COMMISSIONING STATUS OF BOOSTER-BASED BEAM-RECYCLING SWAP-OUT INJECTION AT HEPS

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Abstract

The High Energy Photon Source (HEPS) adopts on-axis swap-out injection to relax the dynamic-aperture requirement of its ultralow-emittance storage ring. To provide high-charge bunches for swap-out operation, a booster-based beam-recycling scheme has been developed, in which a depleted storage-ring bunch is extracted, transported to the booster, combined with a newly accelerated bunch at high energy, damped, and reinjected into the original storage-ring bucket. This paper summarizes the commissioning status of this scheme. Closed-loop beam recycling has been demonstrated, paving the way for user operation toward high bunch charge. The results validate the basic beam-recycling architecture and identify the main directions for further optimization toward routine high-charge operation.

INTRODUCTION

Fourth-generation synchrotron light sources [1, 2] pursue ultralow emittance and high brightness, but the resulting small dynamic aperture makes conventional off-axis accumulation increasingly difficult. On-axis swap-out injection [3], in which a stored bunch is replaced by a fresh bunch with higher charge, can be accommodated with the most relaxed dynamic aperture and releases the full potential of performance optimization. The main challenge is then transferred from storage-ring acceptance to the preparation and high-efficiency transport of high-charge bunches. As a 6 GeV, 1.3 km-scale light source [4–6], the HEPS storage ring features an ultralow natural emittance of 34.8 pm, and therefore adopts swap-out injection. The high-charge filling mode, as required by timing experiments, with 63 bunches and a design bunch charge of 14.4 nC at 200 mA, is the most demanding case for the full-charge injector. For HEPS, this challenge is addressed by using the full-energy booster as a recycling and accumulation stage [7]. The bunch extracted from the storage ring is not discarded. Instead, it is transported back to the booster, combined with a newly accelerated bunch, damped at high energy, and then re-injected into the same storage-ring RF bucket. This approach avoids a dedicated accumulator ring [8, 9] and reduces the demand on high-charge bunch production at the low-energy end of the injector [10, 11]. This paper focuses on the system layout, staged commissioning path, representative diagnostics, and early performance indicators of the booster-based beam-recycling swap-out injection scheme.

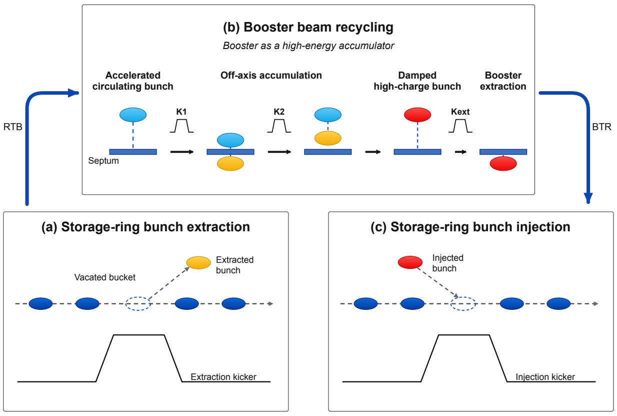

Figure 1: Schematic of on-axis swap-out injection with booster beam recycling. Blue, yellow, and red bunches denote stored/circulating bunches, recycled/injected bunches, and damped high-charge bunches, respectively. In panel (b), K1 first deflects the circulating booster bunch toward the septum, while K2 closes the local bump and brings both the circulating and reinjected bunches into the booster dynamic acceptance. The accumulated high-charge bunch is then extracted by Kext.

BEAM-RECYCLING SWAP-OUT SCHEME

Figure 1 shows the basic scheme. The two high-energy transport directions are denoted as RTB, from the storage ring back to the booster, and BTR, from the booster to the storage ring. In each recycling cycle, a moderate charge bunch is first injected into the booster and accelerated to the extraction energy, then a selected storage-ring bunch is extracted through RTB and injected off-axis into the booster, where it is combined with this circulating booster bunch. The two bunches are captured within the booster dynamic acceptance and merge after radiation damping, forming a higher-charge bunch. This bunch is then extracted through BTR and injected into the vacated storage-ring bucket. Repeating this recycling cycle for a selected RF bucket can progressively build up the stored bunch charge. In multi-bunch operation, the same procedure is applied sequentially to the selected filling buckets. This approach requires only a moderate bunch charge of a few nC to be captured in the booster and accelerated to full energy, but high transmission efficiencies in both directions between the storage ring and the booster are still essential for building up high bunch charge in the storage ring. Combinations of Lambertson septa [12] and vertical deflecting kickers are used for injection into and extraction from both the HEPS storage ring and booster. The bucket spacing is 6 ns in the storage ring [13, 14].

