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# INITIAL IMPLEMENTATION OF A NEW ORBIT FEEDBACK SYSTEM USING MicroTCA.4 FOR THE PF USER OPERATIONS

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*Abstract*

A new fast orbit feedback system has been introduced to the PF-ring since the third user operation in FY2024. The new system incorporates digital signal processing circuits based on the MicroTCA.4 standard. The transition from the legacy VME-based system, which had been in service for nearly 30 years, was conducted meticulously and incrementally during the start-up of the third user operation. The reference orbit was successfully transferred to the new system. At present, the effective bandwidth of the orbit feedback has reached 200 times that of the legacy system. This paper presents the transition process from the legacy system, initial performance results of the new system, and plans for future upgrades.


## FOFB SYSTEM FOR THE PF-RING

In storage ring-based synchrotron light sources, a fast orbit feedback (FOFB) system that continuously corrects the stored beam orbit relative to the reference orbit is essential for stable photon beam delivery. At the Photon Factory storage ring (PF-ring) of KEK, an FOFB system using VME-based digital signal processors had been in service since FY1997 [1]. The system used up to 65 beam-position monitors (BPMs) and 28 fast steering magnets (FSs) for vertical orbit correction[1]. However, because only 12 analog detection circuits were available, semiconductor switches were installed before each circuit to sequentially process the signals from the four button electrodes and from 5–6 BPMs. This switching process limited the closed-orbit distortion (COD) measurement frequency to 80 Hz and reduced the effective feedback bandwidth to approximately 0.3 Hz. Furthermore, the aging of components had increasingly resulted in system malfunctions and more frequent interruptions in user operations over time.

An upgrade project was launched in FY2020 to modernize the system [2]. In the new system, each BPM unit is equipped with its own signal processing channel, obviating the need for switching. The design is based on the MicroTCA.4 standard, which provides high availability and a high-speed data bus [3]. The COD measurement frequency was increased to 10 kHz, thereby enabling a feedback bandwidth exceeding 100 Hz. Circuit fabrication was completed in FY2021, despite difficulties caused by the global semiconductor shortage, followed by extensive hardware and software modifications carried out in parallel with the operation of the legacy FOFB system [4]. During the start-up of the third user operation in FY2024, the transition to the new system was successfully completed; the upgraded FOFB has since maintained stable beam delivery to users.

This paper presents an overview of the FOFB system replacement, completed in February 2025, along with its initial performance and planned future upgrades.

## SYSTEM REPLACEMENT

The legacy FOFB system was replaced with the new system during the start-up of the third user operation in FY2024. The first step was to close the feedback loop with the new system, using 17 BPMs that had not been employed in the legacy system and 8 FSs selected at appropriate intervals. Starting from this configuration, groups of approximately 10 BPMs were gradually transferred from the legacy system to the new system, while confirming that the closed orbit could be stably maintained utilizing orbit feedback. This process was implemented carefully at a low stored current of 30 mA, considering the reproducibility of the beam orbit before and after reconnecting the BPMs, which required dumping the stored beam, as well as the risk of sudden orbit divergence due to feedback failure. Another important issue in such a replacement concerns the transfer of the reference orbit measured with the legacy system to the new system. Our approach was to perform a COD correction[2] each time several BPMs units were reconnected by using the closed orbit measured immediately before the reconnection as the reference. Thus, the orbit drifts at each step were minimized, and the original reference orbit defined by the legacy system could be reliably inherited by the new system.

After four reconnection steps, the number of BPMs incorporated into the new system was successfully increased to 63. The number of FSs was also increased to 16 during this process. The distributions of BPMs and FSs resulting from this staged replacement are shown in Fig. 1. Although 15 BPMs were intentionally retained on the legacy circuits for comparison, those integrated into the new system were distributed almost uniformly around the storage ring.

Subsequently, with the FOFB turned on, the beam was gradually accumulated up to the nominal current of 450 mA for the PF-ring, confirming that the feedback operated correctly even at high current. Tests were conducted at 100 mA and full 450 mA by closing the gaps of the in-vacuum undulators (IVUs) so as to verify that the reference orbit had been correctly transferred to the new system. In this procedure,

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[1] The horizontal orbit is stabilized solely by a slow orbit feedback (SOFB), running every few tens of seconds.

[2] This correction was performed manually with the SOFB system, independent of the FOFB.

