Vibration analysis and stability controlling for High Energy Photo Source in China

YAN Fang
On behalf of Ground motion system
HEPS, IHEP, Beijing China

2025-03-19

Outline

1 Introduction of the HEPS project

2 Frequency related beam dynamics model

3 Ground motion measurement

4 The vibration specifications

5 The stability controlling on the SR slab

6 The actual vibration levels on the SR slab

7 The beam instability issue

8 Summary

1. Introduction of HEPS project

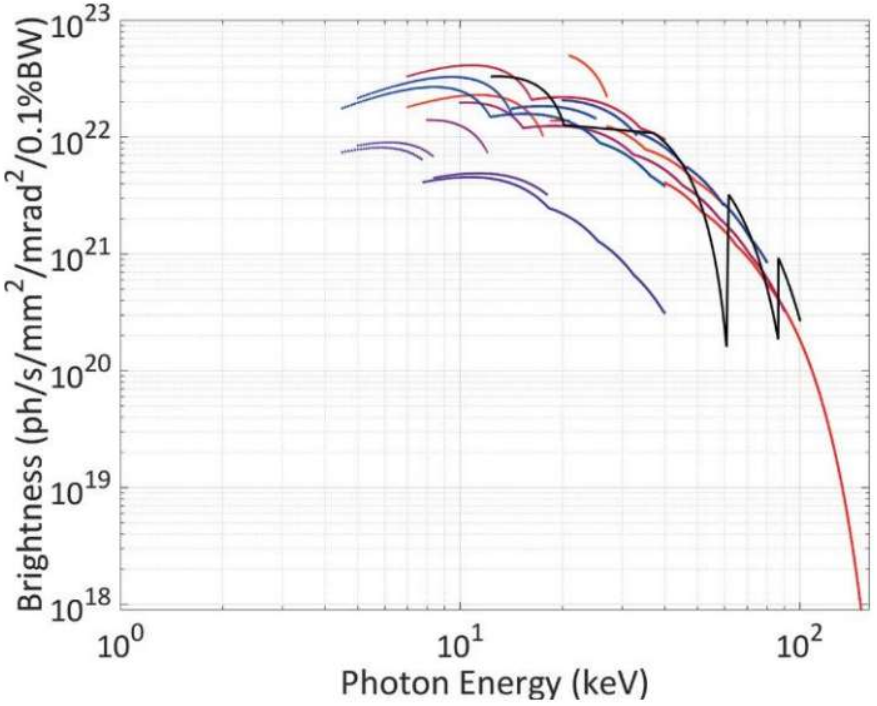
Location at Beijing China	:	Huairou District
SR & booster Energy	:	6 GeV / 500MeV
Designed natural emittance:		34.82 pm.rad
Circumference	:	1360.4 m
Beam current	:	200 mA
Lattice design	:	48 hybrid 7BAs
Phase I beam line number	:	14
Max beam lines number:	:	90

Duration: 6.5 years (2019/7-2025/12: the SR commissioning started at July. 23th , 2024)

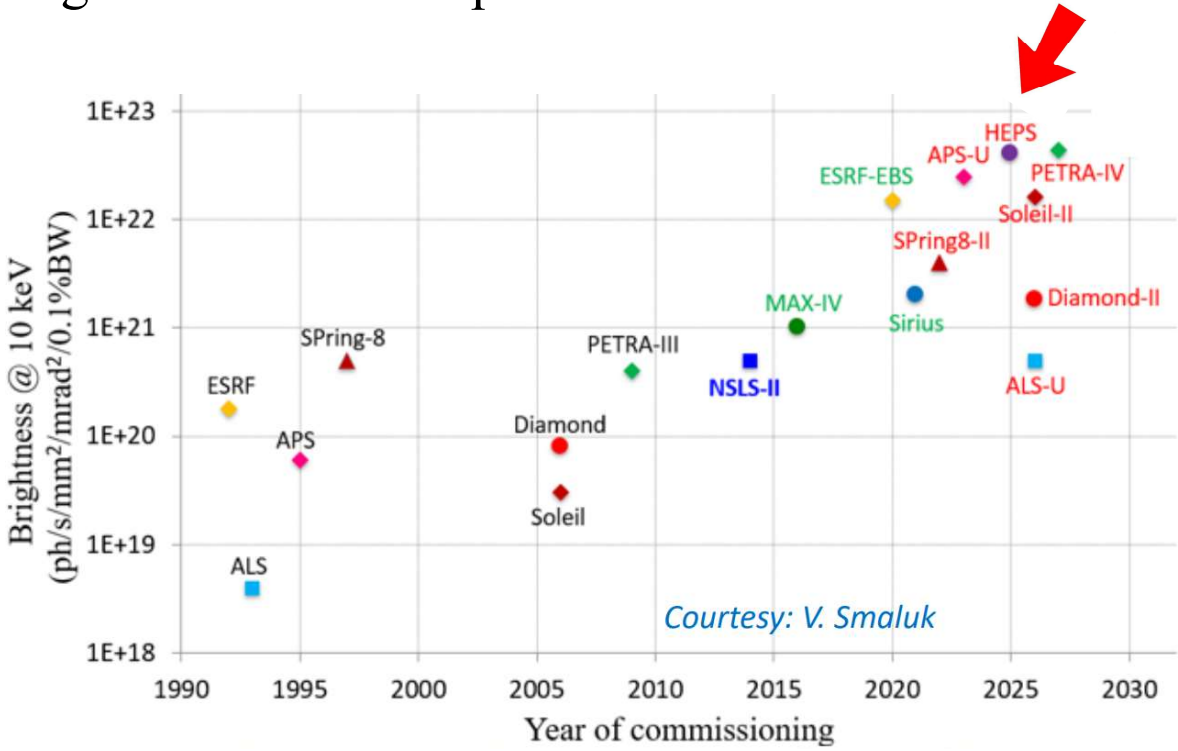
Luminosity: >1×10^{22} photos/s/mm^2/mrad^2/0.1%BW

1. Introduction of HEPS project

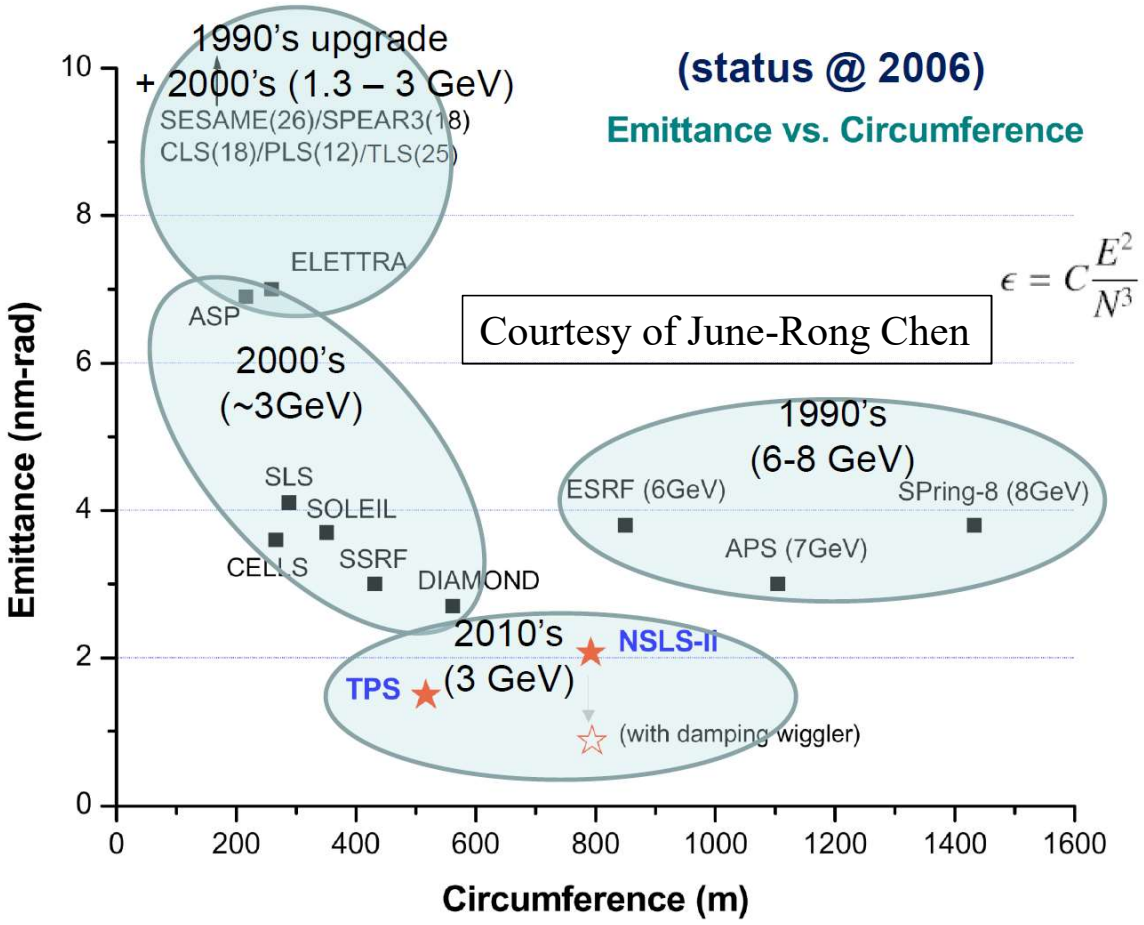
- HEPS is one of the brightest 4th generation synchrotron radiation facilities in the world.
- At the photon energy of 21 keV, the brightness is 5×10^{22} phs/s/mm^2/mrad^2/0.1%BW.



Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).

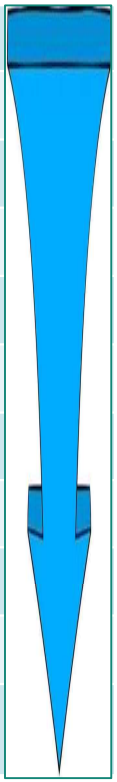


1. Introduction of HEPS project

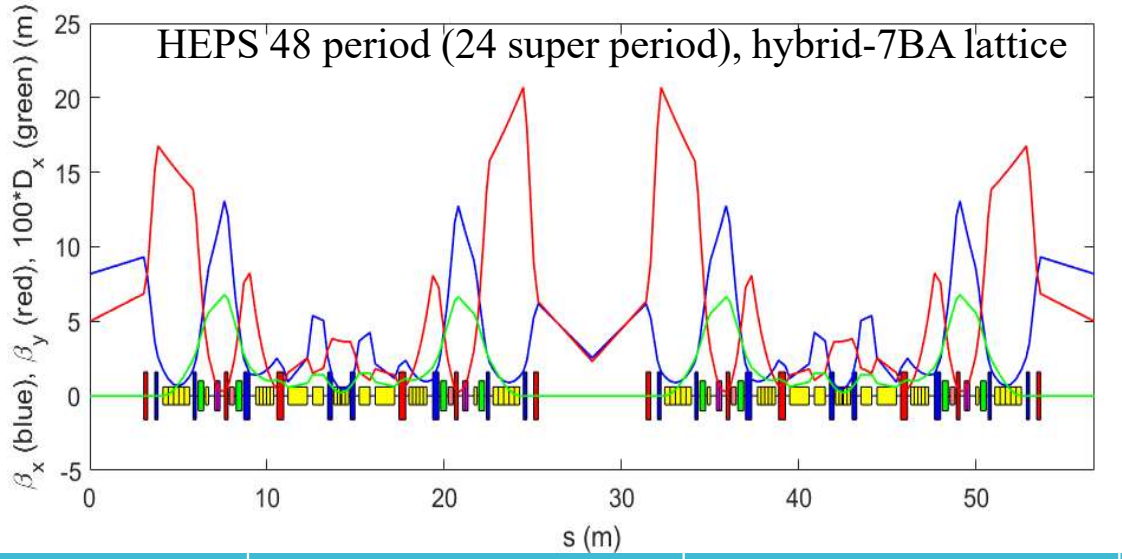


Partial list of light sources since 2006:

Facility	Energy (GeV)	Emittance (pm.rad)
PETRA III	6	1300
MAX-IV	3	200~330
SIRIUS	3	280
SLS2.0	2.7	131-158
ESRF-EBS	6	120
Spring-8-II	6	108
HALF	2.2	86
APS-U	6	42
HEPS	6	35
NSLS-IIU	3	~25
PETRA-IV	6	20



1. Introduction of HEPS project



RMS beam size at ID positions	σ_x (μm)		σ_{px} (μrad)		σ_y (μm)		σ_{py} (μrad)	
	H-beta straight	L-beta straight	H-beta straight	L-beta straight	H-beta straight	L-beta straight	H-beta straight	L-beta straight
Storage ring	17	15	2.1	3.7	4.2	4.7	0.8	1.2

Basing on the 10% stability requirement of the beam, the beam orbit fluctuation limit:

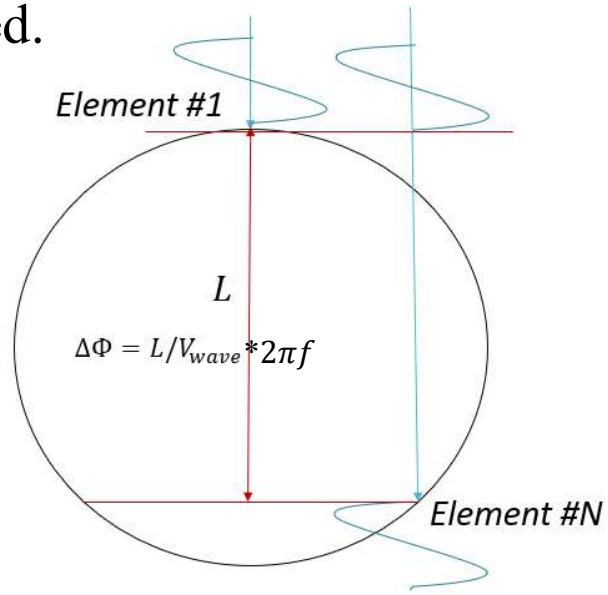
$\sigma_{\triangle x} < 1.5\mu m$ $\sigma_{\triangle px} < 0.2\mu rad$ $\sigma_{\triangle y} < 0.4\mu m$ $\sigma_{\triangle py} < 0.1\mu rad$

2. Frequency related beam dynamics model

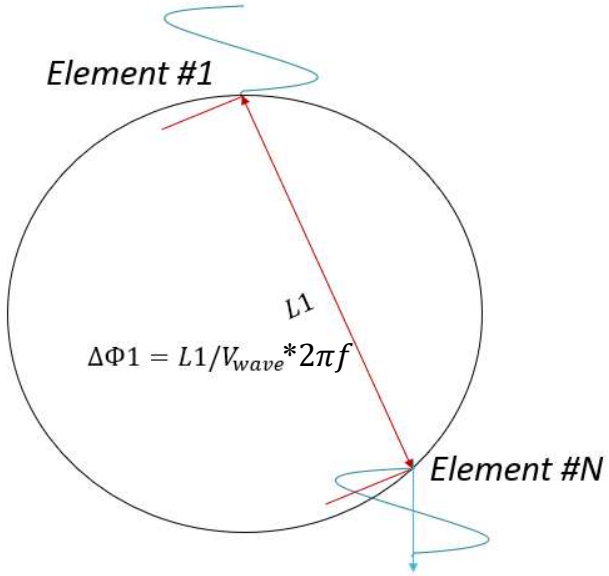
For such rigorous vibration controlling requirement, special cares are mandatory in developing site vibration specifications. To reasonably evaluate the vibration response, a frequency related beam dynamics model has to be established.

Plane wave model is used for simulating vibrations far away. Point wave model is used for simulating vibrations close by. Wave velocity and wave decay (actual measurement results) are considered.

Plane wave model



Point wave model



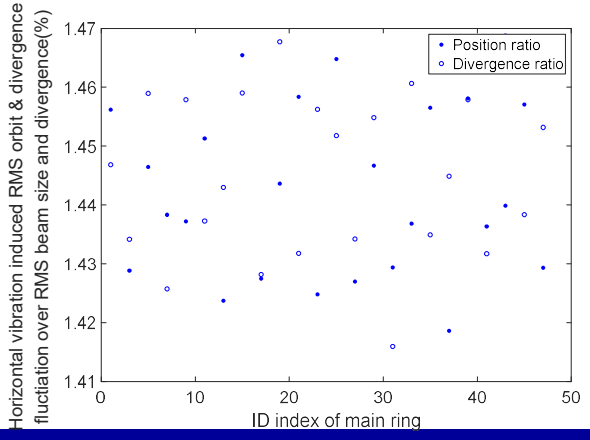
Details can be checked in the report of MEDSI2023 YAN Fang.

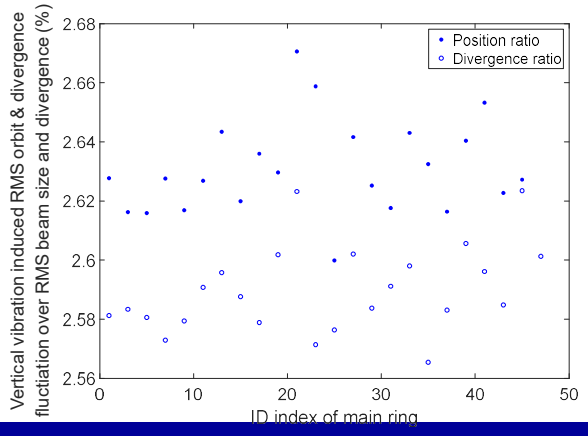
2. Frequency related beam dynamics model

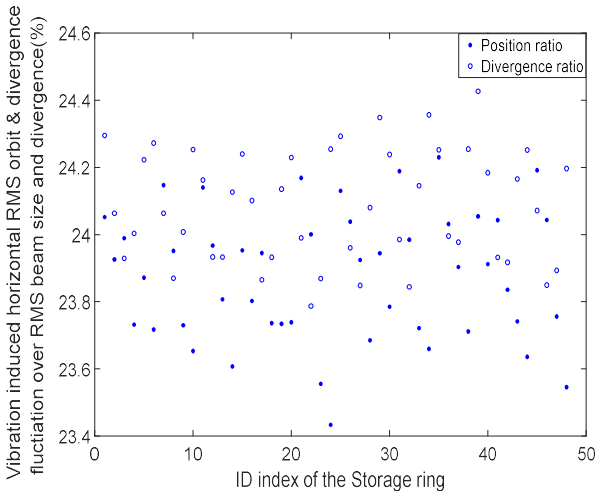
Simulation results

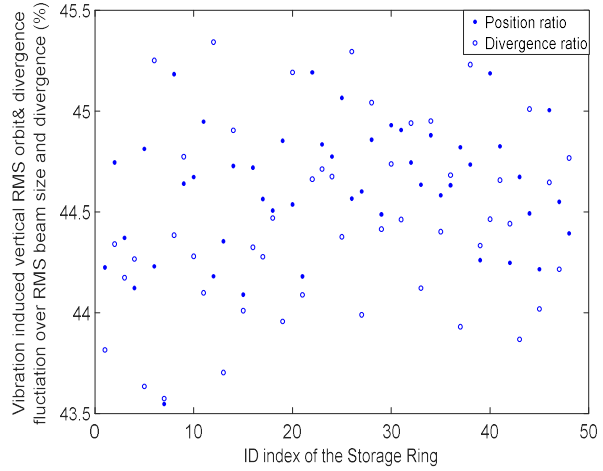
- 1-100Hz 25nm RMS displacement vibration introduced in the lattice of HEPS SR.
- Orbit fluctuation is smaller than 10% of the RMS beam size and divergence with frequency related model.
- The wave speed and velocity are the measurement data of HEPS site.

Frequency unrelated model









3. Ground motion measurement

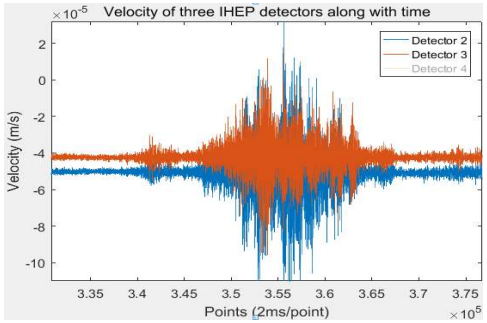
Wave velocity testing on HEPS site

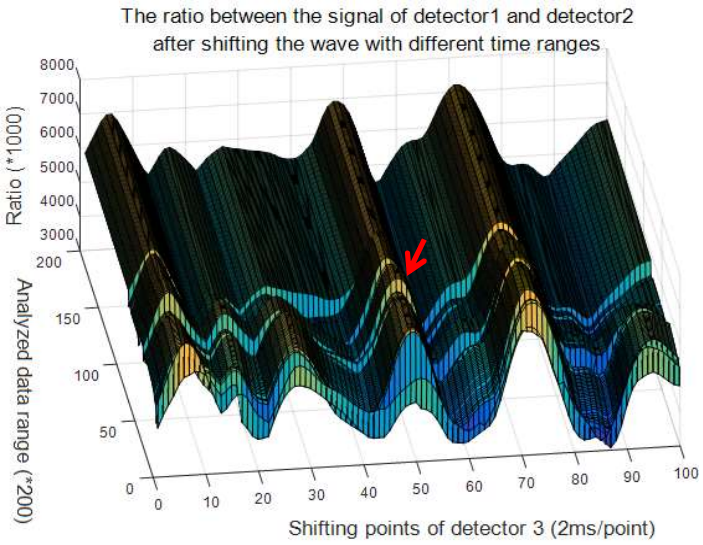
- Three sensors equipped with GPS were placed at 2#/3#/4# locations of HEPS site, the distance in between is 30m long.
- A trunk with 30t load was arrange to run on the perpendicular direction of the measurement line as a vibration source.

