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FEW-FEMTOSECOND FACILITY-WIDE SYNCHRONIZATION OF THE EUROPEAN XFEL

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Abstract

In this paper, we report on the first facility-wide evaluation of the optical synchronization system at the European XFEL, resulting in excellent arrival time stability of the electron bunches at the end of the 2 km long linac of the machine. It has been measured using two adjacent, individual single-shot femtosecond-resolution bunch arrival time monitors. While each of the monitors is independently connected by a stabilized optical fiber link to a master laser oscillator, with one being installed in the injector building and one in the experimental hall, these two reference lasers are tightly synchronized through another few-km long fiber link and by balanced optical cross-correlation. Thus, our results are not only benchmarking the accelerator performance, but at the same time the optical synchronization infrastructure itself. Femtosecond arrival time stability can only be achieved by also locking the RF reference for cavity field control to the stabilized optical reference and requires an unprecedented synchronization of the master laser oscillator to the accelerator's master RF oscillator, enabled by a novel laser-to-RF phase detection scheme. Finally, with the seed oscillators of the experiment's optical lasers tightly synchronized to the master laser oscillator, first pump-probe experiments at two independent scientific instruments proved a relative X-ray/optical timing jitter in the low tens of femtoseconds.

OVERVIEW

In 2017 the European XFEL officially started operation with early user experiments and has meanwhile been fully commissioned with all three SASE beamlines and six scientific instruments. The machine is capable delivering up to 27,000 hard and soft X-ray pulses per second with a few tens of femtoseconds duration in flexible patterns to the three beamlines, such that three user experiments can be carried out simultaneously. At each beamline, a distinct laser system is available with matching pulse patterns, providing ultrashort optical pulses for exciting samples in pump-probe geometries, and usage in local timing tools. In addition, every scientific instrument is equipped with another optical laser system fulfilling specific requirements of the instrument. One key component for such time-resolved experiments at the instruments and crucial for accelerator stability is the optical synchronization infrastructure, which had been under commissioning since early 2016 [1–5]. Founded on an ultra-low noise laser oscillator (master laser oscillator, MLO) locked to the facility's master RF oscillator, the synchronization signals are distributed over actively-stabilized optical fiber links, and are used to re-synchronize the reference signal of the accelerator's low-level RF (LLRF) system, the synchronization of the various laser systems, and to provide a reference for longitudinal electron bunch diagnostics. The system evolved from the implementation at the soft X-ray free-electron laser FLASH [6], which showed already 28 fs rms X-ray/optical relative pulse arrival time jitter [7] based on earlier work on electron bunch arrival time stabilization [8]. Since then, significant improvement in all core systems, computing and controls [9, 10] had been made, additional components were developed, and a robust implementation is realized.

TOPOLOGY AND CORE SYSTEMS

At the European XFEL, shown schematically in Fig. 1, the main synchronization laboratory provides precisely controlled environmental conditions with < 0.1 K temperature and < 3% RH (relative humidity) for the core systems of the synchronization infrastructure. The optical timing reference is a commercial, SESAM-based passively mode-locked oscillator at telecom wavelength emitting 200 fs FWHM pulses at a repetition rate of 216.667 MHz. For redundancy, a second identical laser oscillator is operated as hot-spare, such that the system can be switched from one to the other within minutes, with an automated failure detection and switching process under development.

Both laser oscillators are synchronized to the 1.3 GHz main RF oscillator [11] of the facility, which had been realized by a standard heterodyne scheme based on RF generation in a fast photodetector [12] in the first two years of operation. Recently, a Mach-Zehnder-Modulator (MZM)-based laser-to-RF phase detection scheme has been commissioned, resulting in a significant improvement of the timing jitter from 7.2 fs rms (bandwidth 10 Hz to 100 kHz) of the old scheme down to 3.0 fs rms, while also nearly eliminating long-term drifts. This performance is permanently monitored by a second, identical MZM-based laser-to-RF phase detector providing a true out-of-loop measurement (see Fig. 2).

The pulse train of the MLO is then distributed and split by means of polarizing beamsplitters and half-wave plates on a SuperInvar optical table to up to 24 so-called fiber link stabilization units, with presently 18 units in operation.

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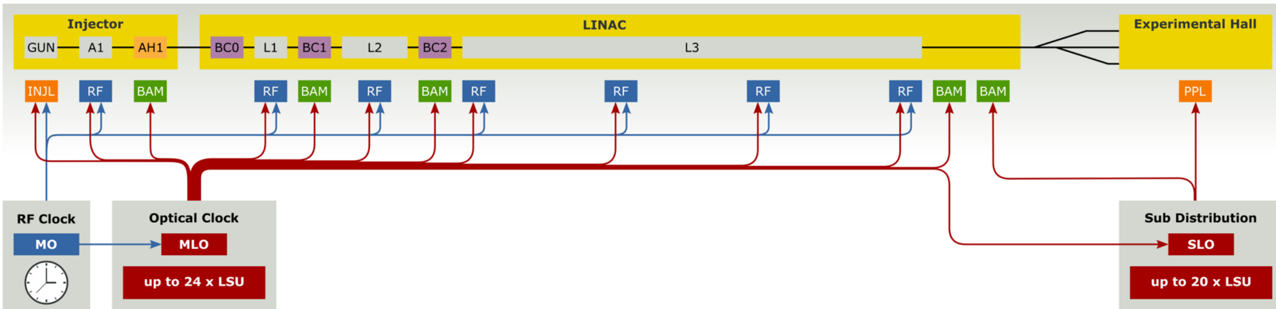

Figure 1: Schematic overview of the main building blocks of the optical synchronization infrastructure installed at the European XFEL.

