the first version

- Technical changes:
  - The resolution is improved to  $40\mu\text{m}/\text{revolution}$  based on the same methodology
  - Linear range is increased to  $\pm 1.5\text{mm}$  in all axis
  - Angular range is increased to  $\pm 4\text{mrad}$  in pitch and yaw and  $\pm 12\text{mrad}$  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

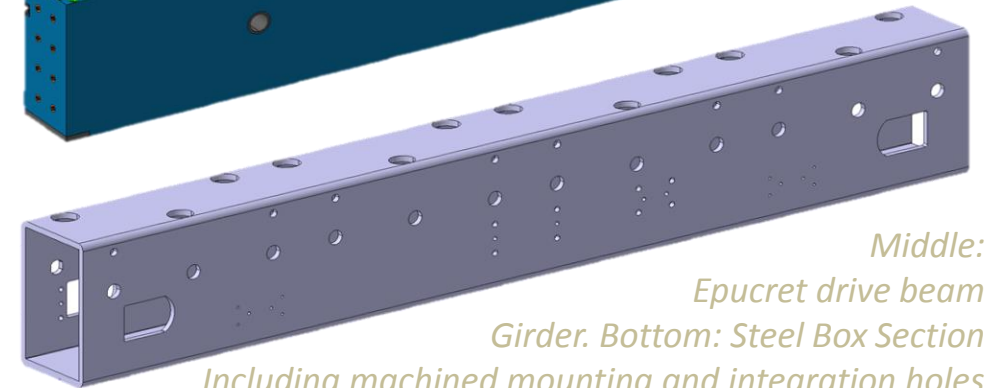
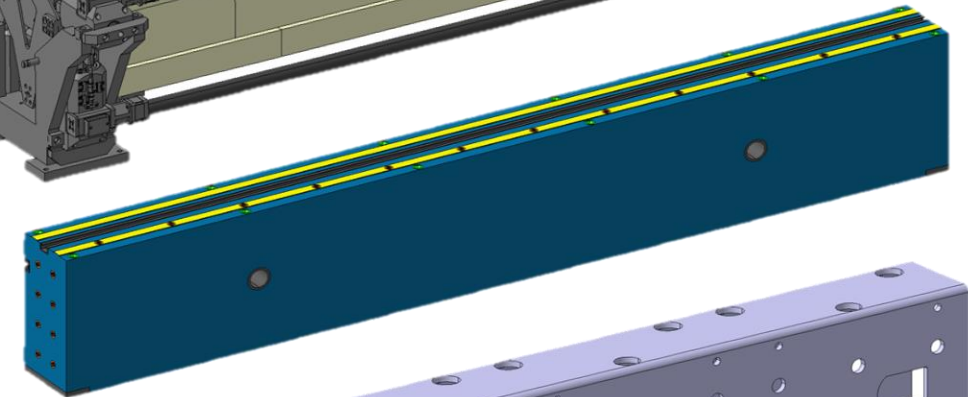
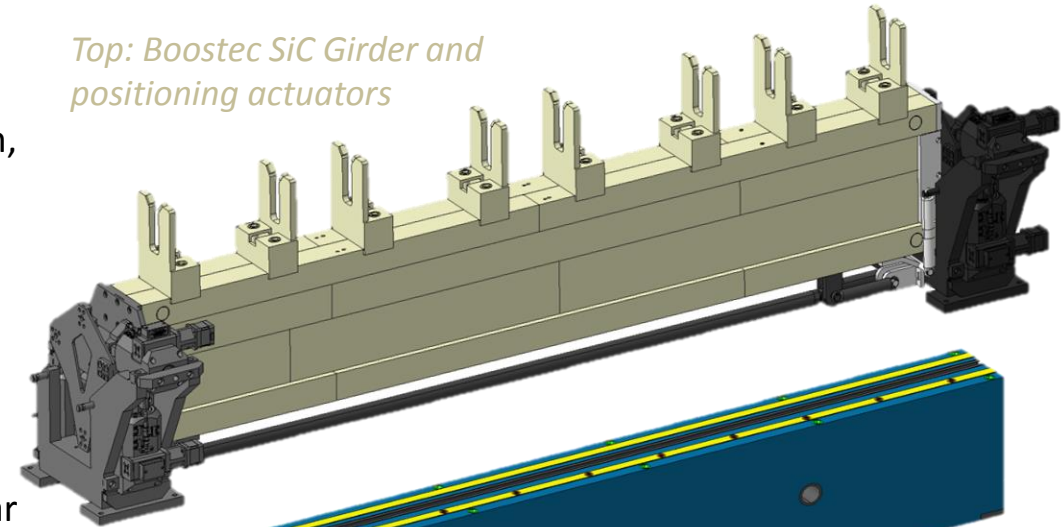
Details and justification of the selection of the support girder material and profile

# Girder Material and Design



- Previous girder designs:
  - Silicon Carbide (SiC)
    - Sintered Silicon Carbide provides the  $<10\mu\text{m}$  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
  - Epucet (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  $<50\mu\text{m}$  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*



