Wir schaffen Wissen – heute für morgen

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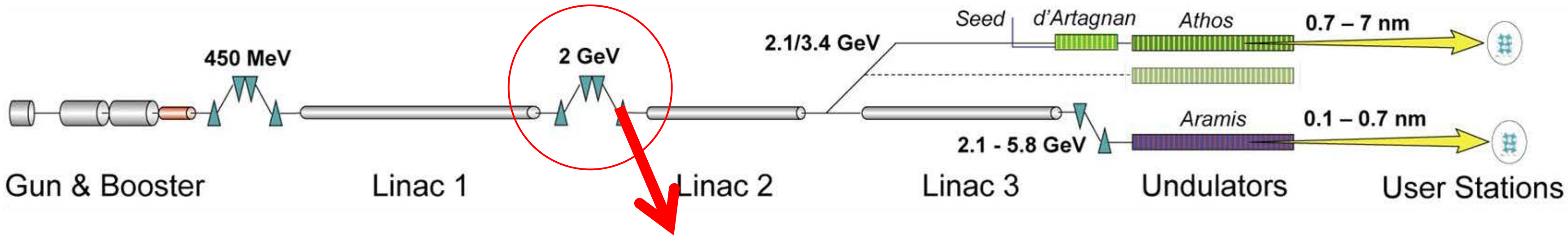
Structural dynamic modelling and measurement of SwissFEL Bunch Compressor

Overview of SwissFEL Bunch Compressor

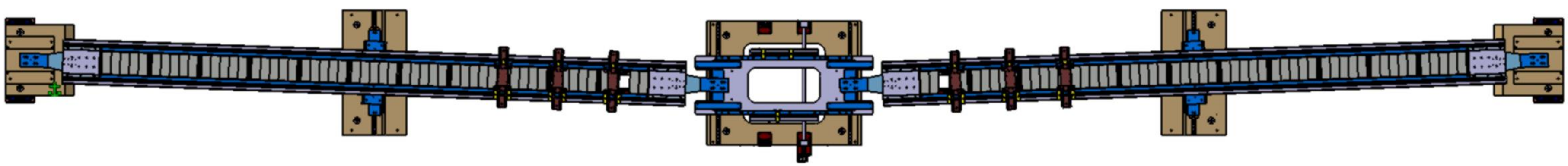
Magnetic chicanes are used in SwissFEL to longitudinally compress the accelerated particle bunches.

The second compression chicane (BC2) of SwissFEL consists of four dipole magnets bending the beam on the horizontal plane along a C-shaped orbit with adjustable deflection angle

