STATUS OF HEPS BOOSTER OPERATION

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Abstract

The High Energy Photon Source is the first fourth-generation synchrotron light source in Asia. As a greenfield facility, HEPS began construction in 2019 and now the commissioning of the storage ring has been basically finished. The booster synchrotron, serving as the second-stage accelerator, completed its initial beam commissioning between July and November 2023 and was officially put into operation in July 2024 to support the storage ring commissioning. This paper presents the beam performance of the booster since the start of operation, key upgrades and optimizations implemented, major operational challenges encountered, and the ongoing plans for further performance enhancement.

INTRODUCTION

Asia's first fourth-generation synchrotron radiation light source—the High Energy Photon Source (HEPS)—is being built in China [1]. HEPS successfully passed its process acceptance in October 2025. This marks the successful completion of its construction phase and the transition from the construction stage to the preparation phase for trial operation and open access.

HEPS complex consists of a 500 MeV Linac [2], a low energy transport line (named LB) [3], a 454 m booster synchrotron with a max repetition rate of 1 Hz [4], two high energy transport lines (named BR and RB) [5], a 6 GeV storage ring with an emittance lower than 60 pm.rad [6], and multiple beam line experimental stations. The layout of HEPS complex is shown as Fig. 1.

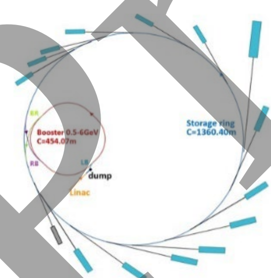

Figure 1: Layout diagram of the HEPS complex.

As a full energy injector, the HEPS booster increases the energy of the electron beam from 500 MeV to a design energy of 6 GeV and provides a sufficiently high-quality electron beam for injection into the storage ring. The installation and conditioning of the equipment were completed in January 2023, beam commissioning of the booster began in July of the same year, and process acceptance was finalized in November [7] —all while the storage ring and its subsystems were still under installation. The beam commissioning of the HEPS storage ring began in July 2024. The stable operation of the injector has laid the foundation for this process.

DESIGN AND RAMPING CONTROL

The HEPS booster lattice features four-fold symmetry. Each super-period comprises 14 standard FODO cells with matching sections at both ends, housing 32 dipoles, 37 quadrupoles, and 17 sextupoles. Such a period also delivers a dispersion-free straight section of roughly 8.8 meters to accommodate the injection/extraction systems and RF cavities. The quarter-lattice optics are presented in Fig. 2 and the main parameters are listed in Table 1.

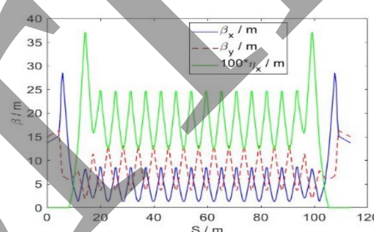

Figure 2: Optics of a super-period in the booster.

The HEPS booster is designed to support both single-bunch and multi-bunch operation. Bunches are injected and extracted one by one using a set of kickers operating at 50 Hz. Due to the pulse width limitation of the current kickers, the minimum achievable bunch spacing restricts the maximum number of stored bunches in the booster to five.

Full-energy bunches can either be injected directly into the storage ring or be merged with bunches reinjected from the storage ring using a "high-energy accumulation" injection scheme. To realize this scheme, the HEPS booster is operated as an accumulator ring at its extraction energy. By combining the charge replaced from the storage ring with the bunches accelerated to 6 GeV in the booster, the single-bunch charge is increased, meeting the requirements of the storage ring's high-charge mode. Consequently, in addition to a high-energy transport line for extracting the beam from the storage ring back to the booster, an off-axis injection system has also been installed in the booster to facilitate beam accumulation.

To accommodate both multi-bunch filling patterns and the high-energy accumulation injection scheme, the booster's energy ramping profile features extended flat-tops at the injection energy (500 MeV) and the extraction energy (6 GeV). A schematic diagram of the energy ramping cycle is shown in Fig. 3.