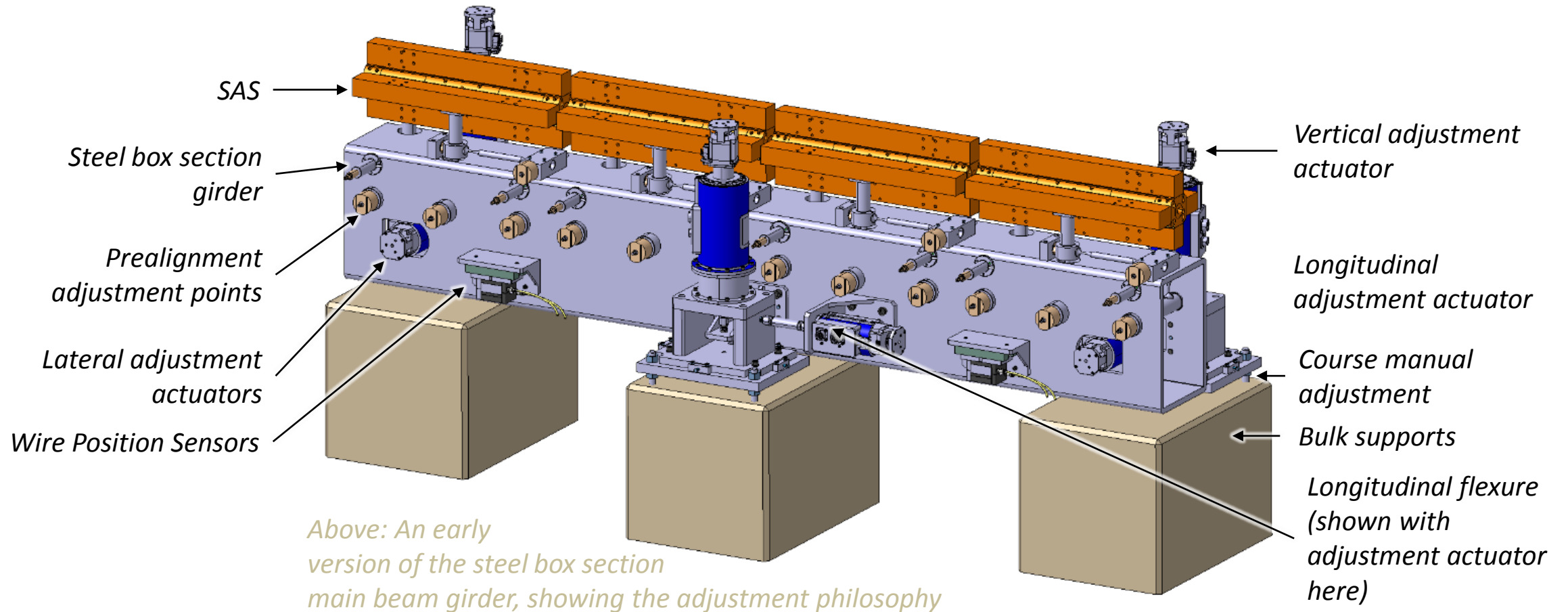
*Middle: Epucet drive beam*

*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.





# Module Stability

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

# Stability: Harmonic Modes

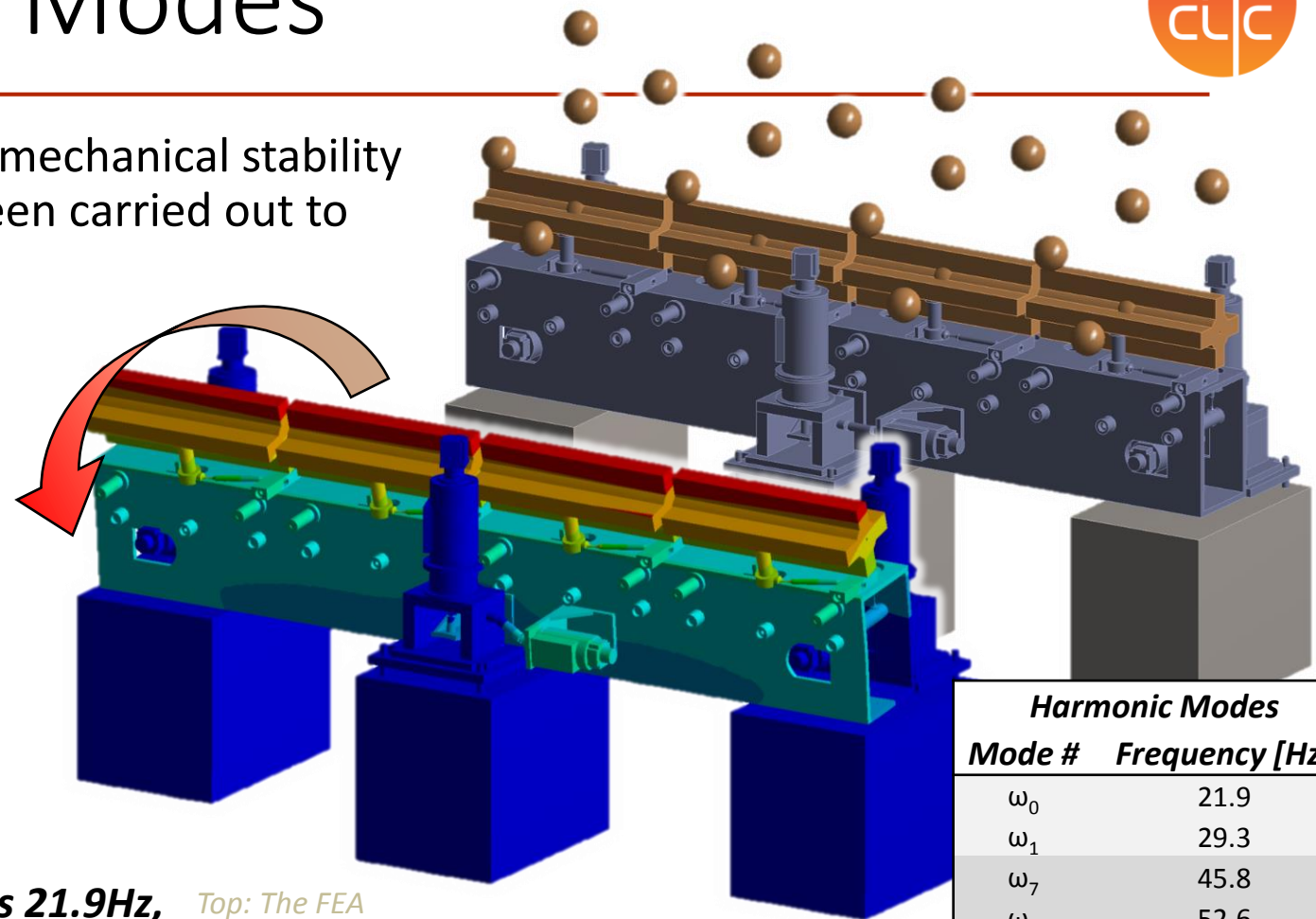
A primary concern with this design is the mechanical stability of the structures. Modal analyses have been carried out to determine the harmonic frequencies.

## 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 ( $\omega_0$ ) of the MB girder is 21.9Hz, with several harmonic modes around 50Hz.**

- **Concerning for the alignment and stability**



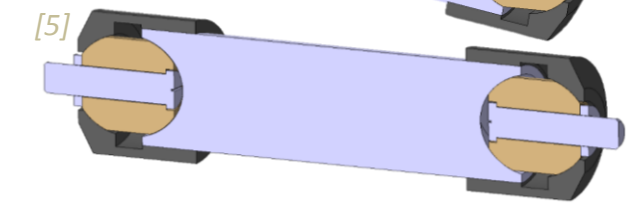
Harmonic Modes	
Mode #	Frequency [Hz]
$\omega_0$	21.9
$\omega_1$	29.3
$\omega_7$	45.8
$\omega_8$	52.6
$\omega_9$	58.4
$\omega_{17}$	87.6
$\omega_{18}$	117.3

