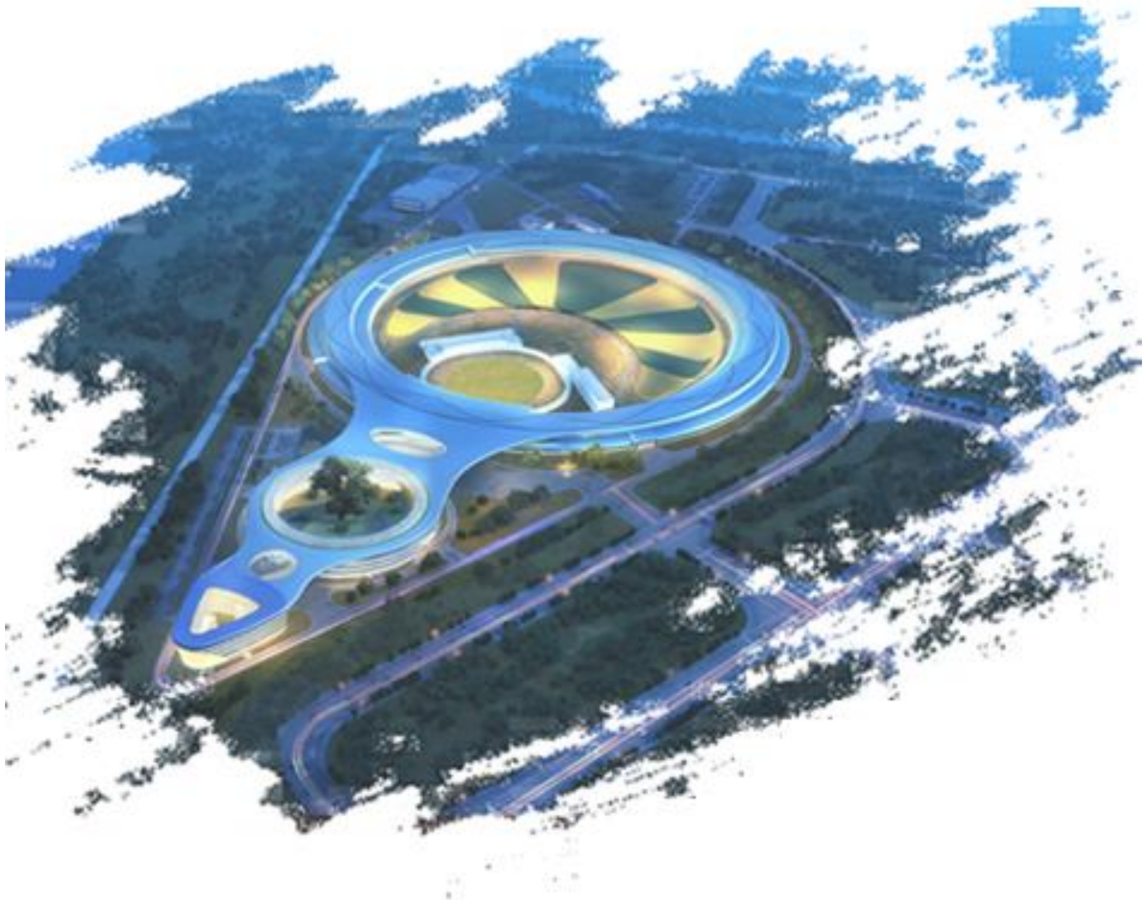
HEPS储存环束流轨道稳定性研究

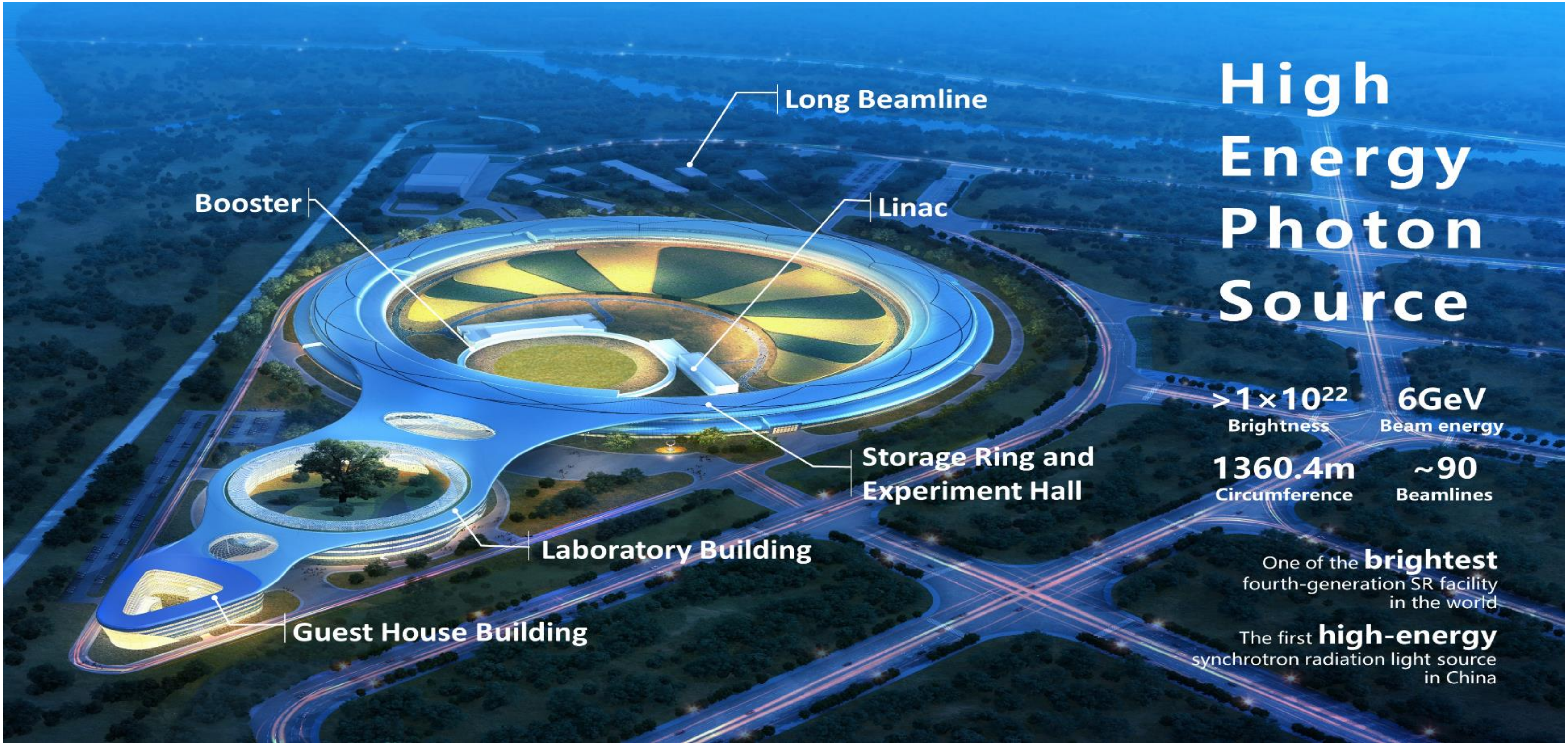


黄玺洋, 代表HEPS调束团队
高能物理研究所

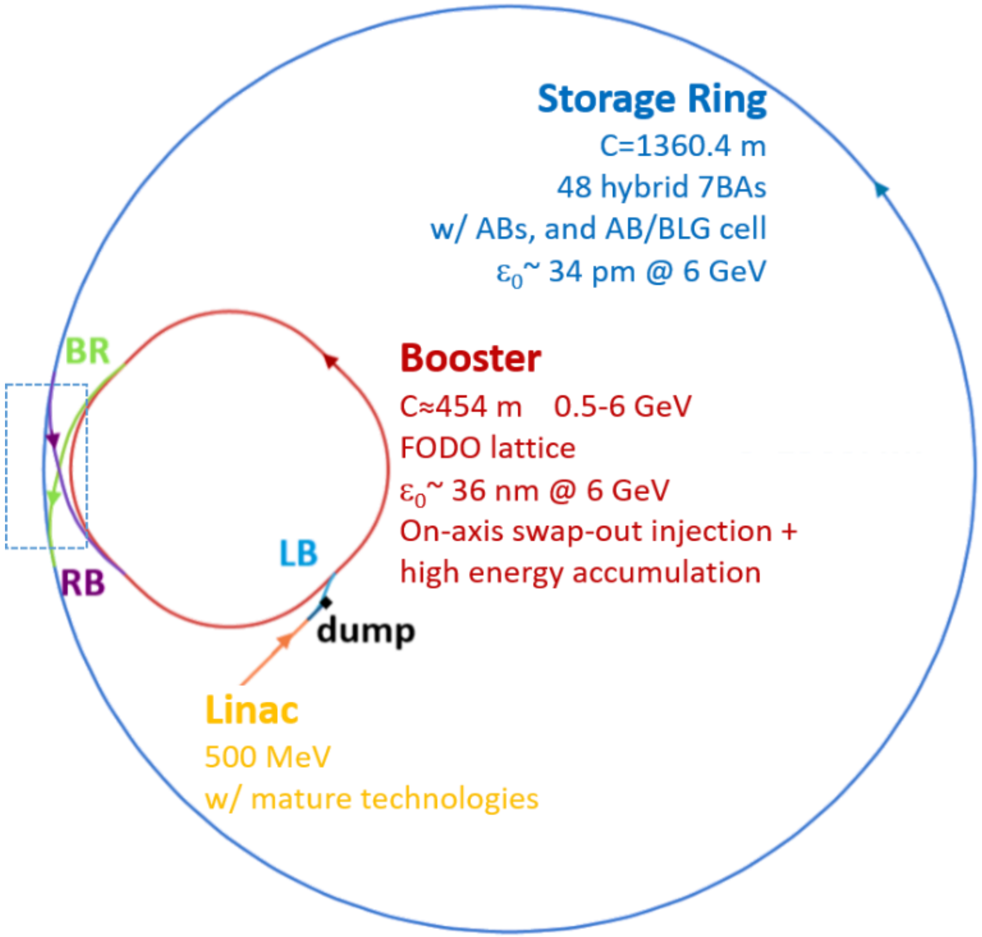
2026/07/01

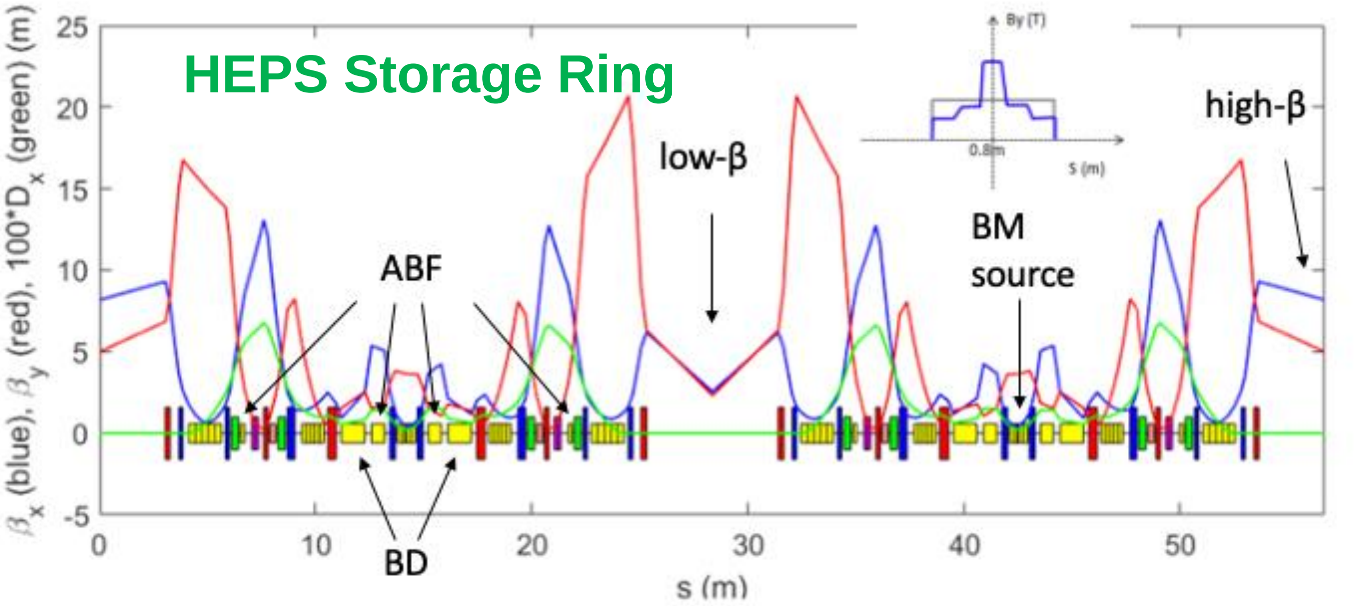
Introduction

Overview of HEPS



Main parameters: Accelerator



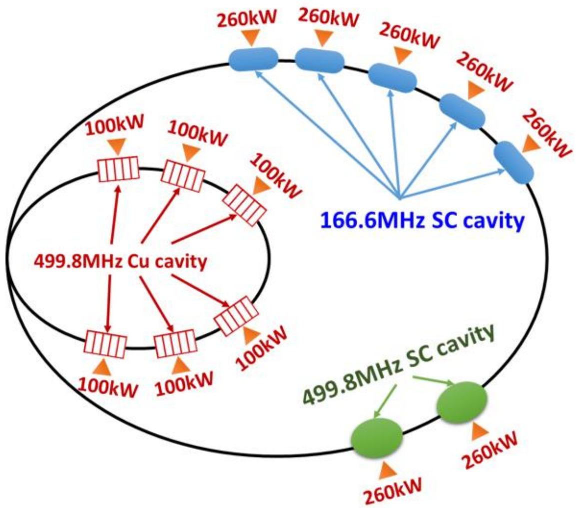


1700+ Magnets **90** Beamlines

~1300 Vacuum chambers

500+ BPMs **288** Girders

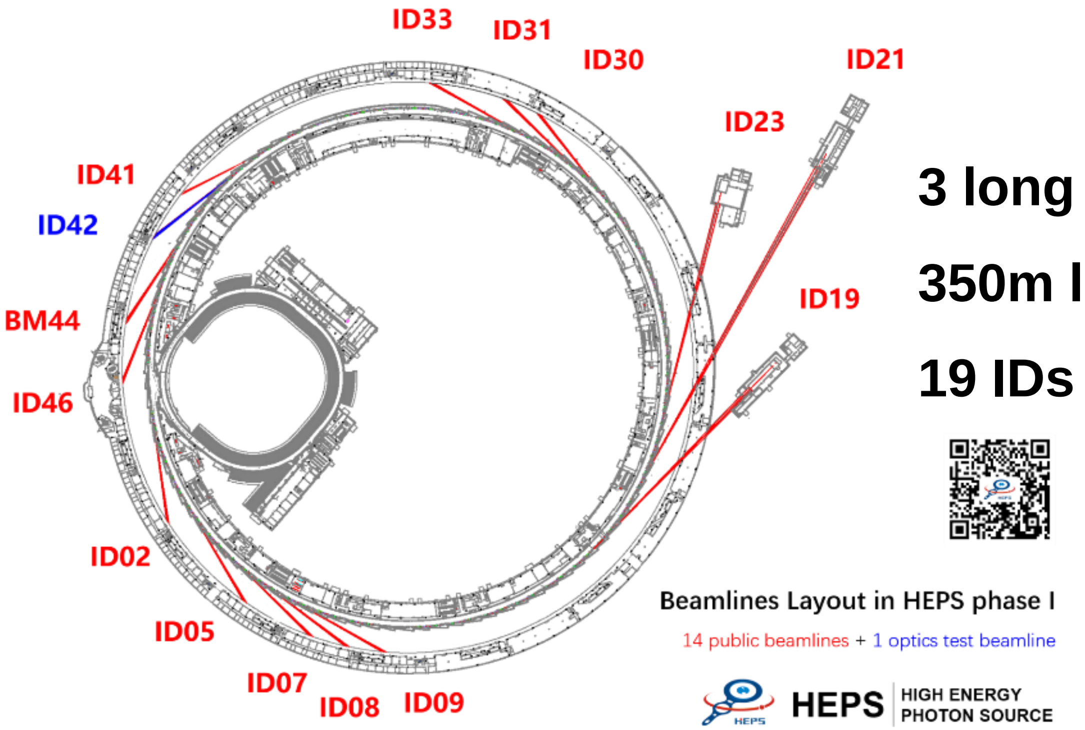
5 166MHz SRF **2** 500MHz SRF



[1] Y. Jiao *et al.*, *J. Synchrotron Rad.* 25, 1611–1618 (2018).
[2] Y. Jiao, *RDTM* 4, 399 (2020).
[3] H. Xu *et al.*, *RDTM* 7, 279–287 (2023).

