FUTURE CIRCULAR COLLIDER

FCC-ee Arc Half-Cell: methods to evaluate the systems' stability

FCC-ee Arc Half Cell Mock-up Project team – CERN EN/MME

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With the contribution of the Mechanical Measurement Lab – CERN EN/MME

M. Guinchard, D. Thuliez

Tuesday 14th November 2023 / FCCIS WP2 Workshop

Outline

1. FCC-ee arc half-cell mock-up project
2. The problem of stability: How to assess it?
3. Results of the experimental campaign
4. Simulation results: Collider & Booster
5. Conclusion / Next steps

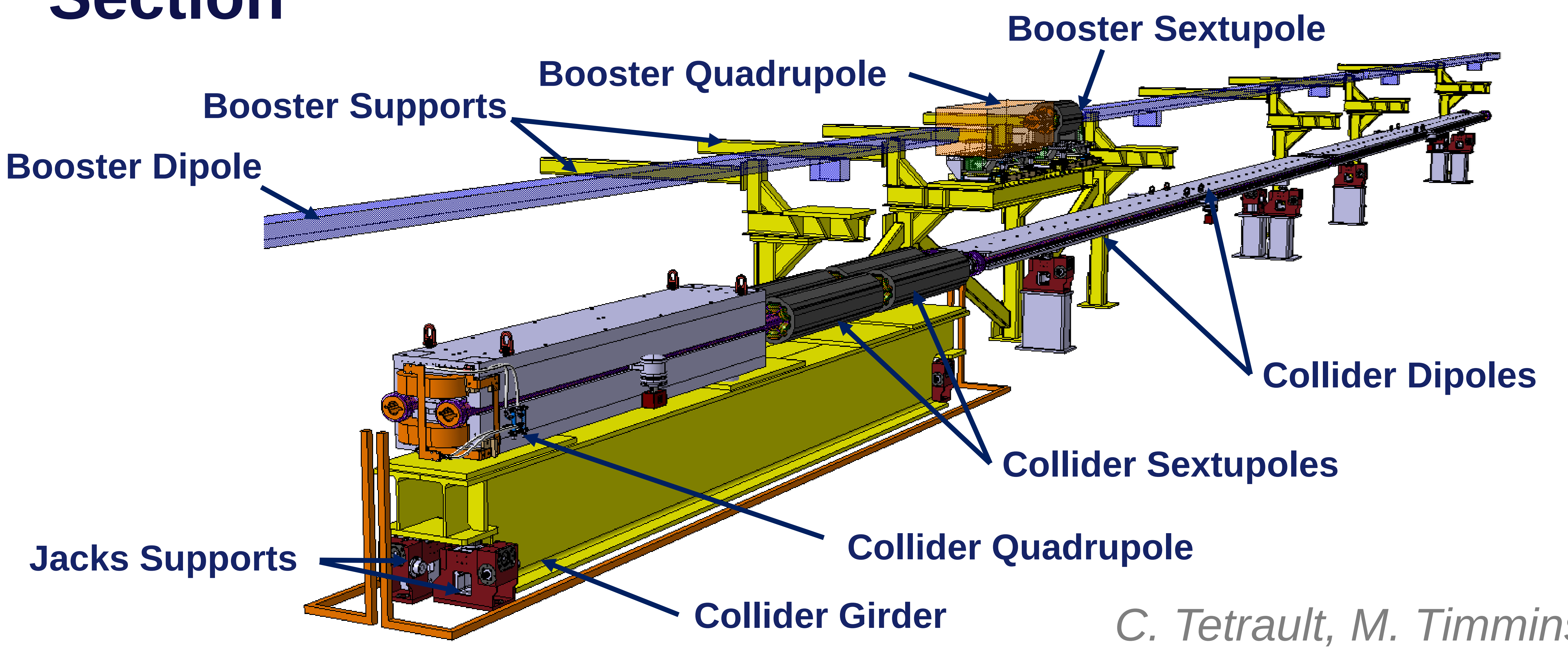
1. FCC-ee arc half-cell mock-up project

Arc half-cell = the most repeated region of mechanical hardware in the tunnel
→ *77 km over 90 km are arc cells*

Goal = construct a half arc cell mock-up to test aspects related to:

- Fabrication
- Integration
- Assembly
- Stability inspection
- Transport
- Installation
- Alignment
- Maintenance

Systems considered = Mostly the Short Straight Section



C. Tetrault, M. Timmins

Timeline = the project is divided into 3 phases

2022				2023				2024				2025			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
		Phase 1	Phase 1	Phase 2	Phase 2	Phase 2	Phase 2	Phase 2	Phase 2	Phase 2	Phase 2				
									Phase 3	Phase 3	Phase 3	Phase 3	Phase 3	Phase 3	Phase 3 ...

Phase 1: Concept development
Phase 2: Engineering design
Phase 3: Fabrication

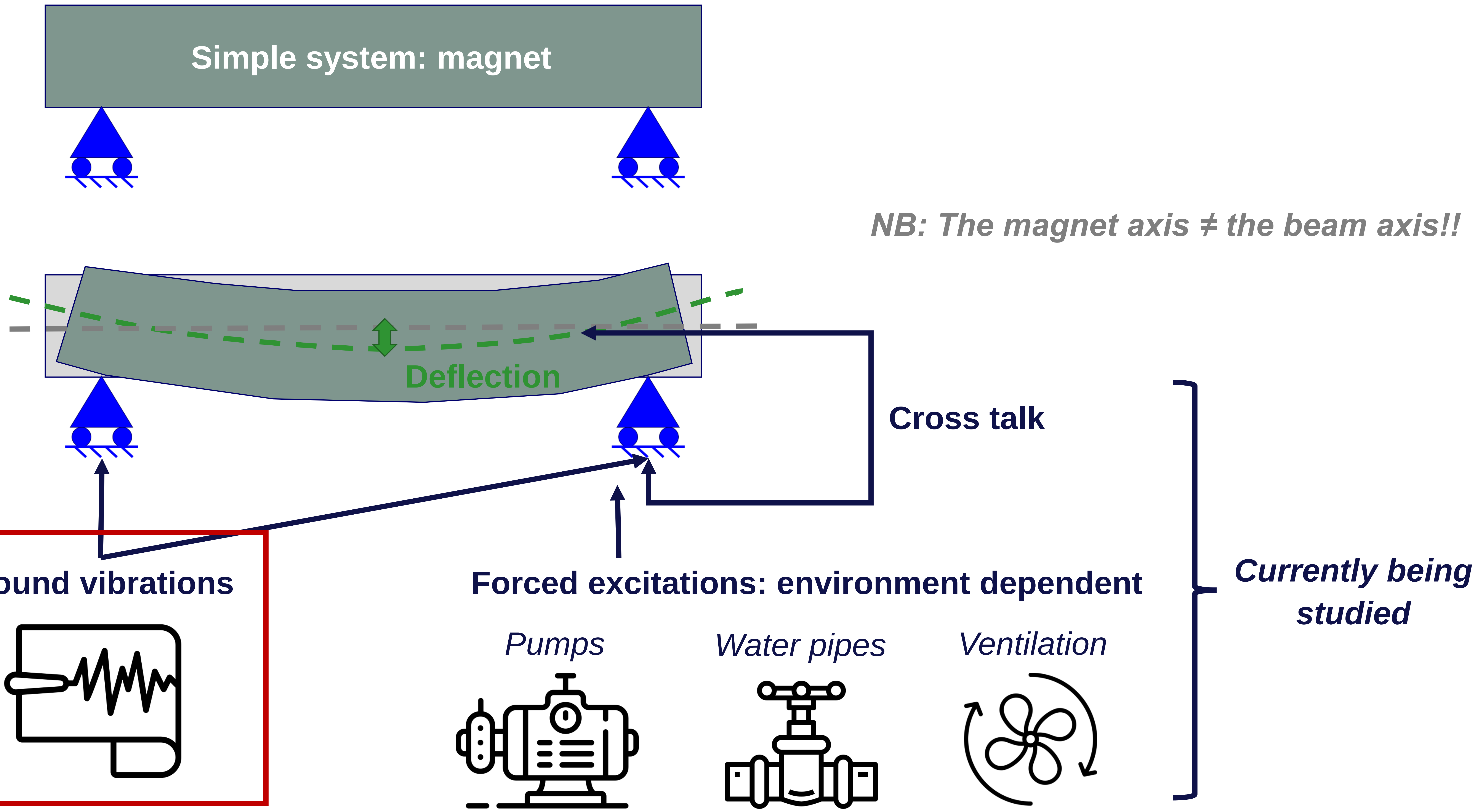
2. The problem of stability

→ ***What will impact the stability of the particle beam?***

→ Static stability

Requires mitigation via alignment, extra supports, wedges, etc.

→ Dynamic stability

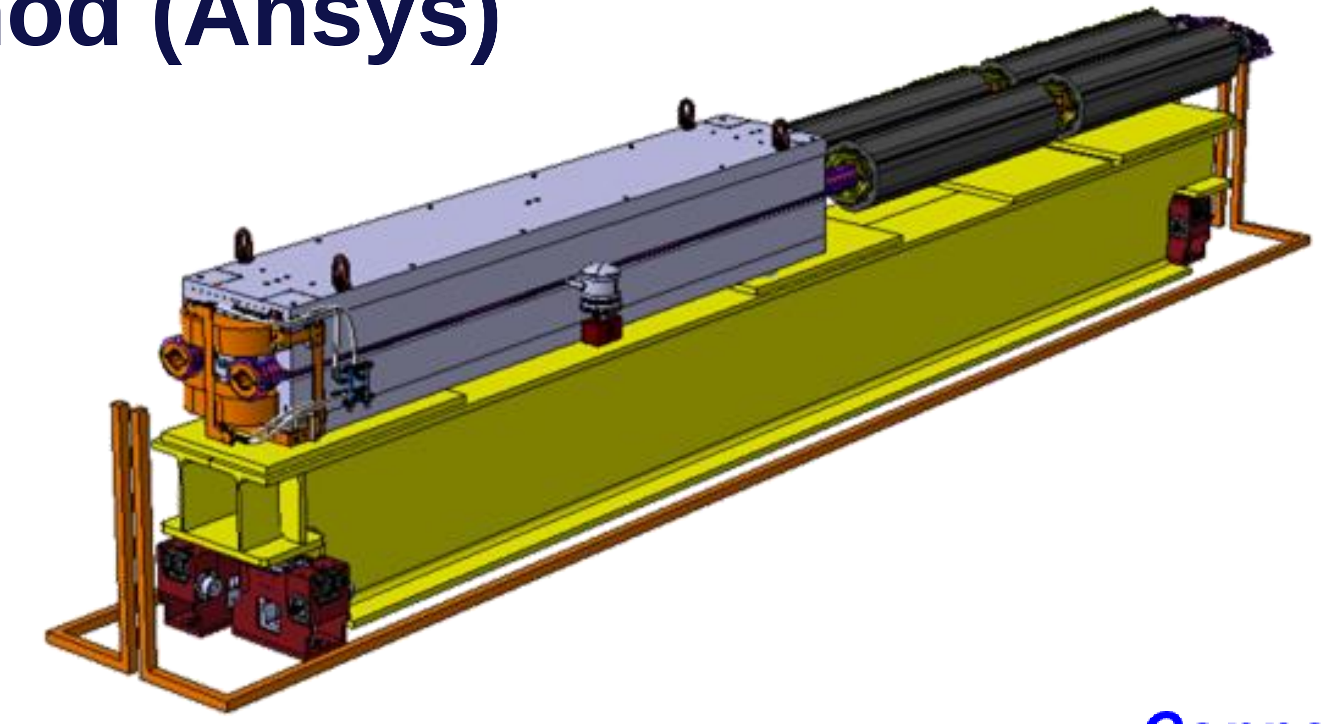


The presentation will focus on the impact of the ground motion

Etc.

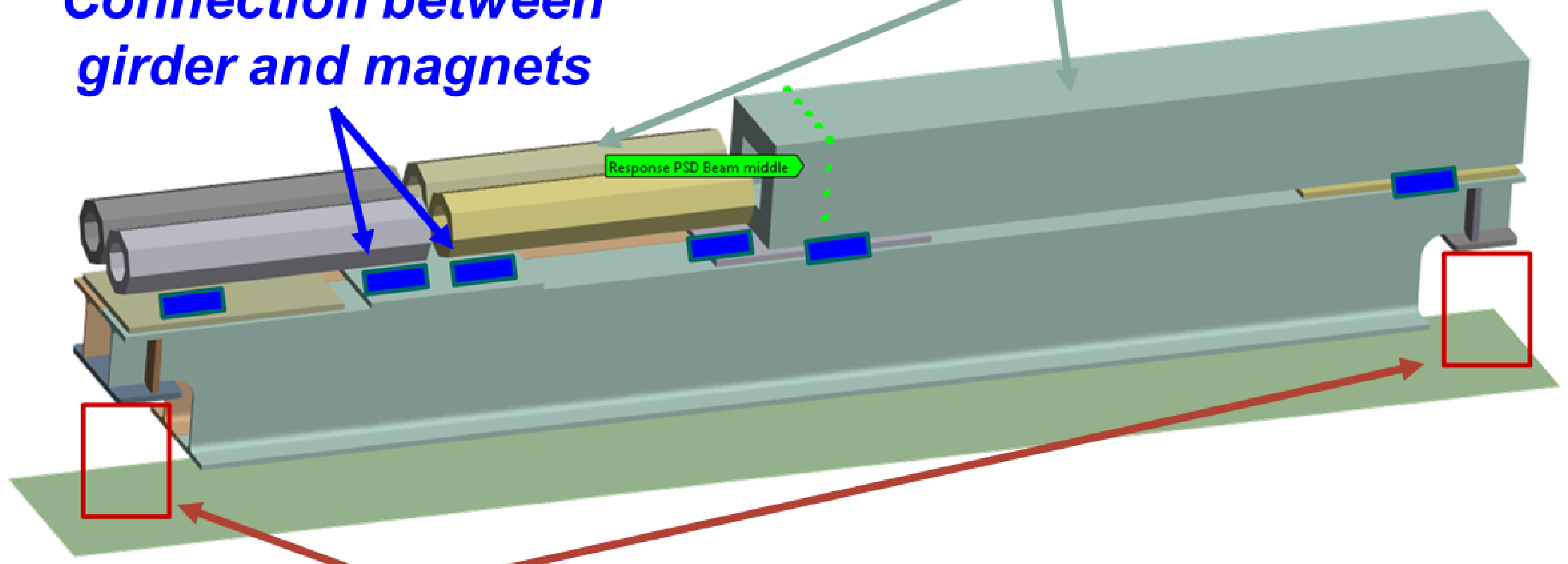
2. Numerical stability assessment methodology

→ **Numeric analysis: Finite Element Method (Ansys)**

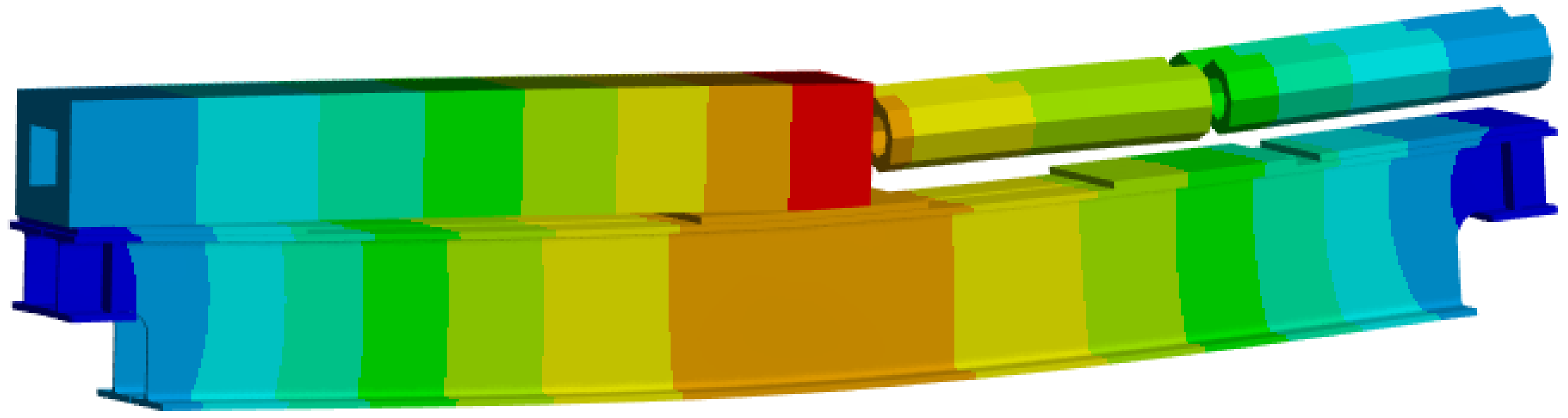


1- Model the system in 3D

2- Static analysis of the system
Define: Contacts, boundary conditions, material, geometry etc.
Analyse: Deflection, structural resistance



3- Modal analysis of the system
Extract mode shape results of the system
Analyse: Rigidity of the system



→ Modal analysis = study of the dynamic characteristics of a system in the frequency domain

2. Numerical stability assessment – PSD

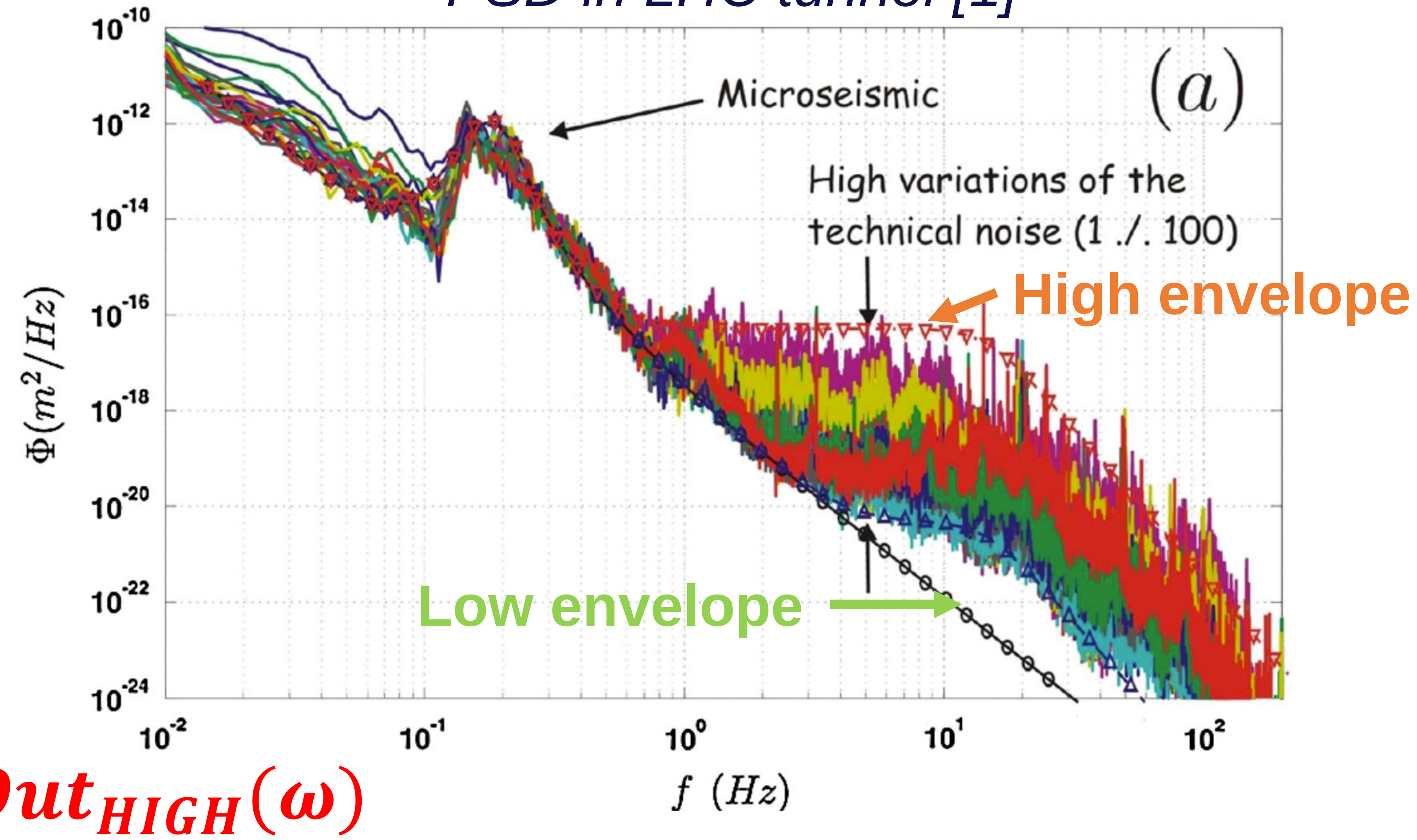
4- Random vibration analysis in response to ground motion