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 the modal frequencies

# '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)**



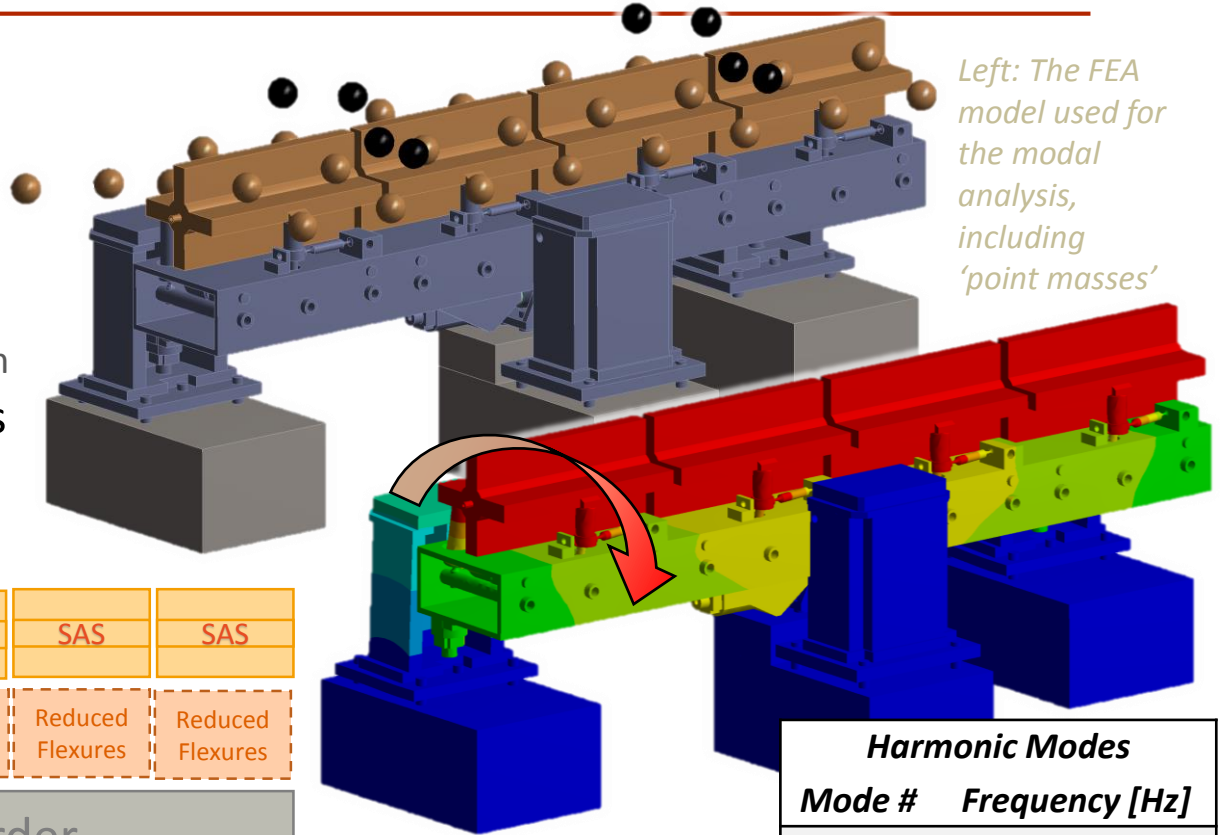
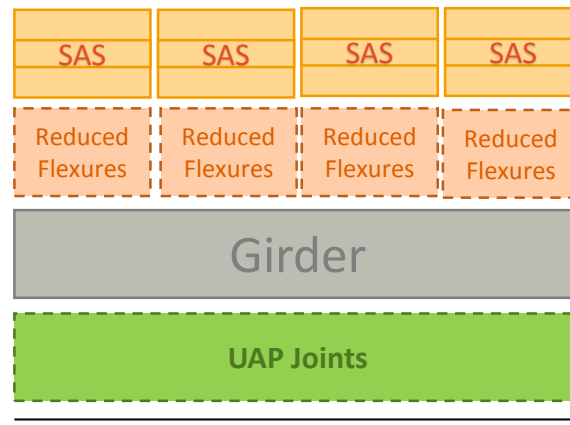
(1) SAS adjustment platform flexures  
(2) Von Mises Stress distribution within SAS flexure under flexion  
(3) Girder support flexures  
(4) A cross section of a 'Universal Adjustment Platform' style joint showing off-axis displacement  
(5) The 'UAP' Joint, un-deformed

# 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  $\pm 1.5\text{mm}$  to  $\pm 0.5\text{mm}$
  - The height of the centre-of-mass of the waveguide network, vacuum manifolds, and RF loads is lowered

**The natural frequency ( $\omega_0$ ) of this MB girder is 60.6Hz.**



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]
$\omega_0$	60.6
$\omega_1$	61.5
$\omega_2$	98.9
$\omega_3$	158.7
$\omega_4$	169.5

