Development of the RF Phase Shifter with Femtosecond Time Delay Resolution for the PAL-XFEL Laser System

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Abstract

We will introduce the RF Phase Shifter (RPS) used in the Pohang Accelerator Laboratory X-ray Free-Electron Laser (PAL-XFEL) optical laser system. This equipment is designed to finely adjust the laser signal in femtosecond time by manipulating the phase of the RF reference signal using a couple of Direct Digital Synthesizer (DDS) devices. Furthermore, it is designed with low phase noise and low phase drift feature in order to minimize the impact on the system.

Currently these units are installed at the Injection site, Hard X-ray and Soft X-ray Beamline. They are installed for feedback control of the electron beam at the Injector and for use in pump-probe experiments at the Beamline. This paper will introduce the design, fabrication, and experimental results of the RPS, as well as its usage status at PAL-XFEL.

Motivation of Development

The time delay feature is an important functionality in the PAL-XFEL laser system. Typically, controlling the time delay of lasers involves adjusting the physical length of the laser path using a delay stage, which consists of a motion stage and mirrors. However, this approach, which relies on the use of a delay stage, can lead to degradation in laser quality due to vibrations and shifts in laser focus. Furthermore, adjusting the time delay pulse by pulse is challenging and can result in significant wastage of XFEL or probe laser energy in pump-probe experiments. Therefore, we explored a digitally controlled method with a fast response speed, leading us to develop the RF Phase Shifter (RPS)."

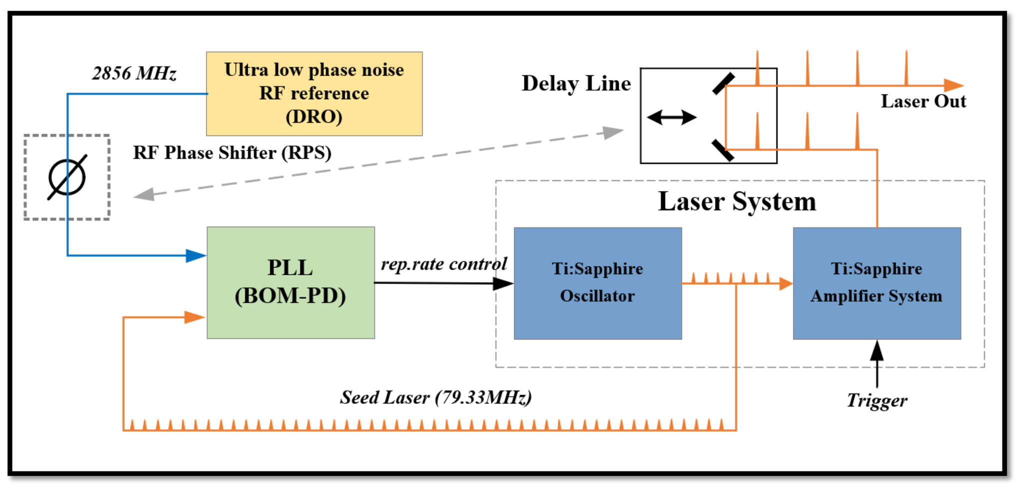

Figure 1: Block Diagram of the PAL-XFEL injector laser system.

In the left image, we planned to replace the 'Delay Line' system with an 'RF Phase Shifter'.

Specification

- Phase Control Resolution : 0.0055°
- Control Range : $(-2^{30} \sim 2^{30})$ * resolution
- Linearity(0~360 degrees) : ≤ ±0.05°
- Update Rate : ≥ 10 kHz
- Stability degrees/day : ≤ 0.1°
- Phase Noise : ≤ -150 dBc@100kHz ~ 1MHz

RPS Block Diagram

The figure below depicts the block diagram of the RPS.

The output phase of the RPS is controlled by adjusting the Phase Offset of the DDS #2. The phase change of the IF signal is maintained in the RF signal .