Define the input: PSD of the ground motion

→ PSD = *Power Spectral Density*

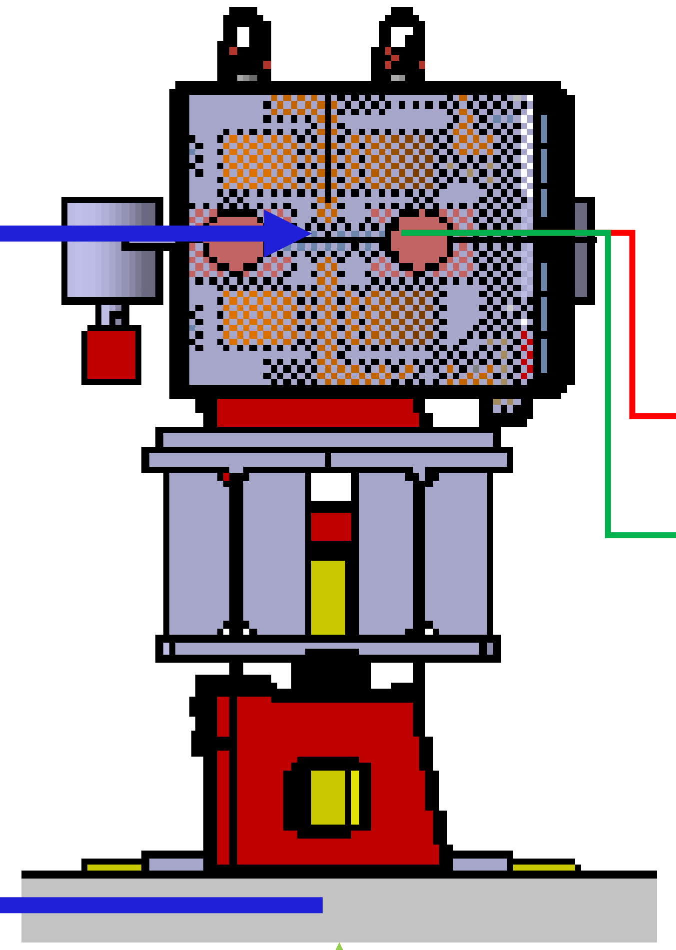
Distribution of the signal's power over frequency $[m^2/Hz]$

PSD in LHC tunnel [1]



Analyse: difficult to 'assess' directly the PSD → the Root Mean Square is needed

$$H(\omega) = \frac{Out(\omega)}{In(\omega)}$$

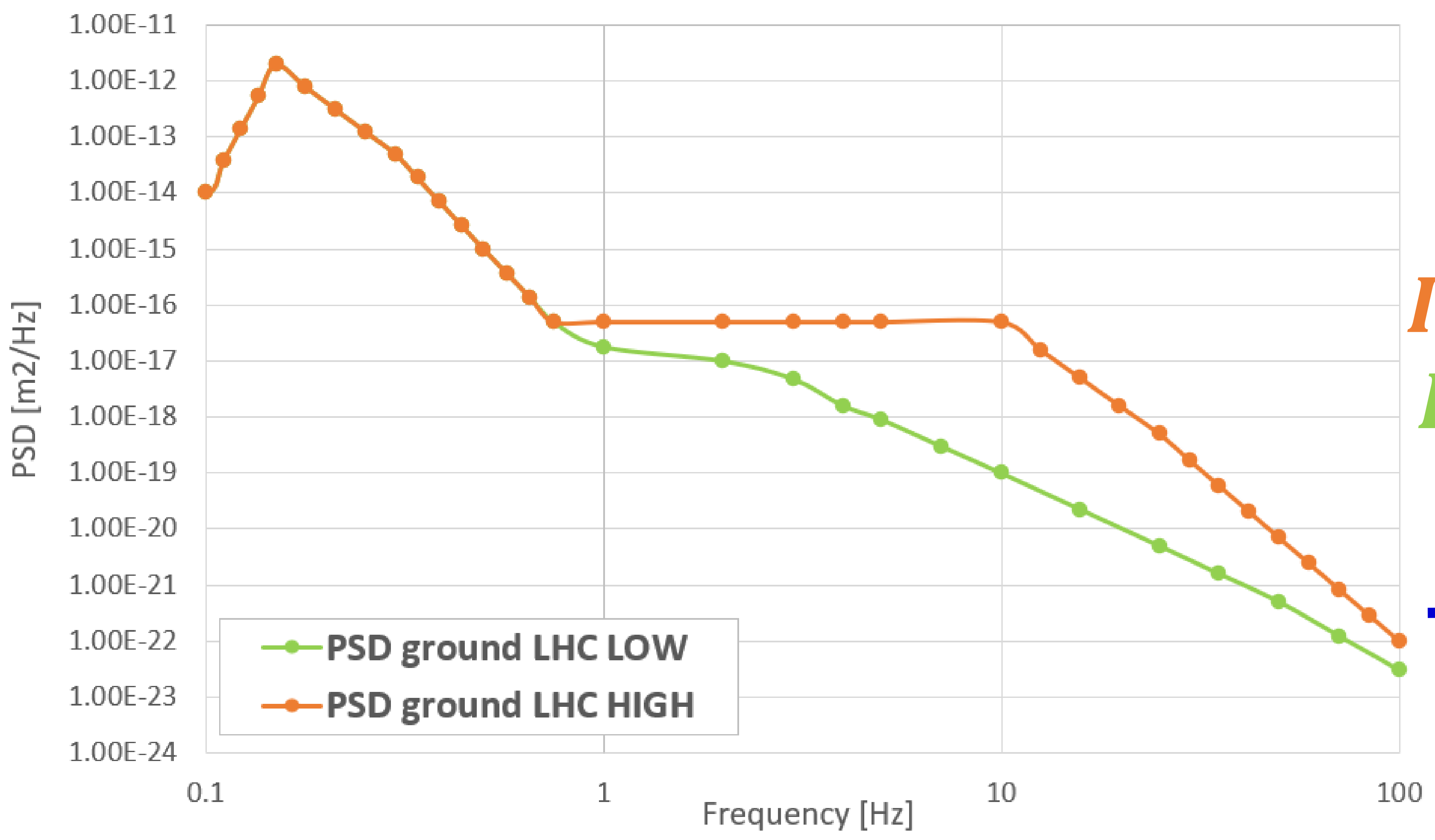


$Out_{HIGH}(\omega)$

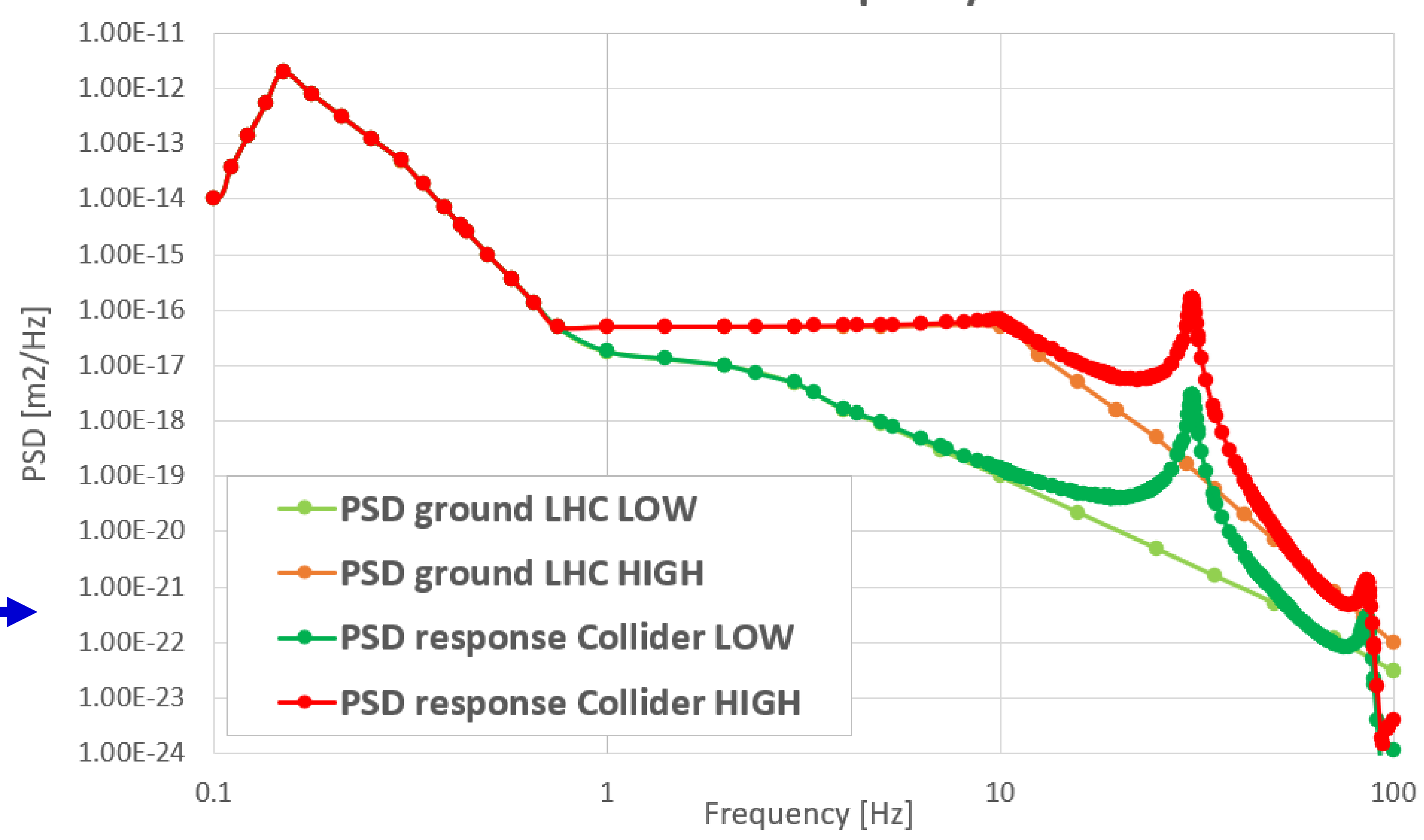
$Out_{LOW}(\omega)$

$In_{HIGH}(\omega)$

$In_{LOW}(\omega)$



Random vibration of the system



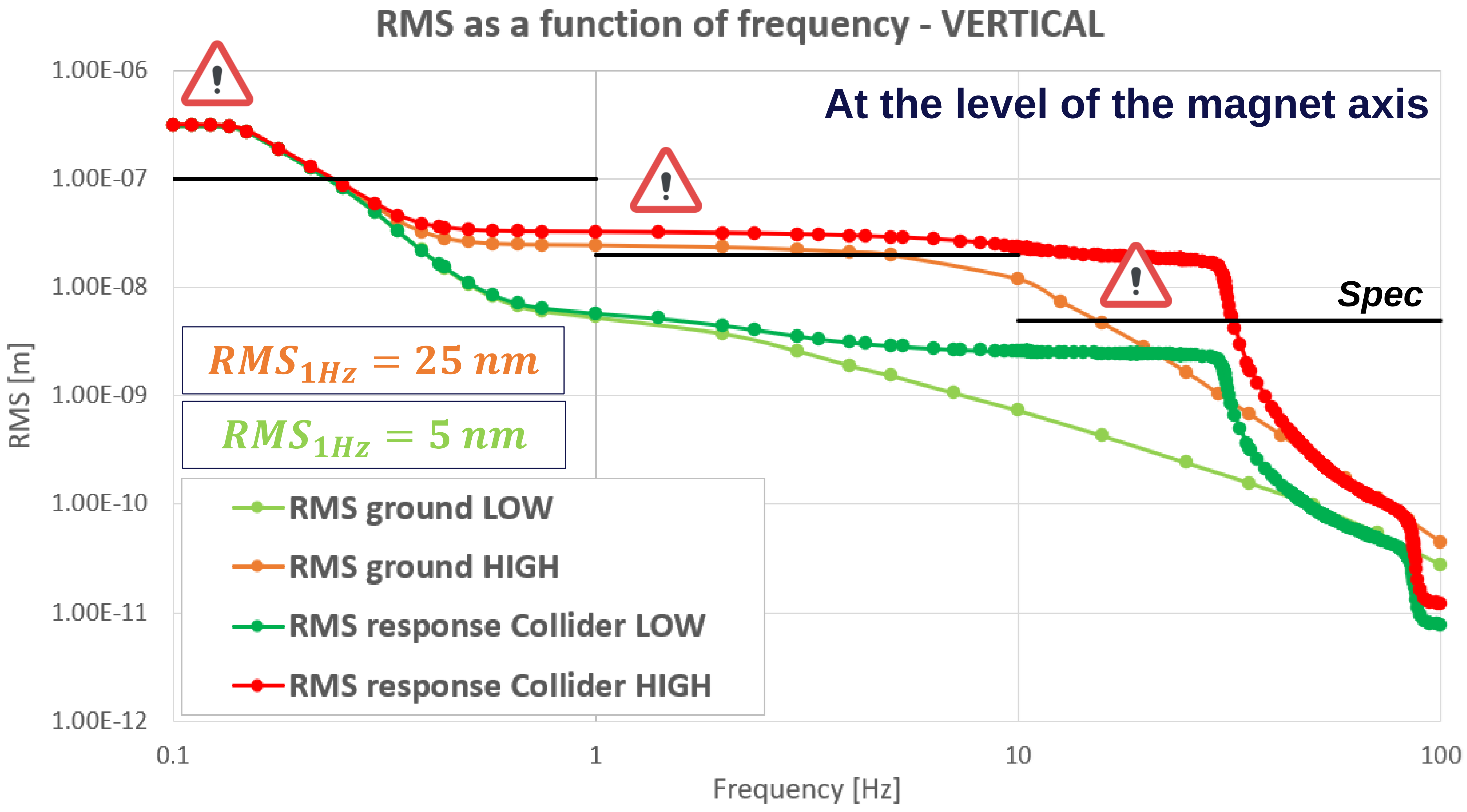
[1] Seismic response of linear accelerator - C. Collette, K. Artoos, M. Guinchard, and C. Hauviller

2. Numerical stability assessment – RMS

5- Compute the RMS Integrated at the level of the magnet axis and compare with specifications

→ RMS = *Root Mean Square – Square root of the area under the PSD curve [m]*

$$RMS(f_2\_f_1) = \sqrt{\sum_{f_1}^{f_2} PSD(f)\Delta f}$$



Specifications at the level of the beam [2]

Frequencies	Tolerance
1 > f > 0.01 Hz	100 nm
10 > f > 1 Hz	20 nm
100 > f > 10 Hz	5 nm
f > 100 Hz	1 nm

→ With just the high envelope of ground motion (LHC level), the specifications are not met

Magnet axis → $H(\omega)$ → **Beam**

NB: *Orders of magnitude of difference are needed!*

+ *The following are not considered:*

- *The crosstalk between structures;*
- *Forced excitations: vibrations from pumps, ventilation systems, etc.*

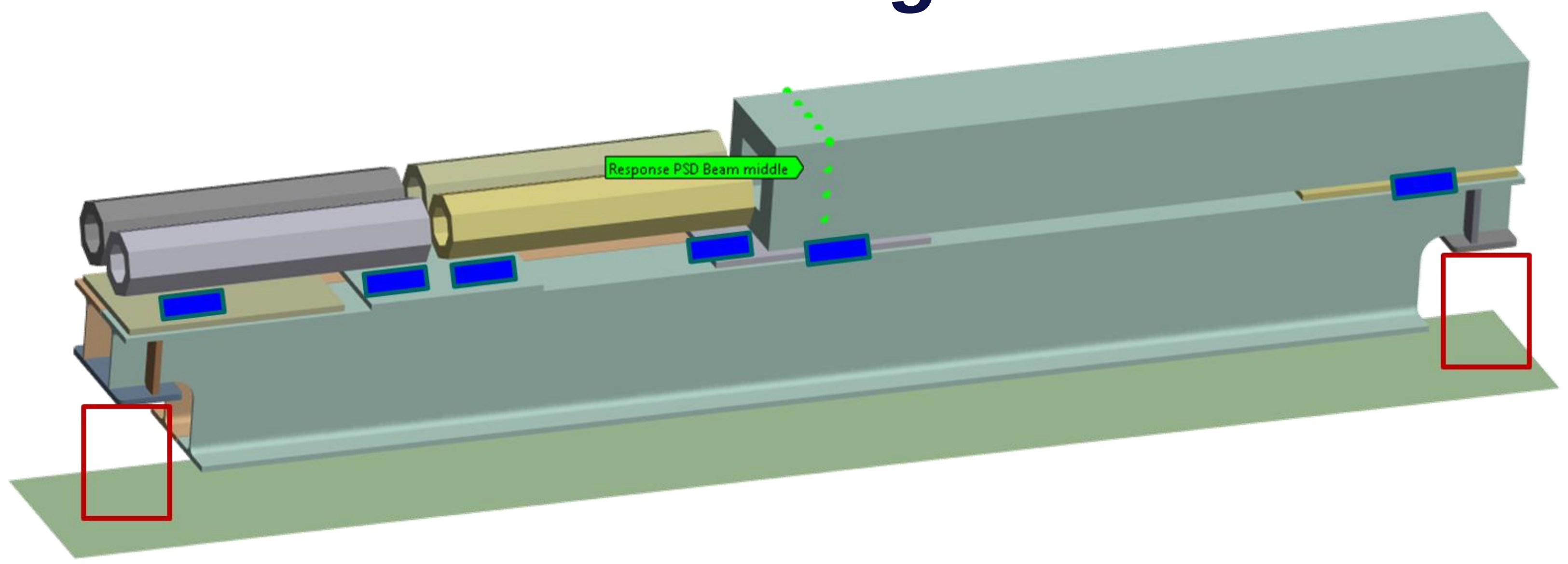
[2] FCC Arc Alignment Requirements T. Raubenheimer

3. Experimental campaign overview

Goals = Benchmark the simulations i.e., refined the assumptions made

Determine the contribution of the different elements on the overall stability – *where to invest design and prototyping efforts!*

Simulation of ***6m-long*** *collider SSS*

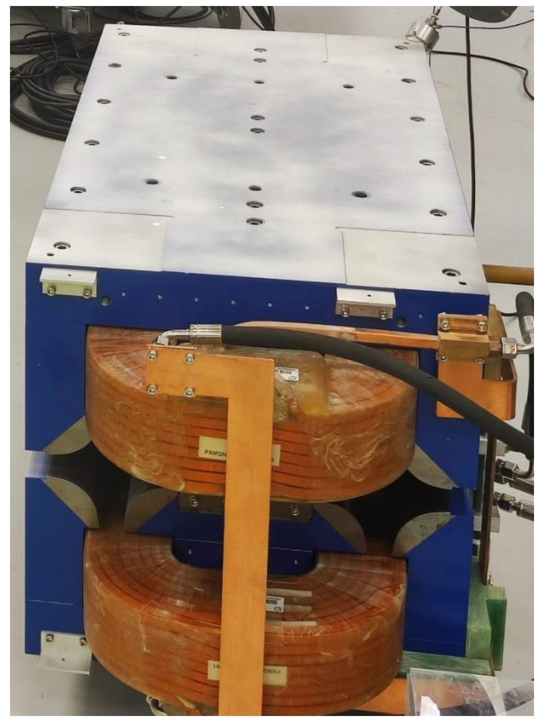


Step 1: Characterisation of a Quadrupole Prototype

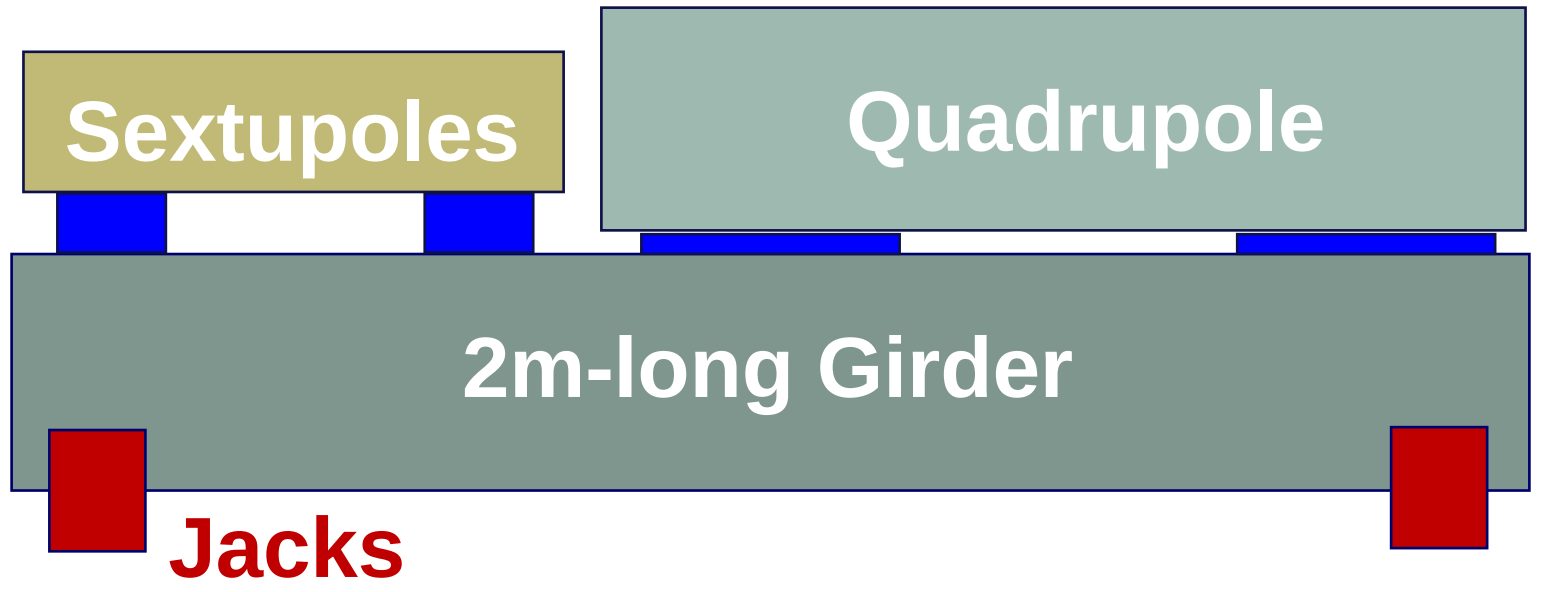
1m-long Quadrupole Prototype based on design parameters of CDR (1,5 ton)

EXP: Experimental modal analysis

SIMU: Compare with modal simulations



Preliminary ***2m-long*** *collider SSS prototype*



Step 2: Characterisation step by step of a simplified supporting structure

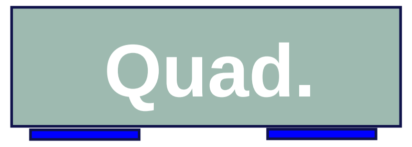
2m-long girder + 1m-long Quadrupole + Jacks + Dummy sextupoles etc.

