ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP031

TIMING SYNCHRONIZATION ACTIVITIES FOR DRIFT-FREE OPERATION OF ULTRAFAST ELECTRON DIFFRACTION SYSTEM AT KAERI

J. Shin, J. Kim†, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea,
I. H. Baek, H. W. Kim, K. Y. Oang, S. Park, Y. U. Jeong, Korea Atomic Energy Research Institute, Daejeon, Republic of Korea

Abstract

Precise timing synchronization of an ultrafast electron diffraction facility is essential requirement for femtosecond resolution structure analysis. Recent studies of THz-based electron deflectors have enabled the timing drift measurement between ultrafast electrons and an optical pump beam with few femtosecond resolution. In this work, we will introduce timing synchronization activities to suppress the drift of an electron beam. As timing drift of the electron beam originates from every sub-element, each timing drift contribution from RF transfer, RF-to-optical synchronization, and optical amplification is measured. Timing drift of RF transfer through coaxial cable, which exposed to temperature fluctuation, is actively stabilized from 2 ps to 50 fs by active feedback loop. Further additive drift from RF-to-optical synchronization is maintained below 100 fs. Also optical drift due to the regenerative amplifier, measured by optical correlator, is maintained below 20 fs over an hour. This work allows ultrafast electron diffraction system to operate with less drift correction procedure and increased user availability.

INTRODUCTION

Ultrafast electron diffraction allows time-resolved structure analysis at atomic scale [1,2], which enables many potential applications on material science. Note that ultrafast electron offers unique opportunities as a matter, and it takes complementary role with light-based method such as free electron lasers. To further pave the way for ultrafast electron diffraction, it is of importance to optimize the temporal stability of electron sources. High temporal stability of electron sources will flourish not only ultrafast electron diffraction, but also ultrafast electron microscopy [3], and free electron lasers [4]. To generate low noise ultrafast electrons with MeV energy, DC photoguns and RF photoguns could be utilized. DC photogun itself is inherently synchronized with optical gating pulses, while further accelerating stages should be managed properly [5]. RF photogun could provide MeV energy electrons without further acceleration stages due to its intrinsically high electric field strength. Unfortunately, synchronizing RF field with injected optical pulses train could be a challenge [6]. With the recent advancement of THz-driven streak camera [7], jitter-free operation of RF photogun is enabled by optimizing laser injection phase. To fully exploit the jitter-free ultrafast electron sources, suppressing timing drift and maintaining performance over long time are essential. In this paper, we optimize the timing drift of the ultrafast electron diffraction facility in KAERI, which already achieved jitter-free condition with a RF photogun. To stabilize the timing drift of entire system, all timing contribution from subsystems are investigated. Subsystems are classified into RF distribution, RF-to-optical synchronization, and optical amplification as depicted in Fig. 1. Optimization of each subsystem is described in following sections.

†jungwon.kim@kaist.ac.kr

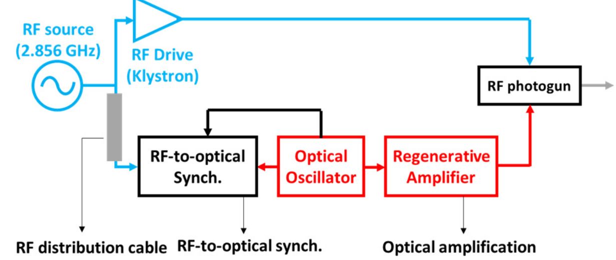

Figure 1: Subsystems contributing timing drift of electron pulses.

RF DISTRIBUTION

To distribute RF carrier from RF oscillator to laser, coaxial cable is installed across the facility. Due to the distance between two locations, cable length of 30 m is required. Note that longer length of coaxial cable is more vulnerable to thermal fluctuation. To mitigate the impact of thermal fluctuation, many previous researches such as stabilizing the cable temperature and measuring thermal sensitivity of cable are reported [4]. In our system, SUCOFLEX404 (H&S) cable is installed for high stability against temperature. Furthermore, active drift compensation system is introduced as shown in Fig. 2. The proposed scheme compares phase between original RF signal and round-trip signal, which reflected from the end of coaxial cable. Detected phase error is feedback controlled by voltage-controlled phase shifter.