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Table 1: Main Performance Parameters of Booster

Parameter	Unit	Value
Injection energy	GeV	0.5
Extraction energy	GeV	6
Circumference	m	454.066
Max. repetition rate	Hz	1
Emittance @ 6 GeV	nm.rad	16.5
Tune(H/V)		21.15/11.21
Energy spread @ 6 GeV		9.6×10^{-4}
Momentum compaction factor		2.26×10^{-3}
Energy loss per turn @ 6 GeV	MeV	3.88
Damping time @ 6 GeV	ms	4.7/4.7/2.3
RF Voltage@6GeV	MV	8
Harmonic number		757

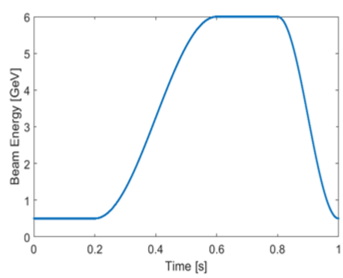

Figure 3: A schematic diagram of the energy ramping cycle.

To enable more flexible beam commissioning, the power supplies and RF cavities of the HEPS booster were designed with two control modes: ramping mode and tuning mode, which can be switched online. The ramping mode is used for beam energy ramping, while the tuning mode allows for beam parameter optimization at any given energy point. The ramping process is guided by a pre-generated lookup table, which is established based on the I-BL curve derived from magnetic field measurements. The ramping sequence can be programmed to stop and dwell at any energy between the injection and extraction energies, effectively operating the booster as a storage ring. This feature enables researchers to perform energy-dependent machine studies and to optimize the ramping curve.

OPERATION

Since July 2024, the HEPS booster has been reliably supplying beam to the storage ring in accordance with operational requirements, and has now been in service for over one year. This section focuses on the booster's key performance metrics during this period, as well as the technical issues encountered.

Beam Performance

For routine operation, the booster runs in single-bunch mode, delivering 2–3 nC of charge per bunch to the storage ring with a repetition period of 2 seconds. The multi-bunch mode functioned normally during the initial beam commissioning of the booster. However, subsequent major modifications to the injection control program—implemented to meet the specific injection requirements of the storage ring—have adversely affected booster operation in multi-bunch mode. Although this mode remains technically available, it is not yet suitable for routine operation, as it compromises the booster's repetition period.

The beam accumulation function at the booster's extraction energy was commissioned in January 2025. Initially, only five RF cavities were installed in the booster, operating at a maximum cavity voltage of 6 MV [8]. This configuration proved sensitive to the longitudinal parameters of the reinjected beam, requiring frequent adjustments to the master oscillator frequency of the storage ring. After six cavities became operational in November 2025, the booster was able to provide a cavity voltage of 7.2 MV, significantly enhancing its longitudinal acceptance. Currently, the maximum single-bunch charge delivered for storage ring injection can reach approximately 10 nC.

During the period of stable operation, we statistically analysed the stability of the extracted beam trajectory and charge from the booster over approximately one week, as shown in Fig. 4. The standard deviations of the extracted horizontal and vertical trajectories are both approximately 20 μm, while the charge stability is about 0.3 nC. From the figure, a diurnal variation in the extracted beam trajectory is evident (with a peak-to-peak variation of approximately 80 μm within a day), which is suspected to be caused by temperature fluctuations.

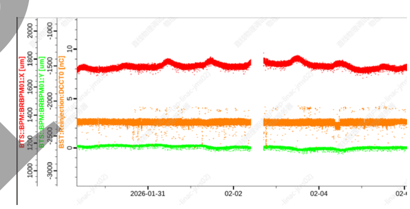

Figure 4: Extracted beam trajectory and charge.

Operation Efficiency and Main Problem

Throughout the past year of operation, the booster has maintained a generally stable operational status. Although sporadic hardware failures occurred during this period, their impact on beam supply was relatively brief.

This report presents fault statistics for a three-month operational period from November 12, 2025, to February 12, 2026. The data indicate that the cumulative downtime due to faults during this period was approximately 20 hours, accounting for about 0.9% (i.e., nine-thousandths) of the total operation time. The specific distribution of these faults is shown in Fig. 5. Among the various subsystems, the power supply (PS), injection/extraction system, and timing system were the three main contributors to the longest downtime.

