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Vibrational study of the booster and collider supporting system

E. Bernard, F. Carra, M. Guinchard, A. Piccini, G. Roy, O. Sacristan de Frutos, D. Thuliez, M. Timmins, J. Wenninger
CERN, Geneva, Switzerland

Abstract

The FCC-ee arc half-cell mock-up project team is currently developing a **Short Straight Section** (SSS) demonstrator, combining **experimental measurements and simulations** to evaluate the **vibrational budget** of various elements including the feet, the supports, the magnets, etc. The results of this study have shown that **vibrations will have a non-negligible effect on the stability** of the magnet's magnetic center, and consequently on the stability of the particle beam.

Context and Historical Background

The **effect of vibrations** on particle accelerators is **detrimental** for performance and beam stability. The oscillations of SSS along the quadrupole axis must be minimized through **proper design and material choices**, especially for supporting elements.

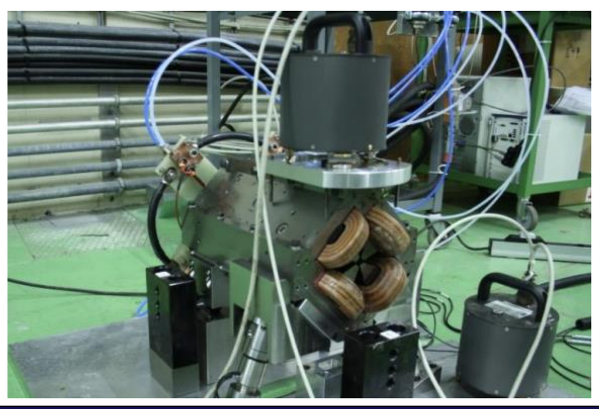
CLIC

[1]

Acceptable displacements at the quad axis:

- Vertical integrated RMS at 1 Hz: **1 nm**
- Lateral integrated RMS at 1 Hz: **5 nm**

Achieved with **active stabilization with piezo-actuators** and stiff design over short lengths.



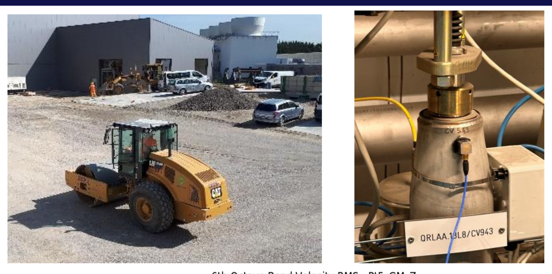
[1] https://edms.cern.ch/document/1173340/1

HL-LHC

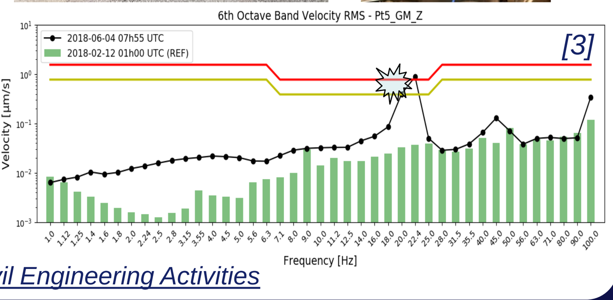
Experimental observations at the quad axis:

- Standard operation: **< 5 µm** at 1 Hz
- Beam instabilities: between **5** and **20 µm** at 1 Hz
- Beam dumping: **> 20 µm** at 1 Hz

Civil engineering works and malfunctioning of systems in the tunnel occasionally lead to instabilities and beam dump.



[2]



[3]

[2] https://edms.cern.ch/document/3057091/1
[3] Investigation and Estimation of the LHC Magnet Vibrations Induced by HL-LHC Civil Engineering Activities

FCC-ee

The specifications for the collider and the booster will be developed by CERN BE-ABP colleagues.

Preliminary discussions with J. Wenninger to estimate the order of magnitude: expected to be more relaxed than CLIC, but tighter than HL-LHC.

Initial tentative estimation - arcs

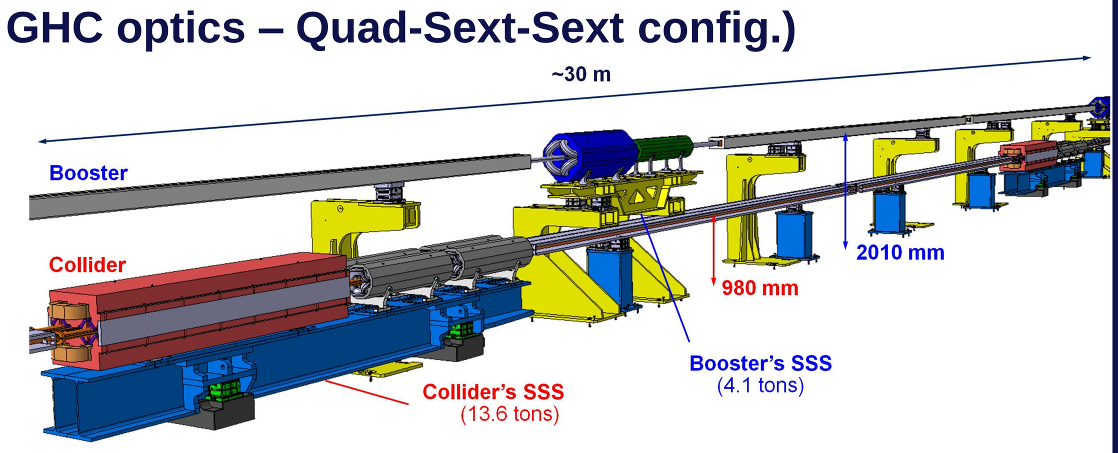
Tolerance at 1 Hz frequency	
Collider vertical direction	20 nm
Collider lateral direction	200 nm
Booster vertical direction	40 nm
Booster lateral direction	400 nm

FCC-ee Arcs: Configuration & Stability

In the FCC-ee arcs, booster and collider are superposed: best for integration but challenging for stability (big lever arm for booster!). Ground vibrations are **amplified by support system eigenmodes**, so supports must be **carefully designed**.

FCC-ee arcs (H, $t\bar{t}$ – GHC optics – Quad-Sext-Sext config.)

- **77 km of arcs:**
  - 6.000 girders
  - 40.000 pillars,
  - 24.000 supports
  - 68.000 jacks
- **Active stabilization** systems too expensive
- Compromise to be found between **stability performance and cost**



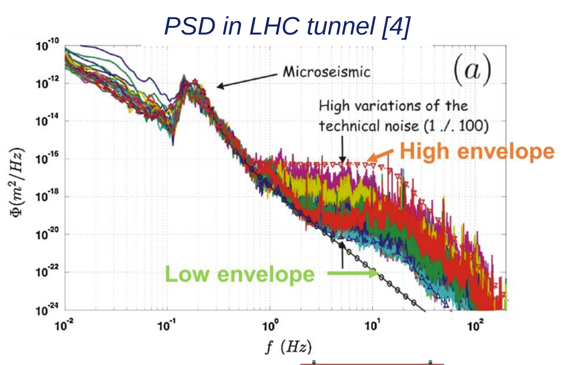
Dynamic stability evaluation method

Requires combination of experimental and numerical techniques.

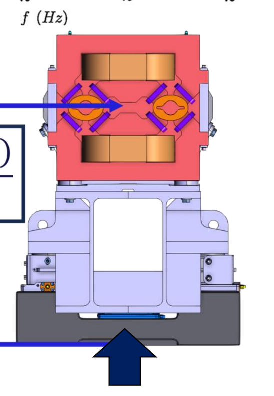
To evaluate the effect of "natural" vibrations coming from the tunnel ground motion:

1. Start with an **input PSD** (*e.g.* HL-LHC data, or "quiet" surface environment)
2. Evaluate the **vibration amplification up to the magnetic axis** via:
   - **Simulations** (Random Vibration Analysis)
   - **Measurements** (Laser-Doppler Vibrometer or accelerometers on an **SSS demonstrator**)
3. Compare with **stability specifications**