SwissFEL layout schematic



Bunch Compressor 2

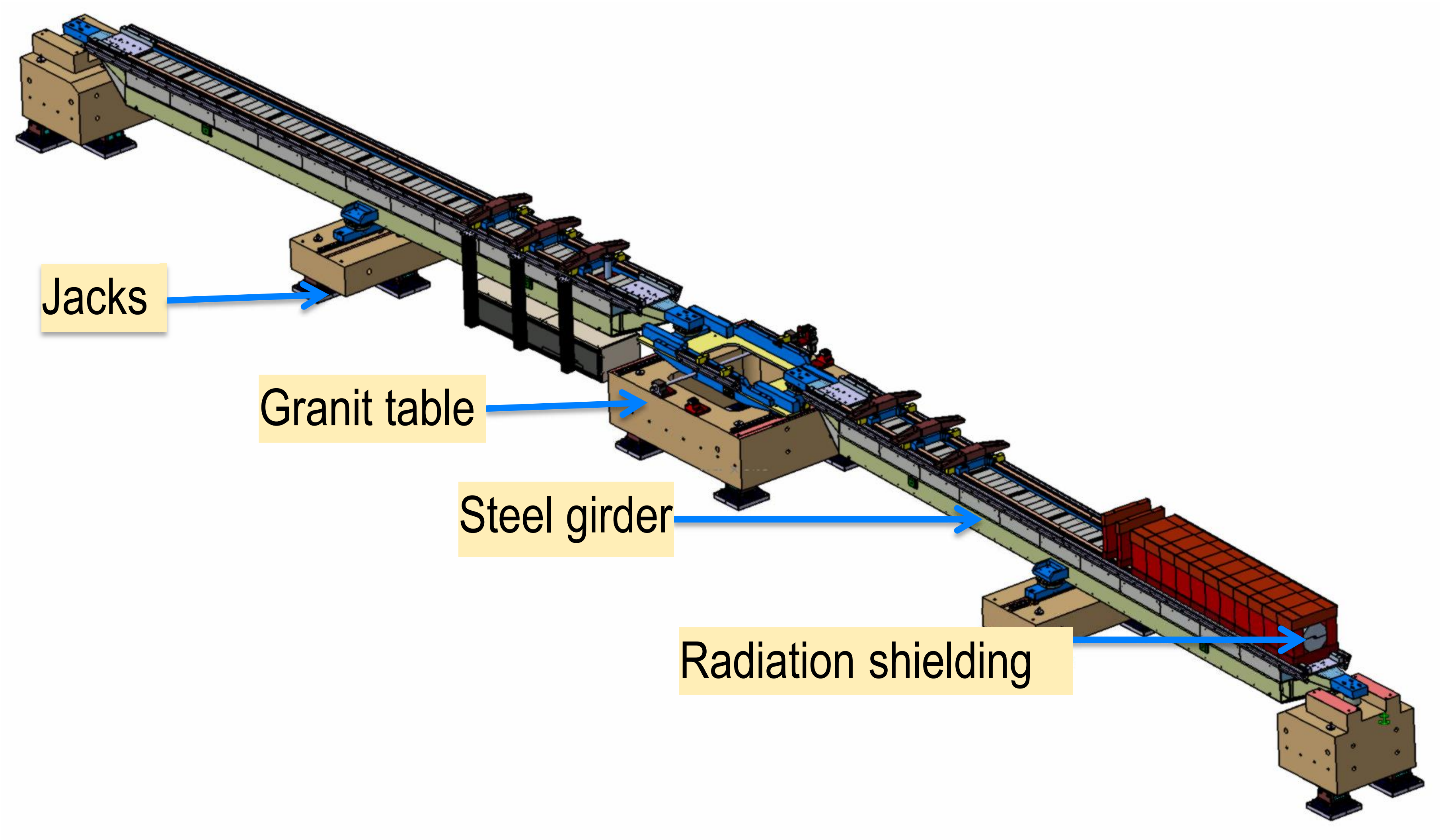


Outline

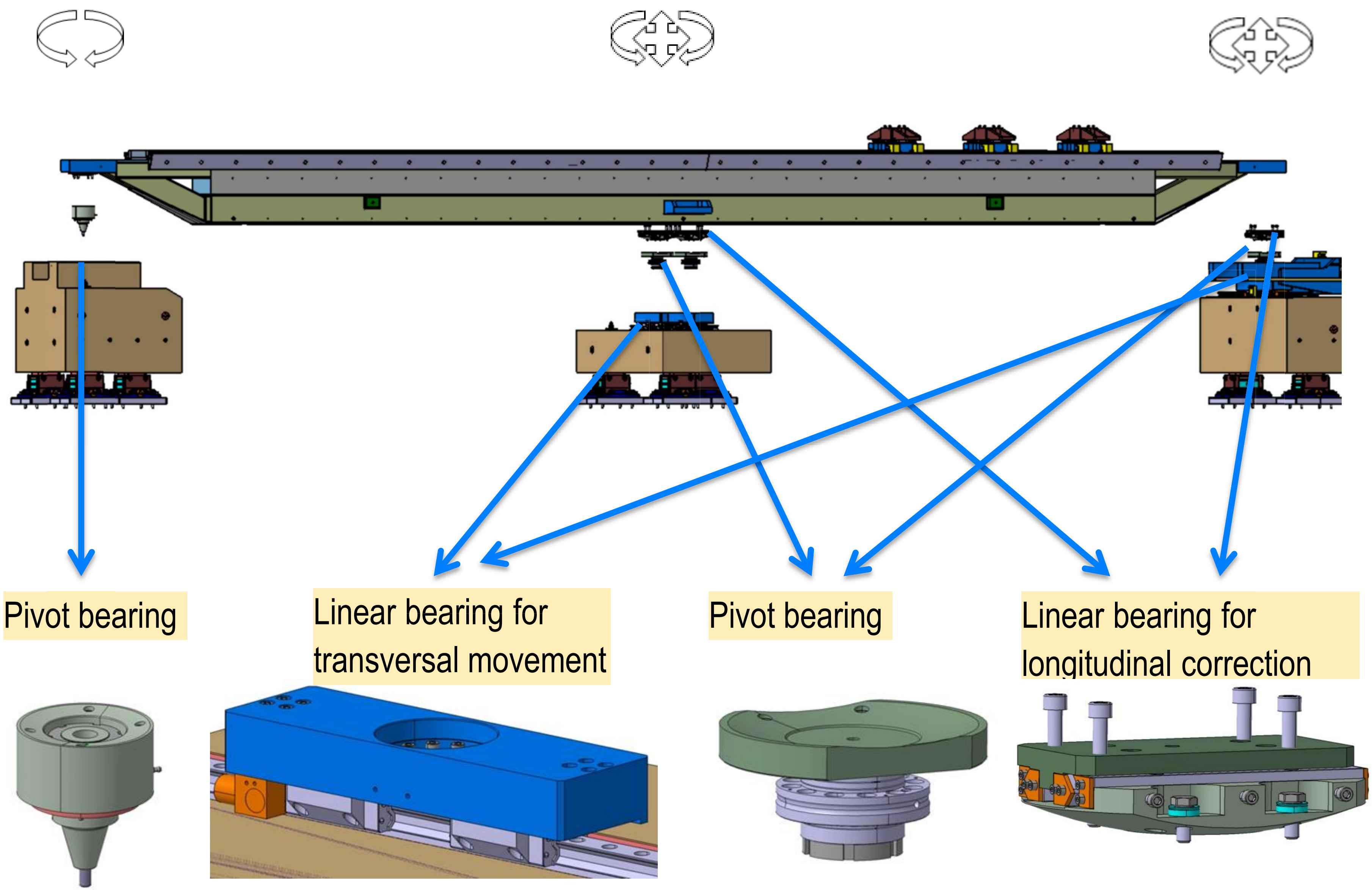
- BCII Structural design and stability requirement
- Finite element analyses
  - Static and modal analysis
  - Harmonic response analysis
- Random Vibration measurement
- Random vibration analysis
- Summary