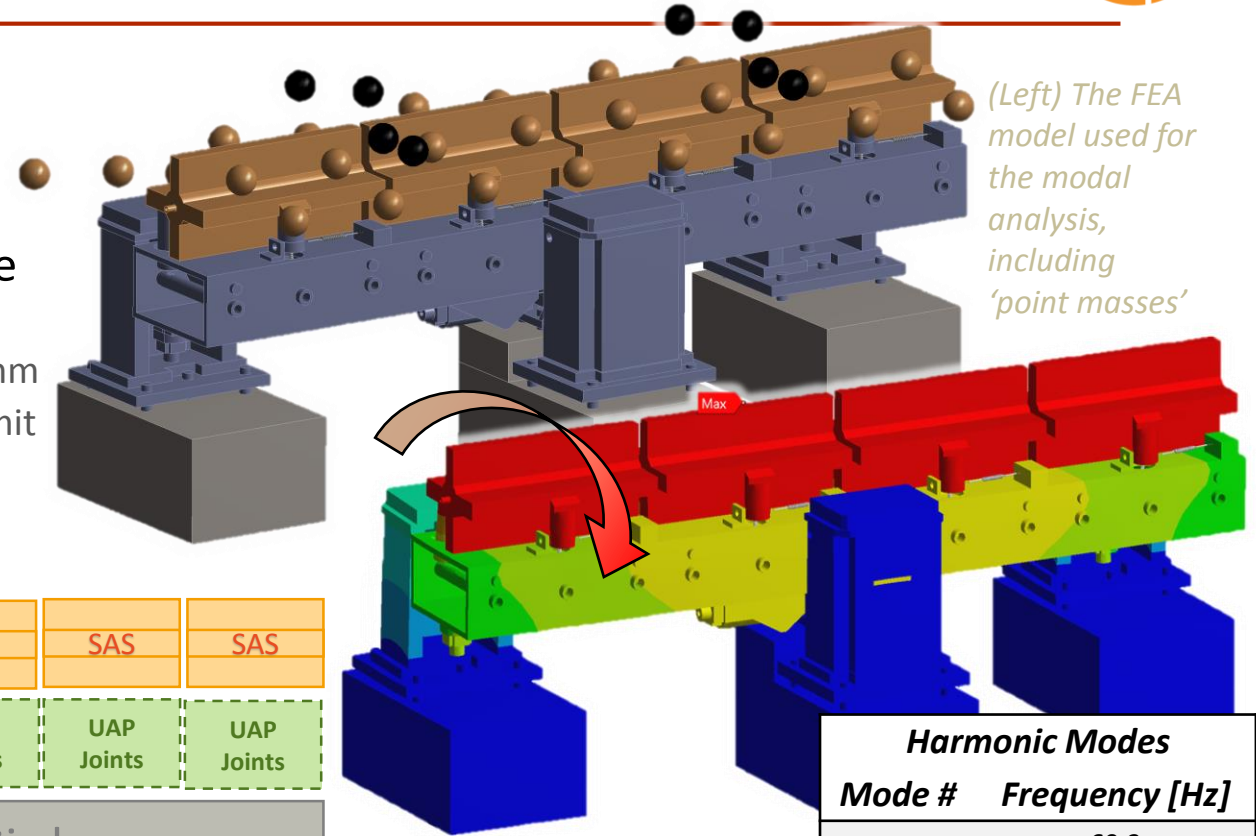
# Stiffness Optimisation



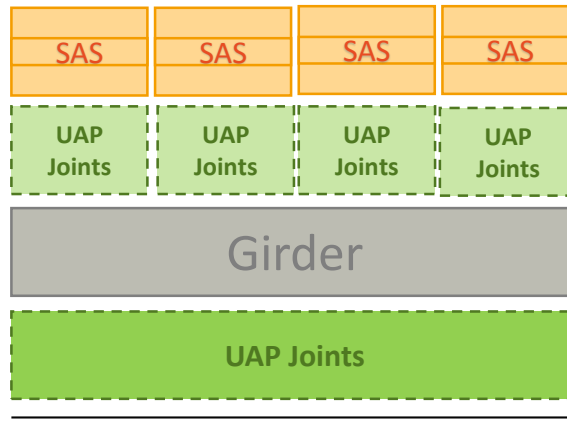
- In order to further increase the fundamental frequency the following alterations been made:
  - All flexures within the alignment system have been replaced with UAP joints
    - The diameter of the UAP joints is increased to 50mm
    - For integration purposes it may be necessary to limit the diameter 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 ( $\omega_0$ ) 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]
$\omega_0$	69.3
$\omega_1$	72.2
$\omega_2$	110.6
$\omega_3$	153.1
$\omega_4$	171.4



