COMMISSIONING EXPERIENCES OF ACTIVE DOUBLE-RF SYSTEM IN HEPS STORAGE RING*

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Abstract

The High Energy Photon Source (HEPS) is the first fourth-generation synchrotron light source in Asia. In HEPS storage ring, there are five 166.6 MHz superconducting cavities serving as fundamental cavities and two 499.8 MHz superconducting cavities as active third harmonic cavities. The employment of active harmonic cavities enables 'ideal bunch lengthening' at any beam current, laying a foundation for flexible beam operation. Beam commissioning of the HEPS storage ring started on July 23, 2024. Due to the presence of delays in the 166.6 MHz cavities, the 499.8 MHz cavities were temporarily utilized as fundamental cavities to provide the required beam acceleration for the first-year commissioning. Starting from August 2025, we initiated the commissioning of an active double-RF system composed of the 166.6 MHz and 499.8 MHz cavities, successfully realizing ideal bunch lengthening under different beam current. Since August 2025, we have commissioned the active double-RF system, successfully achieving ideal bunch lengthening under various beam current conditions. During the ring commissioning process, some beam phenomena associated with the operation of the double-RF system were observed, and experiences in commissioning active double-RF systems was accumulated. This paper reports the key experiences gained from the commissioning and operation of the active double-RF system in the HEPS storage ring, aiming to provide references for similar accelerator projects.

INTRODUCTION

The High Energy Photon Source (HEPS) [1,2], as China's first fourth-generation synchrotron light source, is under the trial operation stage in Beijing, China. HEPS aims to provide ultra-bright hard X-rays for frontier scientific research in various fields. Its accelerator complex is composed of three key parts: a 500 MeV linear accelerator (Linac), a 6 GeV full energy booster for beam energy ramping, and a 6 GeV ultra-low emittance storage ring. The beam commissioning of the HEPS storage ring was officially initiated on July 23, 2024. The first beam storage was achieved in two weeks [3]. Notably, HEPS passed the process acceptance on October 29, 2025, marking that HEPS fulfilled the construction contents and tasks approved by the National Development and Reform Commission, which was a critical step towards the formal operation of HEPS.

The HEPS storage ring is designed with the on-axis swap-out injection scheme as its baseline injection strategy, which ensures efficient beam replenishment while maintaining beam quality. One of its core baseline operation modes is the so-called 'high-bunch charge mode', featuring 63 bunches with a total beam current of 200 mA and a single-bunch charge of approximately 14.4 nC. To meet the strict requirements for beam stability, long lifetime, and operational flexibility in this mode, the storage ring is equipped with an double radio-frequency (RF) system. For keeping the flexibility to test the longitudinal injection scheme based on RF gymnastics proposed by ourselves, the higher-harmonic cavities was selected to be active. This system consists of five 166.6 MHz superconducting cavities serving as the fundamental RF system and two 499.8 MHz superconducting cavities acting as active third harmonic cavities [4], shown in Fig. 1. By implementing active harmonic cavities, the HEPS storage ring has the flexibility of achiving arbitrary bunch lengthening at any beam current, for instance, enabling the 'ideal bunch lengthening' condition at any beam current, which is crucial for suppressing collective beam instabilities and supporting stable high-performance operation for users.

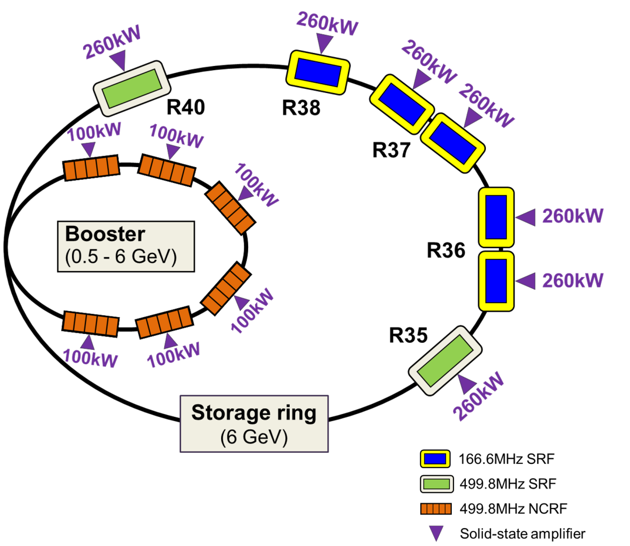

Figure 1: Schetch of the HEPS RF system (Courtesy of Pei Zhang).