Main parameters: Beamlines

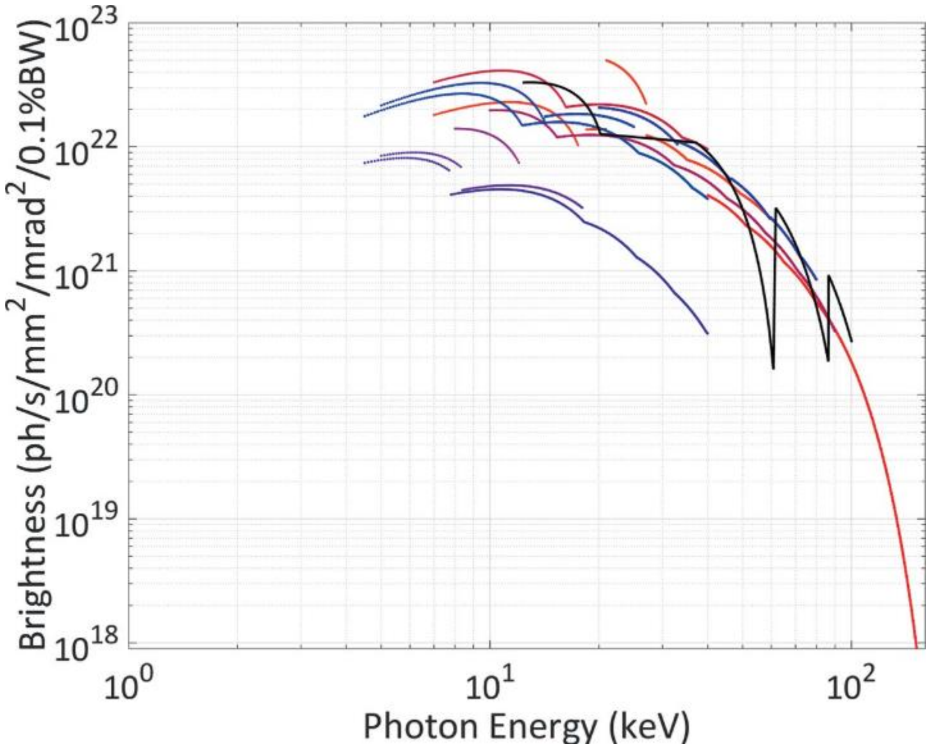
- Brightness of 5×10^{22} phs/s/mm^2/mrad^2/0.1%BW at the photon energy of 21 keV, can provide X-ray with energy up to 300 keV
- **14 user beamlines + 1 test BL** in Phase 1, HEPS can accommodate up to 90 BLs



3 long BLs

350m longest

19 IDs 6 types



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

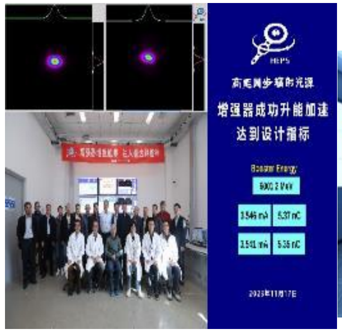
Key milestones since mid-2019

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

Mar. 14, 2023
The first electron beam



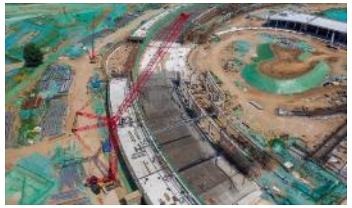
Nov. 17, 2023
Electron Beam Ramped Up to 6 GeV

July. 23, 2024
Storage ring commissioning commenced.

Sep. 29, 2025
HEPS accelerators passed performance tests

June 29, 2019
Groundbreaking ceremony

July 1, 2020
The first steel beam was installed



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

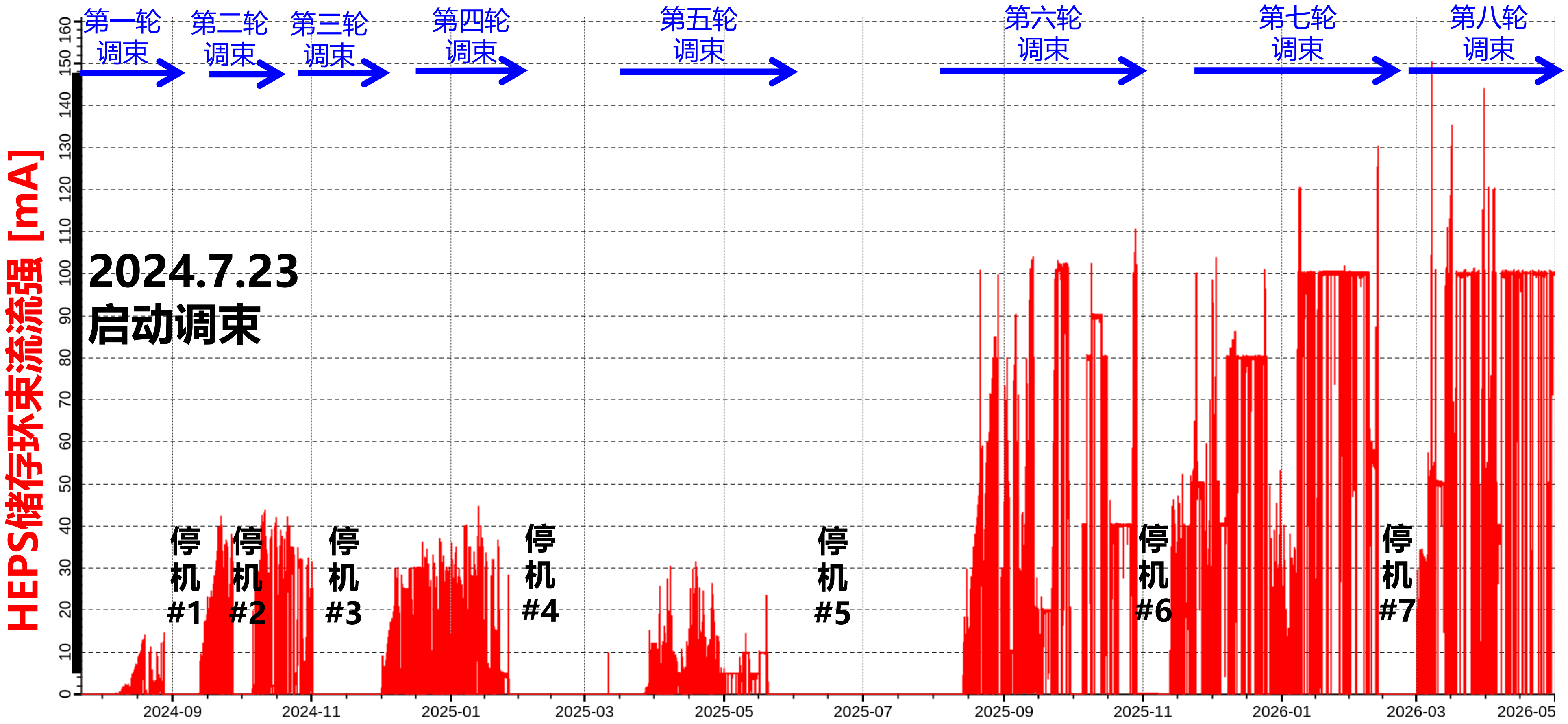
June 27, 2021
Roof-sealing work for the main ring building completed

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

Nov. 3, 2023
Civil Construction for ancillary buildings completed

History of SR commissioning

- Staged commissioning
  - injection: slotted-pipe kicker -> stripline kicker
  - RF: 500MHz RF -> 166 MHz RF + 500 MHz (3rd harmonic)



1st round:
1，from first turn to 12 mA

2nd round:
1，ramp up current to ~40mA

3rd round:
1，first light from ID, beamline tuning

4th round:
1，optics corrections, < 100 pm emittan
2，demonstration of the injection schem
3，beamline tunings

5th round:
1，more optics corrections
2，beamline tunings

6th round:
1. Ramp up current to ~100mA
2. Orbit stability < 20% beam size
3. Optics corrections, <60 pm emittanc
4. Beamline tunings

7th round:
1. Orbit stability < 10% beam size
2. Optics corrections, <50 pm emittance

Status of HEPS Storage Ring Commissioning

- Passed accelerator performance tests in Sep 26-29， 2025.
- **This presentation will focus on the of orbit stability, including actual beam orbit fluctuation, noise source identification, optimization and FOFB commissioning.**

Parameter	Design	KPP#	Measurement	Unit
Beam energy	6	6	6.01	GeV
Beam current	200	100	100.5	mA
Natural emittance	34.8	100	56.8$	pm·rad
Beam stability	10%	20%	< 19.8%	fraction of rms beam size & divergence
Brightness	$>1\times10^{22}$	2×10^{21}	4.00×10^{21}	phs/s/mm²/mrad²/0.1%BW
Capability of providing X-ray photons of 300 keV			349.57	keV

Key performance parameters for national acceptance test

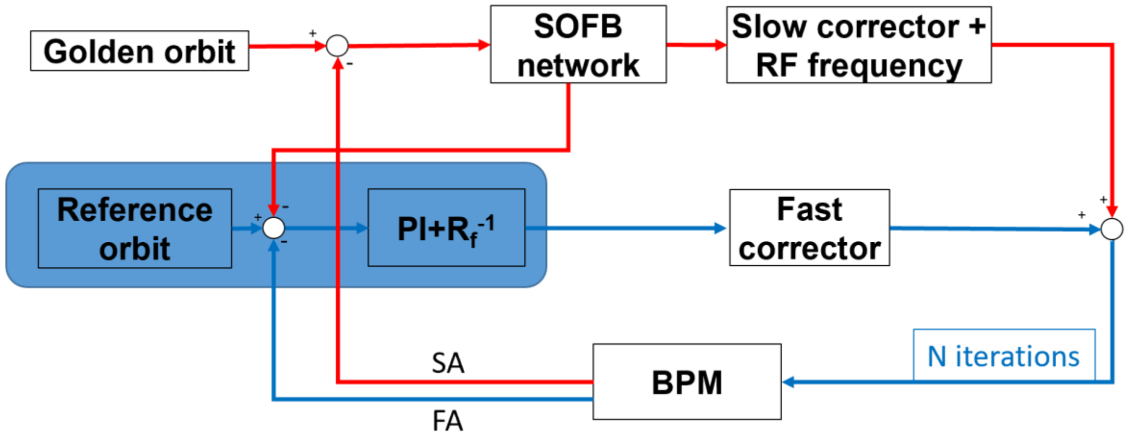
$ Measured horizontal + vertical emittance @ 100 mA, with grating interferometry

Stability requirement

- RMS beam position & angular motion <10% beam size or divergence in both planes. Some critical reference values for the final lattice design are :

HEPS Stability requirement	Short time (0.1-500 Hz)	
	orbit	angular
Horizontal	0.94 μm	0.2 μrad
Vertical	0.28 μm	0.06 μrad

Parameter	Feedback design
Algorithm implementation	FOFB+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



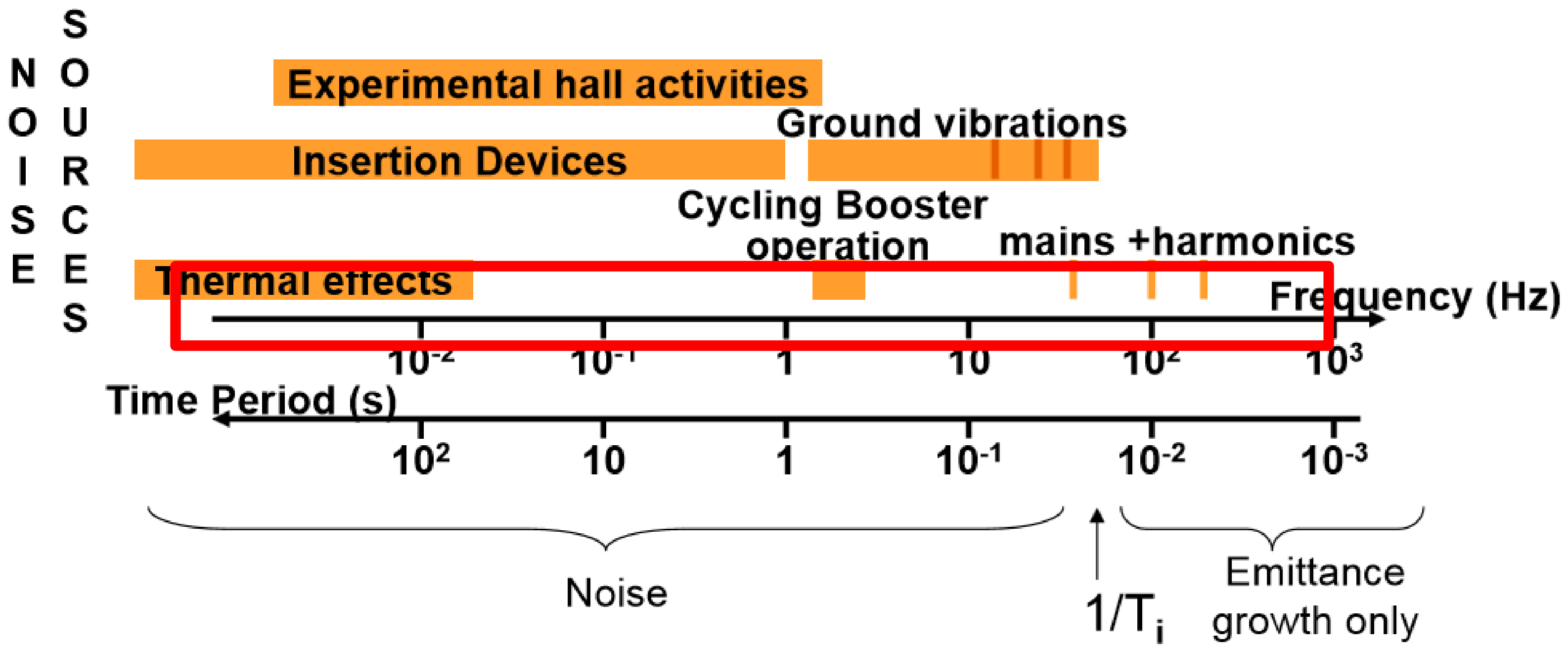
Designed global orbit feedback scheme

Beam Stability Issue and Noise Source Identification

Major sources of orbit motion

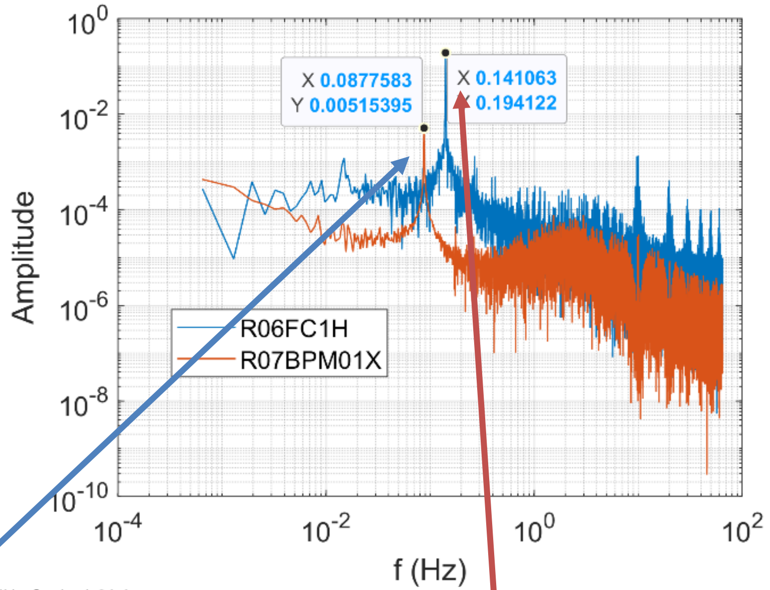
– Beamlines Integration time:
  - If $F_{PERTURBATION} > 1/T_{INTEGRATION}$ → Emittance growth → Lower photon flux in a stable way
  - If $F_{PERTURBATION} < 1/T_{INTEGRATION}$ → Noise on the measurement

