RF TIMING DISTRIBUTION AND LASER SYNCHRONIZATION COMMISSIONING OF PAL-XFEL

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Abstract

PAL-XFEL requires sub 100 fs synchronization of LLRF systems and optical lasers for stable operation and even lower jitter is favorable for the higher performance of FEL and the better time resolution of pump-probe experiments. The RF timing distribution system is based on a 476 MHz reference line, which is converted to 2.856 GHz at 16 locations over 1.5 km distance using phase-locked DRO. The 2.856 GHz signals are amplified and split to 10 outputs, which is connected to LLRFs, BAMs, and DCMs through low timing drift cables. The jitter between two different PLDRO units is estimated to ~1 fs from 1 Hz to 1 MHz. The synchronization jitter between a Ti:sapphire laser and the 2.856 GHz signal is measured less than 20 fs..

INTRODUCTION

PAL-XFEL is a hard X-ray SASE FEL, which is based on a normal conducting 10 GeV linear accelerator, undulators and experimental hutches. Additionally, soft X-ray SASE FEL is generated from branched electron bunches at 3 GeV in the main linac. Initially we are aiming to generate ≈100 fs X-ray laser pulses. For the stable operation of the machine, well-defined and consistent electron bunches are required in energy and time axis. To satisfy this, we want to synchronize phase sensitive components within the X-ray pulsewidth.

Two time scales are considered in our timing distribution and synchronization scheme. The phase change at less than one second is jitter that should be stabilized passively. The phase change in the longer term is drift that would be stabilized actively. The jitter is caused by phase locked loop between oscillators, phase noise of oscillators, and delay. The drift is mainly from the length change of signal transport due to environmental effect.

Beside RF systems, another part of the machine with high timing sensitivity is an optical laser, which is used to the generation of photoelectrons in the beginning and another femtosecond pulsed light source of time-correlation experiments

In following sessions, we describe our passively stabilized RF timing distribution and the synchronization of optical lasers to the RF timing reference.

RF TIMING DISTRIBUTION

The schematic of timing distribution system is shown in Fig. 1. The timing distribution is based on 476 MHz reference, which is locked to 10 MHz Rubidium and OCXO for the frequency stability and the phase noise improvement in low offset frequency at 1 and 10 Hz. The 476 MHz reference signal is distributed to 16 locations over 1.5 Km distance including soft X-ray branch using a low loss cable. At each location, 476 MHz signal is converted to 2.856 GHz signal using a low phase noise DRO and phase-locked loop, which is developed by RUPP-tronik. One 2.856 GHz phase-locked DRO signal is amplified and is split to drive up to six LLRFs and additional diagnostic systems such as BAM and DCM. This end S-band distribution is done by low temperature coefficient cable in phase (LCF38-50J). Its temperature coefficient is measured as 7 fs/mK at 30ºC. The phase drift of the maximum 50 m length cable with the temperature stability of 0.1 ºC is estimated to 35 fs, which is considered small.

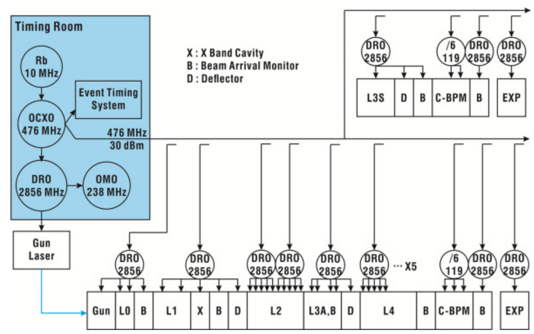

Figure 1: Schematic of timing distribution system in PAL-XFEL.

The phase noise spectrum of 2.856 GHz, which is our S-band frequency, is shown in Fig. 2. The bumps in the spectrum at 30 Hz and 30 KHz is correspond PLL between 10 MHz and 476 MHz, and between 476 MHz and 2.856 GHz DRO respectively. The integrated phase noise of the S-band is measured as small as ≈1 fs from 1 KHz to 10 MHz offset. The differential phase noise from PLL of DRO is also estimated to ≈1 fs from 1 Hz to 1 MHz offset.

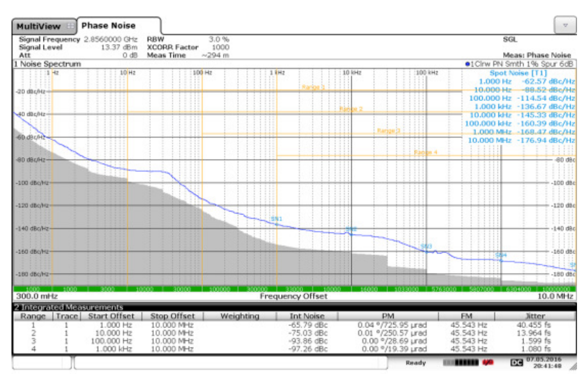

Figure 2: Phase noise spectrum of 2.856 GHz.