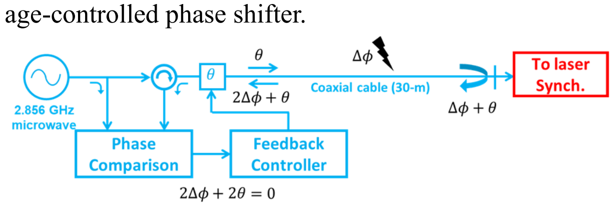

Figure 2: Active drift compensation scheme for the 30-m coaxial cable.

Timing drift of the coaxial cable is stabilized for 60,000 s and recorded with 10 s sampling time. All of stabilization performance, compensated drift amount, and temperature change of cable are recorded and plotted in Fig. 3. Note

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP031

that compensated drift amount implies the timing performance without feedback control. The compensated drift shows close relation with temperature. Sharp temperature change near 42,000 s is due to warming up of the entire facility. Large phase shift due to temperature change is about 2 ps. After active stabilization, timing is stabilized in sub-100 fs even under drastic temperature change.

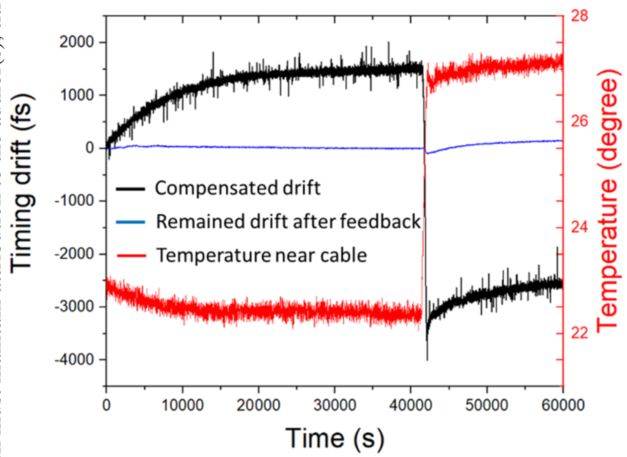

Figure 3: Measurement result of timing drift at coaxial cable after active stabilization.

RF-TO-OPTICAL SYNCHRONIZATION

Synchronization between the optical pulse train and RF carrier has been actively researched over decades. Traditional approach utilizes photodiodes and frequency mixers to compare phase in electrical domain. To overcome the unwanted nonlinearities of mixers and photodiodes, phase detection by electro optic sampling method is actively researched [8]. Electro-optic sampling method is based on the optical interferometer and an electro-optic phase modulator for high precision. In our system, fiber Sagnac loop based interferometer is implemented for RF-to-optical synchronization as shown in Fig. 4. Repetition rate of optical oscillator is 79.3 MHz, and its 36th harmonic is 2.856 GHz. Note that 2.856 GHz is also the operating frequency of RF oscillator. Phase-locked loop is established via modulating repetition rate of optical oscillator.

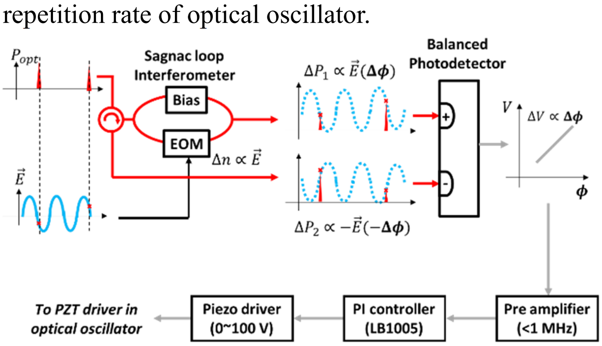

Figure 4: Schematic of fiber Sagnac loop based RF-to-optical phase synchronization. EOM : electro-optic modulator.

