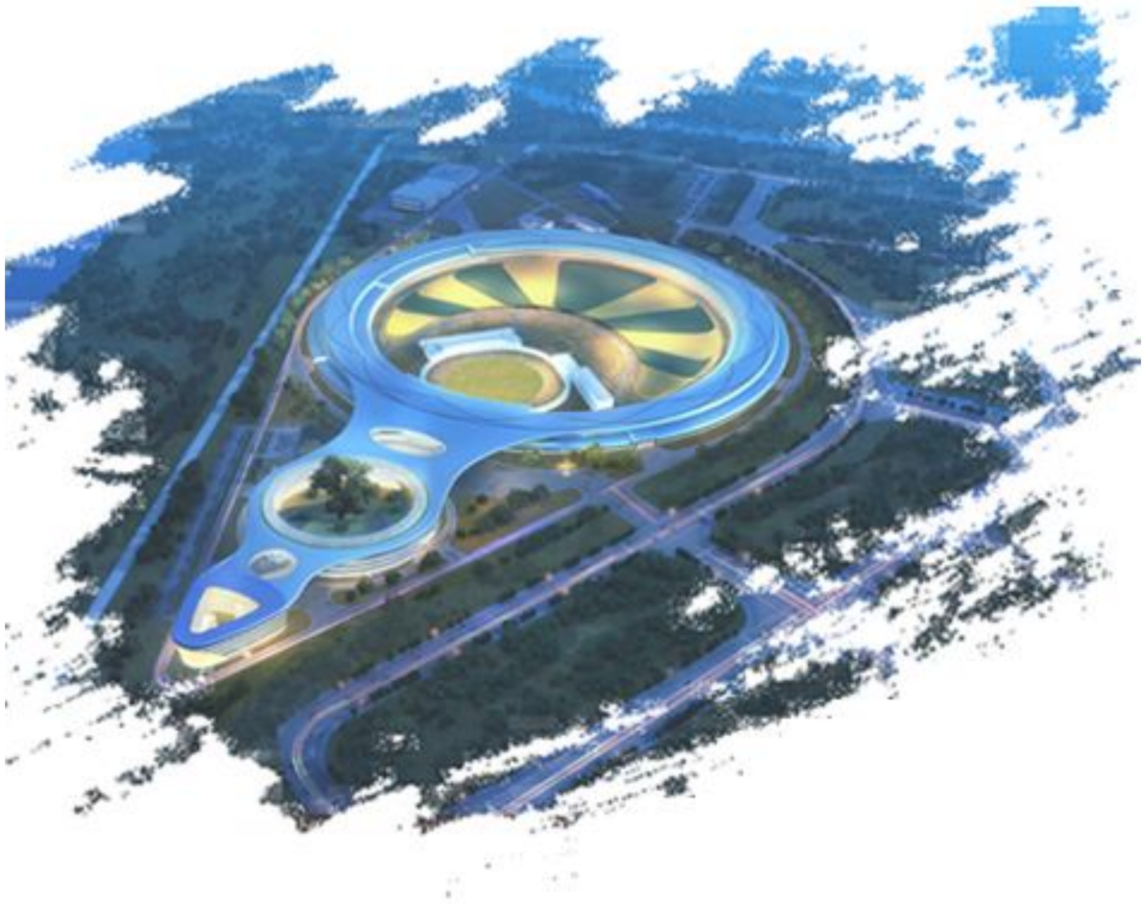
The orbit stability issue in the initial commissioning stage of High Energy Photon Source



Huang Xiyang

Accelerator Physics System, HEPS

March 18，2025

I.FAST Workshop 2025 · Karlsruhe, Germany

CONTENT

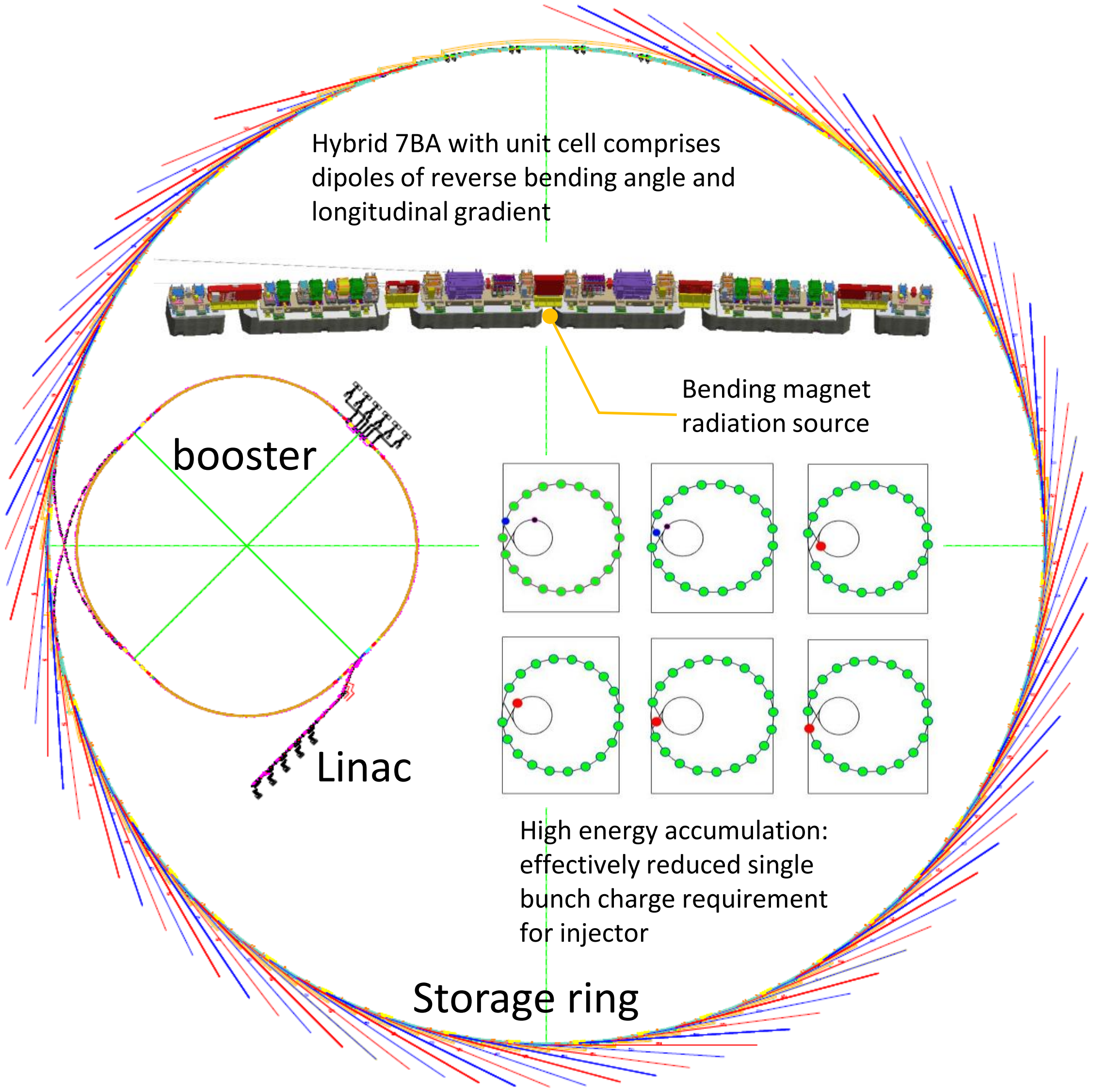
1. Introduction
2. Orbit motion issue
3. Orbit feedback
4. Summary

Introduction

High Energy Photon Source

(HEPS | High Energy Photon Source)

Parameter	Value
Energy	6 GeV
Circumference	1360.4 m
Emittance	34 pm·rad
Brightness	>1x10^{22} phs/s/mm^2/$mrad^2$/0.1%BW
Betatron tune	115.15/104.29
Radiation loss	2.64 MeV
Momentum compaction factor	1.83e-5
Harmonic ratio	3



Hybrid 7BA with unit cell comprises dipoles of reverse bending angle and longitudinal gradient

Bending magnet radiation source

High energy accumulation: effectively reduced single bunch charge requirement for injector

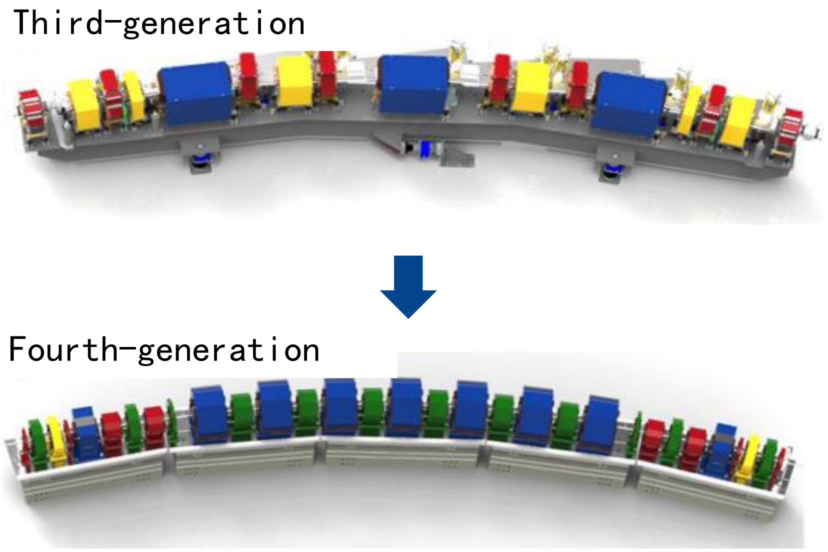
The Fourth-generation Light Source

Multi Bend Achromat, MBA

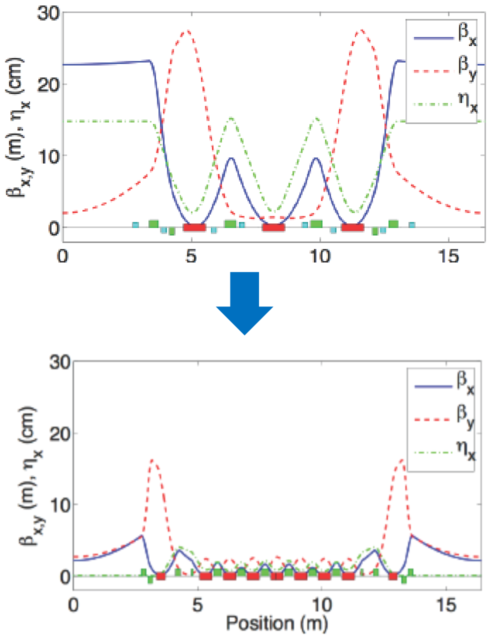
M = number of bending magnets in one achromat cell

Emittance in third-generation light source： 1000~5000 pm·rad

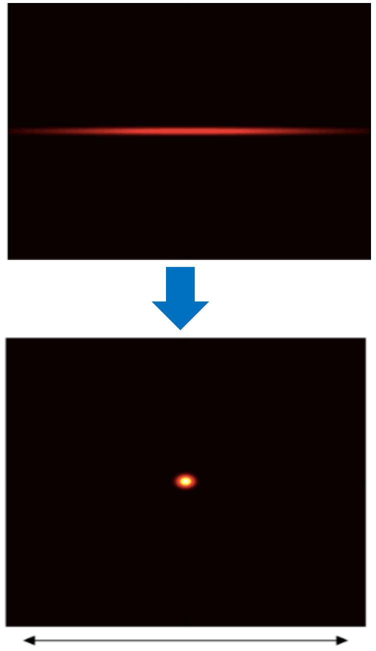
Emittance in fourth-generation light source： ≲ 100 pm·rad →**X-ray diffraction limit**



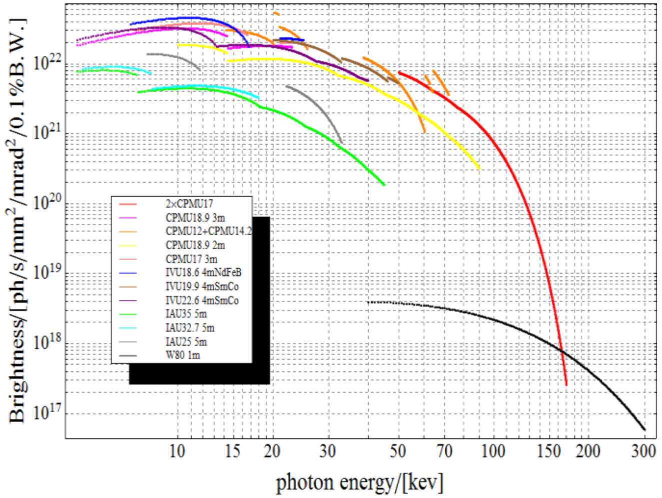
Layout of one cell



Lattice



Beam profile



Milestones

May 12, 2022
The Linac Vacuum-sealing in the tunnel completed

Jan. 13, 2023
The Booster Vacuum-sealing in the tunnel completed

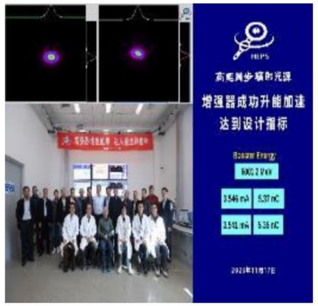
Feb. 1,2023
The first girder was installed in the storage ring tunnel


中国新闻网 中新网
WWW.CHINANEWS.COM

HEPS LINAC

Beam Energy	500 MeV
Bunch Charge	2.61 nC
Trans. Efficiency	94 %

Mar. 14, 2023
The first electron beam



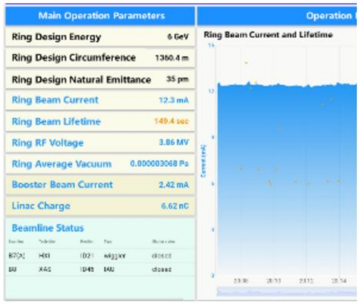
高能同步辐射光源
增强器成功升能加速
达到设计指标

Booster Energy

6000.2 MeV	
3.546 mA	5.37 nC
3.541 mA	5.35 nC

2023年11月17日

Nov. 17, 2023
Electron Beam Ramped Up to 6 GeV



Main Operation Parameters	
Ring Design Energy	6 GeV
Ring Design Circumference	1360.4 m
Ring Design Natural Emittance	35 pm
Ring Beam Current	12.3 mA
Ring Beam Lifetime	149.4 sec
Ring RF Voltage	3.86 MV
Ring Average Vacuum	0.000003068 Pa
Booster Beam Current	2.42 mA
Linac Charge	6.62 nC

Beamline Status

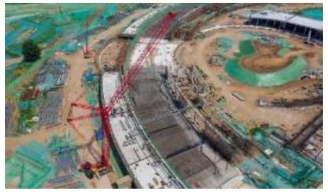
Aug. 18, 2024
Electron beams with currents higher than 10mA were successfully stored.


2121A W75 第一束光
2024.10.12 21:30
距光源点 330m
1mA 流强
11mm Gap

Oct. 12, 2024
the SR X-ray emitted from the R21 wiggler was successfully transmitted to the end station.