During the initial phase of storage ring commissioning, due to delivery delays of the 166.6 MHz fundamental cavities, the 499.8 MHz cavities were temporarily repurposed as fundamental cavities to provide the necessary RF voltage and beam acceleration for initial beam commissioning. Starting from August 2025, the formal commissioning of the

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full active double RF system—integrating both 166.6 MHz fundamental cavities and 499.8 MHz third harmonic cavities—was launched. Through systematic commissioning efforts, ideal bunch lengthening was successfully achieved under various beam current conditions, and valuable practical experience in the operation and optimization of the double RF system was accumulated. This paper focuses on reporting the key experiences gained from the commissioning process of the HEPS storage ring active double RF system, with the aim of providing useful technical references for similar advanced synchrotron light source projects worldwide.

FINE TUNING OF THE RF PHASE OF THE FUNDAMENTAL CAVITIES

The HEPS storage ring is equipped with five 166.6 MHz superconducting cavities as the fundamental RF system, which play a crucial role in compensating for the synchrotron radiation energy loss of the beam and providing a stable longitudinal phase space for beam storage and operation. For the fundamental cavities to function as designed, the phases of the beam passing through each cavity need to be nicely aligned. Only when the beam experiences the same phase in all five fundamental cavities can the RF voltage provided by each cavity superimpose in-phase, thereby achieving the required total cavity voltage and sufficient longitudinal stable area for the beam.

A key challenge in the phase tuning of the HEPS fundamental cavities stems from the high beam energy of the storage ring (6 GeV). At this energy level, the average synchrotron radiation energy loss per turn of the bare lattice reaches 2.64 MeV, which exceeds the maximum RF voltage (no more than 1.5 MV) that a single fundamental cavity can provide. This means that a single fundamental cavity alone cannot compensate for the synchrotron radiation energy loss, making it impossible to achieve stable beam storage. Therefore, it is necessary to operate more than two fundamental cavities simultaneously, and their phases must be relatively accurately aligned to ensure effective superposition of their RF voltages.

A commonly used method for phase alignment of multiple fundamental cavities is the step-by-step commissioning approach: only one cavity is turned on at a time, and its phase is adjusted to maximize the number of beam transmission turns in the storage ring. After optimizing the phase of the first cavity, the second cavity is turned on, and its phase is tuned to further maximize the beam transmission turns, with this process repeated sequentially until all five cavities are turned on and their phases are aligned.

In this work, we propose a simple and feasible method for phase alignment of multiple fundamental cavities, which is based on the correlation between beam energy loss and the average horizontal orbit. The specific implementation process is as follows: first, only one fundamental cavity is turned on, and the number of transmission turns of the injected beam in the storage ring is recorded. Meanwhile, the turn-by-turn horizontal position data from all beam position monitors (BPMs) in the storage ring are collected, and the average horizontal orbit of the entire ring is calculated from these turn-by-turn data. This average horizontal orbit variation reflects the contraction of the average horizontal orbit of the injected beam caused by synchrotron radiation energy loss.

The first-turn commissioning application, shown in Fig. 2, was developed using the *Pyapas* framework, which allows for real-time data acquisition and processing during the commissioning process. By analyzing the correlation between the average horizontal orbit variation and the number of beam transmission turns, we can precisely align the RF phase for each cavity.

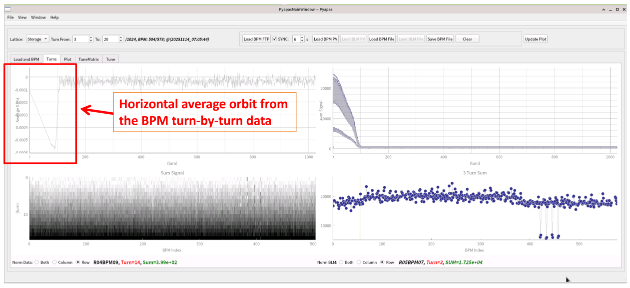

Figure 2: Schematic of the first-turn commissioning application.

The data obtained from the first turned-on cavity (including the number of beam transmission turns and the average horizontal orbit) are taken as the reference. Subsequently, the remaining four fundamental cavities are turned on one by one. For each newly turned-on cavity, its RF phase is adjusted continuously until the variation of the average horizontal orbit of the injected beam is consistent with the reference data obtained from the first cavity. By ensuring that each cavity, when turned on individually, induces the same average horizontal orbit variation as the reference, the phase alignment of all five fundamental cavities can be effectively achieved. The measured bunch length bofore and after the phase alignment are shown in the left and right plots in Fig. 3, the value of which is approximately 31.6 ps and 24.0 ps, respectively.

INITIAL COMMISSIONING OF THE ACTIVE DOUBLE RF SYSTEM

Beam commissioning of the active harmonic cavities has been successfully performed at HEPS starting from August 2025. The first commissioning attempt achieved approximately 1.6 times bunch lengthening, and further optimization eventually realized a lengthening ratio up to 3.2 times. Benefiting from flexible tuning of the harmonic cavity phase and voltage, a nearly ideal flat bunch distribution was successfully obtained at arbitrary beam current.

