Stability and vibration control for High Energy Photon Source in China

YAN Fang on behalf of ground motion system of HEPS

2023.11.10

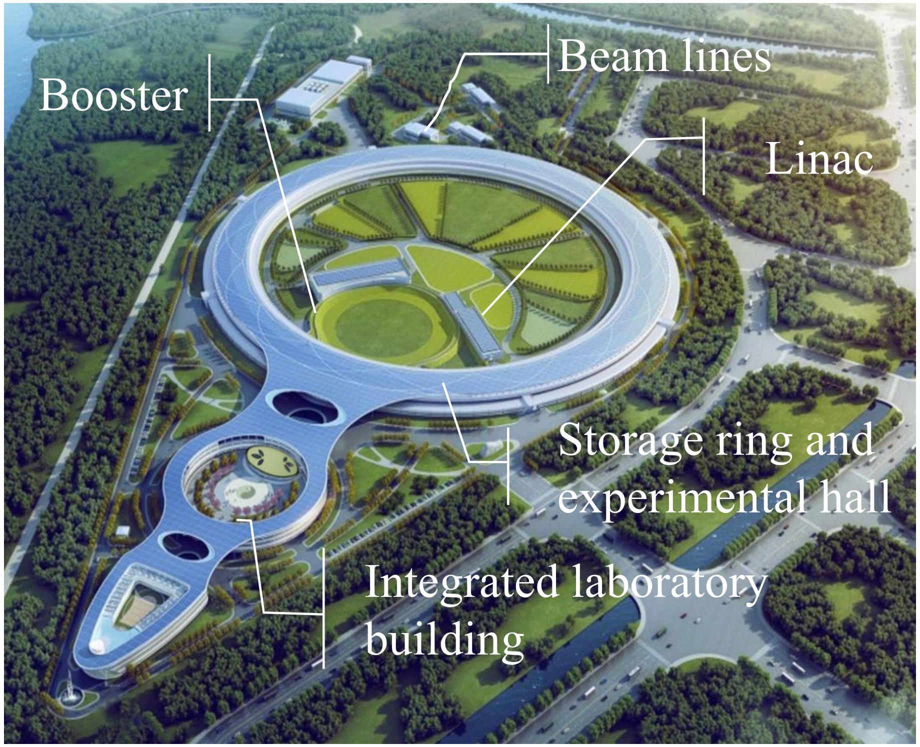
Outline

- Introduction
- Beam dynamics model for ground motion simulations
- Stability specifications
- Actual stability controlling effect
- Summary

Introduction

High Energy Photo Source (HEPS)

Location	:	Huairou
Energy	:	6 GeV
Natural emit.	:	34 pm.rad
Circumference	:	1360.4 m
Beam current	:	200 mA
Lattice design	:	48 7BAs
Phase I	:	14 beam lines



Duration	:	6.5 year（2019/7-2025/12）
Luminosity	:	$>1\times10^{22}$ photos/s/mm^2/mrad^2/0.1%BW

Introduction

Sub-micro beam stability requirement

Minimum expected beam size/divergence in IDs and bending magnet sources

assume a vertical emittance ~ 5 pm, diffraction limit for 20 keV photon

lattices	σ_x (μm)		σ_{px} (μrad)		σ_y (μm)		σ_{py} (μrad)	
	straight section	BM sources	straight section	BM sources	straight section	BM sources	straight section	BM sources
T3_P24_33pm	9.3	5.2	1.72	8.61	**3.2**	5.1	**0.7**	1.1

Beam stability requirements:

- in the frequency range 1 Hz ~ 100 Hz, rms beam position & angular motion < 10% beam size / divergence in both planes for undulators and vertical plane for bending magnet sources. Some critical reference values for the final lattice design are:

$\sigma_{\Delta x}$<1μm $\sigma_{\Delta px}$<0.2μrad

$\sigma_{\Delta y}$<0.3μm $\sigma_{\Delta py}$<0.1μrad

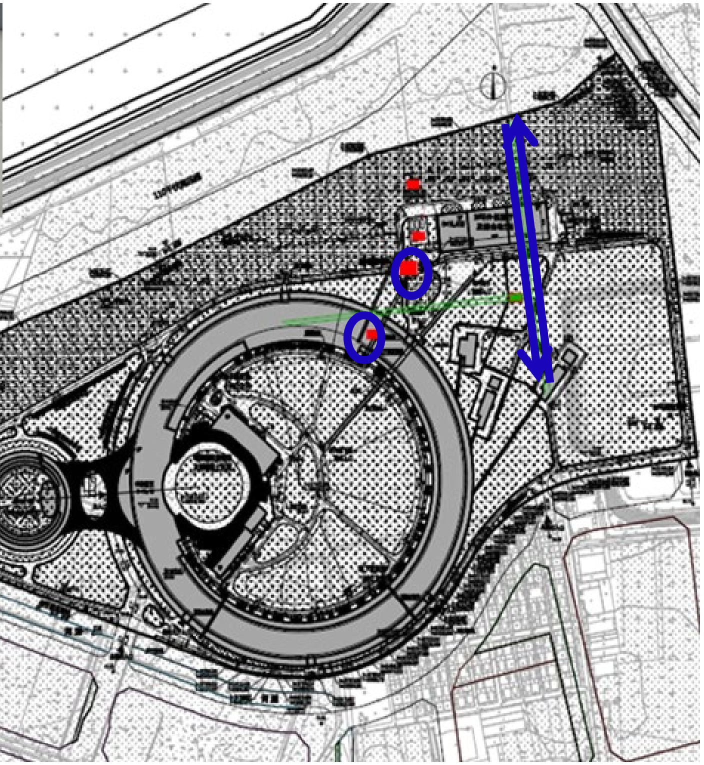
Courtesy of Z. Duan

Introduction

Vibration levels measurement on bare ground of HEPS site

- Time: <u>2019.4.18~2019.4.29</u> (a week)
- Vibration source: traffic on a civil road inside the HEPS site (closed now).
- Seismometer positions:
  - ✓ One sensor is on the ground closer to the road.
  - ✓ Another sensor is on the ground of HEPS Storage Ring close by.