EXP: Experimental modal analysis + Transfer function with the ground motion

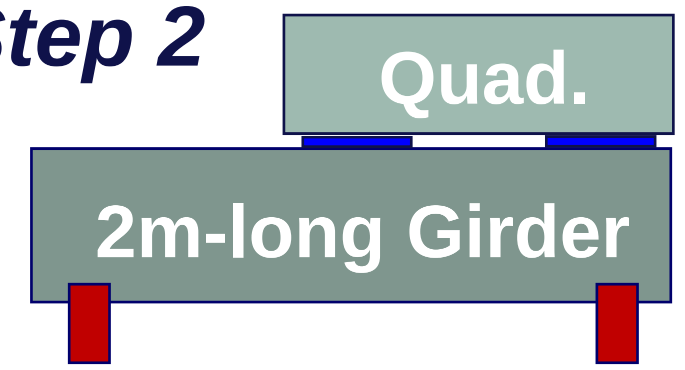
SIMU: Compare with modal and random vibration simulations

EXAMPLE:

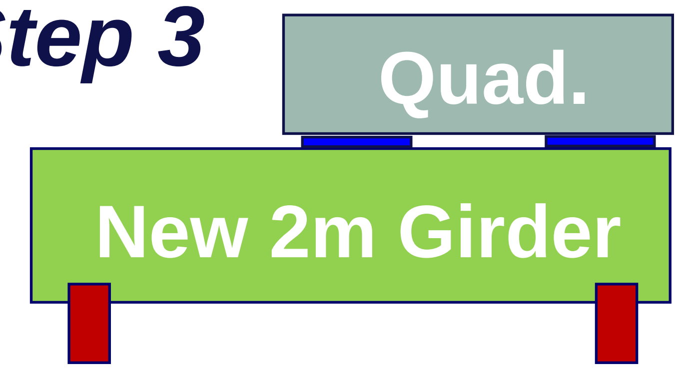
Step 1



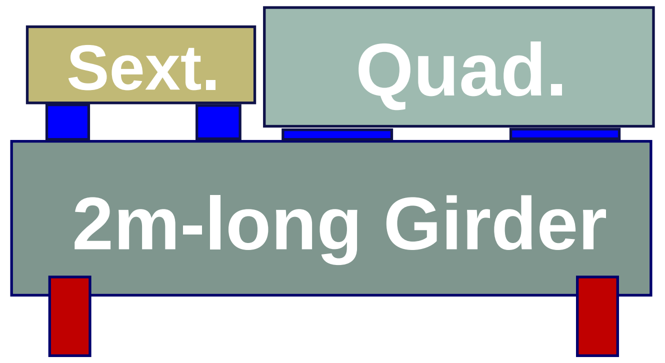
Step 2



Step 3



Step 4



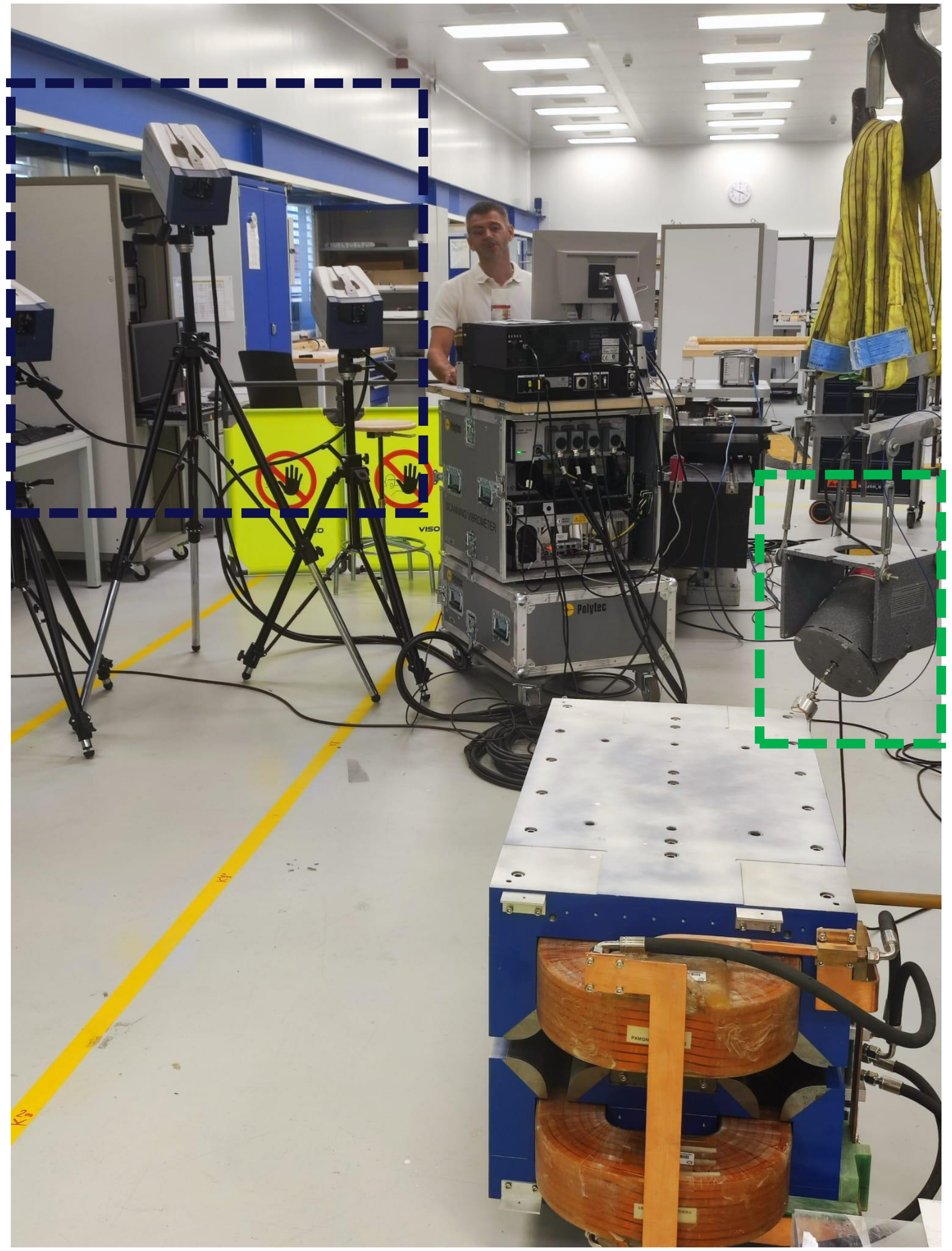
ETC.

3. Results of the experimental campaign – Modal analysis

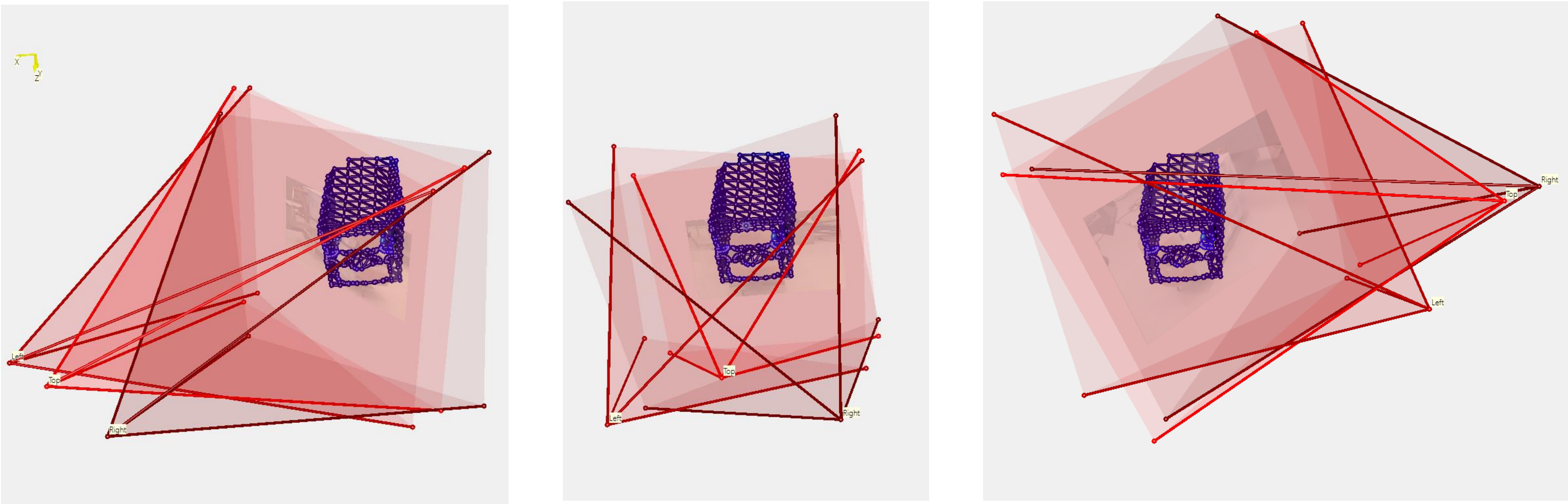
Experimental Modal Analysis / FCC quadrupole

M. Guinchard, D. Thuliez

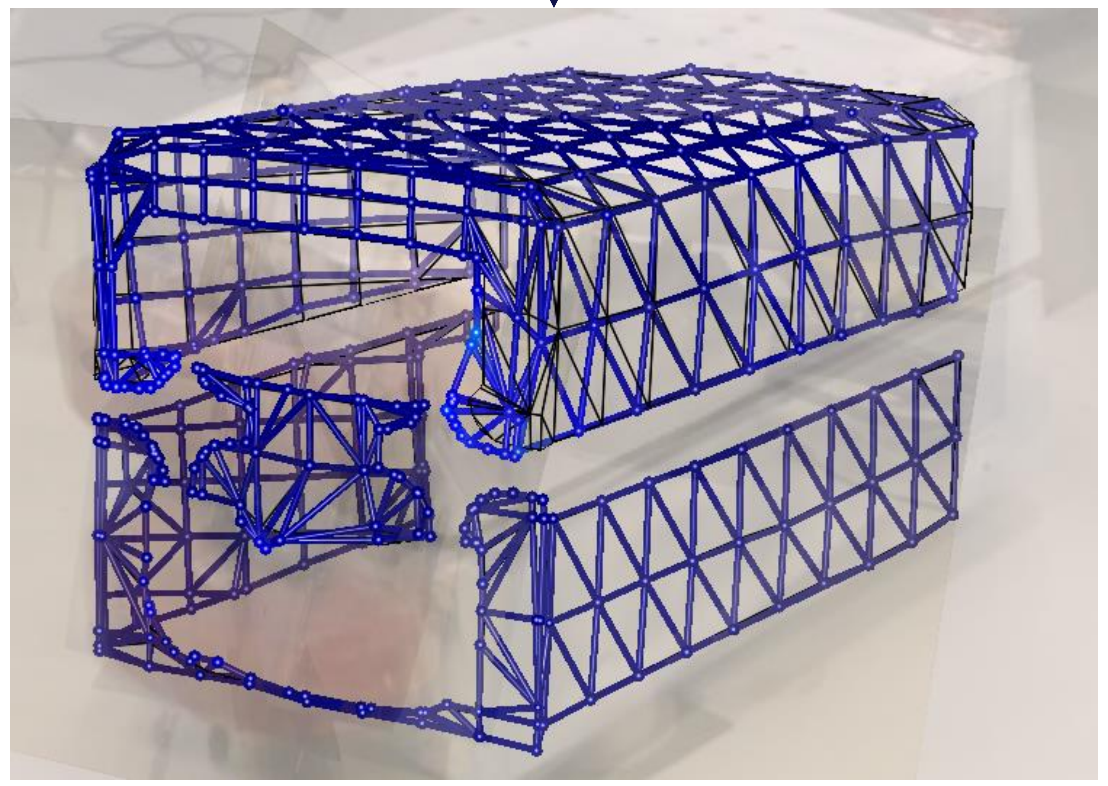
3D Scanning vibrometer



Shaker excitation :
White noise
Accelerometer : 100 (m/s²)/V



3 Sets of measurements + stitching process



Geometry scan performed with 747 scan points

3. Results: experimental vs simulations

Comparison of specific mode shapes results

Experimental results:

Simulation results:

308 Hz **539 Hz** **682 Hz** **1277 Hz** **1454 Hz**

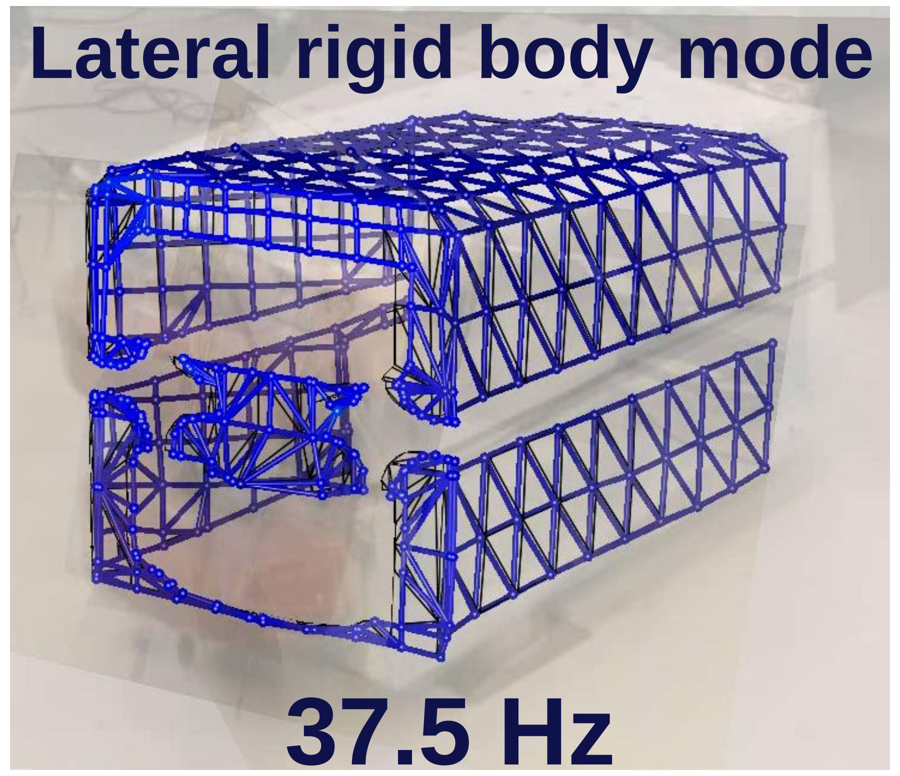
3. Results: experimental vs simulations

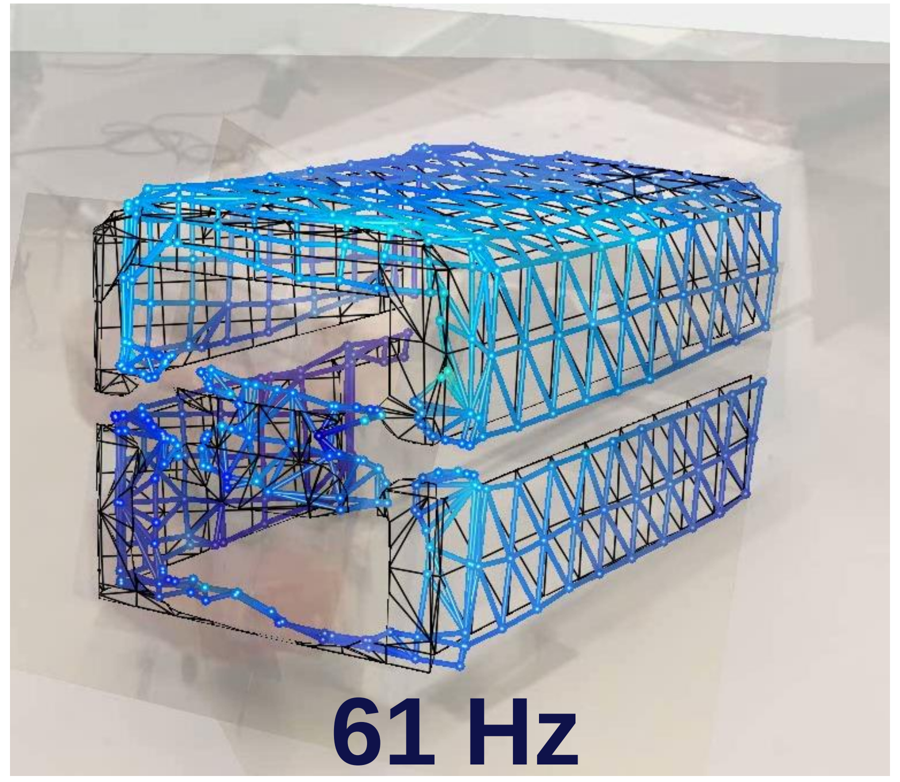
Comparison of the rigid body mode

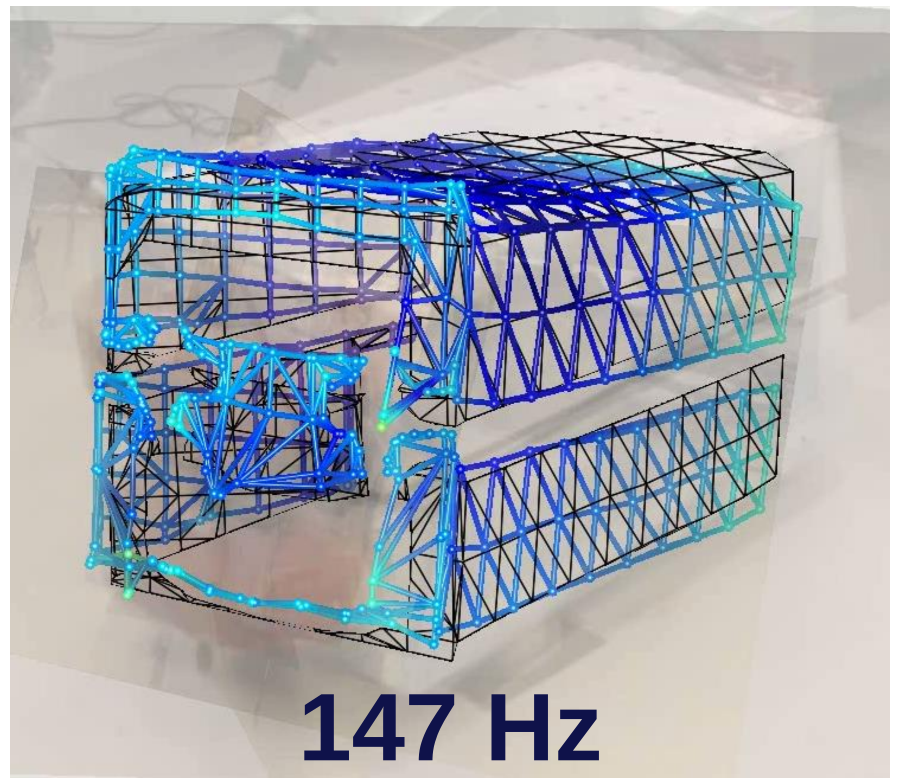
→ *Tests with 10 mm elastomer under each foot (Chloroprene/Styrene-butadiene)*

Experimental results:

