Progress in Large Scale, Longterm Stable Timing Distribution and Synchronization

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Abstract

We review a scalable, sub-10-fs precision timing distribution system for next generation accelerator and light source facilities and discuss its extension to sub-femtosecond performance using polarization maintaining dispersion compensated fiber links and integrated waveguide cross-correlators.

I. INTRODUCTION

X-ray free-electron lasers (FELs) are poised to realize the dream of solving structure and function of biomolecules on a femtosecond time scale using shorter, more brilliant and ever better controlled X-ray pulses. However, for a long time the temporal measurement capabilities of FELs have been limited to about 50-100 fs by the timing stability of electron beams and rf-distribution and synchronization with optical lasers. Conventional microwave timing synchronization, which is based on coaxial cables, has difficulties in achieving even picosecond 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 measurement of X-ray pulse and optical pulse arrival time can be used to reduce the timing uncertainty to the ~6 fs level using post-processing [2]. However, in order to generate and manipulate X-ray pulses on the fs and in the future even sub-fs time scale, future X-ray FELs require an active solution to the timing problem by achieving a much higher level of synchronization and control of electron beams and optical subsystems often used for electron beam diagnostics and control itself.

For seeded FELs, 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 echo enhanced high harmonic generation [3] or seeding with ultraviolet HHG [4]. When e-beam modulation or seeding lasers are tightly synchronized with the pump-probe lasers, X-ray/optical pump-probe experiments can be carried out with that precision in synchronization. All of these requirements can be met if the critical microwave and optical sub-systems are synchronized with drift-free sub-10 fs or even sub-femtosecond accuracy. Pervasive synchronization of the entire FEL facility to a master oscillator is the most promising approach to achieve this level of accuracy and improve FEL performance in general. These demanding synchronization requirements recently triggered the pursuit of optical techniques for large-scale FEL timing and synchronization [5,6].

In this talk, we review a comprehensive set of techniques developed to enable timing and synchronization of large-scale X-ray FELs with sub-10 fs precision. Such systems are now in operation at FLASH in Hamburg, Germany, FERMI in Trieste, Italy and are under implementation at the European XFEL in Hamburg, LCLS in Stanford, USA and PAL in Pohang, Korea. Furthermore key components that allow longterm stable performance of these systems, eventually reaching sub-femtosecond performance, are demonstrated.

II. TIMING SYSTEM SCHEMATIC

Figure 1 shows the schematic layout of the pulsed timing and synchronization system for advanced large-scale X-ray FELs. 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 the master microwave oscillator (RMO) (optical-to-RF synchronization), this laser serves as the optical master oscillator (OMO) of the facility.[7] The optical pulse train from this laser will be distributed to all critical microwave and optical sub-systems via dispersion-compensated and timing-stabilized optical fiber links. [7] Optical-to-optical synchronization via balanced optical cross-correlators (BOC) enables precision timing of remotely located mode-locked lasers (photo-cathode laser, modulating/seeding laser, and pump-probe laser) via the delivered timing pulse train. [7]

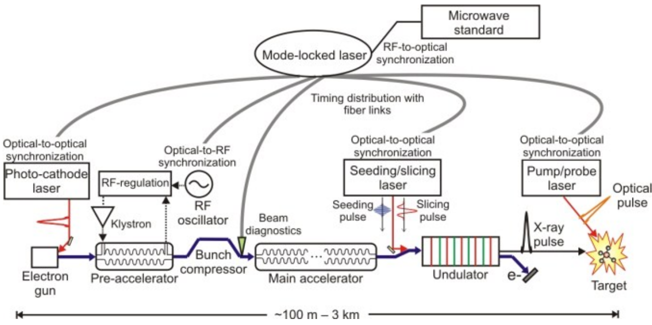

Figure 1: Schematic outline of timing distribution and synchronization for a large-scale X-ray FEL facilities. [7]

The delivered optical pulse train itself can directly seed amplifiers or is used for diagnostic purposes, i.e. arrival time monitors [8]. Optical-to-RF conversion at the link output with a balanced optical microwave phase detector results in ultralow jitter (sub-10 fs) microwave signals, which completes the synchronization task list [7].

III. PROGRESS TOWARDS SUB-FEMTOSECOND PRECISION

The above described system using standard single-mode fiber (SMF) for the fiber links enables stable sub-10-fs timing distribution [7] and as discussed above, several of these systems have been implemented in FEL facilities around the world. As demonstrated by Kim et al., BOCs can be used to characterize the timing jitter of mode locked lasers with attosecond precision. We used this technique to characterize the jitter of two identical, commercially-available femtosecond lasers (OneFive-ORIGAMI) and confirmed that their high-frequency jitter for frequencies higher than 1 kHz is less than 70 as. These lasers therefore have sufficiently low noise to serve as OMOs for sub-fs timing distribution systems. Also Kim et al., have demonstrated femtosecond fiber laser sources with similar jitter levels [9].

Second, to eliminate slow drifts in the fiber links induced by polarization mode dispersion, we implemented with the help of OFS a 1.2-km polarization-maintaining fiber link using 1 km of standard PM fiber and 0.2 km of novel dispersion-compensating PM fiber. Link operation for 16 days showed only 0.9 fs RMS timing drift and during a 3-day interval only 0.2 fs drift, Fig. 2 (a), which is overall at least an order of magnitude better than what has been demonstrated previously with SMF links.

Lastly, we present a hybrid integrated BOC (fabricated by AdvR) using PPKTP waveguides [10], Fig. 3 (a) shows the experimental setup and (b) the measured and partially rescaled cross-correlation trace, since the device was not yet fiber coupling and therefore, one arm of the BOC had increased coupling losses. The sensitivity of the fiber coupled device is 10-100 times larger than its bulk counterpart.

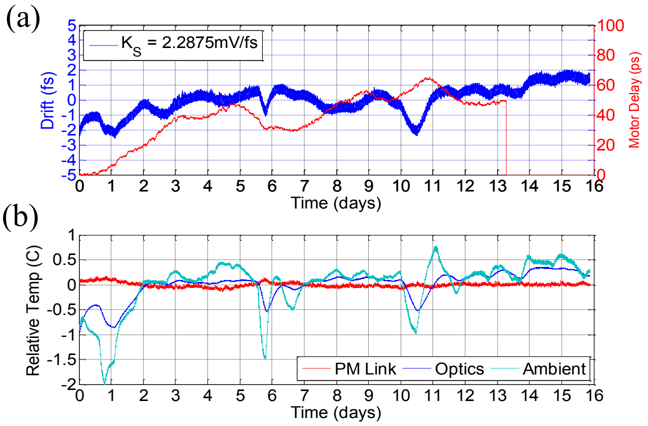

Figure 2. (a) Long-term timing drift measurements of a 1.2 km PM-fiber link over 16 days of uninterrupted operation; includes out-of-loop drift (as measured by the BOC), and motor translation stage position. (b) Corresponding long-term temperature drift measurements; includes internal temperatures of the PM link and free-space optics enclosures and the external ambient temperature.

In general, we seek to remove all long-term drift issues by eliminating alignment drifts in free-space BOCs by replacing them with integrated devices. The much reduced required optical power by a factor of 10-100 while achieving similar signal-to-noise levels as those from bulk-crystal BOCs enables also a low power and fully fiber coupled distribution of the power to the different fiber links. With further development of these components a completely fiber-coupled, sub-fs optical timing distribution system seems feasible.

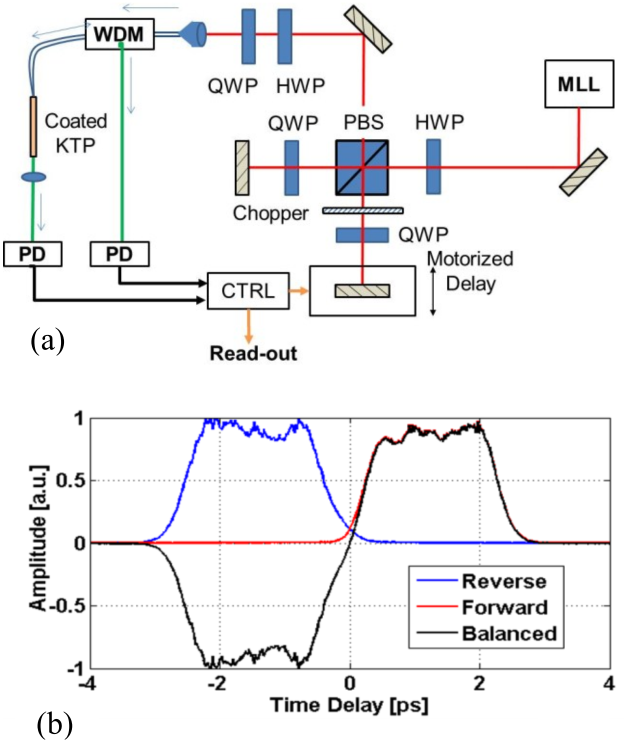

Fig. 3: (a) Experimental setup for cross-correlation measurements. Abbreviations are as follows: MLL – mode-locked laser, HWP – half-waveplate, QWP – quarter-waveplate, PBS – polarization beam-splitter, COLL – collimator, WDM – wavelength division multiplexer, PD – photodiode, CTRL – controller. (b) Correlation traces for the forward path(red), reverse path (blue) and balanced output (black).

REFERENCES

[1] A. Cho, "Breakthrough of the year", Science 388, 1530 (2012).

[2] M. Hamand et al., “Achieving few-femtosecond time-sorting at hard X-ray free-electron lasers”, Nature Photonics 7, 215 (2013).

[3] Stupakov, G., “Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation.” Phys. Rev. Lett. 102, 074801 (2009) and Phys. Rev. Lett. 105, 114801 (2010).

[4] G. Lambert et al, Nature Phys. 4, 296 (2008).

[5] J. Kim et al, “Large-scale timing distribution and rf-synchronization for FEL facilities,” FEL ’04, Trieste, Italy, September 2004.

[6] R. B. Wilcox and J. W. Staples, “Systems design concepts for optical synchronization in accelerators,” PAC ’07, Albuquerque, New Mexico, USA, June 2007.

[7] J. Kim J. Cox, J. Chen, and F. X. Kärtner, “Drift-free femtosecond timing synchronization of remote optical and microwave sources,” Nature Photonics 2, 733 (2008).

[8] F. Löhl et al., “Electron Bunch Timing with Femtosecond Precision in a Superconducting Free-Electron Laser,” Phys. Rev. Lett. 104, 144801 (2010).

[9] T. K. Kim et al., „Sub-100-as timing jitter optical pulse trains from mode-locked Er-fiber lasers,“ Opt. Lett. 36, 4443 (2011).

[10] A. Nejadmalayeri et al., “Guided wave optics in periodically poled KTP,” Opt. Lett., 34, 2522 (2009).