ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPRB018

LARGE-SCALE OPTICAL SYNCHRONIZATION SYSTEM OF THE EUROPEAN XFEL WITH FEMTOSECOND PRECISION

T. Lamb†, M. K. Czwalinna, M. Felber, C. Gerth, T. Kozak, J. Müller,
H. Schlarb, S. Schulz, C. Sydlo, M. Titberidze, F. Zummack
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

Femtosecond pulsed optical synchronization systems have evolved over the last few years and are now a mature technique to synchronize FELs. A large-scale femtosecond-precision synchronization system with up to 44 end-stations has been constructed at the European XFEL to meet the FEL synchronization stability requirements. The synchronization system is used to phase-lock various laser systems with femtosecond accuracy, to precisely measure the electron bunch arrival time along the accelerator for fast arrival time feedbacks and to locally phase stabilize the phase of the RF reference signals for the accelerator RF controls on a femtosecond level. The architecture of the large-scale synchronization system and design choices made to achieve the reliability, maintainability and performance requirements are presented together with measurement results from the past year of operation.

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) uses a superconducting linear accelerator (linac) providing 17.5 GeV electron beam energy and up to 27000 bunches per second to drive the FEL. As a user facility, the European XFEL is delivering ultra-short soft and hard X-ray pulses with extremely high brilliance and a duration in the femtosecond range. In order to perform time-resolved pump-probe experiments, the synchronization between the FEL and the pump-probe laser systems needs to be on the same timescale. To meet the requirement a pulsed optical synchronization system has been built and is operated 24/7 at the European XFEL, see Fig. 1 for a schematic overview.

OPTICAL SYNCHRONIZATION SYSTEM

Master Laser Oscillator

The core component of the optical synchronization system is a commercial, passively mode-locked semiconductor saturable absorber mirror (SESAM) based master laser oscillator (MLO) at a wavelength of 1553 nm and with a repetition rate of 216.7 MHz (the sixth sub-harmonic of 1.3 GHz RF reference of the accelerator). Two redundant master lasers are permanently operated in order to avoid a single point of failure. They are situated in the main synchronization laboratory within the accelerator injector building and synchronized in a phase-locked loop (PLL) to the 1.3 GHz RF master oscillator (RF-MO).

Free-Space Distribution

A free-space distribution (FSD) comprised of polarizing beamsplitter cubes and half-wave plates is used to distribute the laser beam from the MLO to 24 link stabilization units (LSUs). Currently, 18 of these units have been commissioned and are permanently operated. The FSD is installed in a precisely climate controlled (peak-to-peak < 0.1 K, < 3 %RH) environment to provide the best differential stability (< 1 fs) between end stations. Further details on the type of optical table, the ventilation concept, beam distribution and stability considerations can be found in [1].

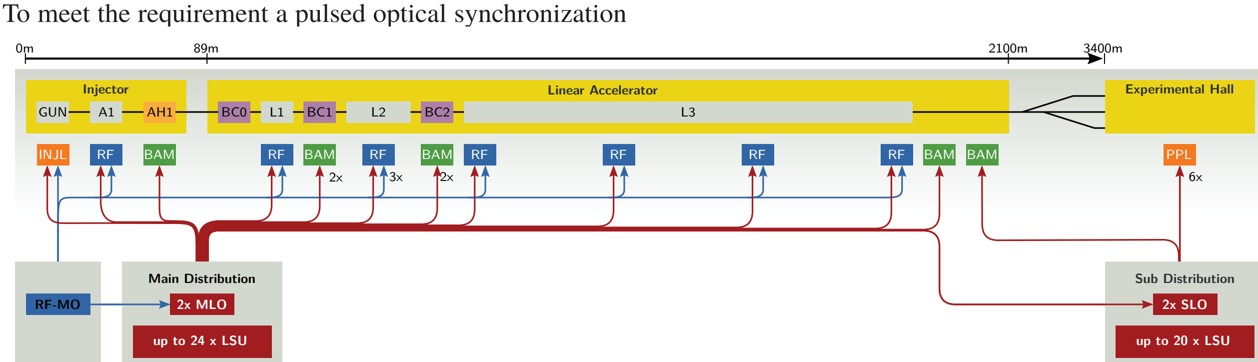

Figure 1: Layout of the pulsed optical synchronization system of the European XFEL. Stabilized fiber links, MLO/SLO and FSD are presented in red. The RF reference distribution system including the RF-MO and the REFM-OPTs is shown in blue. BAMs are illustrated in green and external laser systems in orange.