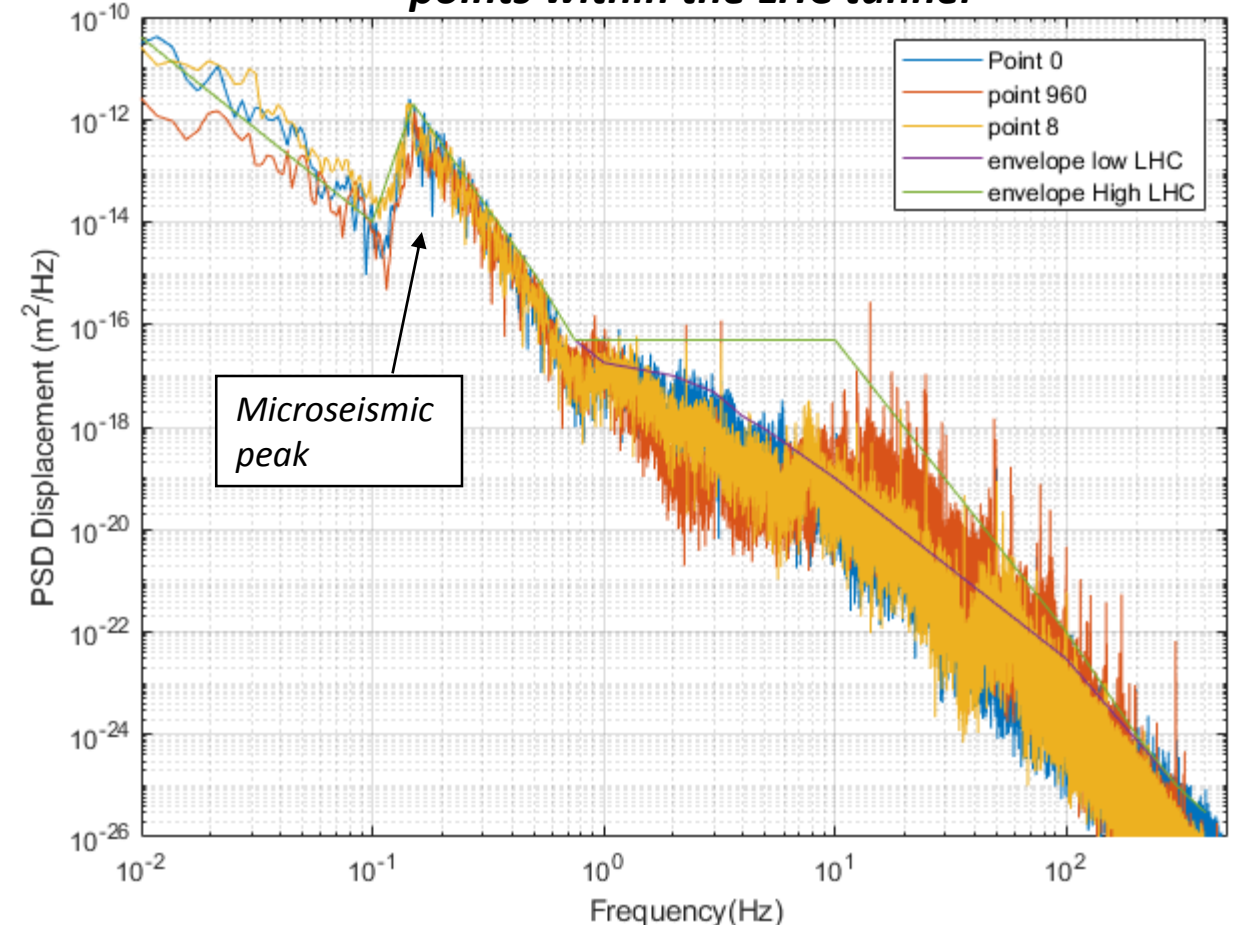
# Ground Noise



- 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

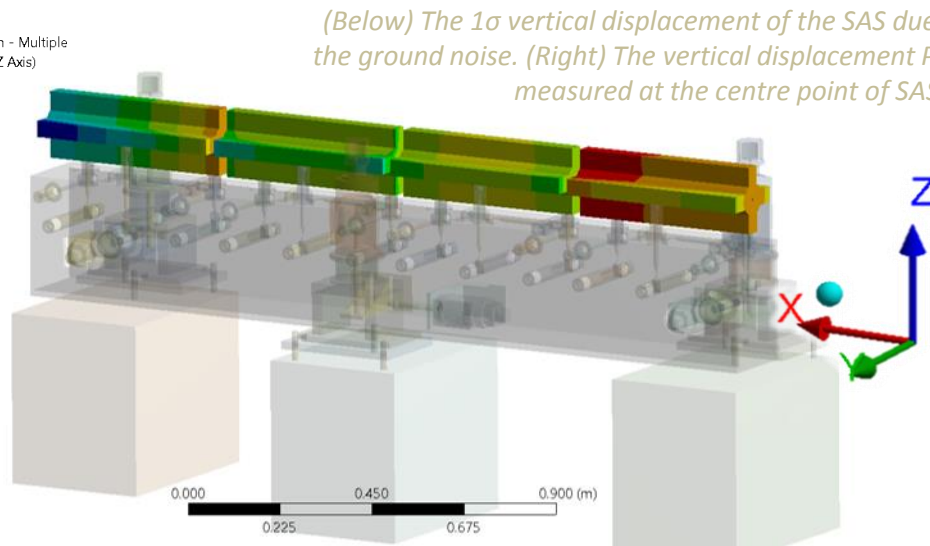
## Results for Box Section Flexure Supported Girder:

- $3\sigma$  vertical displacement of the SAS due to ground noise is  $0.8\mu\text{m}$
- The PSD shows the excitation due to the harmonic modes

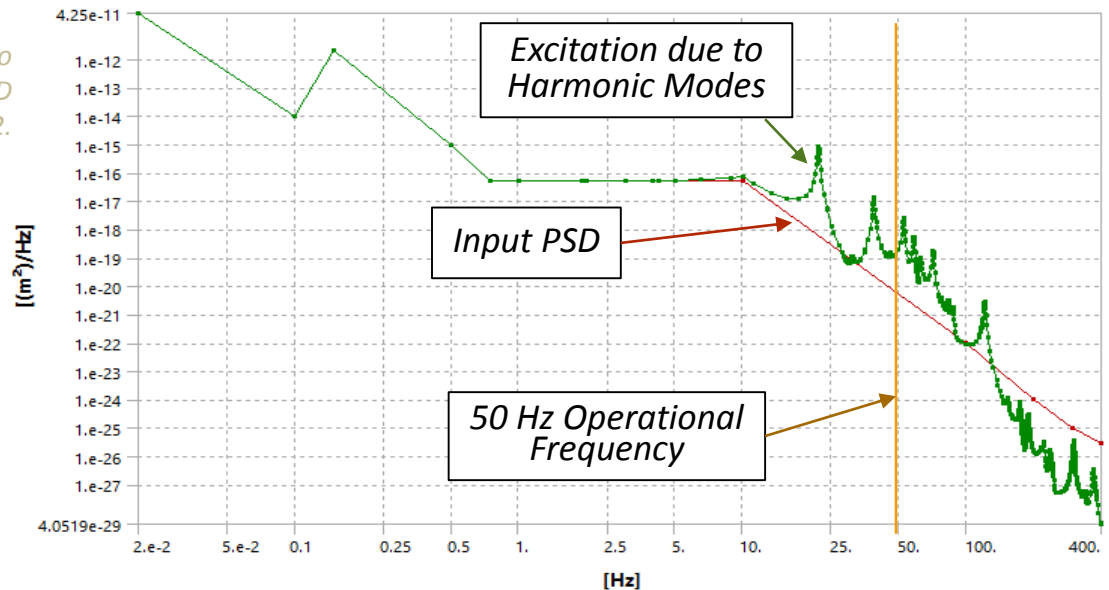
Normal Distribution	Maximum Displacement [ $\mu\text{m}$ ]		
	X Axis	Y Axis	Z Axis
1 $\sigma$ (66.27%)	0.1254	0.1256	0.2635
2 $\sigma$ (95.45%)	0.2508	0.2512	0.527
3 $\sigma$ (99.73%)	0.3762	0.3768	0.7905
4 $\sigma$ (99.99%)	0.5016	0.5024	1.054

I: Random Vibration  
 Z Axis - Directional Deformation - Multiple  
 Type: Directional Deformation(Z Axis)  
 Scale Factor Value: 1 Sigma  
 Probability: 68.269 %  
 Unit: m  
 Solution Coordinate System  
 Time: 0  
 21/06/2020 12:45

2.635e-7 Max  
 2.4226e-7  
 2.2101e-7  
 1.9977e-7  
 1.7852e-7  
 1.5728e-7  
 1.3603e-7  
 1.1479e-7  
 9.3541e-8  
 7.2296e-8 Min



(Below) The 1 $\sigma$  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.

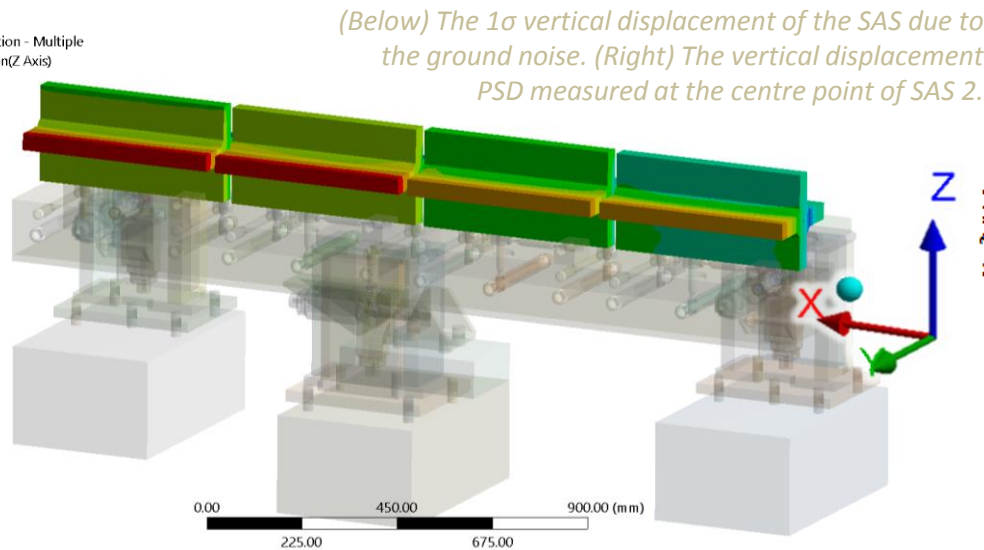
## Results for Box Section Joint Supported Girder:

- $3\sigma$  vertical displacement of the SAS due to ground noise is  $0.4\mu\text{m}$
- 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  $\omega_0$  the SAS follow the ground displacement