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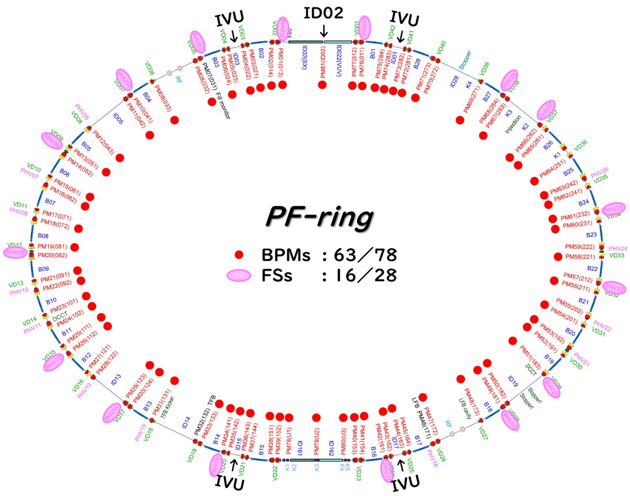


Figure 1: Distributions of 63 BPMs and 16 FSs transferred from the legacy system to the new system.

although the gaps of the four IVUs were closed individually to the minimum setting of 4 mm, no changes in the beam lifetime due to beam loss or instabilities were observed. This result confirms that the beam passed almost parallel through the centers of the narrowest IVU gaps in the PF-ring, and that the reference orbit used before the BPM circuit replacement was accurately inherited by the new system.

Finally, the new system was verified to be capable of handling all operations necessary for photon beam alignment and user operations without any issues. As a result, the third user operation could begin on schedule, two days after the BPM circuit replacement began. Thereafter, improvements and fine adjustments to the new system were carried out in parallel with the operation. The FOFB currently operates with 60 BPMs and 27 FSs, almost the same configuration as before the BPM circuit replacement. To date, no machine troubles caused by the new system have been observed, and no issues regarding photon beam stability have been reported.

## INITIAL PERFORMANCE RESULTS

Before operating the new BPM circuits, the level differences among the eight channels and dominant crosstalk components were corrected based on measurements obtained using a signal generator. The variable attenuators at the front-end stage were adjusted to 16 dB in order to prevent current dependence caused by A/D converter saturation. With these initial settings, the absolute beam position readings from each circuit were verified, through single-kick response tests and other methods, to be in good agreement with the analytical calculation results. In addition, to mitigate the temperature dependence of approximately 1 µm/°C, the temperature inside each rack housing the BPM circuits was stabilized to within ±0.2 °C by using inverter-controlled coolers. This section presents several examples of the initial performance achieved within six months after introducing the new system.

### *Orbit Drift*

Figure 2 compares the vertical orbit drift over a 2.5 h period, measured in the decay mode, for cases with and without the FOFB in operation. In both cases, the stored current at the beginning of the measurement was approximately 420 mA. The horizontal axis shows the BPM numbers, assigned counterclockwise from the BPM at the center of ID02 on the northern side of the ring. Turning on the FOFB significantly reduced the DC-like orbit drift across the ring compared with the case without the FOFB. Same orbit drifts had already been observed using the legacy system. Because they do not appear in the horizontal plane, these drifts clearly arise from the current dependence of the actual beam orbit, not from the BPM circuits. The RMS orbit drift after 2.5 h was 5.6 µm with the FOFB on, corresponding to approximately one-sixth of that with the FOFB off. The remaining drift could be further reduced by increasing the number of FSs in the FOFB or by operating it together with the SOFB provided by another system. Moreover, beam-based alignment, which is scheduled for the near future, as well as identifying the sources of COD patterns that are uncorrectable by feedback, is also expected to be effective.

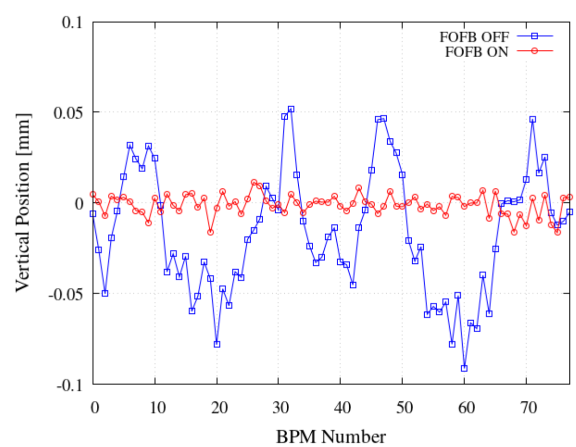


Figure 2: Comparison of orbit drift after 2.5 h in decay mode.

### *PI Gain Tuning and Gain Curves*

In the new FOFB system, the proportional–integral (PI) gains can be set individually for each D/A converter (DAC) channel (i.e., for each FS). The gain values were adjusted by turning on the FOFB with one BPM and one FS, and observing the response to a step-like orbit perturbation. The proportional gain was set to approximately half the value at which sustained orbit oscillations were observed. The integral gain was then tuned to achieve the fastest orbit recovery without undershoot under the selected proportional gain. Figure 3 shows the orbit feedback gain curves measured before and after the tuning. The effective feedback bandwidth, which was approximately 20 Hz at the −3 dB point before tuning, was extended to 60 Hz after tuning; this was nearly

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200 times the value of the legacy system. However, because discontinuous gain growth was observed above 130 Hz, a final optimization of the PI gains across the entire frequency range remains necessary.

