FEMTOSECOND SYNCHRONIZATION OF LARGE-SCALE X-RAY FREE-ELECTRON LASERS

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Abstract

Future X-ray free-electron lasers (FELs) require femtosecond timing accuracy between electron beams and optical lasers for improved FEL performance and to study the spatiotemporal dynamics of ultrafast processes. We present a set of new ultrafast optical techniques for long-term stable femtosecond synchronization of large-scale X-ray FELs. We use low-noise optical pulse trains generated from mode-locked lasers as timing signals, and distribute them via timing-stabilized fiber links to end-stations where tight synchronization is required. At the end-stations, optical and RF sub-systems are synchronized with the delivered timing signals. Using these techniques, we demonstrate that remotely located lasers and microwave sources can be synchronized with femtosecond accuracy over typical operating periods of FELs. We experimentally demonstrate synchronization of lasers and RF sources over 300 m long fiber links with sub-10 fs precision over more than 10 hours.

INTRODUCTION

Linear accelerator-driven X-ray free-electron lasers (FELs) have the potential to realize the dream of more brilliant, shorter, and better controlled X-ray pulses. However, the measurement capabilities of FELs are currently limited to about 100 fs by the timing stability of the electron beams and the synchronization capabilities between the electron beams and the optical lasers. Conventional microwave timing synchronization, which is based on coaxial cables, has difficulties in achieving even picoseconds long-term stability as a result of the large timing drifts over the extent of a FEL [1]. As a remedy for this timing problem, it has been shown that the post-processing of X-ray pulse arrival time can be used to reduce the timing uncertainty to the ~60 fs level [2]. However, in order to generate and manipulate X-ray pulses on the fs and sub-fs time scale, future X-ray FELs require a more active solution to the timing problem by achieving a much higher level of synchronization and control of electron beams and optical lasers.

The electron bunch arrival time at the entrance to the undulator must be controlled much tighter than the bunch duration. With such stable electron bunches, ultrashort pulse lasers can be used for targeted electron beam manipulation, such as slicing with near-infrared few-cycle pulses [3] or seeding with ultraviolet HHG [4]. When the slicing or seeding lasers are tightly synchronized with pump-probe lasers, much higher precision X-ray/optical pump-probe experiments are possible. All of these requirements can be met if the critical microwave and optical sub-systems are synchronized with drift-free sub-10 fs accuracy. Pervasive synchronization of the entire FEL facility to a master oscillator is the most promising approach to achieve this level of accuracy. These demanding synchronization requirements recently triggered the pursuit of optical techniques for covering large-scale FELs [5,6].

In this paper, we report on the demonstration of a set of techniques that will enable the synchronization of large-scale X-ray FELs with sub-10 fs accuracy over long continuous operating periods of more than 10 hours.

SCHEMATIC LAYOUT OF SYNCHRONIZATION SYSTEM

Figure 1 shows the schematic layout of the timing synchronization system we envision for advanced large-scale X-ray FELs. First, an ultralow jitter and long-term stable optical pulse train is generated from a mode-locked laser. By tightly locking the mode-locked laser to a microwave standard (RF-to-optical synchronization), this laser serves as the optical master oscillator. The optical pulse train will be distributed to all critical microwave and optical sub-systems. To distribute the optical pulse train, we use dispersion-compensated and timing-stabilized optical fiber links. Optical-to-optical synchronization enables the synchronization of remotely located mode-locked lasers (photo-cathode laser, seeding/slicing laser, and pump-probe laser) with the delivered timing pulse train. Optical-to-RF synchronization synthesizes a low-noise microwave signal. By using the resulting well-synchronized microwave signal for driving the pre-accelerator, in combination with beam diagnostics and control, stable electron bunch arrival timing at the undulator input can be achieved.

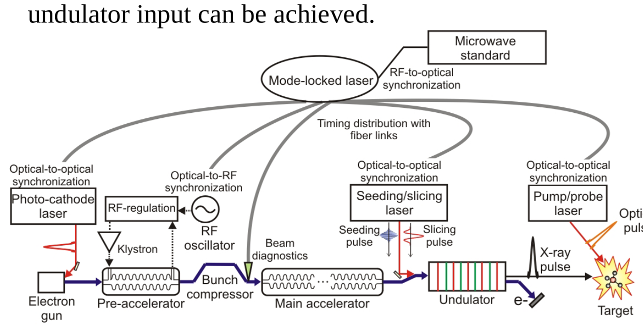

Figure 1: Schematic outline of timing distribution and synchronization for a large-scale XFEL facility.