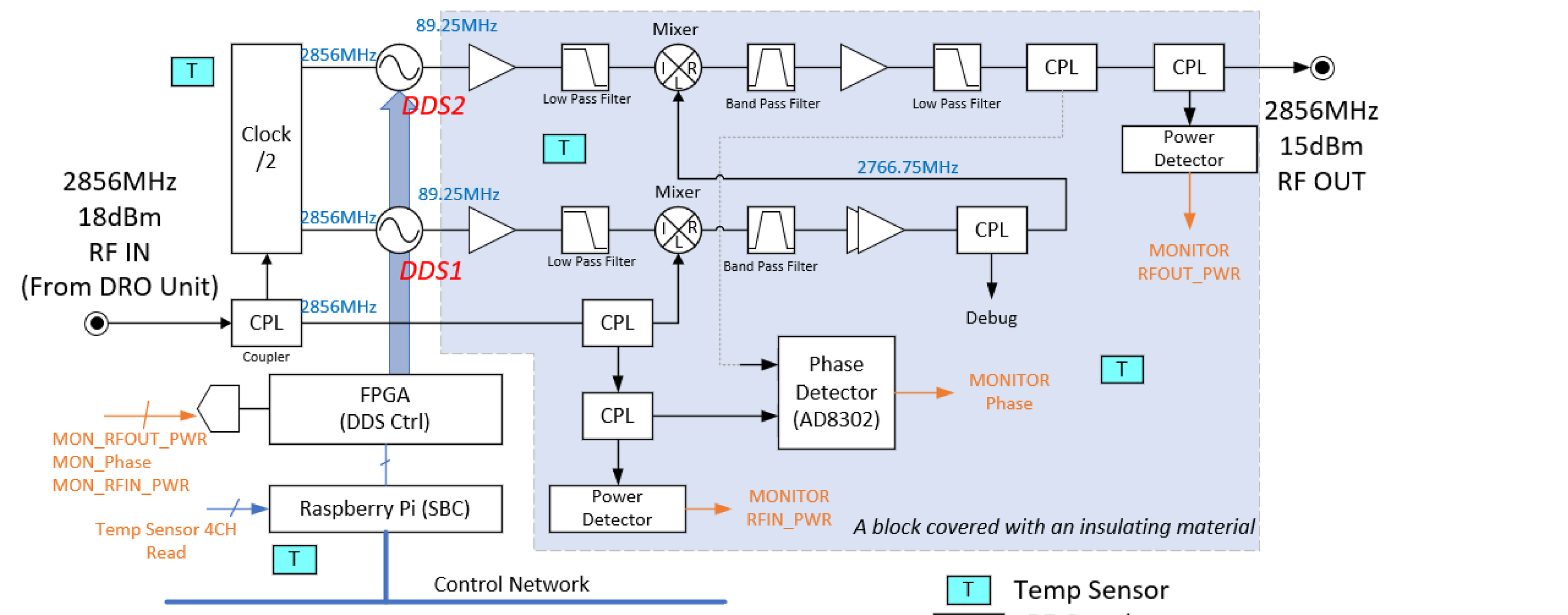

Figure 2: RPS Block Diagram

Phase vs Time

- Phase Resolution = 360° / (DDS Phase Offset (2^{16})) ≈ 0.00549°
- Time Resolution = T(Period of the 2856MHz REF) / (DDS Phase Offset (2^{16})) ≈ 5.34 fs

During the PLL (Phase-Locked Loop) process, changes in the phase of the Reference(REF) signal are monitored and tracked in real-time. These changes are reflected in the output laser signal with a time delay, ensuring synchronization between the output signal and the REF signal.