BC2 Mechanical Structure Design

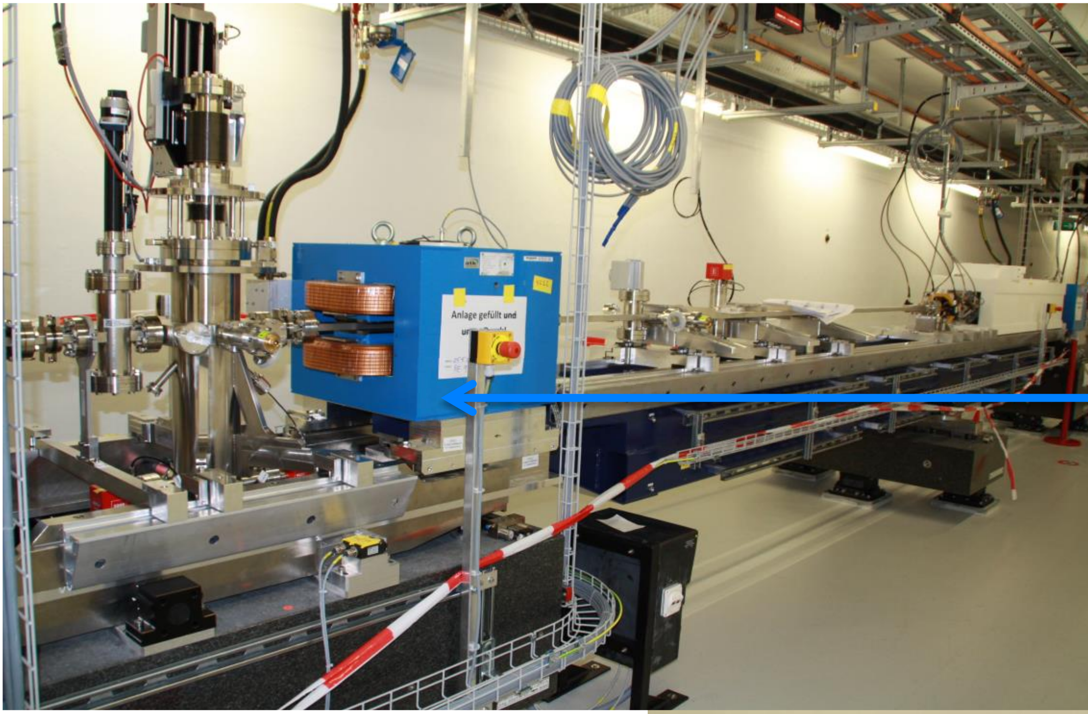
Total length: 17 m

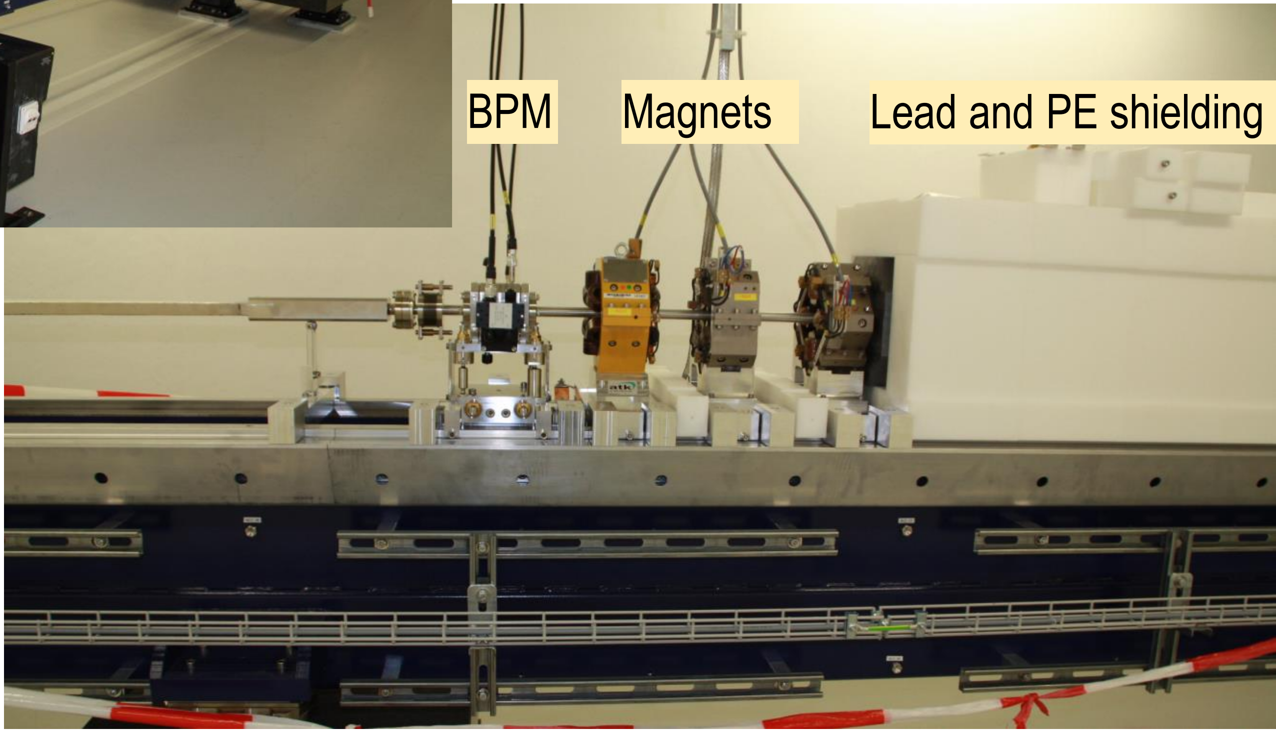


SwissFEL BC kinematics



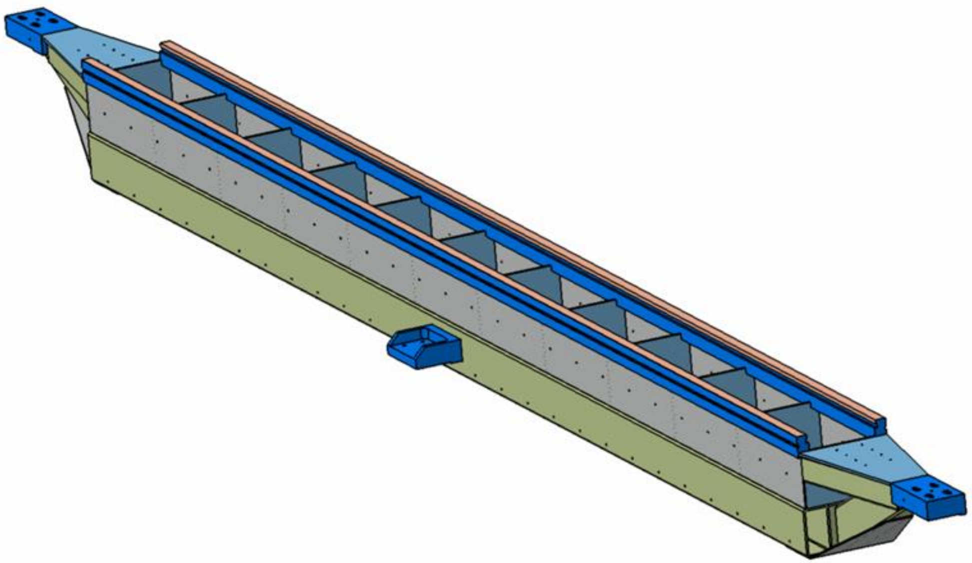
Mechanical stability requirement





Design Goal:
Vibration below 1 μm

BC2 Girder Structural design



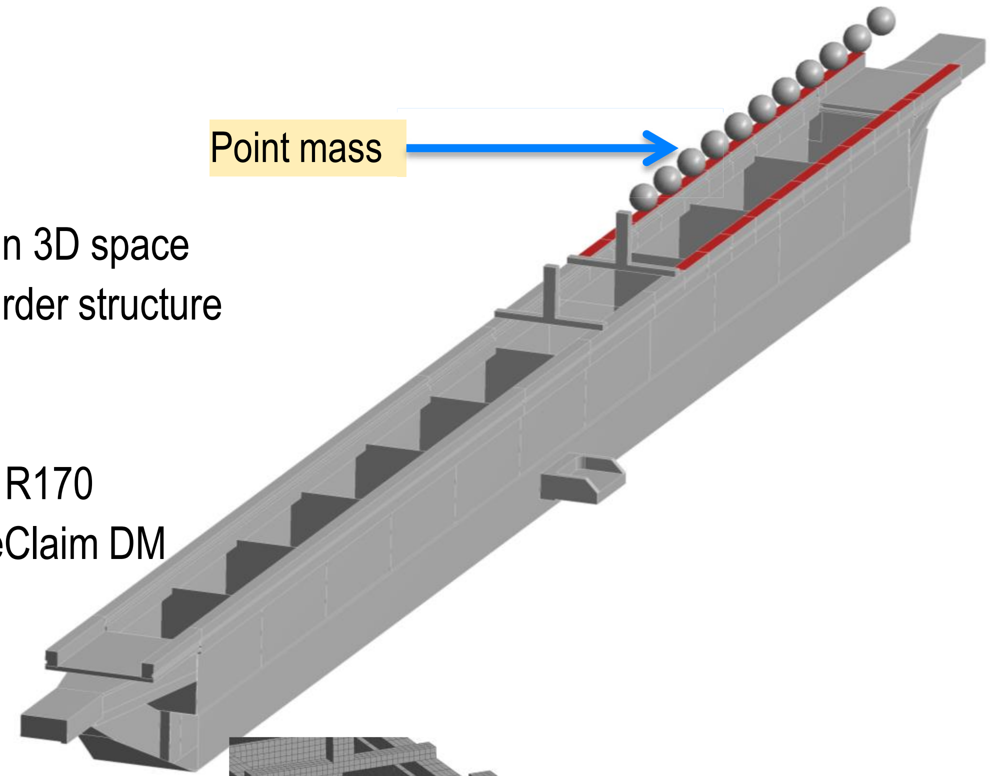
FE Modelling

Finite element model

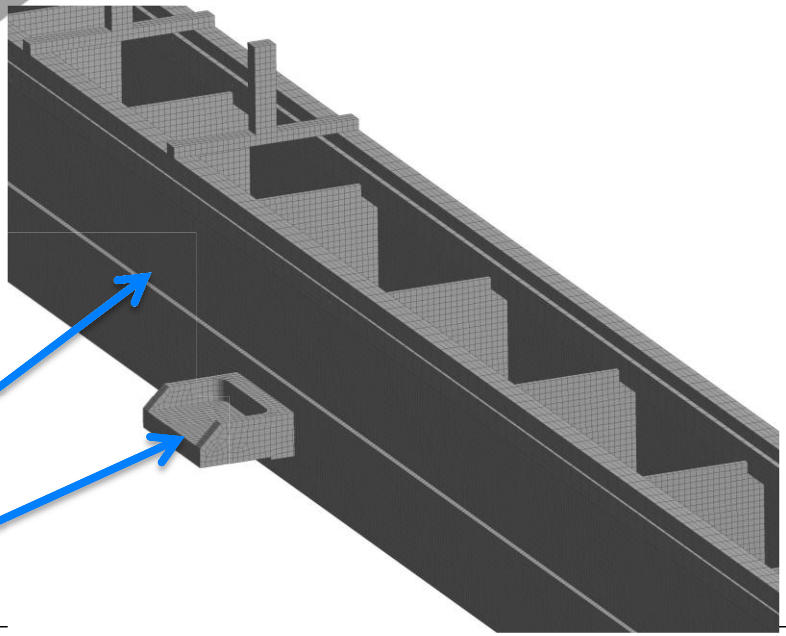
- Point mass to present shielding masses in 3D space
- Shell elements for the thin walled steel girder structure