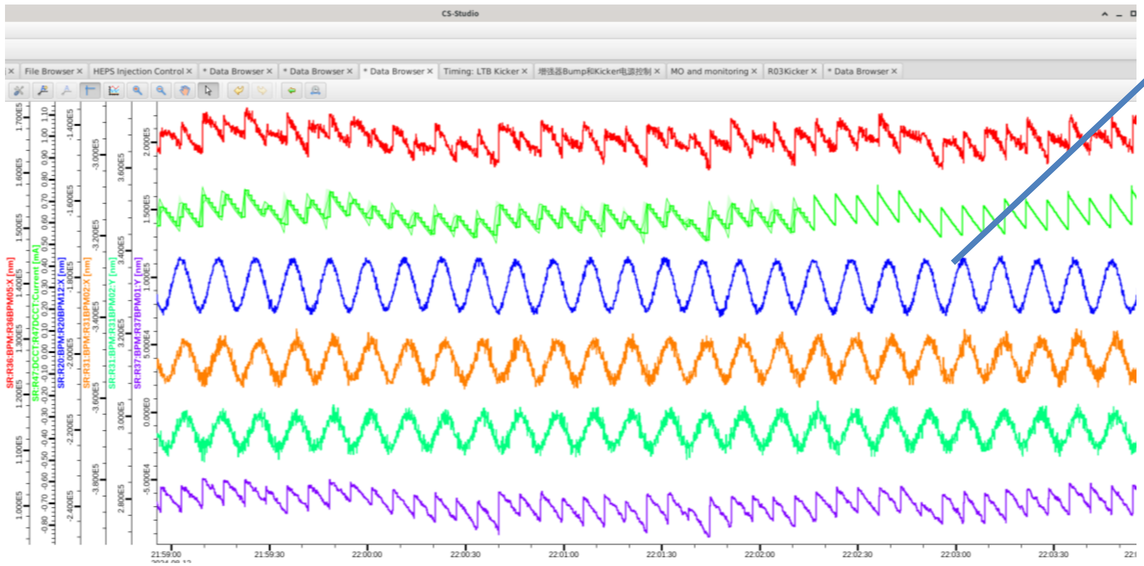
Courtesy of Lin. Zhang

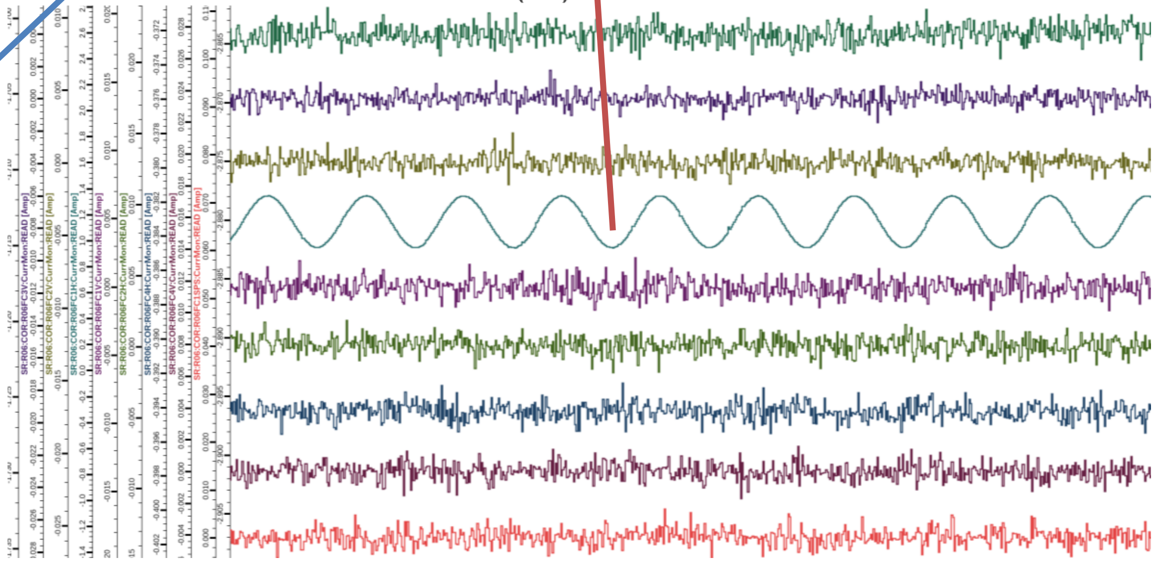


Beam stability issues (2024.8)

- Orbit fluctuation ~ 0.088Hz in database
  - Most BPMs exhibit periodic orbit fluctuations in both the horizontal and vertical planes.
  - The measured response matrix is inaccurate.
  - The current waveform of R06FC1H was significantly inconsistent with those of other corrector power supplies.

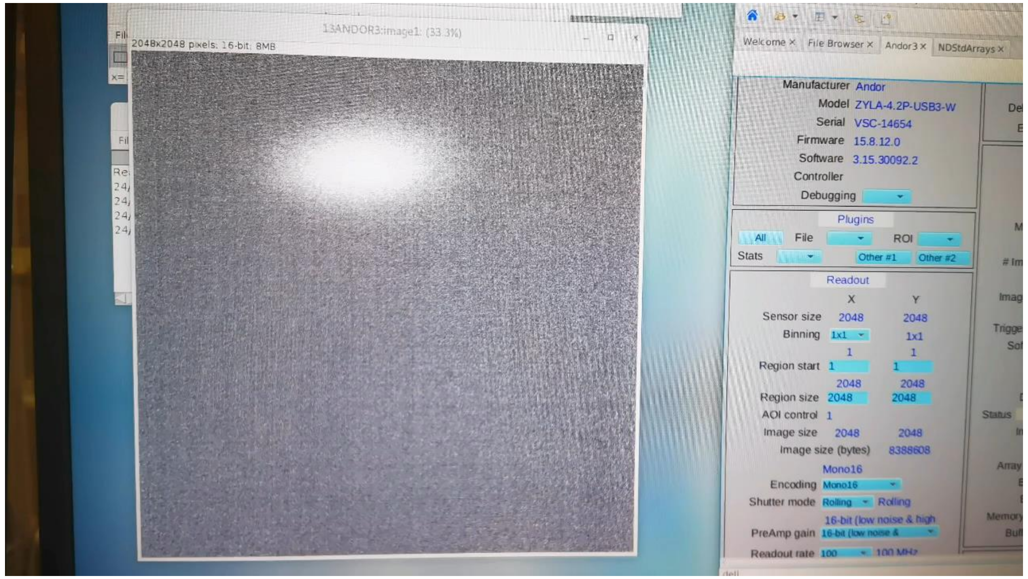


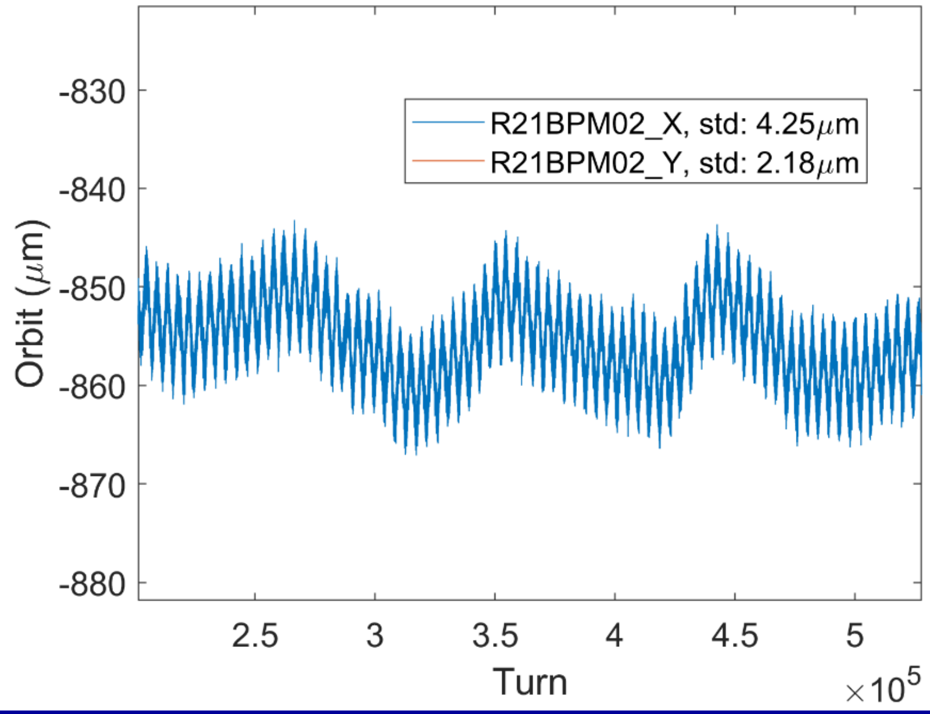




Beam stability issues (2024.12-2025.8)

- Orbit fluctuation ~ 2-4 μm rms @IDBPM
  - 1-5 Hz low-frequency (vibration or PS?)
  - 50 Hz (mains frequency, pump vibration)
  - 65-120Hz and 360Hz contribution is very small (<1%) 。
- SOFB and RF feedback commissioned
  - Effectively mitigate the periodic variations (period~ 12 hour) of the horizontal beam orbit (10 um)
- FOFB not ready





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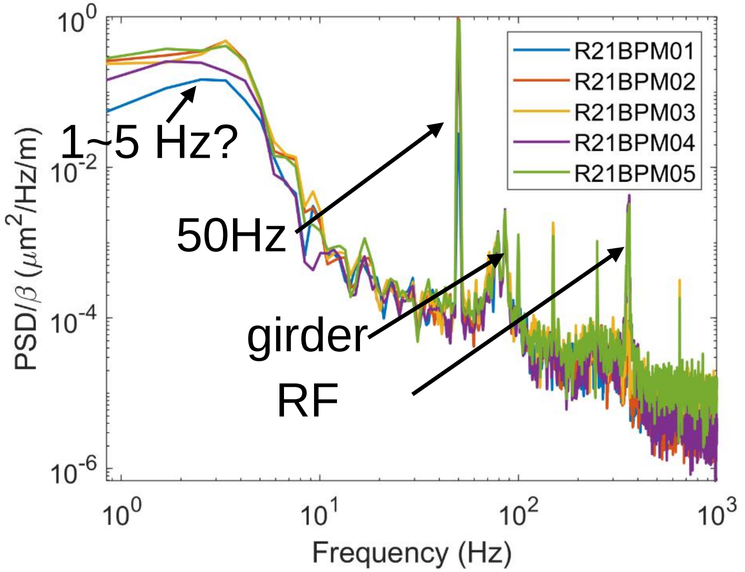
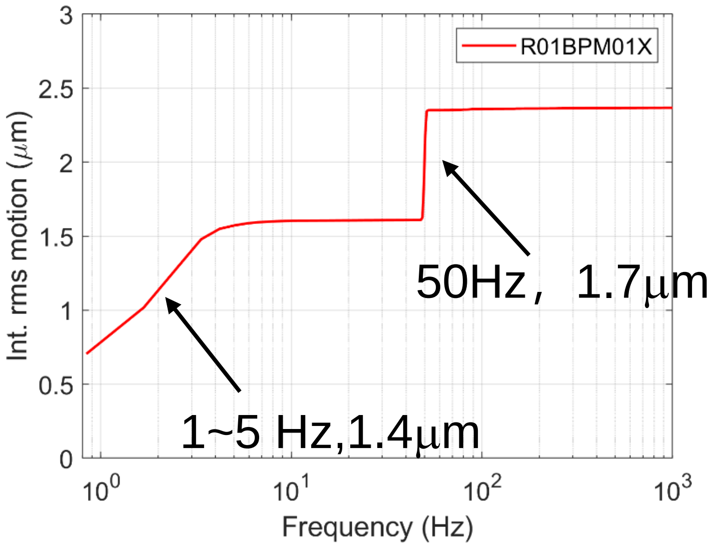
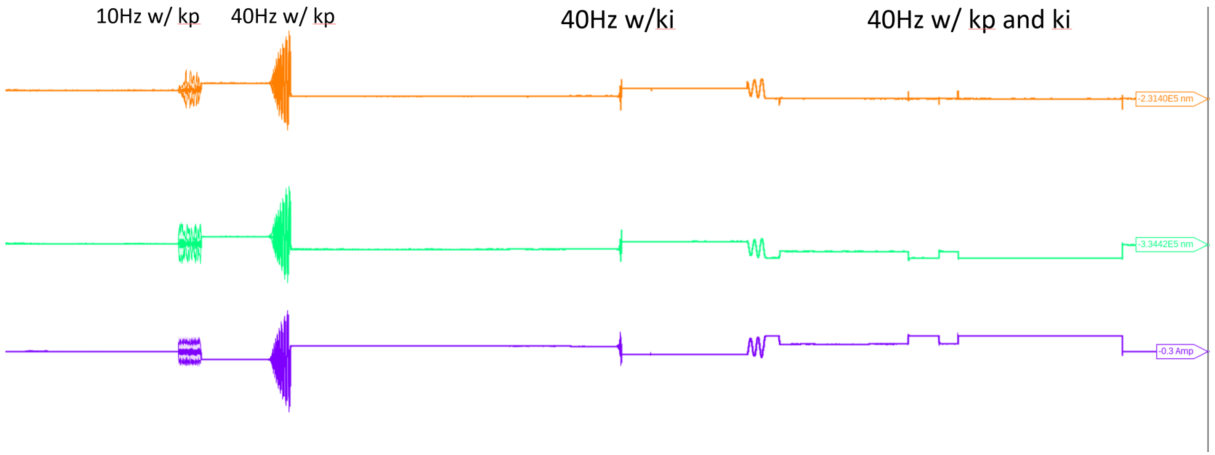
  - Effectively mitigate the periodic variations (period~ 12 hour) of the horizontal beam orbit (10 um)
- **FOFB not ready**

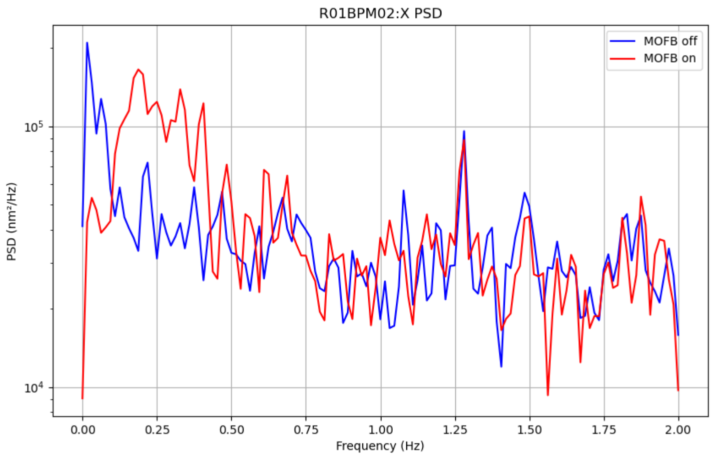




Improvement of SOFB

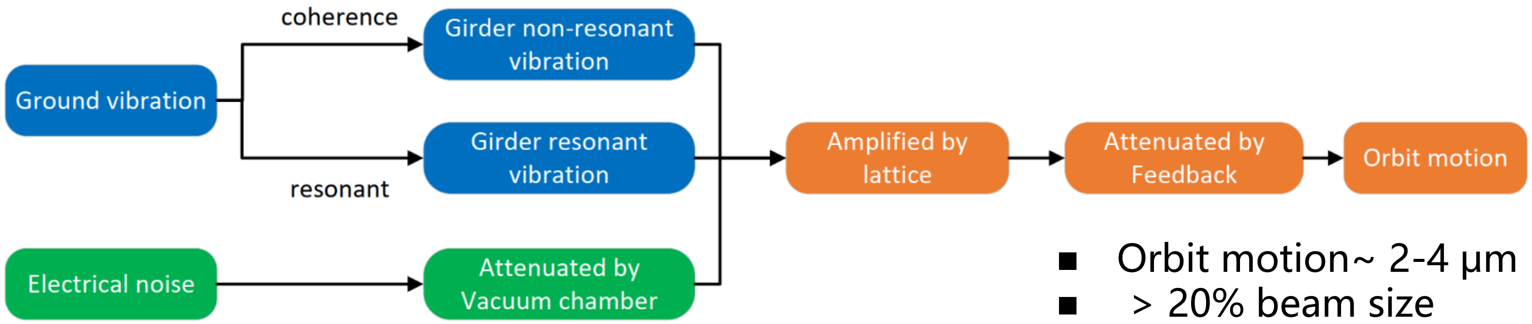
- Since the FOFB hardware would not be ready until September, 2025, we attempted to improve the SOFB performance.
- Increase the BPM SA data sampling rate from 10Hz to 40Hz, implement the physical IOC and feedback algorithms in ECPICS.
- With PI controller, SOFB can operate stably at a working frequency of 40 Hz, however the closed-loop bandwidth is smaller than 0.25Hz.
- The only remaining solution is to identify the source of the low-frequency disturbance…