† Thorsten.Lamb@desy.de

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPRB018

Link Stabilization Unit

The laser pulses are further distributed in polarization maintaining optical fibers to the end stations throughout the accelerator facility. Optical length changes of these fiber links are individually measured with a balanced optical cross-correlator (OXC) and compensated using a fast (1 kHz bandwidth) piezo-based fiber stretcher and a long-range (4 ns) free-space optical delay line within the link stabilization units (LSUs) [2].

Control System Integration

The motor and piezo drivers, control algorithms, ADCs and DACs are implemented using MicroTCA.4 off-the-shelf electronics thus allowing a high modularity, availability, state-of-the-art performance and direct control system integration [3]. An integrated controller board, called LASY, which is optimized for laser snchronization and provides different types of locking and phase detection mechanisms, is under development [4]. First prototypes are currently investigated at DESY.

Sub-Synchronization Laboratory

Two redundant fiber links connect a second synchronization laboratory in the experimental hall, where the scientific instruments of the European XFEL are located. There, two redundant slave laser oscillators (SLOs) are phase locked via a balanced OXC to these fiber links [5]. This so-called sub-synchronization laboratory is providing the same infrastructure as the main synchronization laboratory (FSD, optical table, precise climate control, MicroTCA.4 control system integration). While the laboratory supports the connection of up to 20 end stations, presently 7 LSUs are commissioned. Six are used to synchronize the experiment lasers and one link is connected to the bunch arrival time monitor (BAM) at the end of the main linac. Further links are planned for future laser systems and as tools to improve the synchronization at the experiments.

FIBER LINK END STATIONS

In general, three different types of end stations are supplied by fiber links with optical reference signals and synchronized with femtosecond precision:

Remote Laser Synchronization

Basic laser synchronization is performed using fast photodetectors, RF filters and amplifiers with down-conversion and under-sampling [6]. This scheme is called *RF locking*. The ultimate performance, as need for the pump-probe lasers or the SLOs, is achieved by an all-optical balanced OXC as drift-free phase detector [7]. Six experiment laser systems are currently connected to the optical synchronization system with at least one more being commissioned in the near future.

Optical Reference Module

The second type of end station is the optical reference module (REFM-OPT). It is used to locally re-synchronize the 1.3 GHz RF reference signals distributed throughout the accelerator tunnel in order to meet the low-level RF (LLRF) phase stability requirement of 0.01 deg (≈ 20 fs) [8]. The conventional RF reference distribution system itself is susceptible to temperature and humidity variations. The REFM-OPT is employing a drift-free MACH-ZEHNDER amplitude modulator (MZM)-based laser-to-RF phase detector [9], which allows to measure the phase changes of the 1.3 GHz RF reference signals with respect to the optical reference with femtosecond precision and directly correct them locally using a PLL. Phase corrections of tens of picoseconds are routinely applied after maintenance days or accelerator operation interruptions in order to maintain stable RF reference phases for accelerating field control [10]. All nine planned REFM-OPTs are installed and routinely operated.

Bunch Arrival Time Monitor

The bunch arrival time monitors (BAMs) allow to measure non-destructively the arrival time of every single electron bunch with femtosecond resolution. A transient signal induced into RF pick-ups [11] at the electron beamline is imprinted via an electro-optical amplitude modulator onto the stabilized laser pulse train provided by the optical synchronization system. The amplitude modulation of the optical pulse train is - within the dynamic range of the BAM - proportional to the arrival time of the electron bunch [12–14]. A fast feedback system can be used to stabilize the electron bunch arrival time on a femtosecond level [15].

SYSTEM OPTIMIZATION EXAMPLES

MLO Synchronization

In the first two years of operation of the European XFEL, the MLO has been synchronized to the RF-MO using the standard *RF locking* technique. Meanwhile, MZM-based laser-to-RF phase detection is used to achieve an improved synchronization performance. The in-loop jitter amounts now to 3.2 fs rms in a bandwidth of 10 Hz to 100 kHz as shown in Fig. 2. The performance of the MLO PLL has been verified with a second, independent MZM-based out-of-loop laser-to-RF phase detector. The out-of-loop performance of 2.7 fs rms is a significant improvement over the 7.2 fs rms (also measured out-of-loop) achieved with the standard *RF lock* before employing the laser-to-RF phase detector.