- 3D solid elements for supports

Analyses have been performed with ANSYS R170

Geometry preprocessing with ANSYS SpaceClaim DM



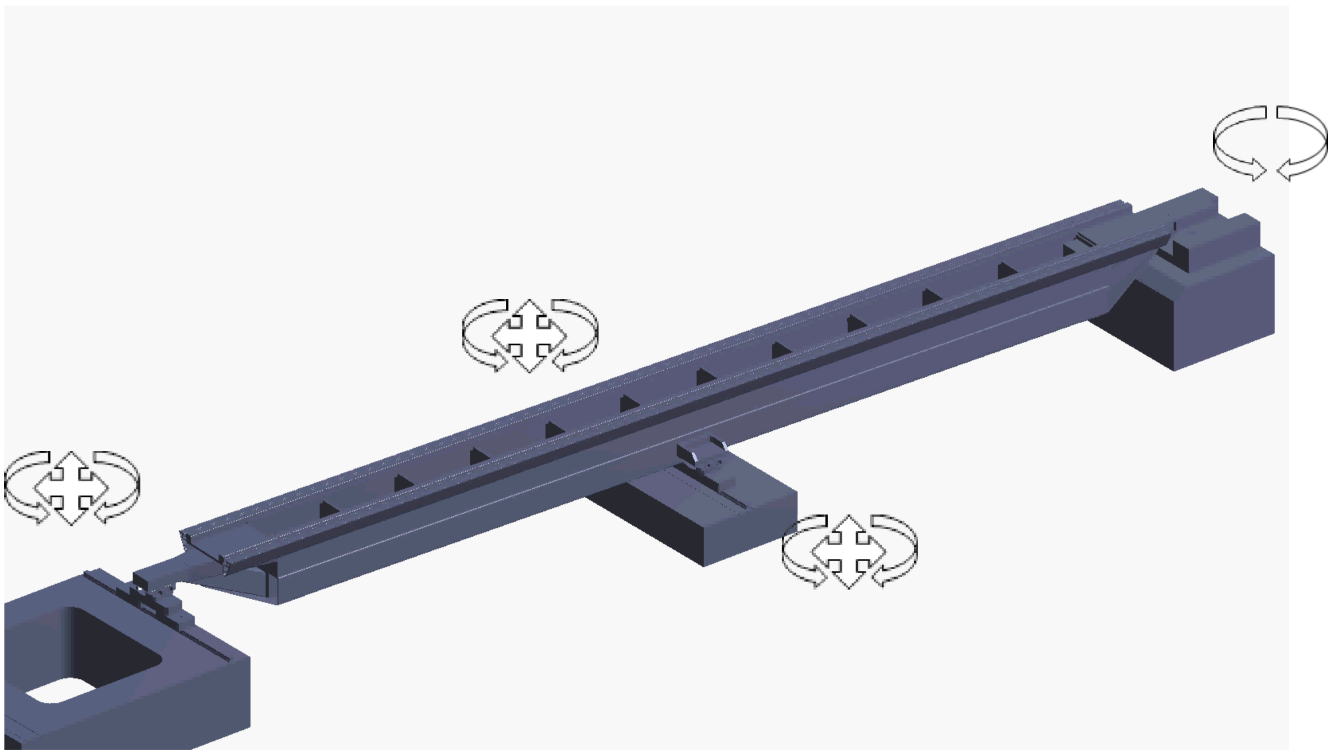
– Number of nodes:	329K
– Number of elements:	216K
shell elements:	122K
– Degrees of freedom:	1’326K



Total weight:	3.2 t
Structure:	1.3 t
Shielding material:	1.9 t

Boundary Conditions – kinematics

Girder length (dipole separation): 7.7 m
Transverse movement of dipole: -10 to 495 mm
Bending angle: 3.8 deg.