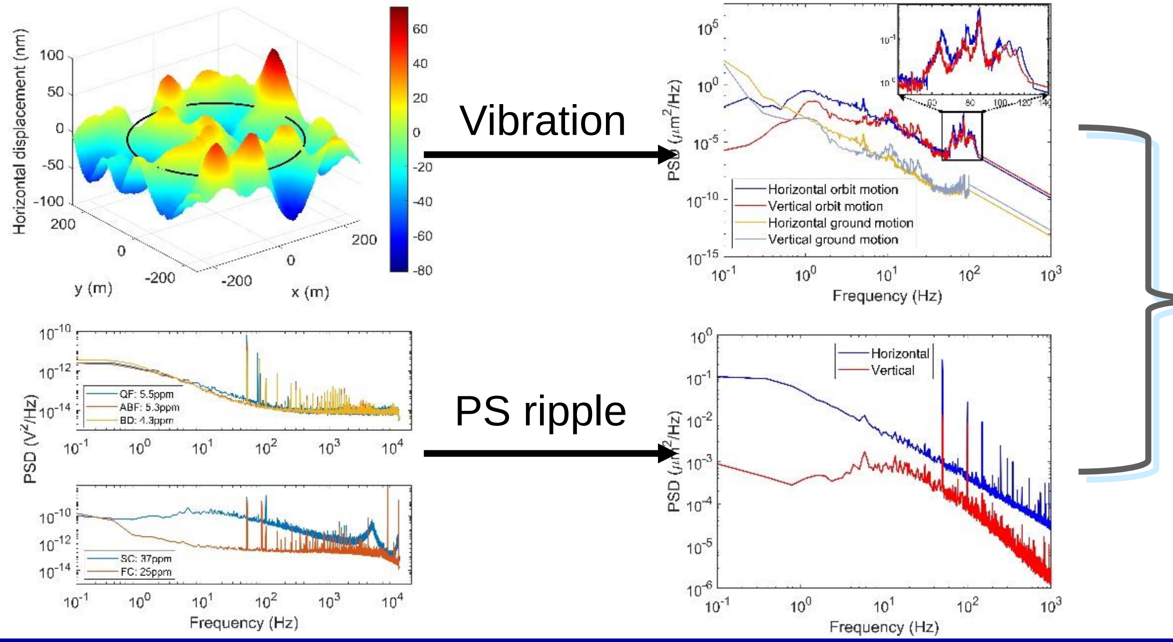


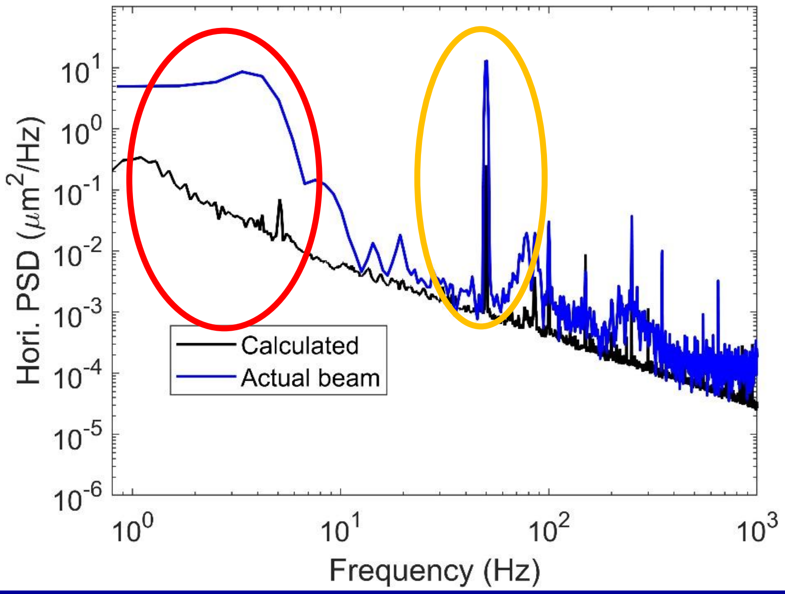
Simulation

Model → Simu. vs. Actual → Source? → Optimize



- Orbit motion~ 2-4 μm rms @IDBPM
- > 20% beam size
  - 1-5 Hz low-frequency
  - 50 Hz



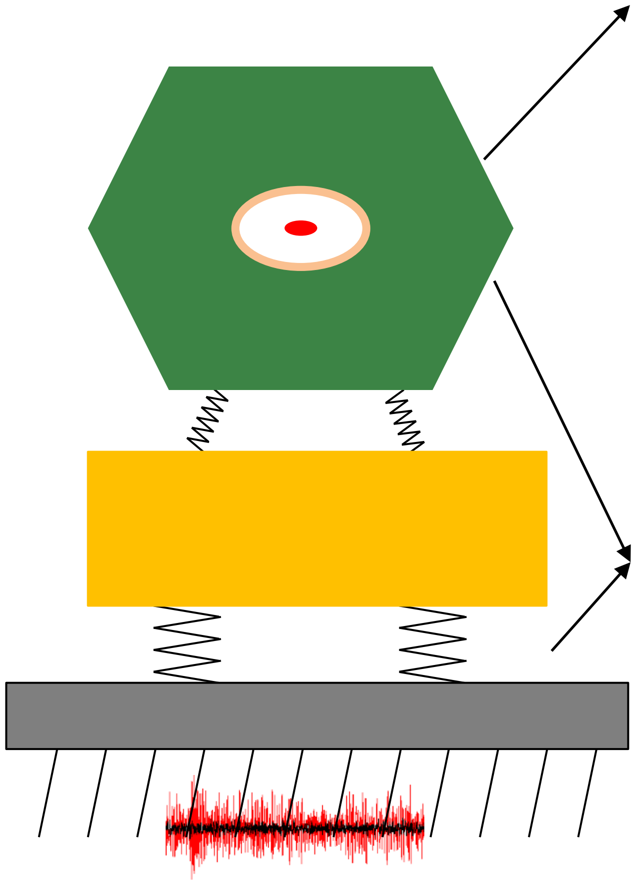


X. Y. Huang *et al.*, *Nucl. Sci. Tech.* to be published

Potential sources

(Tests conducted from2024.3-2024.9)

Courtesy of Fang Yan, Fengli Long



电信号

机械振动

可能5-2：束线前馈线圈的电信号
Experiments：抽查6个线圈（36-72ppm）

可能5-1：抖动通过SC（慢轨道反馈）校正子磁铁电信号传导至束流
排查实验：R30周期所有SC校正子及R02/38/45部分SC校正子 (31ppm-99ppm)

可能1-1：京密引水渠的水流影响
排查实验：排查了R35-40周期隧道内每个周期地面的振动（午间20nm以下）

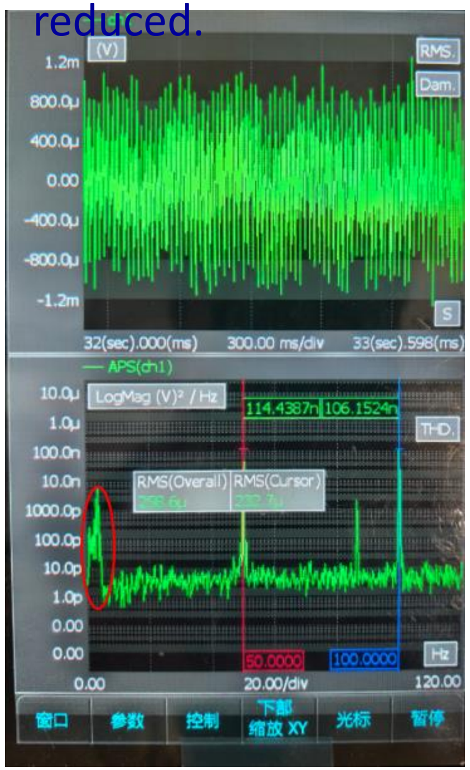
可能4：低温液氦/氮管道抖动及压缩机、泵振动传导至超导腔引起束流抖动
排查实验：管道有套管无法测试，改测腔束管下支撑抖动 （看到40Hz附近峰值）

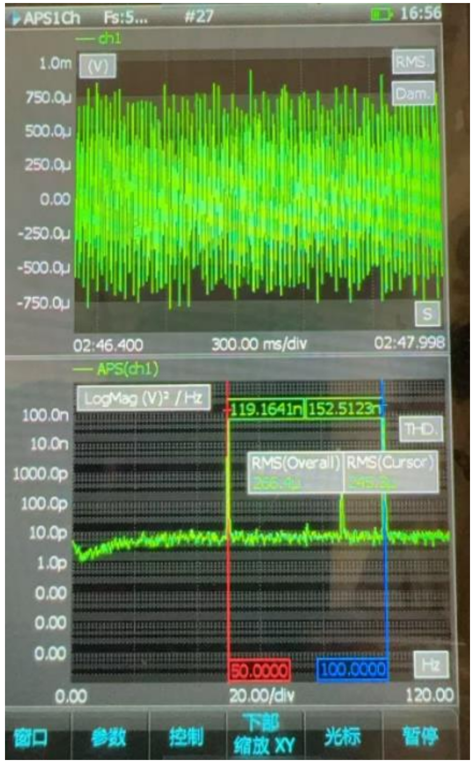
可能3：某些周期或元件振动异常，排查了R05、R45周期（无异常）

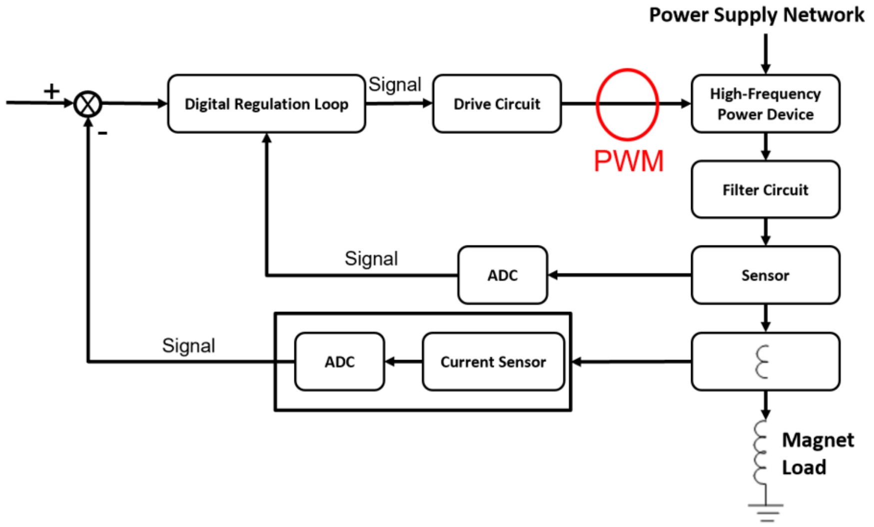
可能2： 1）地面的振动被四极类磁铁、FC放大
2）冷却水引起四极类磁铁抖动
3）冷却水引起真空管道抖动，切割四极类磁铁磁力线产生的扰动
排查实验：测试了R18周期所有四极类磁铁、波纹管连接的10条真空管道开水前后的振动对比情况，BPM、FC的振动 (已完成：振动均小于25nm)

可能1：束流的抖动通过地基传导，振源来自于内环动力设施
排查实验：内环8个水泵房、12个空调机房附近隧道的振动
（已完成测试，完成了一部分数据处理：小于几十nm量级）

- By sequentially turning on different types of power supplies, we found that adjacent SCs can crosstalk with each other, resulting in a large low-frequency noise coupled out.
- Through in-depth analysis and experiments by our power supply system colleagues, it was found that one solution is applying the frequency staggering method to set different PWM frequencies for different SC (50.01Hz,49.98Hz,etc…), the low-frequency ripple of SC power supplies was significantly reduced.





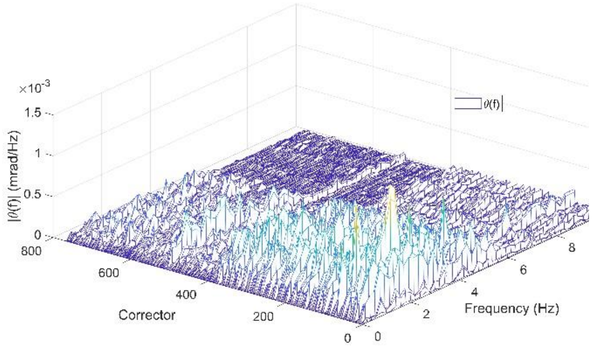


PWM frequency set at 50kHz

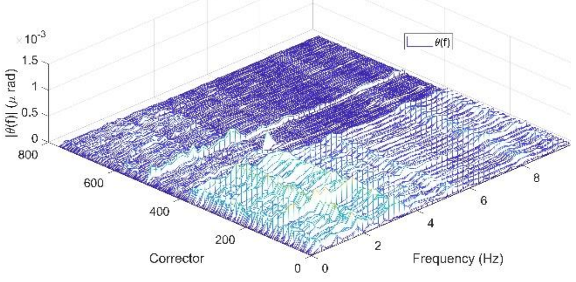
Effects after staggering the SC PWM frequency

- We optimize the correctors in batches. With spectrum analysis, the low-frequency noise of the SC power supplies has been gradually reduced.
- The orbit motion can be reduced from 40% to smaller than 20% of the beam size.

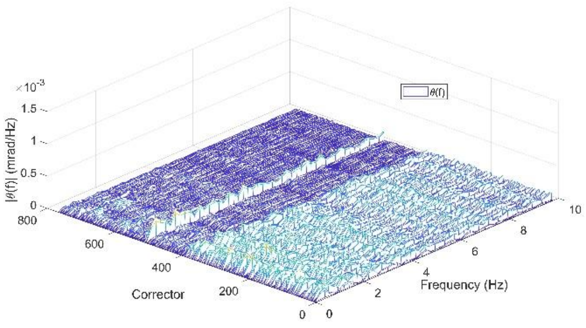
PS ripple reduced



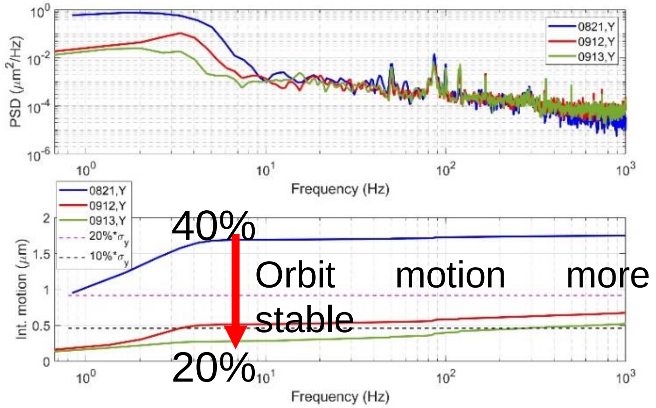
a) 250821, before optimization



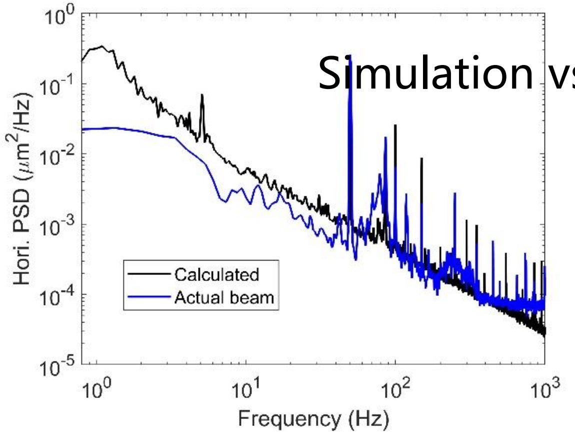
b) 250912, stagger PWM frequencies of SD2/3/4V