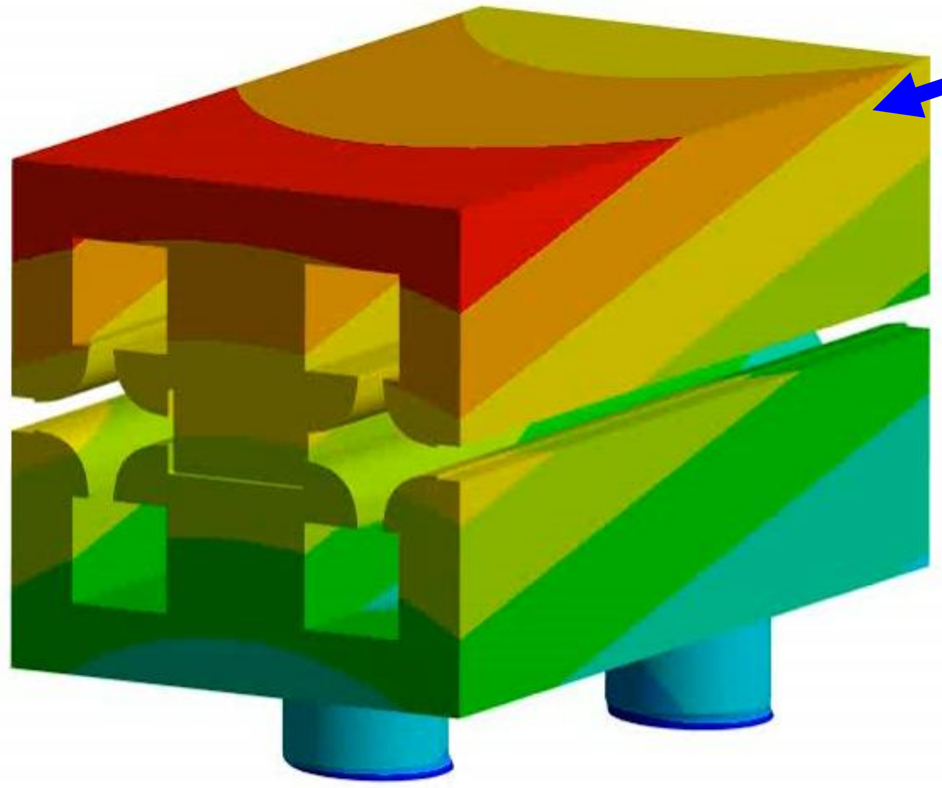
Vertical rigid body mode
6 Hz



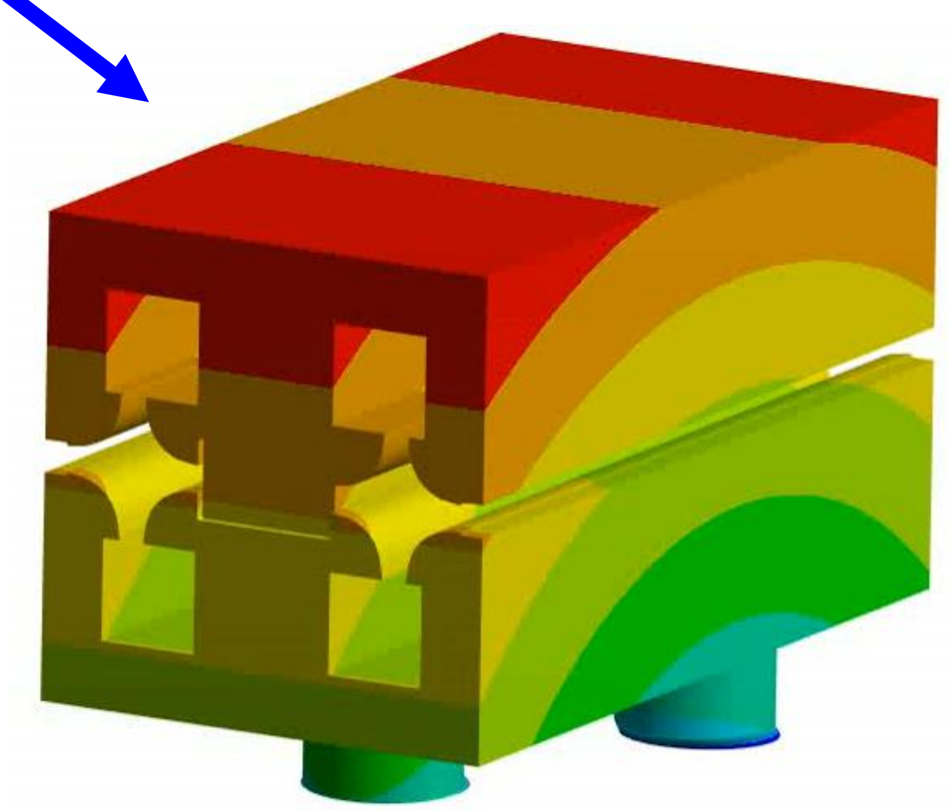




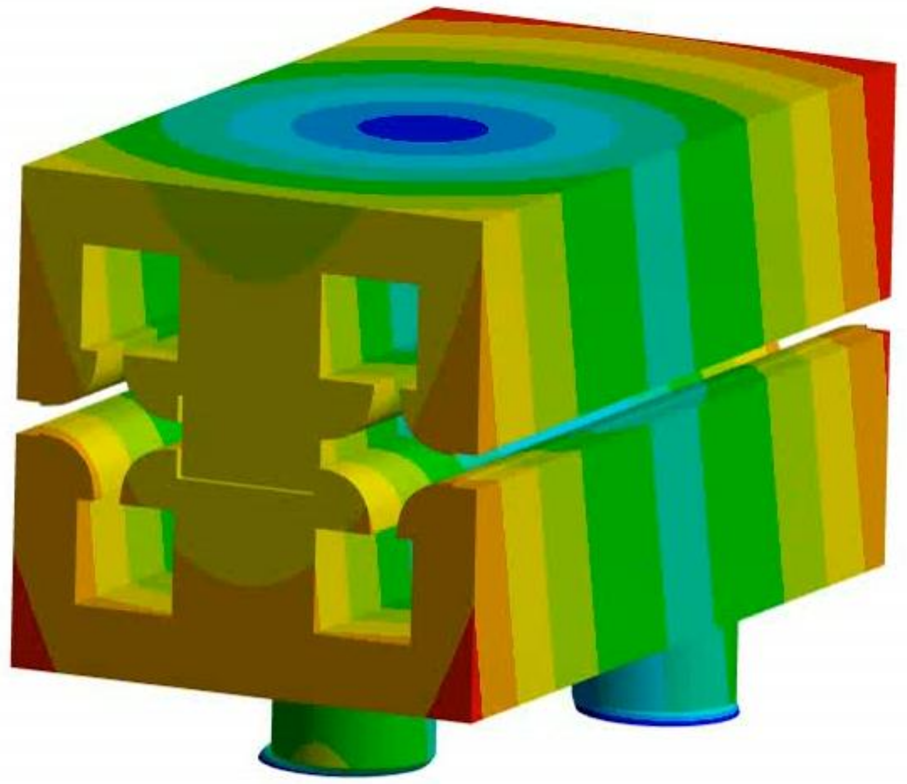
Simulation results:



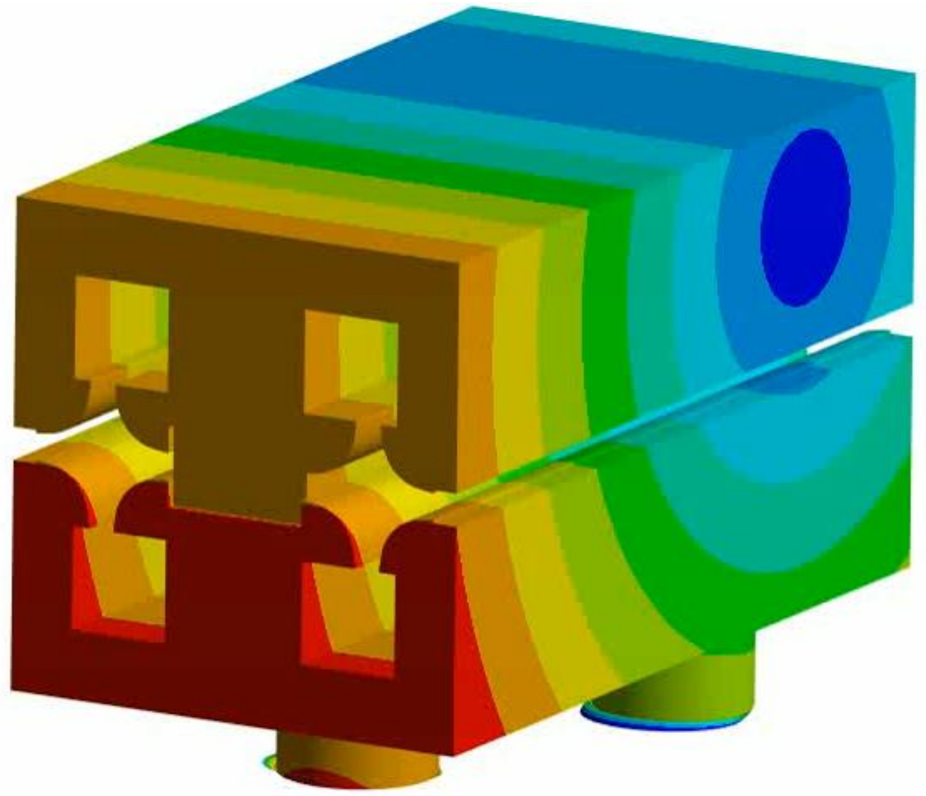
4 Hz
Lateral rigid body mode



6 Hz
Vertical rigid body mode



7 Hz



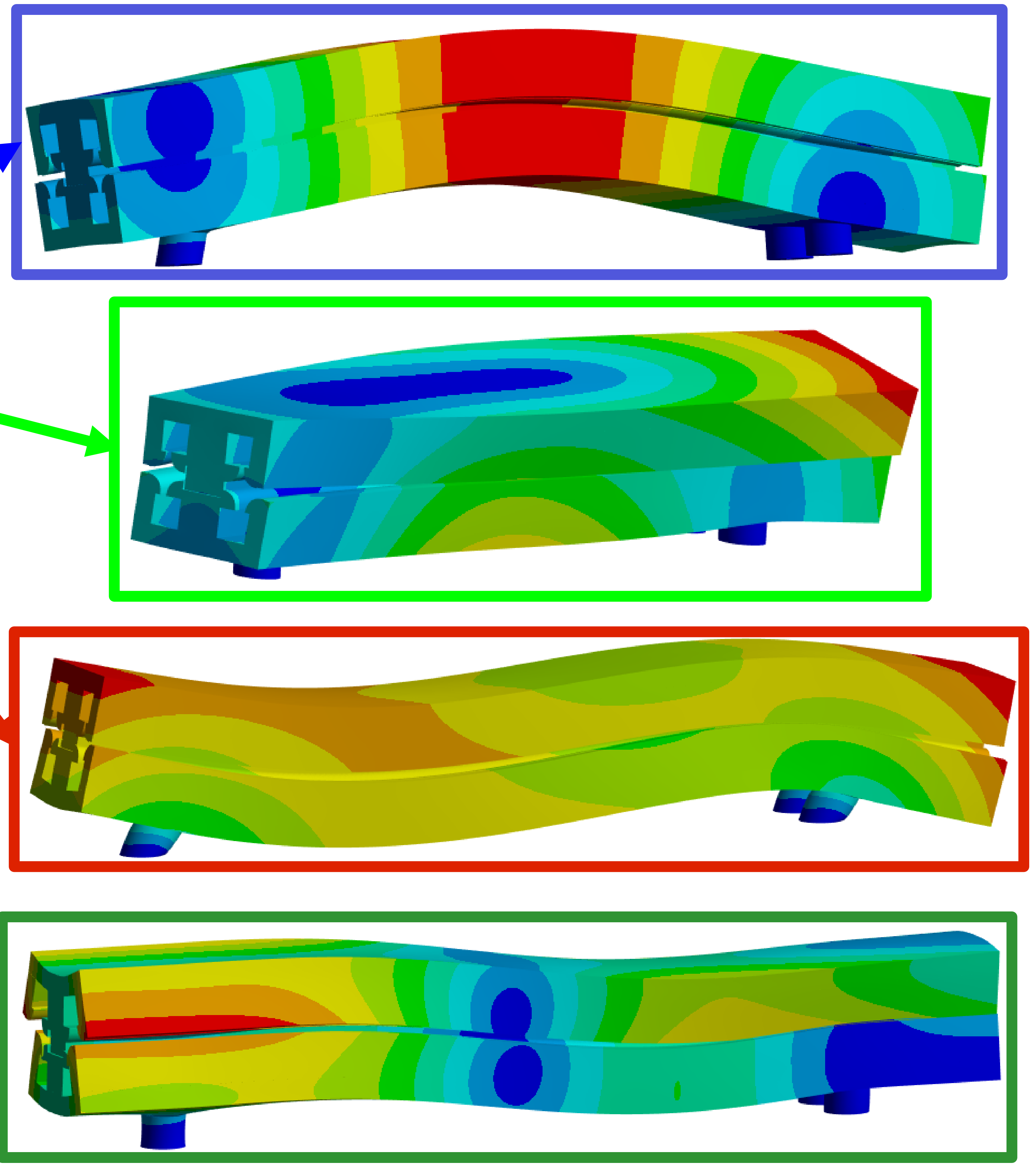
16 Hz

3. Results: extrapolation of simulations

Mode shape results for the 2.9 m long quadrupole

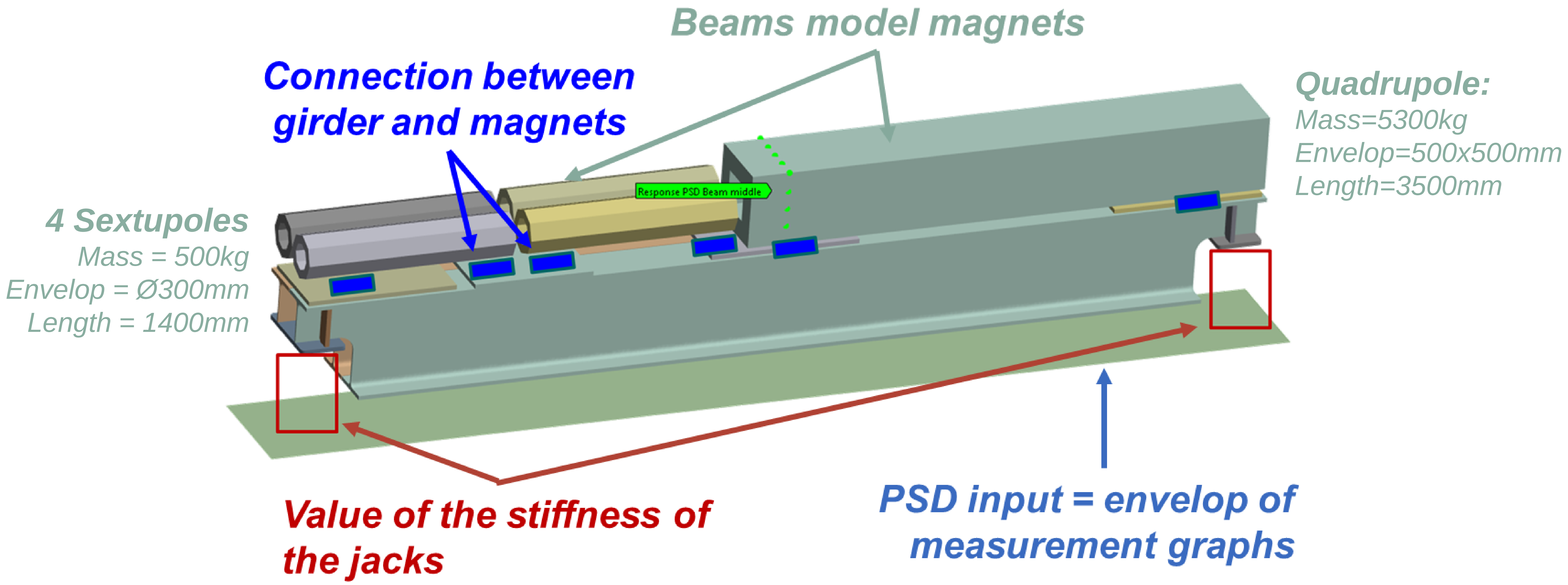
	SIMULATION 1 m long
Modes	Frequency (Hz)
S1	187
S2	308
S3	363
S4	460
S5	539
S6	597
S7	614
S8	652
S9	682
S10	780
S11	810
S12	867
S13	973
S14	1037
S15	1151
S16	1277
S17	1314
S18	1332
S19	1349
S20	1418
S21	1454

	SIMULATION 2.9 m long
Modes	Frequency (Hz)
S1	88
S2	181
S3	260
S4	269
S5	290
S6	362
S7	430
S8	469
S9	476
S10	482
S11	529
S12	547
S13	559
S14	580
S15	594
S16	608
S17	628
S18	642
S19	659
S20	669
S21	684



→ The mode shapes have relatively high frequencies
→ The rigid body modes are of lower frequency = important to work on magnet fixation

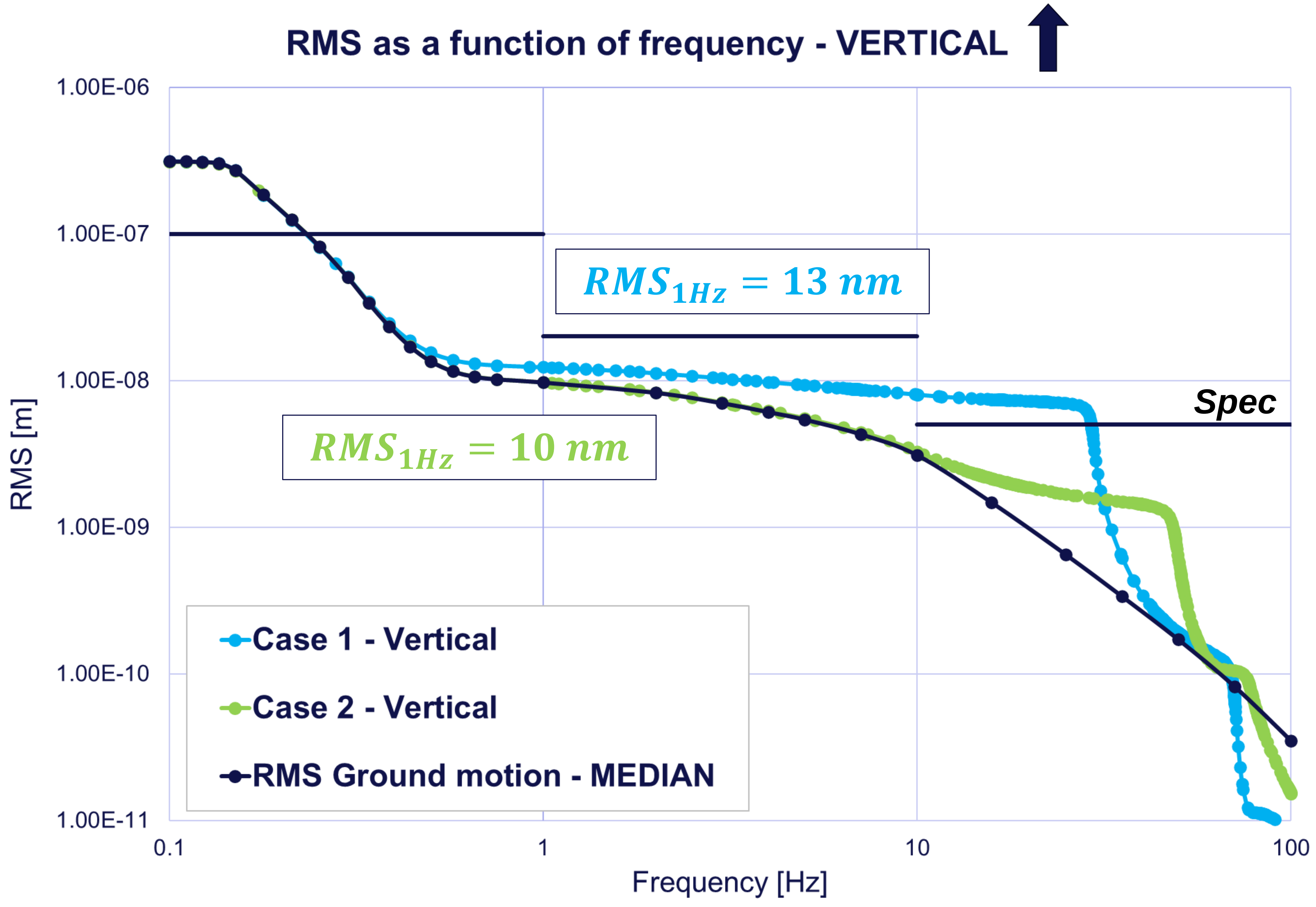
4. Simulation results of the collider stability

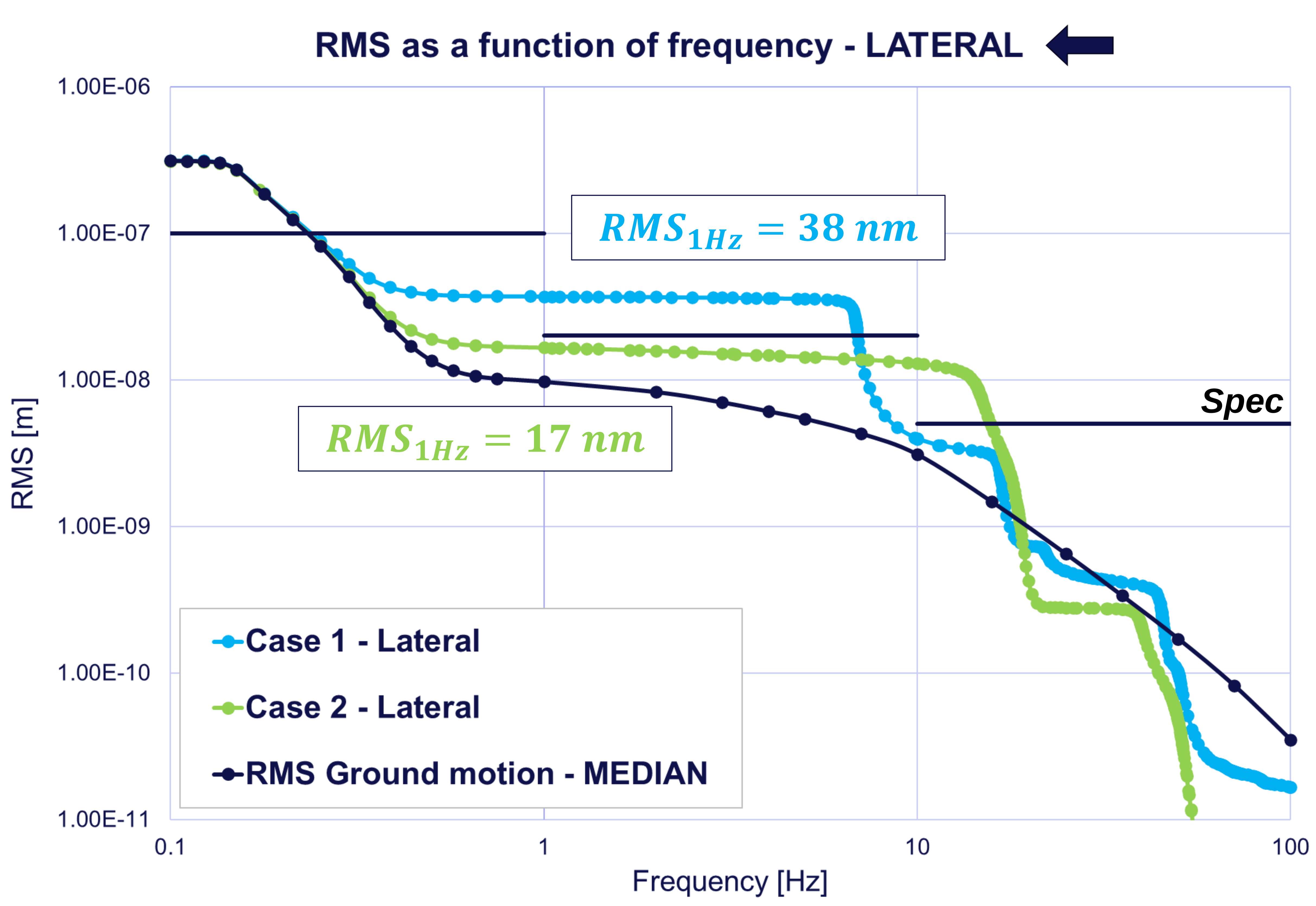


What parameters can we play with? What do we want to study and compare?