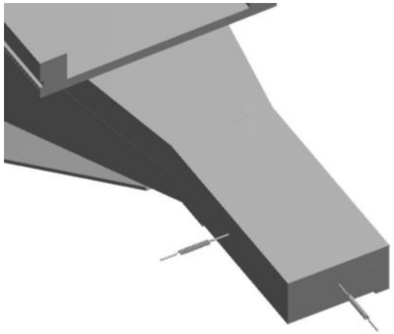
Static and Modal Analysis

Linear bearings

- If friction forces in the joint are high enough to withstand excitation forces, joint is well defined, contact is closed.
- f the excitation force is higher than friction force, the contact becomes open

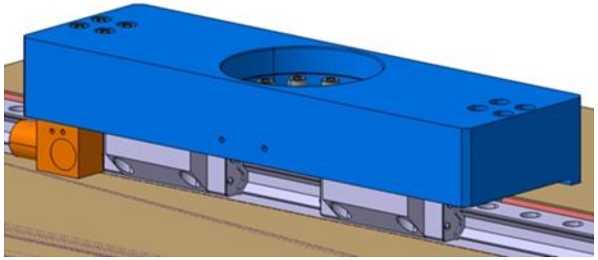
Free: in the rigid dynamic analysis

Fixed or Constraint Stiffness: in modal based dynamic analysis, only if excitation force is too small to overcome friction force



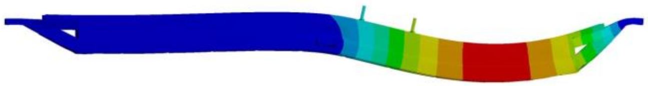
Boundary conditions:

1. Free
2. Constraint stiffness k=2e4 N/mm
3. Constraint stiffness k=2e7 N/mm
4. Fixed



Static and Modal Analysis

Static deflection under gravity load:



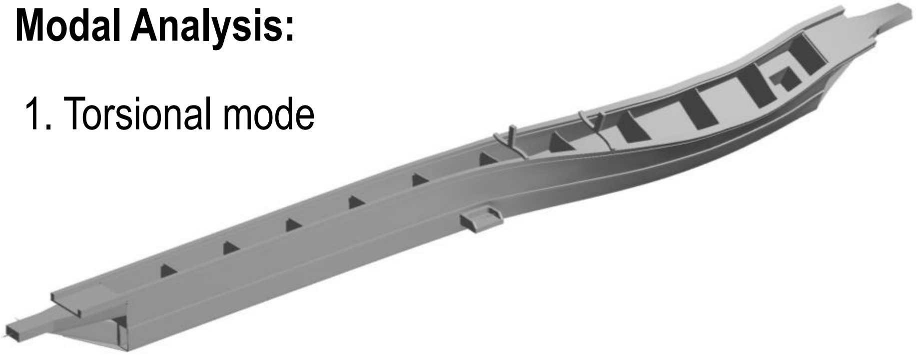
Deflection:
0.152 mm (fixed) to 0.157 (free)
Relationship between natural frequency *f*/Hz and maximum static deflection *d*/mm for pinned-pinned prismatic beam:

$$f = 17.8/\sqrt{d}$$

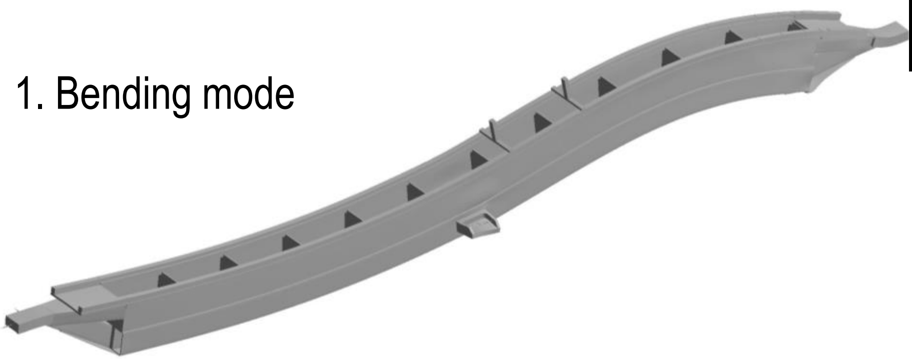
First bending frequency estimated to be
45.7 Hz (fixed) to 45.1 Hz (free)

Modal Analysis:

1. Torsional mode



1. Bending mode



	1. Torsional mode	1. Bending Mode	2. Torsional mode
Free	16.4 Hz	41.3 Hz	47.8
Soft	20.3 Hz	41.7 Hz	45.5
Hard	22.7 Hz	42.0 Hz	48.6
fixed	22.8 Hz	41.8 Hz	49.0

Free boundary has in addition first rotational mode at 1.6 Hz and transversal bending mode at 31.2 Hz
Soft boundary hat additional transversal bending mode at 34.6 Hz

Harmonic Response Analysis

In a harmonic response analysis system response to steady-state sinusoidal loading at a given frequency

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F\}$$

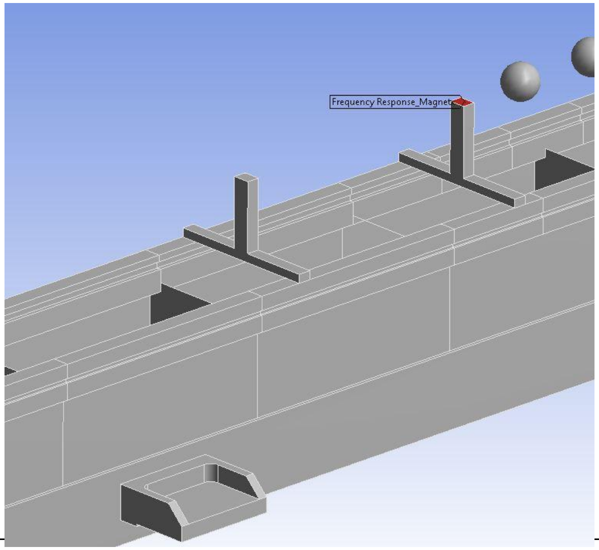
Both excitation {*F*} and response {x} are assumed to be harmonic.