Fabrication

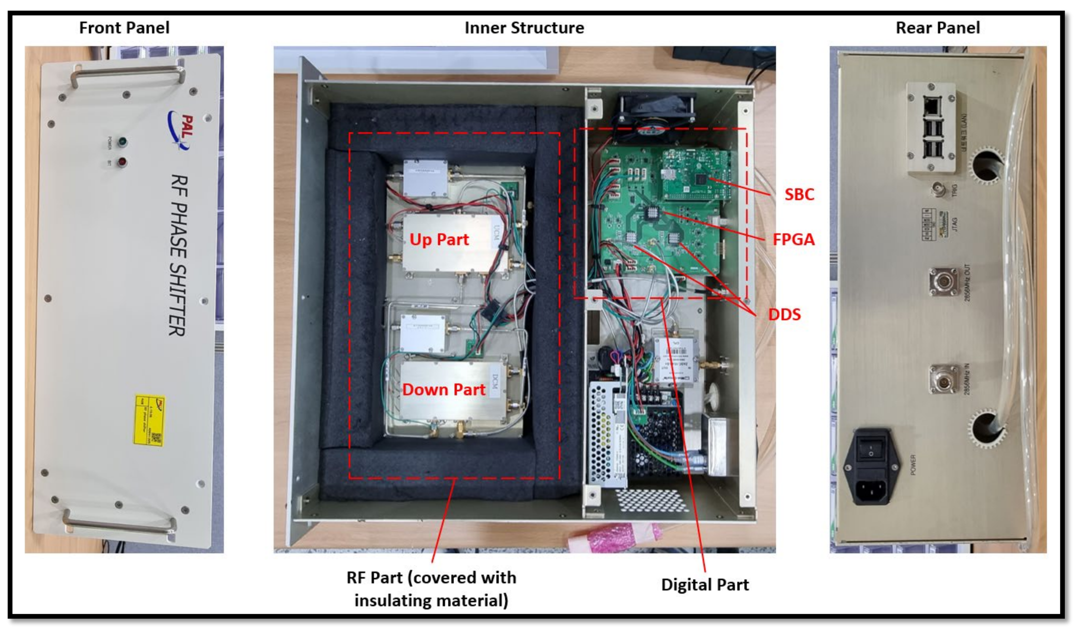

Figure 3: RPS Photos

The temperature-sensitive RF circuits are placed within a controlled temperature environment, while the digital circuit is exposed to room temperature. Water cooling is used for temperature control.