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PASSIVE STABILIZATION OF TIMING DISTRIBUTION AND TIMEING DRIFT MONITORING

476MHz reference signal start from a timing room near injector laser room. It goes through klystron-modulator gallery and finally gets to experimental laser room. In the gallery, each taped signal is converted to our S-band by PLDRO. Vibration resistant hard corrugated copper cable is used for both 476 MHz and 2.856GHz signal transport. LCF38-50J cable for 2.856 GHz provides low timing drift but 1-5/8" cable for 476 MHz gives low power loss and relatively high drift with temperature variation (≈130 fs/mK). Figure 3 shows schematics of temperature stabilization of duct using water. The stability of water temperature is 29±0.1 ºC. The rack temperature for the PLDRO is also stabilized to 26±0.1 ºC.

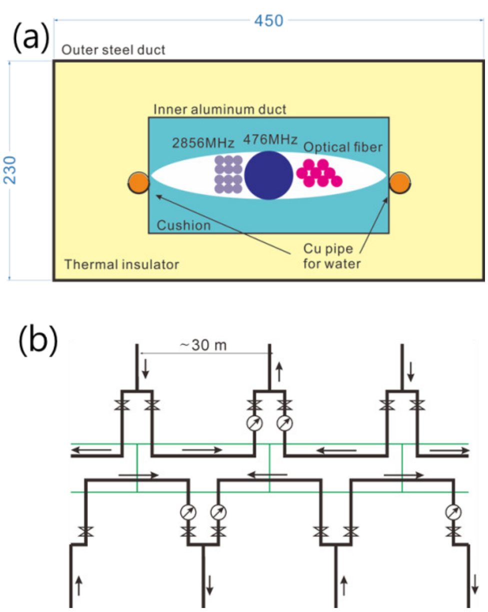

Figure 3: Temperature stabilization system for cables. Schematic of (a) cable duct and (b) LCW flow.

The long term phase drift between adjacent PLDRO outputs is monitored using LLRF systems and is depicted in Fig. 4. The crossed measurement can remove the contribution from the monitoring cable and gives drift results between splitter outputs of adjacent PLDROs.

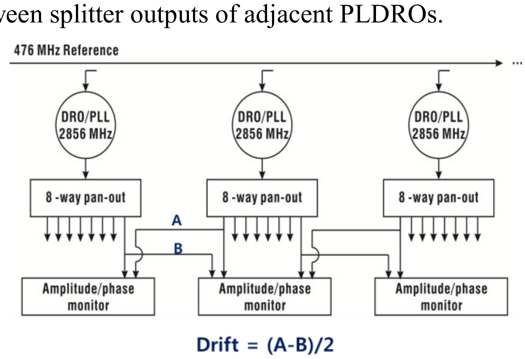

Figure 4: Schematic of phase drift monitoring.

Figure 5 shows the measurement results of temperature drift of ducts and relative phase drift at each location for a week. The total length of linac is ≈750 m and the distance between adjacent PLDROs is 50~100 m. In the linac, the drift between the first station at L002 and the last station at L425 is shown as drift sum in Fig. 5(b). The total timing drift of the linac shows less than 1 ps pk-to-pk stability for one week. The sharp peak is considered as systematic error. It could be happened by opening of the rack door and it induces the change of rack temperature of L002 by ≈1 ºC. The duct temperature is well maintained within 0.1 ºC. The data shows that the rise of the temperature of ≈0.05 ºC gives the additional phase delay of ≈0.2º. The magnitude of drift sum gives similar value of the adjacent drift, which means that the temperatures are uncorrelated.