During the statistical period, failures in the power supply system primarily manifested as two types of equipment shutdown events. The first involved unexplained shutdowns of the quadrupole magnet power supplies without any fault indications. The second involved shutdowns triggered by an "input Ib software overcurrent" fault reported by the power unit of the dipole magnet power supplies. Preliminary analyses and corresponding countermeasures have been undertaken for both types of failures. The specific cause of the quadrupole magnet power supply failures remains unclear, but it is preliminarily suspected to be related to communication link anomalies. The current remedial action involves replacing the fiber optic boards of the power supplies and resecuring the connections to eliminate the possibility of poor contact or communication module failure. In contrast, the cause of the dipole magnet power supply failures has been identified as an over-sensitive protection threshold for AC overcurrent. This issue has been effectively resolved by appropriately increasing the protection threshold.

Figure 5: The specific distribution of faults.

The frequent failures of the high-energy injection kickers are primarily due to the significant impact of the repetition rate on the output pulse current amplitude. During active beam kicking operations in the storage ring, the booster's high-energy injection kickers operate under high repetition rate conditions, which can cause the pulse capacitors' charging voltage to greatly exceed their limits and lead to damage. By standardizing the beam kicking procedure and improving the structural design and manufacturing process of the pulse capacitors to increase the design margin, the failures have been avoided.

During this period of operation, occasional protection trips of individual RF cavities occurred, and the associated fault times were statistically recorded. Nevertheless, owing to the adequate total cavity voltage, a single cavity trip does not compromise the booster's beam delivery to the storage ring. It only increases the sensitivity of the high-energy reinjection process to energy fluctuations in the storage ring.

Another issue worth mentioning is that, approximately every ten days, the vacuum at the low-energy injection kicker would suddenly deteriorate, triggering the kicker interlock protection. It was initially suspected that the problem was caused by outgassing from the ion pumps themselves. We attempted to shut down the ion pumps one by one, but the issue persisted. Further tests showed that turning off all ion pumps in the vicinity, although resulting in a slight degradation of the vacuum level, still met operational requirements. Therefore, since February 2026, all ion pumps in this area have been kept off, and no further events have been observed through the end of April.

Impact of Thermal Effects

Long-term temperature variations can induce slow and irregular deformations in the accelerator tunnel. During the operation of the HEPS booster, seasonal temperature changes caused the concrete tunnel to expand. The HEPS booster had not undergone any alignment measurement since the pre-commissioning alignment performed in July 2023. When measured at the end of November 2024, it was found that the circumference had increased by approximately 8.6 mm relative to the theoretical value, with transverse deviations exceeding 2 mm at certain locations, indicating irregular deformation across the tunnel. Consequently, the booster was realigned during the summer maintenance period in 2025. After realignment, the deviation between the measured and theoretical circumference was reduced to 1.6 mm. As a result, the energy deviation of the booster decreased from −0.8% to −0.1%, and the average residual orbit after correction improved from approximately −1.4 mm at the end of 2024 to approximately −0.3 mm, effectively enhancing the physical aperture of the booster.

As shown in Fig. 4, a quasi-periodic variation in the extracted beam trajectory with a daily cycle can be clearly observed, exhibiting a peak-to-peak amplitude of approximately 80 μm within a day. This variation is closely correlated with diurnal fluctuations in ambient temperature. The most likely cause is that daily temperature variations induce thermal deformation of the magnet support structures, which in turn leads to shifts in the magnetic centres of the magnets. These findings indicate that temperature stability is a key factor influencing the long-term stability of the beam extracted from the booster.

CONCLUSION

Since its commissioning in July 2024, the HEPS booster has operated stably for over a year, reliably supplying beam to the storage ring. It routinely delivers 2–3 nC per bunch in single-bunch mode; after the RF upgrade in December 2025, the maximum charge reached approximately 10 nC with optimized high-energy accumulation injection.

Operational efficiency is high, with a fault downtime rate of only 0.9% in the latest quarter. Major faults originating from power supplies, kickers, and the timing system have been effectively mitigated. Thermal effects significantly impact performance: seasonal tunnel deformation was corrected by realignment in mid-2025, improving physical aperture and energy accuracy; diurnal temperature fluctuations cause periodic beam drift, indicating the need for better thermal control.

Over the past year, limited time has been available for re-optimization to compensate for machine parameter drift. If time permits this year, we plan to optimize the injector and beam conditions. Looking ahead, future work will focus on resolving remaining equipment faults, developing multi-bunch operation, increasing the booster repetition frequency, and implementing a slow orbit feedback system in the high-energy transport line to maintain storage ring injection efficiency.

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