June 29, 2019
Groundbreaking ceremony

July 1, 2020
The first steel beam was installed



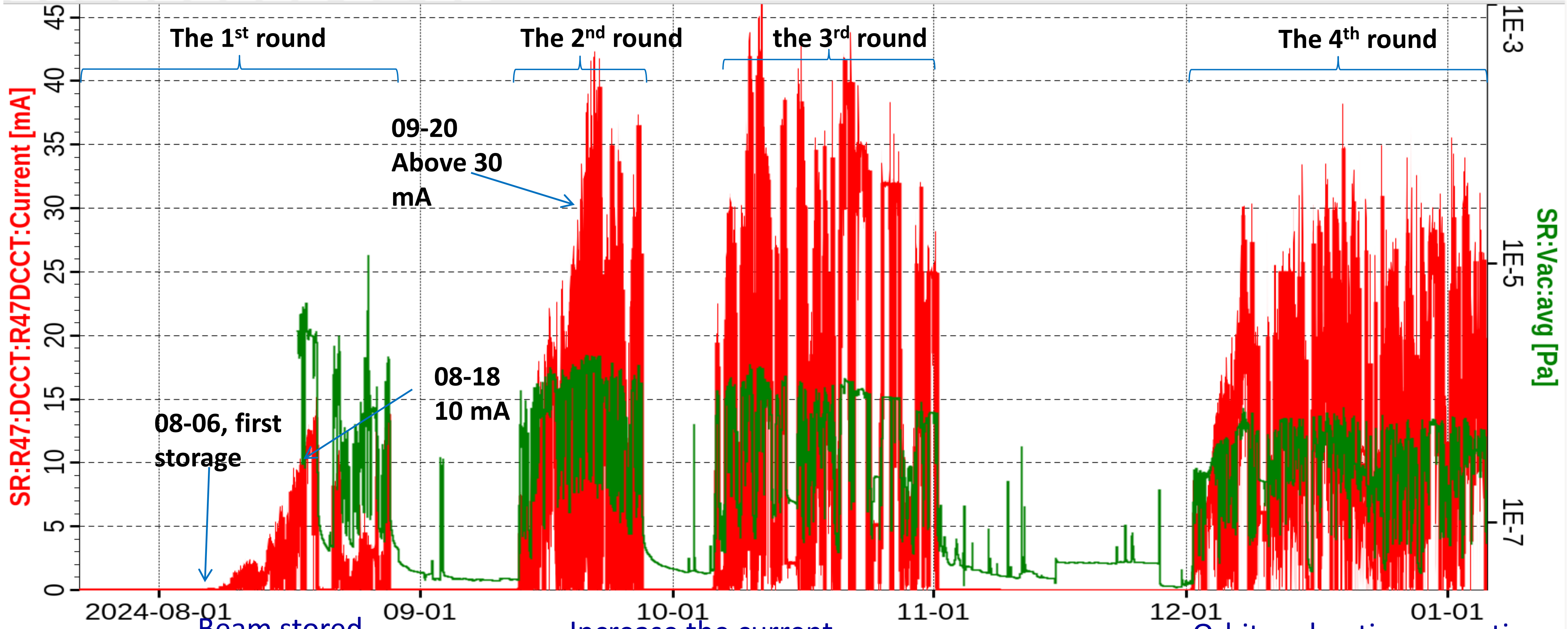
Apr. 13, 2021
Utility installation in NO.2 Hall commenced

June 27, 2021
Roof-sealing work for the main ring building completed

June 28, 2021
HEPS Installs First Piece of Accelerator Equipment in Linac Tunnel.

Nov. 3, 2023
Civil Construction for ancillary buildings completed

4 Rounds of SR Commissioning



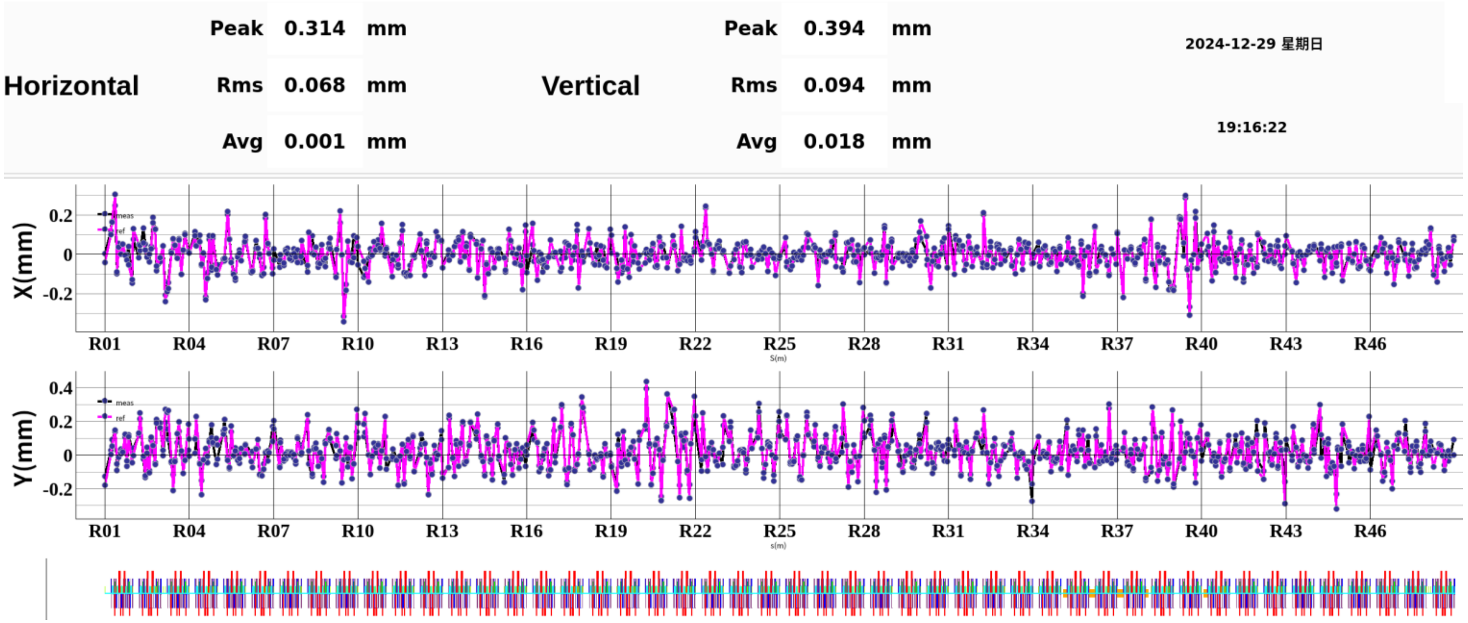
Beam stored,
current reach 10mA

Increase the current,
Beamline commissioning

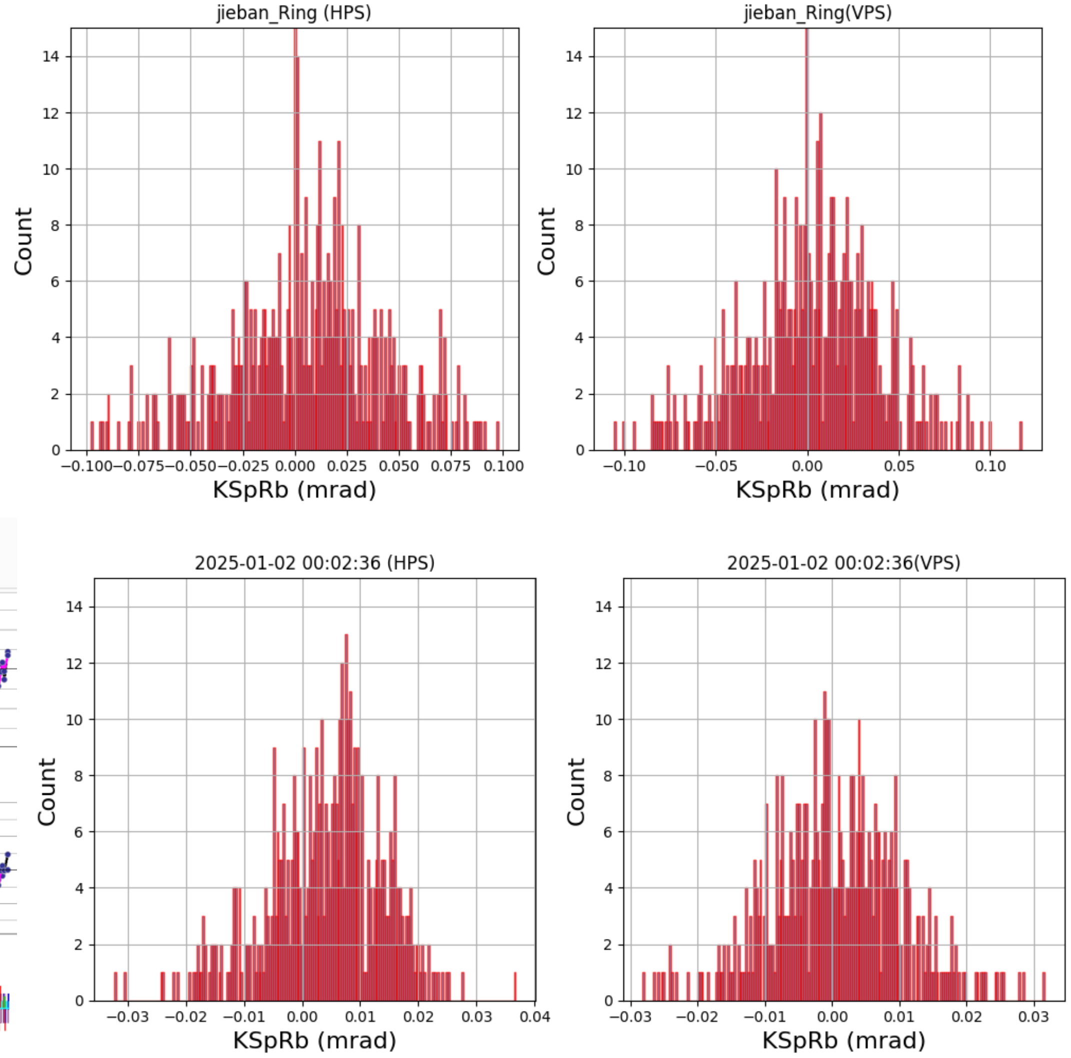
Orbit and optics correction,
parameter optimization.

Orbit Correction

- Based on measured response matrix
  - Using 20%~50% SVD values
  - H/V RMS Orbit <100um (w/ BBA)
  - Reduce the corrector strength while remaining rms orbit

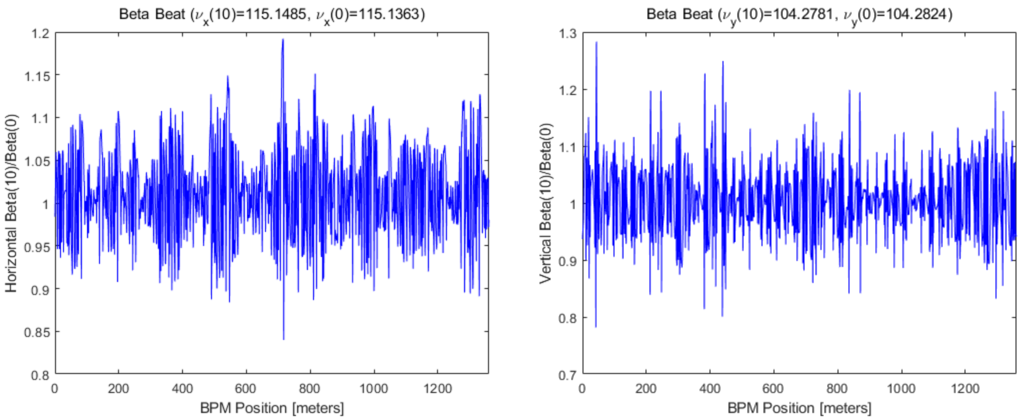


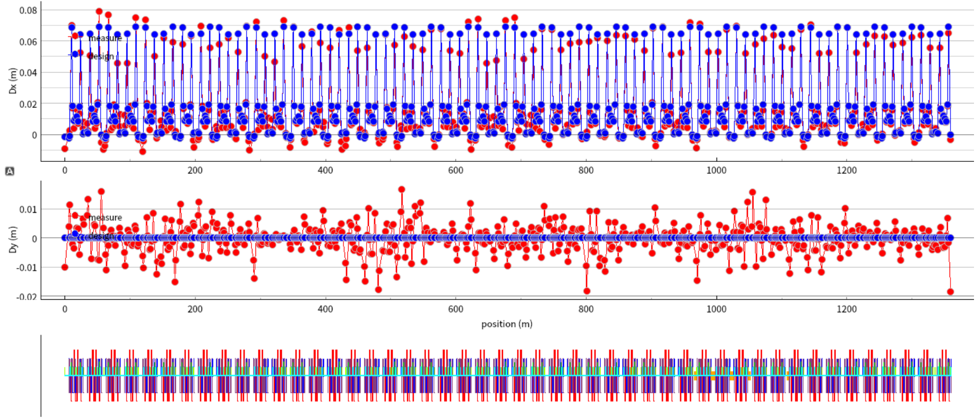
	Peak	0.314	mm		Peak	0.394	mm	2024-12-29 星期日
Horizontal	Rms	0.068	mm	**Vertical**	Rms	0.094	mm	
	Avg	0.001	mm		Avg	0.018	mm	19:16:22

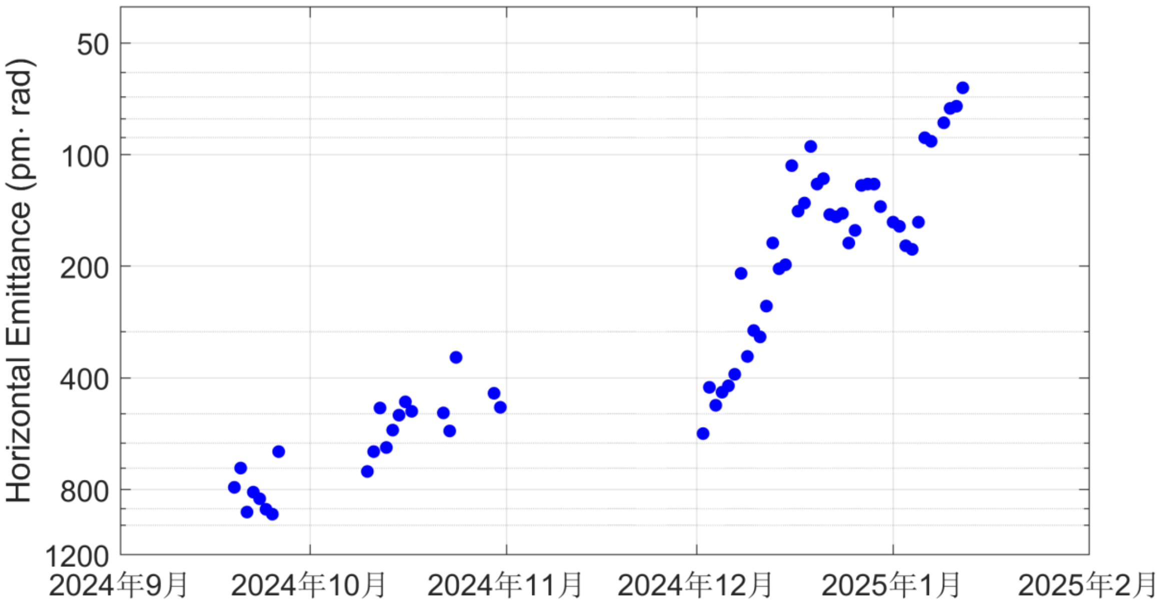


Optics Correction

- Using LOCO, RM and measured dispersion
  - ▪ Multi-iterations of correction
  - ▪ Using skew quads to reduce coupling and Dy
    - ◆ BetaBeating~4.7%/5.6%
    - ◆ std(ΔDx/ΔDy)~3.9mm/5mm
    - ◆ Coupling~10%
    - ◆ H emittance less than 100 pm.rad







