ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-MOYN03

COMMISSIONING OF THE HEPS*

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Abstract

The High Energy Photon Source (HEPS) is the first 4th generation light source being built in China, with a beam energy of 6 GeV, a circumference of 1360 m and a natural emittance of a few tens of picometers. As a green-field light source, the HEPS construction started in 2019 and is scheduled to be completed in 2025. Now civil construction, component fabrication and tunnel installation, and beam commissioning of the HEPS has been basically finished. In this report, the accelerator and especially the storage ring commissioning results, and main physics issues faced and corresponding measures during the beam commissioning will be presented.

INTRODUCTION

The High Energy Photon Source (HEPS) is the first fourth-generation synchrotron radiation facility project in China, and also China's the first synchrotron radiation light source project in high-energy region [1, 2].

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

The HEPS storage ring is designed with electron energy of 6 GeV and natural emittance of 35 pm·rad. It is capable to accommodate not fewer than 90 high-performance beamlines (with 15 beamlines for Phase I). HEPS can provide X-rays with energies up to 300 keV, delivering synchrotron radiation with brightness of up to 1×10^{22} phs/(s·mm²·mrad²·0.1%BW) level at typical hard X-ray wavelength. It will feature spatial resolution on the order of 10 nanometers, energy resolution on the order of 1 meV, and temporal resolution on the order of 100 picoseconds. Main performance parameters of the HEPS are listed in Table 1.

After more than ten years' R&D, including the HEPS test facility project (2016-2018), the HEPS project started construction in mid-2019 [3] and has achieved multiple significant milestones [4]. In July 2022, the main civil construction was essentially completed; in 2023, beam commissioning of the Linac and booster was completed; in 2024, storage ring main equipment fabrication and tunnel installation were finished (with the exception of some devices whose fabrication and installation were delayed) and initial beam commissioning were completed; in March 2025 joint commissioning of the accelerator and beamlines was launched, and in May 2025 a few pilot experiments were performed. Right now, the last round of equipment installation is under way.

From the perspective of beam physics, following the completion of the preliminary design report in 2018 [5, 6], modification of the accelerator's overall design was performed and finished by the end of 2019 to address emerging challenges in the hardware and engineering design [7-11]. Before the end of 2021, design and studies on relevant physics issues were basically completed based on the final design [12,13]. From 2022 to the present, pre-commissioning preparations and beam commissioning were conducted. Pre-commissioning preparations include planning for the beam commissioning, commissioning process simulation, commissioning software development, and joint-debugging before the commissioning. It is worth mentioning that we developed a new modular framework for high-level application development, named *Pyapas*, based on which we developed the required high-level applications and adopted them in the HEPS commissioning [14-16]. Regarding the beam commissioning, in 2023 we completed the injector commissioning with beam parameters satisfying the design specifications. Details can be found in Refs. [17-19]. In 2024, storage ring commissioning was initiated and much advancement has been achieved. In the following specific progress on storage ring commissioning will be introduced in a detail.

STORAGE RING COMMISSIONING

As mentioned above, a few hardware systems were not fully ready at day one of the commissioning, e.g., stripline kickers and power supplies, some insertion devices (IDs) and ID vacuum chambers, 166 MHz RF cavities,

* Work supported by High Energy Photon Source (HEPS), a major national science and technology infrastructure and NSFC (12275284, 11922512).

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ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-MOYN03

collimators, and pre-dump kickers and power supplies. Measures were adopted to assure the initial commissioning can be performed in the absence of these components, e.g., injection kickers with longer-pulse kicker power supplies (hundred-nanosecond pulse duration), and a 500 MHz single-frequency RF system (one SC and two NC cavities) were temporarily used. According to the hardware availability and other considerations, the commissioning was paused a few times mainly for equipment installation. Details are illustrated in Fig. 1.

It took about one month to achieve the first beam storage and beam accumulation with a current exceeding 10 mA. The first-turn circulation is achieved within one day, by using both the tools for automatically tuning (previously validated on the booster) and manual knobbing of the beam trajectories. This fast achievement should also be attributed to rigorous joint-debugging before the commissioning that verified the polarity across all magnets (more than 1000). Nevertheless, great challenges were faced to achieve multi-turn circulation, primarily due to the physical-aperture limitation, i.e., two 1.6-meter ±2.5mm vertical apertures at the injection and extraction Lambertson magnets. After extensively trying knobbing various parameters, we successfully established 11-turn circulation mainly by implementing multi-corrector strength scans and working point adjustment. Subsequently we turned on the RF and gradually increased sextupole magnet strengths to 90-100% of the design values. Again, tuning all the tuneable parameters were done to let the beam circulate for more turns. In this process, a critical measure is to knob the RF frequency by about 200 Hz to match the beam path length. First beam storage was achieved on August 6 with 40 μA current and approximately lifetime of one minute, marking a significant milestone after approximately one week of dedicated effort following the achievement of multi-turn circulation. Details can be found in Ref. [20].

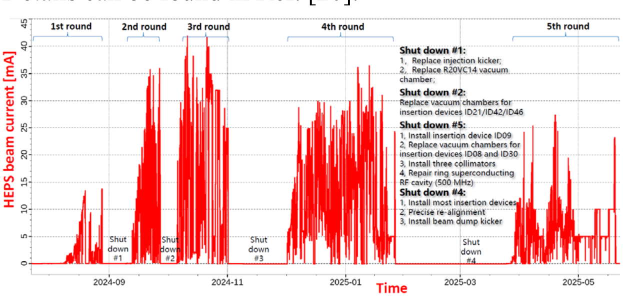

Figure 1: Historical beam current record of the commissioning of the HEPS storage ring.

Right after the beam storage, we met a great vacuum challenge. The beam current was severely limited by poor local vacuum (~10^{-4} Pa) in R20 region (the 20th 7BA of the storage ring). A couple of beam experiments and tunnel inspections revealed that a silicone rubber ring was left in the extraction light pipe of the R20 vacuum chamber, which caused extraordinary outgassing when synchrotron light is hitting on it. This vacuum bottleneck was broken through when this part of vacuum chamber was replaced. In addition, we installed the design stripline kicks and power supplies when replacing the vacuum chamber. This enabled to inject and store much more bunches in the ring, thereby removing the constraints on stored bunch numbers and beam current. We then rapidly increased the beam current to about 40 mA, where a new limitation from the RF voltage and power was met. In May to July of 2025, full installation of harmonic cavities (499.8 MHz) and fundamental cavities (166.6 MHz) is underway, which will enable substantial current enhancement.

Orbit and optics correction can be roughly separated to two phases. In early 2025, re-alignment of storage ring magnets was performed to position all magnets towards their theoretical locations, so as to facilitate subsequent beamline commissioning. During the first four rounds prior to re-alignment, we achieved rms closed orbit deviation of about 100 μm, rms beta beating of about 5%, rms dispersion deviation of about 3 mm, and measured beam emittance of below 100 pm·rad. In the fifth round following re-alignment, it took about one month to restore closed orbit, beta beating, dispersion and measured emittance to comparable levels.

Both orbit and optics corrections rely on response matrix (RM) measurements. Throughout these five rounds, RM measurements covered all correctors, and each measurement took about 4 hours after optimizing the parameter settings for RM measurement. Recent simulations, however, indicate that including correctors on quadrupoles (trim coils on quadrupoles) in RM measurements may be not beneficial for subsequent optics correction. Next, we will try to measure RM using a part of correctors for optics correction and compare with that with all correctors.

Beam-based alignment (BBA) proved effective during iterative orbit and optics correction. After the beam storage, we implemented fast BBA [21] using turn-by-turn BPM data, which allowed us to quickly get a rough estimation of the BPM offsets relative to adjacent quadrupoles and reduce the rms closed orbit deviation from 0.6 mm to be below 0.3 mm. After that we employed conventional BBA using BPM slow acquisition data. The most recent two rounds of BBA show obvious convergence. For the lattice calibration, currently a discrepancy exists between simulation prediction and measurement, i.e., simulations suggest that the actual emittance should be close to the design values given achieved beta beating and dispersion levels, while measured emittance remains around 100 pm·rad. We are continuously investigating this deviation. One of the possible reasons is that high-frequency beam fluctuation may cause increase in the measured transverse beam size and consequently the measured emittance.

Regarding beam stability, we are continuously identifying related issues, tracing error sources, and implementing measures to enhance the beam stability. During initial commissioning, periodic fluctuations (~100 μm amplitude, ~10 Hz frequency) were observed on most BPMs. Through investigation of potential factors (power supplies, vibrations, cooling water, timing, BPM electronics, etc.), it was identified as being caused by an unclosed current excitation in an FC corrector. This was a primary factor contributing to poor precision of actual RM measurements and the suboptimal effectiveness of subsequent orbit and optics

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corrections at that time. During the third round of commissioning, significant fluctuation of the positions of injected beam was observed, which also affected storage ring beam orbit readings. This source was identified after two weeks and then solved, i.e., abnormally large ripples in corrector power supplies of the high-energy transport line from the booster to ring.

Currently, the rms beam fluctuation is about 2-3 µm, which is already evident relative to current beam size, 10-20 µm, and affects the efficiency and effectiveness of beam line commissioning and initial experiments. Spectral analysis of the beam motion revealed noises mainly come from two frequency bands, 1-5 Hz low-frequency, and neighbouring 50 Hz (industrial frequency). For the 50 Hz noises, besides the power supply ripples, it was found the vibration (~50 Hz) from a cooling water pump near the RF hall has ignorable impact to beam motion. This contribution was reduced after taking further vibration isolation measures. During and after the fifth round of commissioning, the focus shifted to identifying low-frequency sources, by investigating of vibrations (ground, magnets, supports, cooling water) and low-frequency ripples in power supplies (especially for slow correctors). To date no definitive disturbance source has been pinpointed yet. To control the beam motion, slow and fast orbit feedback, SOFB and FOFB, were considered. SOFB and frequency feedback are now operational, which can effectively control the periodic changes (period~ 12 hour) of the horizontal beam orbit. FOFB is now under installation and debugging, and the FOFB commissioning is scheduled for September 2025. The aim is to suppress the beam fluctuation, reducing the RMS variation of the orbit to smaller than 20% (and later 10%) of the RMS beam size.

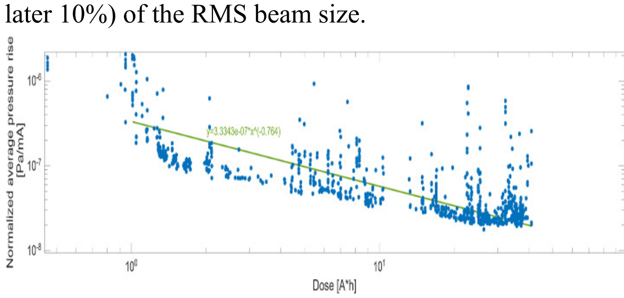

Figure 2: Normalized average vacuum pressure rise vs. the dose (integrated beam current).

To date, during the five rounds of commissioning, the highest beam lifetime achieved is about half an hour. The primary factors affecting beam lifetime include the vacuum pressure, beam dynamics, and bunch length. Over five rounds, the integrated beam current reached 40 A·h. As can be seen from the Fig. 2, the average vacuum pressure around the entire ring has gradually improved. The current average vacuum pressure around the ring is approximately 1×10^{-6} Pa (~7.5 nTorr). Although this is still higher than the design value (1 nTorr), according to theoretical estimates, vacuum is no longer the main limiting factor for beam lifetime. Regarding beam dynamics, till now efforts primarily focus on optimizing linear beam dynamics. It was observed that in case orbit and optics are not well corrected, the beam lifetime drops to around 10 minutes or even lower, which accords with simulations that indicated strong coupling between the linear and nonlinear beam dynamics in the storage ring. Preliminary tests showed that adjusting sextupole strengths affects lifetime, while the influence cannot be ruled out as coming from orbit and tune changes induced by feed-down effects. It is planned to optimize the sextupole and octupole strengths once orbit and optics corrections are further improved. Additionally, 500 MHz harmonic cavities have been used temporarily as the fundamental-frequency cavities, resulting in a relatively short bunch length (10 ps order). When the designed fundamental and harmonic cavities are ready, the bunch is expected to be lengthened by a factor of 5-10 compared to the current status. The lifetime would increase to the order of hours, approaching the design value.

Regarding the injection, HEPS employs an on-axis swap-out injection scheme based on high-energy accumulation in the booster. We have now completed beam testing and validation of this injection scheme, and put it into operation. Since the ultra-short pulse power supplies for injection were not available on the first day of beam commissioning, we progressively carried out commissioning activities as hardware components and timing control programs became ready. For instances, the power supplies for the injection stripline kicker became available one month after commissioning started, and the power supplies for the extraction stripline kicker became available three months after commissioning started. During injection commissioning, we have gradually completed beam validation of the injection, extraction and the timing systems. We have mastered the method of adjusting the ultra-short pulse kicker delay based on measured beam signal, and established methods of monitoring of the injection status using turn-by-turn and bunch-by-bunch BPM readings, and methods of optimizing residual oscillation of the injected beam. Next, we will continue to optimize injection efficiency and increase the single-bunch charge in the storage ring to meet the requirement of 14.4 nC per bunch for timing experiments.

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. Up to July 2025, HEPS beam commissioning has achieved several important progresses. The last batch of equipment installation is near completion, and the next round of commissioning is to be started soon. It is planned to meet the key performance parameters of the light source by the end of 2025, paving the way for the facility to be operational and open to users in 2026.

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