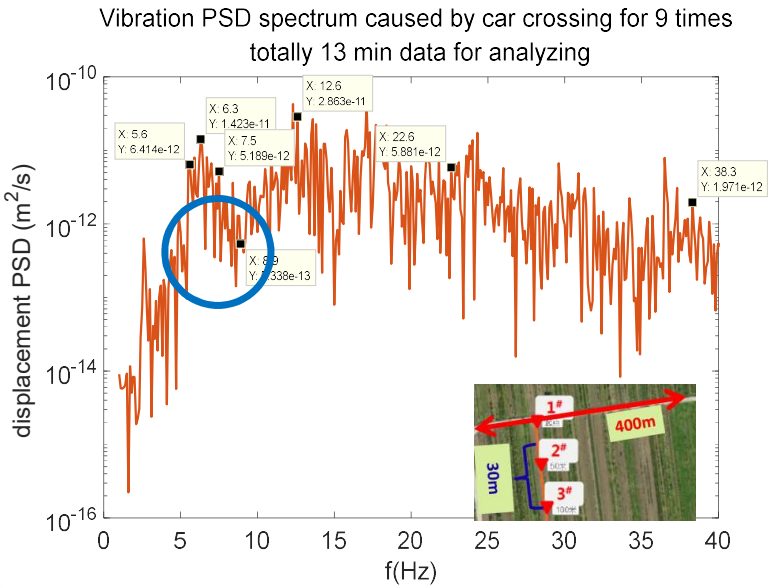
* Note: Collaborated with China Electronics Engineering Design Institute (CEEDI)

3. Ground motion measurement

Wave velocity testing on HEPS site







Valley position	Time diff. of two detector (ms)	Corr. To f (Hz)
13 points	26	38.5
22 points	44	22.7
40 points	80	12.5
56 points	112	8.9
64 points	128	7.8
82 points	164	6.1
88 points	176	5.7

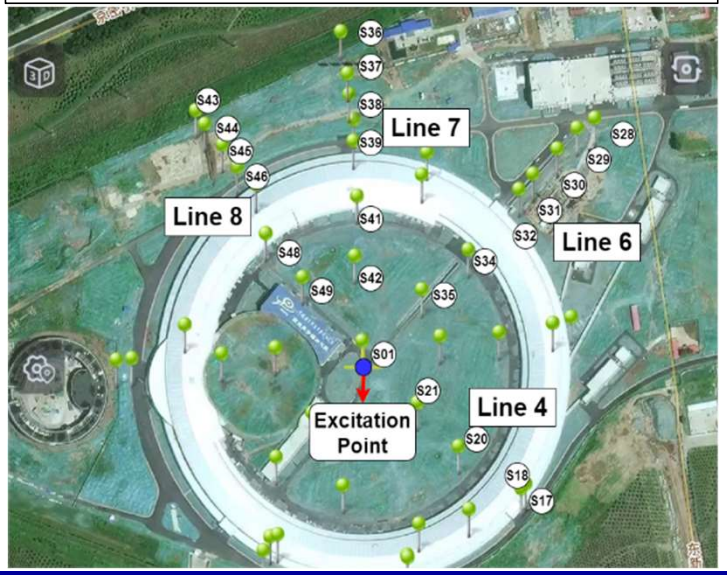
Sampling rate: 500Hz Corr. To: 2 ms/point, Thus the wave velocity in vertical direction is 30 m/(56*(2 ms))=268 m/s

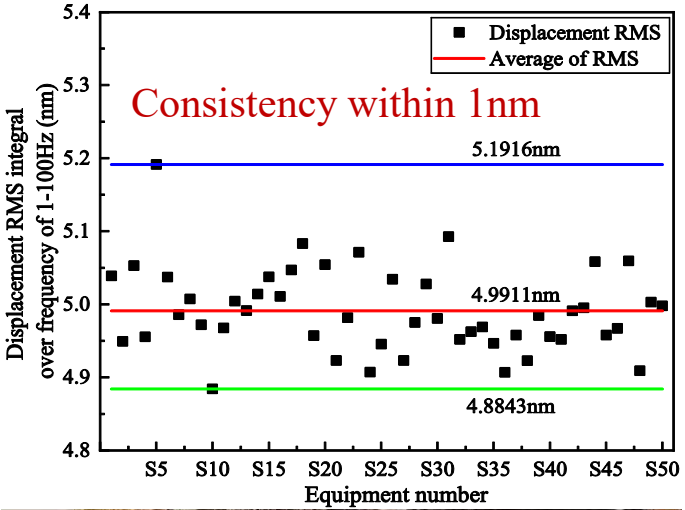
3. Ground motion measurement

Wave decay testing on HEPS site

Vibration generator
- 1~100Hz signal
- forces of 1-70kN
- Weight:1 ton

Exciting at center of the ring
- 4 testing lines / max. 395m
- Smartsolo Seismic node
- 0.2~1000 Hz / 76.7 V/m/s



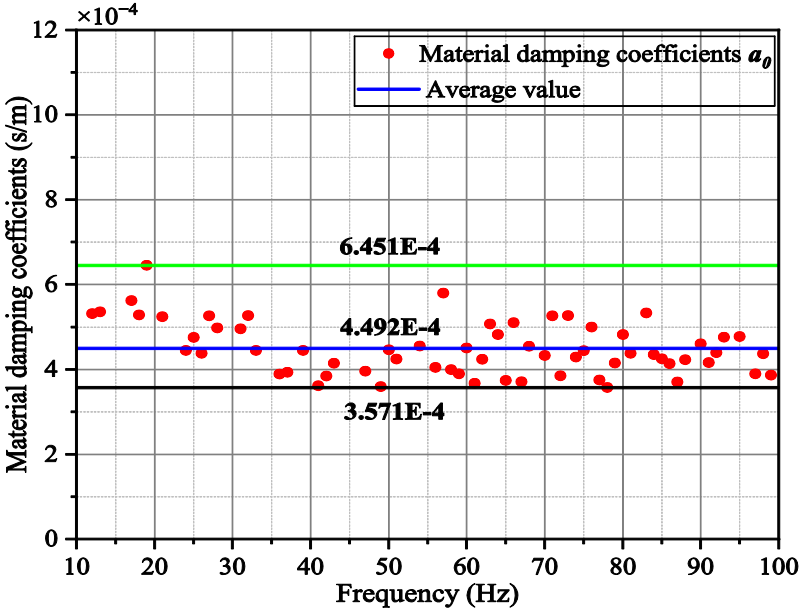


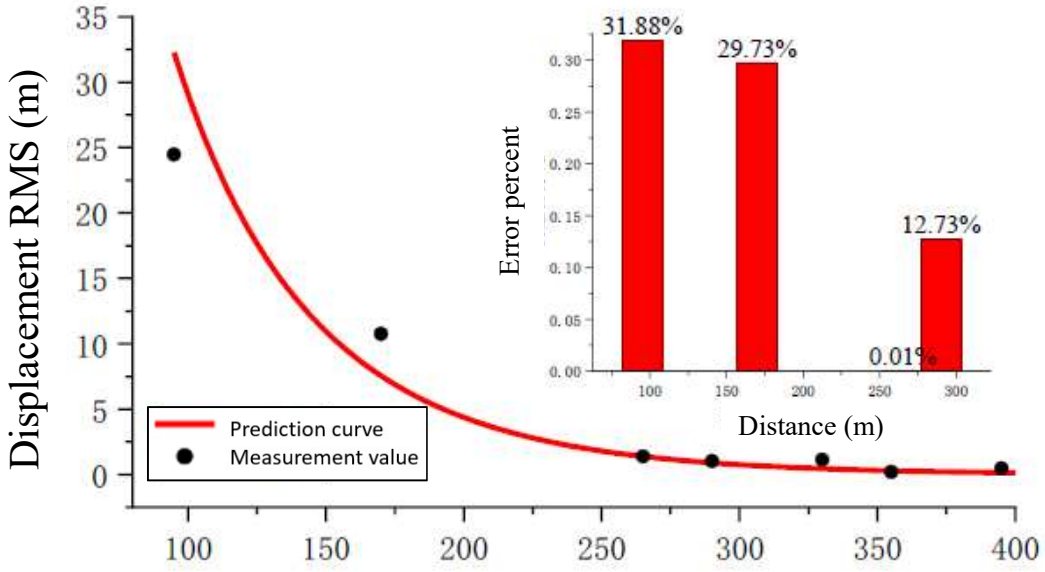
3. Ground motion measurement

Wave decay testing on HEPS site

$$A = A_0\left[\left(\frac{r_0}{r}\right)^2 * 0.3 + \left(\frac{r_0}{r}\right)^{0.5} * 0.7\right] e^{-a_0 f_0 (r-r_0)}$$

A_0: Amplitude at r_0 from vibration source;
A : Vibration amplitude at r from the source;
α_0: Material damping coefficient.





3. Ground motion measurement

Vibration levels measurement on green field of HEPS site

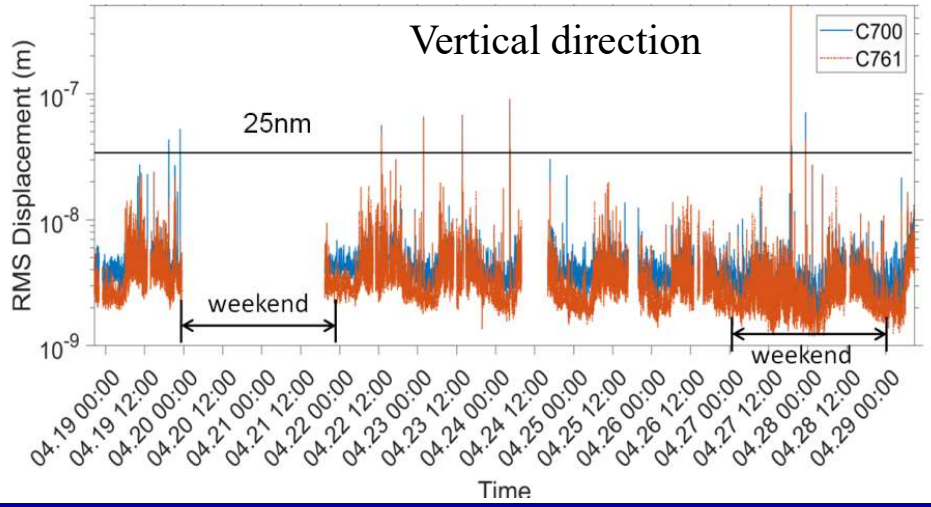
- Time: 2019.4.18~2019.4.29 (a week)
- Major vibration source: traffic on a civil road inside HEPS site(closed now).
- Seismometer positions:
  - ✓ One sensor is on ground closer to the internal site road.
  - ✓ Another sensor is on the ground of the storage ring.

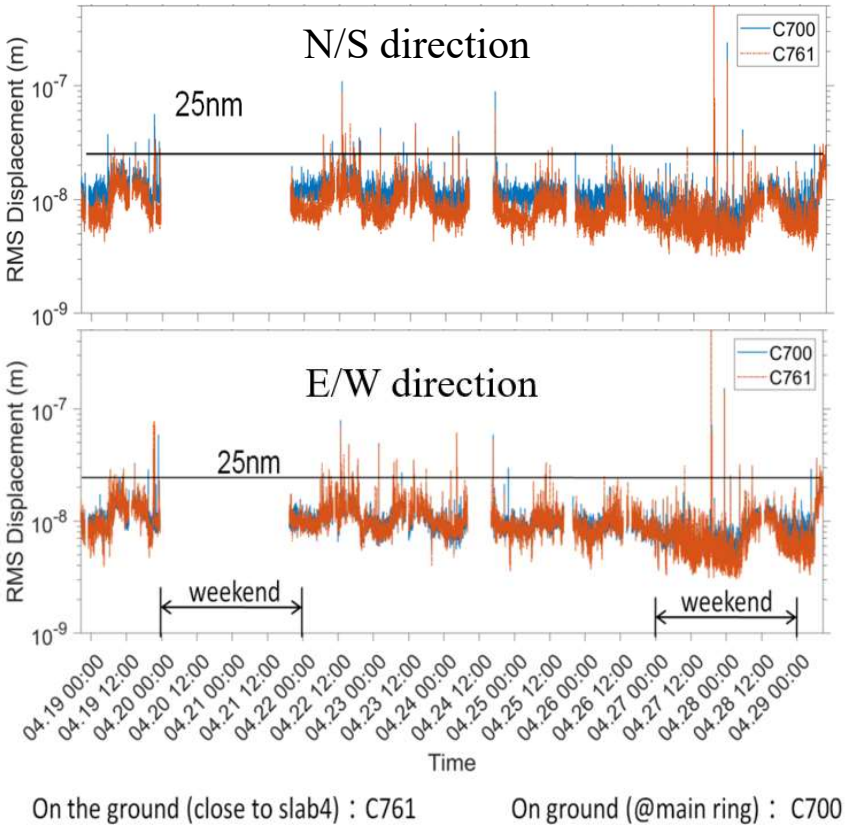
Seismometer	Frequency Ranges	Sensitivity
3espcde	0.017~100Hz	2000V/m/s

3. Ground motion measurement

Vibration levels measurement on green field of HEPS site

- **RMS of every min, 0.1Hz frequency resolution**
- Ground motion shows clearly day and night shift
- During night, the motion on ground is ~4/10nm(z/x)
- During day time, it is about 10/20nm (z/x)