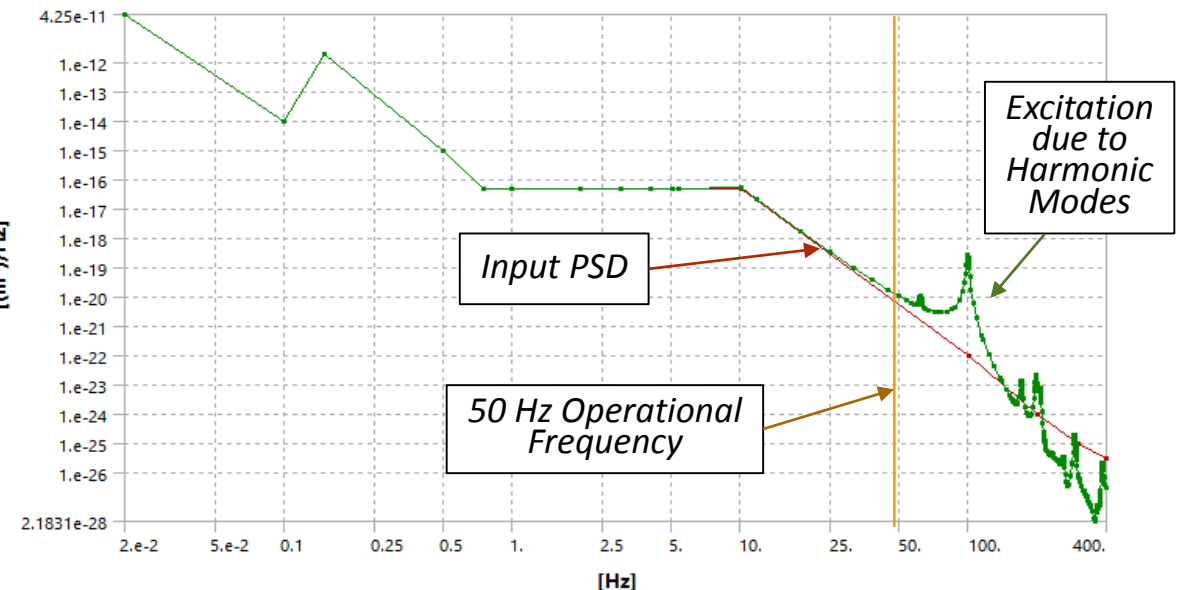
Normal Distribution	Maximum Displacement [ $\mu\text{m}$ ]		
	X Axis	Y Axis	Z Axis
1 $\sigma$ (66.27%)	0.1254	0.1371	0.1348
2 $\sigma$ (95.45%)	0.2508	0.2742	0.2696
3 $\sigma$ (99.73%)	0.3762	0.4113	0.4044
4 $\sigma$ (99.99%)	0.5016	0.5484	0.5392

W: Random Vibration  
Z Axis - Directional Deformation - Multiple  
Type: Directional Deformation(Z Axis)  
Scale Factor Value: 1 Sigma  
Probability: 68.269 %  
Unit: mm  
Solution Coordinate System  
Time: 0  
21/06/2020 12:56

0.0001231 Max  
0.00010947  
9.5834e-5  
8.22e-5  
6.8565e-5  
5.4931e-5  
4.1296e-5  
2.7662e-5  
1.4027e-5  
3.9302e-7 Min



(Below) The 1 $\sigma$  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.

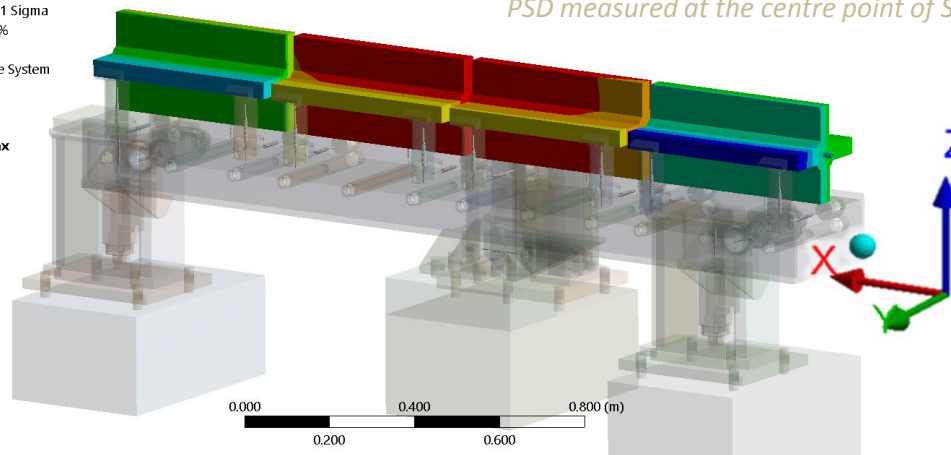
## Results for Joint Supported Box Section Girder and SAS:

- $3\sigma$  vertical displacement of the SAS due to ground noise is  $0.3\mu\text{m}$
- 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  $\omega_0$  the SAS follow the ground displacement

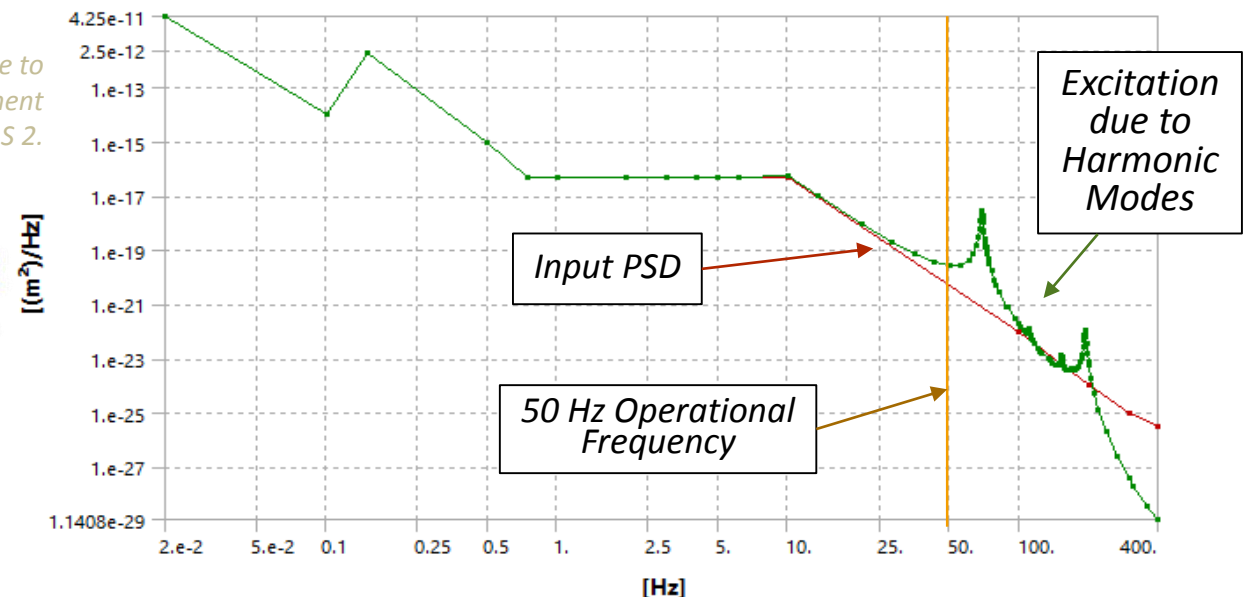
Normal Distribution	Maximum Displacement [ $\mu\text{m}$ ]		
	X Axis	Y Axis	Z Axis
1 $\sigma$ (66.27%)	0.11	0.0677	0.1041
2 $\sigma$ (95.45%)	0.22	0.1354	0.2082
3 $\sigma$ (99.73%)	0.33	0.2031	0.3123
4 $\sigma$ (99.99%)	0.44	0.2708	0.4164

