PROGRESS OF PHYSICS STUDIES AND BEAM COMMISSIONING OF THE HIGH ENERGY PHOTON SOURCE*

Y. Jiao†, W. Bao, J.S. Cao, S.Y. Chen, X.H. Cui, Y.H. Dong, Z. Duan, Y.Y. Guo, P. He,
X.Y. Huang, Y.S. Huang, D.H. Ji, H.F. Ji, W. Kang, D.B. Li, J. Li, J.Y. Li, N. Li, X.Y. Li, Y. Li,
Z.Q. Li, S.Y. Lin, Y.Z. Liu, X.H. Lu[1], Y.H. Lu, C. Meng, W.M. Pan, Y.M. Peng, L.Y. Qin,
H.M. Qu, M.Y. Su, S.K. Tian, J.Q. Wang, N. Wang, Z.H. Wang, Y.Y. Wei, Y.F. Wu, G. Xu,
H.S. Xu, F. Yan, Y.C. Yang, C.H. Yu, F.C. Zeng, J. Zhang, F.C. Zhao, Y.L. Zhao, Z.H. Zhao,
H.J. Zheng, Institute of High Energy Physics, Beijing, China
[1]also at Spallation Neutron Source Science Center, Dongguan, China

Abstract

The High Energy Photon Source (HEPS) is a 35-pm, 1360-m storage ring light source built in the suburb of Beijing, China. The HEPS construction started in 2019, with the main civil construction finished at the end of 2021. Beam commissioning of the storage ring began in July 2024. In about 14 months of commissioning interleaved with equipment installation, all key performance parameters have met or exceeded the acceptance targets. In this paper, we will briefly introduce commissioning of the HEPS storage ring, and relevant physics studies.

INTRODUCTION

The High Energy Photon Source (HEPS) is a 6-GeV, 1360.4-m storage ring light source built in Beijing, China. It adopts a hybrid seven-bend achromat (7BA) lattice and achieves a natural emittance of 34.8 pm·rad, making it the first fourth-generation synchrotron radiation facility in Asia [1, 2]. The main parameters are listed in Table 1.

Table 1: HEPS Main Performance Parameters

Parameter	Value	Unit
Beam energy	6	GeV
Beam current	200	mA
Circumference	1360.4	M
Natural emittance	34.8	pm·rad
Momentum compaction	1.83	10^{-5}
Energy loss per turn (w/o ID)	2.64	MeV

After more than ten years' R&D, including the HEPS test facility project (2016-2018), construction of the HEPS project began in mid-2019 [3], and multiple milestones have been achieved since then (see, e.g., [4, 5]). The main civil construction was largely completed in July 2021, followed by equipment installation and beam commissioning of the injector in 2023. Equipment Installation of the storage ring was largely finished in July 2024, and beam commissioning commenced shortly afterward. Joint commissioning of the accelerator and beamlines was completed in October 2025, at which point HEPS passed its performance acceptance review.

From the perspective of accelerator physics, following the completion of the preliminary design report in 2018, modification of the accelerator's overall design was performed and frozen by the end of 2019 to address emerging challenges in the hardware and engineering design. By the end of 2021, design and studies on relevant physics issues were basically completed based on the final design. From 2020 to the end of 2022, pre-commissioning preparations were preformed, where we programmed the commissioning plan, implemented the commissioning simulation for specific commissioning process, and especially developed a set of commissioning software (that for storage ring finally finished in 2024). In 2023, we finished the commissioning of the injector (including Linac and booster). In July 23, 2024, the storage ring beam commissioning commenced. Over the past year and a half, the HEPS accelerator team has completed eight rounds of commissioning, interspersed with shutdowns for equipment installation and conditioning. All key performance parameters passed the acceptance review in October 2025. In the following we will introduce reports the detailed progress on equipment installation, beam stability, orbit and optics correction, high-current commissioning, and insertion device (ID) commissioning. Details of previous physics design, related studies and commissioning progress can be found in Ref. [6-13].