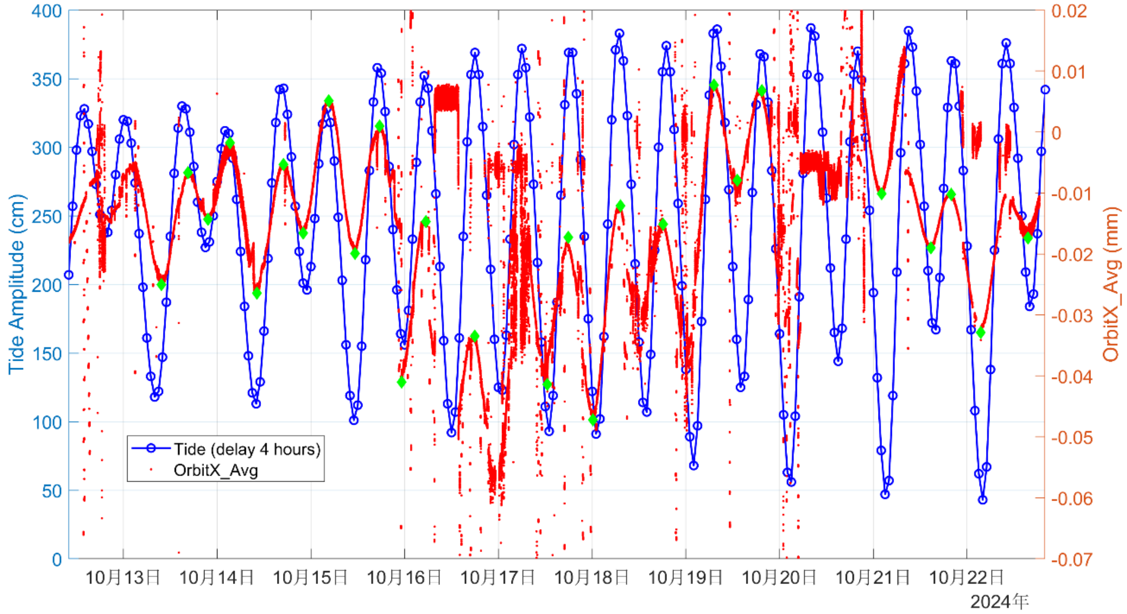
Orbit stability issue

Beam Orbit Motion and Sources

- Long-term stability ($< 10^{-2}$Hz) :

➢ We observed that the horizontal average orbit drifts slowly with a period of about 12 hours. This is believed to be related to periodic changes in the circumference. This issue can be compensated by adjusting the RF frequency. The source of the slow drift is still under investigation, but it is currently speculated that it may be related to tides and temperature.

➢ The blue dots represent the tidal height data of Tanggu station in Tianjin (about 140 km in straight-line distance from HEPS), and the red dots represent the horizontal average orbit. It is evident that they have the same period.

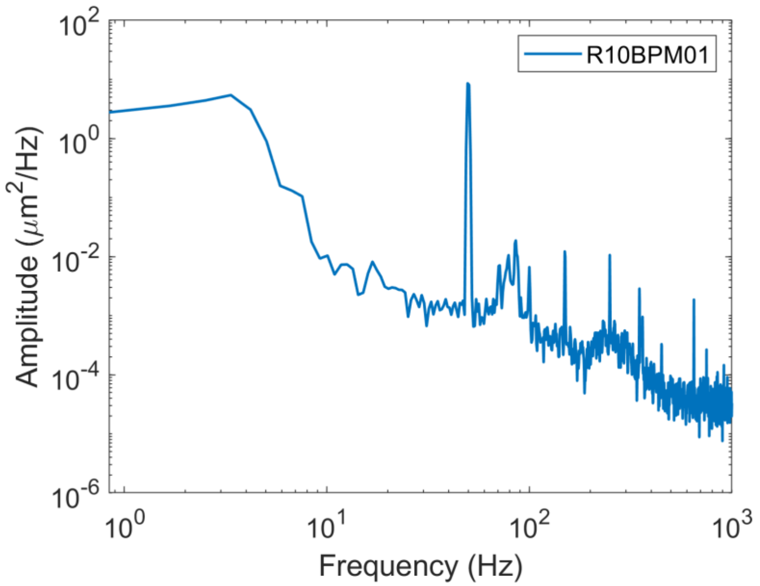


Beam Orbit Motion and Sources

- Mid-term orbit motion (10^{-2}-10^{3}Hz):

➢1,000,000 turns TBT data was used to analyze the mid-term orbit motion.

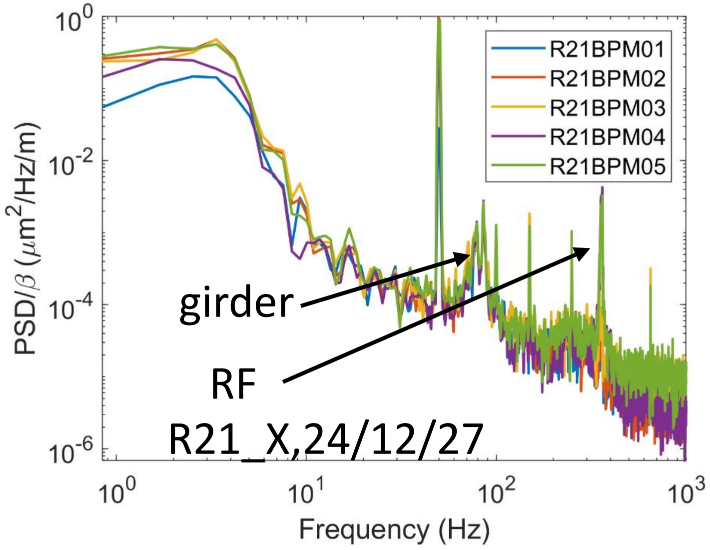
➢Without orbit feedback, the integrated orbit motion is about 4μm/2μm in both planes @ID BPM in the low beta-section.

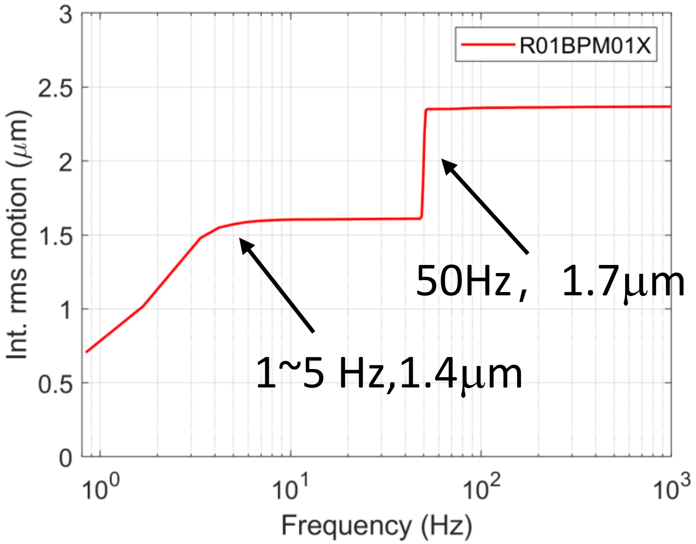


Frequency range or Spectral peaks	Sources
<5 Hz	Ground vibration
50 Hz	Power supply noise?
70~84 Hz	Girder resonant
360 Hz	RF
1000-TBT	BPM noise

Beam Orbit Motion and sources

- Mid-term stability (10^{-2}-10^{3}Hz):
  - 1,000,000 turns TBT data was used to analyze the mid-term orbit motion.
  - Without feedback, the integrated orbit motion is about 4μm/2μm in both planes @ID BPM.
  - The fluctuation of orbit motion mainly caused by low-frequency vibrations (1~5Hz) and power frequency (50Hz).
  - PSD shows peaks around 70-84 Hz and 360 Hz. These peaks may caused by girder resonance and RF noise.
  - However, the contribution of both to beam fluctuation is very small.





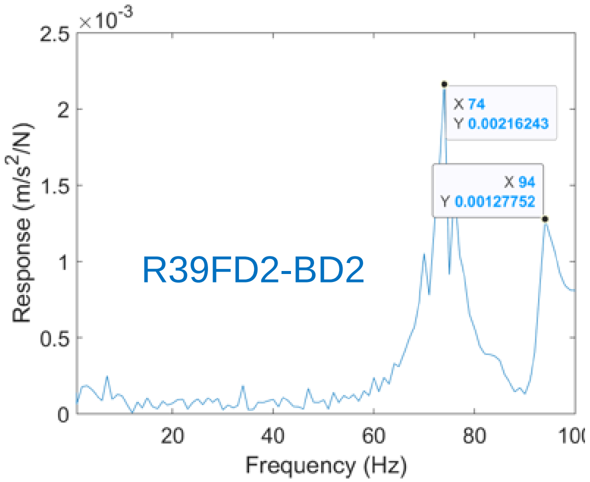
Girder resonant

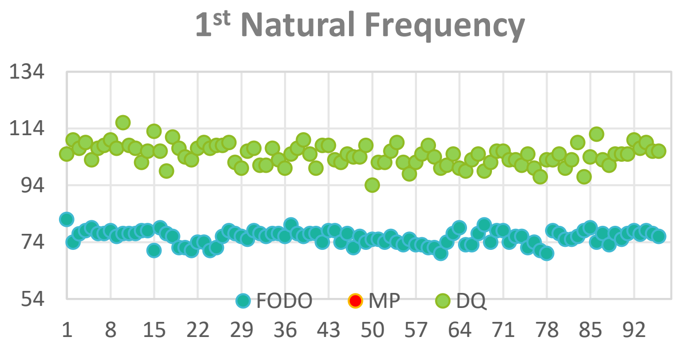
- All 288 support modules have been tested after the alignment in the tunnel, and all meet the requirements.