Seismometer	Frequency Ranges	Sensitivity
3espcde	0.017~100Hz	2000V/m/s



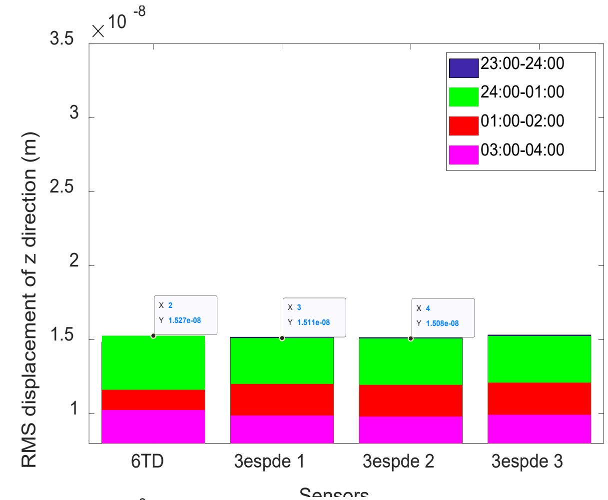
Introduction

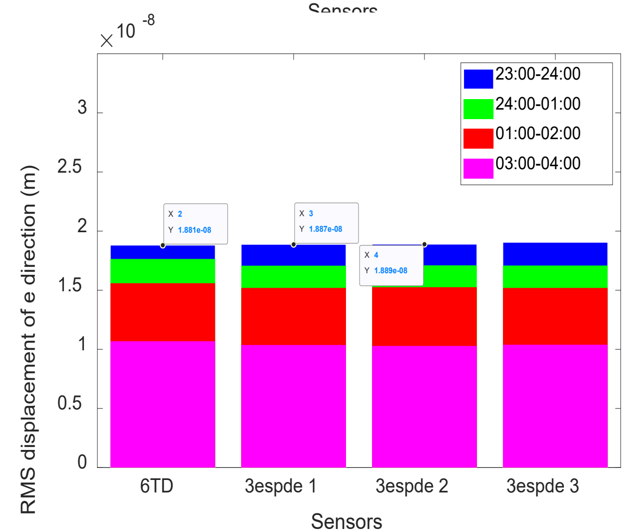
Consistency of the seismometers

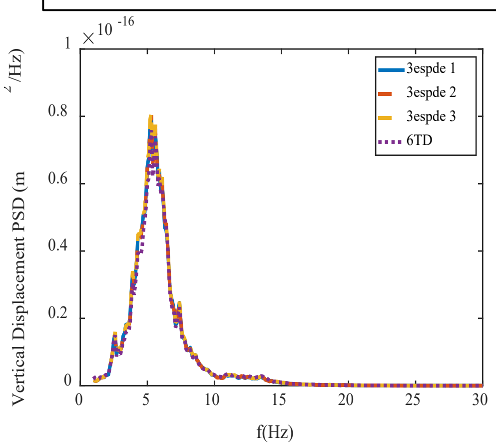
Instrument: 3/3espcdes and 1/6TD:

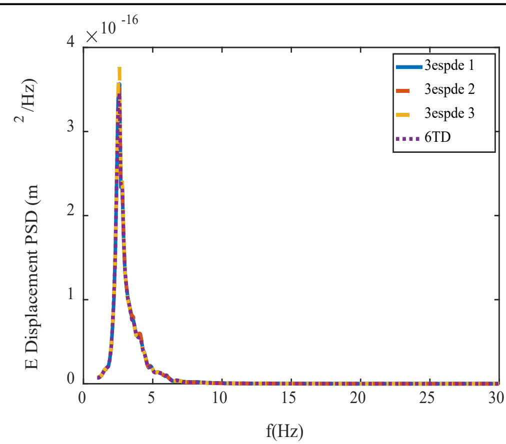
- Four hours data were taken from midnight 23:00 to 3 o'clock of the next day;
- Comparing RMS & PSD of each hour with frequency resolution of 0.1Hz

Conclusion: the distinguish of the displacement RMS integral over 1-100Hz for the seismometers in use is smaller than 1nm.





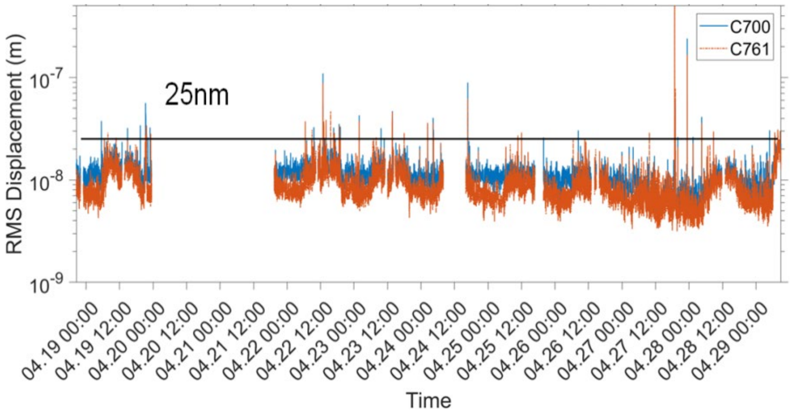


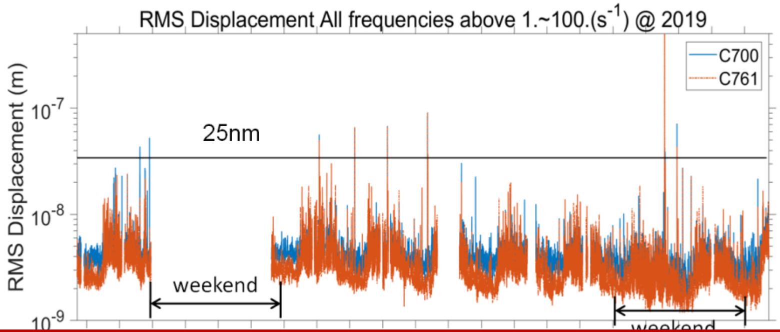


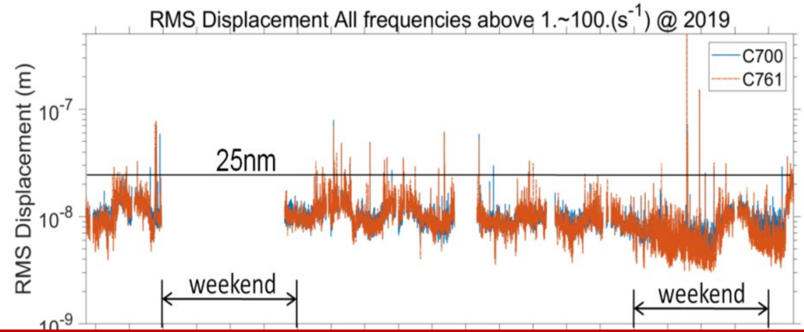
Introduction

Vibration levels measurement on bare ground of HEPS site

- **0.1Hz frequency resolution, RMS of every 1 minute.**
- The ground motion shows clearly day and night shift.
- Horizontal vibrations are bigger than vertical direction.
- During night, the motion on ground is ~4/10nm(z/x) .
- During day time, it is about 10/20nm (z/x).
- Most of the time, the green field vibration is smaller than 25nm, the sparks mainly caused by the traffic on the civil road is under control.



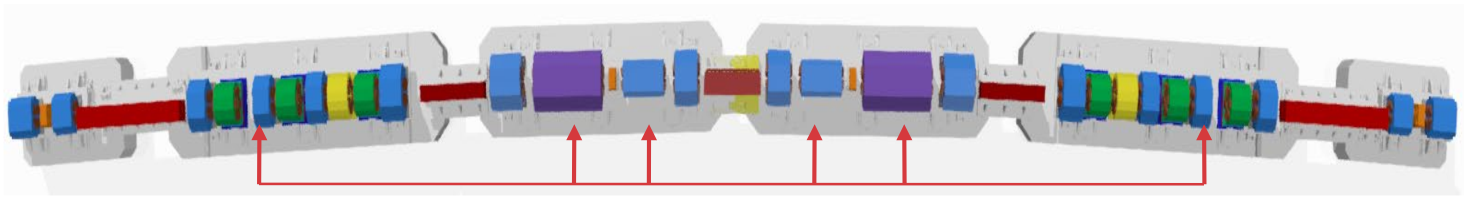




Worthy to mention that, besides the frequency range, the frequency resolution and the time span used during the displacement RMS calculation are also important to be specifed. As the RMS integral are different for averaging in different time span.