To verify the performance of the phase locked loop, additional out-of-loop performance is measured with a secondary phase detector. The measured phase noise by a in-loop phase detector only represents loop performance, while the resolution of the phase detector is not observed. Both in-loop and out-of-loop phase noise are plotted in Fig. 5. In-loop and out-of-loop phase noise follows closely from 100 Hz to 100 kHz offset frequency range. Below 100 Hz offset frequency shows difference due to resolution of the phase detectors. As feedback bandwidth is limited to 2 kHz due to finite bandwidth of the laser actuator, phase noise of the optical oscillator above 2 kHz is not suppressed. This could be mitigated by improvement of the optical oscillator and optimization of the feedback loop with a lead compensator. Integrated timing jitter from 100 kHz to 1 Hz is 17.9 fs (23.14 fs) at in-loop (out-of-loop).

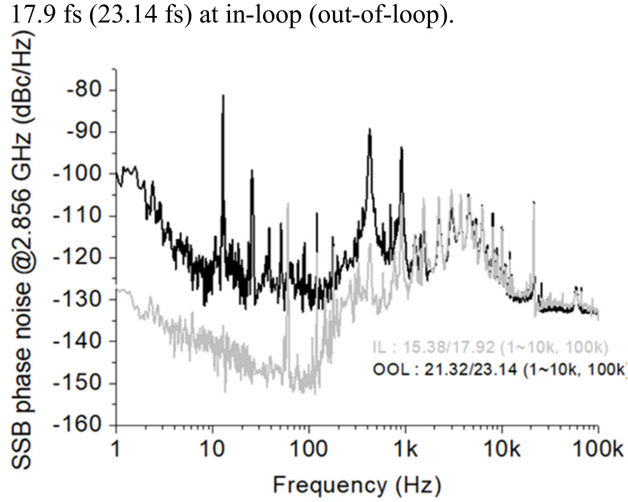

Figure 5: Measured relative phase noise between RF and optical pulse train after synchronization. IL : in-loop, OOL : out-of-loop.

OPTICAL AMPLIFICATION

For optical amplification, a regenerative optical amplifier which operates up to 1 kHz repetition rate is installed. As optical pulses travel repeatedly in the amplifier to build up pulse energy, timing jitter of the regenerative amplifier could be affected by thermal fluctuation. To measure the timing drift between the optical oscillator and the regenerative amplifier, optical correlation method [9] based on second harmonic generation is applied as shown in Fig. 6. By controlling the temporal overlap between optical pulses, second harmonic optical power will be proportional to timing fluctuation.

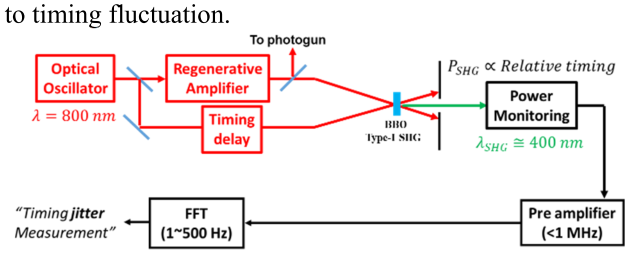

Figure 6: Schematic of optical correlation method to measure timing jitter of the regenerative amplifier. FFT : Fourier Frequency Transform.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP031

Measured timing jitter by optical correlation method and background noise due to instrument is plotted in Fig. 7. Both the background noise and measured timing jitter show strong electrical noise at 60 Hz. The electrical instability is due to the high gain (>1000) applied on baseband. The used photodetector has 100 MHz bandwidth. Note that huge discrepancy between detector bandwidth (100 MHz) and pulse repetition rate (1 kHz) requires very high electrical gain to make signal observable. Regenerative amplifier shows strong fluctuation near 80 Hz. As a future work, measurement of timing drift and improvement of resolution is required.