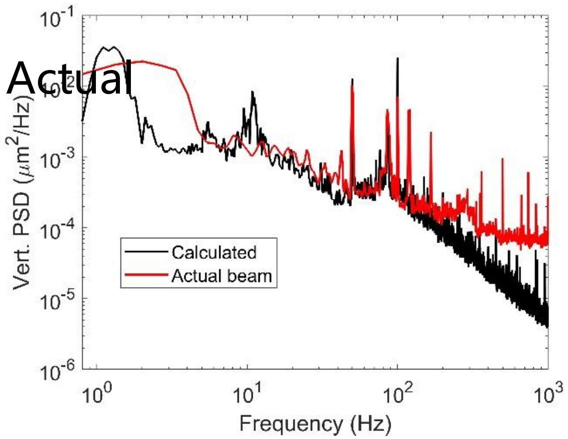


c) 250913, stagger PWM frequencies of all SDVs



Simulation vs. Actual



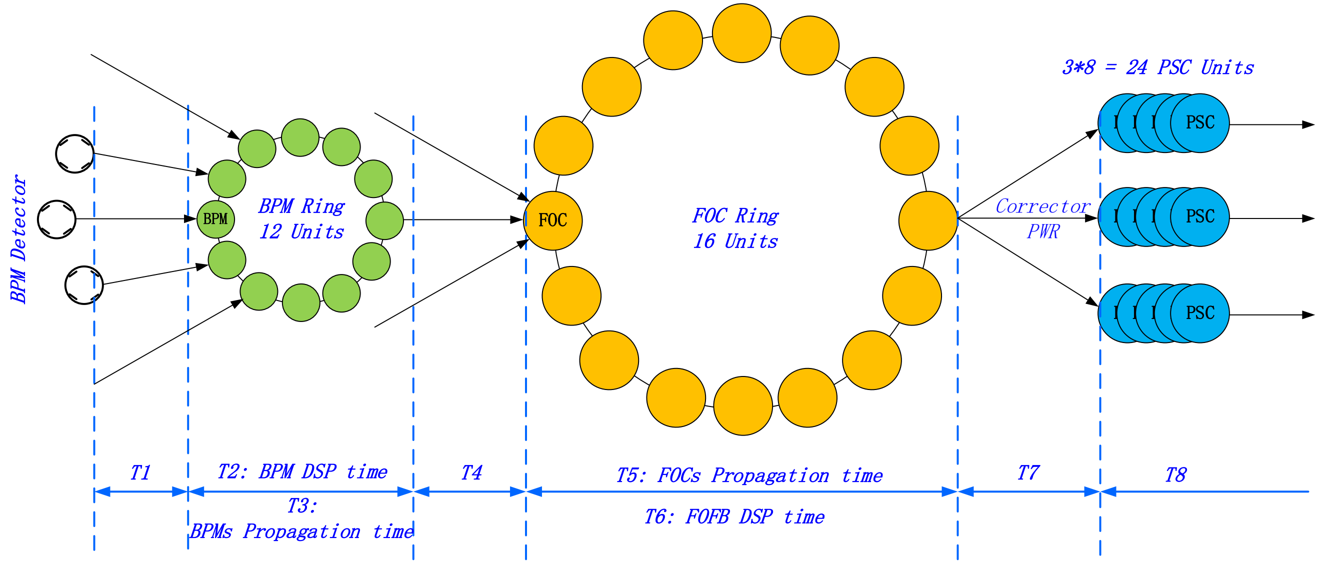


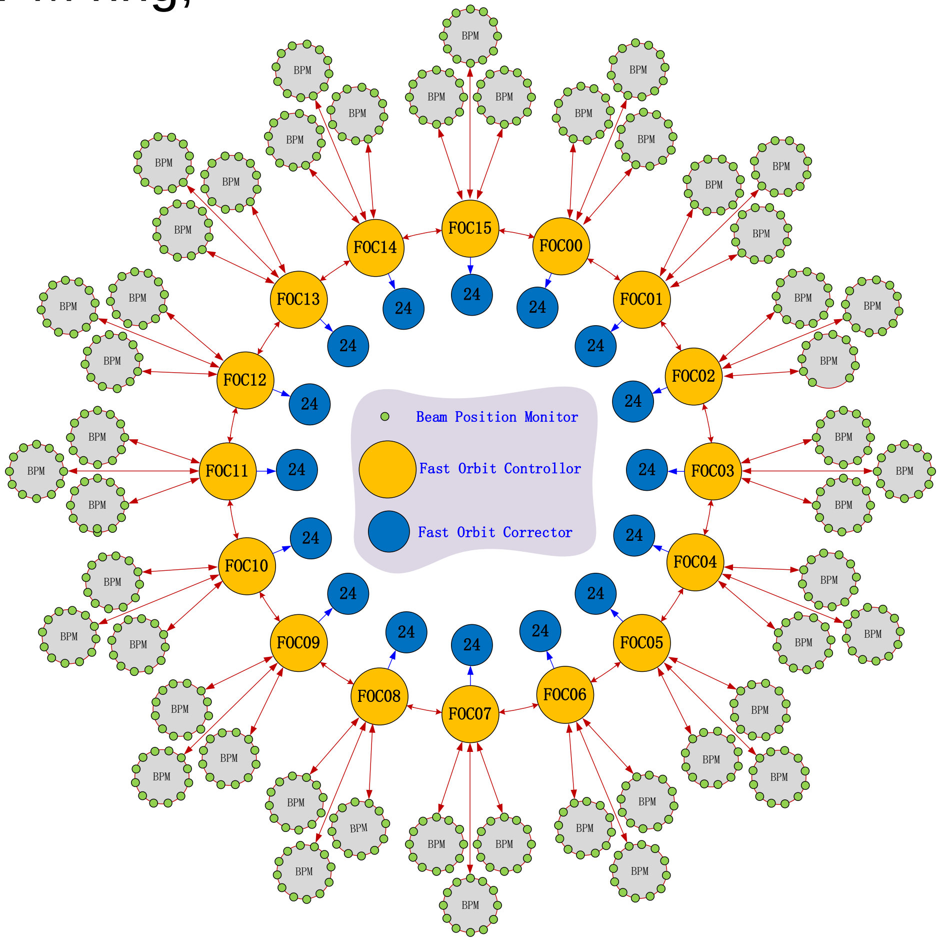
FOFB Commissioning

FOFB system framework

➢"Ring-Star-Ring" structure

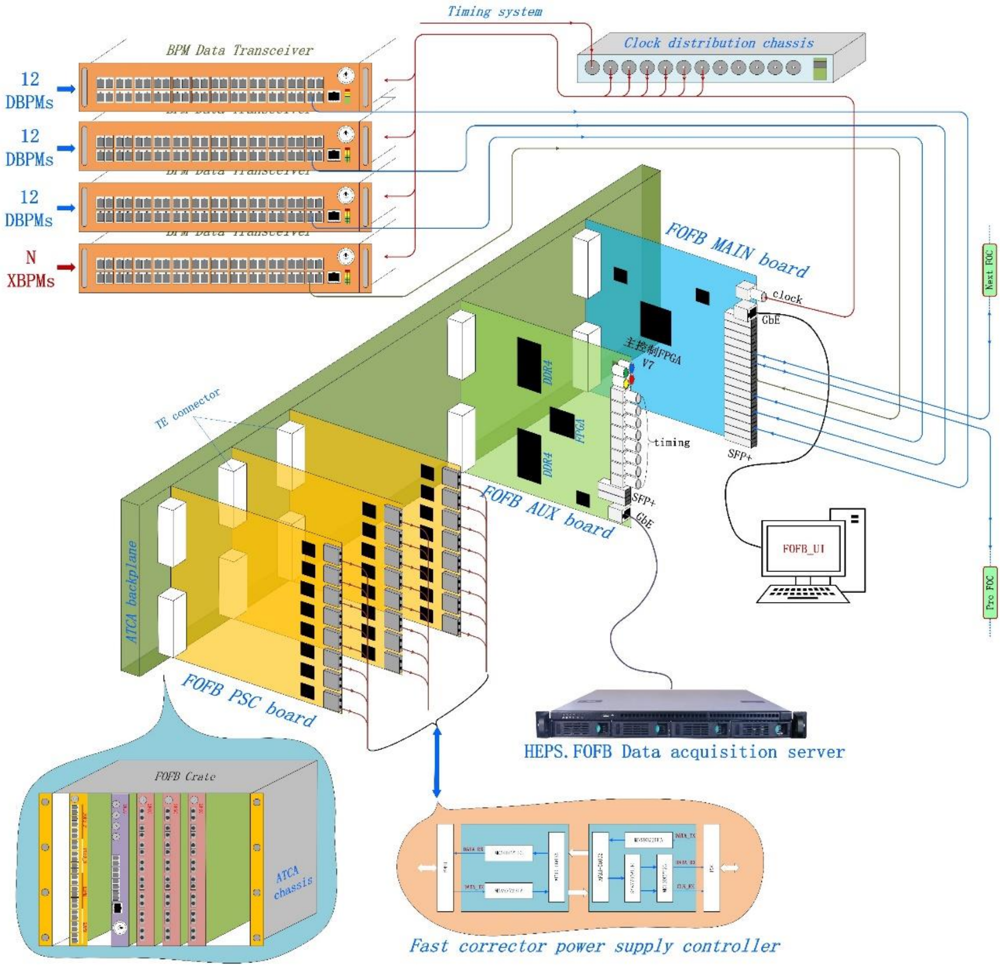
- For each BPM station, construct all 12 BPMs to a BPM ring;
- Connecting adjacent 3 BPM rings to 1 FOFB unit.
- Link all 16 FOFB units to 1 large FOFB ring.
- Connecting 1 FOFB unit to 3 FC PSC units.



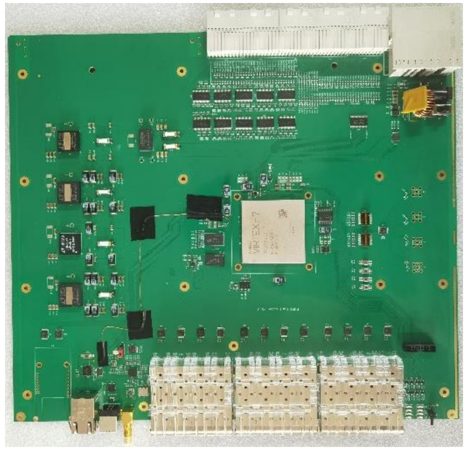


Hardware design of FOC

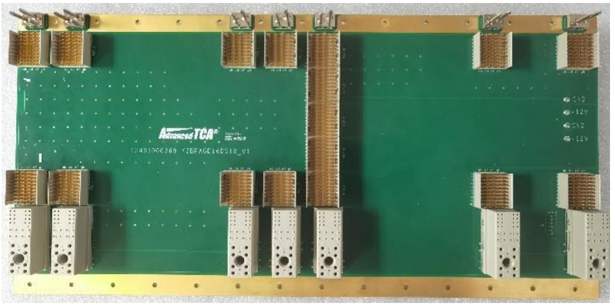
- The overall hardware of the crate adopts a custom ATCA architecture. The front plug-in board includes 1 main control board, 1 auxiliary function board and 3 power interface boards.
- MAIN board： Complete all core operations of FOFB, receive BPM data, communicate with the upper computer, etc. （X7VX690T FPGA）
- AUX board： Receive timing signals, store and read FOFB data, update firmware programs online, monitor the crate status, etc. （XCKU060 FPGA）
- PSC board： With 8-channel optical fiber interface to communicate with the fast corrector power supply controller.