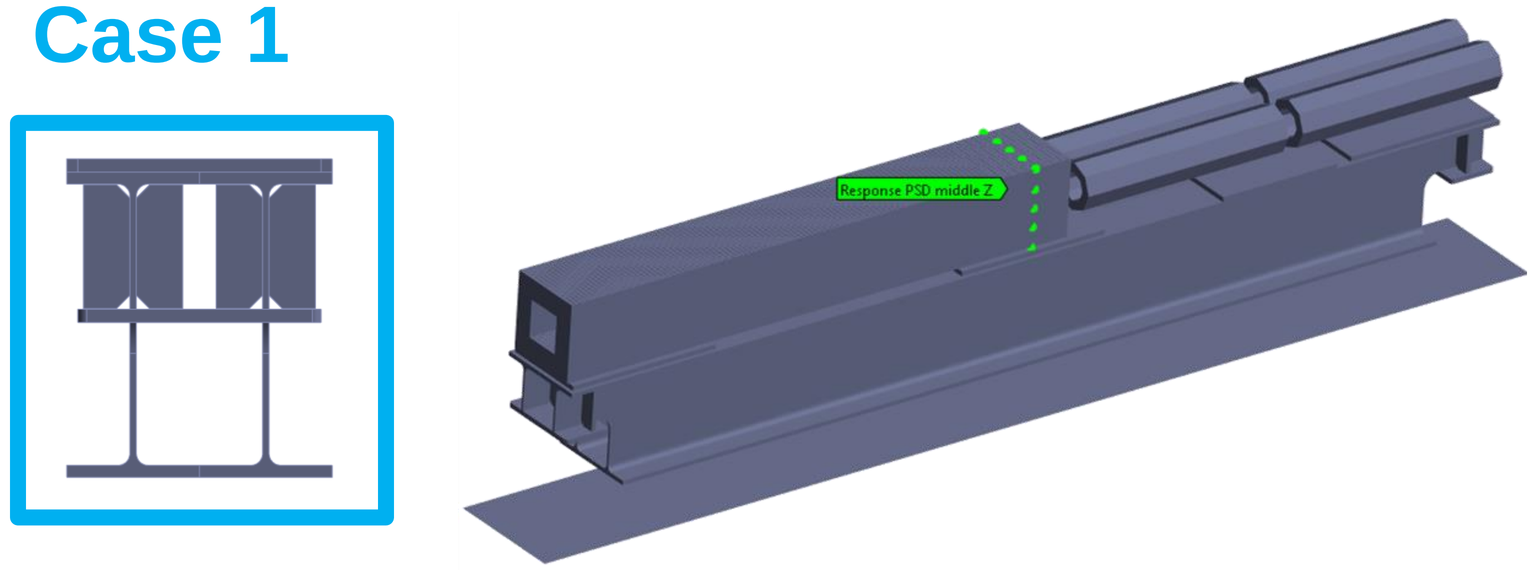
Parameters	Case 1	Case 2
Number of jacks	3 jacks	4 jacks
Geometry of the girder	Thin steel girder	Steel girder with wider feet
Material of the girder	Steel girder	Steel girder fill with damping material

4. Simulation results of the collider stability

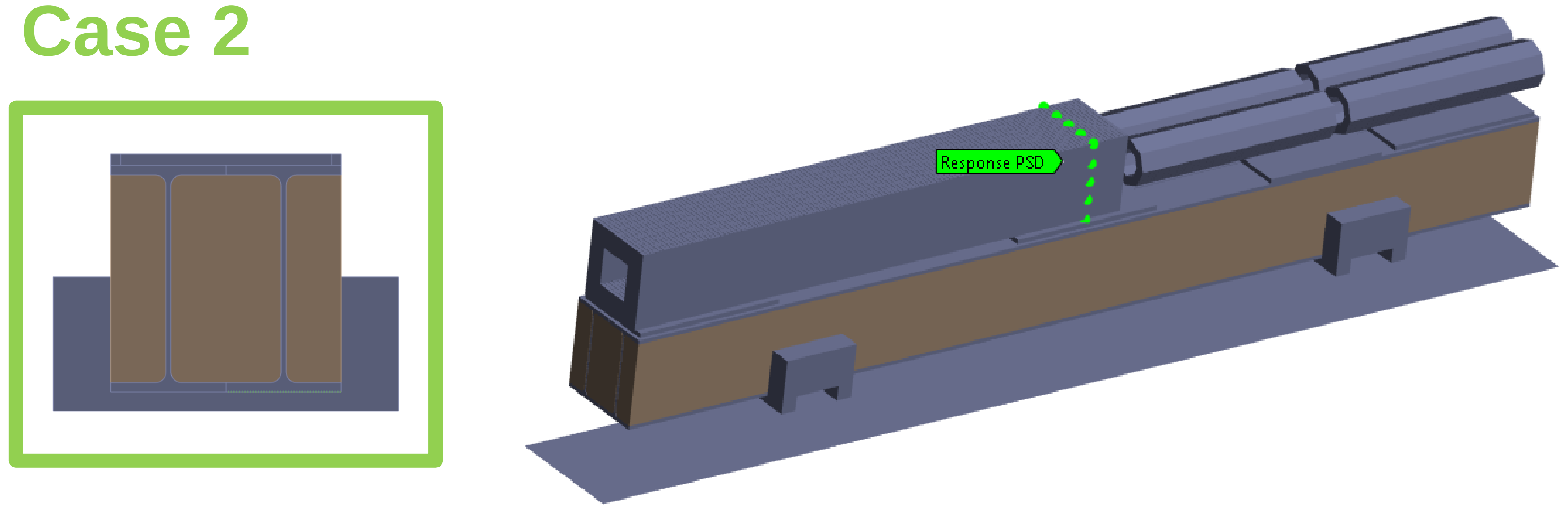




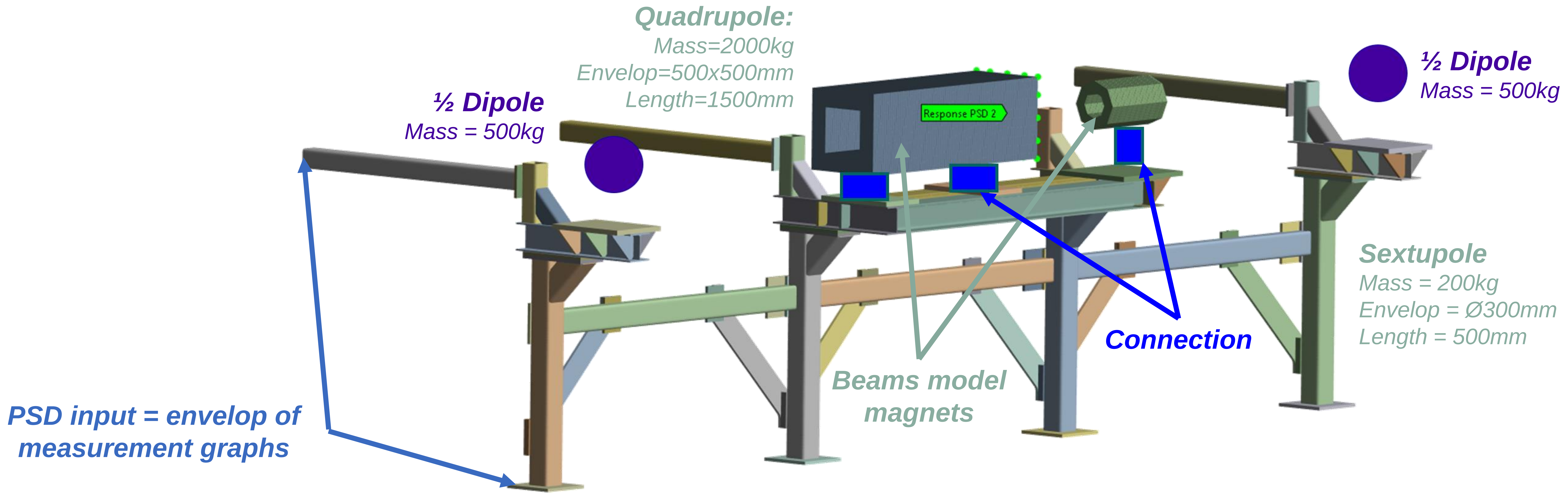
Case 1



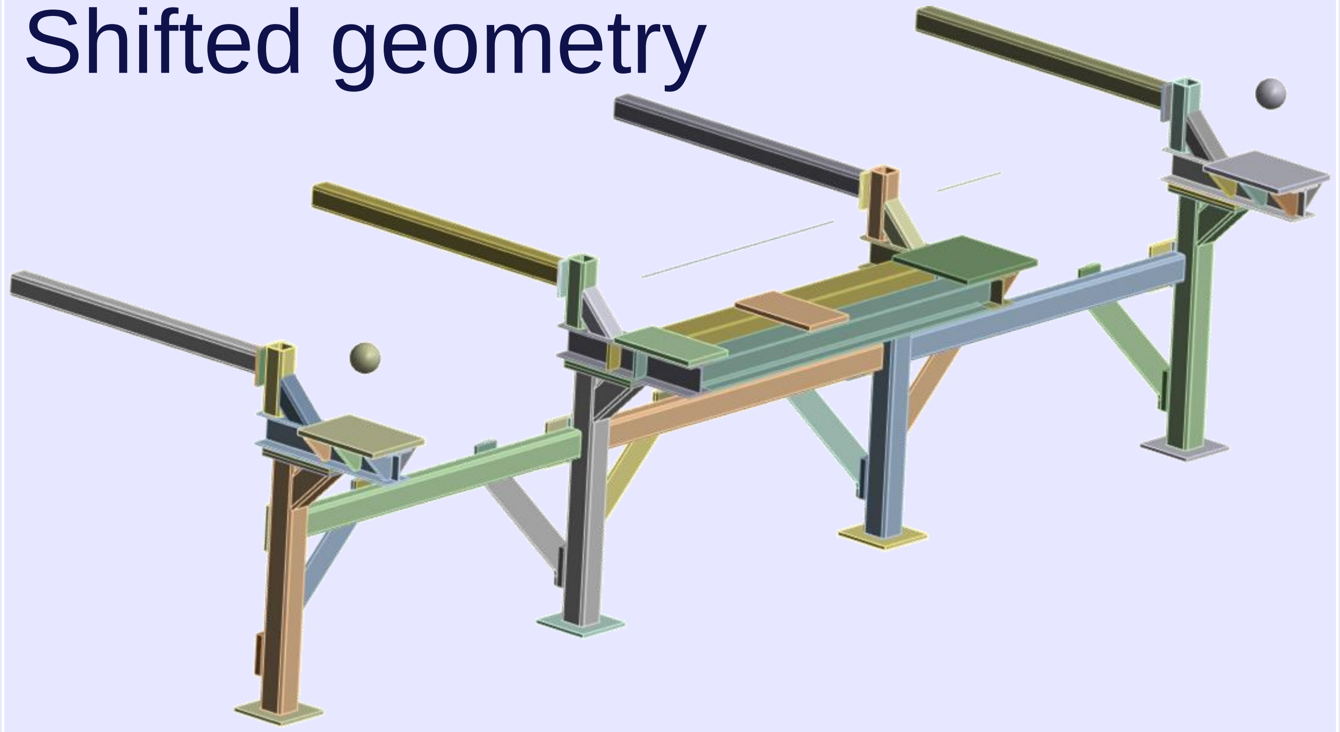
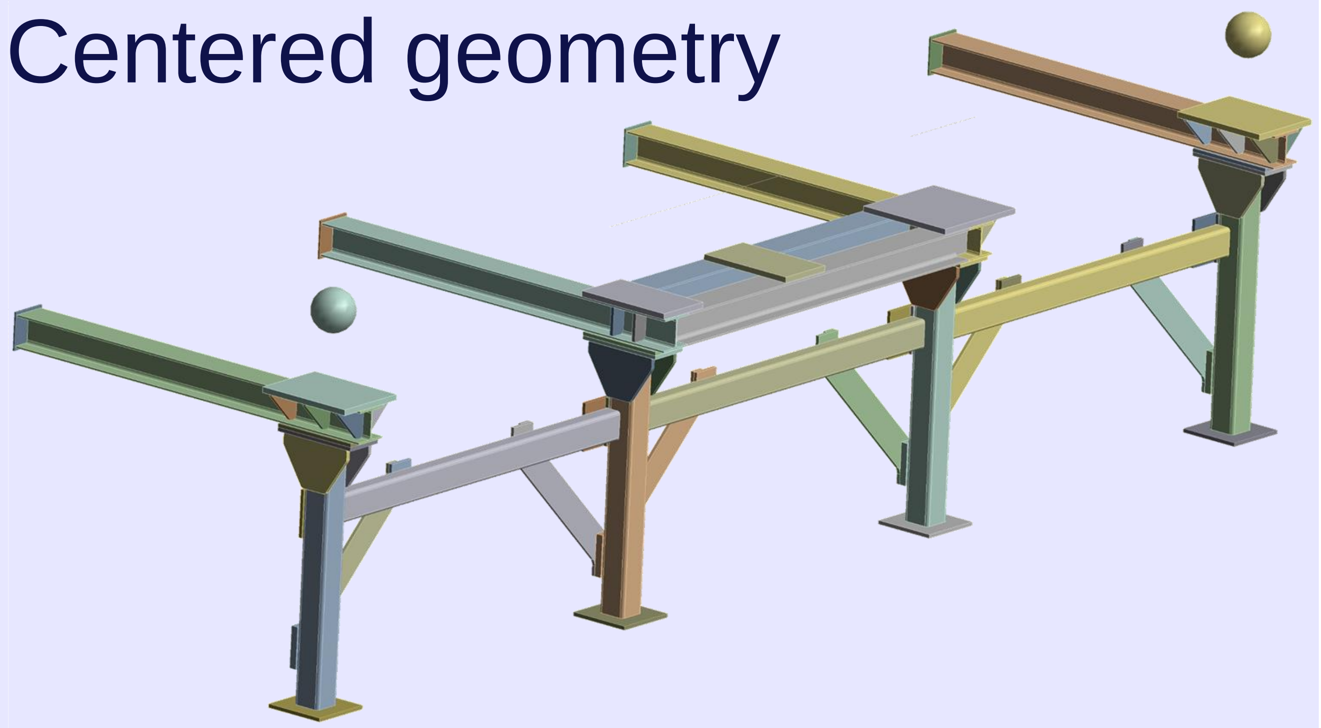
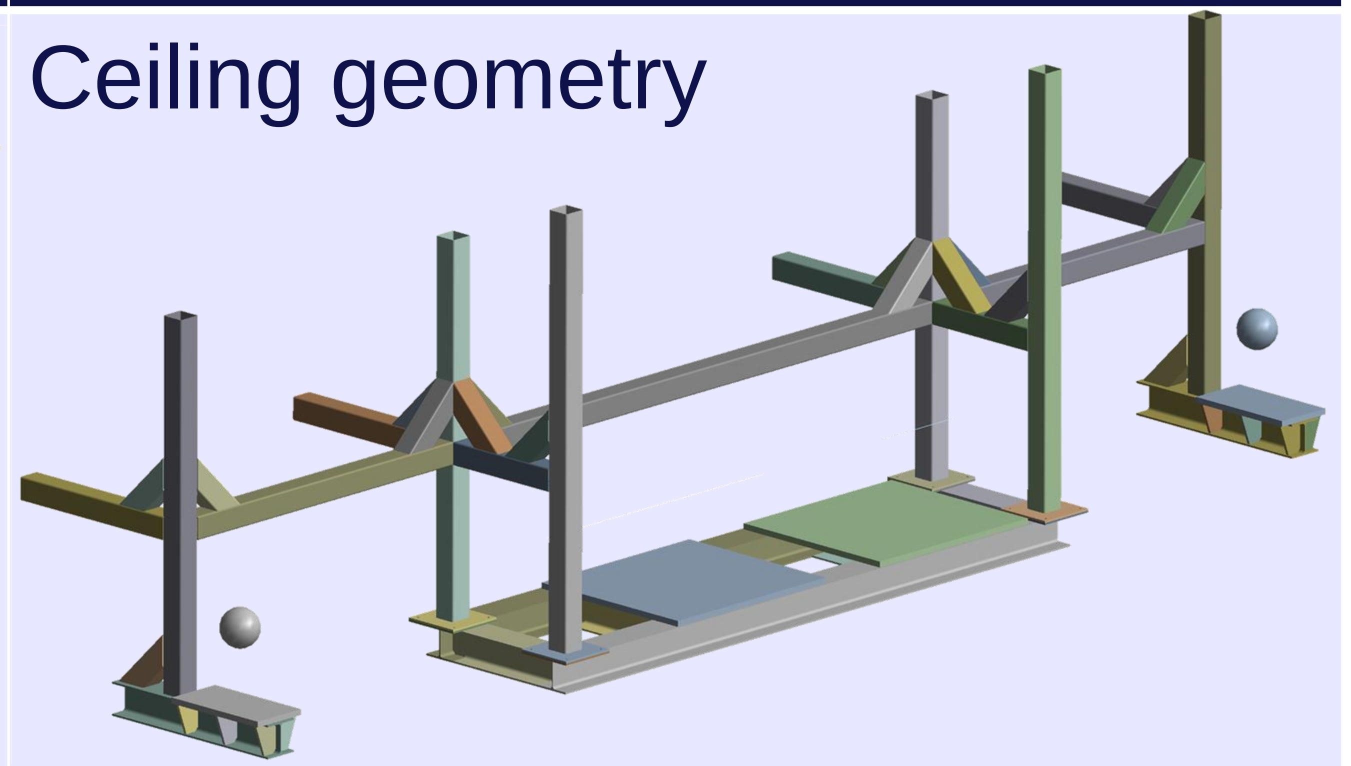
Case 2