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LOW-JITTER MODE-LOCKED LASER

It has been long recognized that mode-locked lasers have an enormous potential for generating optical and microwave signals with ultra-low timing jitter [7]. Progress in high repetition rate and low-jitter Erbium-fiber mode-locked lasers has enabled optical pulse trains with ~100 fs pulsewidth and higher than 200 MHz repetition rate at 1550 nm [8]. Recent high-resolution timing jitter characterization [9] has confirmed that the high-frequency timing jitter is less than 1 fs and 5 fs in the 100 kHz – 10 MHz and 10 kHz – 10 MHz ranges, respectively. Figure 2 shows the measured timing jitter spectrum and the corresponding integrated timing jitter of a commercial 200-MHz Er-fiber laser (M-Comb-Custom from MenloSystems GmbH). The optical master oscillator is now commercially available, and can feed several timing links with the use of Er-fiber amplifiers.

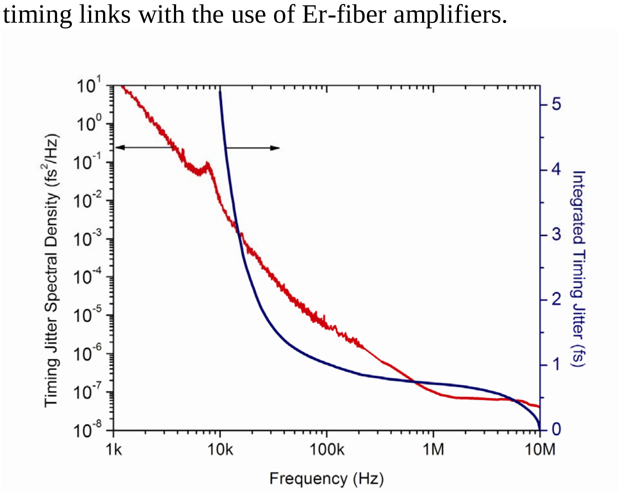

Figure 2: Timing jitter spectral density and the corresponding integrated timing jitter of a free-running Er-fiber laser (M-Comb-Custom, MenloSystems GmbH).

TIMING DISTRIBUTION

The use of optical signals as a means for timing delivery in an accelerator environment has many advantages compared to conventional temperature-stabilized coaxial cables, such as better robustness against electromagnetic interference (EMI), ease of installation, and space efficiency. Furthermore, compared to other optical techniques like continuous-wave transmission [6], the use of pulse trains enables direct stabilization of the group-delay of the fiber link and strong suppression of Brillouin scattering and residual reflections. It also adds more flexibility in the operation and diagnostics of FELs by using the delivered ultralow-jitter pulse trains for direct seeding of optical amplifiers or down-conversion of microwave signals.

However, acoustic noise and thermal drift can cause excessive timing noise in the fiber links. The typical coefficient of thermal expansion for standard single-mode fiber is ~10^{-5}/K. For a 400-metre long fiber link in an accelerator environment, this led to a drift in the fiber group delay of up to 40 ps in 12 hours [10]. To compensate for this timing drift, a fiber length correction feedback loop is employed. One can detect the timing error introduced to the link by comparing a pulse reflected back from the end of fiber link with a fresh pulse directly from the laser.

We used a single-crystal balanced cross-correlator [11] for the timing error detection and long-term stable timing link stabilization. Two 300-meter long, independently stabilized fiber links are constructed, and the two outputs from these links are compared with an out-of-loop cross-correlator. The measurement shows a sub-fs short-term (1 Hz-100 kHz) jitter and a sub-7 fs long-term drift over 72 hours. More detailed information on the experiments and results will be presented in Ref. 12 in the near future.

OPTICAL-TO-OPTICAL SYNCHRONIZATION

Once the optical pulse train – unperturbed in transmission via the stabilized fiber link – arrives at the intended end-stations, the optical or RF sub-system must be tightly synchronized with this pulse train. In FEL facilities, the photo-cathode laser should first be synchronized to emit well-timed electron bunches from the electron gun. Then the timing of the seeding/slicing laser should be tightly locked to the electron bunch entering the undulator to enable the manipulation of a fraction of the electron bunch at a well defined time. Finally, the seeding/slicing lasers and the pump-probe lasers, separated by more than 100 meters, should be synchronized for high-precision pump-probe experiments between X-ray pulses and optical pulses. To meet all these requirements, each mode-locked laser needs to be synchronized with the delivered pulse trains with sub-femtosecond accuracy, over multiple days of operation.