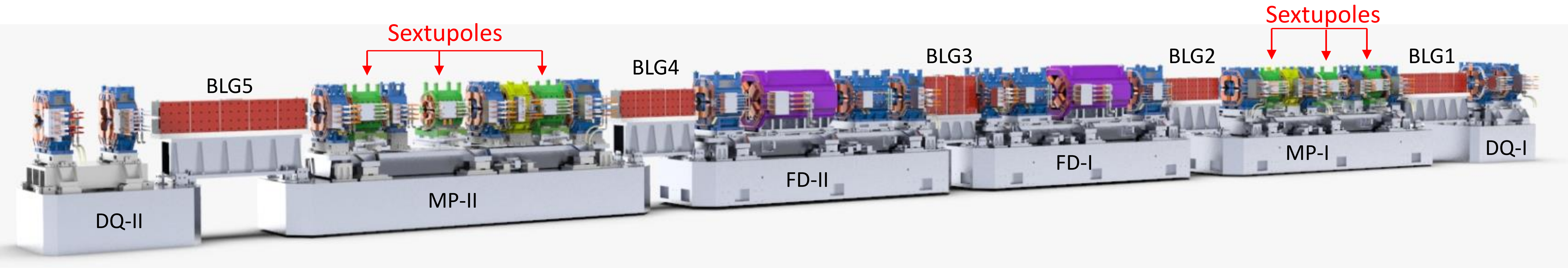
➢- Eigen frequency：≥70 Hz

➢- Transmissibility: ≤1.05

➢- Adjustment resolution : 1 μm

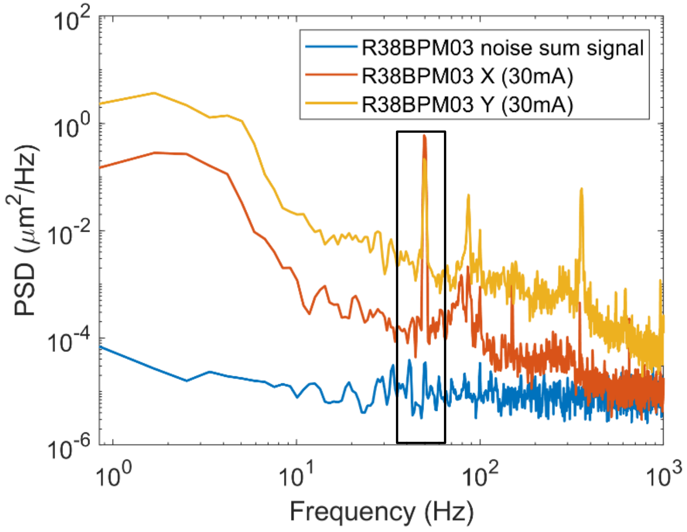


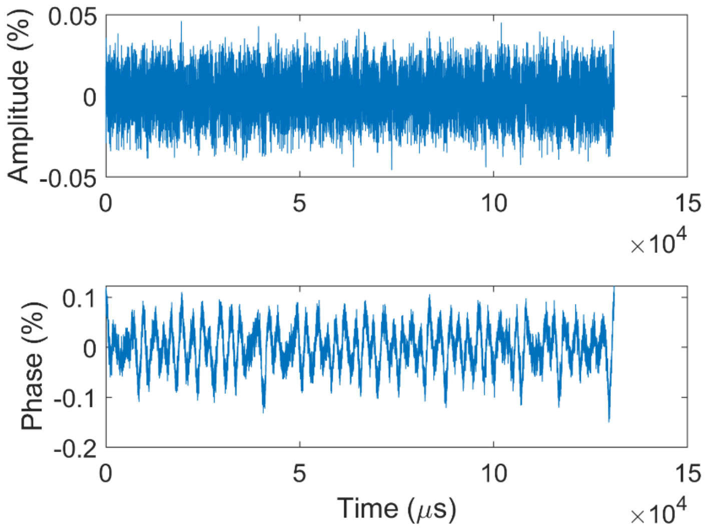




Potential source of 50 Hz noise

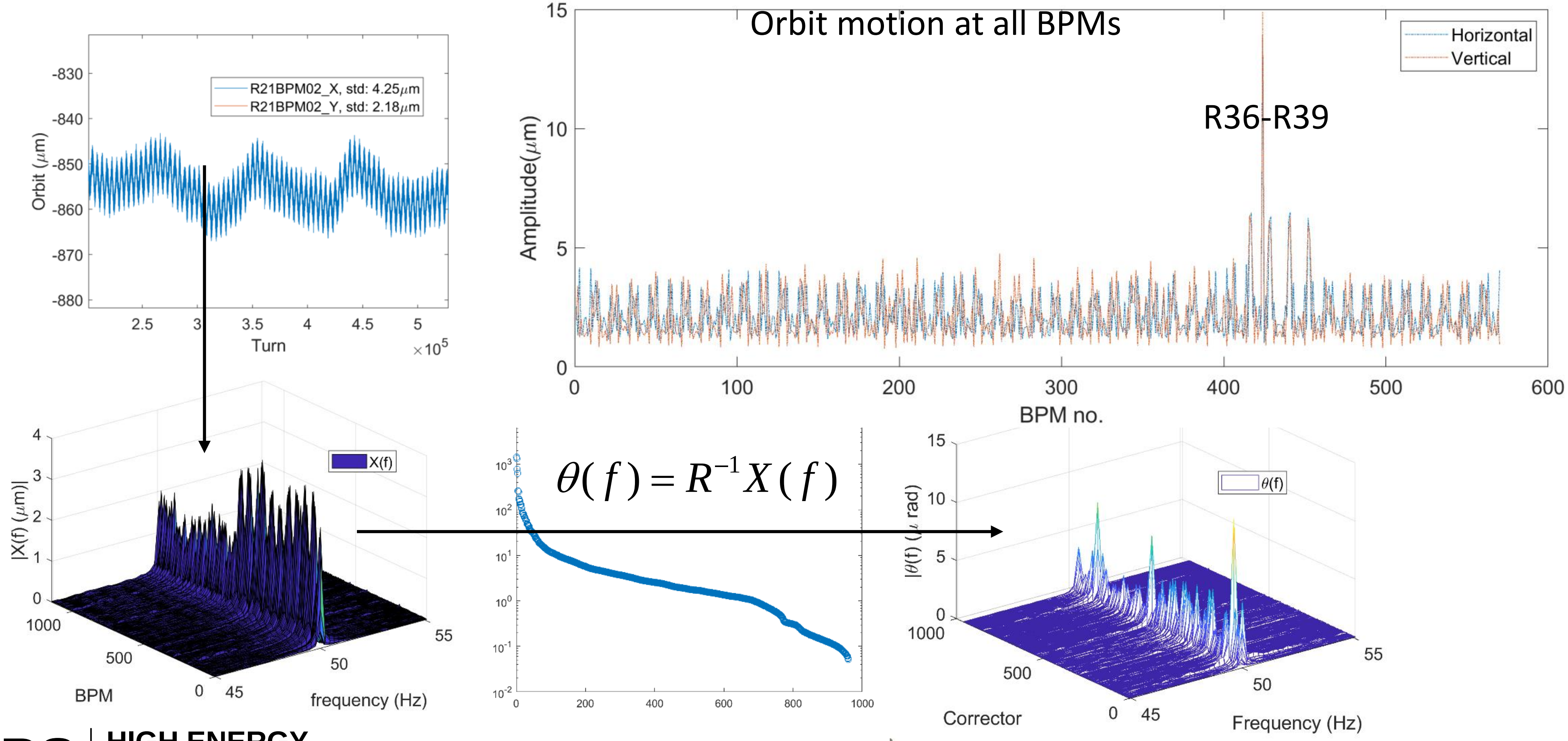
- BPM signal were compared w/ & w/o electron beam, there’s no 50Hz noise w/o beam.
- The amplitude and phase of the three RF cavities were found to be sufficiently stable.
- The 50 Hz peak of beam motion does not originate from BPMs and RF cavities.





Potential source of 50 Hz noise

- We analyze the location of perturbation source by global orbit motion and inverse response matrix.



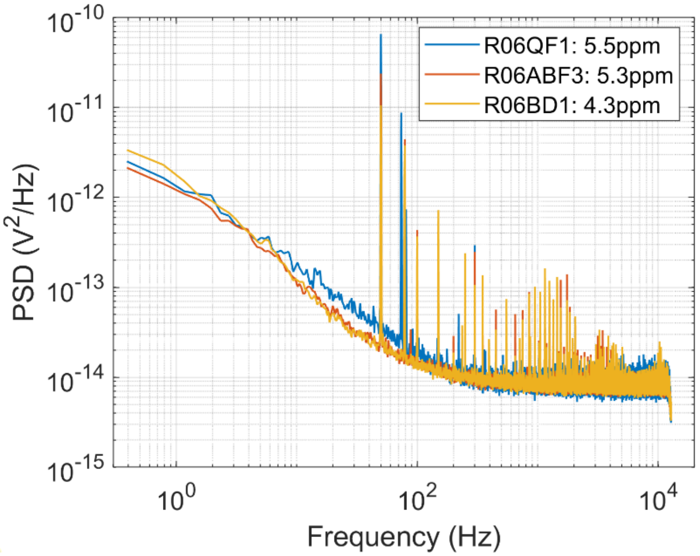
Orbit motion at all BPMs

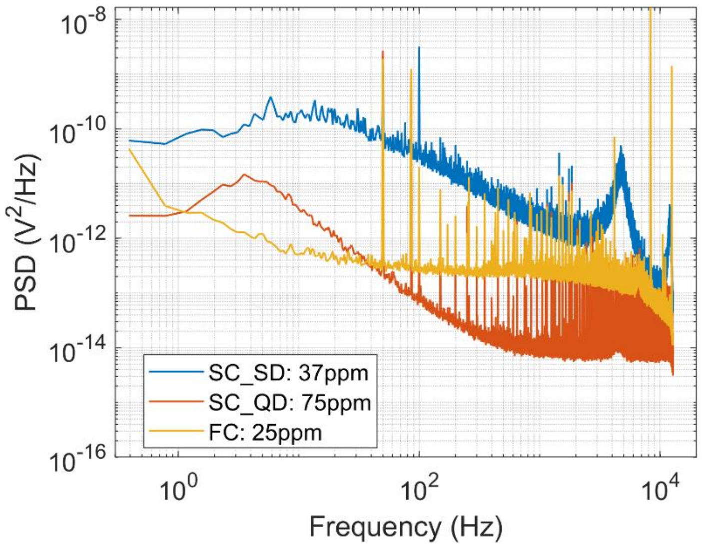
R36-R39

$$\theta(f) = R^{-1}X(f)$$

Power Supply Noise

- To invest the 50Hz noise, we need to evaluated the orbit motion induced by power supply noise.
- The measurement of power supply noise's PSD is done by the CoCo - 80X oscilloscope, including all types of magnets (quadrupole, combined dipole-quadrupole magnet, trim coil, and fast corrector).





Power Supply Noise Induced Orbit Motion

- Power supply current noise ΔI_{rms} can be calculated by measuring the current noise PSD $S_n(f)$

$$\Delta I^2_{\mathrm{rms}} = \int_{f_1}^{f_2} S_n(f)df,$$

- Usually quoted in units of ppm:

$$n = \frac{\Delta I_{\mathrm{rms}}}{I_{\max}}.$$

- Considering the effect of vacuum chamber,

$$H_v(f) = \begin{cases} e^{-0.0001\times f^{0.96}}, & for\ \mathrm{FC} \\ e^{-0.05\times f^{0.58}}, & for\ \mathrm{other\ magnets} \end{cases}$$

- We define the reduced power supply noise:

$$\tilde{n} = \frac{\Delta \tilde{I}_{\mathrm{rms}}}{I_{\max}} = \sqrt{\int_{f_1}^{f_2} H_v^2(f)S_n(f)df / I_{\max}},$$

Power Supply Noise Induced Orbit Motion

- Orbit motion amplification factor A is defined as : $A_{ps} = \frac{z}{\sqrt{\beta_0}\tilde{n}},$

  where

$$z = \frac{\sqrt{\beta\beta_0}}{2\sin\pi\nu_z}\cos(\phi - \pi\nu_z)\theta_z,$$

- For quadrupole:

$$\theta_{\rm rms} = \tilde{n}KLd_{\rm rms}\frac{I_{\rm max}}{I_{\rm K}},$$

where， K and I_k is the strength and operation current， L is the effect length， d_{rms} is the rms displacement。

- For corrector

$$\theta_{\rm rms} = \tilde{n}\theta_{\rm max}.$$

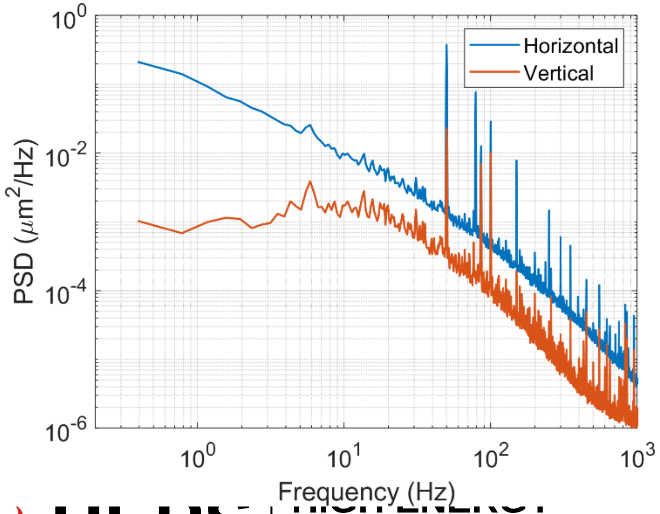
- Finally, the amplification factor can be calculated:

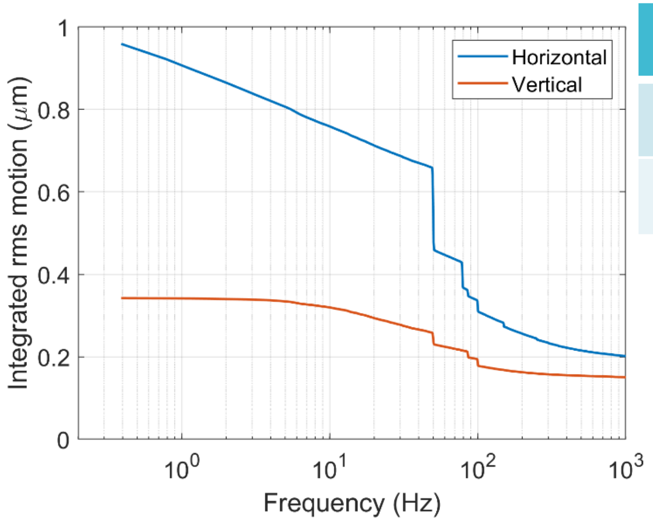
$$A_{ps}^2 = \begin{cases} \frac{6\beta_a}{\sin^2\pi\nu}\sum_j^{corr}\theta_{j,\rm max}^2, & for \text{ corrector} \\ \frac{6\beta_a}{\sin^2\pi\nu}\sum_j^{quad}(KLd_{\rm rms}\frac{I_{\rm max}}{I_{\rm K}})_j^2, & for \text{ quadrupole} \end{cases}$$

Power Supply Noise Induced Orbit Motion

Table: Contribution of each type of magnet power supply

	Ax($m^{1/2}$)	Ay($m^{1/2}$)	Noise (ppm)	H (um)	V (um)
Q	4.4*10^{-3}	3.1*10^{-3}	5.5	0.023	0.016
ABF	8.6*10^{-2}	1.2*10^{-3}	5.3	0.34	0.005
BD	2.6*10^{-1}	1.1*10^{-3}	4.3	0.80	0.003
SC	1.2*10^{-2}	8.0*10^{-3}	37(trim on SD)	0.42	0.28
FC	6.1*10^{-3}	4.6*10^{-3}	25	0.25	0.19
Total				0.96	0.34

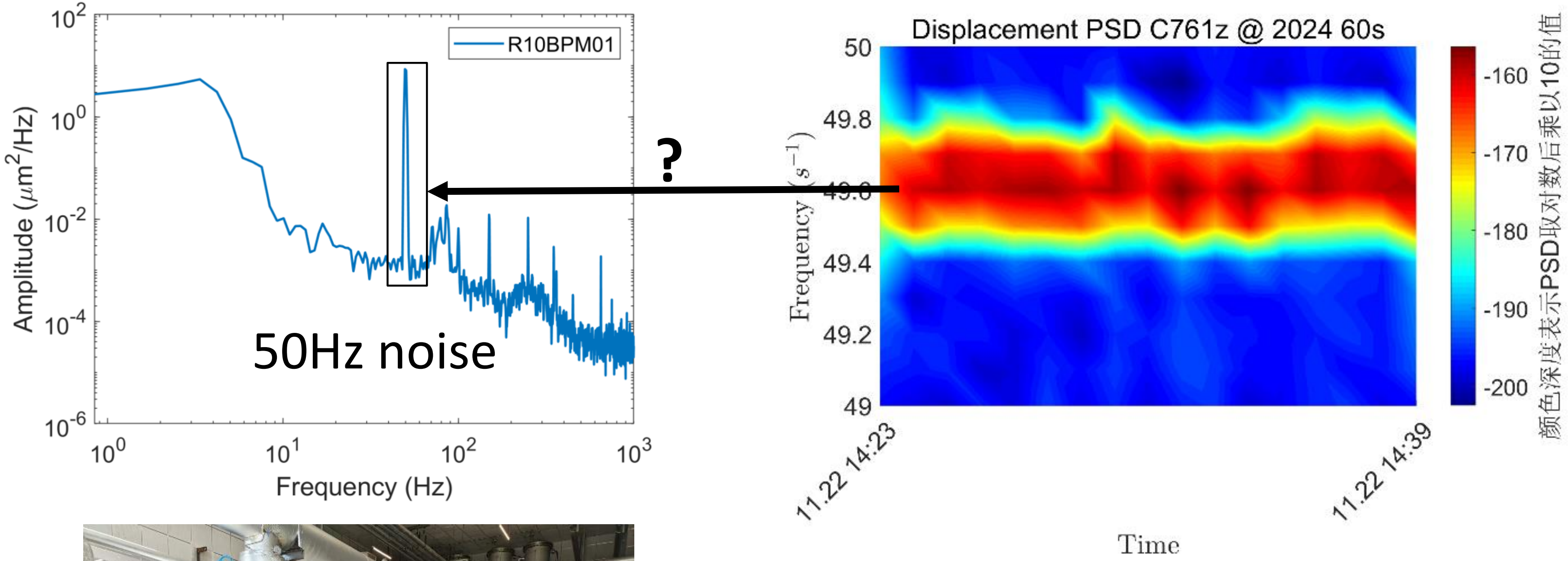




50Hz	PSD (um^2/Hz)	Integrate (um)
H	0.375	0.2
V	0.023	0.03

The PS noise does not significantly contribute to the 50Hz beam motion.