Ω: imposed circular frequency, ψ, φ: phase shift

$$\{F\}=\{F_{\max}\}e^{j(\Omega t+\psi)}$$
$$\{x\}=\{x_{\max}\}e^{j(\Omega t+\phi)}$$

Base excitation RMS 1 mm/s^2 is applied to all support conditions in all directions. Damping ratio 2% is assumed to be 2%.

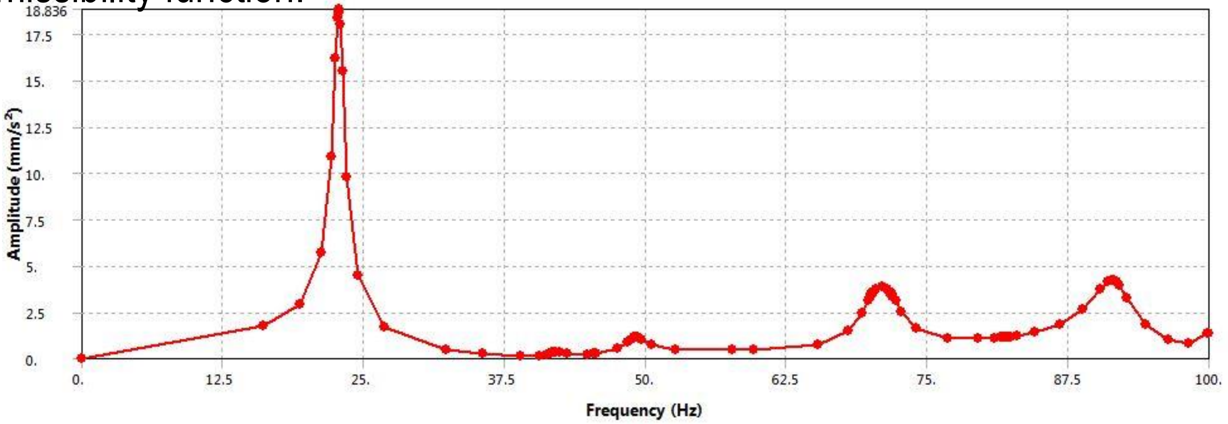
Ground vibration has in general broadband distribution.
In harmonic response analysis excitation frequency is swept linearly to identify critical frequency at critical location.



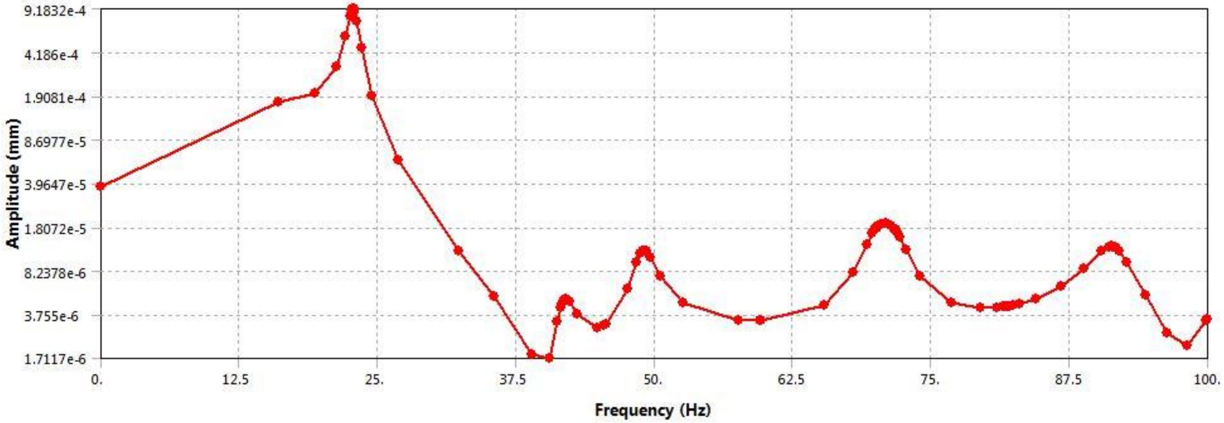
Harmonic Response Analysis

Frequency response at magnet position , Acceleration in transversal direction, base excitation 1 mm/s^2 in all directions at all supports. Damping ratio 2%.

Transmissibility function:



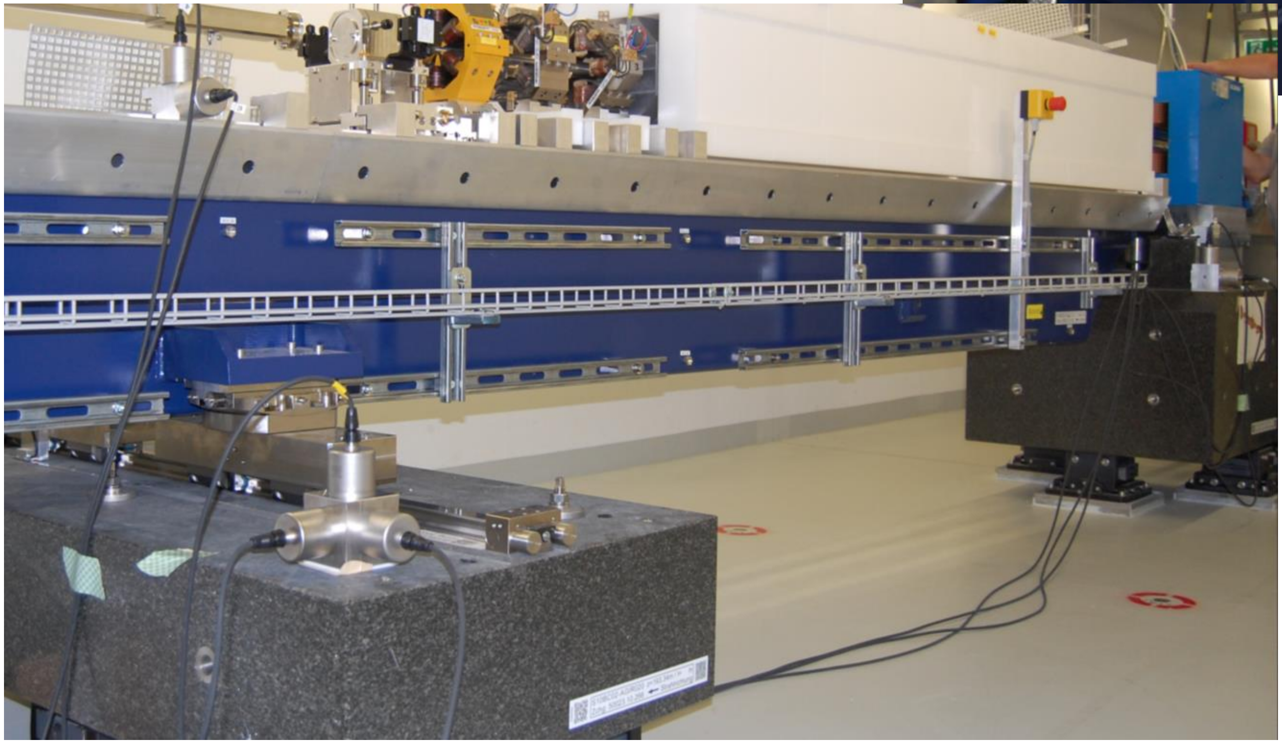
Transversal displacement frequency response at position of magnet. At a frequency of 22.8 Hz, the maximum response was 0.9 μm for fixed and stiff linear bearing. With soft spring constraints, the maximum response was 1.7 μm at 22 Hz.