Hardware implementation

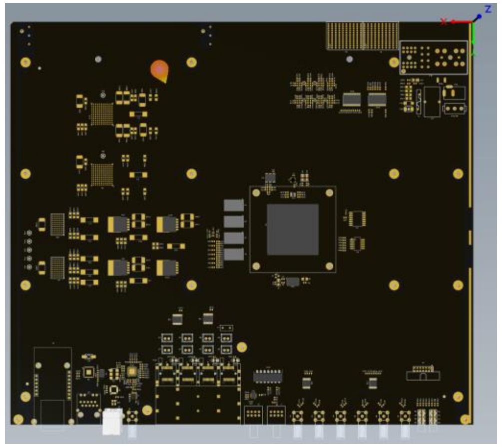


MAIN board

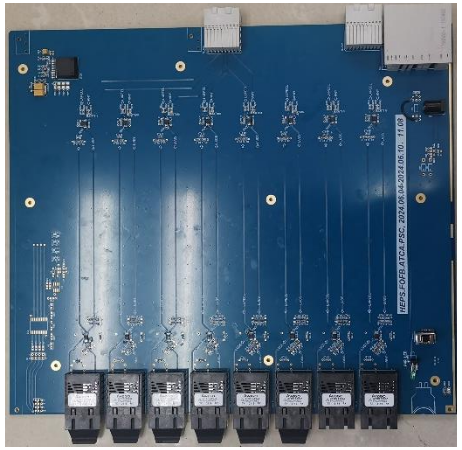


Backboard

ATCA crate

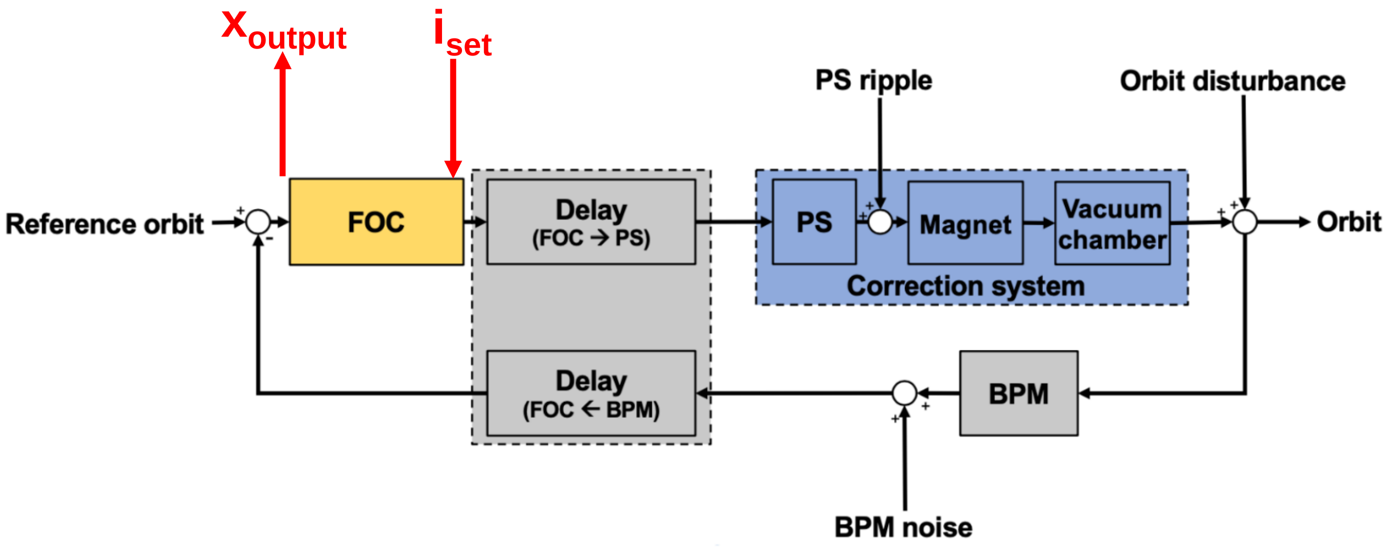


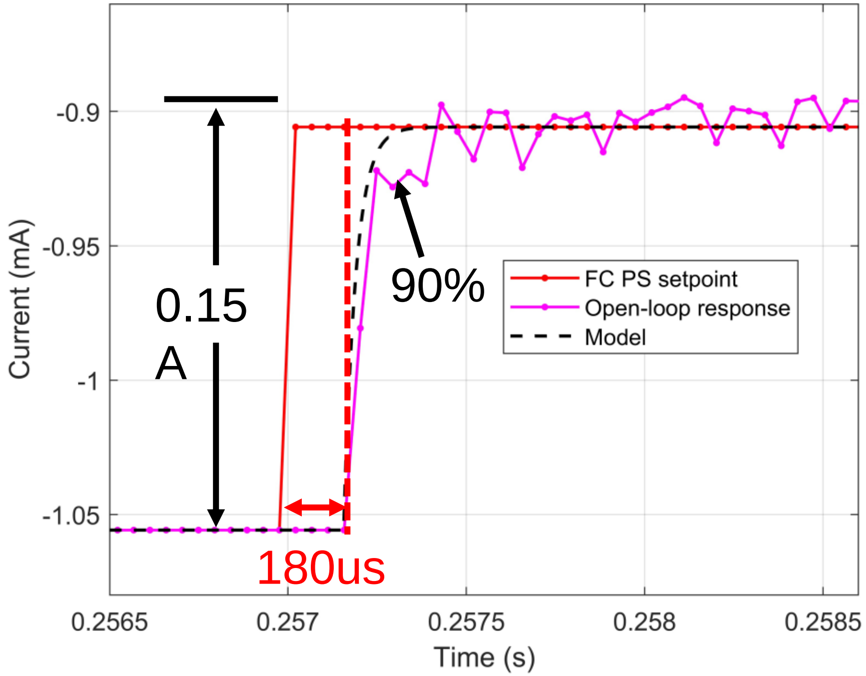
AUX board



PSC board

Open-loop response



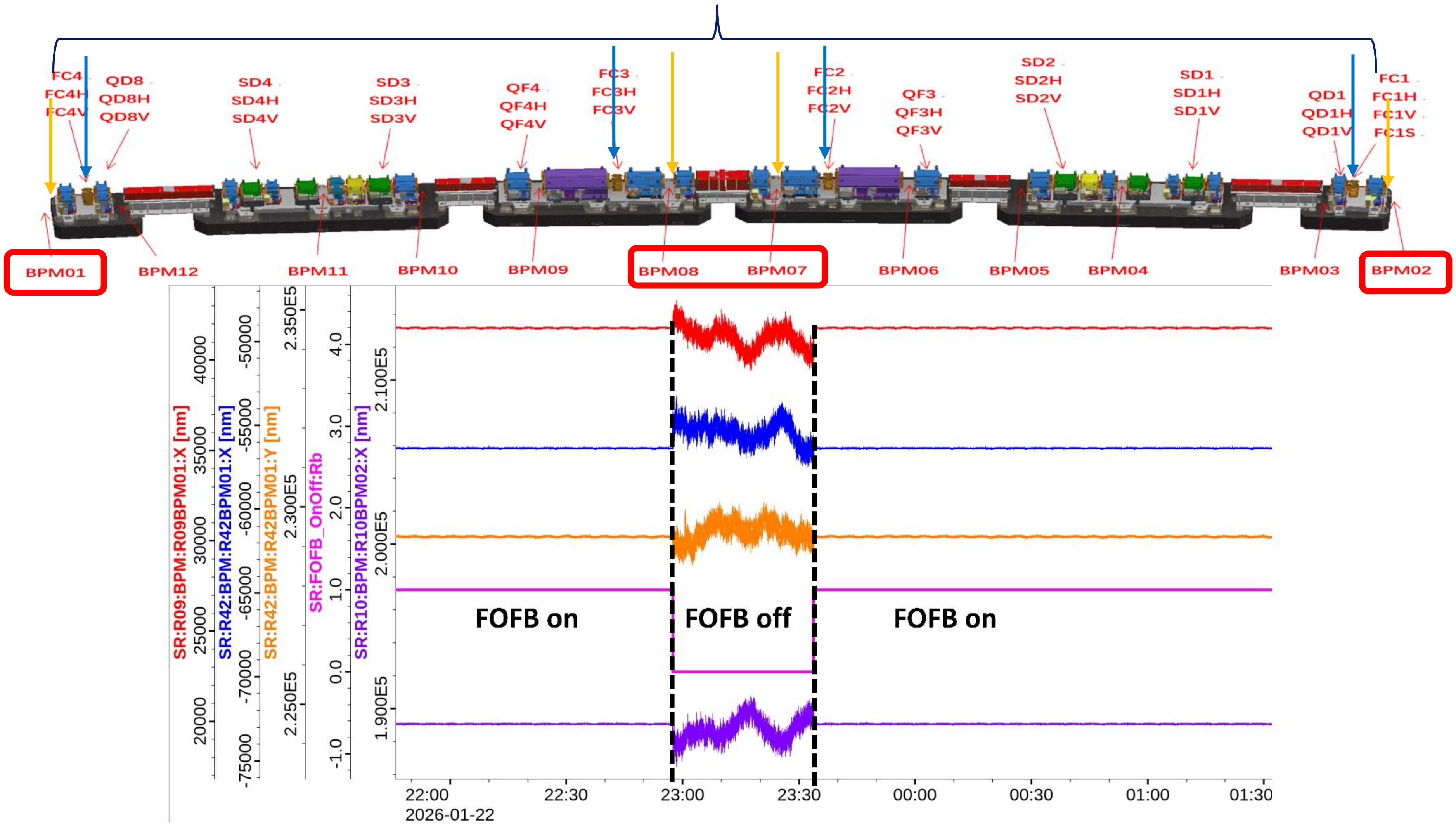


- Open loop step response was conducted by providing 0.15A step on FC and using inverse response matrix on all bpm data.
- It measures the total latency in the system. The plot shows 180 μs latency where no output from the fast corrector is observed. After this initial latency, the risetime from 0 to 90 % full value is 90 μs.

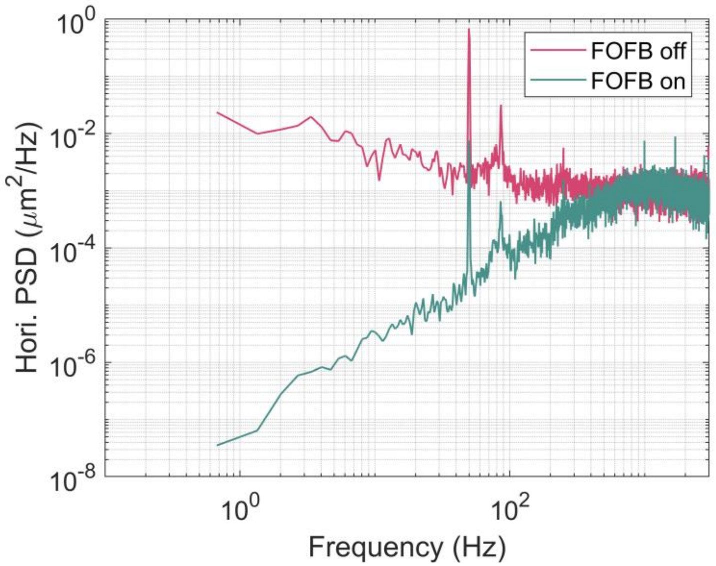
$$G_{op} = \frac{29300}{s + 29300} e^{-0.00018s}.$$