Vibration on CW10 Pump Room

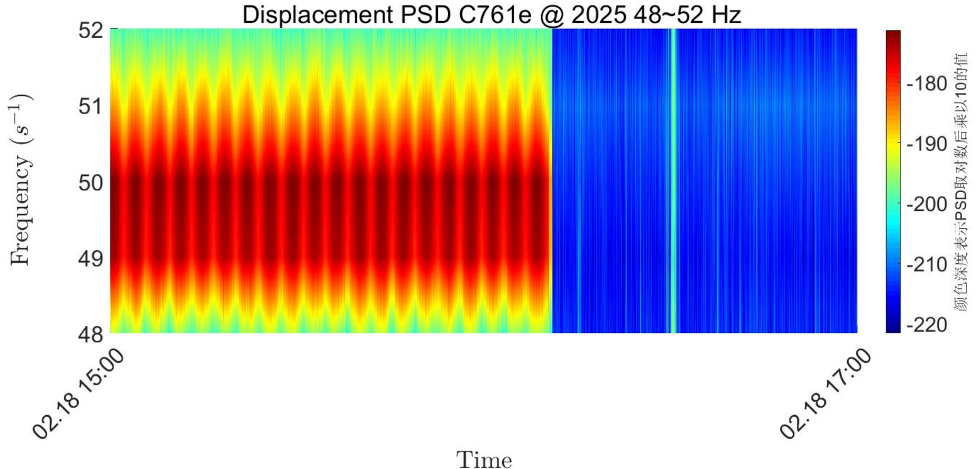


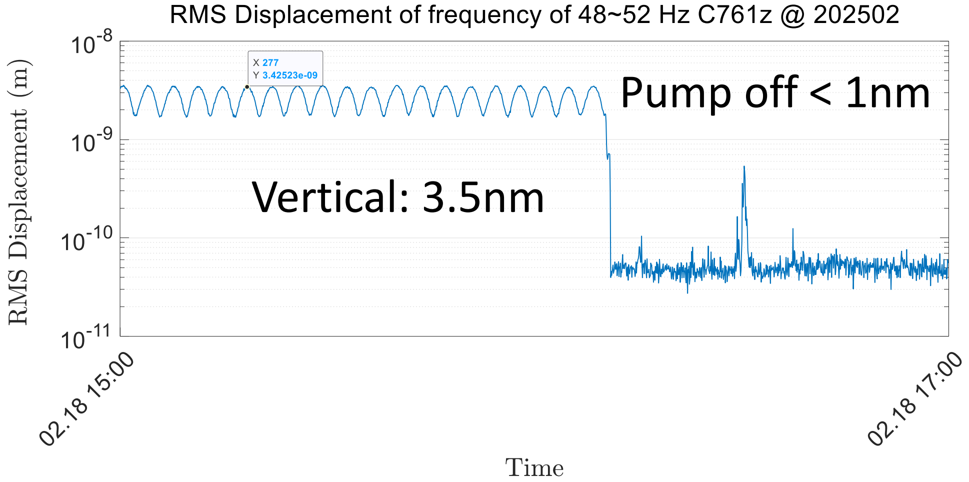
CW10 pump

- ➢ We have detected vibrations around 50Hz on the floor of the water pump room near R42.
- ➢ Vibrations with an amplitude of 5nm rms were found at 49.6Hz on R42QD6 according to further measurements.

Experiment with CW10 Pump on/off

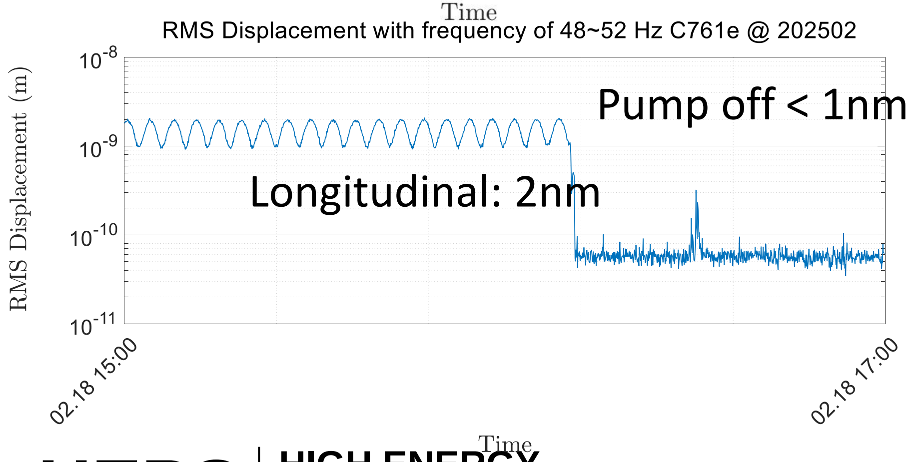
- Vibration on the regular monitoring point U206 (on the floor in R42 area)


Displacement PSD C761e @ 2025 48~52 Hz


RMS Displacement of frequency of 48~52 Hz C761z @ 202502

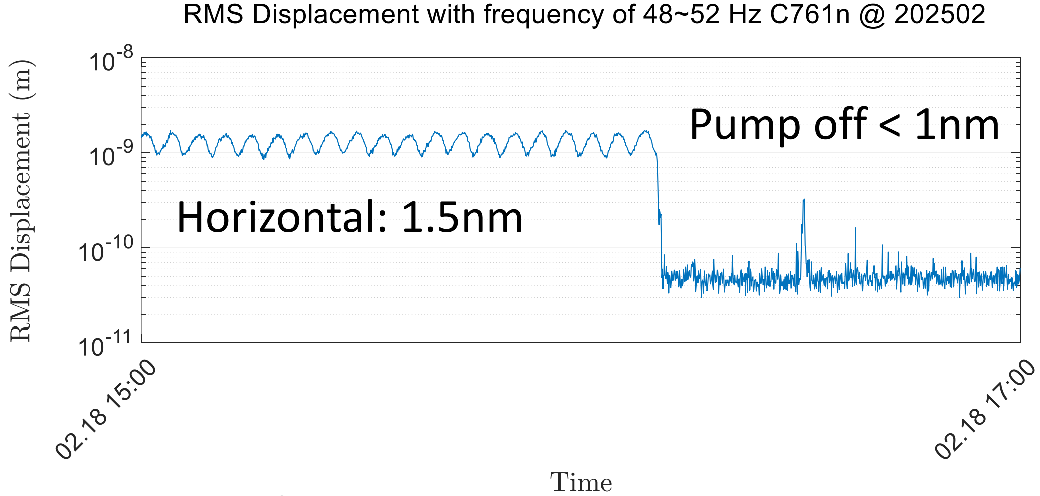
Pump off < 1nm

Vertical: 3.5nm


RMS Displacement with frequency of 48~52 Hz C761e @ 202502

Pump off < 1nm

Longitudinal: 2nm


RMS Displacement with frequency of 48~52 Hz C761n @ 202502

Pump off < 1nm

Horizontal: 1.5nm

Experiment with CW10 Pump on/off

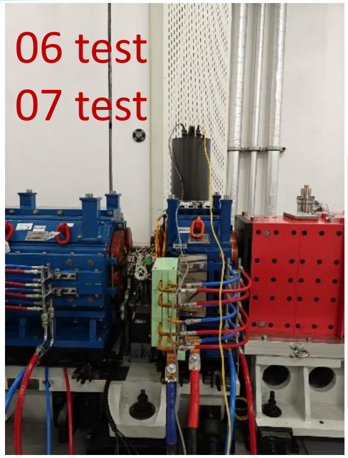
- Find the position with largest vibration amplitude in R42 area.

02+ 05+ 07 08+ 11 13

bridge

U206： 3.5nm

04 test near R42ABF4：： 4.8nm

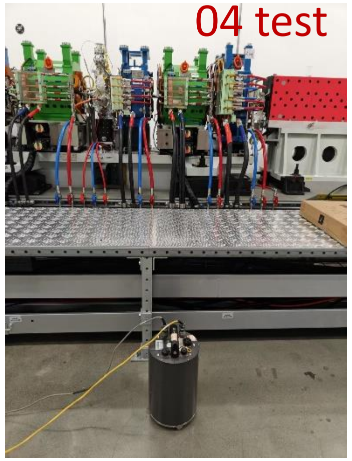


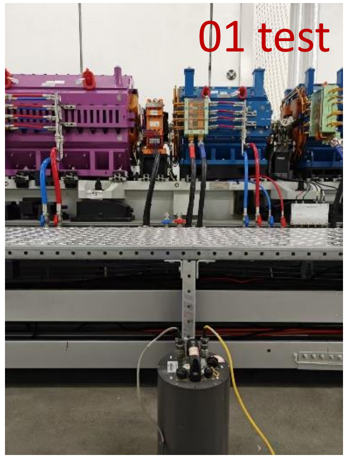
01 test： near R42ABF3： **6nm**

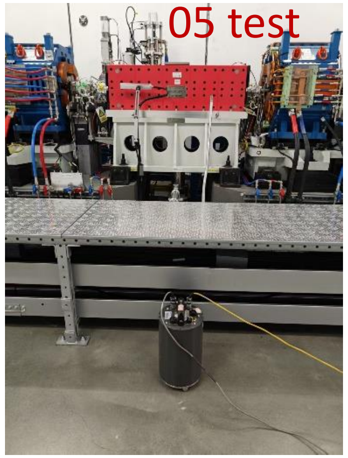
05 test： near R42QD4： 5nm

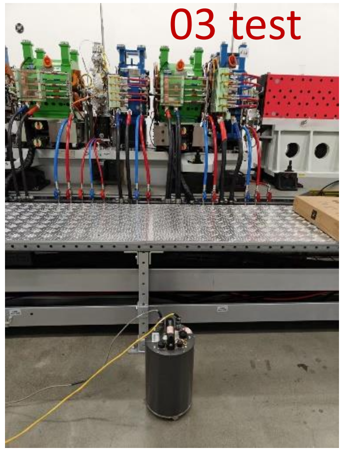
02 test： near R42QD3： 2nm

03 test: near R42QD2： 2nm





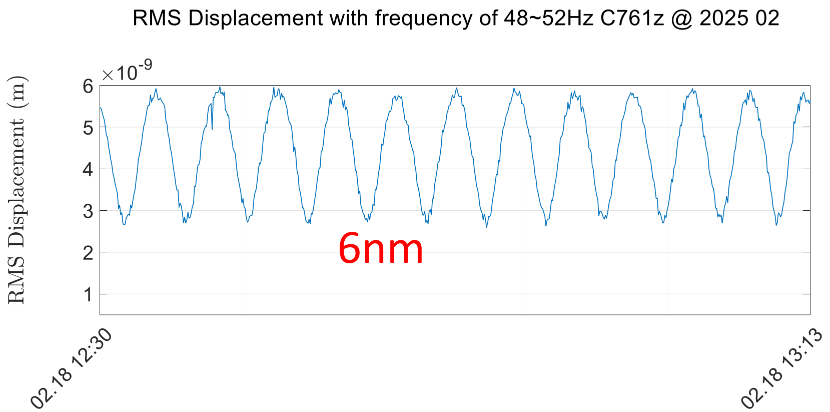


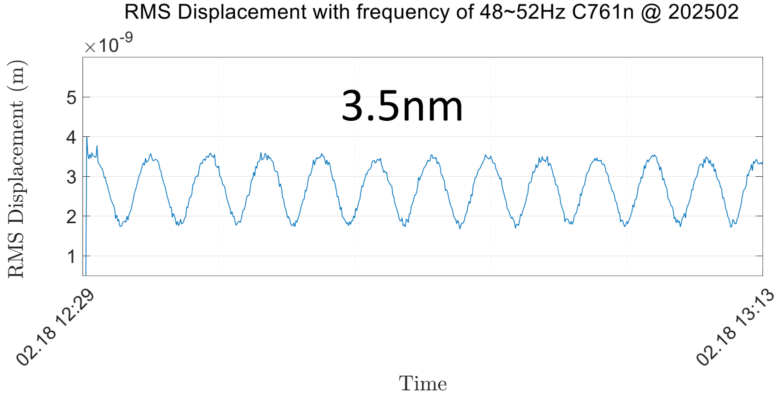


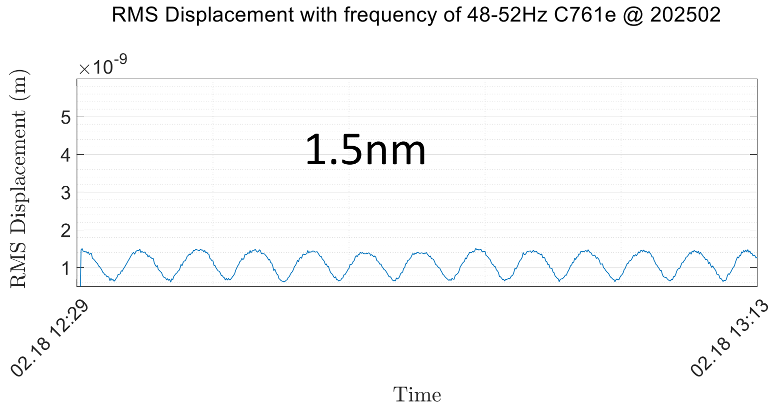
Experiment with CW10 Pump on/off

- The direction of largest vibration on the floor is vertical, while on a magnet, the direction of largest vibration is horizontal, due to the girder has larger amplification factor in the horizontal plane.