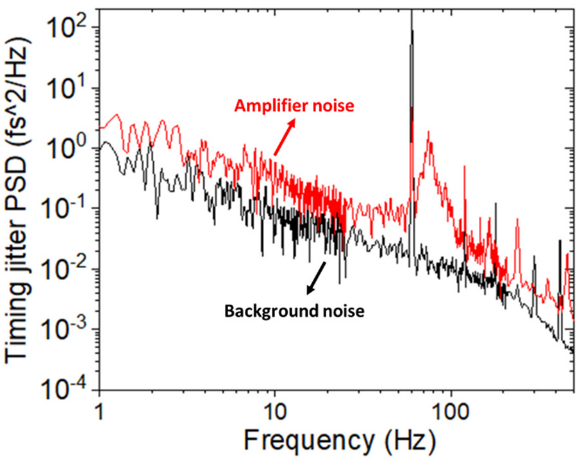

Figure 7: Measured relative timing jitter of optical regenerative amplifier with respect to optical oscillator.

CONCLUSION

In this work, we have implemented timing systems to optimize long-term temporal drift at ultrafast electron diffraction facility in KAERI. To further enhance the long term stability of the electron beam, timing drift of RF signal after Klystron should be handled. Note that optimization of RF drive is within the reach of current technology such as low level RF. This work will could be a foot step to operate the jitter-free ultrafast electron sources over very long time scale. As future work, timing drift of ultrafast electron pulses will be examined by THz-driven streak camera.

REFERENCES

[1] G. Sciaini, and R. J. Dwayne Miller, "Femtosecond electron diffraction: Heralding the era of atomically resolved dynamics," *Rep. Prog. Phys.*, vol. 74, no. 9, p. 096101, 2011. doi:10.1088/0034-4885/74/9/096101

[2] S. P. Weathersby *et al.*, "Mega-electron-volt ultrafast electron diffraction at SLAC National Accelerator Laboratory," *Rev. Sci. Instrum.*, vol. 86, p. 073702, 2015. doi:10.1063/1.4926994

[3] D. J. Flannigan, and A. H. Zewail, "4D Electron Microscopy: Principles and Applications," *Acc. Chem. Res.*, vol. 45, no. 10, p. 1828, 2012. doi:10.1021/ar3001684

[4] Chang-Ki Min *et al.*, "RF Timing Distribution and Laser Synchronization Commissioning of PAL-XFEL," in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 4234-4236, doi: 10.18429/JACoW-IPAC2016-THPOY057

[5] D. Zhang *et al.*, "Segmented terahertz electron accelerator and manipulator (STEAM)," *Nat. Photonics,* vol. 12, pp. 336-342, 2018. doi:10.1038/s41566-018-0138-z

[6] M. R. Otto, L. P. Rene de Cotret, M. J. Stern, and B. J. Siwick, "Solving the Jitter Problem in Microwave Compressed Ultrafast Electron Diffraction Instruments: Robust Sub-50 fs Cavity-Laser Phase Stabilization," *Struct. Dyn.*, vol. 4, p. 051101, 2017. doi:10.1063/1.4989960

[7] J. Fabianska, G. Kassier, and T. Feurer, "Split ring resonator based THz-driven electron streak camera featuring femtosecond resolution," *Sci. Rep.*, vol. 4, p. 5645, 2014. doi:10.1038/srep05645

[8] H. Yang, B. Han, J. Shin, D. Hou, H. Chung, I. H. Baek, Y. U. Jeong, and J. Kim, "10-fs-level synchronization of photocathode laser with RF-oscillator for ultrafast electron and X-ray sources," *Sci. Rep.*, vol. 7, p. 39966, 2017. doi:10.1038/srep39966

[9] A. Casanova, Q. D'Acremont, G. Santarelli, S. Dilhaire, and A. Courjaud, "Ultrafast amplifier additive timing jitter characterization and control," *Opt. Lett.*, vol. 41, p. 898, 2016. doi:10.1364/OL.41.000898

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI