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DEVELOPMENT OF BUNCH SELECTOR MODULES FOR DOUBLE BUNCH OPERATION IN PAL-XFEL BPM SYSTEM*

D.C. Shin†, G.J. Kim, C. Kim, H. Yang, S.-W. Jang, H. Heo
Pohang Accelerator Laboratory, Pohang, South Korea

Abstract

PAL-XFEL plans to begin double-bunch operation in 2027, with two electron bunches separated by 25 ns. The existing beam position monitor (BPM) electronics were designed for single-bunch operation, so the two signals overlap and bias the position measurement. To support this mode without modifying the electronics, we developed an external radio-frequency (RF) switch-based bunch selector that routes only the selected bunch to the BPM input. We built a prototype and conducted laboratory and on-site tests. This paper presents the hardware and experimental results.

INTRODUCTION

PAL-XFEL began user service in June 2017 [1]. Initially, only one of the two beamlines could be served at a time. In 2021, time-sharing enabled simultaneous operation of the hard X-ray (HX) and soft X-ray (SX) lines, but it divided the 60 Hz free-electron laser (FEL) repetition rate.

To address this limitation, PAL-XFEL plans to begin double-bunch operation in 2027. Two electron bunches separated by 25 ns are generated in the injector, accelerated together, and then separated by a kicker into the HX and SX beamlines for FEL lasing (Fig. 1). This delivers 60 Hz electron beams to both lines concurrently, effectively doubling facility utilization.

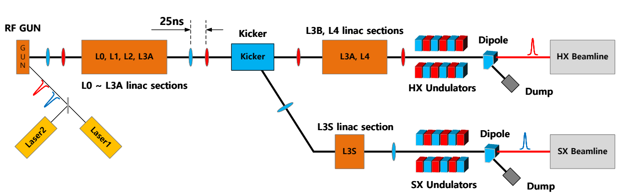

Figure 1: Double-bunch operation at PAL-XFEL.

To realize this mode, several systems are being built or upgraded. This paper reports on the development and initial tests of an external RF switch-based bunch selector that supports double-bunch operation without changes to the existing BPM electronics.

MOTIVATION AND CONCEPT

Because the BPM electronics include a narrow band-pass filter centered at 300 MHz, two bunches separated by 25 ns overlap at the BPM input and are sampled together. This degrades the accuracy of the X/Y position measurement and perturbs the machine feedback, hindering stable operation.

To improve this, we widened the filter bandwidth and synchronized the sampling clock to the RF timing, then modified the program to conduct multi-bunch processing experiments. However, the increased noise due to the wider bandwidth degraded the measurement resolution, and the risk of RF card damage from high temperature during filter replacement led us to exclude this option.

As a second option, we considered digital down-conversion (DDC) with a low-Q cavity pickup as implemented at SwissFEL [2], but the required hardware changes were prohibitively costly; therefore, this option was also excluded.

Discussions with the beam-physics group led to the conclusion that measuring both bunch positions is not necessary. The trailing-bunch trajectory can be inferred from the leading-bunch position, and after the branch section the remaining controls can satisfy the FEL conditions for each bunch. Consequently, as shown in Fig. 2, an external RF switch-based bunch selection was proposed as the alternative.

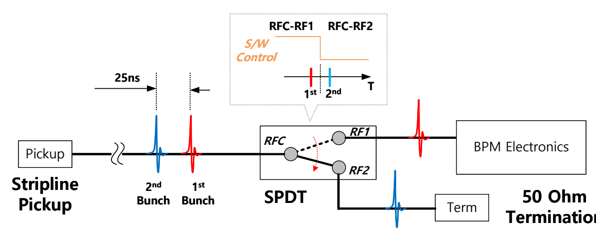

Figure 2: Operating principle of the bunch selector.

By using the switch to pass only one of the two bunches, a single bunch is delivered to the existing BPM electronics. This concept meets the beam-physics requirements while leaving the BPM electronics and operational systems unchanged, and it has the advantage of being realizable within the existing facility operating budget.

SPECIFICATIONS AND TEST RESULTS

Specification

System Specifications

- Operating mode: Select either 1st or 2nd bunch (separated by 25 ns) and route only the selected bunch to the BPM input.
- Resolution: The target position resolution of the selected bunch shall match the single-bunch resolution; the acceptance limit is within 150 % of the single-bunch resolution and shall not exceed 10 µm, as per the initial PAL-XFEL BPM specification [3].

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† dcshin@postech.ac.kr

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- Offset-consistency: Under identical beam conditions, the offset difference between the single-bunch result and the double-bunch selected-bunch result has a target of ±10 µm; the acceptance limit is ±20 µm.

Switch Specifications To selectively measure one of two bunches separated by 25 ns, the switch must provide (i) fast transition and (ii) high isolation, while avoiding saturation when passing the calibration-tone signal [4]. Considering that more than 200 switches may be used, per-unit price was also a key constraint. The switch specifications were set as follows:

- Transition time (10 % to 90 %): ≤ 10 ns
- ON/OFF isolation: ≥ 60 dB @ 300 MHz
- Input 1-dB compression point (P1dB): ≥ 23 dBm @ 300 MHz
- Target price: ≤ USD 50 per unit (if feasible)

Based on these requirements, the Mini-Circuits M3SWA2-63DRC+ RF switch was adopted for the first prototype. A DS1023S-025 delay element was used for fine adjustment of the switching timing, and a Raspberry Pi 4 was employed for control and EPICS connectivity.

First On-Site Test and Video-Feedthrough Assessment

In October 2024, we installed the switch module at PAL-XFEL and performed the first on-site test. The results did not meet expectations. The main issue was video-feedthrough. It is a broadband voltage transient caused by switching, and it appears at the output even when no input RF is present [5]. This transient entered the BPM signal band and was amplified in the downstream chain. As a result, large position errors occurred. Consequently, a quantitative evaluation of the bunch selector was not feasible in this experiment. We identified the switch's intrinsic video-feedthrough as a key performance-limiting factor and decided to re-select the switch.

Because video-feedthrough is not documented in many manufacturers' datasheets, we purchased evaluation boards of several candidates with published RF characteristics and directly compared their video-feedthrough. The candidates were Mini-Circuits MSWA2-50+, M3SWA2-34DR+, M3SWA2-63DRC+ (used in the first prototype), and Analog Devices ADG918 (included for noise-characteristic comparison despite insufficient RF specifications).

Figure 3 shows representative video-feedthrough captures at the RFC port. Table 1 summarizes the comparison. From the comparison, ADG918 did not meet the RF performance requirements but exhibited the lowest video-feedthrough, serving as a useful lower-bound reference. Excluding ADG918, M3SWA2-34DR+ showed the lowest video-feedthrough and was therefore selected for the second prototype.

Fabrication and Tests of the Second Prototype

We fabricated a second prototype and, after laboratory tests, conducted on-site tests in early August 2025. Figure 4 presents the second-prototype hardware (switch modules and the switch controller) and the on-site installation.

Figure 3: Video-feedthrough waveforms at the RFC port for four switches.

Table 1: Video-feedthrough measurements (columns – SW1: M3SWA2-63DRC+, SW2: MSWA2-50+, SW3: ADG918, SW4: M3SWA2-34DR+)

Test Port	Control Bit	Measurement V_{pp} (unit: mV)			
		SW1	SW2	SW3	SW4
RFC	High	35	30	2	7
	Low	12	32	1	6
RF1	High	18	10	2.5	7
	Low	8	27	0.8	3
RF2	High	20	25	1	2.5
	Low	12	20	2.5	6.5

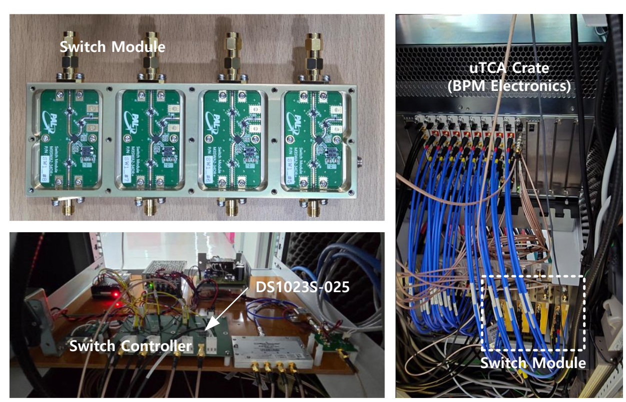

Figure 4: Bunch selector hardware and on-site installation.

Prior to deployment, we generated a double-bunch-like signal in the laboratory (pulse width 1 ns, spacing 25 ns) and fed it to the BPM via the bunch selector. We evaluated two metrics: (i) the mean offset difference ($\Delta X, \Delta Y$) between single-bunch and double-bunch measurements for the same bunch, and (ii) the rms (shot-to-shot standard deviation) under each condition. The switching-pulse delay was swept from 1 ns to 40 ns in 1 ns steps.

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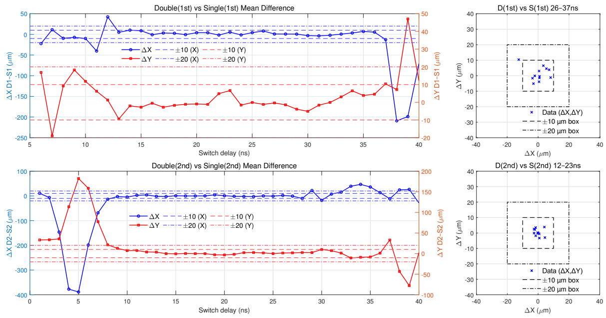

Figure 5: Laboratory offset-consistency results: delay sweep (left) and ΔX–ΔY scatter in selected windows (right).

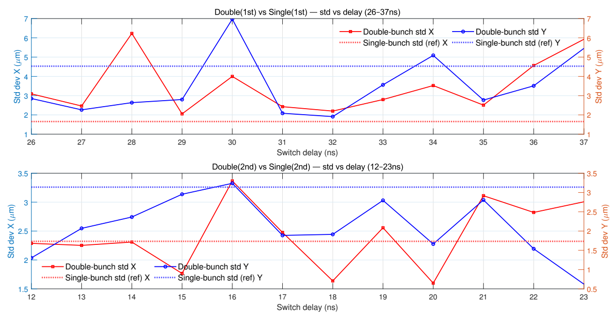

Figure 6: Laboratory rms (standard deviation) results.

Figure 5 shows (left) the offset-consistency results versus delay and (right) scatter plots for selected delay windows. The right-hand plots use 26 ns to 37 ns for the first bunch and 12 ns to 23 ns for the second bunch, plotted on the ΔX–ΔY plane with ±10 µm/±20 µm box guides for reference. Over delay ranges ≥ 20 ns, the bunch selector approached the acceptance limits. Figure 6 shows the rms results.

In laboratory experiments, the first bunch achieved target-level performance in both offset-consistency and rms within 26 ns to 37 ns, and the second bunch did so within 12 ns to 23 ns.

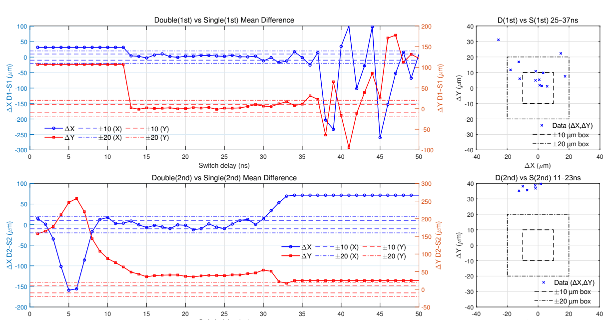

Figure 7: On-site offset-consistency results at BPM-04: delay sweep (left) and ΔX–ΔY scatter in selected windows (right).

Figures 7 and 8 show on-site results at BPM-04 in the injector section. The first bunch showed performance near the targets for both offset-consistency and rms in the 25 ns to 37 ns range, but for the second bunch the Y-axis offset-

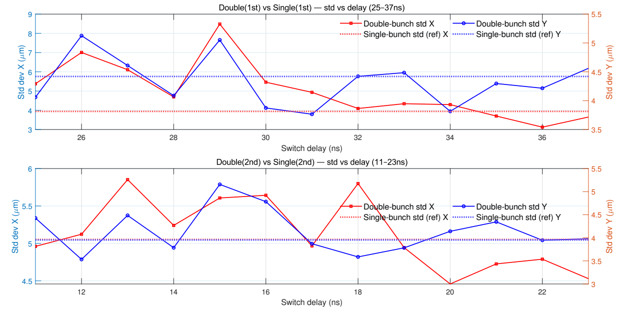

Figure 8: On-site rms (standard deviation) results at BPM-04.

consistency exceeded the limit by a large margin. BPM-01–03 also showed one or two items beyond the limit.

Compared with the first prototype, video-feedthrough decreased, but this noise was still observed in the raw data and was confirmed to adversely affect the system.

CONCLUSION

We built an RF switch-based bunch selector for single-bunch BPM readout in double-bunch mode. The first prototype was limited by video-feedthrough.

After re-selecting the switch, laboratory tests showed good offset and rms performance. On-beam tests at BPM-04, however, revealed a Y-offset beyond specification and residual video-feedthrough.

We will focus on suppressing feedthrough and further improving the bunch selector, and we will expand on-beam validation toward deployment.

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