4. Simulation results of the booster stability

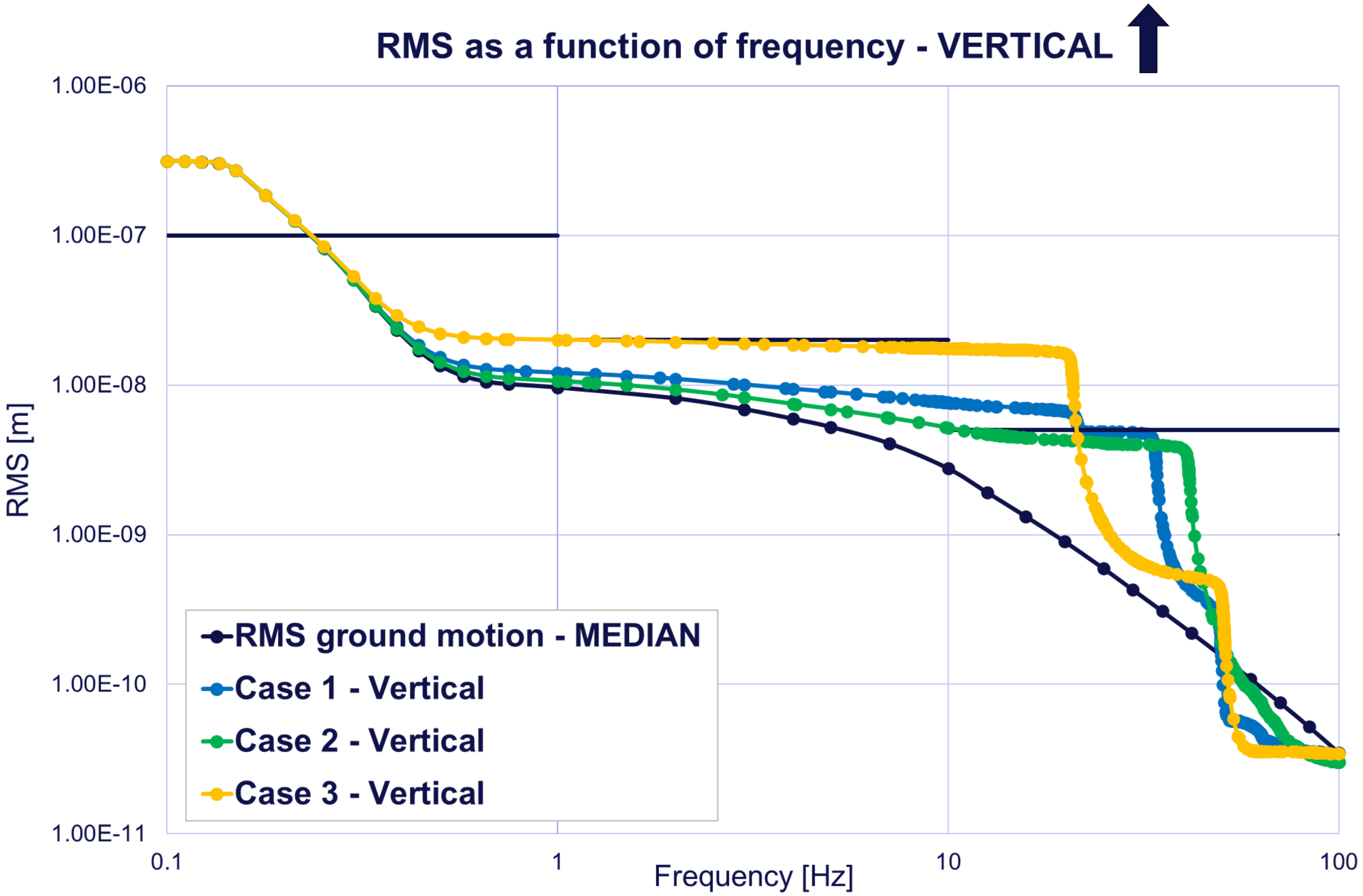


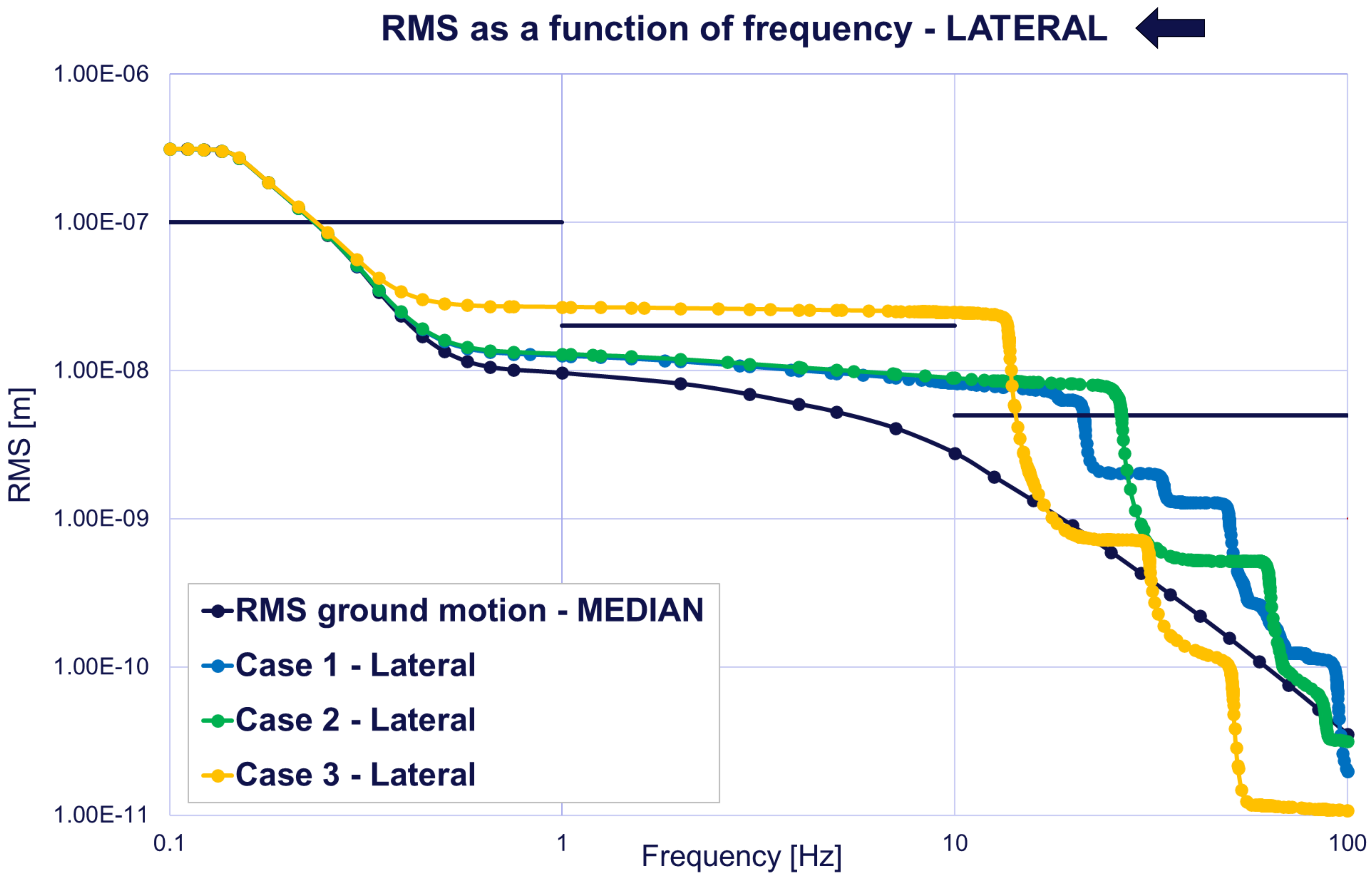
What parameters can we play with? What do we want to study and compare?

Parameters	Case 1	Case 2	Case 3
Geometry of the booster support	Shifted geometry 	Centered geometry 	Ceiling geometry 

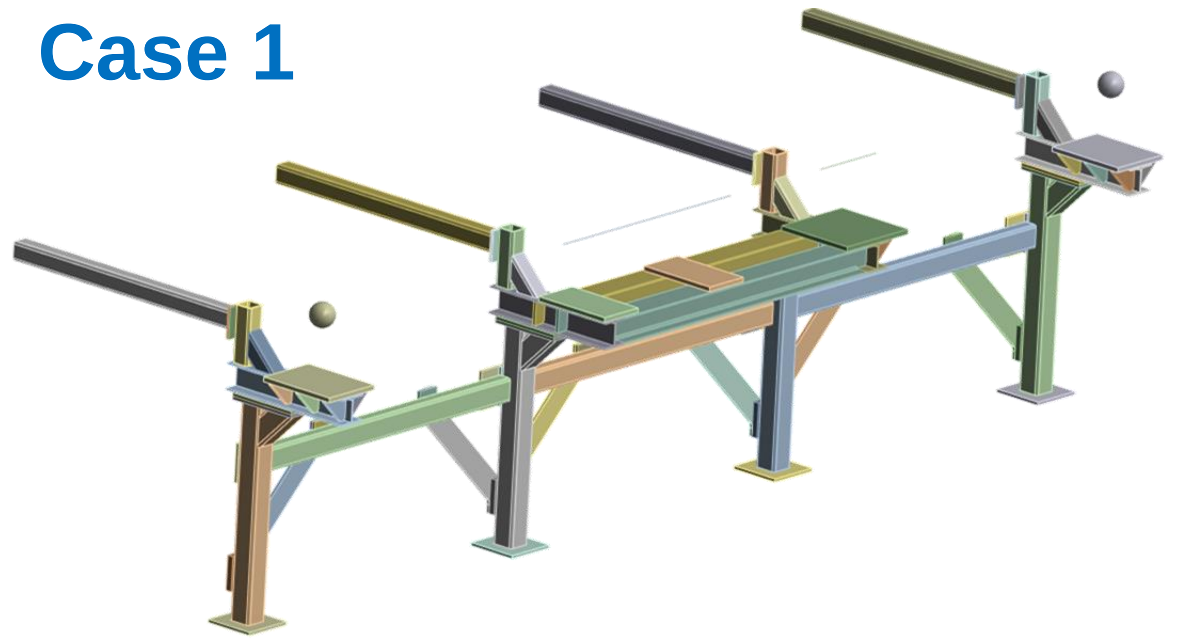
4. Simulation results of the booster stability

L. Hutin

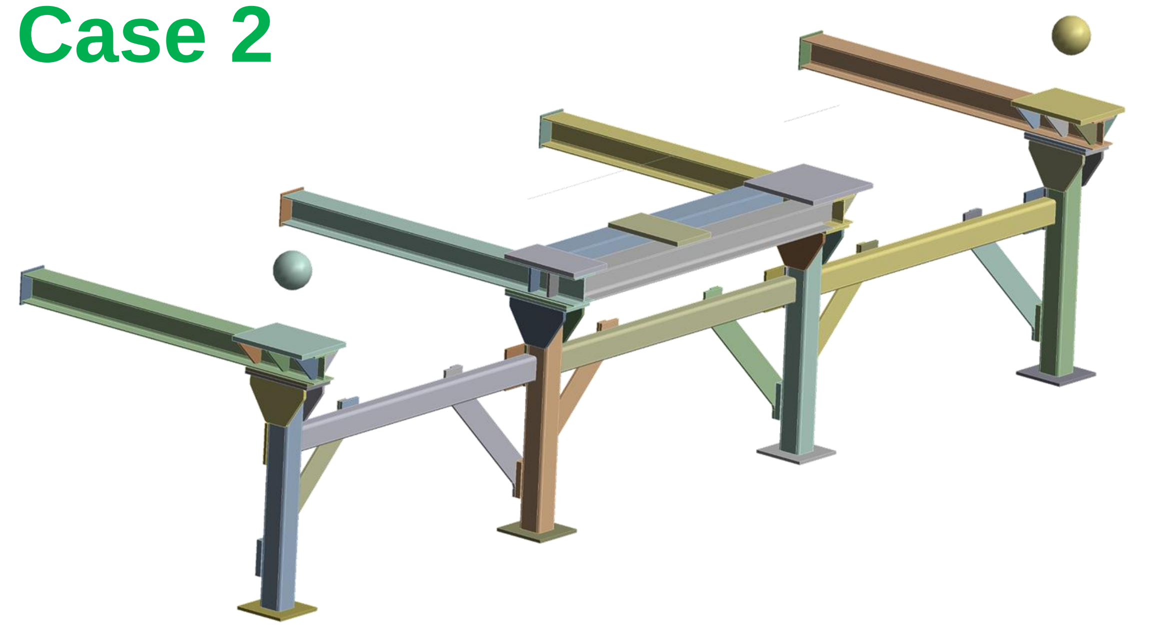




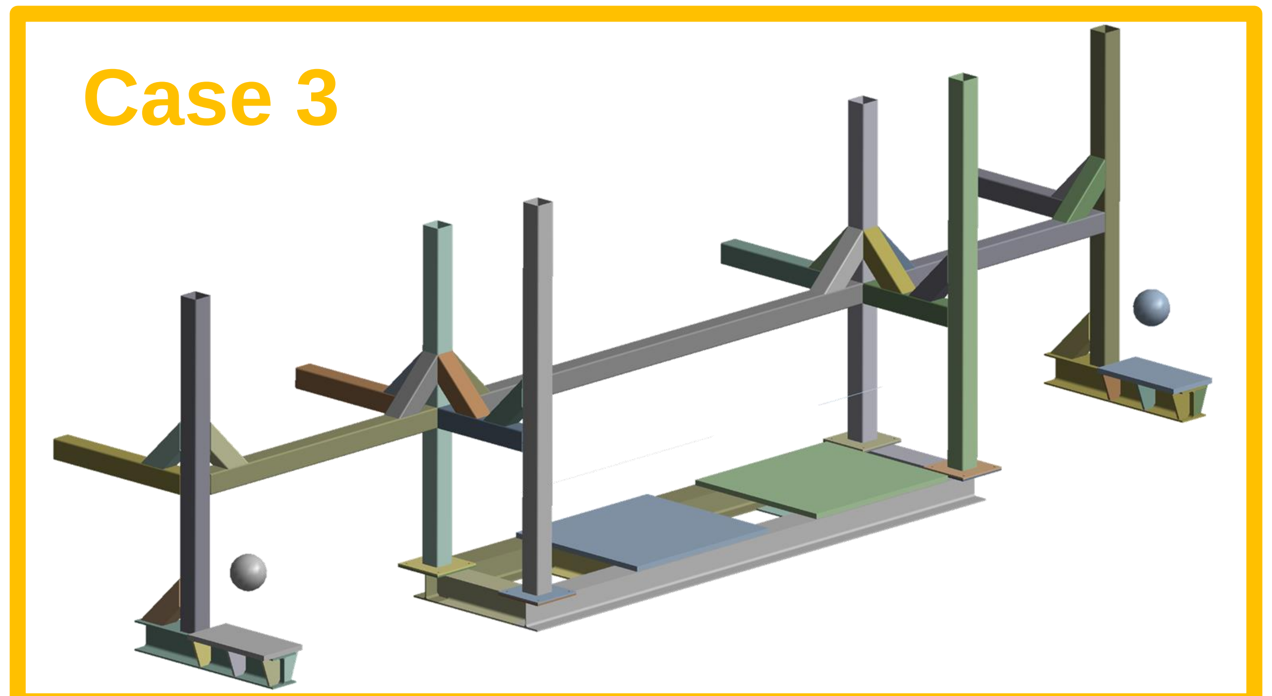
Case 1



Case 2



Case 3



5. Conclusion

→ The methodology for assessing the dynamic stability of the collider and booster support systems has been established.

- ↳ *It allows to compute an RMS at the level of the magnetic axis which can be compared to specifications.*
- ↳ *Different designs can therefore be compared in terms of stability performance.*
- ↳ *The contribution of ground motion alone is problematic for the specifications.*

→ Experimental measurements and analyses are currently in progress.

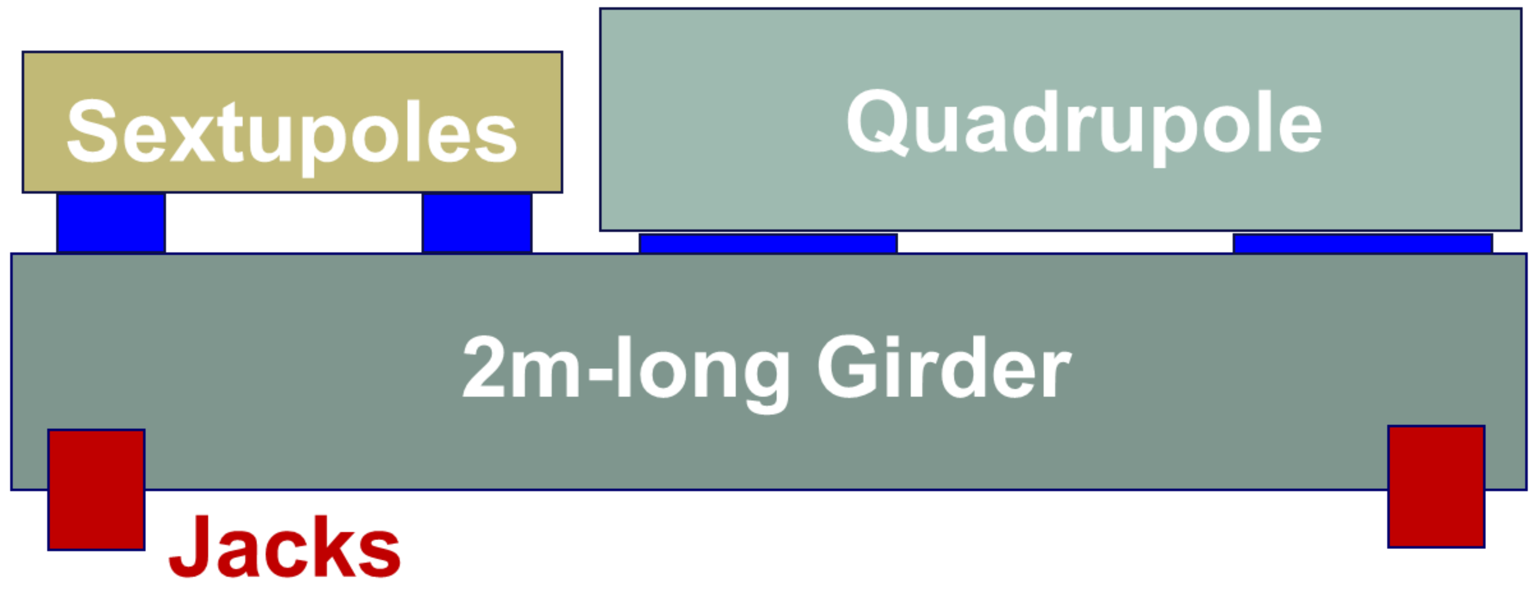
- ↳ *The first step (quadrupole prototype) was used to benchmark the simulations: the results are consistent.*
- ↳ *The following steps will provide a better understanding of the contribution of the different elements on the overall stability.*

5. Next steps

→ Construction and installation of a preliminary mockup of the SSS.

- Fabrication of two short girders:
  - *CERN main workshop (design ongoing)*
  - *PAEC collaboration = specific addendum to the MoU*

*Preliminary **2m-long** collider SSS prototype*



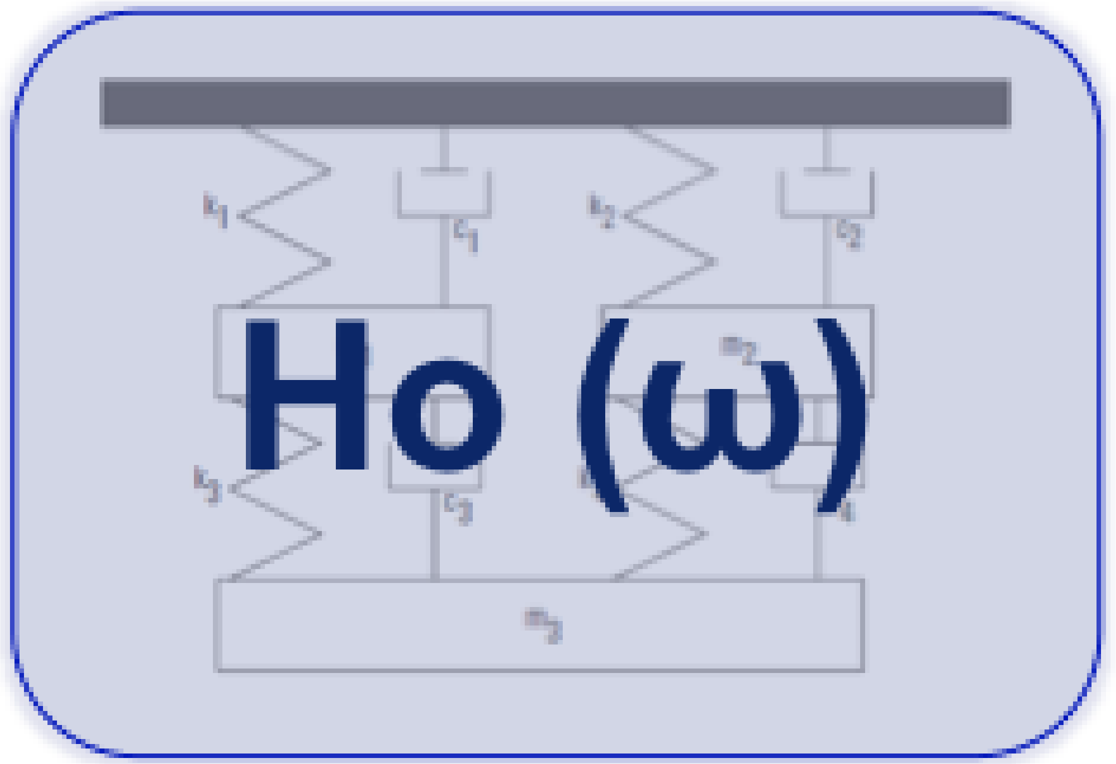
- Continue the measurements (MME Mechanical Laboratory)
- Benchmark with the simulations (MME engineering unit) + Study the vibrational crosstalk between booster and collider in collaboration with Chula University *(Purinut Lersnimitthum).*

→ Simulations of the stability will then be inputs for the LAPP to determine impact on beam optics.