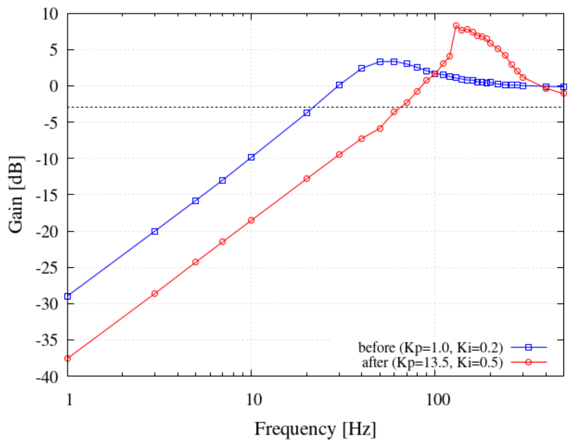


Figure 3: Gain curves of the new FOFB system before and after PI gain tuning.

### *PSD and RMS Motion*

Figure 4(a) presents the power spectral density (PSD) obtained when an FS located outside the feedback loop was driven by a 500 Hz sinusoidal signal. Fast acquisition data recorded at the rate of 10 kHz were used for the measurements. Although the beam was excited at a single frequency of 500 Hz, the spectrum showed an offset resembling that produced by white noise. This likely resulted from eddy currents induced on the surface of the beam duct where the FS was installed. The damping or amplification with the FOFB is consistent with the gain curve shown in Fig. 3. Figure 4(b) shows the effective RMS orbit motion obtained by integrating the PSD from low to high frequencies. In the frequency range below 100 Hz, the RMS motion was less than one-tenth of the smallest beam size at the IVU, namely, 12 µm. In particular, a submicron-level orbit stability was achieved within an FOFB effective bandwidth below 60 Hz. The steps observed at 50 Hz and 100 Hz are attributed to AC line noise and harmonics from the magnet power supply, respectively. As the latter oscillation occurs in a frequency range amplified by feedback, identifying its source and implementing fundamental damping measures are desirable.

## FUTURE UPGRADES

The new FOFB system is being upgraded to enhance its performance. As regards the hardware, circuit updates for all 78 BPMs and FS power supplies capable of digital control are being introduced. Optimization of FS placement to mitigate the eddy current effects on the beam duct, as well as extending the FOFB to the horizontal plane, is also being considered. With regard to software, implementation

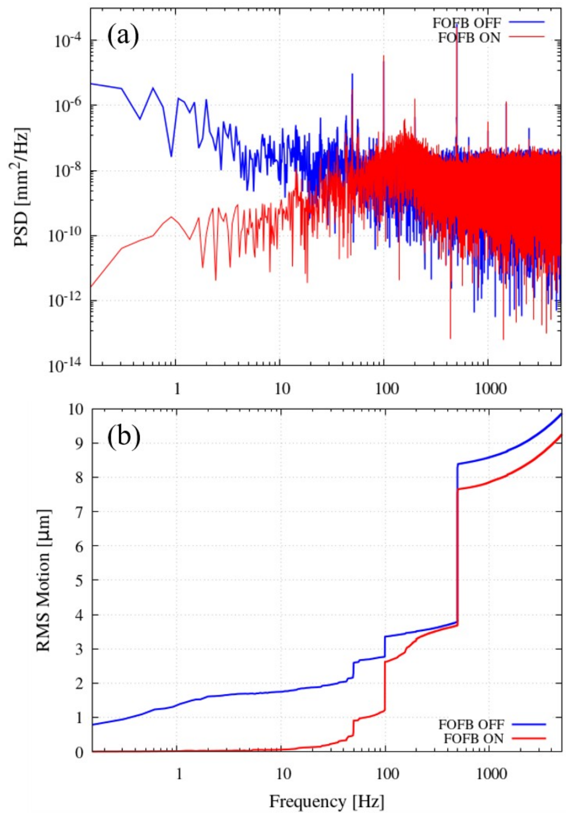


Figure 4: (a) PSD and (b) the resulting RMS motion when the beam is excited at 500 Hz.

of features such as masking to remove injection-induced oscillations, postmortem recording triggered by interlocks, and calibration using tone signals is planned. The initial performance, reported in the previous section, can be further improved through these hardware and software upgrades, followed by parameter tuning.

## SUMMARY

The new FOFB system was successfully implemented at KEK's PF-ring, starting from the user operation in March 2025. The transition from the legacy system was performed stepwise over two days within the normal start-up period and was completed smoothly without affecting the operation schedule. The new system, based on the MicroTCA.4 standard, can suppress orbit fluctuations up to 200 times faster than the legacy system, even shortly after its introduction. Several adjustments and upgrades are planned to be conducted in parallel with user operation, seeking to further enhance the system performance.

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