EQUIPMENT INSTALLATION AND CONDITIONING

Not all hardware systems were ready at the start of ring commissioning. As shown in Fig. 1, two major shutdowns in 2025, totally about 130 days, were used for equipment installation and conditioning. The first shutdown (February–March 2025) focused on installing most insertion devices, performing fine global alignment, and installing the beam dump kicker. The second shutdown (May–August 2025) focused on installing the 166 MHz and 500 MHz superconducting RF cavities, the fourth collimator, and the remaining insertion devices.

By August 2025, tunnel installation and conditioning of nearly all equipment were completed. Theoretical-position alignment of all 288 magnet units was completed during the first shutdown, reducing RMS absolute position

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† jiaoyi@ihep.ac.cn

deviations from 0.34 mm to 0.14 mm horizontally and from 0.17 mm to 0.06 mm vertically.

All 13 insertion devices (including IVUs, CPMUs, an IAU, an AK, and a Mango wiggler) were installed and conditioned in the tunnel. The five 166 MHz SRF cavities and one 500 MHz SRF cavity were assembled, tested, and installed during the second shutdown. All RF systems are now in nominal operation.

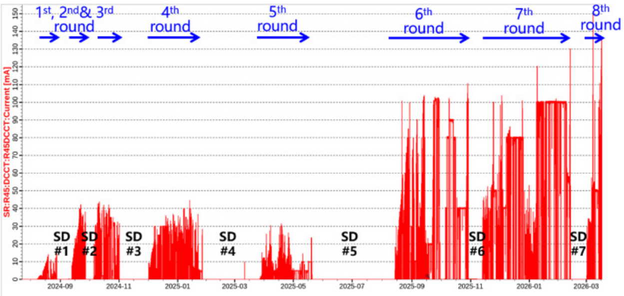


Figure 1: Historical beam current record of the commissioning of the HEPS storage ring, with two major shutdowns (SD#4 and SD#5).

STORAGE RING COMMISSIONING

The key milestones of the HEPS storage ring commissioning are shown in Fig. 2. From March 2025 to February 2026, we conducted three main rounds of commissioning, totally about 230 days, covering accelerator commissioning, beamline commissioning, and initial user experiments.

Round 5 (March 23 – May 20, 2025): Accelerator commissioning focused on orbit and optics correction. The remaining time was dedicated to beamline commissioning.

Round 6 (August 12 – October 29, 2025): Joint commissioning of accelerator and beamlines focused on achieving key performance parameters, culminating in successful performance tests and acceptance review.

Round 7 (November 12, 2025 – February 12, 2026): Accelerator performance optimization, followed by beamline optimization and initial user experiments.

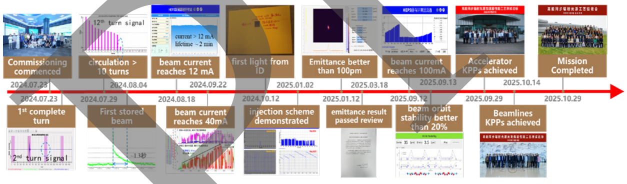


Figure 2: Timeline of the commissioning of the HEPS storage ring.

Beam Stability and Fast Orbit Feedback

Before June 2025, low-frequency beam fluctuations around 2–3 Hz affected both accelerator and beamline commissioning. A comprehensive investigation identified the power supplies for the slow correctors as the main source. After resolving this issue, beam motion was reduced to below 20% of the vertical beam size, as shown in Fig. 3.

In December 2025, the FOFB system was commissioned and put into operation. With FOFB on, beam fluctuations at ID locations were further reduced to below 10% of the beam size, as shown in Fig. 4. The FOFB also largely mitigated interference between different beamlines during simultaneous tuning.