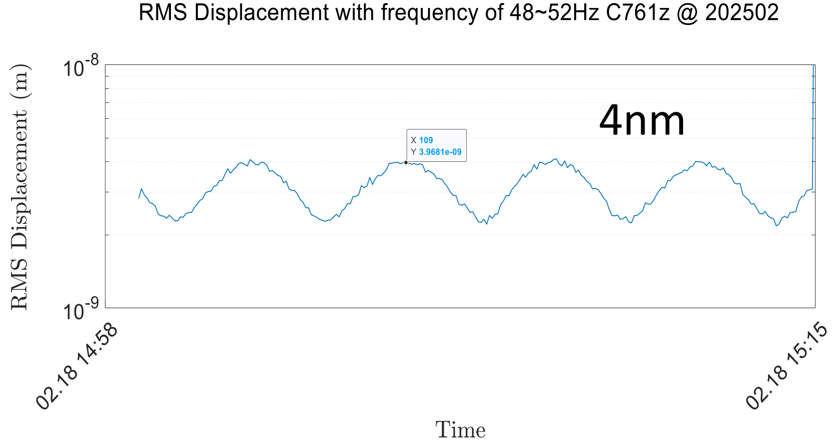
Floor vibration CW10 pump on

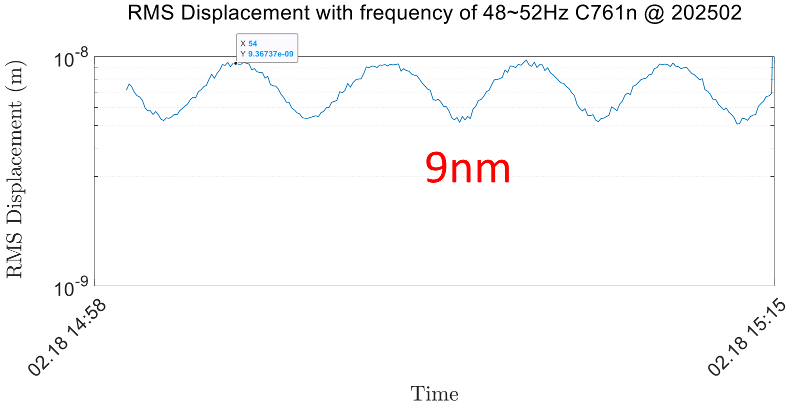

RMS Displacement with frequency of 48~52Hz C761z @ 2025 02

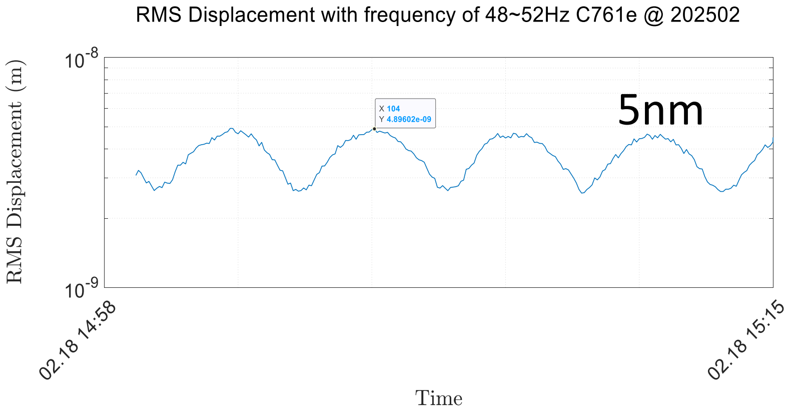

RMS Displacement with frequency of 48~52Hz C761n @ 202502


RMS Displacement with frequency of 48-52Hz C761e @ 202502

Magnet vibration CW10 pump on

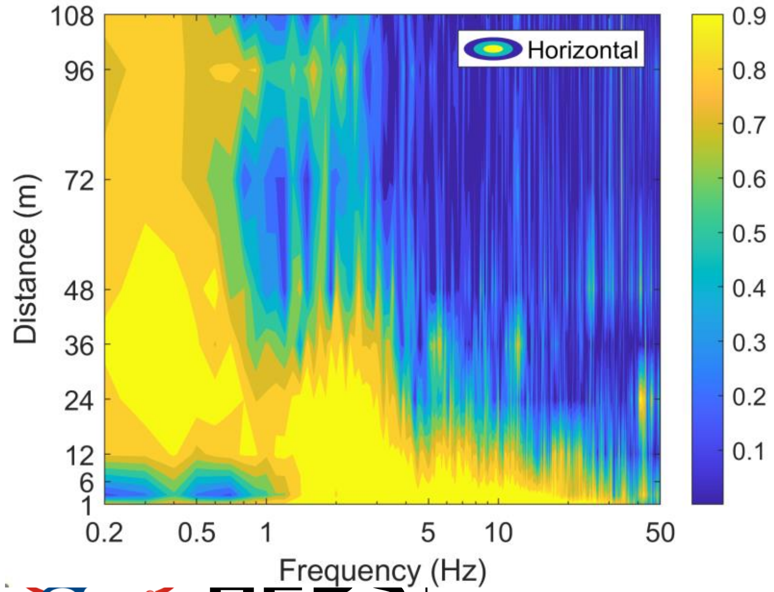

RMS Displacement with frequency of 48~52Hz C761z @ 202502

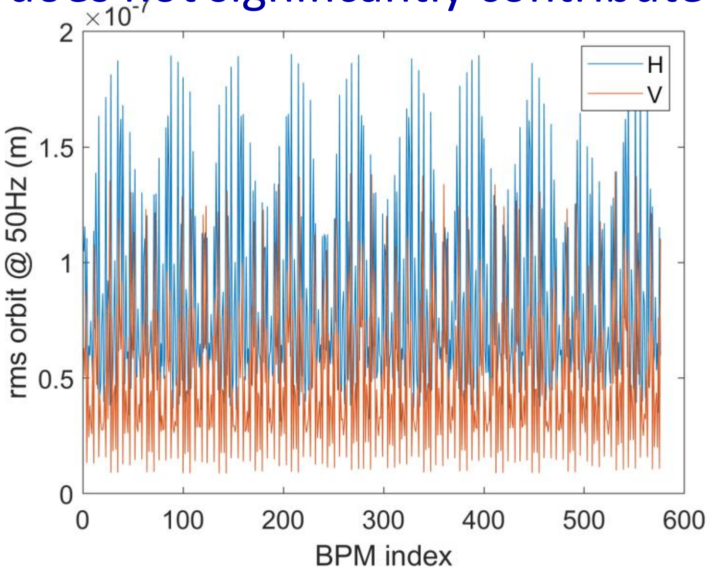

RMS Displacement with frequency of 48~52Hz C761n @ 202502

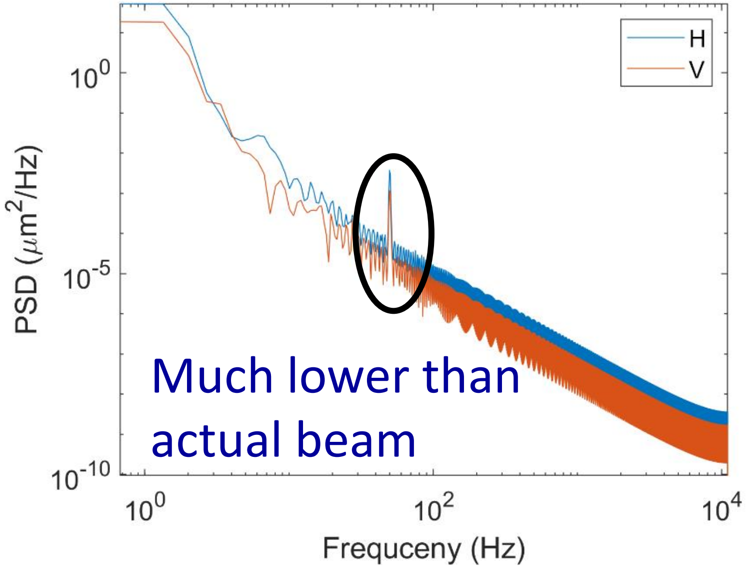

RMS Displacement with frequency of 48~52Hz C761e @ 202502

Estimation of the Water Pump Vibration on Beam

- We establish a vibration model that the 50Hz vibration is the strongest on R42QD5, and it attenuates in the other magnets on both sides of the cell (R42).
- Vibration on the magnet is incoherent since the coherence length is less than 1m at 50Hz according to our measurement. So we assume that all the quadrupoles vibration phase are incoherent.
- Simulation results show that the contribution of pump vibration on beam motion is less than 0.2um at 50Hz.
- It seems that the pump vibration does not significantly contribute to the beam motion at 50 Hz.





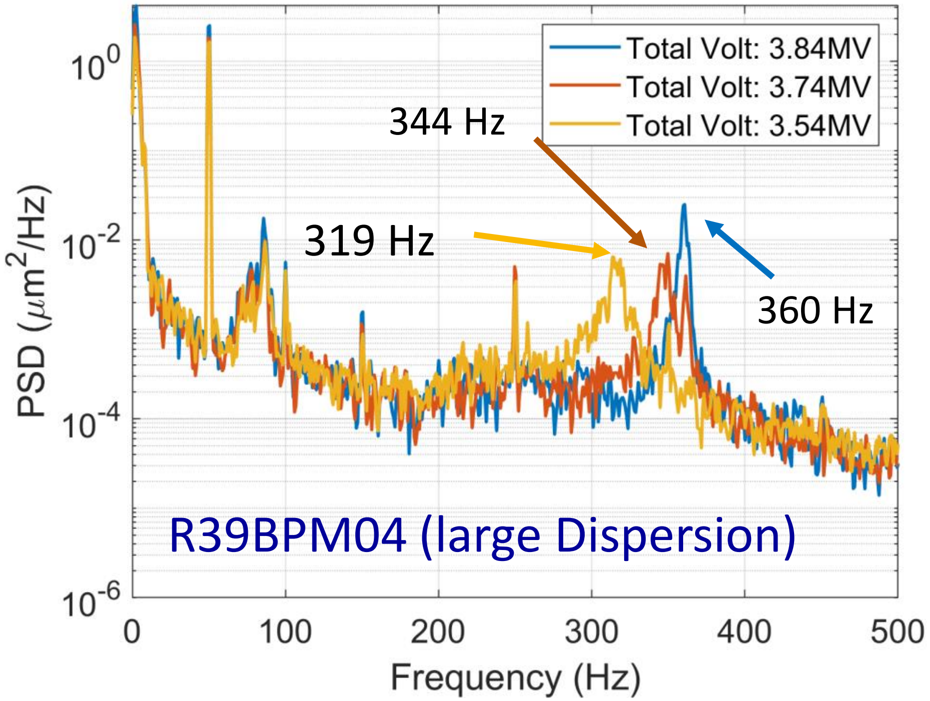


Much lower than actual beam

Potential Source of 360 Hz Noise.

Experiment with tuning RF voltages was conducted to find the source of 360 Hz noise.

1. Total voltage 3.84MV (R35RF volt: 1.54MV,R38RF/R40RF volts: 1.15 MV)
2. Total voltage 3.74MV (R35RF volt: 1.54MV -> 1.44MV)
3. Total voltage 3.54MV (R35RF volt: 1.54MV -> 1.44MV ,R38RF/R40RF volts: 1.15 MV -> 1.05 MV)

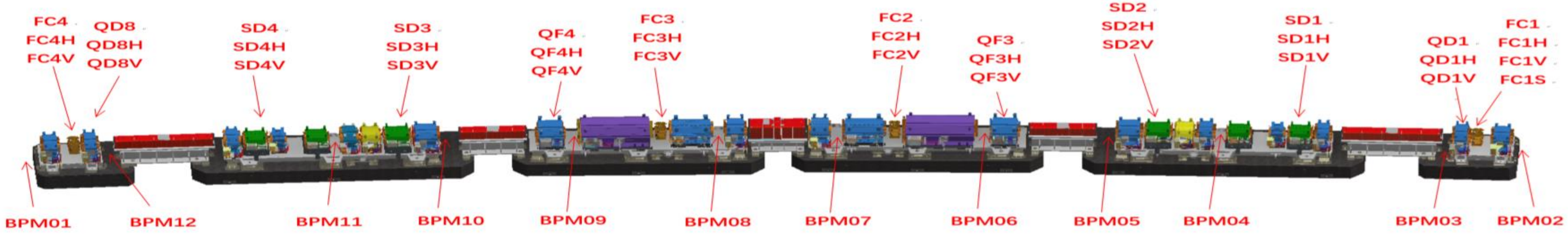


Total voltage （MV)	3.84	3.74	3.54
Theoretical synchrotron Frequency （Hz)	389	379	358
peak （Hz)	360	344	319

- Tuning only the RF voltage will move the peak at 360 Hz, so the noise is not coming from the vibration from any devices.
- Through simple experiment, it may relate to longitudinal oscillation. But for precise mode identification, further experiments with the RF system are needed (for example, RF phase noise tuning).

Orbit Feedback

Orbit Stability Criteria

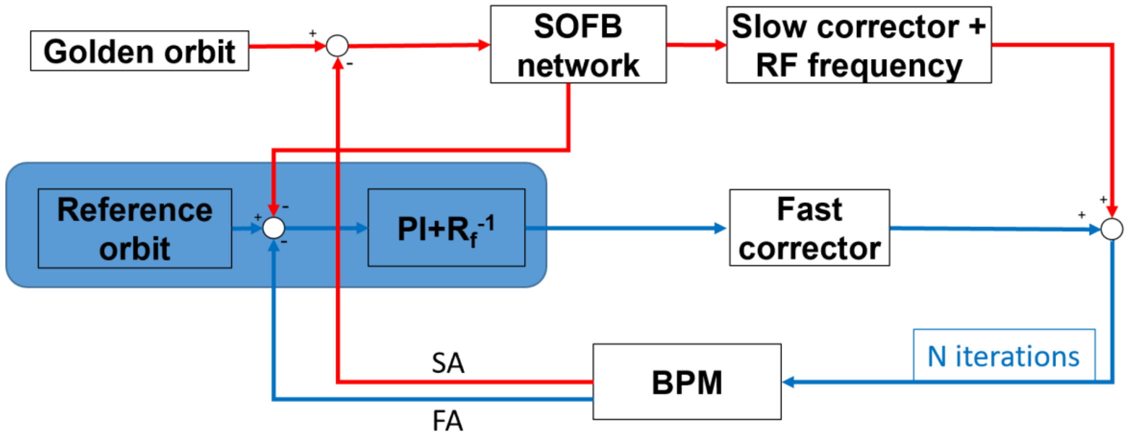


48 7BA cells, 576 BPMs, 192 fast correctors (FC), 288 slow correctors (SC)

HEPS stability requirement	Short time (0.01-1000 Hz)	
	orbit	angular
Horizontal	1.0 μm	0.2 μrad
Vertical	0.3 μm	0.06 μrad

Global Orbit Feedback Scheme

- Strategy: SOFB+FOFB+RFFB
- Commissioning: SOFB+RFFB
- Prototype testing: FOFB

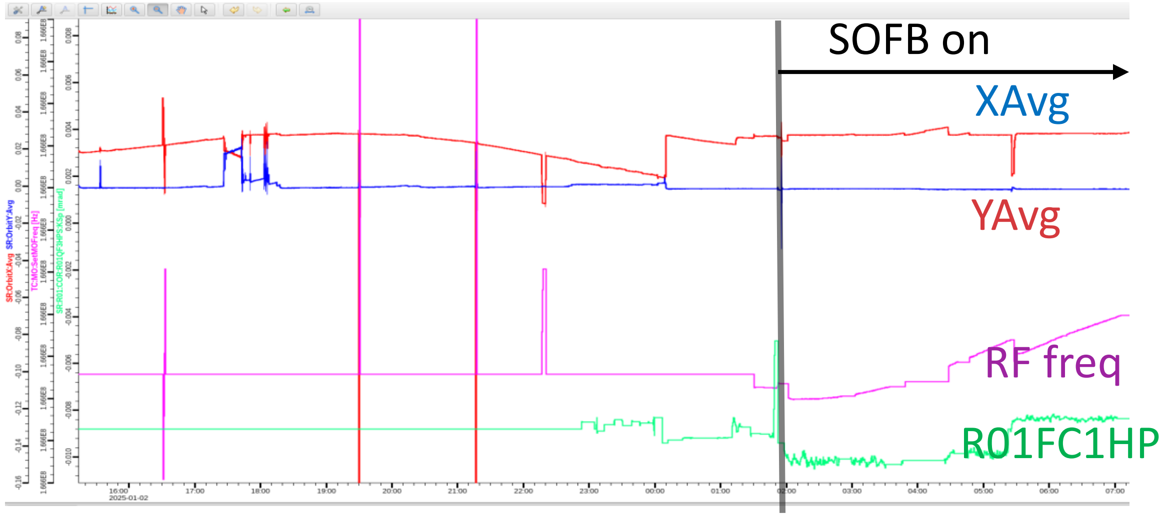


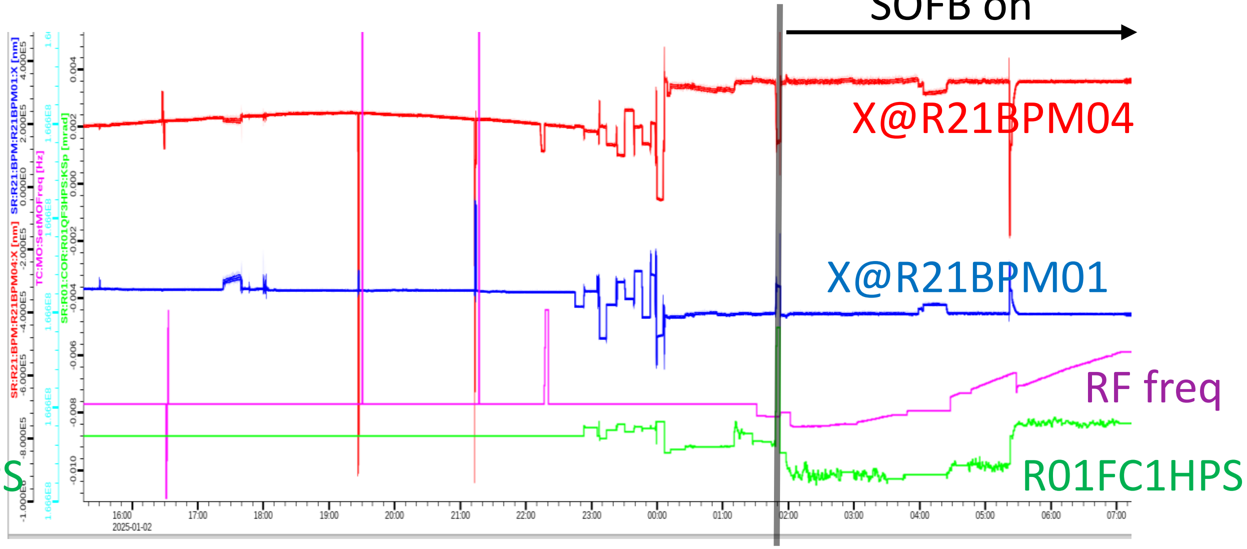
Global orbit feedback scheme

Parameter	Feedback design
Algorithm implementation	Fast + SOFB
BPM sampling rate	22 kHz (FA)
FC sampling rate	22 kHz
Signal processors (16 stations)	FPGA (Virtex-7)
Num. BPMs /plane	576 (12 per cell)
FC /plane	192 (4 per cell)
SC /plane	288 (6 per cell)
FC PS bandwidth	10 kHz
FC latency	< 25 μs
FOFB closed-loop bandwidth	>500 Hz

Slow Orbit Feedback

- ➢To suppress the horizontal orbit drift due to tide effect, RF frequency was used as variable in SOFB (SOFB+RFFB).
- ➢50% of singular values were adopted, and the correction were applied every 3 seconds currently (upgrade to above 1 Hz planned).
- ➢With the adjusting of RF frequency, the long-term stability was improved.
  - ➢The averaged horizontal orbit drift decreased from a peak-to-peak value of 30 micron to 0.8 micron.
  - ➢The averaged vertical orbit drift is smaller than 1 micron.
- ➢The horizontal orbit drifts at dispersive BPMs have been reduced to several microns.

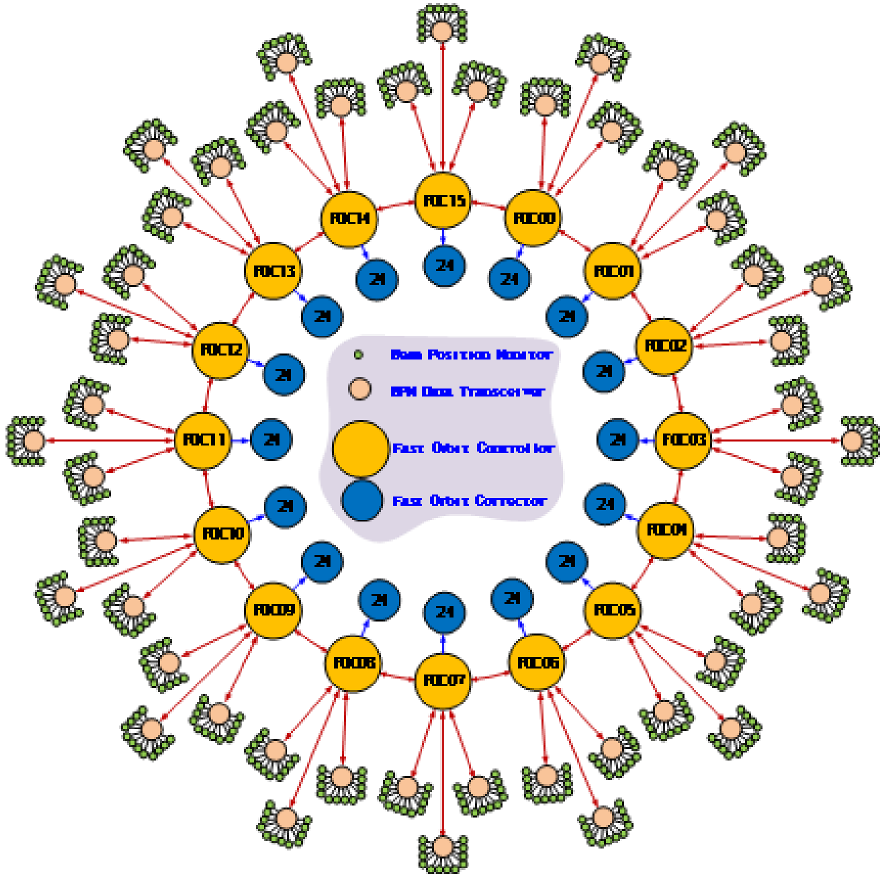




Fast Orbit Feedback

- ➢ 576 BPMs, 16 FOCs and 384 PSCs are connected through optical fiber and optical cable.
- ➢ Adopted a star-ring data transmission network structure.
- ➢ Added BPM data transceiver (BDT) for point-to-point reception of all BPM data corresponding to BPM sub stations, and then sent to FOC.
- ➢ The advantages of star ring structure: Reduce the power of FOC, decrease data transmission latency, and prevent the failure of one BPM from affecting the transmission of data to other BPMs.

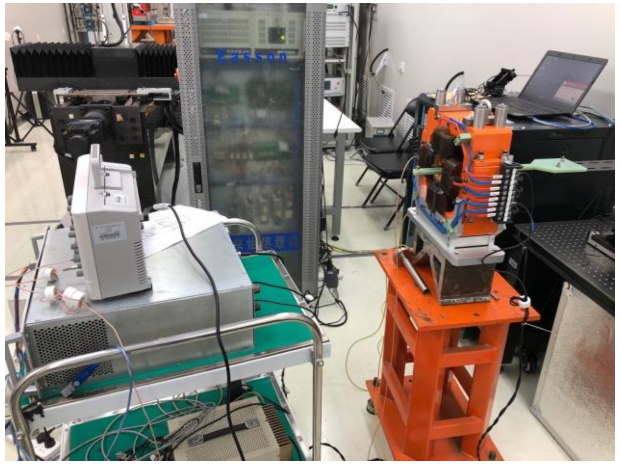
- FOFB Prototype testing is underway……

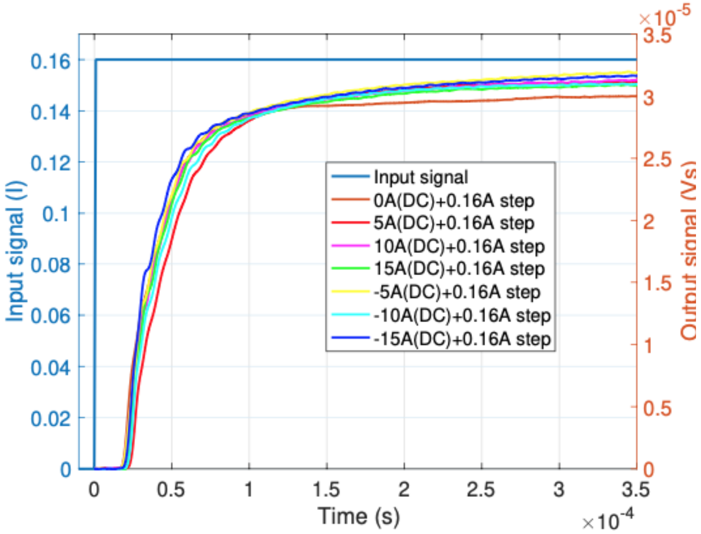


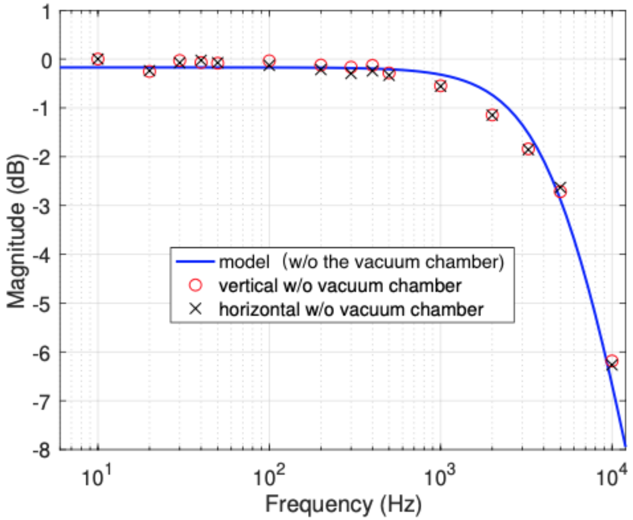
FOFB data transmission network

Fast corrector & Vacuum chamber

- In order to achieve the 10 kHz small signal bandwidth of the power supply, a switchmode power supply was adopted.
- A topology based on multi-level technology, through the hardware cascade of multi-H bridges, was developed to improve the switch frequency and the output voltage of the power supply.
- The fast corrector magnet was made of 0.15 mm thickness laminated silicon-steel plates for the return magnetic flux.
- The vacuum chamber is made of Inconel 625, the thickness is 0.5 mm.







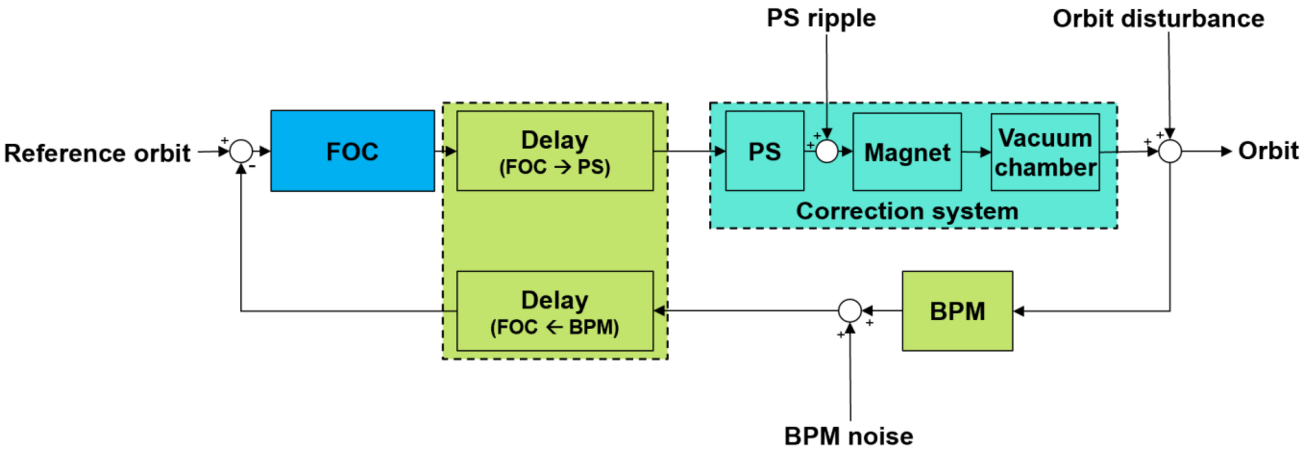
Step response measurement

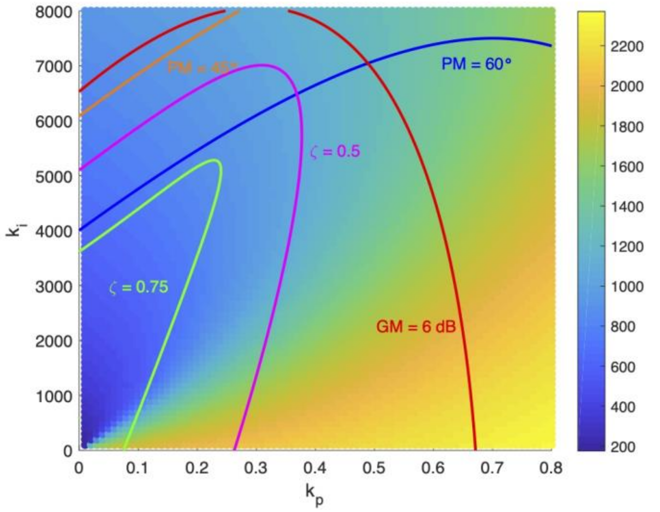
Frequency Domain Analysis of FOFB

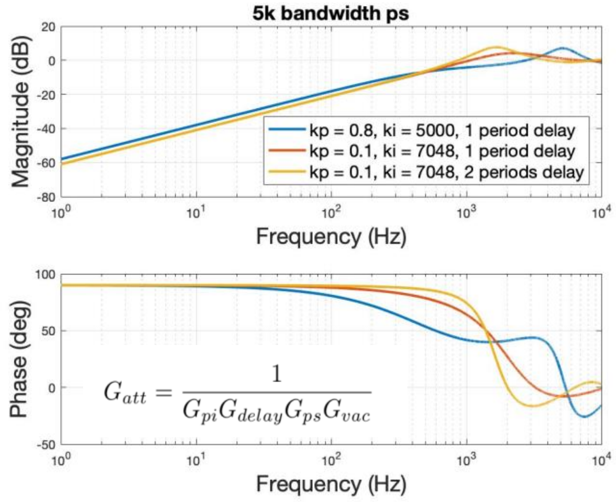
- The frequency domain provides powerful tools for analyzing system stability, and provide examination of a system's dynamic performance, such as overshoot and settling time. By analyzing frequency characteristics, one can assess how the system responds at different frequencies.

- ➢Scan PID parameter, system delay, etc.

- ➢For each set of system delays, we use PSO to find the most suitable controller parameters (with the smallest ISE and appropriate gain margin & phase margin), and then scan different delays to obtain the feedback bandwidth.







Numerical Simulation

- FOFB simulation：Establish a general step-by-step time domain simulation of FOFB, including dynamic modelling of each stage in the flowchart, validation of the numerical simulation results.
- The detailed steps in the flowchart are listed as follow:

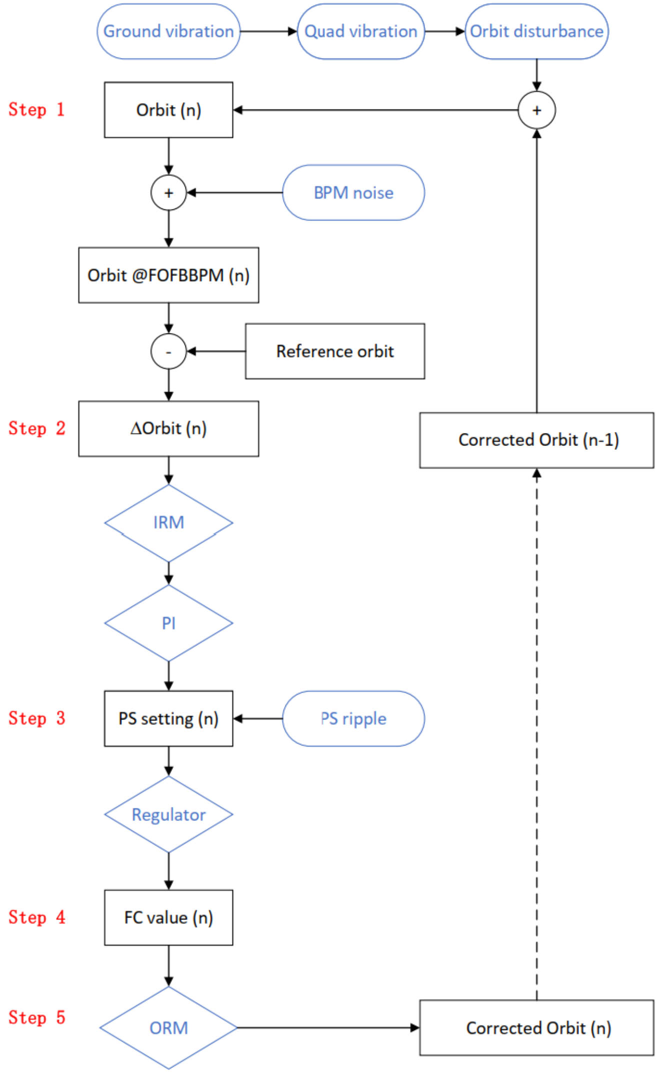
1. Generate the orbit disturbance from random quadruple vibration, then add the n-1th corrected orbit to the nth orbit at all BPMs.

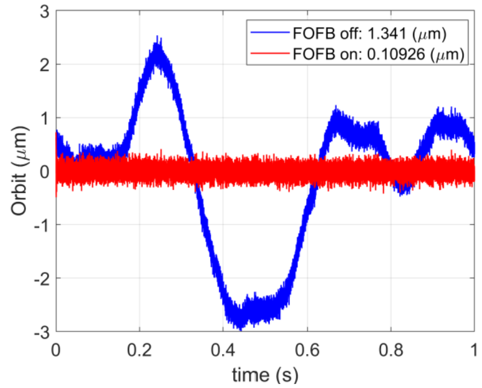
2. Calculate the ΔOrbit by subtracting the current orbit from the reference orbit.

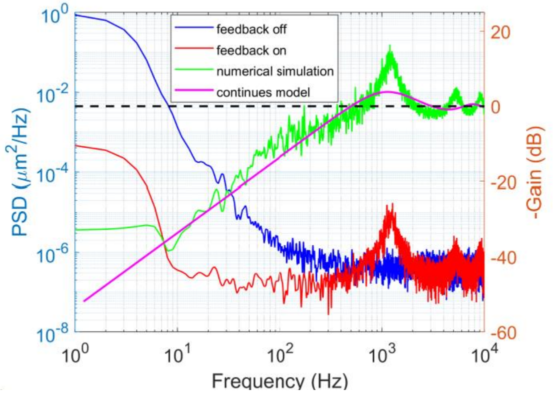
3. Calculate the PS setpoints with IRM and PI parameters. The PI parameters can be tuned to optimize the system performance.

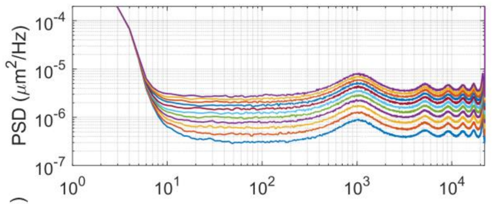
4. Apply the regulator on the nth turn.

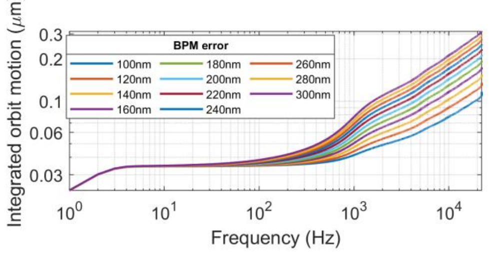
5. Multiply the nth turn FC values by the ORM and generates the corrected orbit.





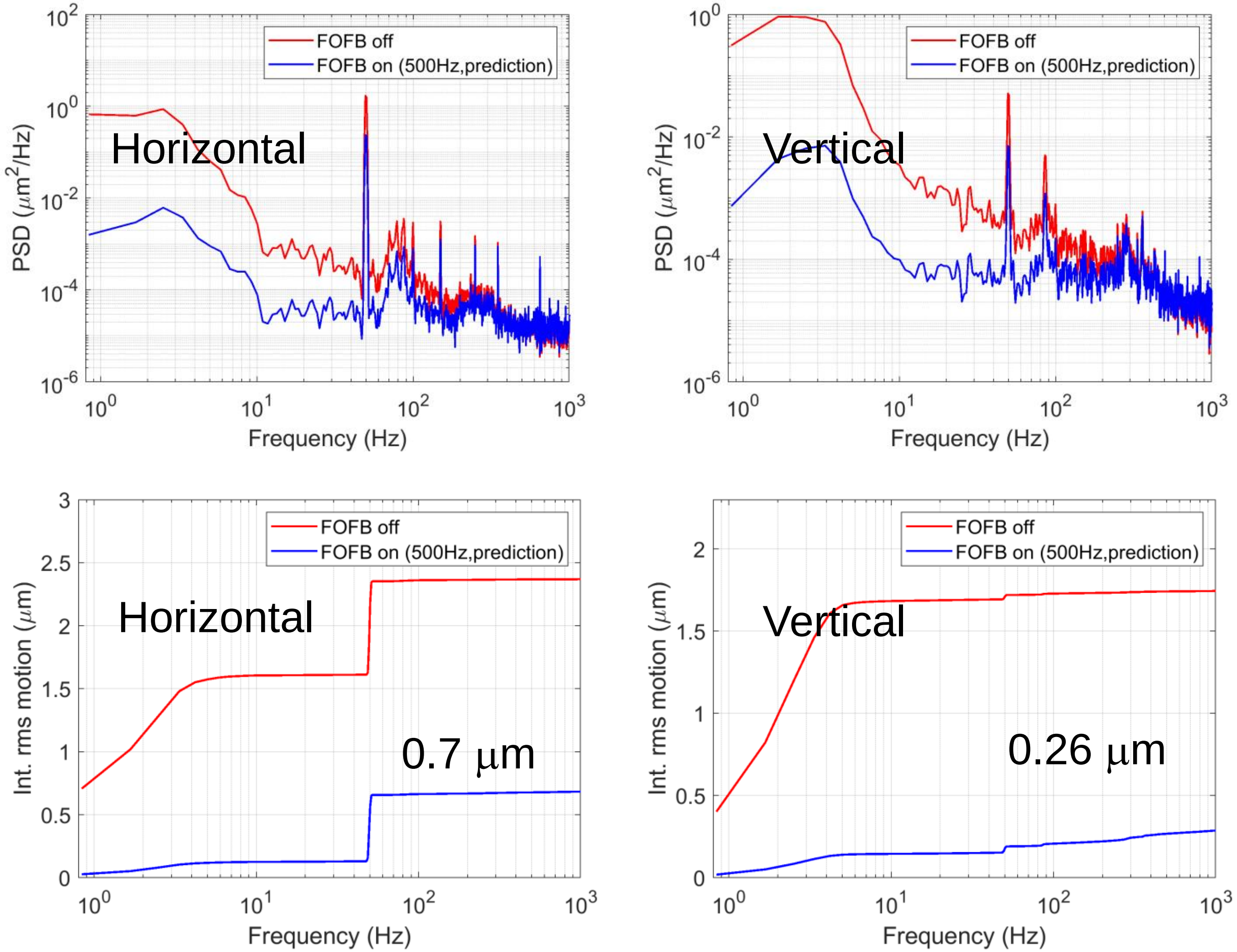






The Estimation of FOFB Performance

- ➢ Without FOFB, the integrated orbit motion is 2.4/1.8um in @R10BPM01.
- ➢ Based on the current latency test results of various systems, the system can achieve a closed loop bandwidth of 500 Hz or even higher (to 1kHz).
- ➢ Applying step-by-step time domain simulation, and use the appropriate PID parameter, the orbit motion can be attenuate to 0.7/0.26μm.



Summary

Summary

- The small beam sizes of HEPS present significant challenges in achieving orbit stability.
- In the horizontal plane, the long-term orbit drift has a strong correlation with the tidal phenomenon at Tianjin Tanggu Station. Currently, we can attenuate the long-term orbit drift using SOFB+RFFB.
- The Mid-term orbit motion is investigated with 1000000 turns TBT data.
- In response to the issue of significant 50 Hz noise of the beam, experiments were conducted to analyze the impact of power supply noise and vibration from the CW10 water pump. However, the experimental data did not conclusively establish these factors as the exclusive sources of the 50Hz orbit motion.
- HEPS will adopt a global orbit feedback system including SOFB/RFFB/FOFB. Now SOFB+RFFB are in commissioning, and the FOFB prototype testing is underway.
- Frequency analysis and numerical simulation were cross-checked to ensure that the design of the FOFB can meet the requirements for orbit stability.

Acknowledgement

- Thanks to the iFAST workshop organising committee.
- Thanks to the experts of International Advisory Committee: A. Chao, Z. T. Zhao, R. Bartolini, etc.
- Thanks to C. X. Yin (SSRF), B. C. Jiang (Chongqing University), L. Liu (Sirius), D. Tavares (Sirius), Fernando de Sa (Sirius), and H. Schlarb (DESY) for their insightful discussions.

Thanks for your attention!

Backup slides

Achieved beam parameters to date

Parameters	Unit	Design values	Achieved values	
Beam energy	GeV	6	6	
Beam current [1]	mA	200	~40	National acceptance criteria: >100 mA
Bunches (high brightness/high bunch charge mode)		680/63	——	
Circumference	m	1360.4	1360.4	
Natural emittance [2]	pm·rad	34.8	80~90 (=$\varepsilon_x + \varepsilon_y$)	National acceptance criteria: <100 pm.rad
Tune		115.15/104.29	115.15/104.28	

1, Now the storage ring operates with three 500 MHz cavities, which is the main obstacle of beam current. In 2025, the 166 MHz cavities (designed fundamental frequency RF cavities) will be installed in May.

2, Emittance optimization had reached a plateau region for not a few days. Then great efforts were made to further reduce the emittance to approach the designed natural emittance.

Peak at 360Hz

- Longitudinal motion including both additive and multiplicative noises from RF is

$$\frac{d^2\phi}{dt^2} + 2\alpha_s \frac{d\phi}{dt} + (\Omega_s^2 + g(t))\phi = f(t),$$

- Use (ϕ, δ) as phase-space coordinates

$$\frac{d\phi}{dt} = h\omega_0\eta\delta,$$

- The transverse motion can be written as

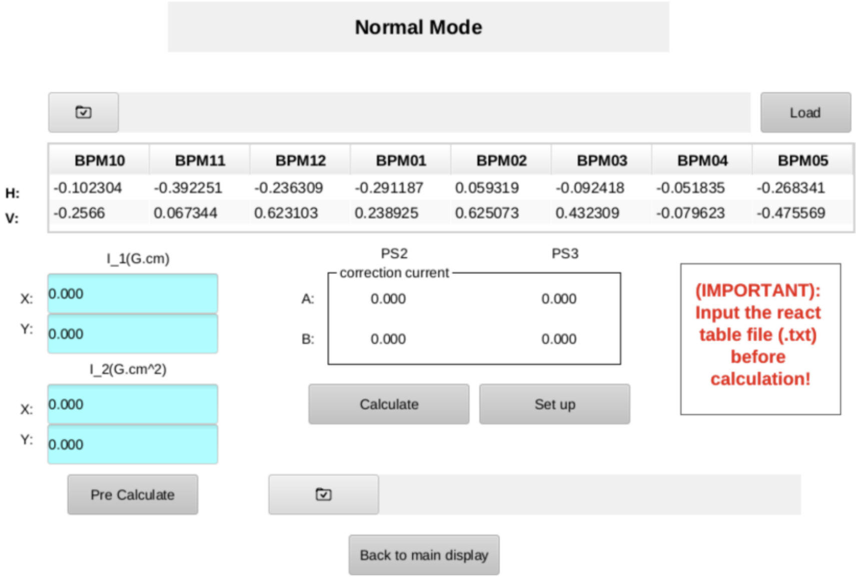
$$x = D\delta,$$

- Combine above equations, we can derive a equation between RF phase noise and obit transverse motion:

$$\frac{d^2x}{dt^2} + 2\alpha_s \frac{dx}{dt} + \Omega_s^2 x = \frac{D\Omega_s^2}{\omega_0\eta}\frac{d\psi}{dt},$$

ID feed-forward compensation

- The full-gap feed-forward calibration has been basically completed for two IDs
- Currently, the disturbance of the gap changing to orbit is around 3~ 4 um after feed-forward compensation. When orbit becomes more stable, a more detailed feed-forward calibration will be carried out.
- After feed-forward compensation, no significant movement of the light source point has been observed when changing the ID gap. The light source point position changes will be continuously investigated.



	BPM10	BPM11	BPM12	BPM01	BPM02	BPM03	BPM04	BPM05
H:	-0.102304	-0.392251	-0.236309	-0.291187	0.059319	-0.092418	-0.051835	-0.268341
V:	-0.2566	0.067344	0.623103	0.238925	0.625073	0.432309	-0.079623	-0.475569

I_1(G.cm)
X: 0.000
Y: 0.000

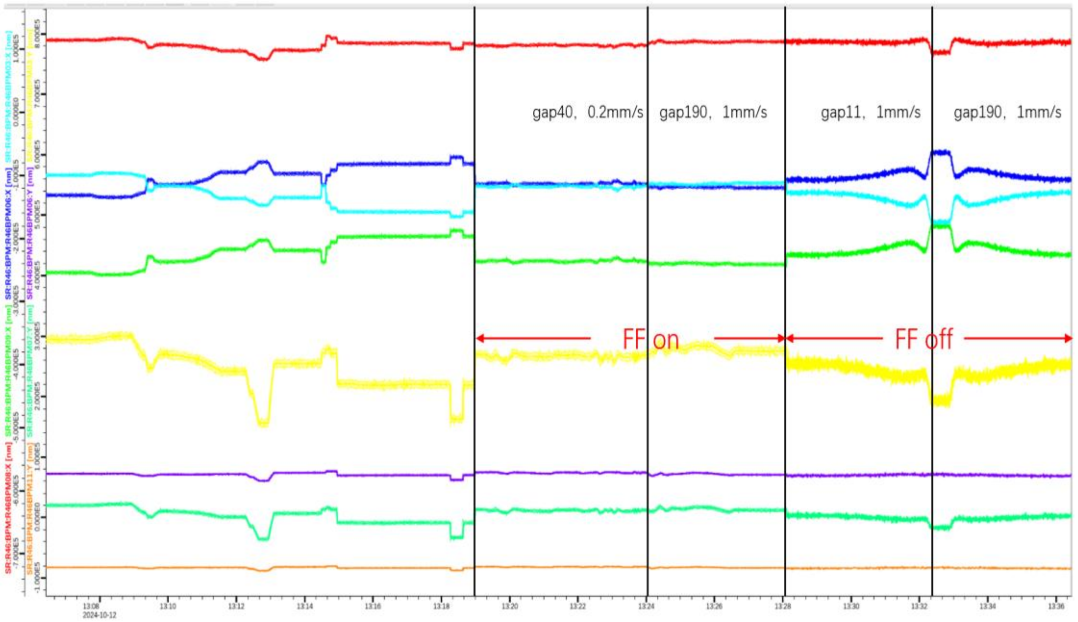
I_2(G.cm^2)
X: 0.000
Y: 0.000

correction current

	PS2	PS3
A:	0.000	0.000
B:	0.000	0.000

(IMPORTANT): Input the react table file (.txt) before calculation!

Interface for FF calibration



COD distortion when R46IAU FF commissioning