On the ground (close to slab4)：C761　　On ground (@main ring)： C700

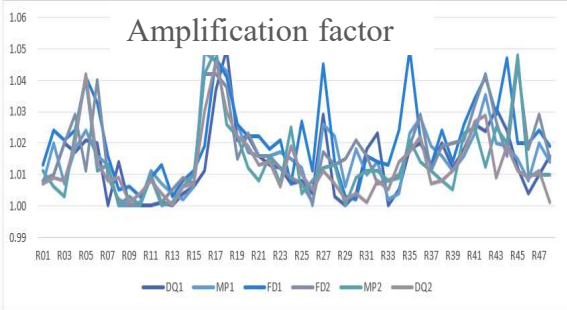
4. The vibration specifications

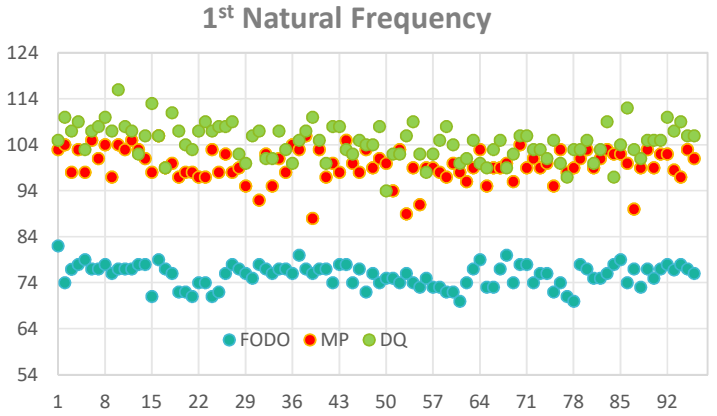
- The HEPS green field vibrations are below 25nm in all three directions.
- The vibration tolerance for the floor motion is set to be 25nm for RMS displacement integration over frequency of 1Hz~100Hz.
- To ensure fulfilling of the final vibration target on critical slabs, the 25nm limitation is further decomposed to three specifications according to the propagation path of the motion waves:
  - No vibration amplification by the plinth-girder-magnet assembling, the eigen frequency of the assembling has to be bigger than 54Hz.
  - No vibration amplification by the BPM girder, the eigen frequency of the BPM girder has to be bigger than 54Hz.
  - No vibration amplification by the slab.
  - Besides the ground motion, ambient motions caused by vibration sources have to be smaller than 1nm (x/y/z).

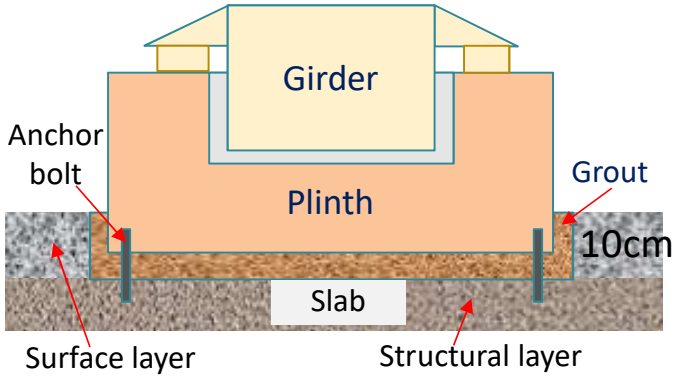
5. The stabilities controlling: the girder magnet assembling

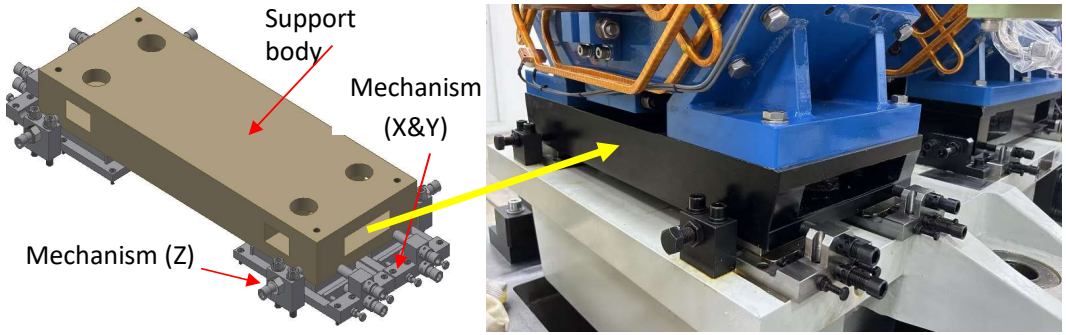
- All 288 support modules have been tested after the alignment in the tunnel, and all meet the requirements.
  - Eigen frequency： ≥70 Hz
  - Transmissibility: ≤1.05

	FD	MP	DQ
Min	70	88	94
Max	82	106	116
Avg	76	100	105









Courtesy of LI Chunhua of IHEP

5. The stabilities controlling: the BPM girder

High stability low expansion BPM support

- Carbon fibre (upper half) and invar alloy (lower half) bounded by expoxy-resin & fixed with rivet to give better magnet permeability.
- Grouting at the bottom.
- BPM girder: eigen frequency ≥66Hz, magnification factor ≤1.05
- Thermal stability： **±20nm； μ < 1.02** （No magnetic field within 670mm of the beam）

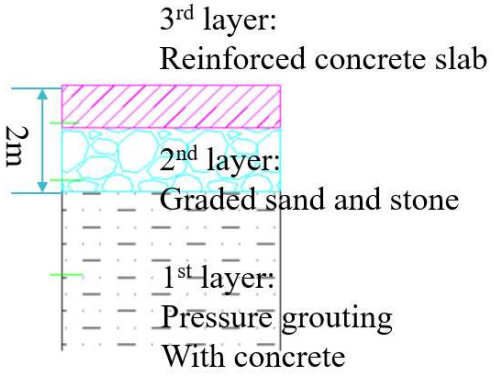
	1st-order freq. （Hz）	2nd-order freq. (Hz)	Horizontal vibration amplification factor	Vertial vibration amplification factor
BPM girder	**66.23**	**88.75**	**1.05**	**1.03**

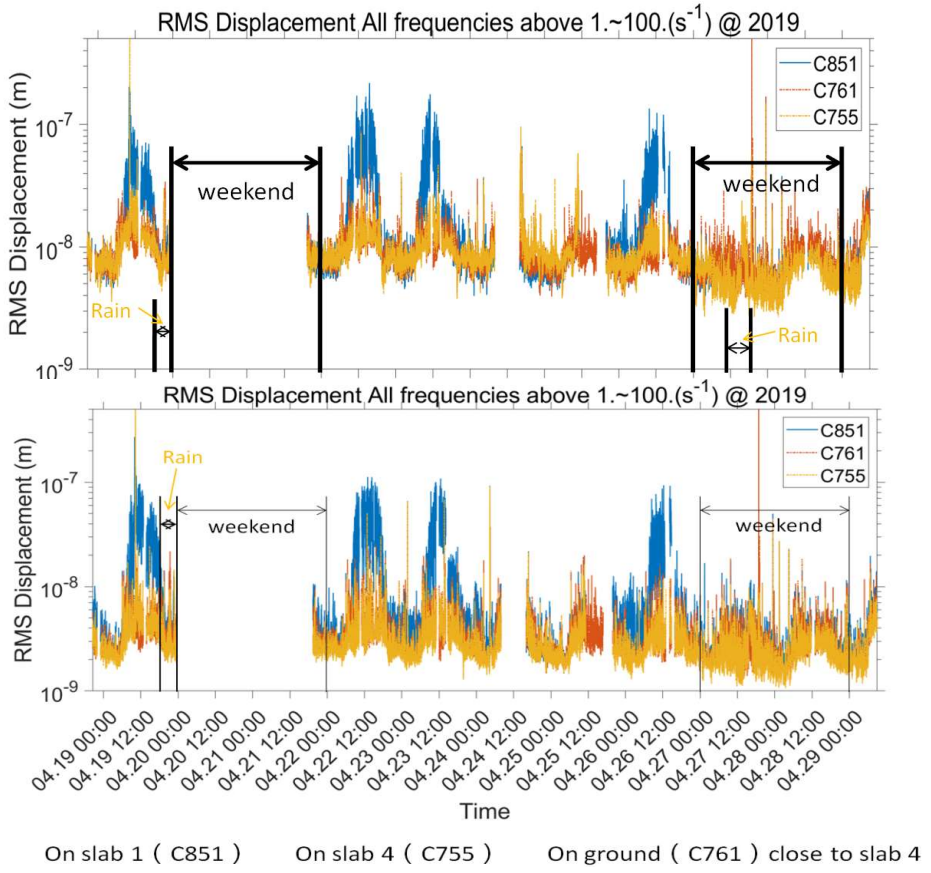
Courtesy of Sui Yanfeng of IHEP

5. The stabilities controlling: the slab

The slab design

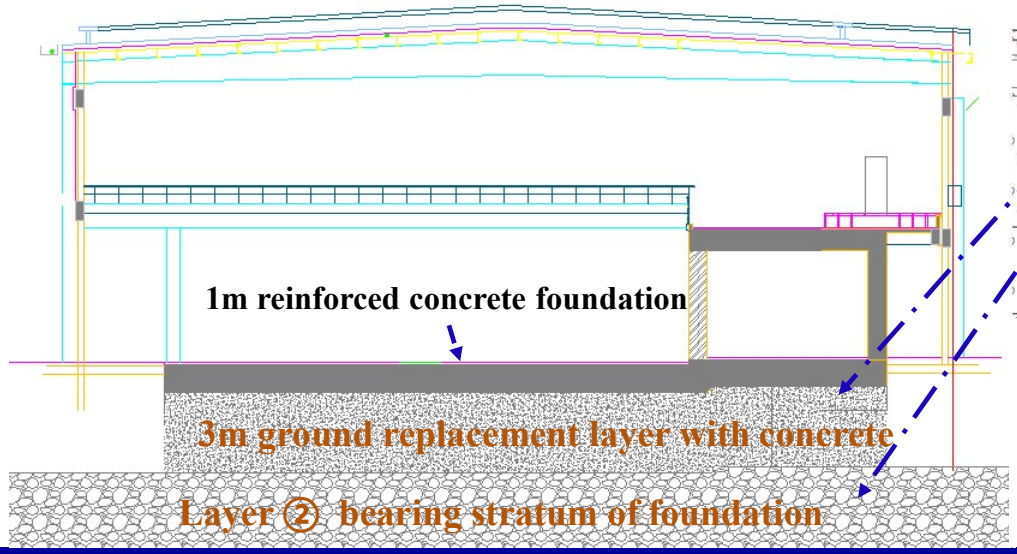
- Two prototypes (slab 1 & Slab 4) were fabricated in HEPS site;
- Slab 4 & slab 1 are all the same for the top two layers, except extra 5m grouting layer for slab 4;
- Comparing with measurement point (red star position) on ground, vibrations are magnified a lot on slab 1, but almost the same level on slab 4.

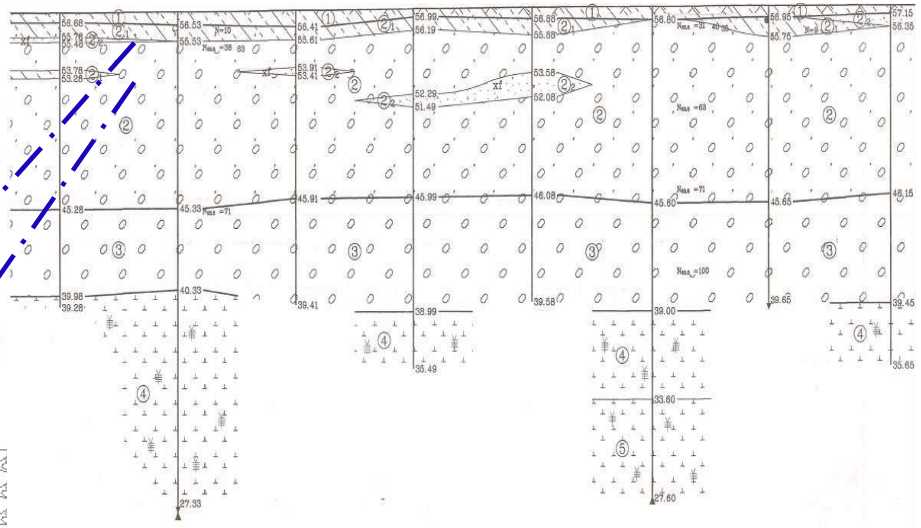




5. The stabilities controlling: the slab

- The finalized foundation-slab design for the SR and experimental hall is fixed to be an 1m reinforced concrete slab & 3m replacement layer underneath using plain concrete which is verified by simulation to be having equivalent effect as the grouting scheme.
- The artificial layer ①, the first cobble layer ②$_1$ and part of the newly deposit cobble layer ②$_2$ (totally 4m) have been dug out and refilled.



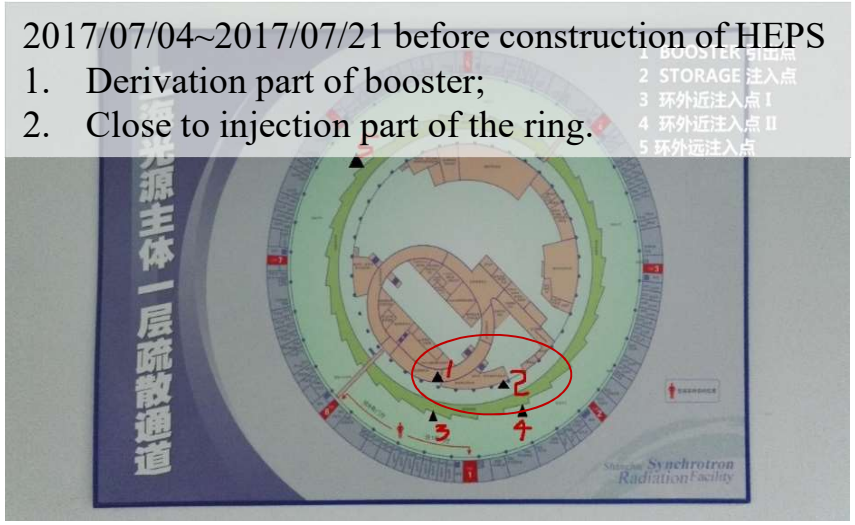


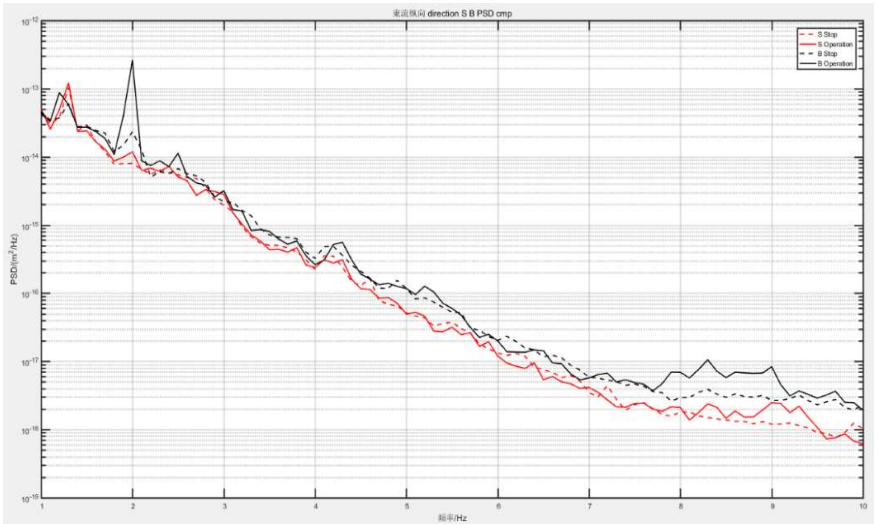
① Artificial fill
②$_1$ Cobble layer
②$_2$ Newly deposit cobble layer
③ Quaternary deposit cobble layer
④ Cobble layer
⑤$_1$ Completely weathered bedrock
⑤$_2$ Strongly weathered bedrock 36.1-45m
⑤ Moderately weathered bedrock

5. The stabilities controlling: the slab

Detached foundation design between the booster and the SR slab

- The 25Hz pulsed magnet operation of CSNS RCS had caused severe vibration of the AC dipole because of resonant (Liu Ren-Hong et al 2014 Chinese Phys. C 38 067005).
- SSRF pulsed mode of the booster: 2Hz V.S. HEPS: 1Hz
- Measurement was done in SSRF tunnel for verifying the detached foundation design



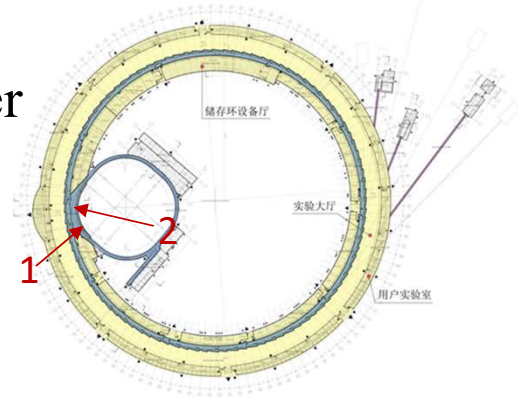


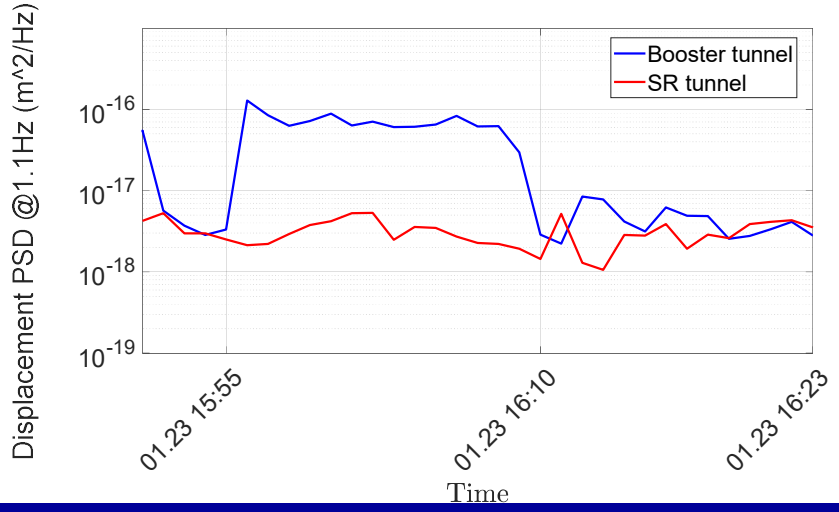
* Note: Collaborated with SSRF beam operation/diagnostic/mechanical groups

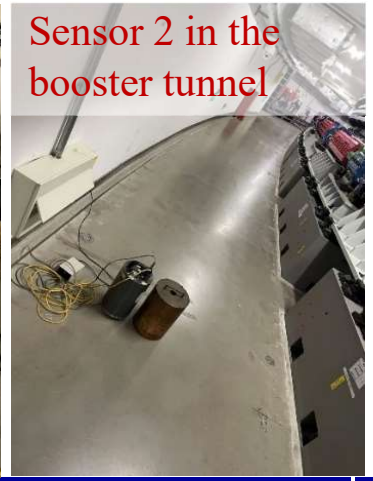
5. The stabilities controlling: the slab

Detached foundation design between the booster and the SR slab

- The same measurement has been done in the HEPS SR and booster tunnel during booster commissioning during year of 2024.
- A 1.1Hz peak appears in booster tunnel but not in SR tunnel;
- The detached foundation design is proved effective.







5. The stabilities controlling: surrounding traffic

HEPS surrounding transportation

- There are 3 major road around HEPS campus, which is 800-1000 meters away;
- The closest is Guanyuan (GY), road, which is ~60m away;
- Xinfen St. is further than GY road which is about 200m away.

5. The stabilities controlling: surrounding traffic

Two tests have been carried out for investigating the transportation influences. Cars and cranes with different load were arranged to run on Xinfen St. and Guangyu Rd. with different speed.

1. 1st test points distribution

2nd test points distribution

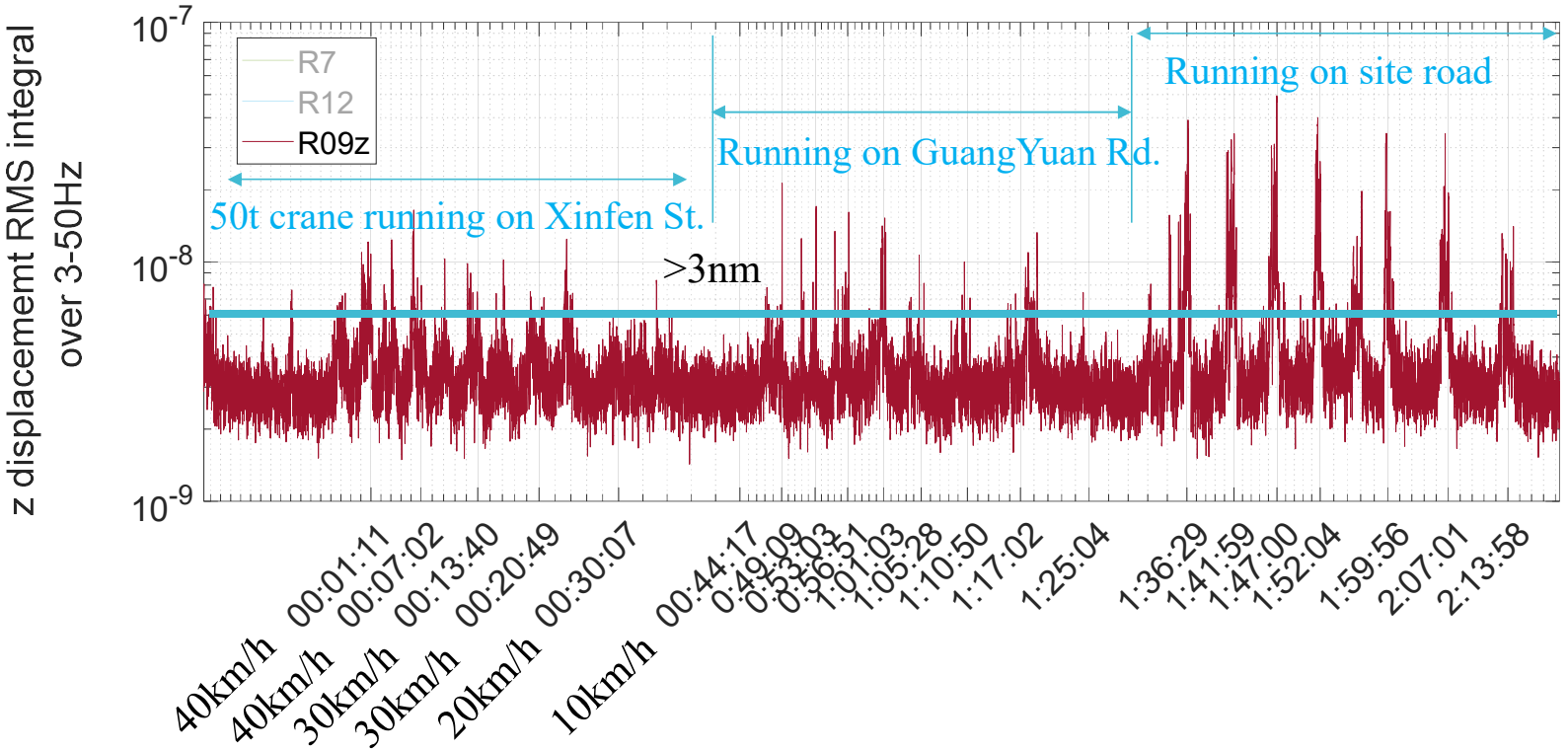
3. Crane driving lines

4. Road closure map during the test

5. Sensors used during the test

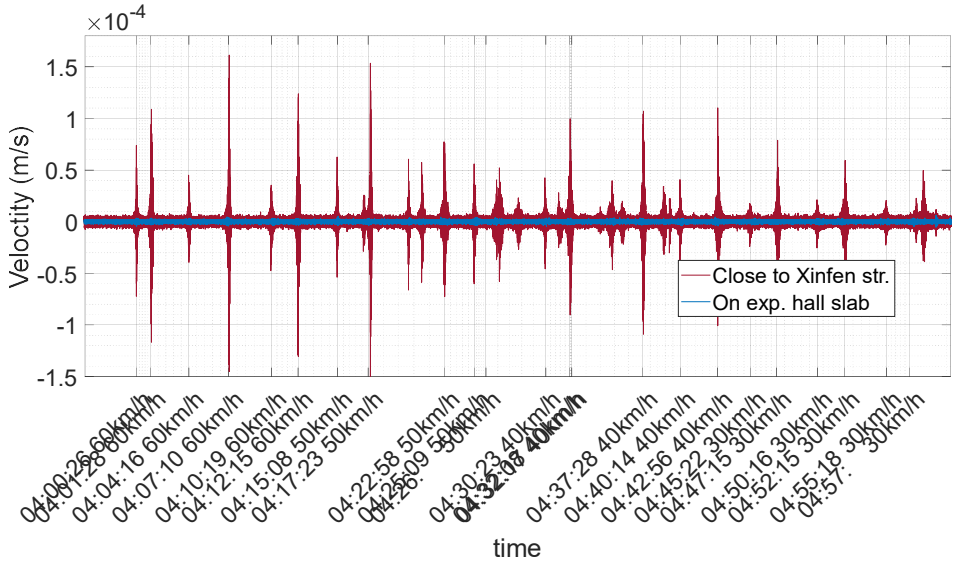
6. Running crane and cars during the test

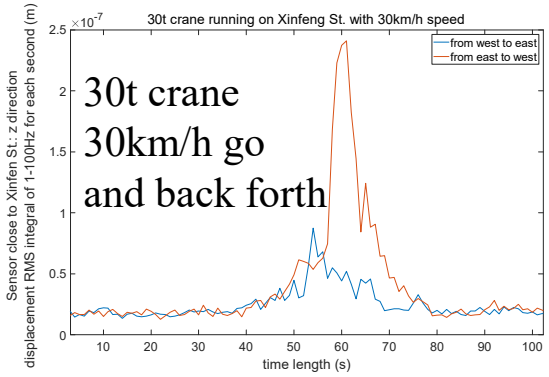
5. The stabilities controlling: surrounding traffic

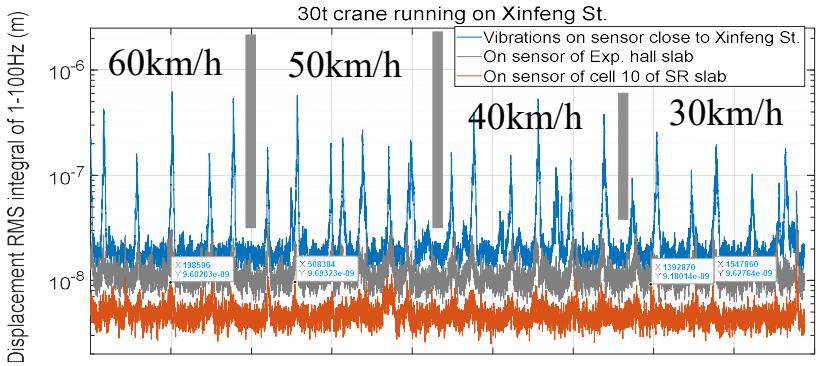


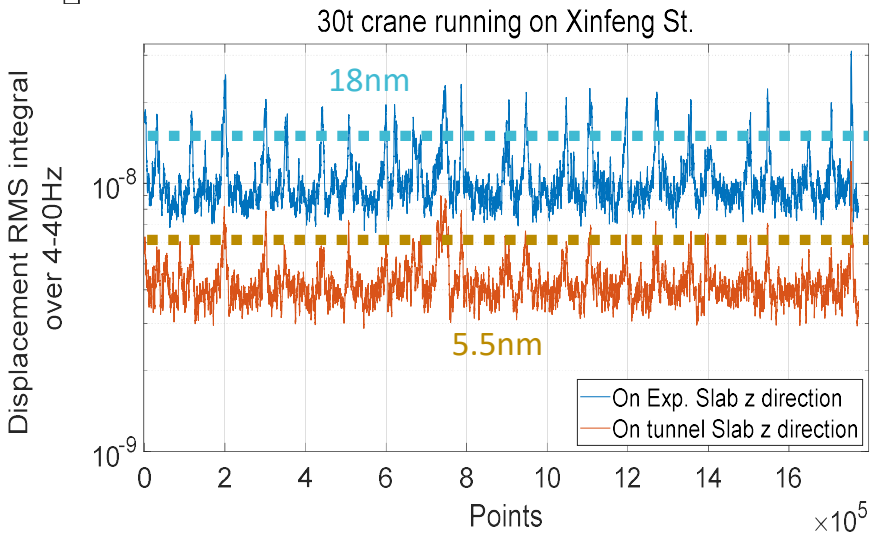
The vibration while 50t trunk running on Xinfen St. with 10km/h is visible on SR tunnel slab.

5. The stabilities controlling: surrounding traffic



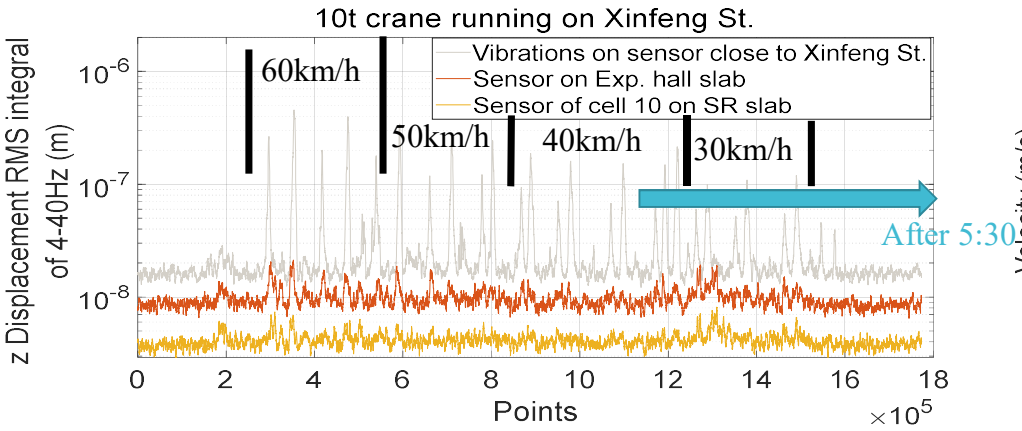




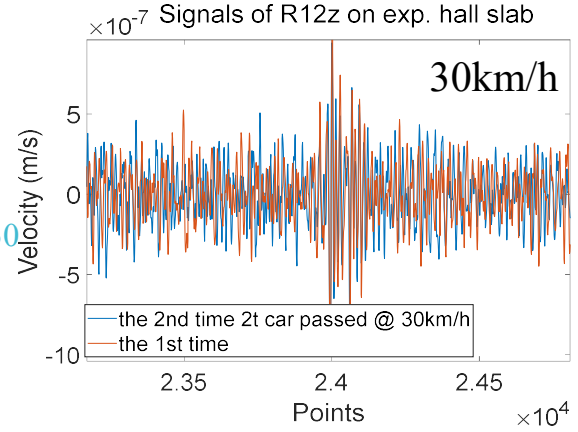


5. The stabilities controlling: surrounding traffic

10t crane running on Xinfen St.



2t car running on Guangyuan St.

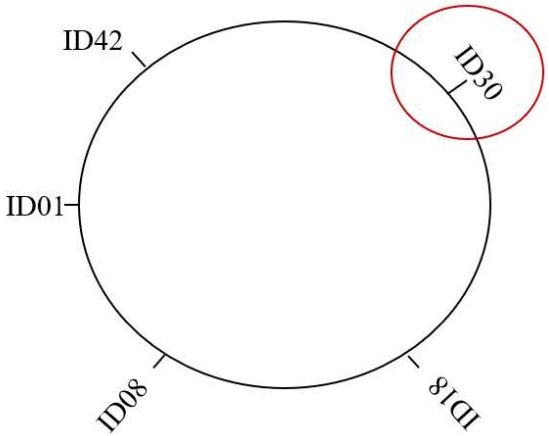


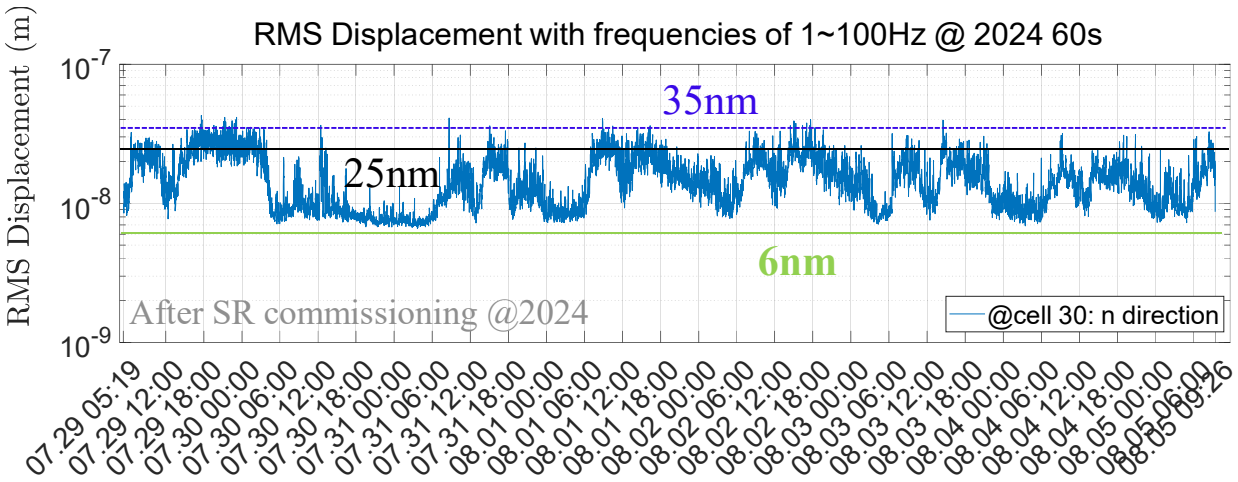
Sensor on	mean	60km/h	50km/h	40km/h
Exp. Hall Slab (nm)	9.7	16-21	13.4-19	11.4-13.6
		>12.7	>9.2	>6.0
SR tunnel Slab (nm)	4.1	5.6-6.6	5.1-6	4.7-4.9
		>3.8	>3	>2.3