Longitudinal bunch profiles were measured by a streak camera and analyzed via fitting. Under different operational settings, the RMS bunch length was effectively stretched from 34.0 ps up to 108.5 ps, corresponding to a physical

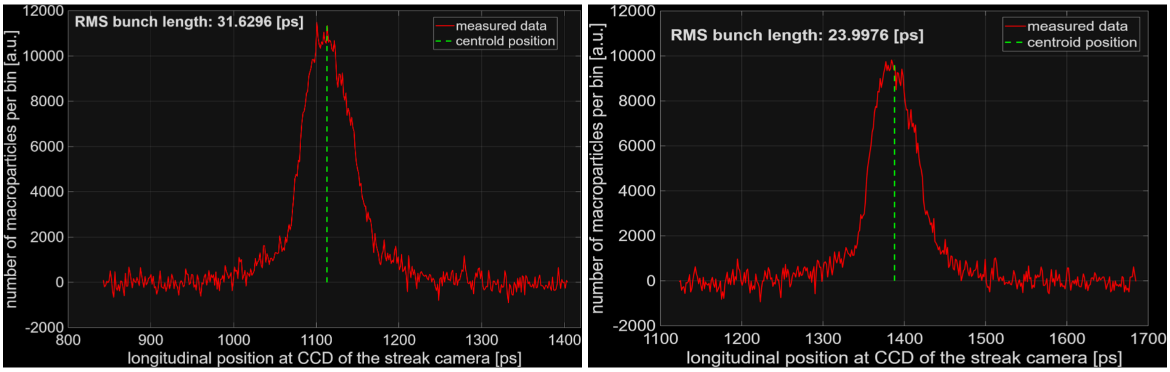

Figure 3: Measured bunch lengthes before (left) and after (right) the fine tuning of the RF phases.

bunch length expansion from 10.21 mm to 32.51 mm, as shown in Fig. 4.

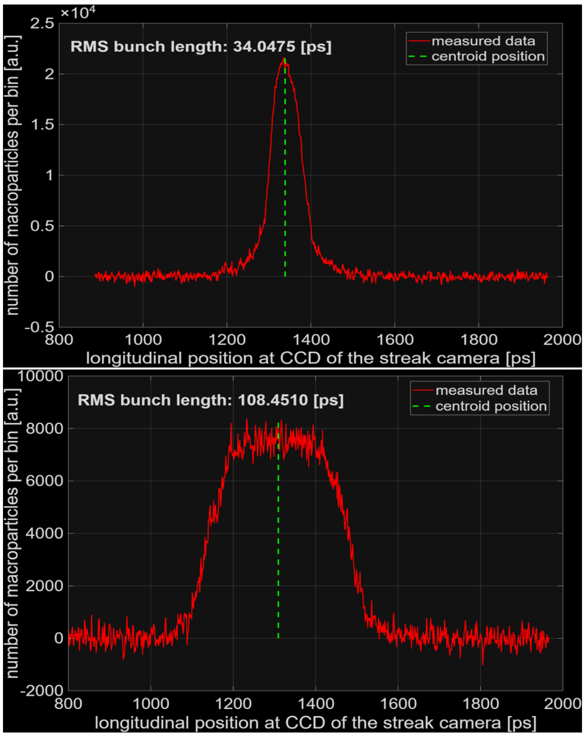

Figure 4: Measured bunch lengthes with fundamental RF only (left) and with double RF under ideal lengthening condition (right).

Moreover, obvious enhancement of beam lifetime was clearly observed during harmonic cavity tuning. The beam lifetime decreases monotonically with the reduction of harmonic cavity voltage. By optimizing the cavity voltage, the beam lifetime can be improved up to three times compared with the baseline, strongly validating the effectiveness of the harmonic cavity in improving beam quality and storage ring operation performance.

DISCUSSIONS AND OUTLOOK

The commissioning of the HEPS active double-RF system has been accomplished successfully. A practical phase tuning method was adopted to align the five fundamental superconducting cavities, effectively optimizing the longitudinal beam profile. Since August 2025, the active third harmonic cavities have been commissioned, realizing nearly ideal flat bunch distribution and a bunch lengthening ratio of 3.2 times. The beam lifetime can be enhanced up to three times the baseline by harmonic voltage optimization, which well demonstrates the capability of the active double-RF system in improving beam quality and storage ring performance.

The active harmonic cavity offers high operational flexibility while bringing new technical topics for further study. No serious collective beam instability has been observed in current commissioning. Future work will focus on reaching the designed 200 mA beam current, maintaining stable high-current operation, and performing dedicated experiments on collective instabilities with active harmonic cavities, to support reliable long-term operation and user experiments of HEPS.

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