Test Result and Usage of PAL-XFEL

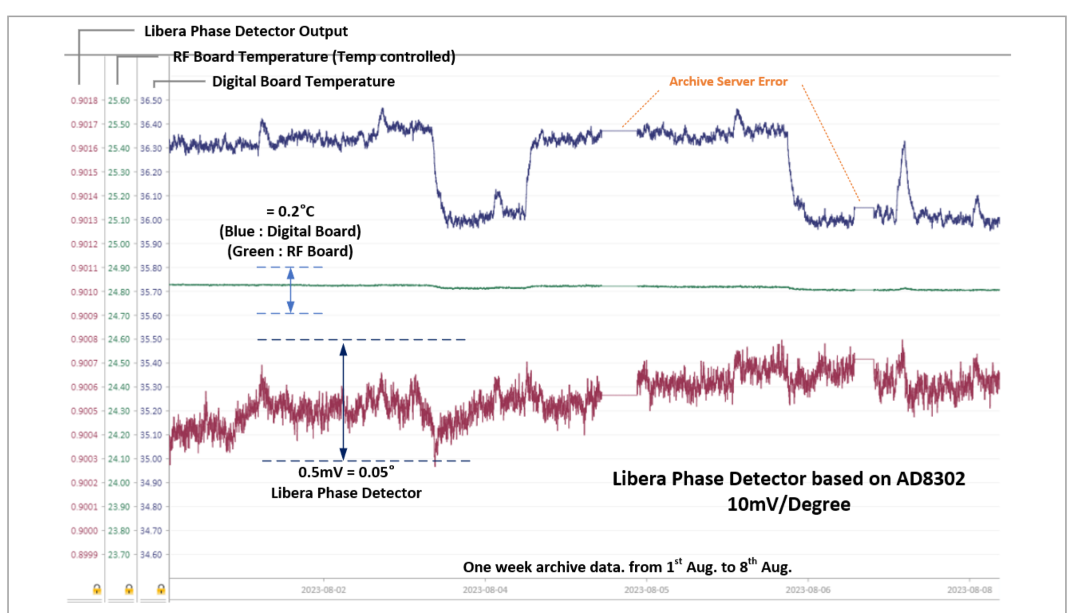

Figure 4: Long-term stability by Phase Detector

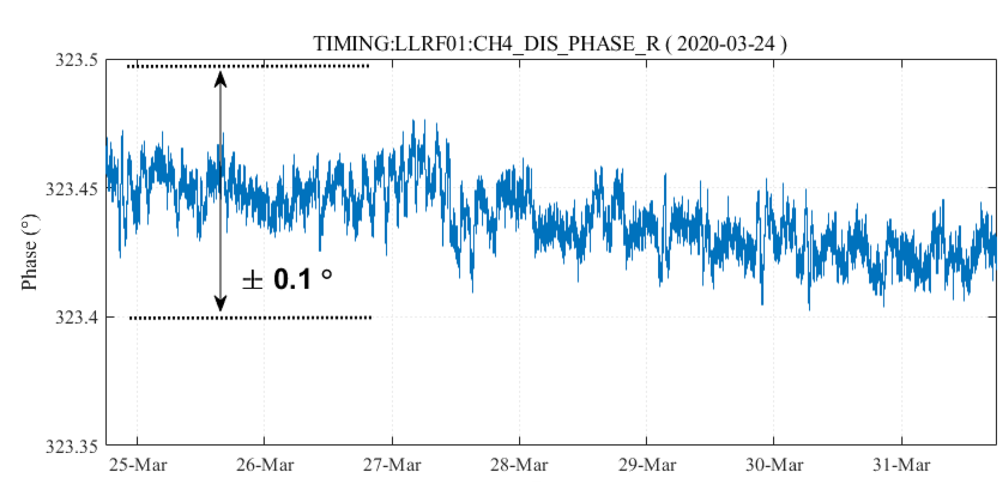

Figure 5: Long-term stability by LLRF

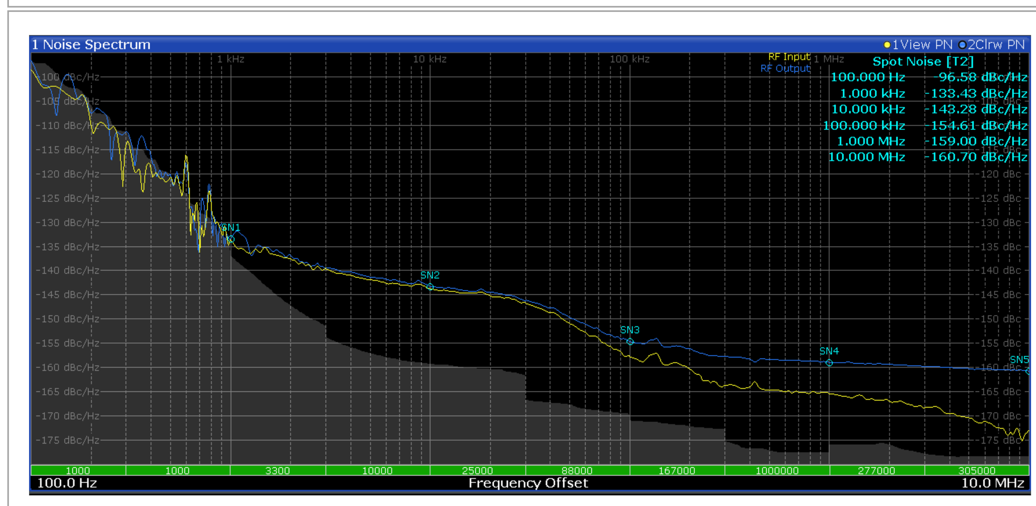

Figure 6: Phase Noise

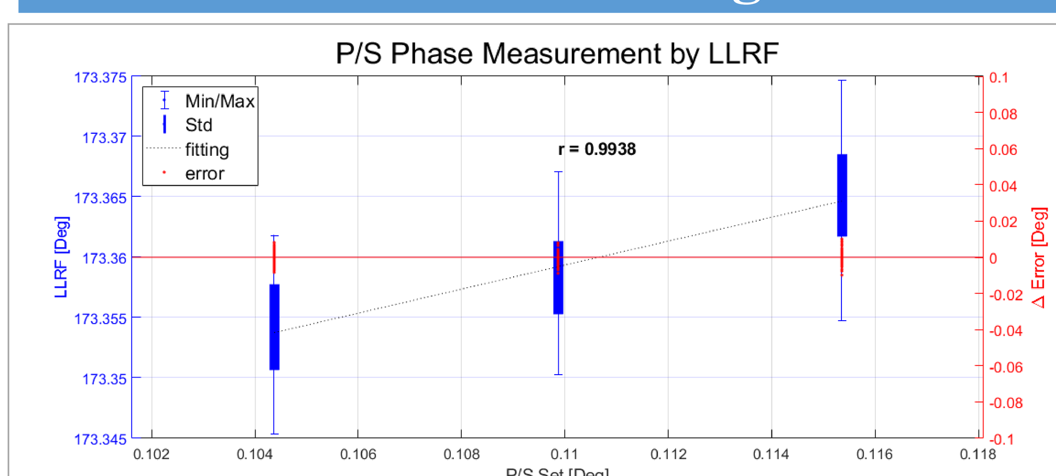

Figure 7: Resolution Test

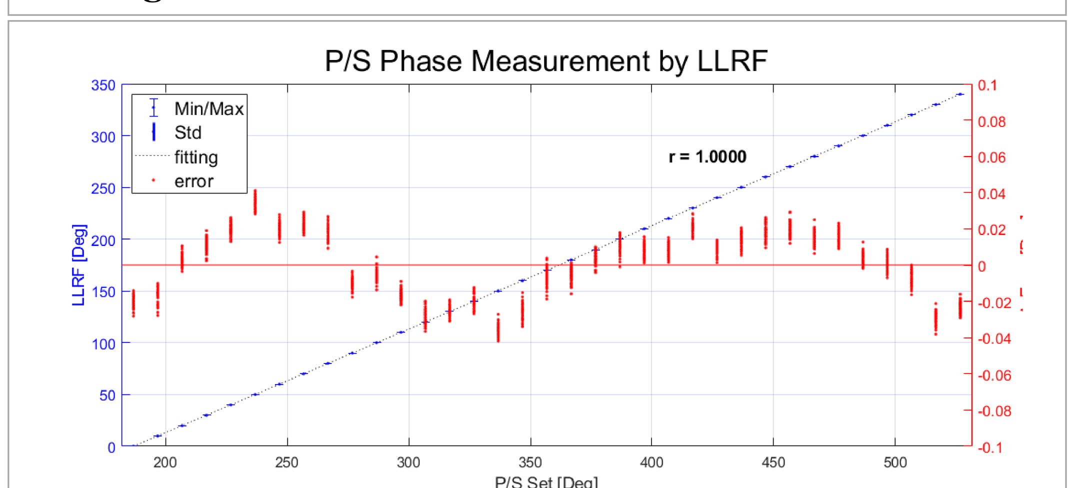

Figure 8: Linearity Test

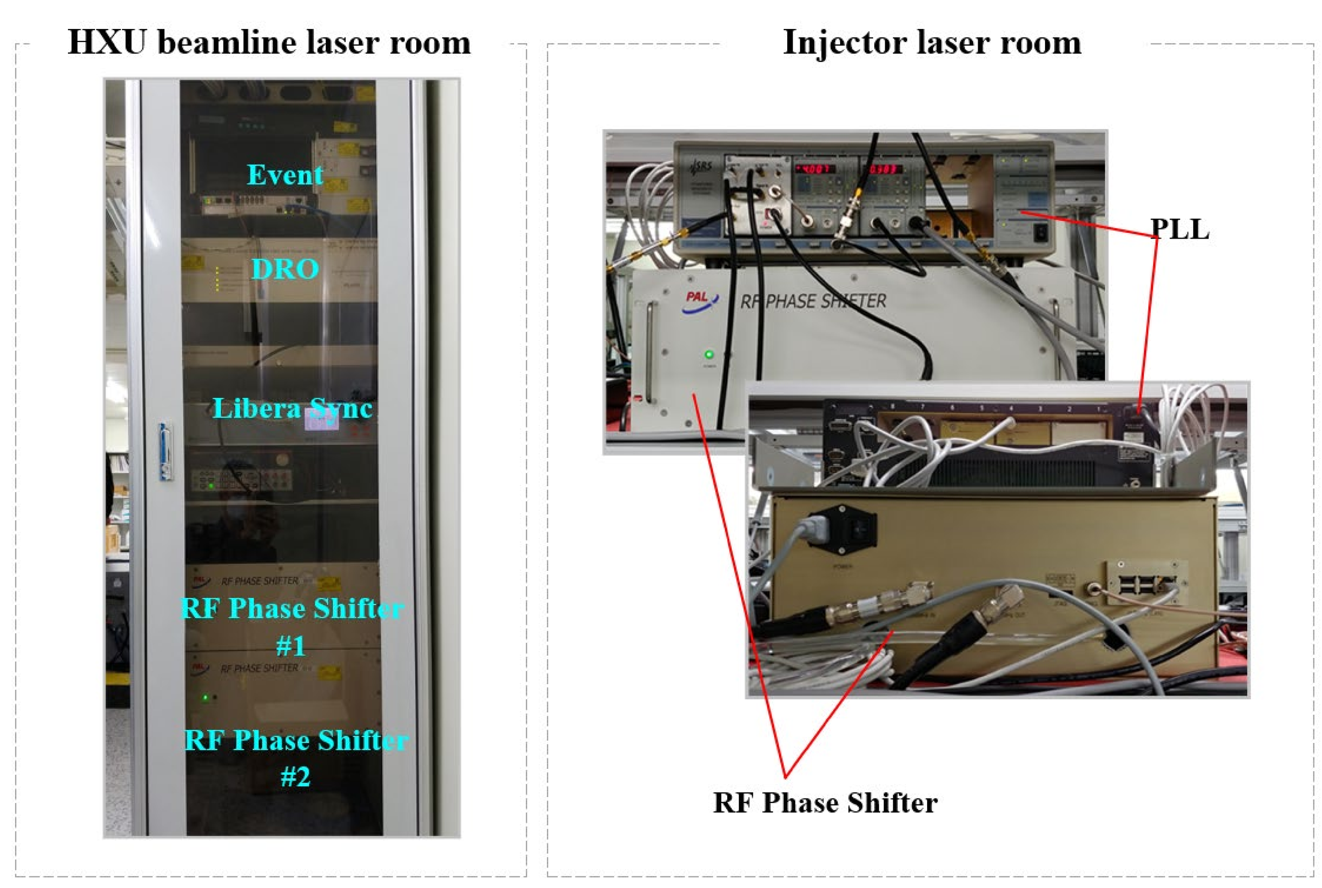

Figure 9: Installation

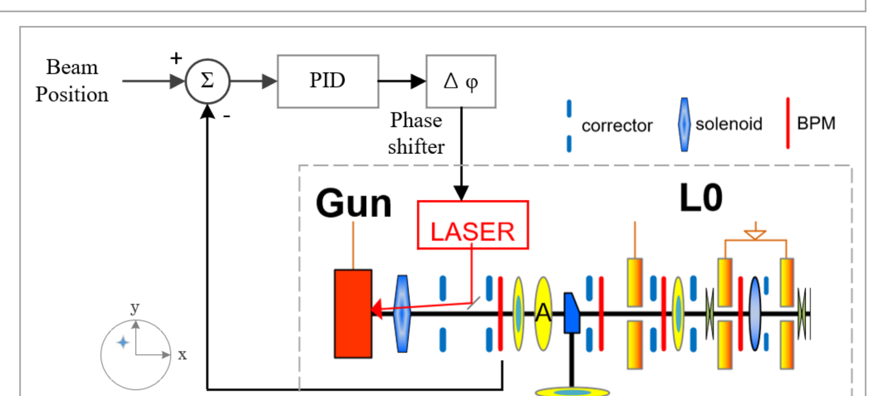

Figure 10: Feedback in Injector

Figures 4 and 5 depict the results of long-term stability experiments in which phase variations were measured over one week, remaining within a range of ±0.05 degrees. Figure 4 displays measurements obtained using I-tech's Phase Detector, while Figure 5 presents measurements acquired using the LLRF device installed at PAL-XFEL.

Figure 6 shows the phase noise measurement results. It confirms that the additive phase noise specification of the RPS unit remains below -150 dBc from 100 kHz to 1 MHz.

Figure 7 represents the results of the resolution test, displaying measurements obtained using LLRF while incrementing the phase value of the RPS by 0.0055 degrees. The 0.0055-degree variations are clearly distinguishable

Figure 8 shows the linearity measurement results, obtained using LLRF while incrementing the phase of the RPS in intervals of 0 to 10 degrees up to 350 degrees. The relative error remains within ±0.05 degrees, and it is noticeable that the slope of the correlation graph is very close to 1.

Figure 9 depicts the installation of RPS in the beamline and Injector laser room. Figure 10 illustrates how the RPS is currently being used in the feedback control of the electron beam in the Injector section. In the case of the beamline, users still tend to prefer delay lines. We plan to promote more active utilization of this device in the future.

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