PSD in LHC tunnel [4]



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



Ground motion spectrum

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

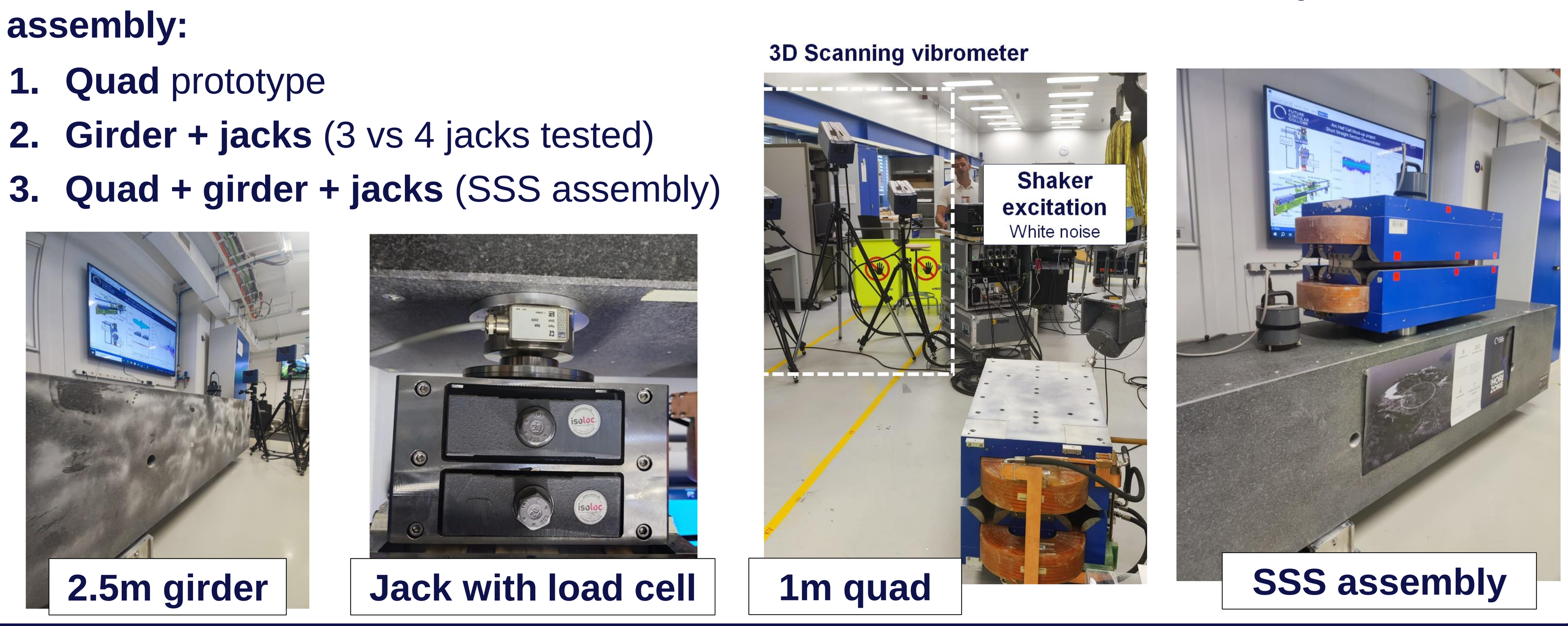
Experimental Campaign

An **SSS demonstrator** was built and installed in b.376 at CERN, based on a 2.5m-long girder equipped with jacks and a 1m quadrupole prototype. Its dynamic behaviour was **experimentally measured** and benchmarked by numerical simulations.

Experimental set-up

The SSS demonstrator main elements were first measured individually, then as an assembly:

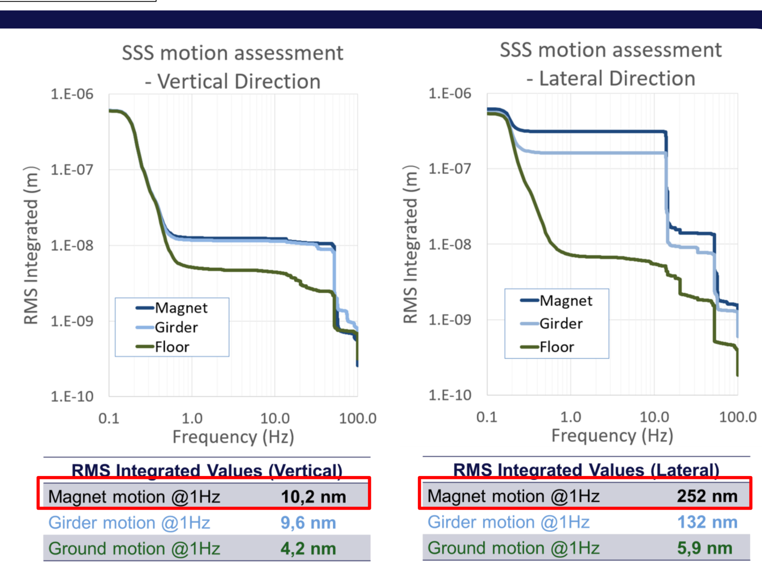
1. **Quad** prototype
2. **Girder + jacks** (3 vs 4 jacks tested)
3. **Quad + girder + jacks** (SSS assembly)

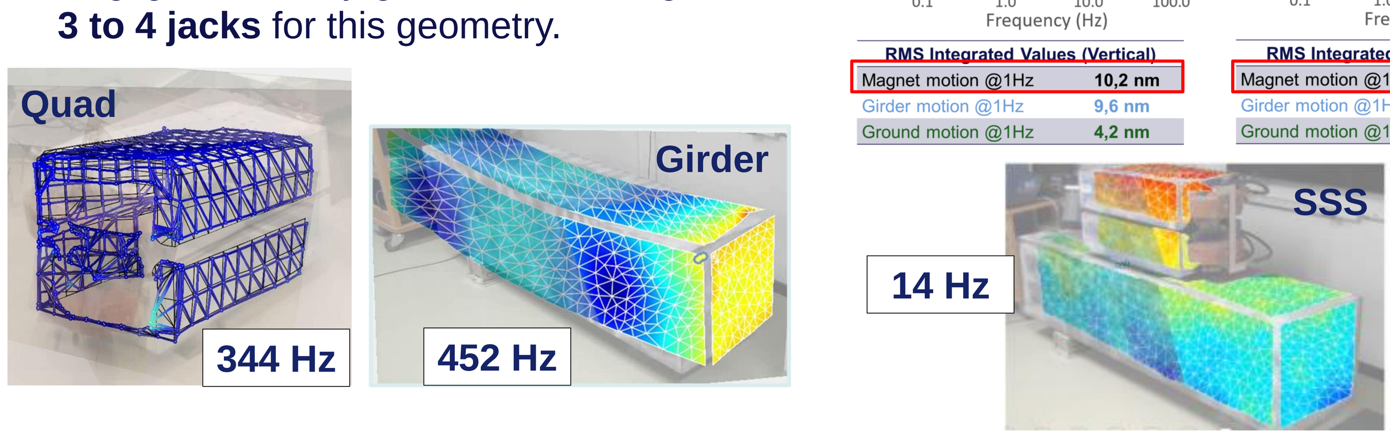


Experimental results

Key observations:

- Magnet is **stiff** (1st natural mode > **300 Hz**)
- Girder is **stiff** (1st bending mode > **400 Hz**)
- Jacks are the **weak elements** (SSS 1st eigenfrequency = **14 Hz** / rigid body mode)
- Negligible stability gain when moving **from 3 to 4 jacks** for this geometry.





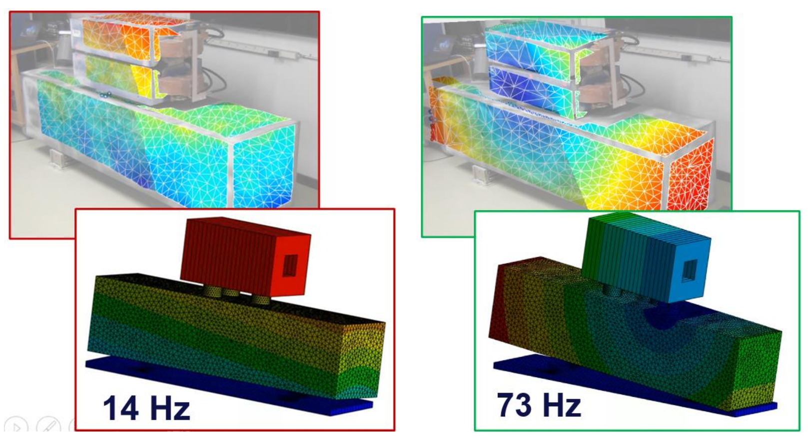
Numerical Models & Results

The numerical model depends on **several parameters** (friction, damping, boundaries, etc.) that **are tuned** based on the experimental measurements. Once the model is tuned, it **can be upsized** to the real scale of the FCC-ee SSS (6m).

Numerical results

Numerical simulations are performed with ANSYS, Modal Response & Random Vibration Analysis modules.

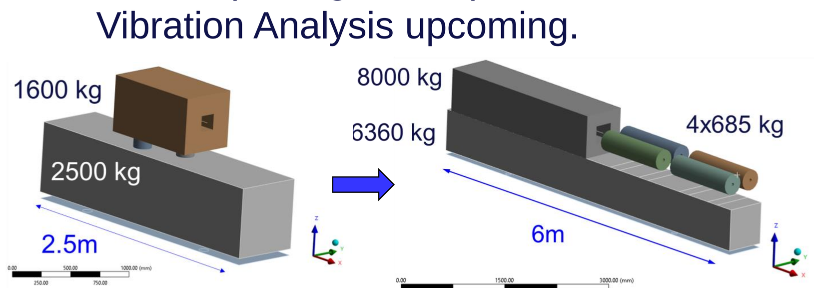
- **Very good benchmarking** between experimental and numerical SSS results



Mode shape	3 PSI jacks + Prototype Quadrupole	
	EXP	SIMU
Tilting around X	14.0 Hz	13.6 Hz
Tilting around Z	43.7 Hz	34.2 Hz
Up and Down	52.5 Hz	55.1 Hz
Up and Down + Tilting Y	73.1 Hz	76.7 Hz
Twist around X	105.0 Hz	/

Numerical model upsizing to 6m

- Modal upsizing is completed, Random Vibration Analysis upcoming.



	Nº Mode	FREQUENCY [Hz]		
		2.5m granite girder + 3 PSI jacks	6m granite girder + 3 PSI jacks	6m granite girder + 3 PSI jacks + magnets
Rigid body modes	1	22.7	14.0	6.0
	2	37.5	20.1	11.7
	3	40.7	27.2	16.0
	4	65.6	41.4	26.1
	5	69.3	44.3	29.3
	6	90.6	57.4	32.1
Natural freq.	7	448.3	89.3	58.4
	8	457.6	91.6	61.4

Conclusions

The FCC-ee regular arcs will include more than **100.000 supporting elements.** Their design must be **optimized for dynamic stability while reducing costs**. The experimental / numerical campaign has shown that the SSS vibration response **depends mainly on supports**, as the current magnet is sufficiently stiff. So far, **only ground-induced vibrations** have been measured, but adding forced excitations (water/air cooling, motorized systems, etc.) will likely **exceed tolerance limits**. Stability will be **even harder to achieve for the booster** due to its higher vertical position. During the Pre-TDR phase, studies of the short SSS demonstrator will continue and studies of full-length collider and booster SSS will begin in the 1:1 scale arc half cell mock-up at CERN b. 355.

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