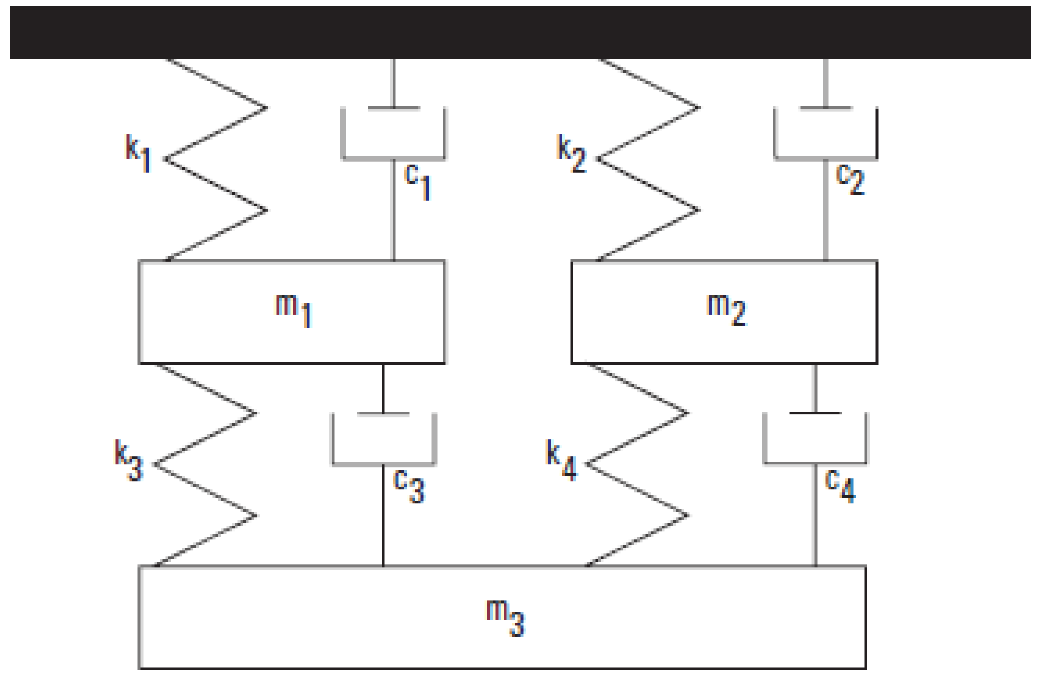
Inputs from FCC's various teams and experts are very welcome!

Thank you for your attention!

Experimental modal analysis



Simulation



$$[m]\{\ddot{x}\} + [c]\{\dot{x}\} + [k]\{x\} = \{f(t)\}$$

$\{\phi\}_r$, r = 1, n modes

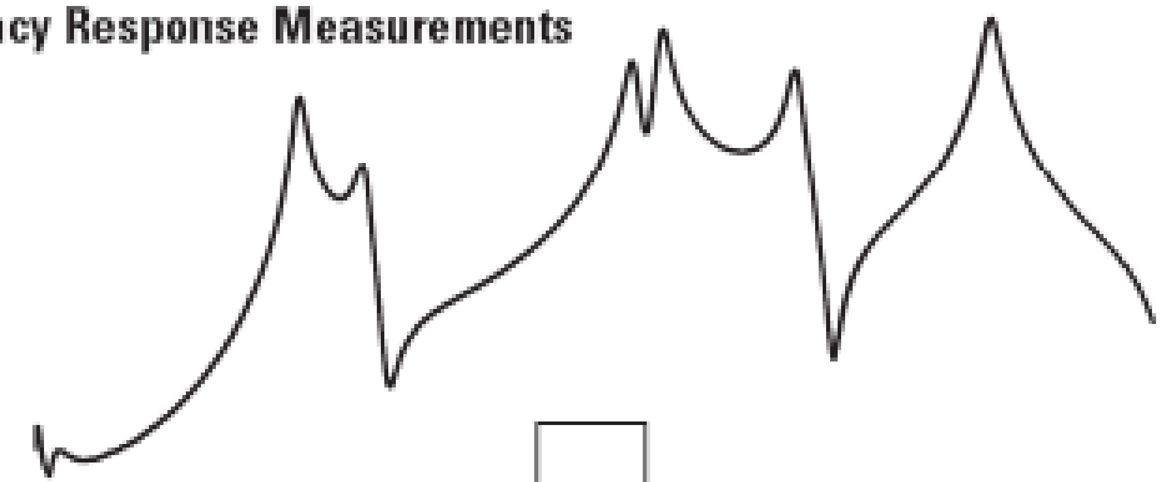
$$\omega_n^2 = \frac{k}{m}, \quad 2\zeta\omega_n = \frac{c}{m} \quad \text{or } \zeta = \frac{c}{\sqrt{2km}}$$

$$s_{1,2} = -\sigma + j\omega_d$$

σ — Damping Rate
ω_ζ — Damped Natural Frequency

Measurements

Frequency Response Measurements



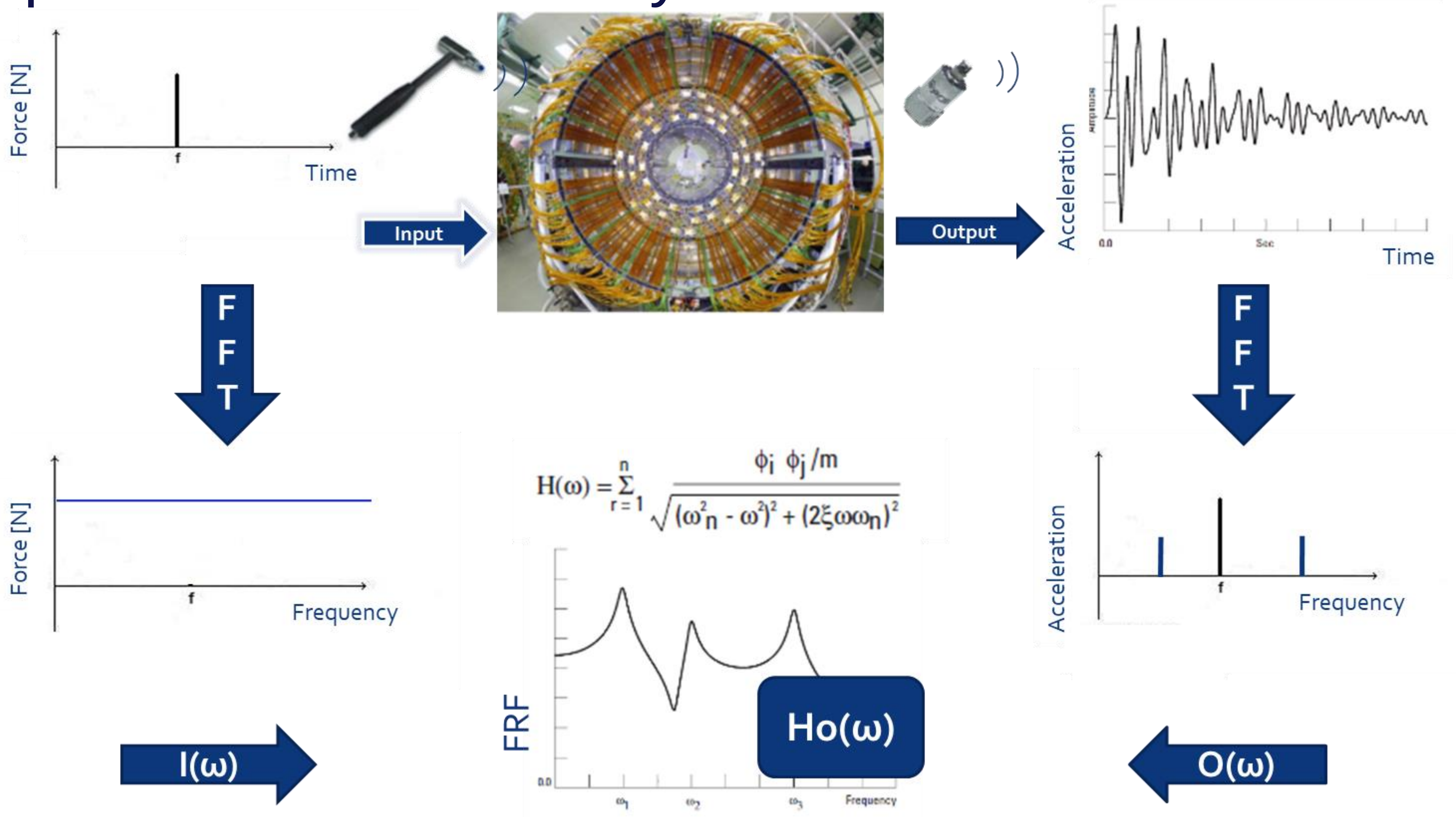
Curve Fit Representation

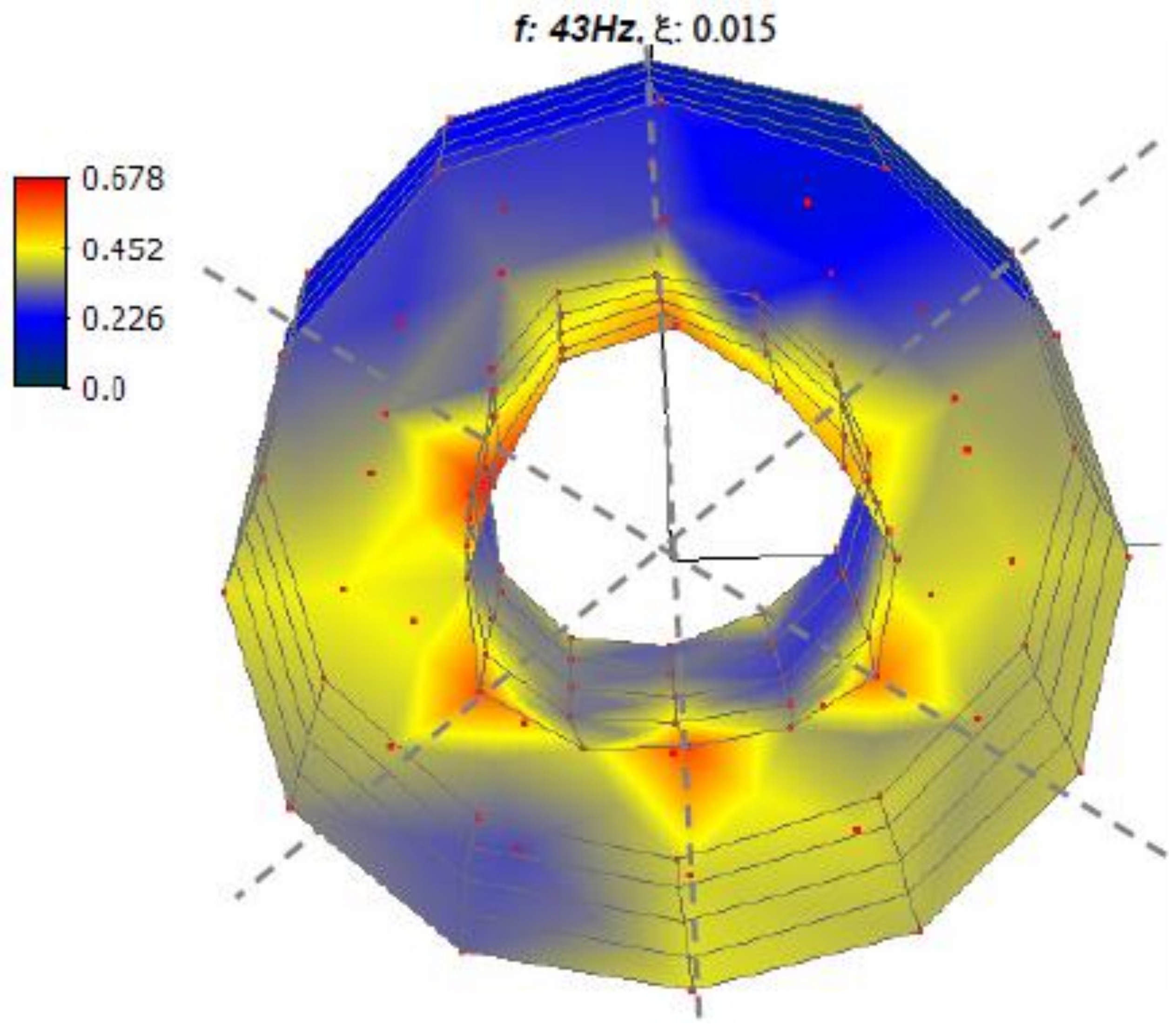
$$H_{ij}(\omega) = \sum_{r=1}^{n} \frac{\phi_{ir}\,\phi_{jr}}{m_r\,(\omega_r^2 - \omega^2 + j2\zeta\omega\omega_r)}$$

Modal Parameters

ω — Frequency
ζ — Damping
$\{\phi\}$ — Mode Shape

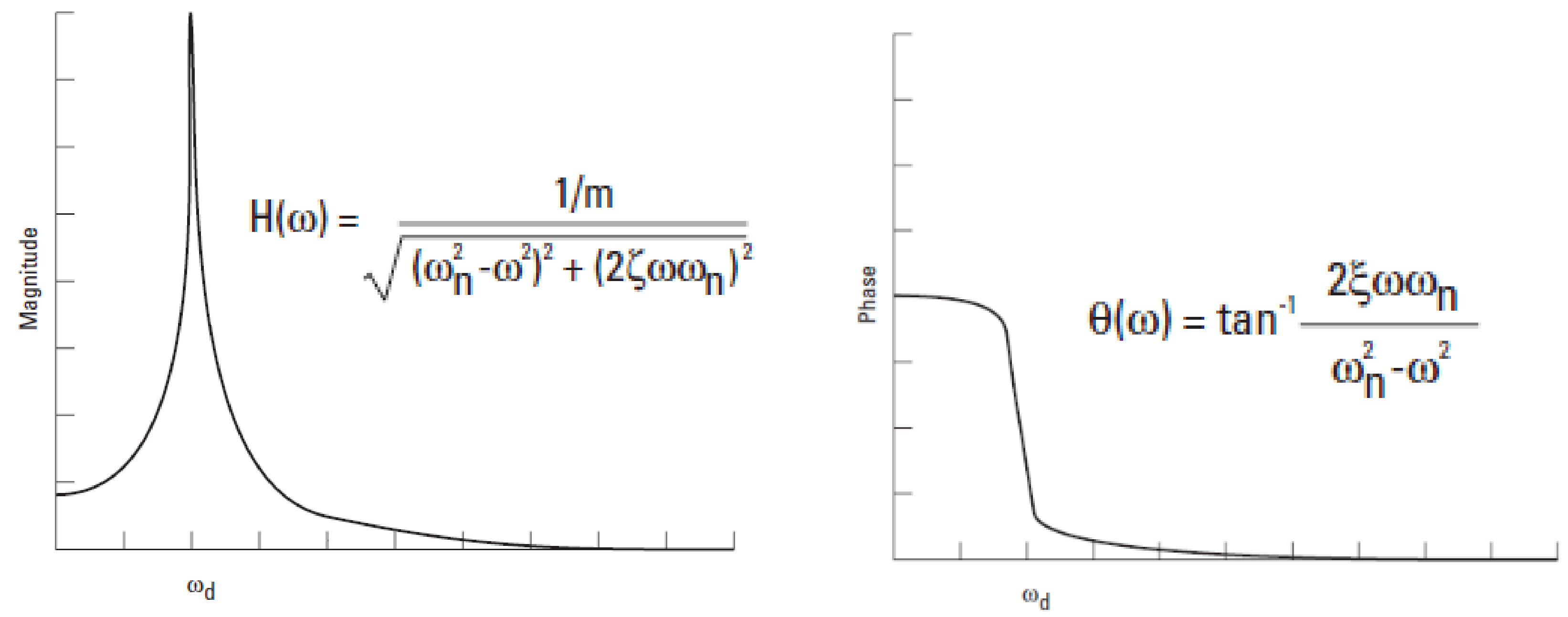
Experimental modal analysis





According to the meshing, from 10 up to few 1000 FRF's are collected

Curve fitting process – Modal parameters such as Natural frequencies, Damping, Mode shapes



Experimental modal analysis of a Quadrupole Prototype - Setup

3D Scanning vibrometer

Model : Polytec PSV500 3D

Acquisition Mode:	FFT
Averaging:	Complex
Averaging Count:	10
Bandwidth:	2.5 kHz
Bandwidth from:	25 Hz
Bandwidth to:	2.5 kHz
FFT Lines:	3200
Overlap:	0 %
Sample Frequency:	6.25 kHz
Sample Time:	1.28 s
Resolution:	781.25 mHz

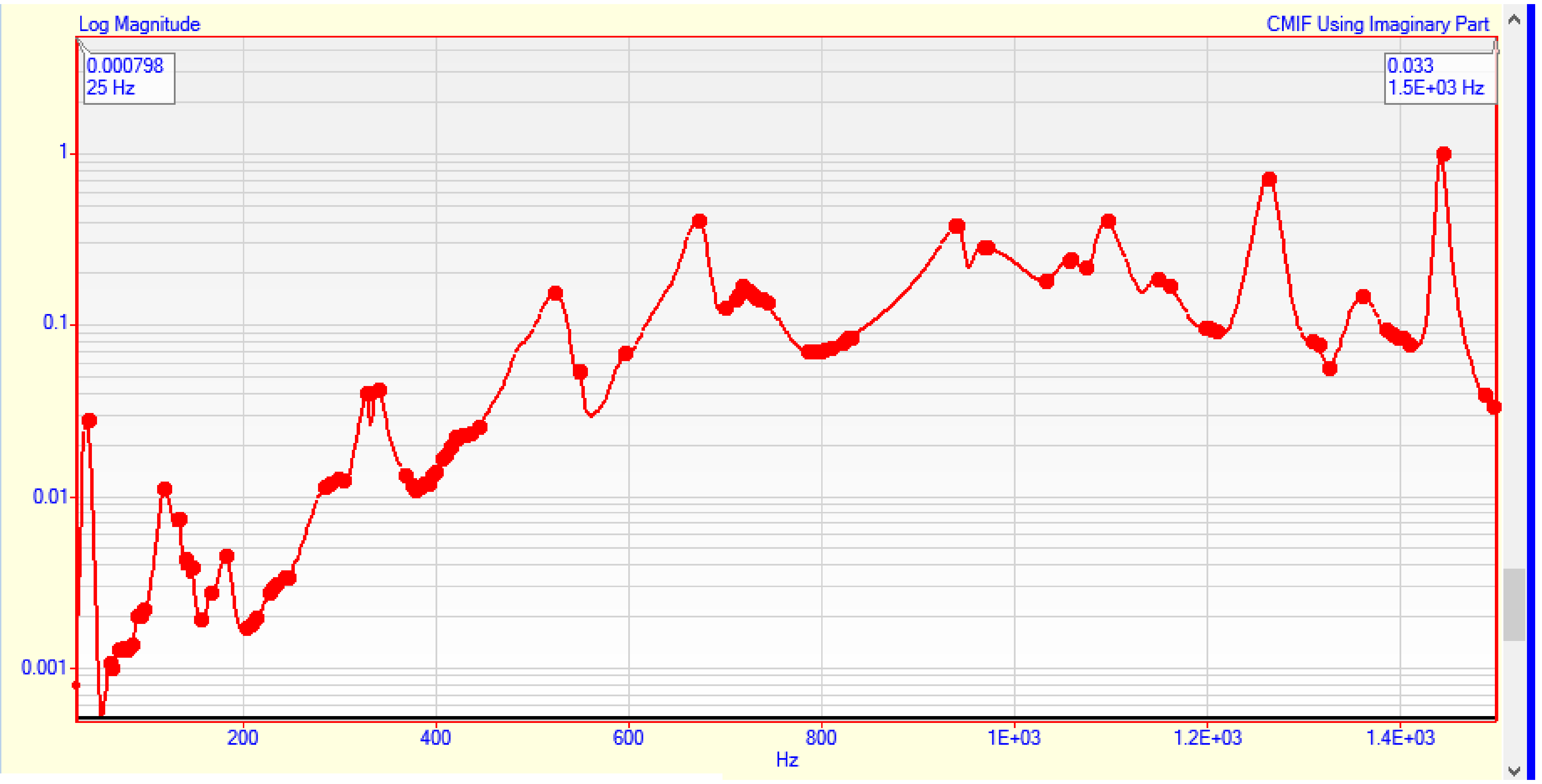
Shaker excitation :

White noise

Accelerometer : 100 (m/s²)/V

Experimental modal analysis of a Quadrupole Prototype - Results

Modes	Frequency (Hz)	Damping (%)	Mode shape identification
S0	6	-	Vertical rigid body mode
S1	37.8	7.08	Lateral rigid body mode
S2	121	4.47	Vertical/lateral rigid body mode
S3	175	0.91	Not identified
S4	330	0.88	Structure mode shape
S5	366	0.19	Structure mode shape
S6	525	2.94	Structure mode shape
S7	662	0.79	Structure mode shape
S8	682	1.12	Structure mode shape
S9	952	1.27	Structure mode shape
S10	1080	1.68	Structure mode shape
S11	1260	1.06	Structure mode shape
S12	1440	0.39	Structure mode shape