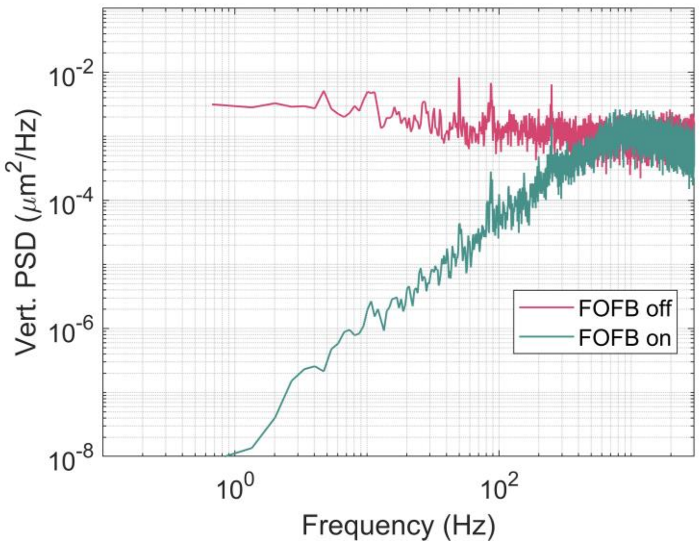
FOFB commissioning

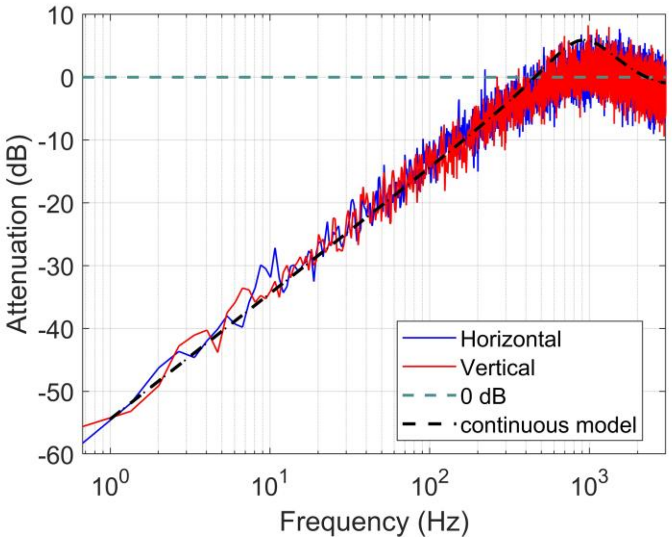
FOFB loop（4*4）

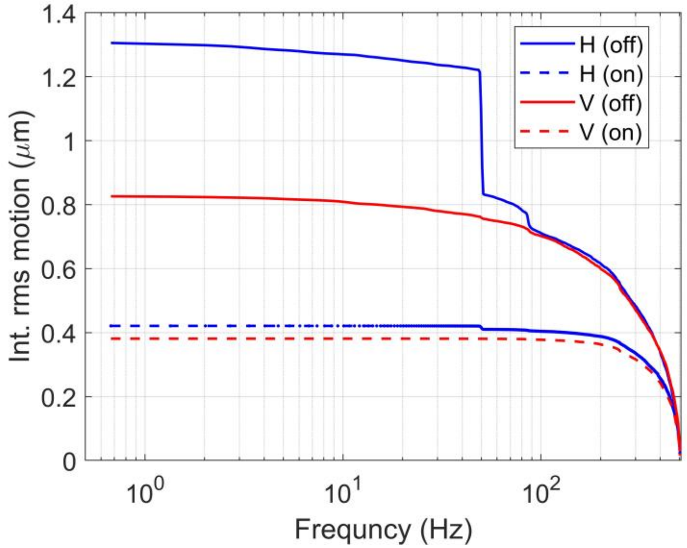


Orbit stability achievement

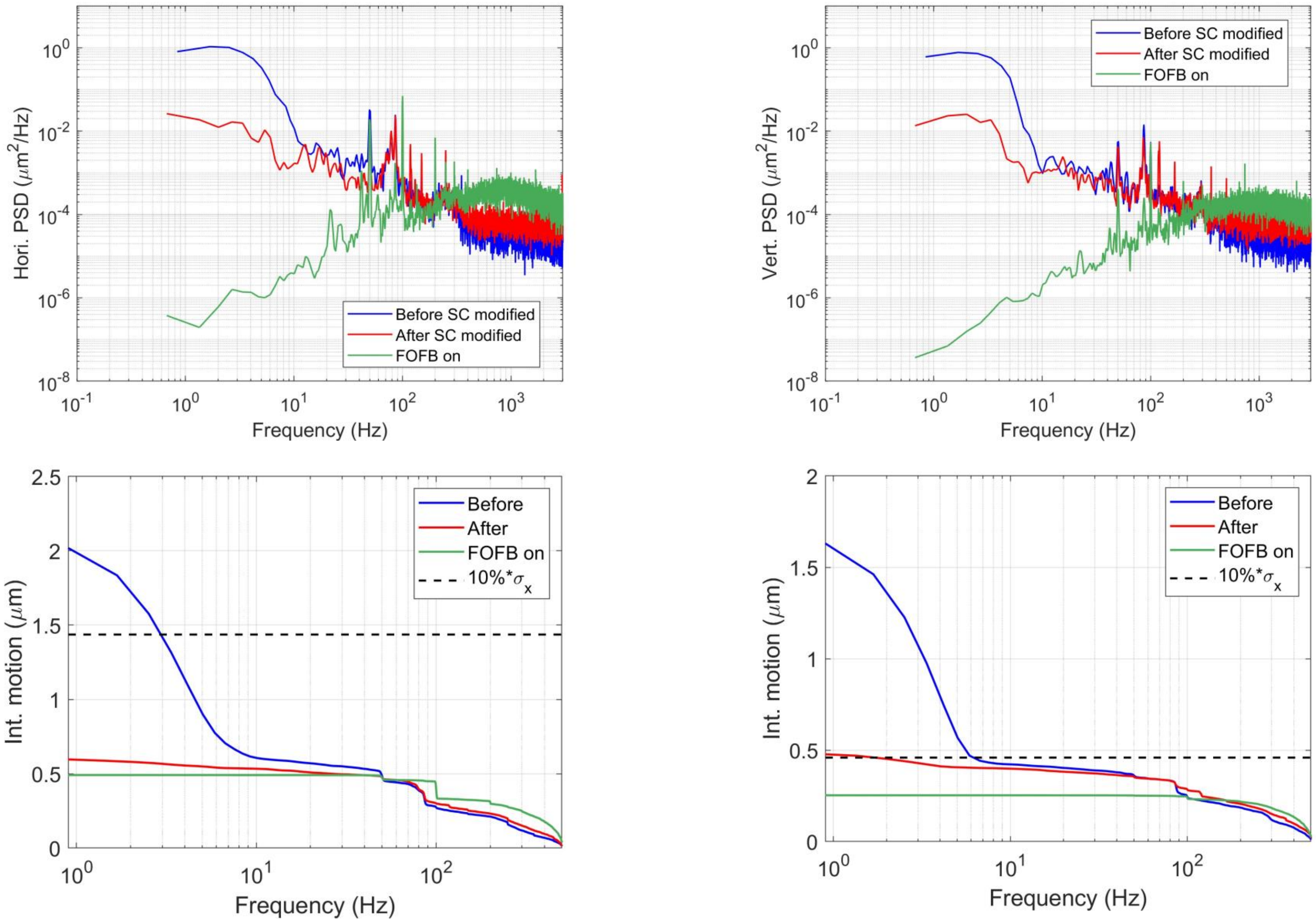








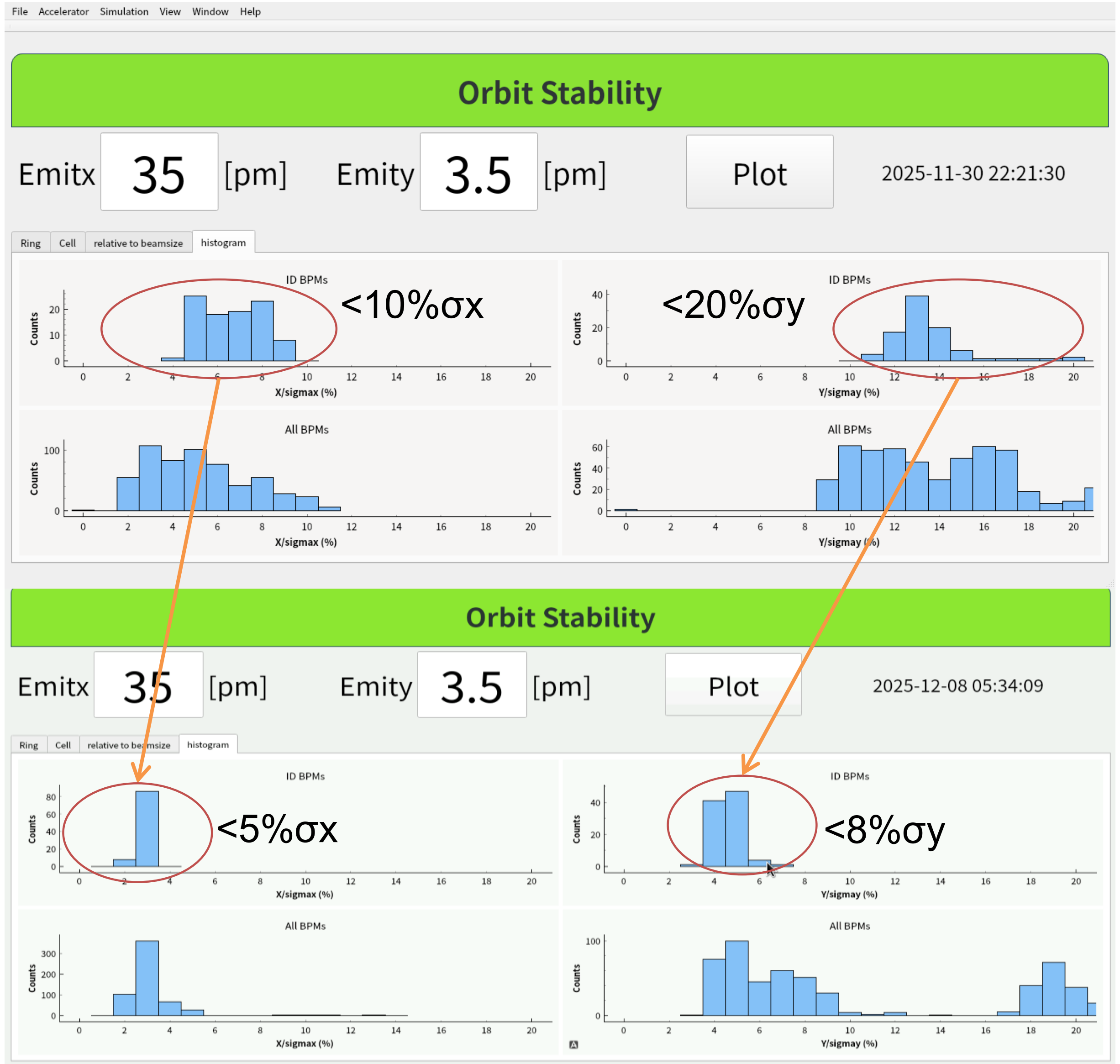
Orbit stability achievement



Orbit stability achievement

FOFB off

FOFB on



stability>40%

Optimize SCPS

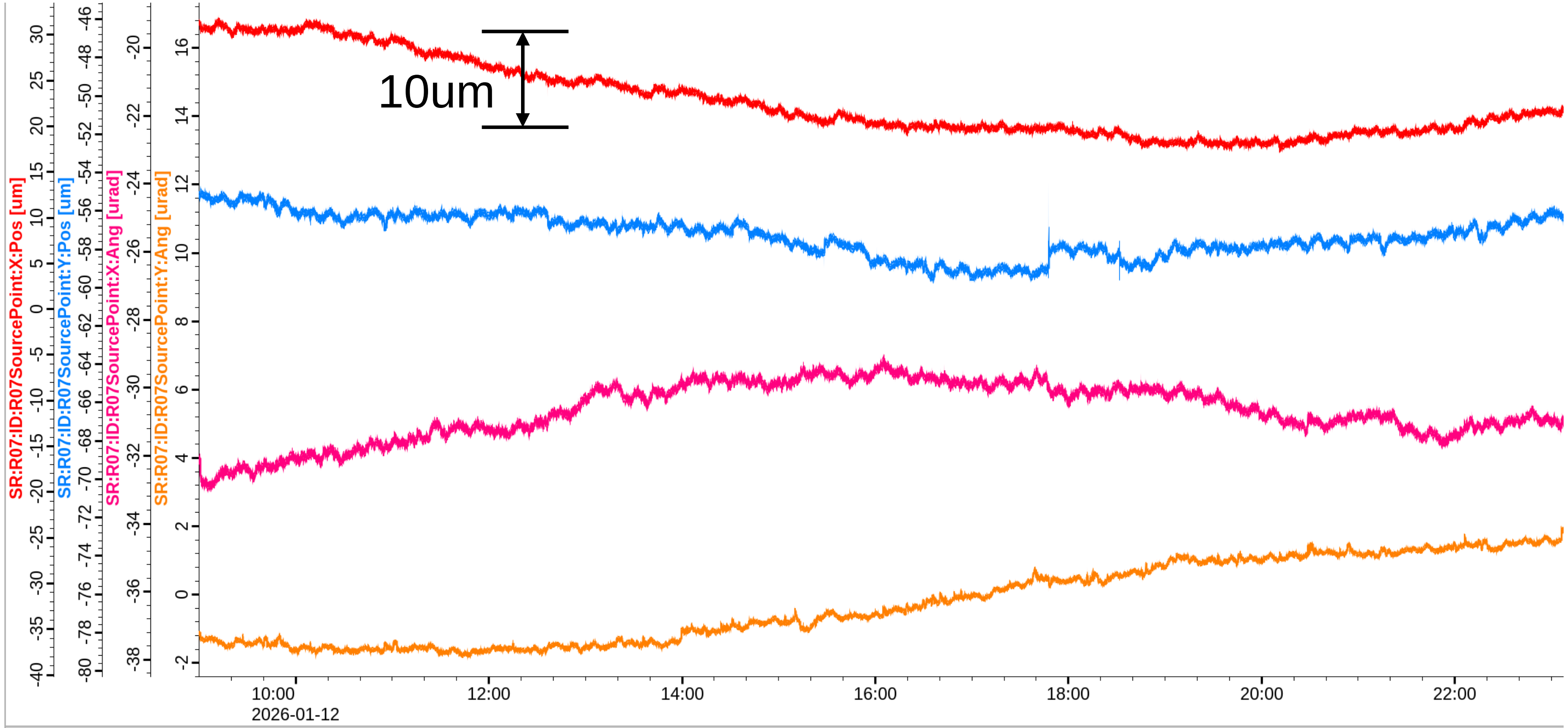
stability<20%

FOFB

stability <10%

FOFB Performance (long-term stability>10h @100mA)

- FOFB off：source point position std ~ 1-10um，source point angle std~0.5-2urad (10h)



Properties ×

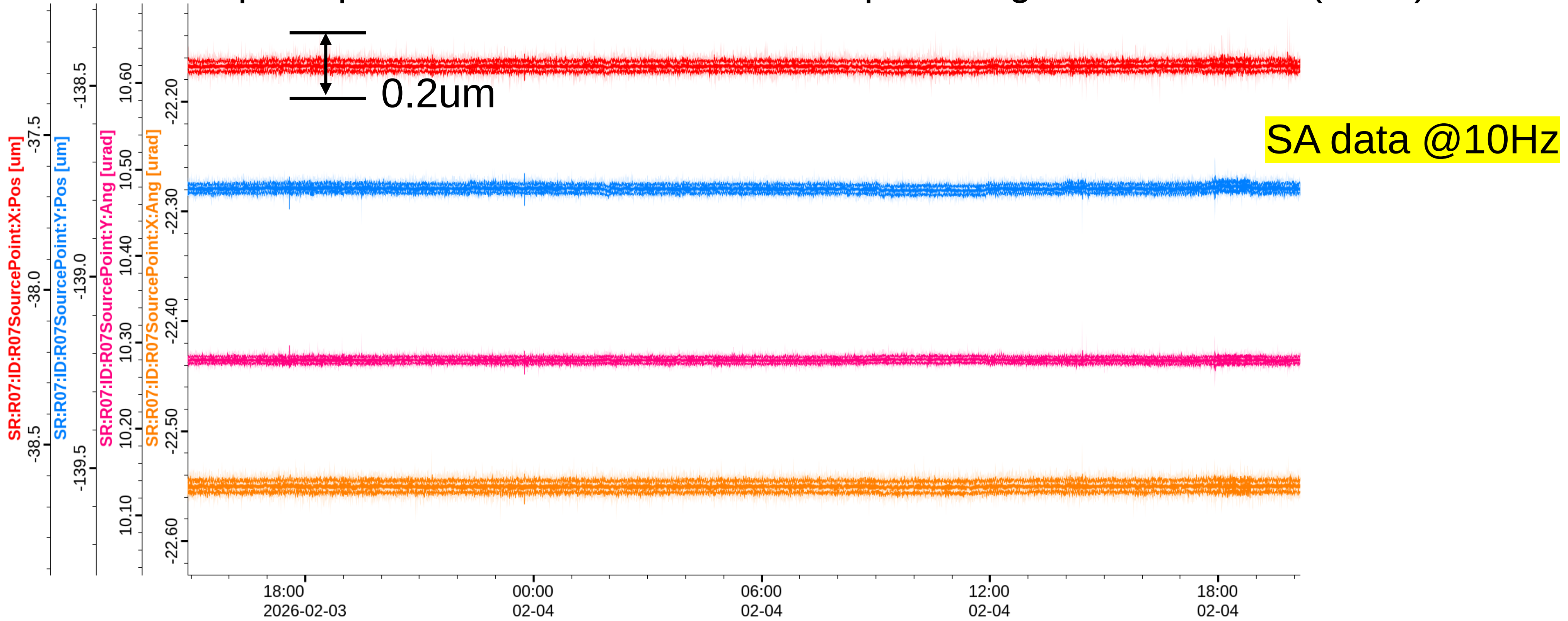
Traces | Time Axis | Value Axes | Misc. | Statistics

Refresh

Display Name	Sample Count	Mean	Median	Standard Deviation	Min Value	Max Value	Sum
SR:R07:ID:R07SourcePoint:X:Pos	8512	22.698096456870143	20.98808928571428	4.141681445738913	17.386066666666668	31.636233333333333	193206.19704087943
SR:R07:ID:R07SourcePoint:Y:Pos	8512	-57.27050858330862	-57.261090476190475	1.0554154309882486	-59.60520000000001	-54.970233333333326	-487486.56906112377
SR:R07:ID:R07SourcePoint:X:Ang	8512	-30.6850257944801	-30.69265799866175	0.8445410023235427	-32.95929273978054	-29.139530388310877	-261190.93956261312
SR:R07:ID:R07SourcePoint:Y:Ang	8512	-0.24661478393552605	-0.5072968190346239	1.17764477292049	-1.799183930516013	2.047202797202797	-2099.1850408592145

FOFB Performance (long-term stability>10h @100mA)

- FOFB off： source point position std ~ 1-10um， source point angle std~0.5-2urad (10h)
- FOFB on: source point position std < **20 nm**, source point angle std < **5 nrad** (>24h)



Properties × | Traces | Time Axis | Value Axes | Misc. | Statistics

Refresh

Display Name	Sample Count	Mean	Median	Standard Deviation	Min Value	Max Value	Sum
SR:R07:ID:R07SourcePoint:X:Pos	8117	-37.27834463845477	-37.27846875	0.004214508678338945	-37.291516666666666	-37.26020967741935	-302588.3234303369
SR:R07:ID:R07SourcePoint:Y:Pos	8117	-138.76917926190995	-138.7693620689655	0.003959282058623966	-138.78276666666673	-138.75320689655175	-1126389.4280689189
SR:R07:ID:R07SourcePoint:X:Ang	8117	-22.550403472364785	-22.550423560179656	0.0013171043826923025	-22.555517653078628	-22.545393630759488	-183041.6249851852
SR:R07:ID:R07SourcePoint:Y:Ang	8117	10.279503491868429	10.279530767335645	0.0011817258988964928	10.275555286570235	10.283266775276871	83438.72984349576

Beam dump due to BPM w/ FOFB on

- BPM error induced beam dump （two runs of pilot operation）

  1. One channel of the BPM electronics is damaged, consequently fluctuations/drifts in the measured FA data. (Solved: Add orbit threshold)

  2. Bit errors in BPM data (Solved: Use a torque wrench to fasten cables)

  3. BPM crashes in R35 (Solved: Replace the clock distribution chassis in this section)

  4. BPM power supply burnt out (Solved: Change the power supplies for all BPMs)

FOFB Optimization during pilot operation (from25/12)

- Software

  1. Added real-time status monitoring function in ON state.

  2. optimized all multi-threaded thread pools to minimize unbounded thread count growth and memory leaks.

- Hardware algorithm

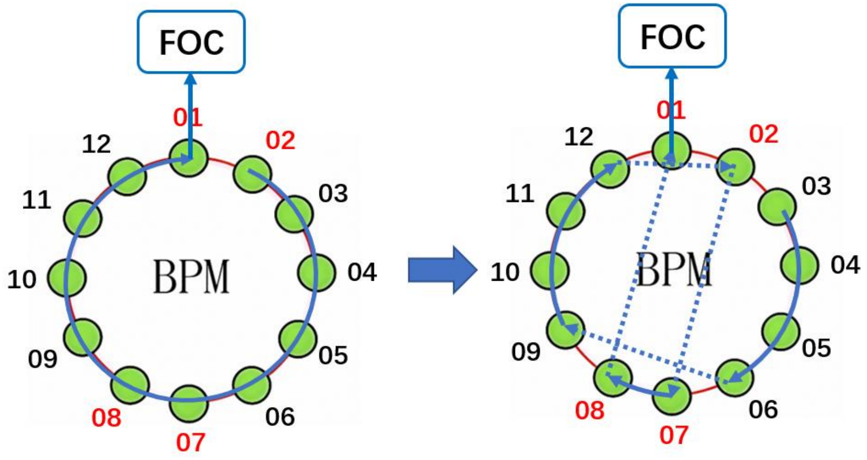
  1. Remove automatic FOFB stop on 5 consecutive same orbit readings.

  2. Add an algorithm to automatically stop FOFB when the orbit value exceeds the threshold (default 100 um)

- Hardware

  1. Adjustment of the digital BPM fiber link configuration, placing the BPMs(01/02/07/08) in the feedback loop at the end of the data transmission path.

  2. Replace the clock distribution chassis in this section.



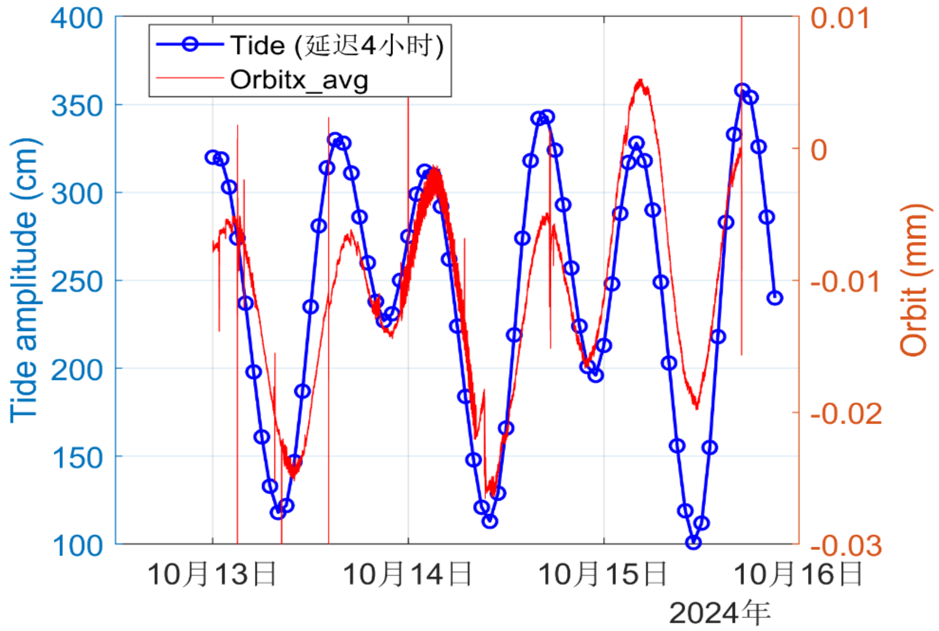
Long-term orbit fluctuation

Long-term stability

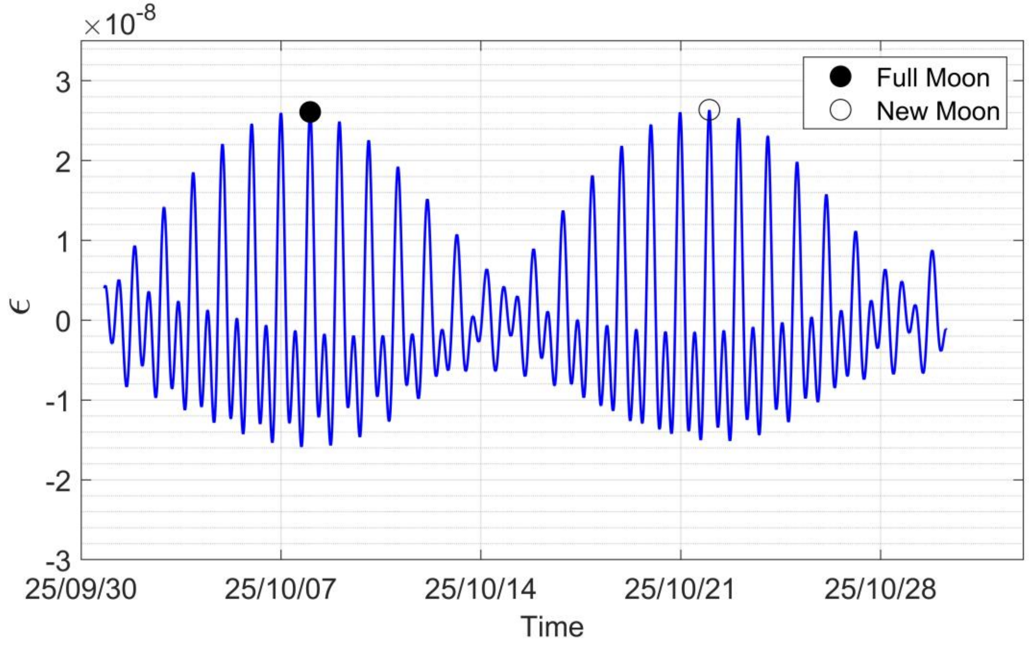
■ Long-term stability (< 10^{-2}Hz) :

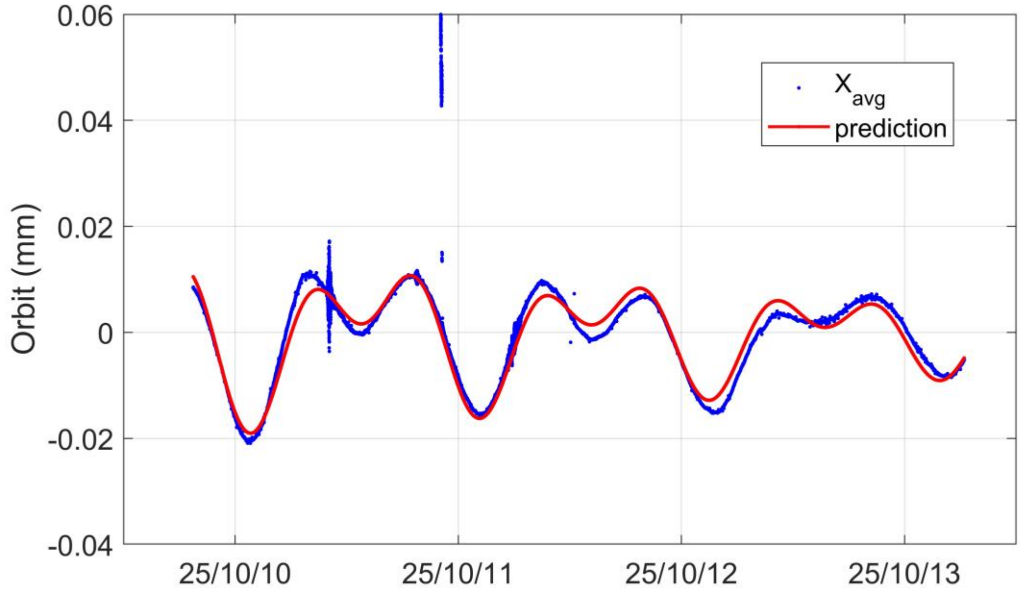
- ➢ We observed that the horizontal average orbit drifts slowly with a period of about 12.5 hours. This is believed to be related to periodic changes in the circumference. The issue can be compensated for by adjusting the frequency. The source of the slow drift is still under investigation, but it is currently speculated that it may be related to tides and temperature.