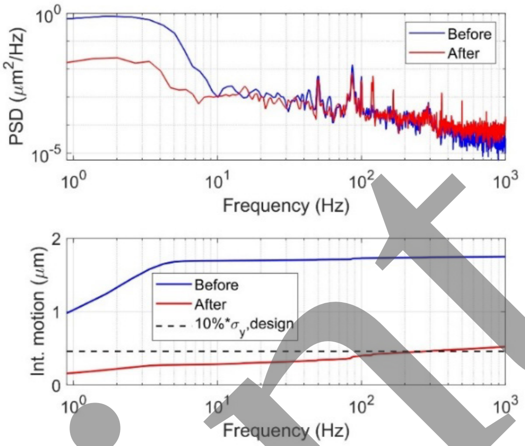


Figure 3: Vertical beam fluctuations before and after resolving low-frequency noise issues in HEPS.

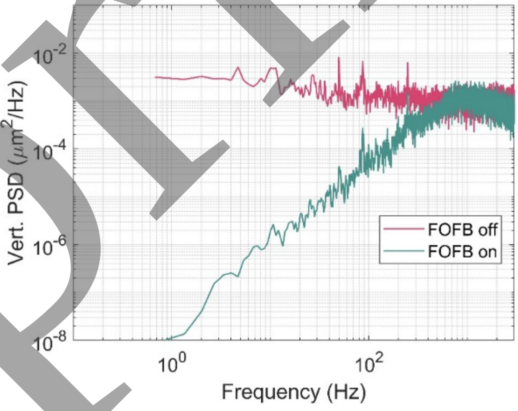


Figure 4: Vertical beam fluctuations with and without FOFB in HEPS.

Beam-Based Alignment and Optics Correction

Multiple rounds of beam-based alignment (BBA) were carried out [14]. After the low-frequency fluctuations were resolved, the proportion of BPMs achieving reproducibility better than 30 µm increased from less than 40% to over 80%. As shown in Fig. 5, the RMS closed orbit is now 70–80 µm, with all BPM readings within ±0.4 mm except at two local bump locations intentionally used for beam loss control and lifetime optimization.

Five rounds of orbit and optics correction were performed using response matrix measurements and LOCO analysis. Beyond optimizing parameter settings, an updated AT lattice model capturing cross-talk effects was introduced, and sextupole movers were used to enhance correction. As shown in Fig. 6, the achieved RMS beta beating is below 2%, and the RMS dispersion deviation is below 2 mm.

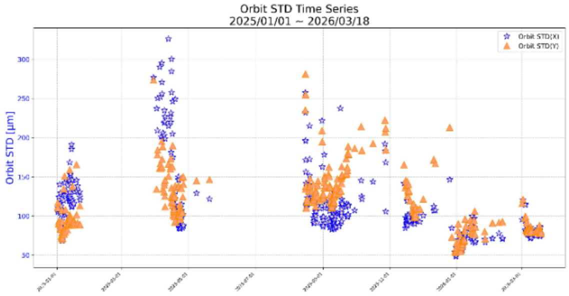


Figure 5: RMS closed orbit of the HEPS storage ring in different rounds of commissioning.

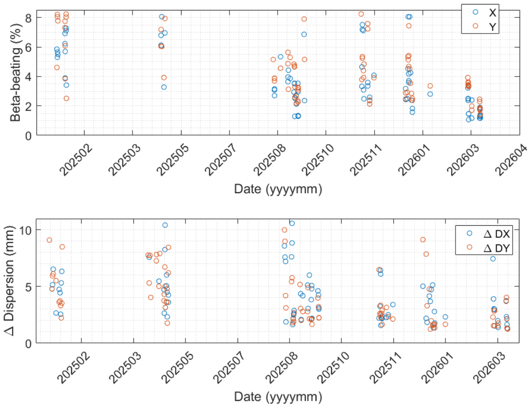
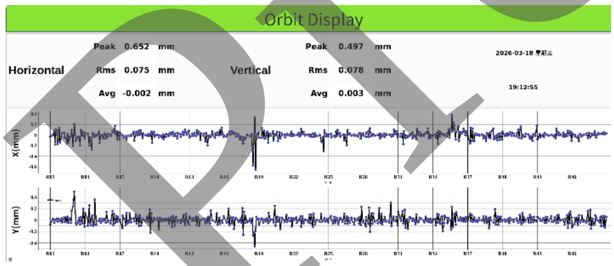


Figure 6: Beta beating and deviation of the dispersion of the storage ring in different rounds of commissioning.