Injector Laser Synchronization

The photoinjector laser oscillator is synchronized directly to the RF-MO. An additional OXC has been installed behind the first three amplifier stages. It is supplied with a reference signal from a stabilized optical fiber link and used for active drift correction of the oscillator and the first three amplifier stages. It has recently been demonstrated that this feedback significantly improves the long-term arrival time stability of the electron bunches at the European XFEL. In an 8 h time

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPRB018

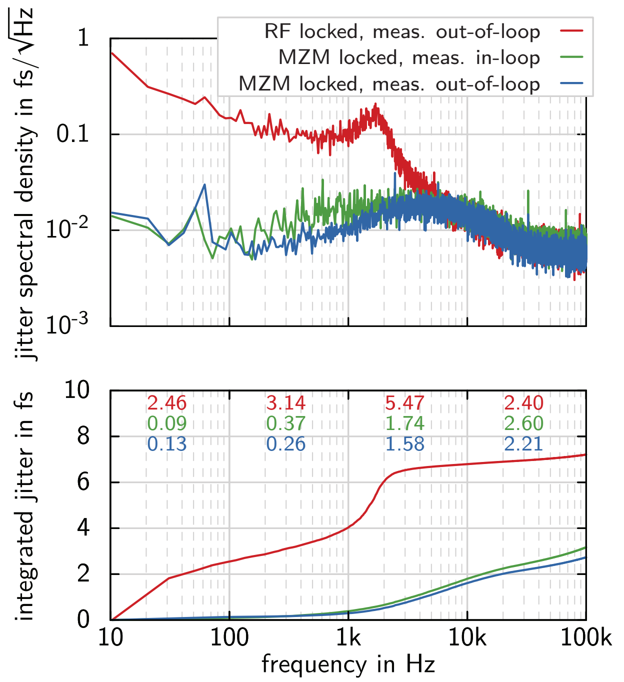

Figure 2: Short term performance of the MLO PLL. A significant improvement has been achieved by implementing an MZM-based laser-to-RF phase detector. The out-of-loop measurements confirm the result.

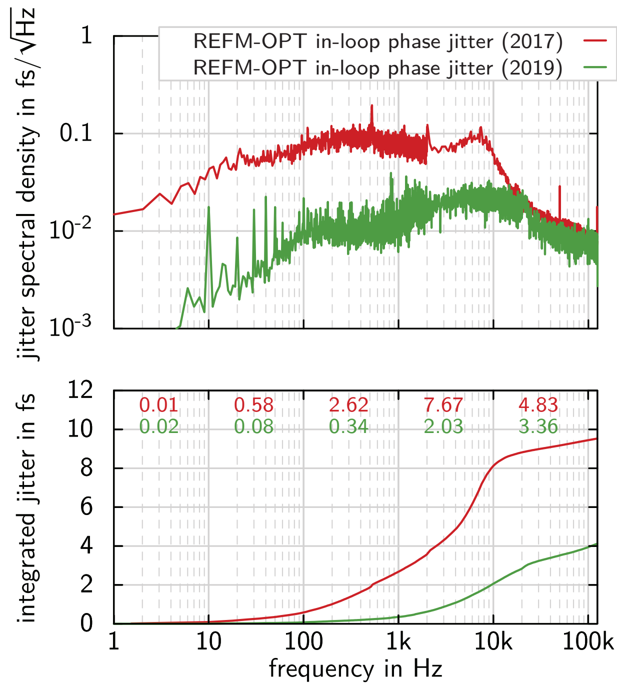

Figure 3: Improvement of the REFM-OPT in-loop jitter over the past two years.

frame, typically 200 fs of peak-to-peak drift corrections are applied to the photoinjector laser oscillator. The peak-to-peak electron bunch arrival time stability as measured with a BAM in the injector section of the accelerator improves by a factor of four and is on the level of 45 fs peak-to-peak [16].

REFM-OPT Performance Improvement

In [10] a REFM-OPT in-loop timing jitter of 9.5 fs rms (1 Hz to 125 kHz) has been reported. The timing jitter was caused by an imperfect high power amplifier (HPA) within the RF-MO which was adding parasitic phase noise around 7 kHz but also due to limitations of the *RF locking* scheme originally applied to synchronize the MLO to the RF-MO. Both error sources caused additional timing jitter in the kHz range which could not be compensated by the digital REFM-OPT feedback electronics. The timing jitter could be significantly improved after the exchange of the HPA and the installation of an MZM-based laser-to-RF phase detector at the MLO. With a larger REFM-OPT locking bandwidth and optimized loop gains an integrated (in-loop) jitter of 4.1 fs, presented in Fig. 3, has been achieved.

SUMMARY

The optical synchronization system of the European XFEL is being continuously extended and improved. Several new fiber links have been build and commissioned in the past year, mostly dedicated to the synchronization of experiment lasers and almost all projected installations are meanwhile finished although the existing infrastructure leaves room for upgrades.