O: Random Vibration LHC High Corrected  
 Z Axis - Directional Deformation - Multiple  
 Type: Directional Deformation(Z Axis)  
 Scale Factor Value: 1 Sigma  
 Probability: 68.269 %  
 Unit: m  
 Solution Coordinate System  
 Time: 0  
 21/06/2020 12:42

1.0409e-7 Max  
 1.029e-7  
 1.0171e-7  
 1.0052e-7  
 9.9335e-8  
 9.8146e-8  
 9.6957e-8  
 9.5768e-8  
 9.4579e-8  
 9.339e-8 Min



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



# 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?***

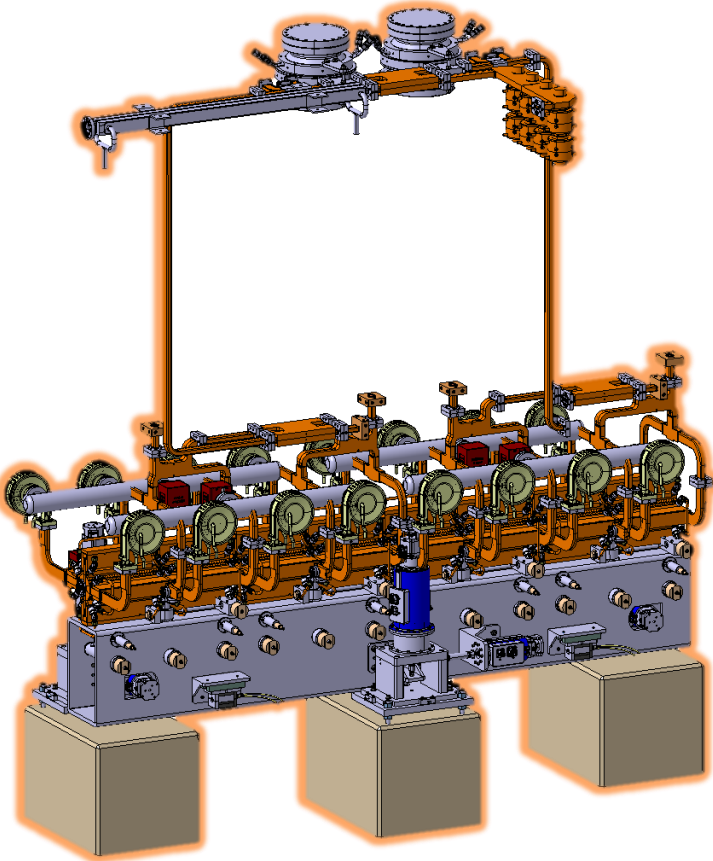
Support Design	Adjustment Range (Girder, SAS) [mm]	Fundamental Frequency $\omega_0$ [Hz]	Ground Noise $3\sigma$ Vertical Displacement [ $\mu\text{m}$ ]	Ground Noise $3\sigma$ Lateral Displacement [ $\mu\text{m}$ ]
Box Section: Flexures Supporting Girder	$\pm 1.0, \pm 0.5,$	21.9	0.7905	0.3768
Box Section: Joints Supporting Girder	$>\pm 1.5, \pm 0.5,$	60.6	0.4044	0.4113
Box Section: Joints Supporting Girder and SAS	$>\pm 1.5, >\pm 1.5$	69.3	0.3123	0.2031