High-Current Commissioning

High-current commissioning progressed in two stages. Initially, only 500 MHz cavities (two normal-conducting, one superconducting) were available, limiting RF power and bunch length. After the double-frequency RF system became available, the first 100 mA was reached on September 12, 2025, and the first 150 mA on March 7, 2026. The double-frequency RF system enables nearly ideal flat bunch distribution at arbitrary current [15].



Horizontal Peak 0.652 mm Rms 0.075 mm Avg -0.002 mm

Vertical Peak 0.497 mm Rms 0.078 mm Avg 0.003 mm

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Figure 7: Orbit bumps (in R03 injection region and especially in R18) are intentionally applied for beam loss control and lifetime optimization.

After more than 200 A·h of vacuum conditioning, the beam lifetime is about one hour at 100 mA, primarily limited by Touschek effects. As shown in Fig. 7, a local bump in the R18 arc region was introduced to resolve the "smaller orbit, smaller dynamic aperture" issue, which also greatly reduced injection beam loss. Dynamic aperture was measured using pre-dump kickers with a 4.5 μs pulse or injection kickers with 4 ns or 10 ns pulses, combined with bunch-by-bunch or turn-by-turn data acquisition.

Injection Commissioning

The swap-out injection scheme with high-energy accumulation in the booster has been adopted [16]. The main bottleneck is the beam transmission efficiency from booster to storage ring, which gradually increased to about 90% after applying the local bump in R18. As shown in Fig. 8, for the timing mode (63 bunches uniformly filled), a maximum beam current of about 100 mA has been achieved [17].

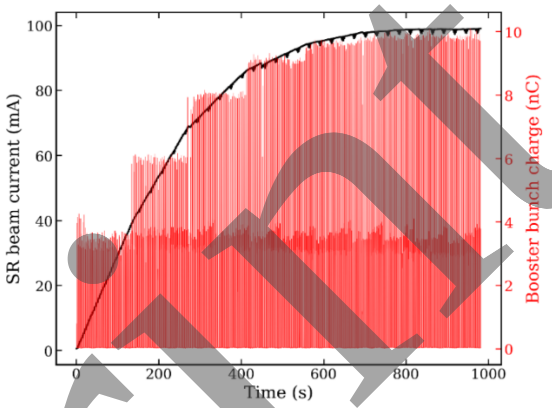

Figure 8: For the timing mode, max. beam current of ~100 mA achieved (7.3nC/bunch).

Insertion Device Commissioning

All ID orbit feed-forward systems are operating stably, effectively compensating for closed orbit changes caused by ID gap variations. In-vacuum ID magnetic alignment has been performed using local bumps or ID girder alignment. A U₀ feed-forward system is under development to control beam synchronous phase changes and bunch lengthening induced by U₀ variations.

Commissioning Software

The high-level application (HLA) framework *Pyapas* [18] was used throughout the commissioning. All HLAs for the storage ring, including global orbit correction, local orbit correction, slow orbit feedback, and fast beam-based alignment, were developed and tested on a virtual accelerator before deployment [19].

CONCLUSION

As a green-field fourth-generation synchrotron radiation light source, the construction and commissioning of HEPS faced various challenges, but have been progressing basically on schedule. The HEPS storage ring beam commissioning began on July 23, 2024. In about 14 months, including shutdowns for equipment installation, all key performance parameters have passed the acceptance review. Currently the beam current has reached 150 mA, the emittance is below 60 pm·rad, and the FOFB system is operational. Installation and conditioning of nearly all accelerator tunnel equipment have been completed. Continued studies are underway to further improve machine performance and ensure long-term stable operation.

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