At the same time, the system is closely monitored and continuously verified. The MLO synchronization accuracy for example has been significantly increased by employing an MZM-based laser-to-RF phase detector. An out-of-loop jitter of 2.7 fs rms has been achieved. It has furthermore been proven that the arrival time stability of the electron bunches in the injector can be improved by a factor of four implementing a drift compensation for the injector laser and its first amplifier stages. The REFM-OPT performance has also been optimized by more than a factor of two.

Besides synchronizing the remaining experiment lasers, the performance of the overall synchronization system will be evaluated and further improved in the next years, aiming for the most reliable operation and the best synchronization performance possible.

REFERENCES

[1] C. Sydlo *et al.*, “Femtosecond optical synchronization system for the European XFEL”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, pp. 3969–3971. doi: 10.18429/JACoW-IPAC2017-THPAB105

[2] C. Sydlo *et al.*, “Femtosecond timing distribution at the European XFEL”, in *Proc. 37th Int. Free Electron Laser Conf. (FEL’15)*, Daejeon, Korea, Aug. 2015, paper WEP047, pp. 669–671.

[3] M. Felber *et al.*, “Implementation of MTCA.4-based controls for the pulsed optical synchronization systems at DESY”, in *Proc. 37th Int. Free Electron Laser Conf. (FEL’15)*, Daejeon, Korea, Aug. 2015, paper MOP040, pp. 115–117.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPRB018

[4] E. Janas *et al.*, "MTCA.4 phase detector for femtosecond-precision laser synchronization", in *Proc. 37th Int. Free Electron Laser Conf. (FEL'15)*, Daejeon, Korea, Aug. 2015, paper TUP045, pp. 474–477.

[5] J. Müller *et al.*, "Large-scale optical synchronization system of the European XFEL", in *Proc. 29th Linear Accelerator Conf. (LINAC'18)*, Beijing, China, Sep. 2018, pp. 253–256. doi: 10.18429/JACoW-LINAC2018-MOPO121

[6] M. Felber *et al.*, "Compact MTCA.4 based laser synchronization", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, paper TUPRI107, pp. 1823–1825.

[7] J. Müller *et al.*, "All-optical synchronization of pulsed laser systems at FLASH and XFEL", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, paper MOPHA032, pp. 854–857.

[8] M. Omet *et al.*, "LLRF operation and performance at the European XFEL", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.–May 2018, pp. 1934–1936. doi: 10.18429/JACoW-IPAC2018-WEPAF051

[9] T. Lamb, "Laser-to-RF phase detection with femtosecond precision for remote reference phase stabilization in particle accelerators", Ph.D. thesis, Technische Universität Hamburg-Harburg, Hamburg, Germany, 2016. doi: 10.3204/PUBDB-2017-02117

[10] T. Lamb *et al.*, "Laser-to-RF synchronization with femtosecond precision", in *Proc. 38th Int. Free Electron Laser Conf. (FEL'17)*, Santa Fe, NM, USA, Aug. 2017, pp. 399–402. doi: 10.18429/JACoW-FEL2017-WEB04

[11] A. Angelovski *et al.*, "High bandwidth pickup design for bunch arrival-time monitors for free-electron laser", *Phys. Rev. ST Accel. Beams*, vol. 15, no. 11, p. 112 803, Nov. 2012. doi: 10.1103/PhysRevSTAB.15.112803

[12] H. Dinter *et al.*, "Prototype of the improved electro-optical unit for the bunch arrival time monitors at FLASH and the European XFEL", in *Proc. 37th Int. Free Electron Laser Conf. (FEL'15)*, Daejeon, Korea, Aug. 2015, paper TUP049, pp. 478–482.

[13] M. K. Czwalinna *et al.*, "New design of the 40 GHz bunch arrival time monitor using MTCA.4 electronics at FLASH and for the european XFEL", in *Proc. 2nd Int. Beam Instrumentation Conf. (IBIC'13)*, Oxford, UK, Sep. 2013, paper WEPC31, pp. 749–752.

[14] M. Viti *et al.*, "Recent upgrades of the bunch arrival time monitors at FLASH and the European XFEL", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 695–697. doi: 10.18429/JACoW-IPAC2017-MOPIK072

[15] S. Schulz *et al.*, "Femtosecond all-optical synchronization of an X-ray Free-Electron Laser", *Nature Communications*, vol. 6, Jan. 2015, paper 5938. doi: 10.1038/ncomms6938

[16] J. Müller *et al.*, "Arrival time stabilization of the photocathode laser at the European XFEL", in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America), 2019, paper SF3I.6. doi: 10.1364/CLEO_SI.2019.SF3I.6