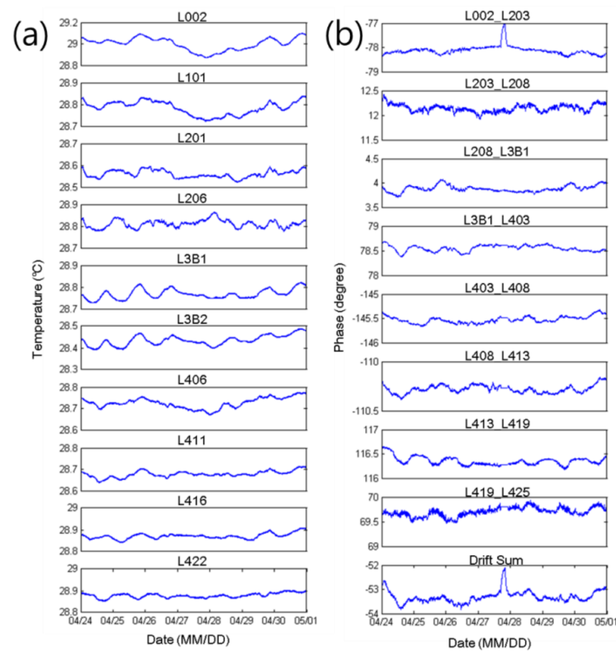

Figure 5: Monitored (a) temperature variation of ducts and (b) phase drift between adjacent PLDRO stations.

SYNCHRONIZATION OF OPTICAL LASER TO RF REFERENCE

The optical oscillator (Ti:sapphire laser) in an injector laser system is synchronized to 2.856 GHz RF signal as shown in Fig. 1. The balanced phase detector between optical pulses and S-band RF is built using Sagnac interferometer [1], in which optical group delay inside the interferometer is modulated by RF and the phase relationship is sensitively detected. The schematic is shown in Fig.6. To get linear phase information from the quadratic nature of Sagnac interferometer, additional modulation and demodulation scheme at a few hundred MHz is implemented. The derivative of the quadratic signal has a linear relationship with phase. For the higher sensitivity, the phase detector is operated in the saturated regime.

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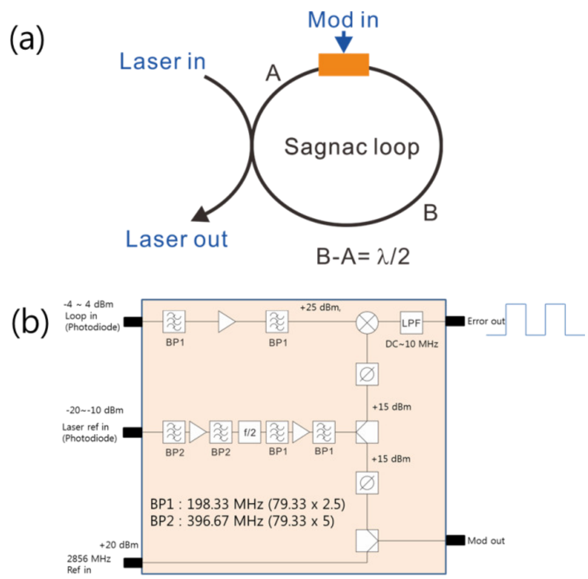

Figure 6: Schematic of balanced optical-microwave phase detector.

The out-of-loop measurement result of the phase noise between Ti:sapphire laser and a free-running 2.856 GHz DRO is shown in Fig. 7. The integrated relative phase jitter from 1 Hz to 100 KHz offset frequency is estimated to ≈14 fs.

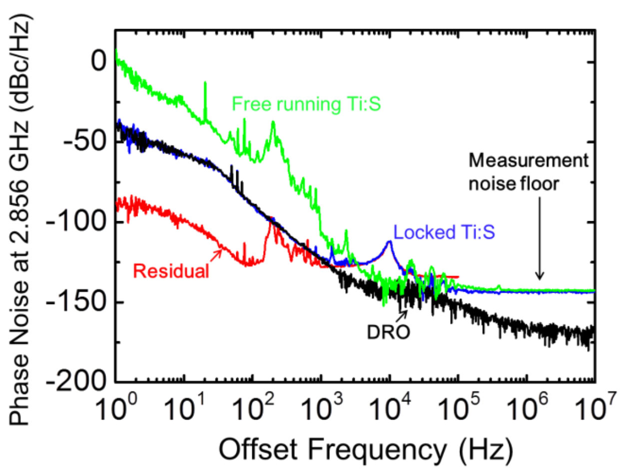

Figure 7: Phase noise measurement result of phase-locking of Ti:sapphire laser and S-band RF.

SUMMARY

The RF timing distribution system and the laser synchronization system in PAL-XFEL are commissioned. Jitter is estimated to ≈ 1fs in RF timing distribution and ≈14 fs in the laser synchronization. The timing drift is measured in 750 m long linac and is estimated to less than 1 ps. In future, drift compensation will be added for the upgrade.

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REFERENCE

[1] K. Jung et al, "Remote laser-microwave synchronization over kilometer-scale fiber link with few-femtosecond drift," J. Lightw. Tech. **32**, 3742 (2014)