(Above) Stability study summary table

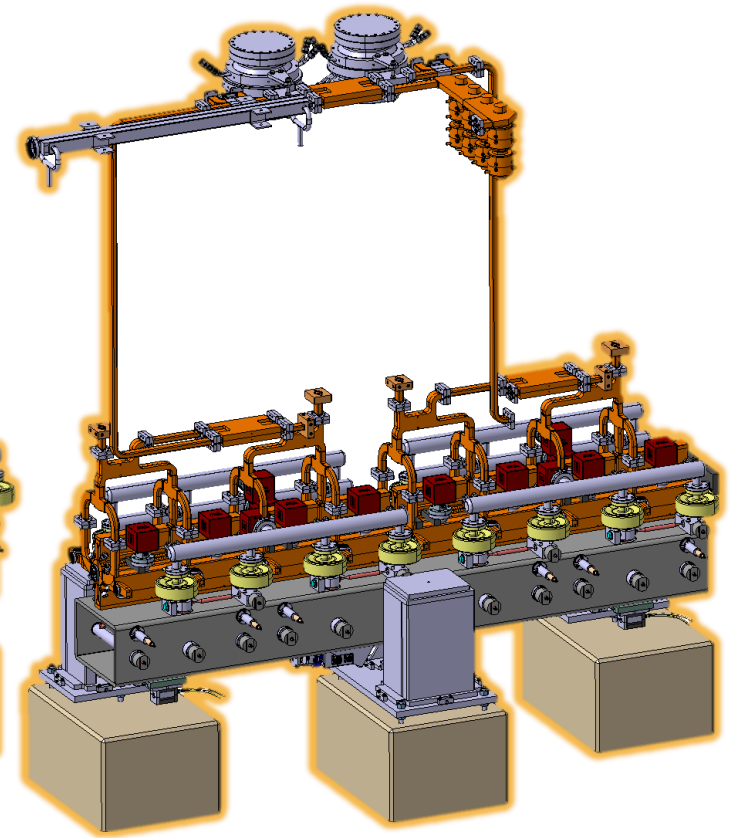
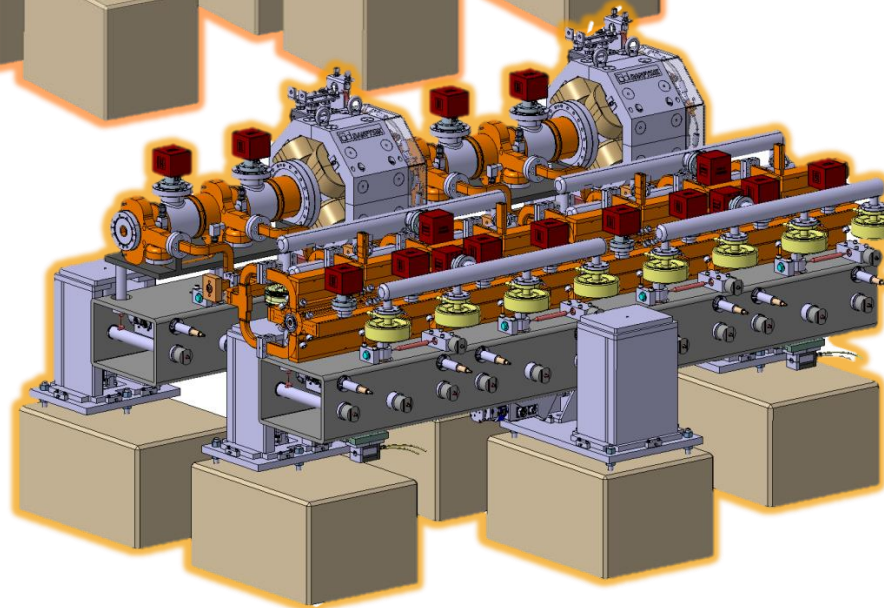
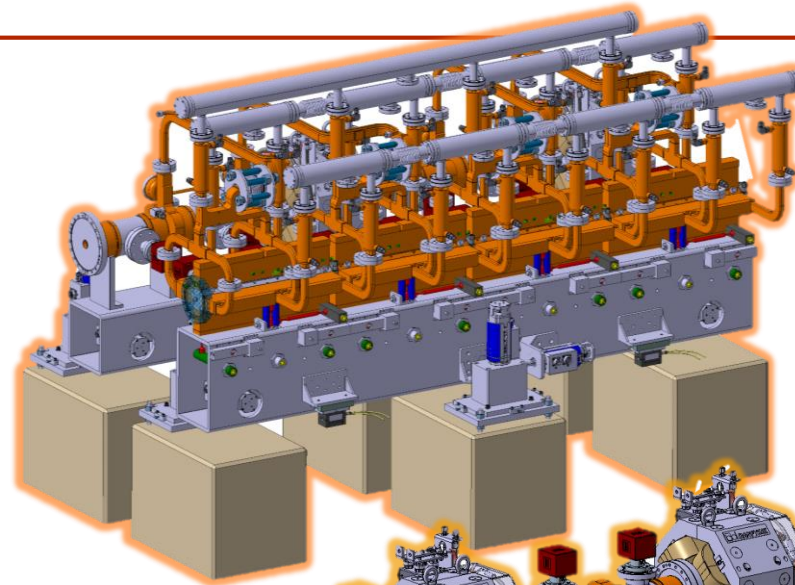
# Module Variations



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



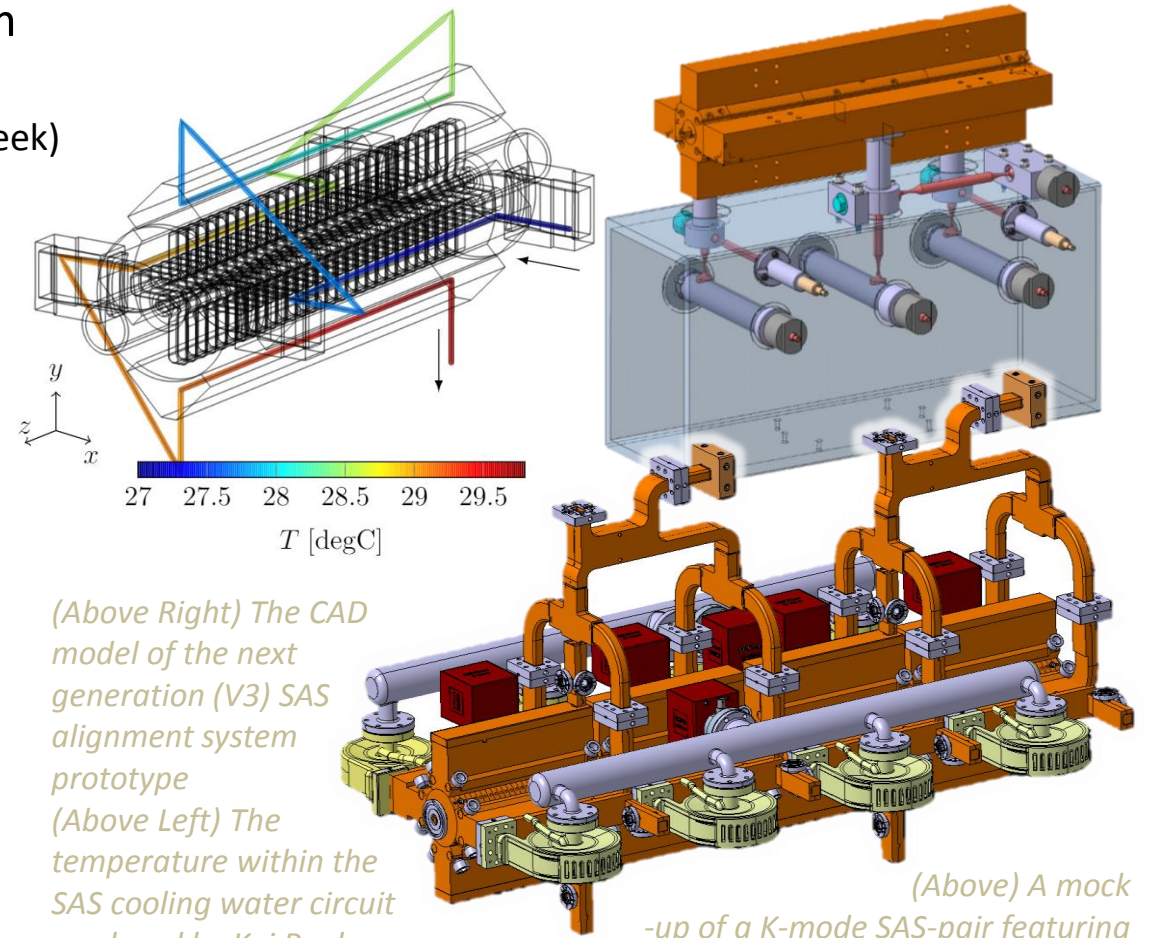
*(Below) A joint based 'High-Stiffness' K-CLIC Module  
(Below Left) A joint based 'High-Stiffness' CLIC Two Beam Module*



# 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