Vibration measurement

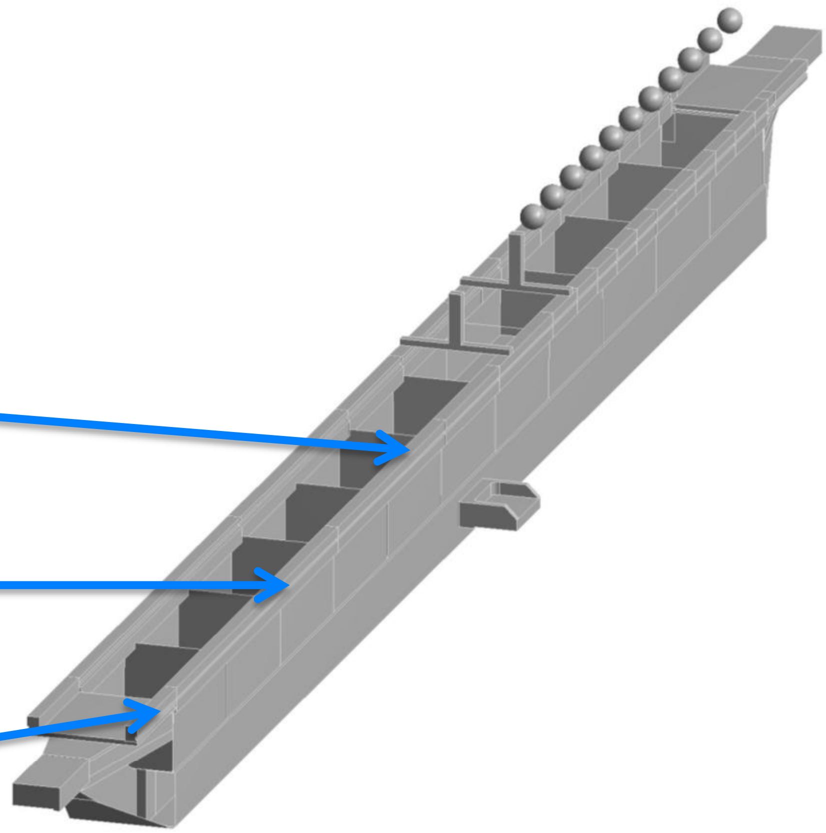
Measurement has performed with eight-channel LMS SCADAS Mobile. Seismic accelerometers PCB393B31 were placed on

- Floor
- Granite tables
- Steel Girder



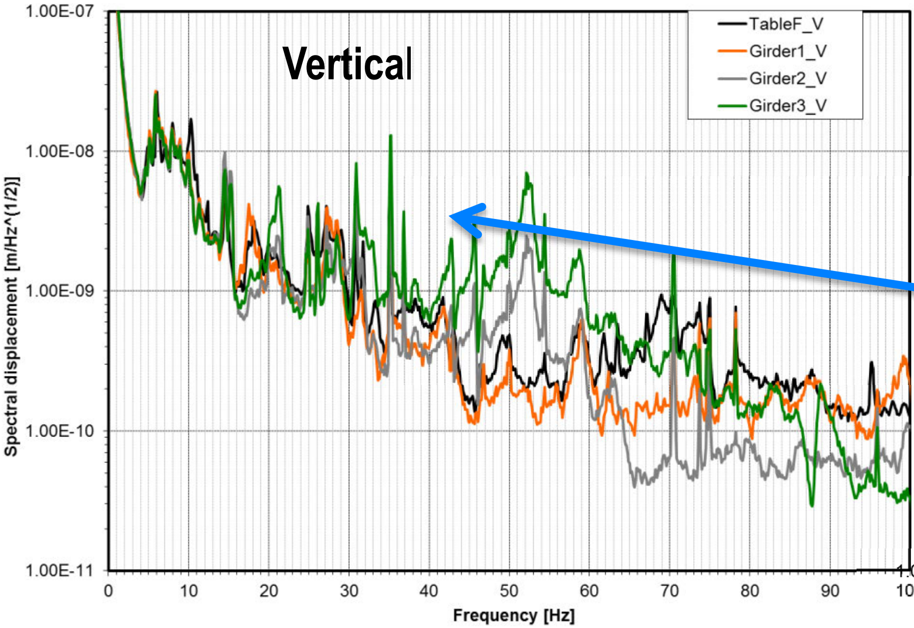
Vibration Measurement

RMS displacement from 5 to 200 Hz	:
Floor Transversal	37nm
Floor Vertical	29nm
Granite table transversal	40 nm
Granite table vertical	31 nm
Girder1 transversal	41 nm
Girder1 vertical	31 nm
Girder2 transversal	49 nm
Girder2 vertical	33 nm
Girder3 transversal	50 nm
Girder3 vertical	32 nm



The amplification ratio girder to ground is below 1.35 in transversal direction, and below 1.14 in vertical direction. BC2 structure shows excellent mechanical stability behavior