Beam dynamics models

Frequency unrelated model

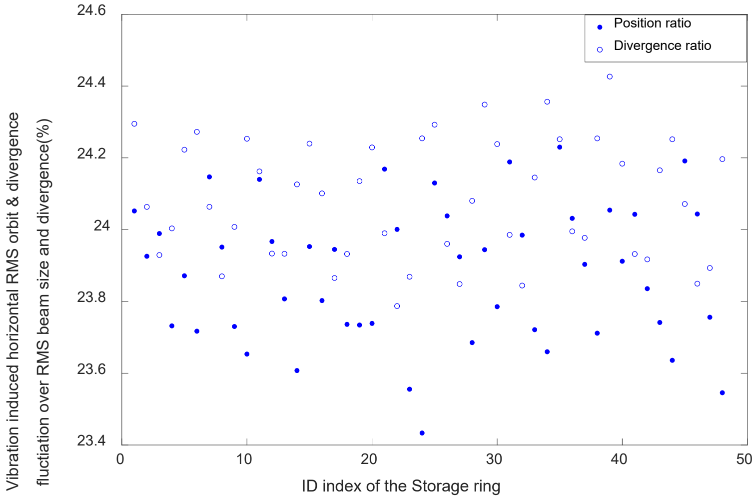


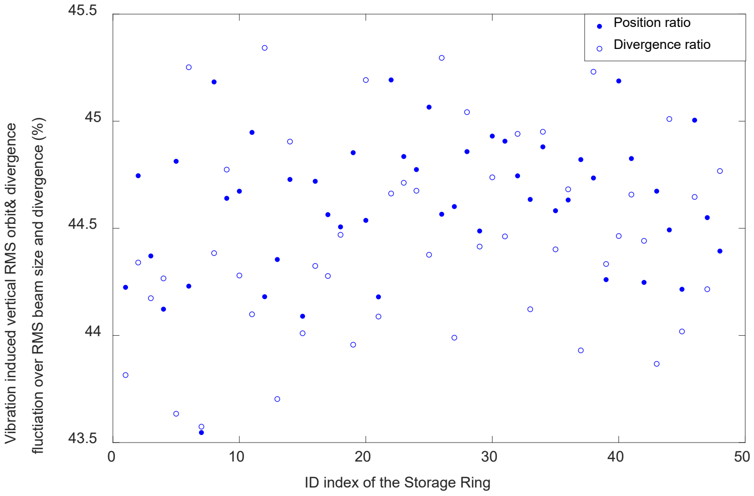
Dipole-quadrupole combined magnet

- Firstly we use the frequency unrelated model for vibration simulation;
- Vibrations are introduced into quadrupoles (blue) and dipole-quad. combined magnet (purple and part of the blue) **randomly**;
- With displacement RMS integral of 25nm over freq. range of 1-100Hz;
- RMS beam orbit fluctuations are obtained over 5000 times run;
- Ratios of RMS orbit fluctuation over RMS beam size and RMS beam divergence at ID positions are obtained.

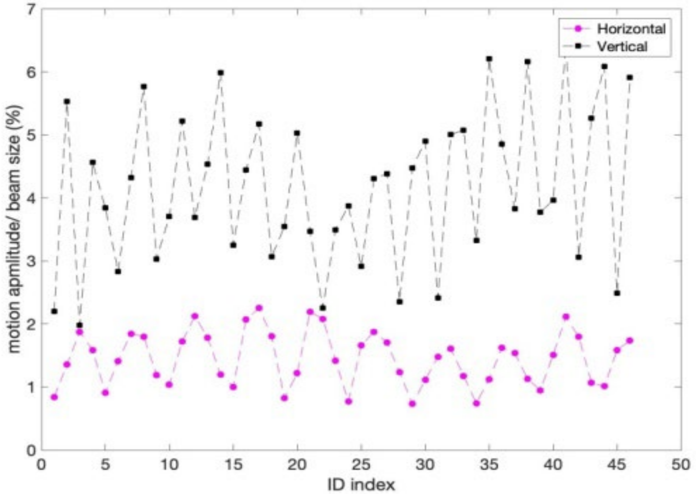
Beam dynamics models

Frequency unrelated model





According to simulation results, the beam fluctuation is bigger than 10% of the RMS beam size & divergence without FOFB but smaller than 10% with FOFB with 25nm random vibrations introduced in.



Beam dynamics models

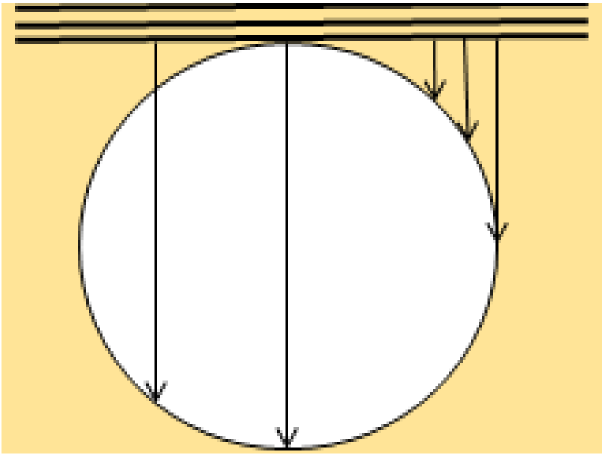
Frequency related model

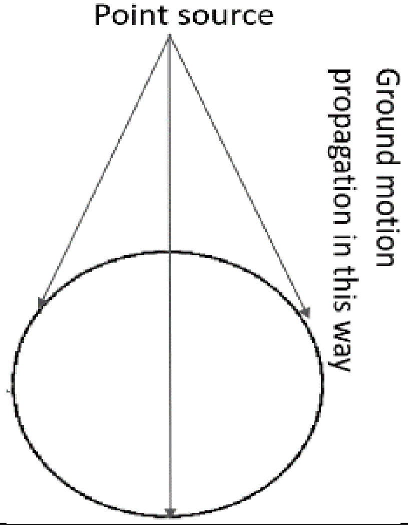
- Although the above-mentioned analysis approaches are widely used for ground motion simulations for many worldwide photo sources;
- The vibrations induced beam orbit and angular fluctuation are closely related with frequencies especially for frequencies of few Hz;
- In the meanwhile vibrations on ground are mainly dominated by low frequencies;
- So that, ground motion analysis models related with frequency are quite essential.

Beam dynamics models

Frequency related model

- According to different vibration types, two different models can be used for ground motion analysis related with frequency;
- Microtremors normally transported from a long distance propagates as a plane wave and the motion levels are almost the same everywhere at the site (the decay is not considered);
- The source of the noises located nearby the photo source and propagate as a point source (decay can not be neglected):





Beam dynamics models

Frequency related model

- The vibrations at each position are a superposition of a series oscillating waves with different frequencies;
- While beam transporting through each element of the lattice, all the vibrations induced by noises with different frequencies added up together, leading to fluctuations of the beam orbit at this element;
- The displacement on each element of the storage ring induced by noise with single frequency follows the formula as below:

$$X_f = A_f \times \mathrm{d(f,r)} \times \cos\left(\mathrm{wt} + \varphi_f\right)$$

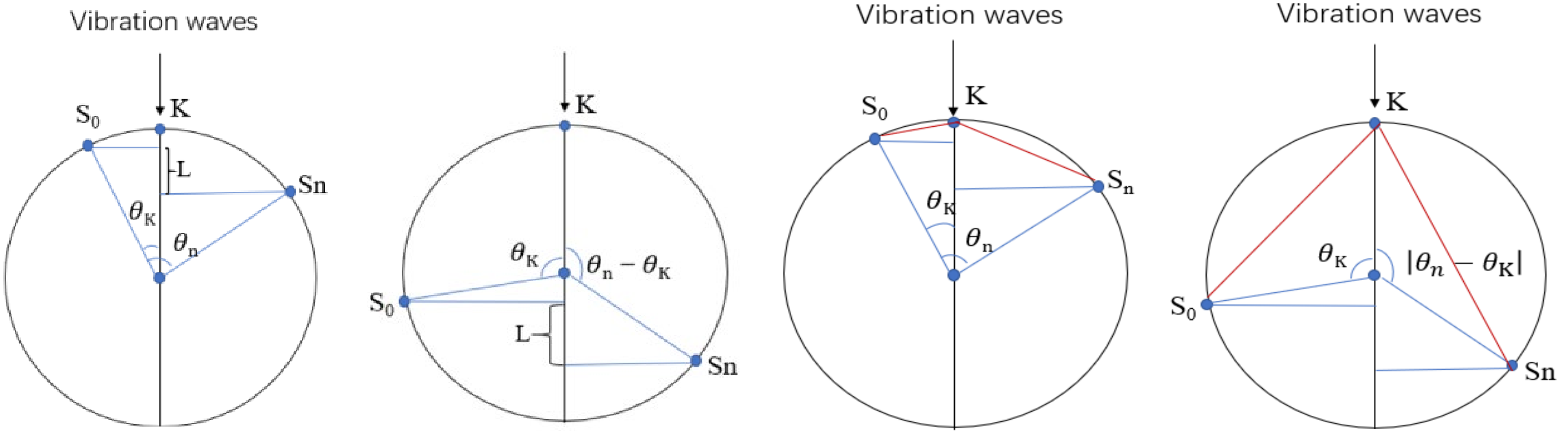
$$\mathrm{t} = \mathrm{t1} + \mathrm{t2} = \frac{L}{V_g} + \frac{S}{c}$$