For this, one can use balanced optical cross-correlation [11, 13]. This technique uses nonlinear optic processes (such as sum-frequency generation or second-harmonic generation) as a means for highly sensitive timing detection. It also has an additional advantage of operating at the point where intensity noise is cancelled, which enables long-term stable operation. We demonstrated optical-to-optical synchronization using two independent mode-locked lasers with sub-fs jitter maintained more than 12 hours [12].

OPTICAL-TO-RF AND RF-TO-OPTICAL SYNCHRONIZATION

Tight synchronization is necessary not only for the ultrafast lasers in the FEL, but also for the RF sources driving the accelerator sections. The electron beam dynamics is controlled by the microwave fields in the accelerator cavities. Therefore, highly stable microwave signals, tightly synchronized with each other in different accelerator sections, are an indispensable prerequisite for the control of electron beams with higher timing accuracy. High-quality RF signals can be extracted from the optical pulse trains delivered by timing-stabilized fiber links. However, the extraction of drift-free RF signals, which is tightly locked with the pulse trains, is a highly nontrivial task. Excess noise in the photodetection processes [14] seriously compromises the achievable timing stability of RF-signals. On the other hand, tight synchronization of a mode-locked laser to a microwave frequency standard (in Fig. 1) is also necessary for the optical master oscillator.

To address these issues, we employed an optoelectronic phase-locked loop (PLL) as shown in Figure 3. The detection of timing error between the pulse train and the RF signal is performed by a balanced optical-microwave phase detector (BOM-PD) [15]. This device is based on a differentially-biased Sagnac-loop interferometer for sensitive timing detection with electro-optic sampling. This PLL can be operated either by using an optical pulse train as a reference and a voltage-controlled oscillator (VCO) as a slave oscillator (optical-to-RF synchronization) or by using a RF signal as a reference and a mode-locked laser as a slave oscillator (RF-to-optical synchronization).

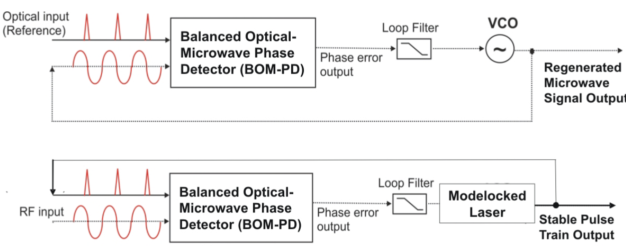

Figure 3: Schematic of optical-to-RF and RF-to-optical synchronization using a balanced optical-microwave phase detector (BOM-PD).

By use of the BOM-PDs, we have synchronized a 10.225-GHz VCO to a 200.5-MHz optical pulse train from an Er-fiber mode-locked laser. The measured short-term jitter is ~5 fs (1 Hz – 1 MHz), and the long-term stability is below 7 fs rms jitter integrated over 10 hours [12]. Most of the short-term jitter is concentrated in a high-frequency range (100 kHz – 1 MHz) due to the free-running noise of the VCO and the limited locking bandwidth. Note that this high-frequency jitter is often not a concern if high-quality microwave cavities, such as superconducting cavities, are used for the electron acceleration and beam control. The effective closed-loop bandwidth of such cavities is typically less than 100 kHz. Thus, the impact of the high-frequency timing jitter on the electron beam is further reduced by the cavity filtering.

When all necessary components and sub-systems are well synchronized, the final issue is to measure precisely, and monitor, the achieved stability at critical points. For example, the electron beam stability at the bunch compressor and the phase stability of the microwave fields driving the accelerator structures must be continuously monitored. Due to the availability of ultralow-jitter pulse trains at many positions in the facility, our demonstrated techniques can be also used for these diagnostic tools (represented by beam diagnostics in Fig. 1). For example, an electron bunch arrival time monitor [16] can be implemented based on electro-optic sampling. The down-conversion of microwave signals in the GHz range using BOM-PDs can be used to verify synchronism with the pulse trains at various points in the accelerator.

CONCLUSION AND OUTLOOK

In summary, we introduced a long-term stable femtosecond timing distribution and synchronization system for future accelerator and XFEL facilities. The key components and technologies, i.e., low-jitter optical master oscillator, timing distribution by stabilized fiber links, and long-term stable optical-to-RF and optical-to-optical synchronization modules, are demonstrated. Today, 10-fs jitter level synchronization over several hundreds of meters is possible. Due to the scalable nature of this approach, we expect that engineering improvements of these techniques will further improve the timing accuracy to the sub-fs regime.

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