- ➢ The blue dots represent the tidal height data of Tanggu station in Tianjin, and the red dots represent the horizontal average orbit. It is evident that they have the same period.



Terrestrial gravitational tide





$$\varepsilon = \frac{\Delta C}{C} = \lambda_T \frac{\Delta g}{g}.$$

$$X_{\Delta \mathrm{g}} = -\frac{\lambda_T \langle D_x \rangle}{\alpha_p g} \Delta g = -\frac{\lambda_T \langle D_x \rangle}{\alpha_p g} \sum_{n=1} G_n \cdot \cos(\omega_n t + \phi_n)$$

1.9e-5

X. Y. Huang *et al.*, *NIM.A* to be published

Earthquake detected

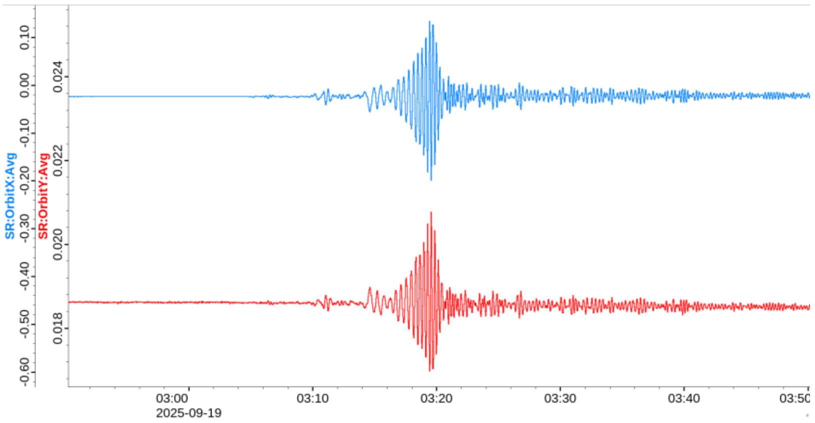
高能同步辐射光源储存环成功记录地震活动

中国科学院高能物理研究所 2025年9月22日 11:45 北京

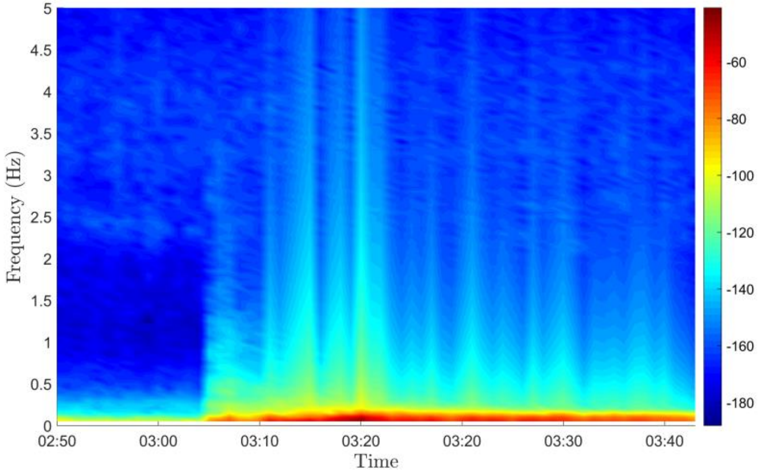
2025年9月19日，高能同步辐射光源（HEPS） 完整清晰地“捕获”了一次地震过程，展示了这台正在调试中的第四代同步辐射光源超高的束流品质和卓越的稳定性与灵敏度。

■Observation of a earthquake

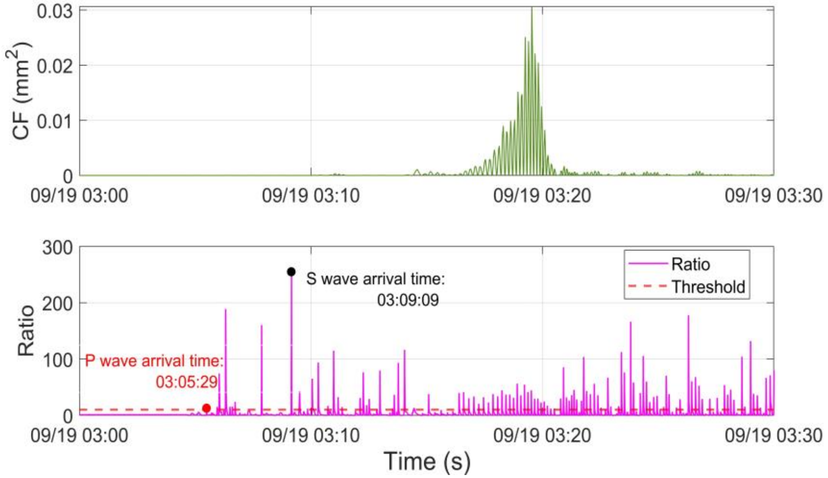
- ➢ We observed an large orbit fluctuation in Sep. 19, 2025, ~1h. (Kamchatka,M7.8)
- ➢ Using horizontal average orbit information, we can determine basic seismic spatiotemporal parameters such as epicentral distance and origin time.



Average orbit

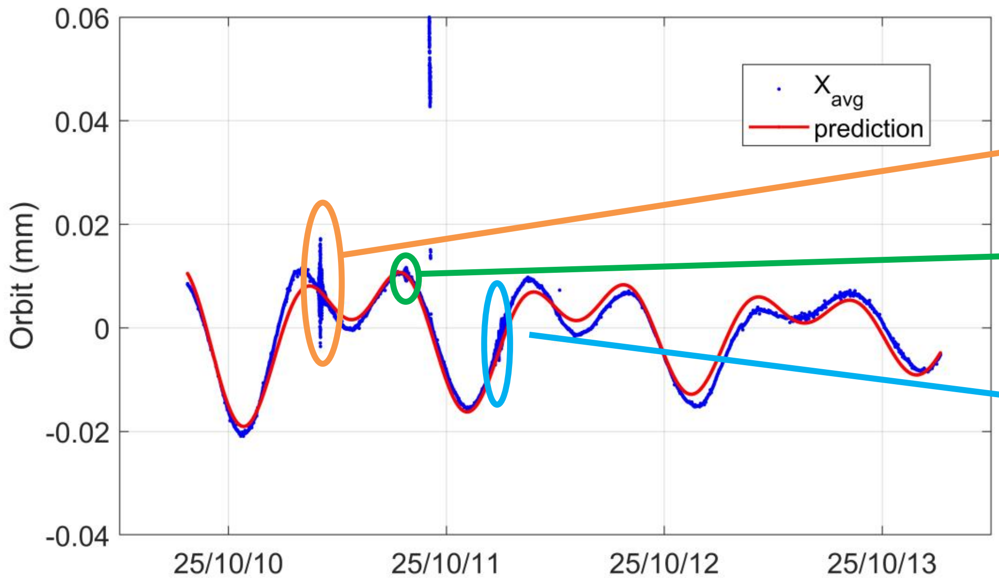


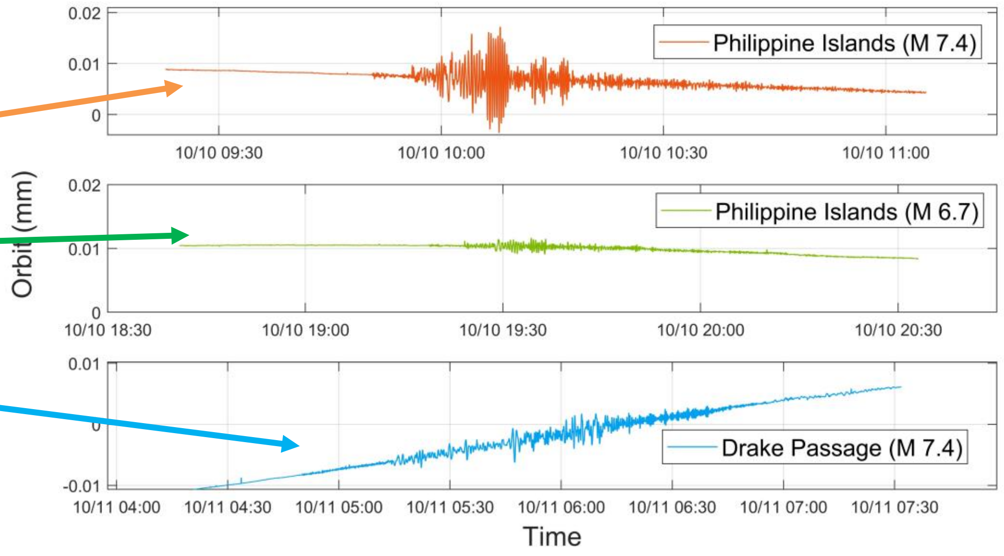
Vibration detected on the tunnel ground



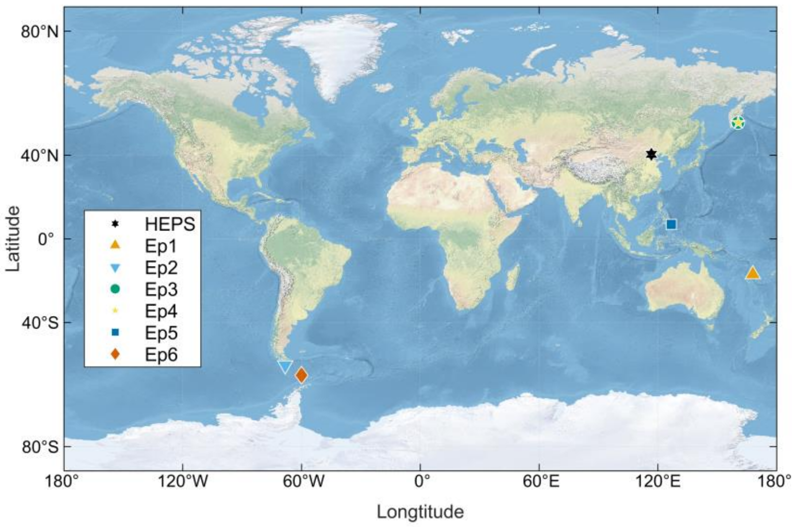
STA/LTA method for picking up the first arrival of natural seismic waves

Earthquake detected

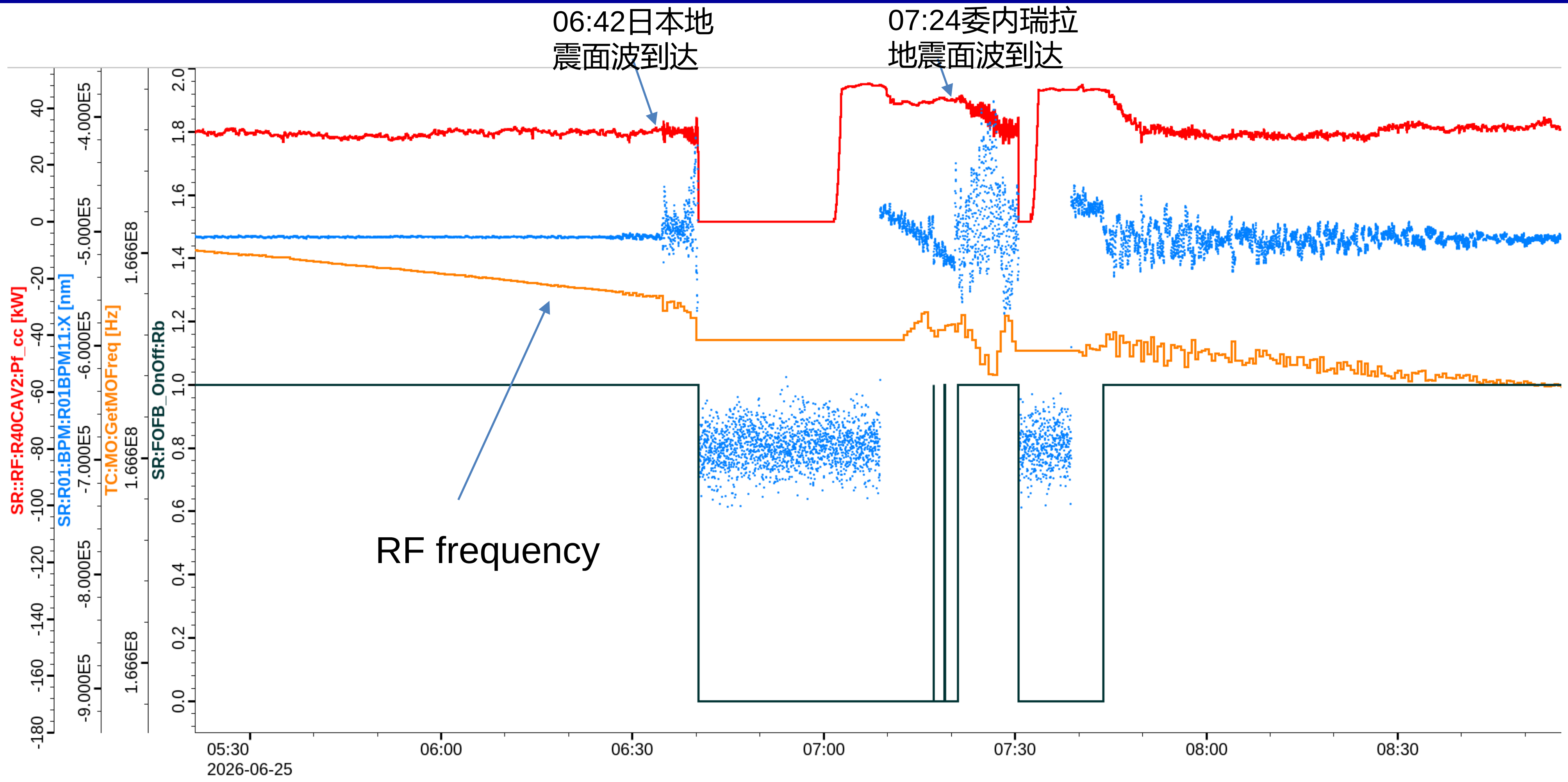




Date (No.)	Information from HEPS			Information from seismic station			
	Δ [km]	Origin time	M_s	Δ [km]	Origin time	Location	M_s
2024/12/17(Ep1)	8909	09:42:56	7.2	8354	09:47:25	17.75°S, 167.95°E	7.2
2025/05/02(Ep2)	17300	20:51:13	7.4	18154	20:58:25	56.80°S, 68.25°W	7.4
2025/09/13(Ep3)	3565	10:37:49	7.2	3563	10:37:53	53.05°N, 160.45°E	7.3
2025/09/19(Ep4)	3560	02:58:11	8.1	3568	02:58:15	53.10°N, 160.60°E	7.8
2025/10/10(Ep5)	3784	09:43:56	6.9	3812	09:44:20	7.30°N, 126.75°E	7.4
2025/10/11(Ep6)	17200	04:23:22	7.2	17794	04:29:21	60.25°S, 60.05°W	7.6



Earthquake detected



2026.06.25 06:30 日本海域40.20°N，142.40°E, 6.9级（2205km）

2026.06.25 06:04 委内瑞拉北部 06:04 10.35°N，68.35°W, 7.2+7.5级，1分钟内发生了2次（14444km）

Summary

- HEPS accelerator and beamline has passed performance tests in 2025/10, reached all KPPs.
- During the early stage of beam commissioning, low-frequency (1–5 Hz) disturbance was excessive by comparing the beam motion spectrum with simulation results. Through a series of experiments, we identified that the issue was caused by coupling from the PWM frequencies of the adjacent slow corrector power supplies. After staggering the PWM frequencies of different correctors, the low-frequency disturbance was reduced, and the beam motion was approximately 20% of the beam size w/o feedback.
- The FOFB system was successfully commissioned. A closed-loop bandwidth of >300 Hz was achieved, and the beam orbit motion was suppressed to less than 10% of the beam size.
- The variation of average horizontal orbit reveals the intrinsic connection between macroscopic geophysical processes and the microscopic beam dynamics but also provides a potential new approach for monitoring beam energy variation and acquiring seismic-related data during the operation and optimization of the HEPS.


Thanks for your attention!