Spectral Displacement Measurement



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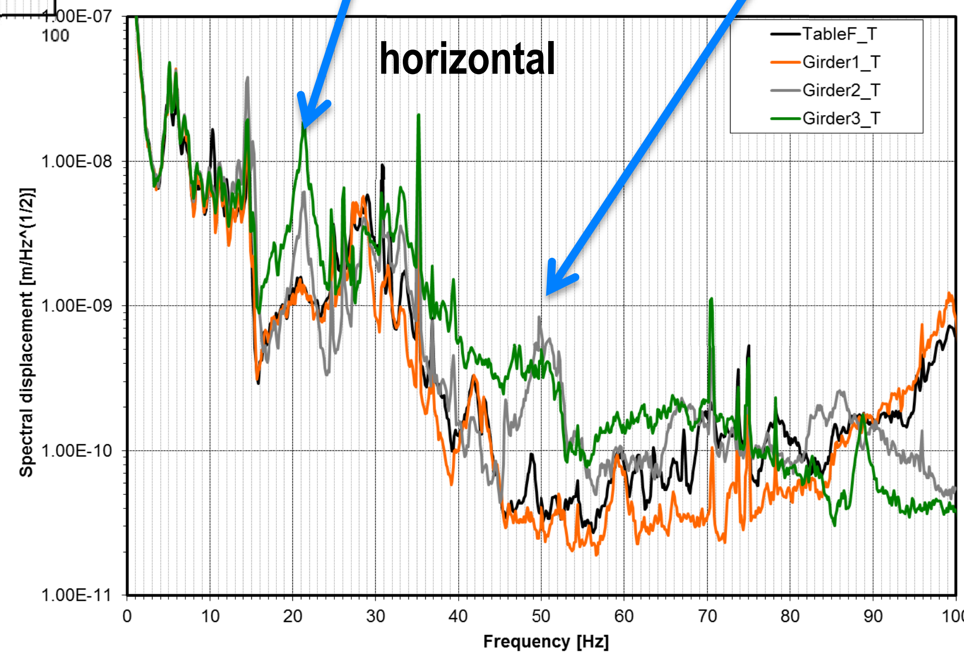


Transversal spectral displacement from measurement shows peaks at 21.4 Hz and 50 Hz, corresponding to the 1. and 2. torsional mode at 22.8 Hz and 49 Hz, respectively

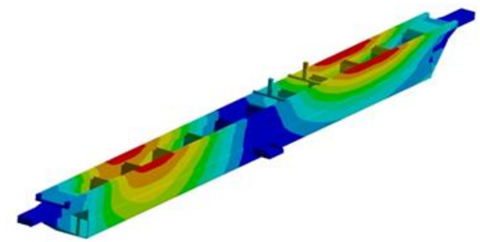
Vertical bending mode at 42 Hz is not confirmed from the measurement.

Random Vibration Analysis

Power spectral density (PSD) of acceleration from 5 Hz to 100 Hz is applied to all supports with fixed boundary conditions. Again a constant damping ratio of 2% is assumed.

Response PSD displacements and reaction forces are solved

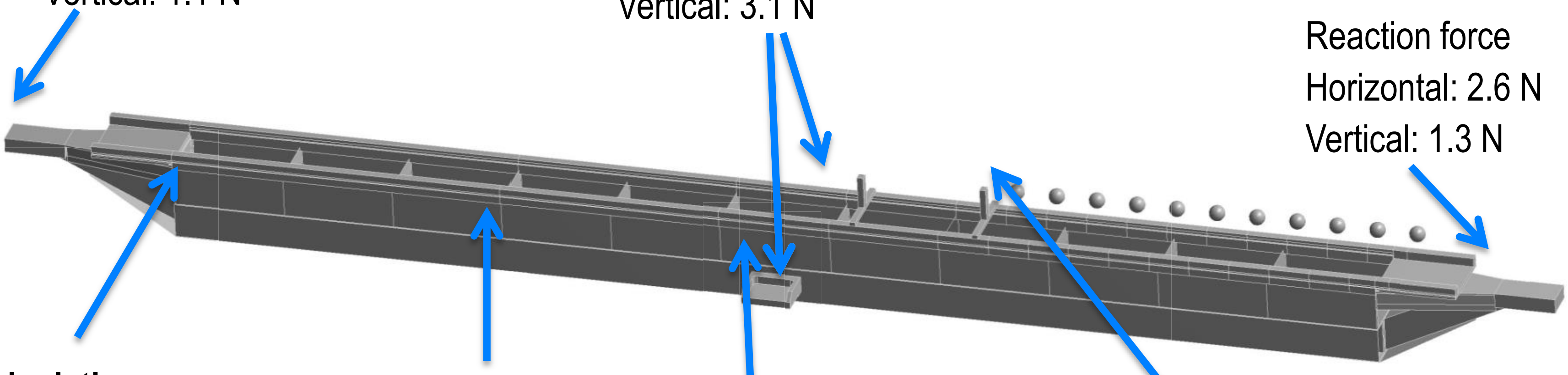
A minimum friction coefficient of 0.00034 is required



Reaction force
Horizontal: 3.3 N
Vertical: 1.1 N

Reaction force of each support:
Horizontal: 3.1 N
Vertical: 3.1 N

Reaction force
Horizontal: 2.6 N
Vertical: 1.3 N



Calculation:
Horizontal: 44 nm
Vertical: 29 nm
Measurement:
Horizontal: 50 nm
Vertical: 32 nm

Calculation:
Horizontal: 109 nm
Vertical: 36 nm
Measurement:
Horizontal: 49 nm
Vertical: 33 nm

Calculation:
Horizontal: 44 nm
Vertical: 31 nm
Measurement:
Horizontal: 41 nm
Vertical: 31 nm

Calculation:
Horizontal: 119 nm
Vertical: 30 nm

Summary

- BCII shows excellent stable behavior. The amplification ratio girder to floor is below 1.35 in transversal direction, and below 1.14 in vertical direction.

- From vibration measurement, the first two transversal modes from finite element analysis can be confirmed. However, the vertical bending mode can not be identified in the measurement. The vibration level in vertical is smaller than in horizontal direction so that not all modes can be measured.

- If dynamic excitation forces are very small compared to sliding friction forces, a good representation can be achieved with fixed degree of freedom.

- The verification of excitation forces can be achieved in a random vibration analysis. This procedure is iterative, because PSD analysis relies on modal representation, and finally on correct modelling of boundary conditions.

- The final confirmation of the linear representation of linear guide system is given by vibration measurement.

We want to thank Peter Hottinger for the support in vibration measurement