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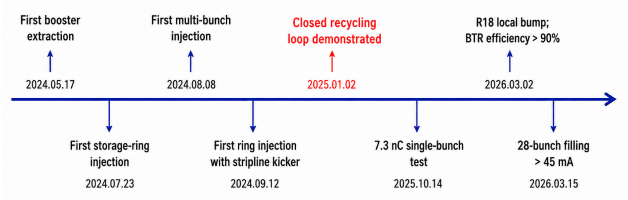

Figure 2: Key commissioning milestones toward on-axis swap-out injection with booster beam recycling at HEPS.

Stripline kickers encapsulated in vacuum modules [15], as driven by high-voltage pulsers [16], are employed to facilitate the swap-out injection, with a pulse width of 10 ns for the injection and 4 ns for the extraction, respectively. A pre-extraction kicker [17] spoils the extracted bunch prior to its extraction to reduce its energy density. In the booster, a pair of kickers separated by a vertical phase advance of π is used for off-axis injection to recapture the depleted bunch from the storage ring. Four pulsed bump magnets and one extraction kicker enable extraction of the damped full-charge bunch. The design of the HEPS injector [18, 19] ensures that the storage-ring and booster reference buckets are periodically aligned by a coincidence clock. The coincidence period is about 3.435 ms, and arbitrary bucket alignment is realized by a coarse delay with 6 ns steps together with a fine delay used for kicker synchronization. This timing architecture [20] allows the selected storage-ring bucket to be extracted, transported through the booster, and returned to the original bucket. The booster has a natural emittance of 16 nm at 6 GeV [18]. The recaptured bunch must stay in the booster for at least 16 ms, so that the vertical emittance is damped to lower than 4 nm, to ensure efficient injection into the storage ring again. Various simulations have been carried out to investigate the mechanisms of beam loss during the transmission [21, 22]. The relevant limitations include the transverse acceptance of the storage ring for BTR injection and the longitudinal acceptance of the booster for recapturing the depleted bunch from the storage ring.

COMMISSIONING PROGRESS AND PERFORMANCE

Staged commissioning for the swap-out injection was implemented, key milestones are shown in Fig. 2. For the initial storage-ring injection, a slotted-pipe kicker, backup for the booster, was installed in the injection straight section, to reduce the risk associated with home-developed stripline kickers and high-voltage pulsers, which had not been beam tested in advance. Then, after stored beam became available in the storage ring, storage-ring extraction tests with stripline kickers were carried out, to deliver the extracted bunches toward a beam dump in the RTB transport line. Next, the slotted-pipe kickers were replaced by stripline kickers for storage-ring injection, so that the beam current could rise further, without the constraint of the available bunch number due to the 450 ns kicker pulse width. With 10 ns home-developed pulsers driving the injection kickers, and 4 ns FID commercial pulsers driving the extraction kickers, RTB transport and reinjection into the booster was achieved. The timing system was then tuned to close the full recycling loop on 2 January 2025. This scheme was subsequently used in commissioning studies and selected operating modes. Improvements on the monitoring and optimization of transmission efficiency continued. By repeated injection into a single storage-ring RF bucket, the high-charge limit was tested and improved gradually. On 14 October 2025, a single storage-ring bunch was iteratively filled to 7.3 nC in a dedicated performance test for single-pulse timing experiments. For multi-bunch filling, the achievable per-bunch charge was further limited by the reduced beam lifetime at high bunch charge. During commissioning optimization, it was important to optimize the final beam trajectory in the transport lines, as well as the kicker amplitude and timing, by minimizing the induced oscillation as recorded by turn-by-turn BPM signals. For storage-ring injection, bunch-by-bunch diagnostics became increasingly important once the machine moved from single-bunch tests to multi-bunch filling. A transmission-efficiency monitoring procedure was established using the storage-ring bunch current monitor (BCM) and the booster DCCT. The storage-ring and booster DCCTs were calibrated in advance and used as absolute charge references. The storage-ring BCM sampled the bunch-by-bunch induced voltage and was scaled against the storage-ring DCCT. During recycling studies, the booster bunch charge before accumulation, $Q_{\mathrm{BST,accelerated}}$, and after accumulation but before extraction, $Q_{\mathrm{BST,extracted}}$, together with the storage-ring bunch charge before extraction, $Q_{\mathrm{SR,extracted}}$, and after injection, $Q_{\mathrm{SR,captured}}$, were recorded to evaluate the RTB and BTR transmission efficiencies, i.e.,

$$\eta_{\mathrm{RTB}} = \frac{Q_{\mathrm{BST,captured}}}{Q_{\mathrm{SR,extracted}}}, \tag{1}$$

for the measured ring-to-booster recycling efficiency with $Q_{\mathrm{BST,captured}} = Q_{\mathrm{BST,extracted}} - Q_{\mathrm{BST,accelerated}}$ and

$$\eta_{\mathrm{BTR}} = \frac{Q_{\mathrm{SR,captured}}}{Q_{\mathrm{BST,extracted}}}, \tag{2}$$

for the booster-to-ring reinjection efficiency. With this definition, η_{RTB} represents an effective RTB recycling efficiency, including capture in the booster and survival up to the charge measurement before booster extraction.