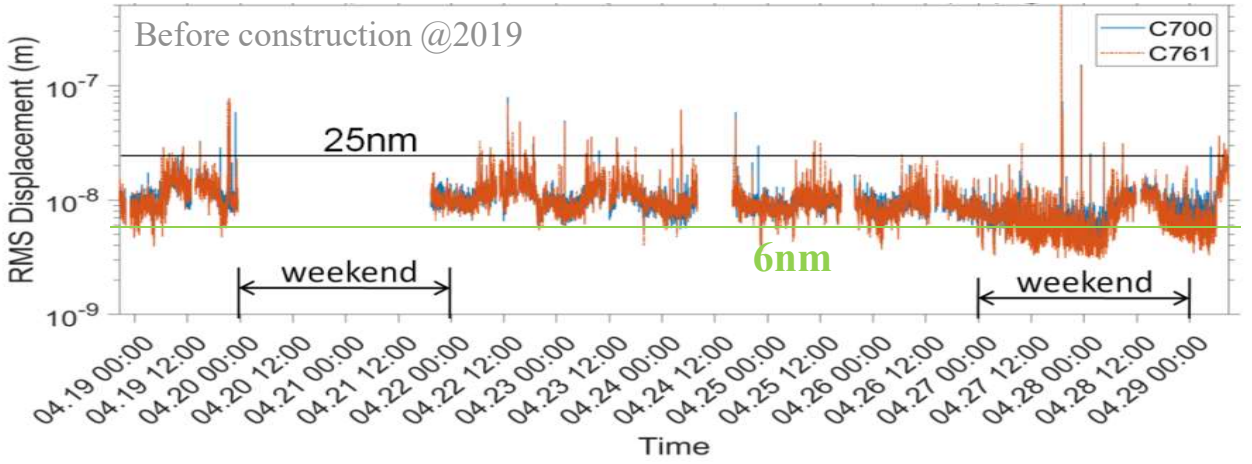
Van cross Yonglebiesi Street at diff. speed (km/h)		30	40	50	50	60	60
On exp. Slab (R12z)	Background noise (nm)	4	3.6	3.3	3.4	3.2	3.3
	Disp. RMS: 1-50Hz (nm)	5	5.1	9.9	9.2	7.2	8.5
	RMS dominated by van (nm)	3	3.6	9.3	8.5	6.4	7.8

6. The actual vibration level on slab: horizontal direction

- Vibrations at the same position has been measured before construction (figure below) and after the SR commissioning (top figure);
- Comparing with vibrations measured before construction, the vibration level increased a little bit during night, but it has more growth during day time.



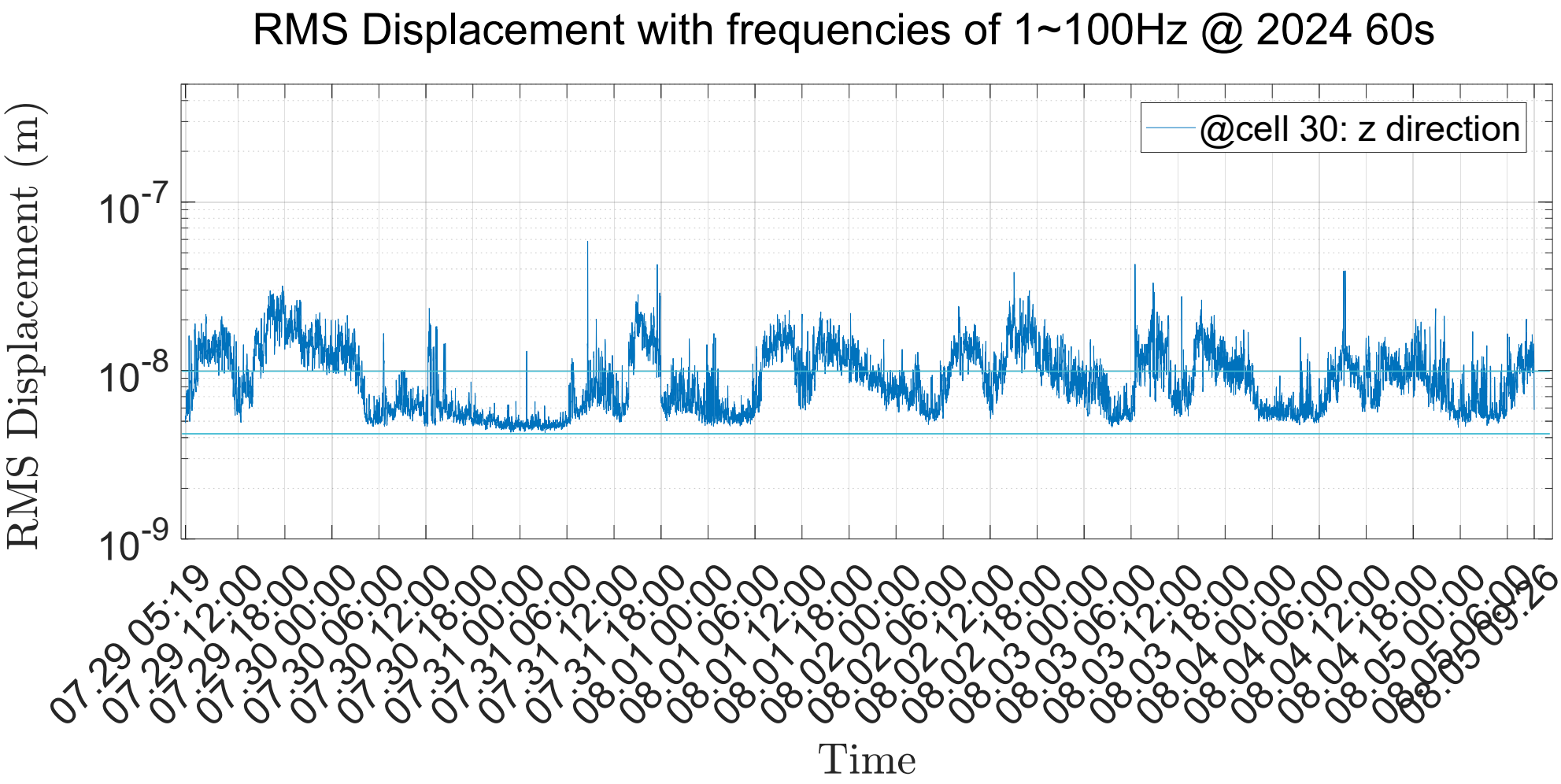




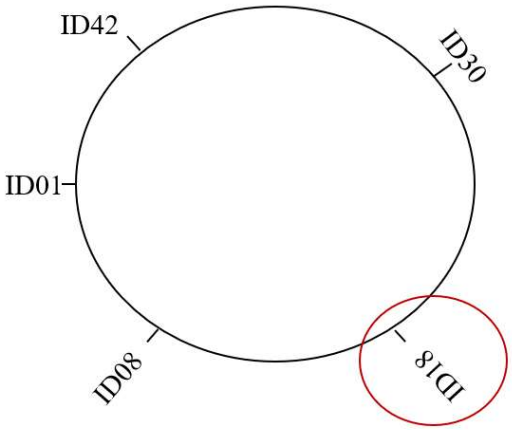
On the ground (close to slab4) : C761

On ground (@main ring) : C700

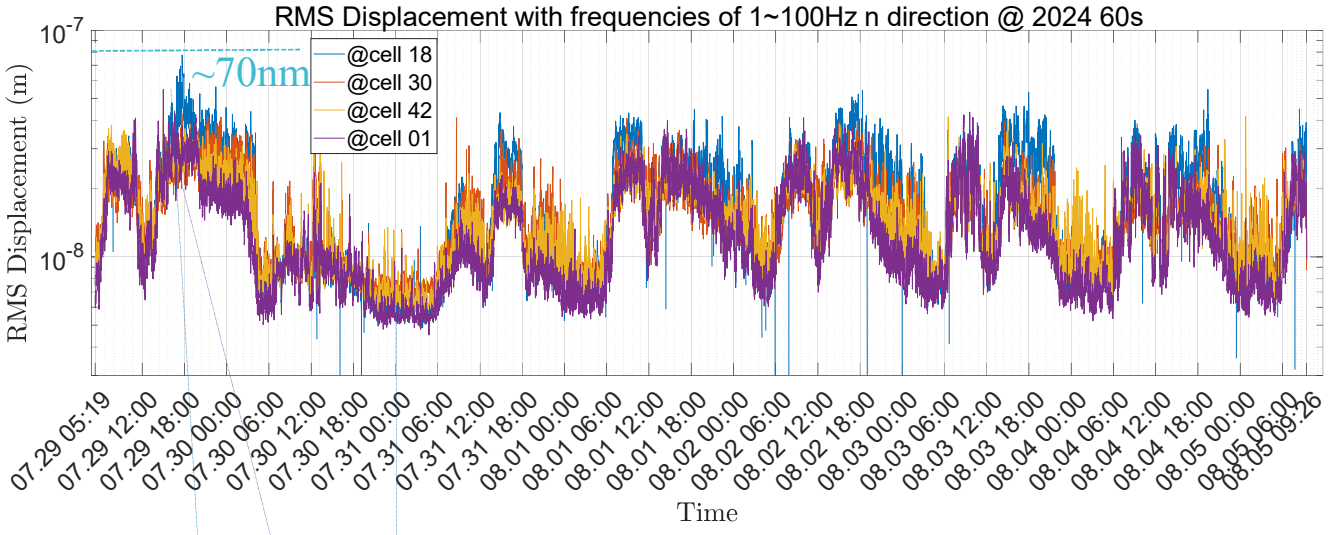
6. The actual vibration level on slab: vertical direction

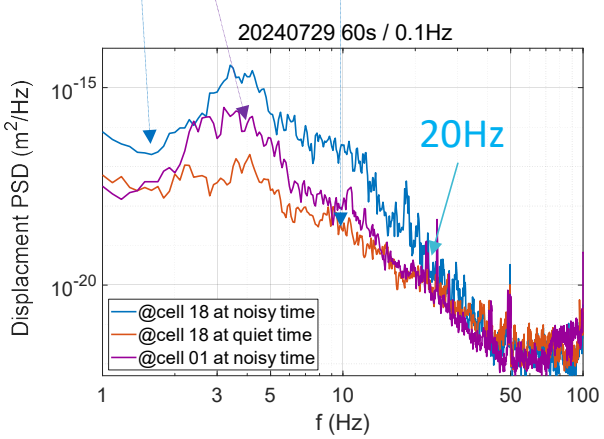


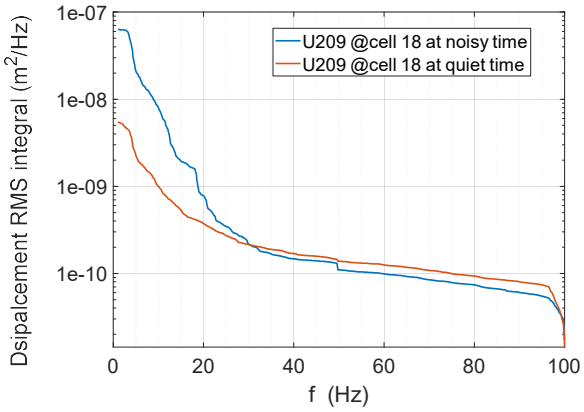
6. The actual vibration level on slab



The noise level close to ID18 is higher than other positions. We suspect it is coming from the traffic close by.