Beam dynamics model

Frequency related model

• The relative displacement of each element on storage ring is mainly determined by the distance difference from vibration source to each element;

• The calculation of relative displacement between each element differs for different model, but they all satisfy certain triangular relationship:



$1/f^2$

Beam dynamics models

Frequency related model

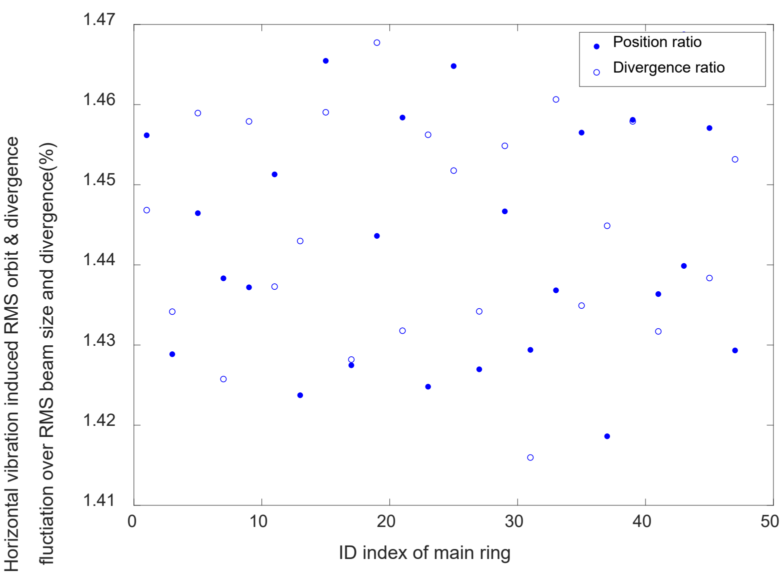
- Assuming the displacement amplitude of the motions are inversely proportional to the vibration frequency, Setting the amplitude of the motion at 1Hz and all the amplitude of motions with other frequencies can be scaled by 1/f to ensure 25nm RMS integral;
- Assuming vibrations with diff. freq. distributed randomly on the SR, and vibration with same freq. all comes from one position;
- The displacement RMS is calculated according to vibration amplitude of each frequency using the formula below:

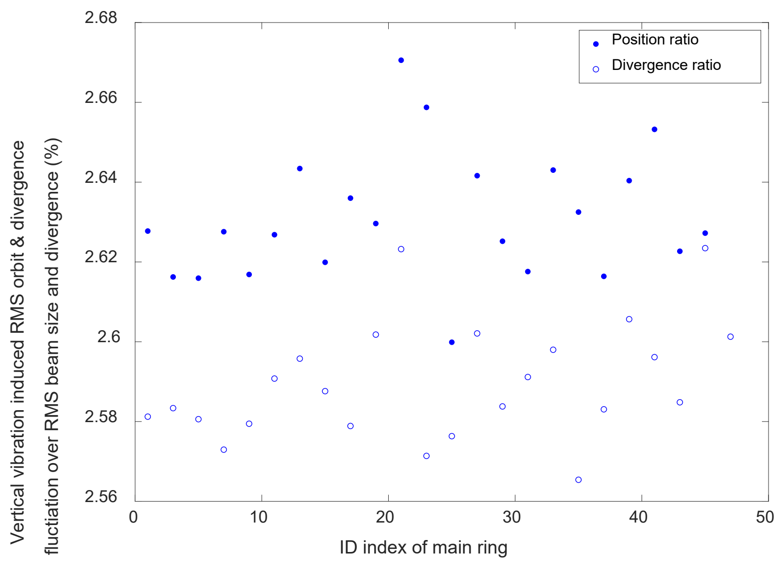
$$RMS = \sqrt{\left[\frac{A_0^2}{2} + \sum_{i=1}^{K-1} A_i^2 + \frac{A_k^2}{2}\right]}$$

Beam dynamics model

Frequency related model

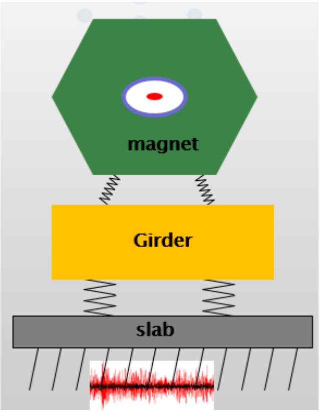
According to simulation results, the beam fluctuation is smaller than 10% of the RMS beam size & divergence without FOFB with 25nm vibrations introduced in the lattice using frequency related model (plane wave model).





Stability specifications

- For stability controlling, the most important thing is site selection, what to do next is keeping the bare ground motion not amplified through slab and girder;
- The HEPS green field vibrations are below 25nm in all three directions under the condition that no civil road is inside HEPS area;
- The vibration tolerance for the floor motion is set to be 25nm for RMS displacement integration over frequency of $\boxed{\text{1Hz\textasciitilde 100Hz;}}$
- To ensure fulfilling of the final vibration target on critical slabs, the 25nm limitation is further decomposed to three specifications according to the propagation path of the motion waves:
  - Besides the ground motion, ambient motions caused by vibration sources have to be smaller than 1nm (x/y/z).
  - No vibration amplification by the slab.
  - No vibration amplification by the base-girder-Magnet assembling and the BPM girder, the eigen frequency of the assembling and the BPM girder has to be bigger than 54Hz.



The figure courtesy of Lin Zhang GM2017

Stability specifications

The lower frequency limit

- ***1Hz choice：***

The characteristic wavelengths of slow ground motions are far greater than betatron wavelength, the dynamic effects to the beam can be neglected：
[courtesy of June-Rong Chen/NSRRC MEDSI2014]

--HEPS Betatron wavelength:

$\lambda_{\beta y} = C / \nu_y = 1360.4\ \text{m} / 115.15 = 11.8\ \text{m}$

$\lambda_{\beta x} = C / \nu_x = 1360.4\ \text{m} / 104.29 = 13\ \ \text{m}$

-- Which is comparable to the ground vibrations with frequency of 10-20Hz

according to the wave velocity on ground of HEPS site $\rightarrow \nu_y$=149~268m/s

$f_{\beta y} = \nu_{\beta y1} / \lambda_{\beta y} = 268 / 11.8 \approx 22.7$ Hz

$f_{\beta y} = \nu_{\beta y2} / \lambda_{\beta y} = 198 / 13 \ \ \approx 12.6$ Hz

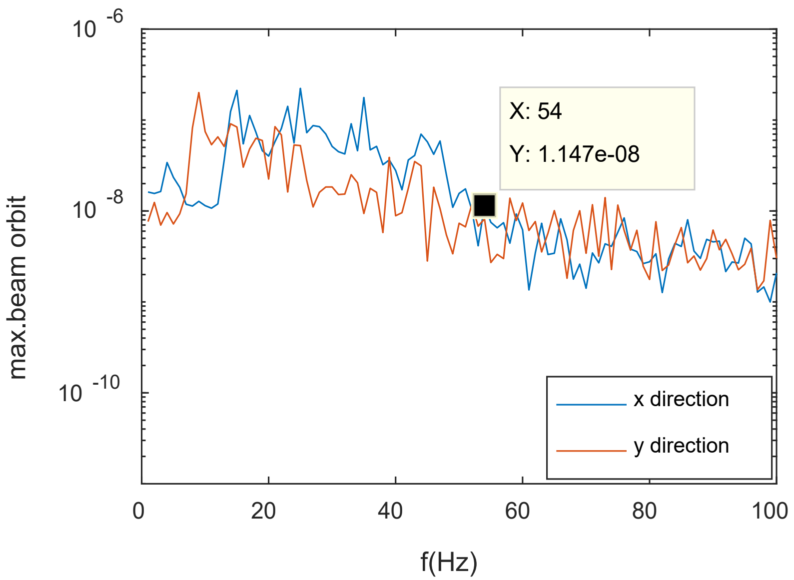
So, for frequency one magnitude smaller， the stability effect to the beam can be neglected, so 1Hz is taken to be the lower limit.

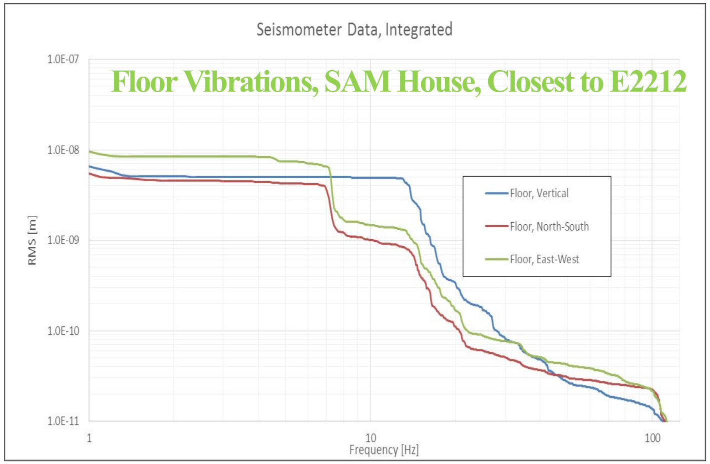
Beam dynamics model

Frequency related model

For the 54Hz girder characteristic frequency limitation, there are two reasons:

1) the vibration influence with higher frequency is relatively smaller;
2) the vibrations on the slab is mainly below 18Hz (MAX-IV).





Courtesy of Brian Norsk Jensen's report / GM2017

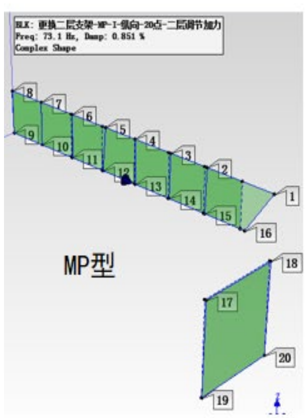
Actual stability controlling effect

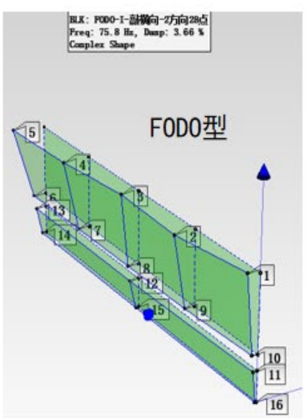
Stability test of the girder-magnet assembling prototype

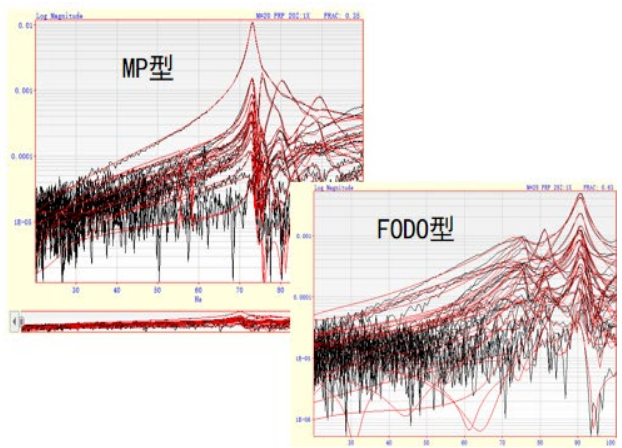
- Natural frequency instrumentation test： Accelerometers, force hammer
- Amplification instrumentation： GeoSIG VE53-BB

Girder type	MP-I	MP-II	FODO-I	FODO-II
Spec.(Hz)	54	54	54	54
Test (Hz)	73	76	74	71

	Amplification factor		
	transversal	longitudinal	vertical
MP	1.07	1.08	0.99
FODO	1.08	1.08	1







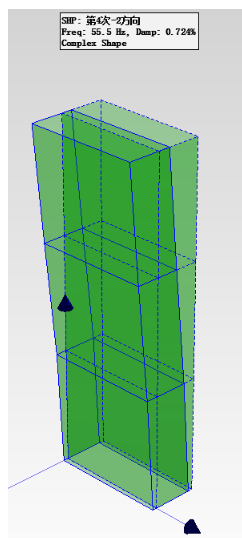
Provided by Zihao Wang of IHEP

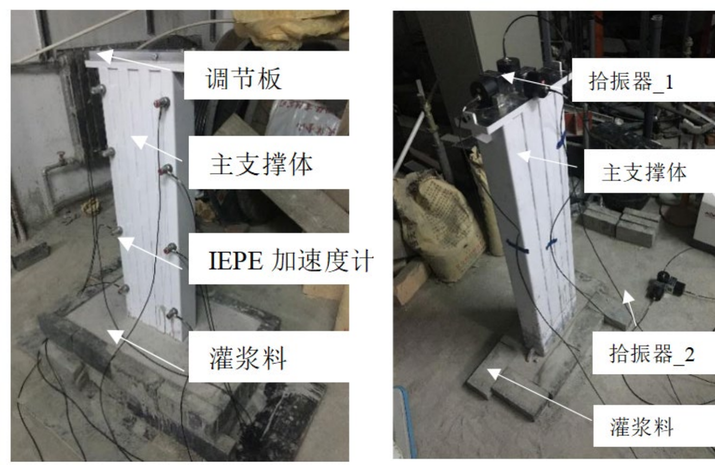
Actual stability controlling effect

Stability test of the BPM girder

- Structure:
  - ✓ Carbon fibre (upper half) and invar alloy (lower half) bounded by expoxy-resin & fixed with rivet to give better magnetoconductivity;
  - ✓ Grouting at the bottom;
  - ✓ Specification: >54Hz.

	Characteristic frequency of the BPM girder
x	107 Hz
z	61.9 Hz



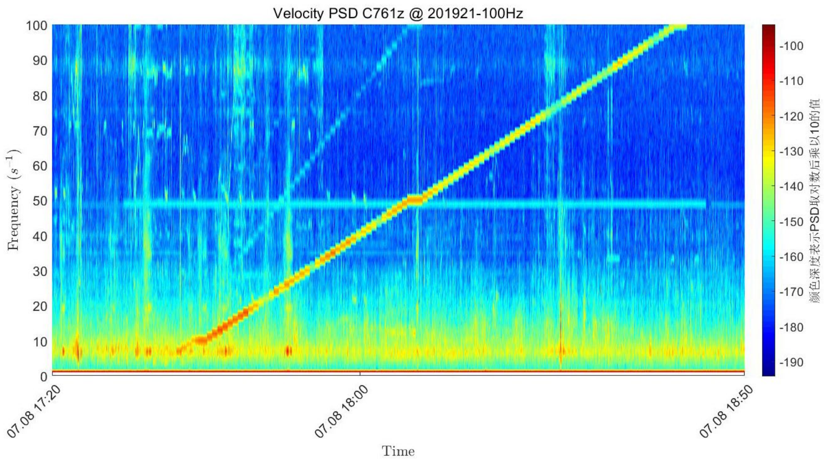


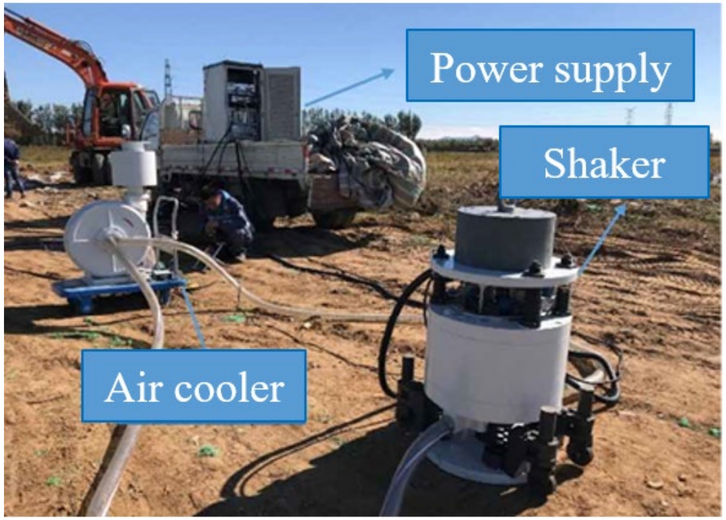
Designed by Anxin Wang & tested by Zihao Wang of IHEP mechanical group.

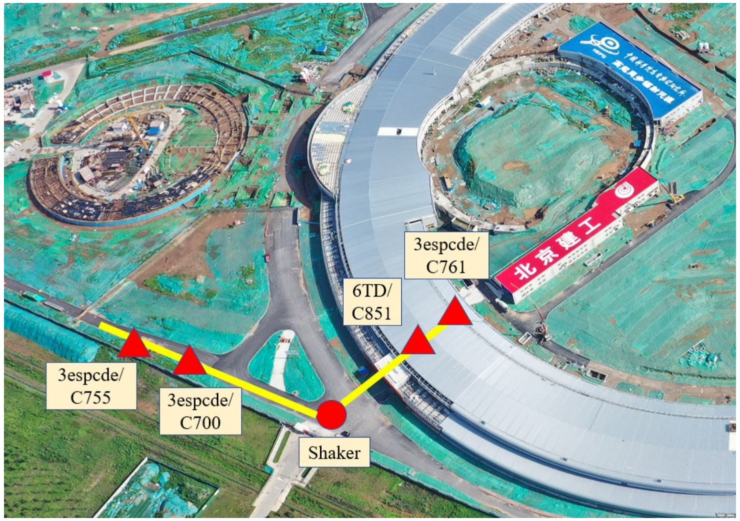
Actual stability controlling effect

Amplification factor test of the HEPS slab

- Shaker is used as the vibration source for generating vibrations with frequency from 1-100Hz;
- The vibration response on slab and on ground are measured at the same distance from shaker using seismometers.

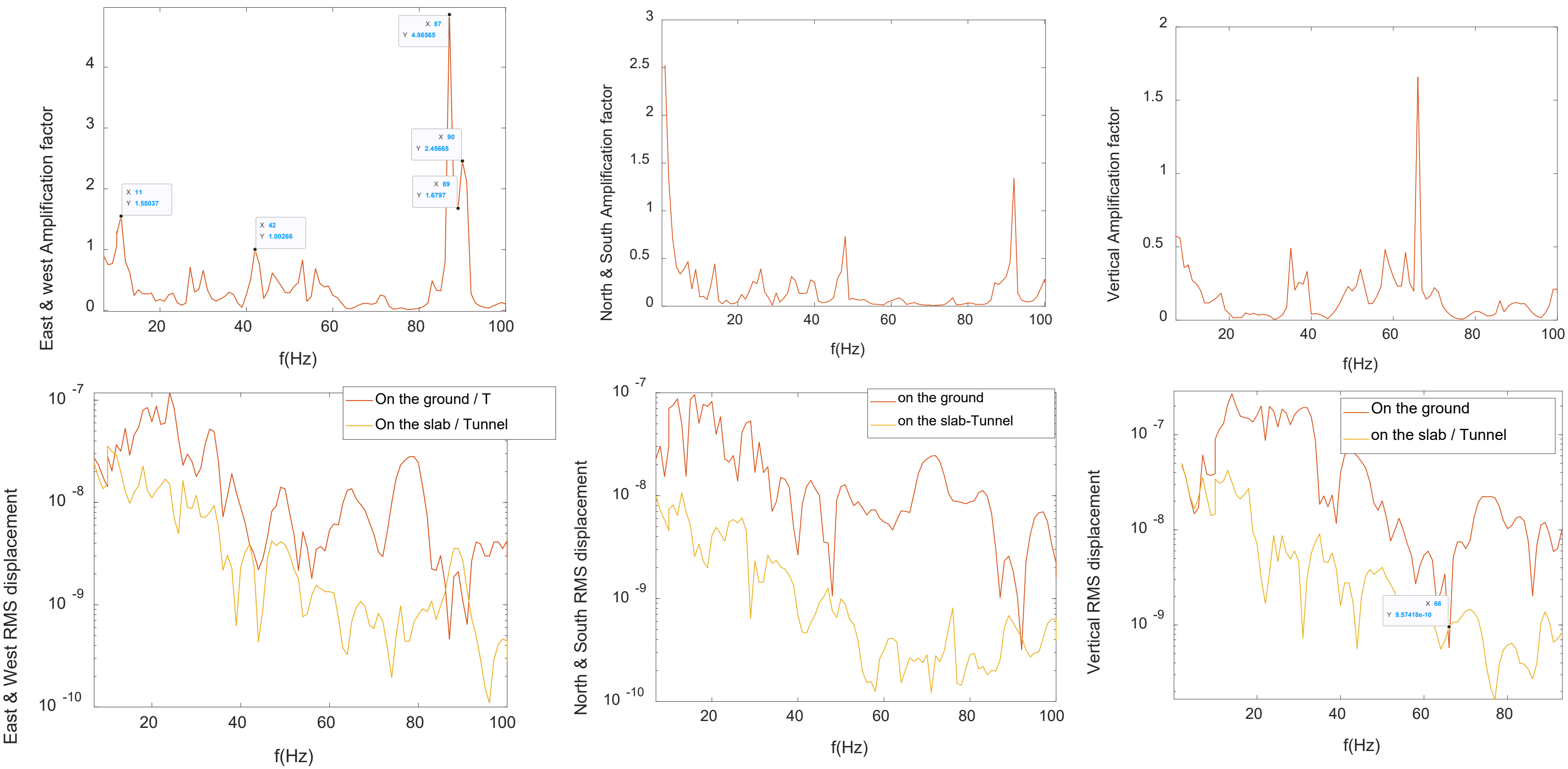






Actual stability controlling effect

Amplification factor test of the HEPS slab



There are only few points are bigger than one. The foundation is not amplified comparing with the ground if considering the whole integral from 1-100 Hz.