In the RTB transmission, η_{RTB} of better than 97% was achieved during commissioning, and there was no clear sign of degradation with injected bunch charge. In contrast, η_{BTR} was generally 50% to 80% during the 2025 commissioning, and it was found that closed orbit variation had a strong influence on the injection efficiency. In March 2026, a local bump in the R18 arc section was found to reduce injection beam loss and significantly improve beam lifetime. The underlying mechanism is still under investigation. After establishing the R18 local bump, η_{BTR} above 90% was achieved during commissioning. A typical filling sequence from an empty storage ring for the 28-bunch timing mode is shown in Fig. 3. Sequential injection into these uniformly distributed buckets increases the storage-ring beam current to above 45 mA,

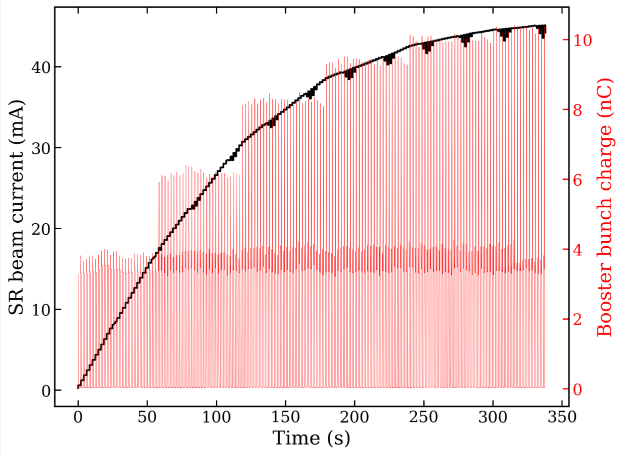

Figure 3: Repeated beam recycling in the 28-bunch filling mode starting from an empty storage ring. Sequential injection into 28 uniformly distributed RF buckets increases the storage-ring current to above 45 mA, corresponding to an average storage-ring bunch charge of about 7.3 nC, while the booster bunch charge rises stepwise to about 10 nC before extraction. The saturation is mainly attributed to the reduction of BTR efficiency at high bunch charge.

while the booster bunch charge increases stepwise. The accelerated bunch charge in the booster was about 3.5 nC. The saturation of the booster bunch charge at about 10 nC was mainly due to the decrease in η_{BTR}, from better than 85% for a 3.3 nC injected bunch to below approximately 70% for a 10 nC injected bunch. No clear degradation of the RTB efficiency with injected charge was observed. With the design dynamic aperture of about 1 mm in the storage ring, increased sensitivity of high-charge bunches to injection mismatch and impedance effects was expected. However, previous simulations could not explain the drop in injection efficiency at this moderate bunch charge. Further machine studies, in particular after the role of the R18 local bump is fully understood, will be devoted to understanding the underlying limitations.

This study demonstrates the scalability of the recycling procedure from single-bucket studies to multi-bunch operation, although the achievable bunch charge was still below the design value because of lifetime and high-charge BTR limitations. These performance figures were obtained during accelerator commissioning. Further studies are required to evaluate the robustness of the scheme during routine user operation, where insertion-device gap changes may introduce additional perturbations to the beam condition. Table 1 gives a compact summary of the achieved performance. In the commissioning studies reported here, the booster cycle period was 2.1 s. Within one cycle, the time from booster low-energy injection to high-energy extraction was about 0.75 s. The interval between booster reinjection and booster extraction was set to about 0.2 s to allow the booster DCCT to record the accumulated bunch charge; this interval can be reduced with faster charge readout.

Table 1: Summary Of Measured Performance During Commissioning

Quantity	**Result**
28-bunch stored beam current	> 45 mA
Average bunch charge in 28-bunch filling	~ 7.3 nC
RTB efficiency	> 97%
BTR efficiency	> 90%
Booster cycle period	2.1 s

SUMMARY

A booster-based beam-recycling swap-out injection scheme has been commissioned at HEPS through a staged high-energy injection and extraction program. The storage-ring-to-booster and booster-to-storage-ring directions were commissioned separately before closing the full recycling loop. Representative closed-loop and multi-bunch filling tests validate the basic architecture and demonstrate that booster-based beam recycling can be implemented as an operational swap-out injection scheme. The commissioning results also show that the two transport directions should be analyzed separately. A single full-cycle efficiency can hide whether the main limitation comes from storage-ring extraction and booster capture, booster survival and damping, or booster-to-ring reinjection. The present performance is therefore not yet the final operational limit, but it provides quantitative guidance for further optimization. Ongoing work will focus on improving high-charge BTR transmission, strengthening charge accounting and bunch-by-bunch diagnostics, and exploring online optimization methods for maintaining transmission efficiency during routine high-charge top-up operation. In addition, closer collaboration with beamline scientists is expected to assess the possible effects on user experiments and develop mitigation strategies.

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