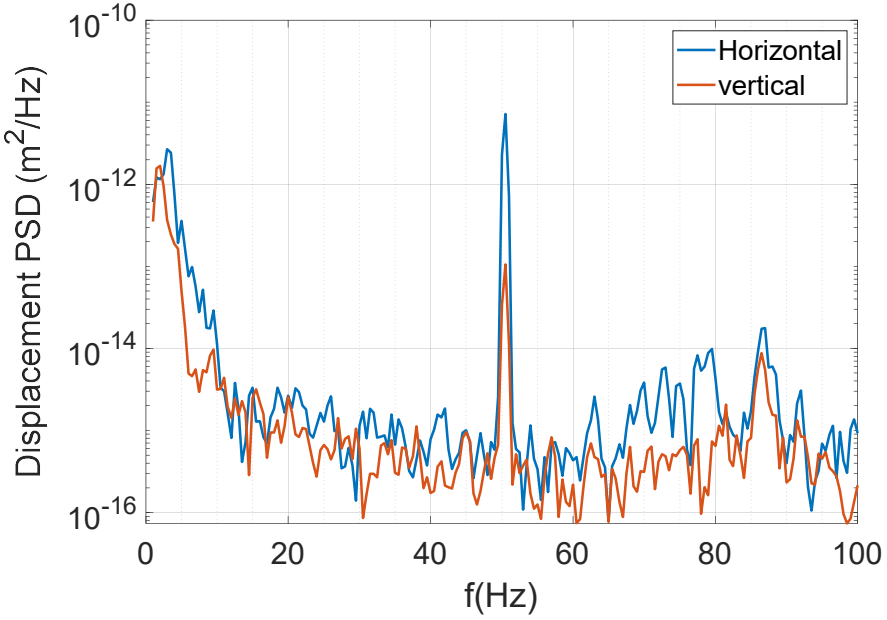


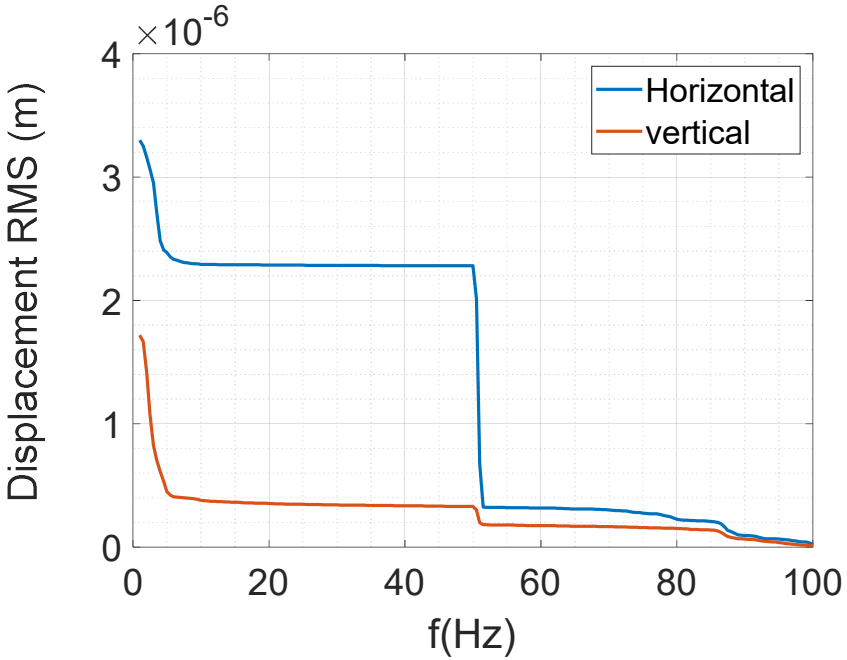




7. Beam instability issue: the 50Hz vibration

The BPM signals of beam on HEPS storage ring shows that there is a 50Hz vibration which causes ~2μm and ~0.3μm orbit displacement horizontal and vertical respectively.

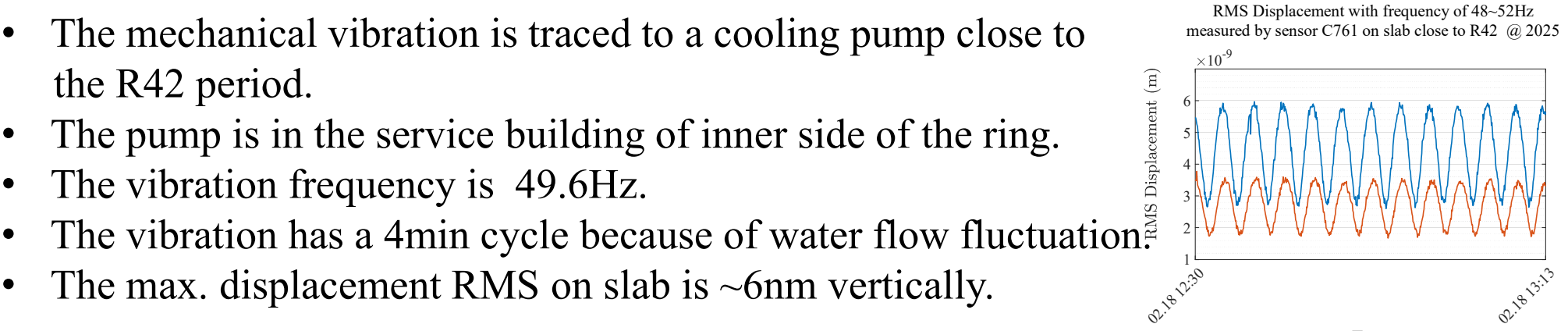


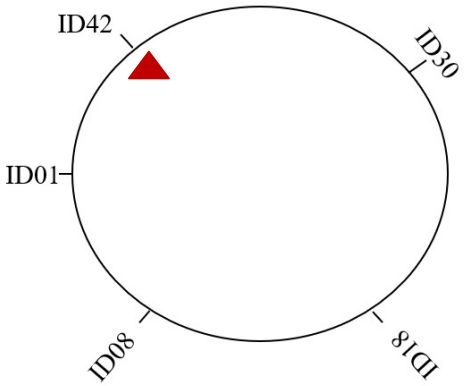


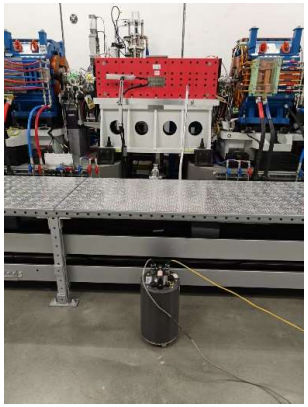
7. Beam instability issue: the 50Hz vibration

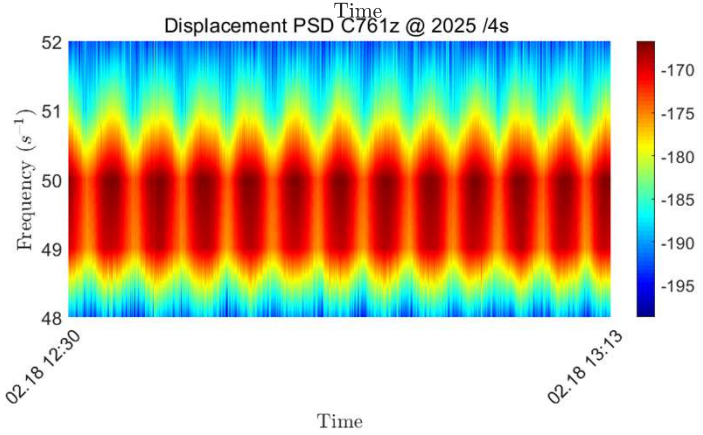
The internal vibration source of HEPS

- The mechanical vibration is traced to a cooling pump close to the R42 period.
- The pump is in the service building of inner side of the ring.
- The vibration frequency is 49.6Hz.
- The vibration has a 4min cycle because of water flow fluctuation.
- The max. displacement RMS on slab is ~6nm vertically.



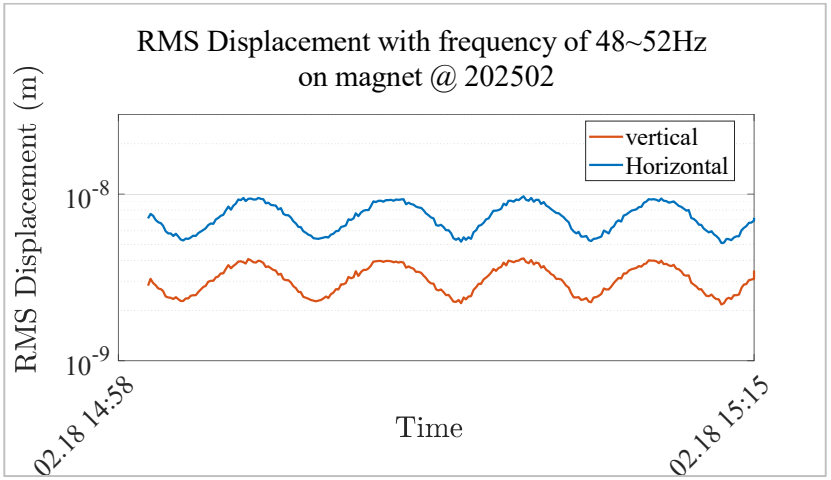


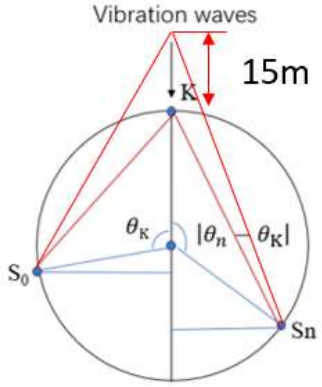


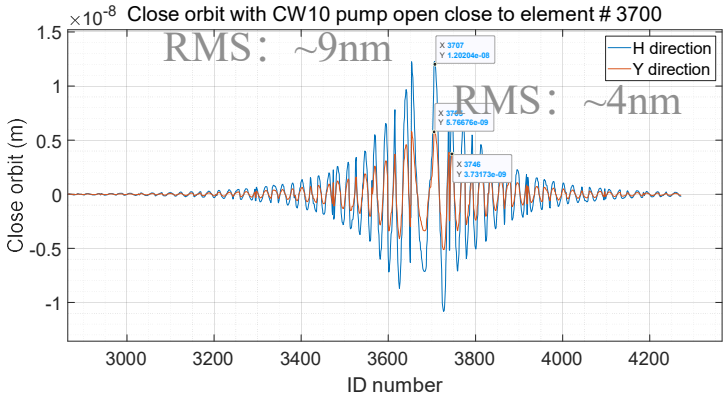


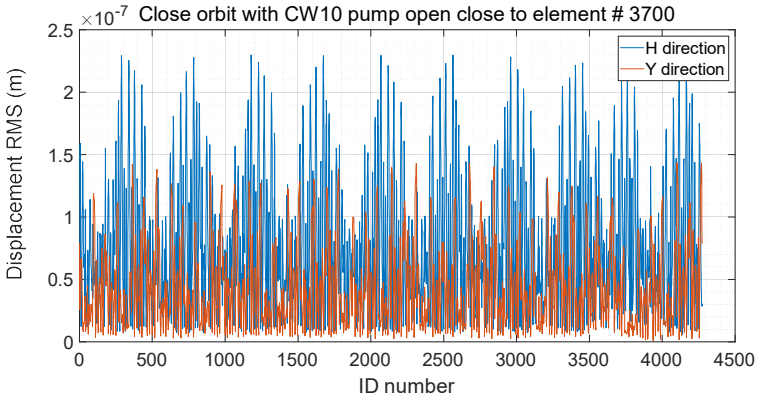
7. Beam instability issue: the 50Hz vibration

- The vibration is magnified horizontally but damped vertically on the magnet.
- The vibration influence to the beam is simulated by the point wave model.
- The results shows that the pump has effects to the beam, but seems not the major cause.
- The reason of the 50Hz vibration of the beam is still under investigation.









Summary

- HEPS is a 4th generation light source with designed natural emittance of 35pm.
- A frequency related beam dynamics model is developed for the vibration evaluation under consideration of the wave velocity and the wave decay.
- The vibration specification is set to be 25nm with decomposed requests to the slab, girder magnet assembling and BPM girder (>54Hz, no amplification).
- All the decomposed specification has been fulfilled. However the vibration level still increased comparing with the bare ground test results before construction. Surrounding transportation is suspected to be the major contribution.
- The transportation influences are measured with different load of crane and cars with different driving speed. Crane with load bigger than 10t running on road about 200m away has visible influence on the vibration level of the SR slab. 2t cars on Xinfen St. has influence to slab of SR.
- The BPM signal of HEPS SR shows big 50Hz noise. Mechanical vibration is traced to a pump close to R42 period. But the pump vibration measurement and simulation results show that it is not the major cause for the 50Hz beam noise. The reason is still under investigation.

Thanks for your attentation