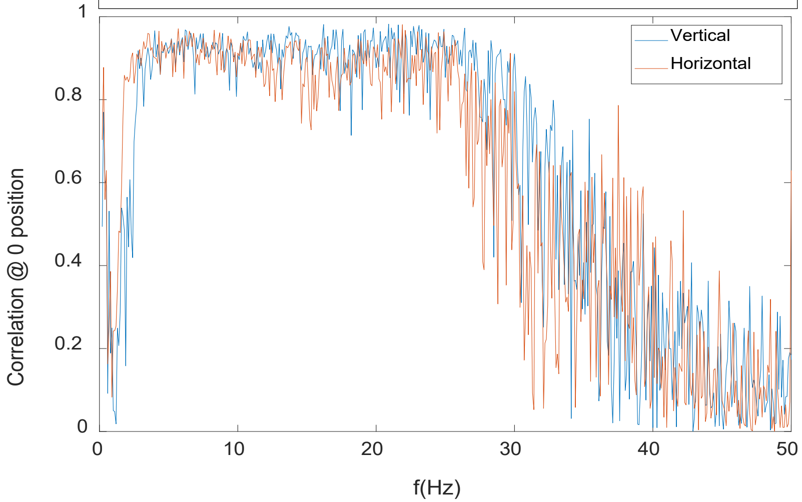
Actual stability controlling effect

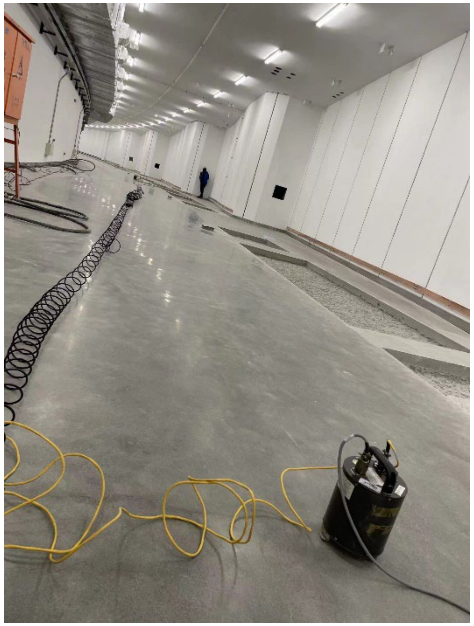
Coherence test on HEPS slab

- Position: in the HEPS storage ring slab;
- Seismometers: Guralp 6TD;
- The north of the sensor always oriented parallel to the beam.

$$C_{xy}(\omega) = \frac{|P_{xy}(\omega)|^2}{P_{xx}(\omega)P_{yy}(\omega)}$$

Sensors next to each other shows very nice coherence

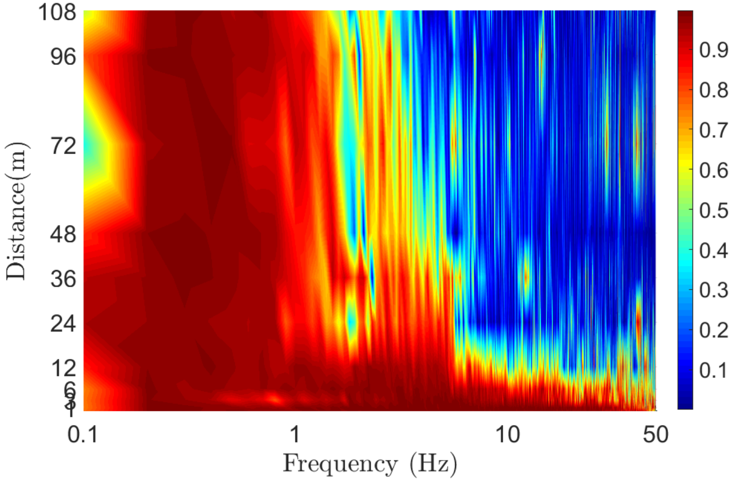




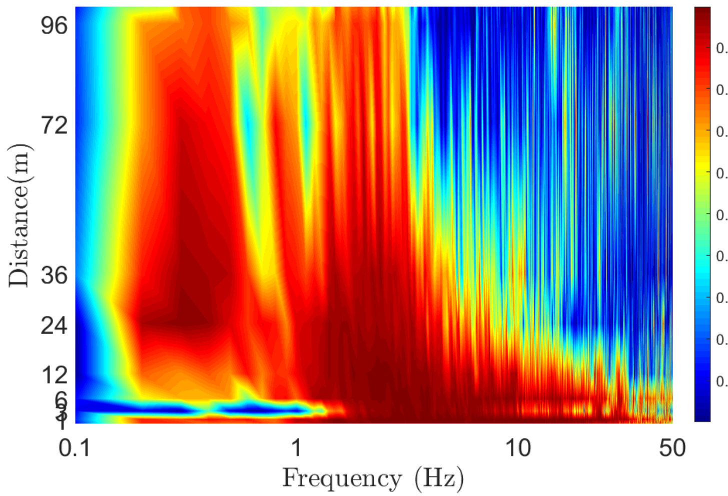
Actual stability controlling effect

Coherence test on HEPS slab

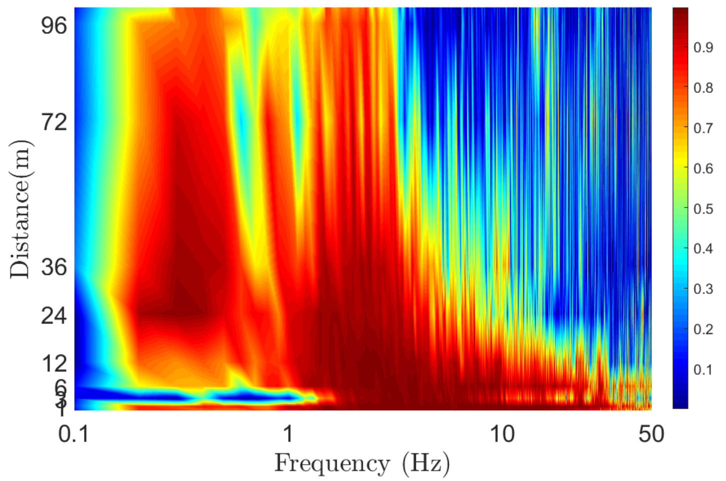
The results shows that two sensors placed about hundred meter away have nicely cohe-rence for vibration frequency of a few Hz.