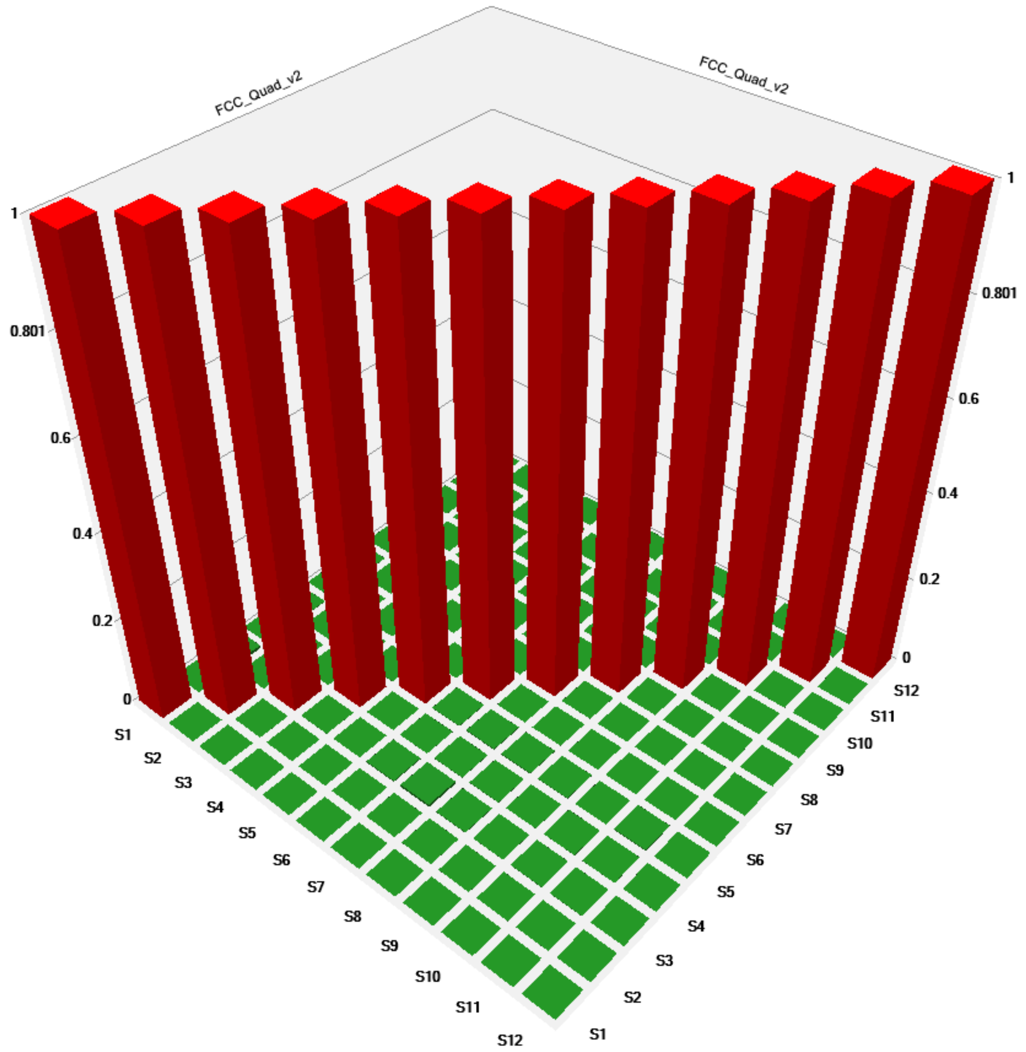
Damping Ratio or Percent of Critical Damping

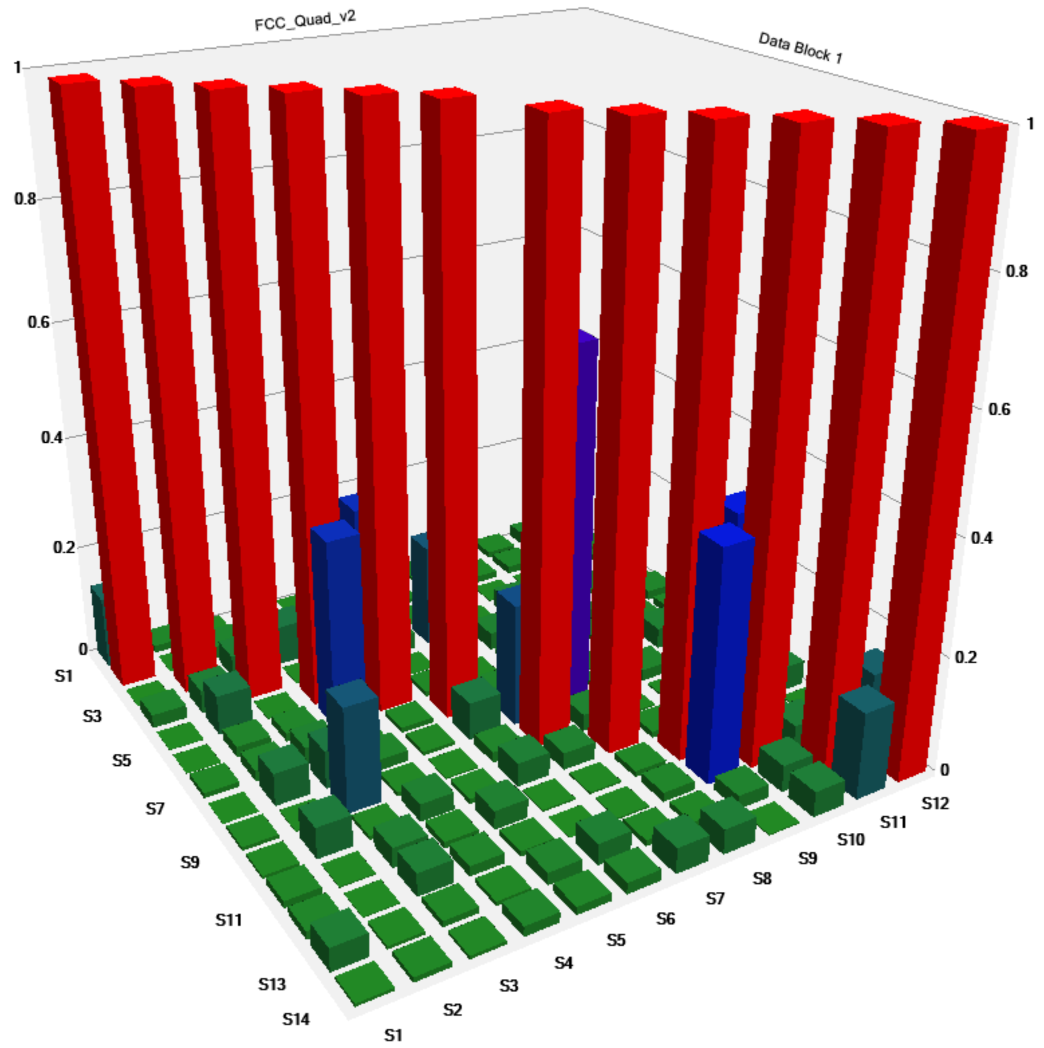
Modal damping is listed as the **damping ratio** or **percent of critical damping** in the **Modal Parameters** spreadsheet

- The *damping ratio* for mode (k) is defined as,

$$\zeta(k) = \frac{\sigma(k)}{\sqrt{\omega(k)^2 + \sigma(k)^2}} \quad (\%)$$

The *width* of the resonance peak in an FRF ***at*** 70.7% ***of its*** magnitude ***at the peak*** is equal to ***twice the damping decay constant.*** The *wide* of a resonance peak is a measure of the damping of a mode. ***The wider the peak, the greater the damping***.



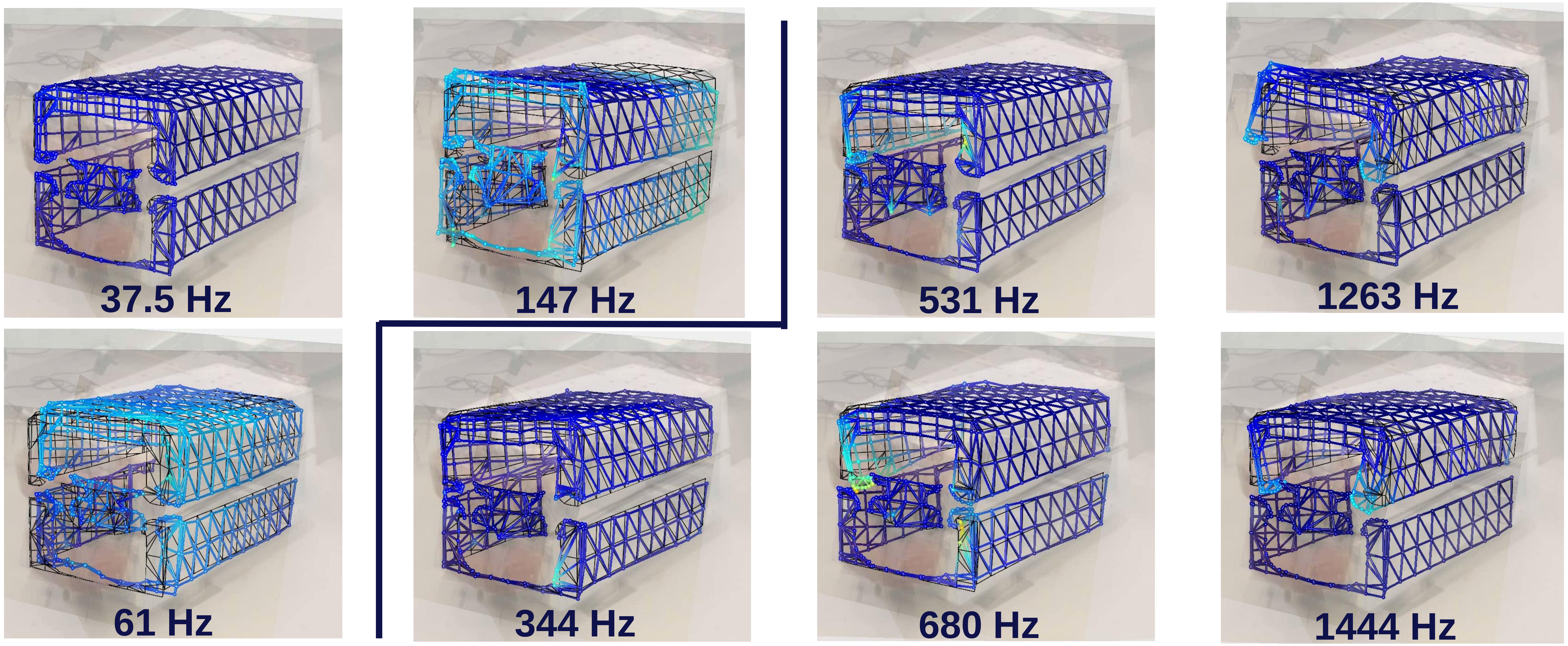


3. Results: experimental modal analysis

M. Guinchard, D. Thuliez

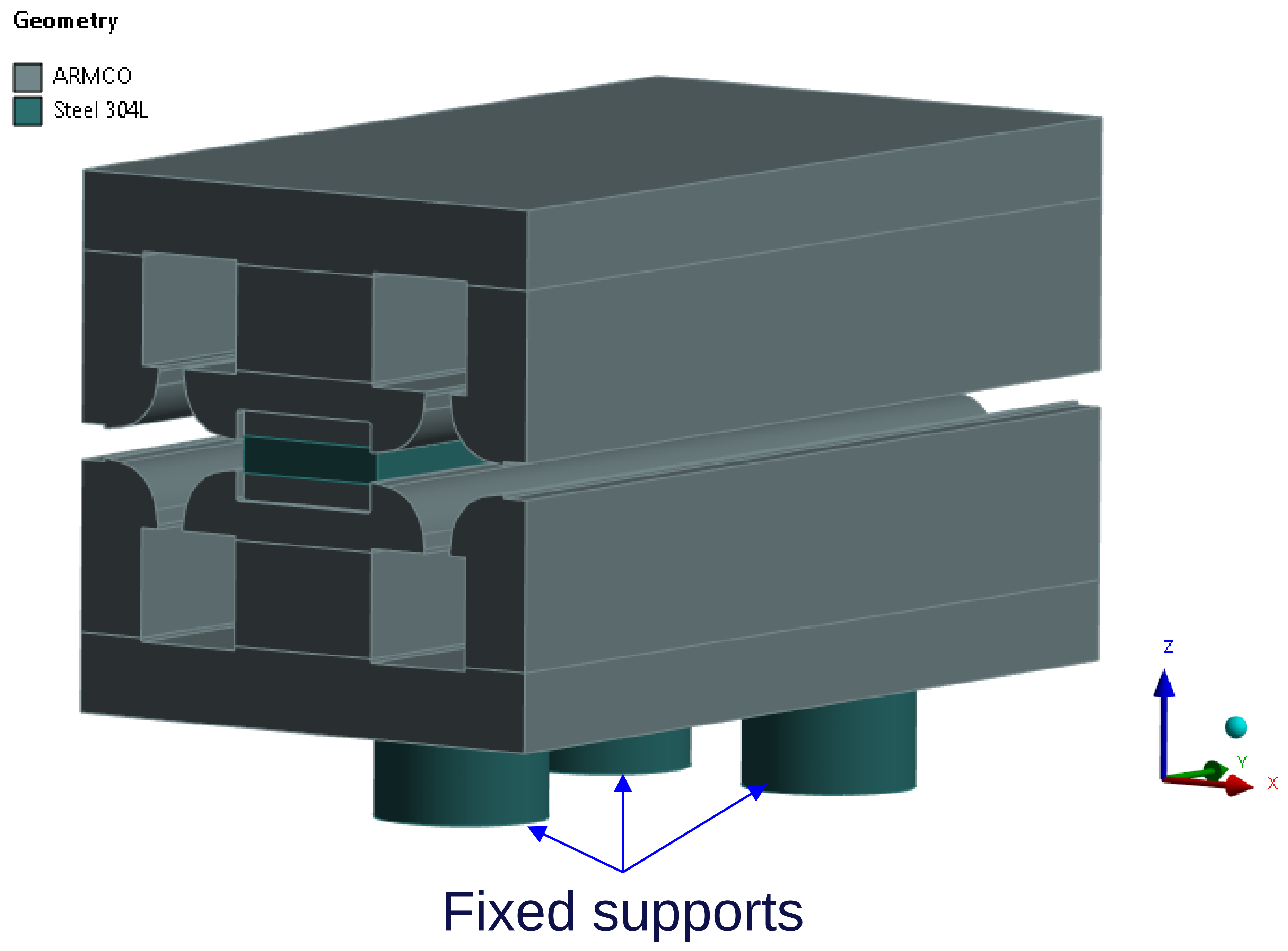
Rigid Body Modes (<200 Hz)

Vertical Rigid Body Mode @ 6 Hz



Structure Mode Shapes

Definition of the model – 1 m long quadrupole



Type of body: SOLID
Material: ARMCO and Steel 304L
Connections: All the contacts are bonded
Loads: Gravity
Boundary conditions: 3 Fixed supports

NB:
Mass of the magnet with the coil: 1500 kg
Mass of the magnet without the coil: 1345 kg
Length: 1000 mm
Cross section: 500x500 mm

Simulation of the coil?

→ NO because
- ➔ Coil bonded to the structure = TOO STIFF
- ➔ Coil with shims = the coil is free to move, which mainly gives the modes of the coil rather than the structure.

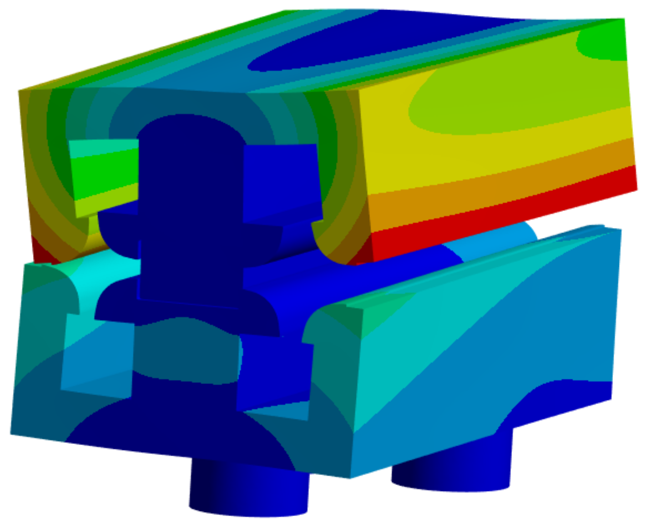
3. Results: experimental vs simulation

Overview of the modal analysis

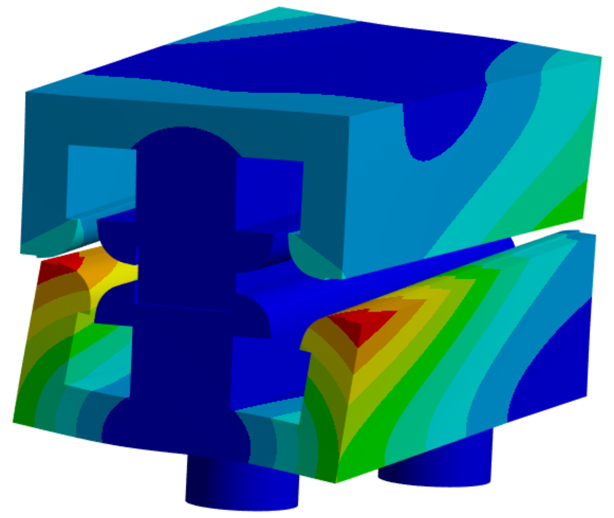
	SIMULATION	EXPERIMENTAL	
Modes	**Frequency (Hz)**	**Frequency (Hz)**	**Mode shape identification**
S0	/	6	Vertical rigid body mode
S0bis	/	37.8	Lateral rigid body mode
S0tris	/	121	Vertical/lateral rigid body mode
S1	187	175	Not identified
S2	308	330	Structure mode shape
S3	363	366	Structure mode shape
S4	460	/	/
S5	539	525	Structure mode shape
S6	597	/	/
S7	614	/	/
S8	652	662	Structure mode shape
S9	682	682	Structure mode shape
S10	780	/	/
S11	810	/	/
S12	867	/	/
S13	973	952	Structure mode shape
S14	1037	1080	Structure mode shape
S15	1151	/	/
S16	1277	1260	Structure mode shape
S17	1314	/	/
S18	1332	/	/
S19	1349	/	/
S20	1418	/	/
S21	1454	1440	Structure mode shape

Mode shapes not found by experience

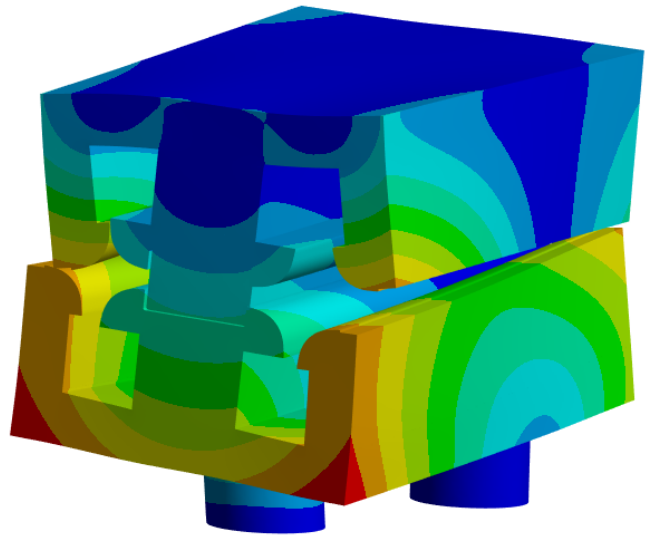
S4 – 460 Hz



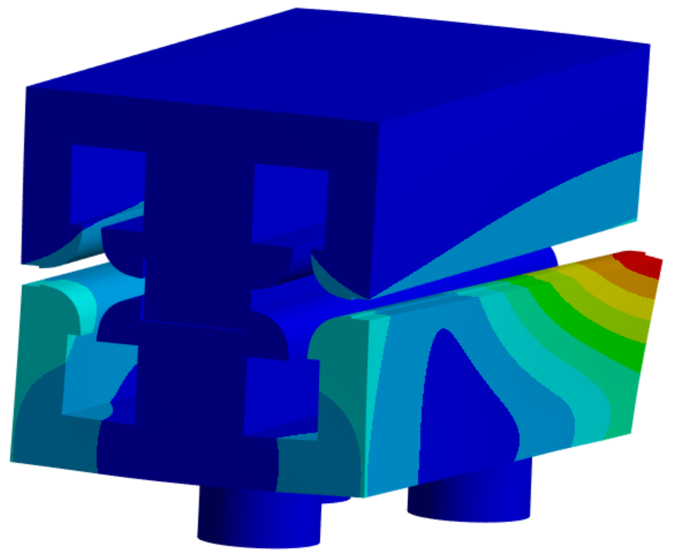
S6 – 597 Hz



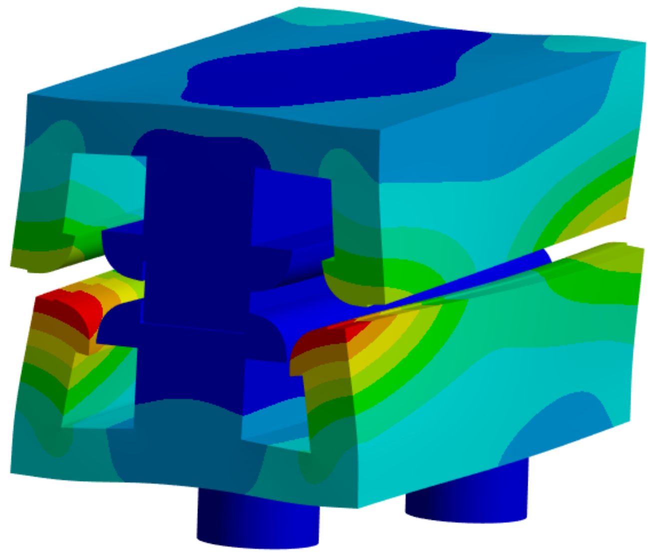
S11 – 810 Hz



S12 – 867 Hz



S18 – 1332 Hz



S19 – 1349 Hz