Coherence of y direction



Coherence of x direction

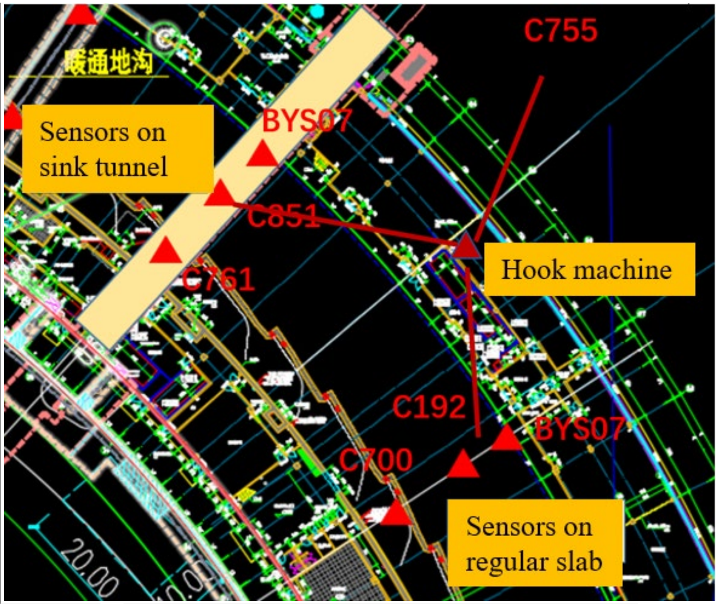


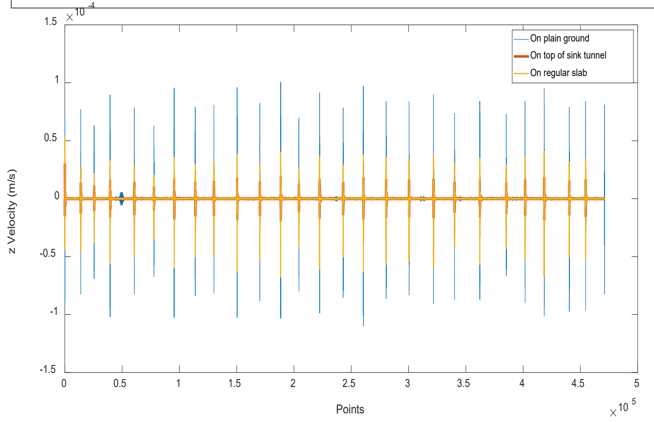
Coherence of z direction

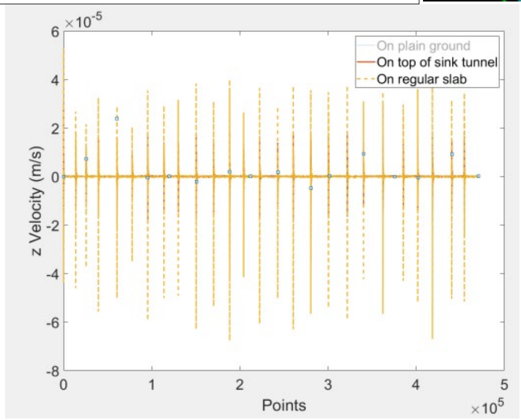
Actual stability controlling effect

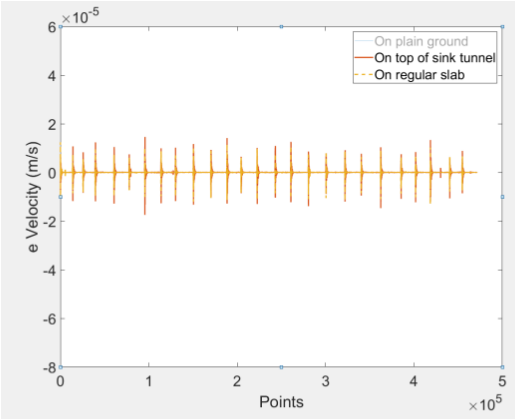
Vibration response of the sink tunnel

- ✓ Using hook machine to make vibrations;
- ✓ Three measurement points with the same distance from the vibration source:
    - One sensor on top of sink tunnel / One on top of regular slab / One sensor on bare ground
- ➢ The vibration response on slab is always smaller than on ground; vibrations is smaller on sink tunnel than on regular slab on vertical plane; on the direction proportional to the sink tunnel, the conclusion is conversely.





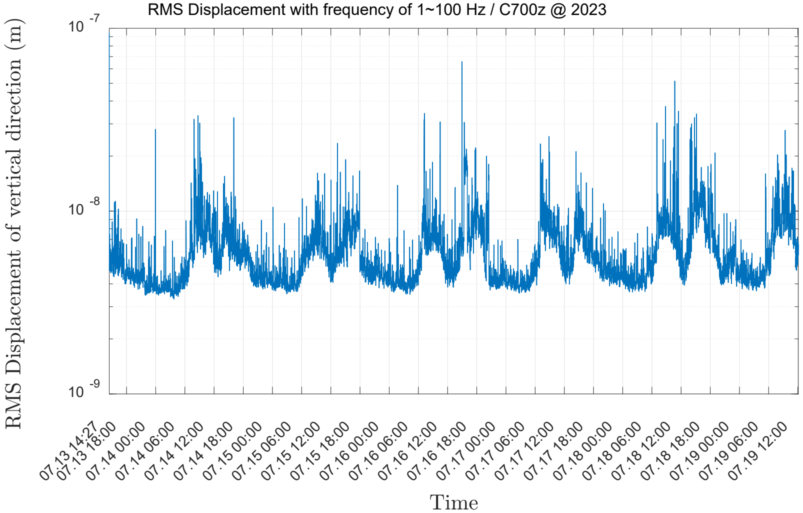


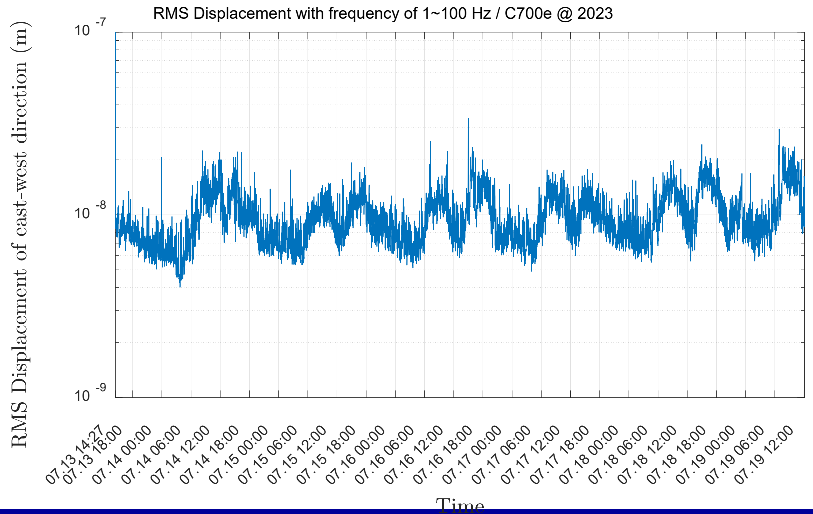


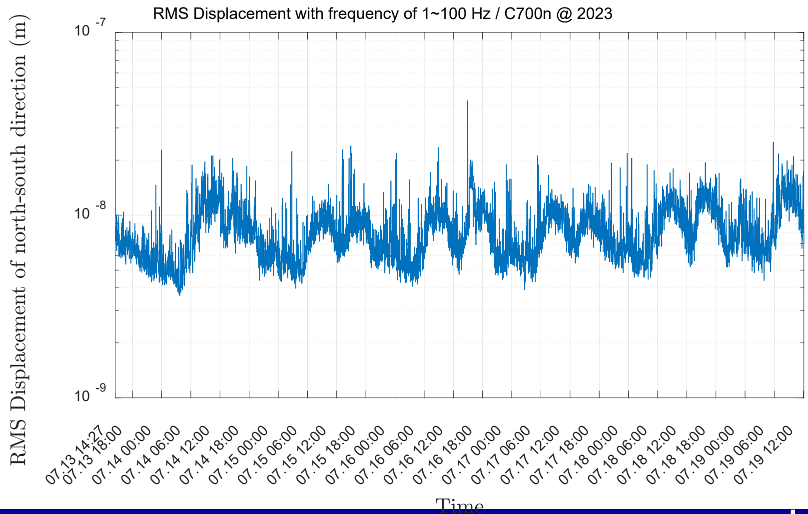
Actual stability controlling effect

Vibrations during commissioning of the booster this July

- ✓ Measurement point: on storage ring slab close to the injection;
- ✓ 0.1Hz frequency resolution;
- ✓ Calculate RMS for every minute;
- ✓ Installing and alignment work is on going during the measurement.







Summary

- Green field motions on HEPS site are smaller than 25nm (0.1Hz frequency resolution/60s average) in all three directions.
- Frequency related beam dynamics models are developed for simulating vibration induced instability and specifications were given accordingly.
- Currently, the construction of the building has been finished, the magnet assembling installation is in process in the storage ring. According to the test:

✓ The foundation is not amplified comparing with the ground if considering the whole integral from 1-100 Hz.

✓ The ground motions have not been amplified by the girder magnet assembling and BPM girder, at least for the prefabricated models.

✓ The vibration response of the sink tunnel doesn't show obvious differences from the regular slab.

Thanks for your attention!