Special care had been taken in the design of the optical setup such that all beam paths are equally long and thus any residual drift, e.g. by uncontrollable air pressure changes, is common for all connected end-stations.

Polarization-maintaining fiber is used to connect all end-stations in the accelerator tunnel, the photocathode laser and second synchronization laboratory in the experimental hall in Schenefeld. There, another laser oscillator (SLO) of the same type as the MLOs is synchronized to the optical reference by means of balanced optical cross-correlation with a timing jitter of sub-2 fs (Fig. 2). Employing the same free-space distribution scheme as in the main synchronization laboratory, further actively stabilized fiber links are connecting presently seven instrument and pump-probe laser laboratories with capability of further extension. Another fiber link is used to provide the reference for an electron bunch arrival time monitor (BAM) at the end of the linac, such that at this location two adjacent BAMs are connected from both the Hamburg and the Schenefeld synchronization laboratories. The stabilization of each individual fiber link is based on measurement of the round-trip time of pulses traveling forth and back on the optical fiber based on balanced optical cross-correlation. Active feedback on the fiber length using a fast (kHz-bandwidth) piezo-based actuator and a 4 ns-long optical delay line ensure practically long-term drift-free laser pulse arrival time at the link end with sub-femtosecond rms timing jitter. As can be seen in Fig. 2,

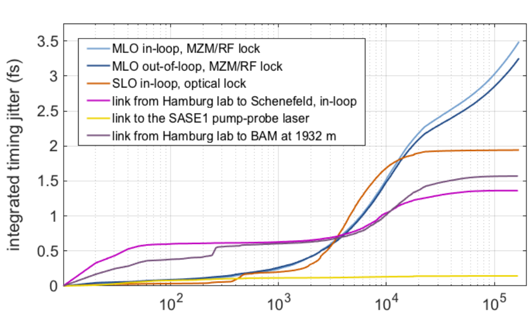

Figure 2: Examples for integrated timing jitter performance of the synchronized master- and slave laser oscillators, and the fiber link stabilization unit from Hamburg to Schenefeld.

the long fiber links to the Schenefeld lab (3.6 km) and to the BAM at the end of the linac (1.6 km) fiber show a significantly higher timing jitter compared to very short links, such as the one at the SASE1 beamline (approx. 100 m fiber). Notably, timing jitter is accumulated in the low-frequency region of the spectrum for long fibers, and this behavior is subject to investigation.

Bunch Arrival Time Monitor

Along the linac, several monitors allow for the non-destructive measurement of the arrival time of every single electron bunch with few-femtosecond resolution. For this, the transient electric field of an electron bunch is exploited to generate an RF pulse in a specifically designed high-bandwidth pickup [13] in the beamline, which then changes the amplitude of the optical reference pulse train in an integrated electro-optical modulator. This amplitude modulation is, within the dynamic range of the monitor of a few hundreds of femtoseconds, proportional to the electron bunch arrival time [14–16]. The signals of the BAMs can be used as inputs for slow and fast feedback loops to stabilize the arrival time of the electron bunches at the end of the accelerator.

Optical Reference Module

The optical reference module (REFM-OPT) is used to re-synchronize the 1.3 GHz RF reference signal distributed throughout the tunnel at distinct locations to fulfill the phase stability requirements of 0.01 deg (approx. 20 fs) of the low-level RF system of the accelerator [17], which cannot be achieved by conventional the RF distribution systems alone. For this, the REFM-OPT employs a drift-free MZM-based phase detection scheme [18] between the optical and the 1.3 GHz electrical reference signals and corrects the phase of the RF signal locally in a PLL. During normal operation of all nine planned and installed REFM-OPTs several picoseconds of drift are corrected to maintain stable RF reference phases for the accelerating field control with a short-term jitter of sub-4 fs rms [19].

External Laser Synchronization

Robust synchronization of all external optical laser oscillators, such as the pump-probe laser systems at the scientific

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instruments, as well as the photocathode laser is routinely provided by the conventional heterodyne detection scheme, which had been used at the MLOs in the past [12]. Depending on the specific laser system, where the scheme is individually adapted to, a timing jitter in the order of a few tens of femtoseconds is achieved. Significantly improved timing jitter performance on the single-digit femtosecond level, e.g. required for locking the SLO (Fig. 2), is realized by balanced optical cross-correlation [20]. In addition, such optical cross-correlation schemes can also be applied in slow feedbacks for drift compensation and had recently been used to stabilize the arrival time of the photocathode laser pulses and thus the electron bunch arrival time in the injector. With the feedback active, it was demonstrated that the peak-to-peak drift of the electron bunches measured with an independent BAM could be reduced by a factor of four from around 200 fs down to 45 fs over an period of 8 hours [21]. An integration into the slow feedback systems of the accelerator is under preparation.

PERFORMANCE EVALUATION

Most recently, the two adjacent bunch arrival time monitors, located at the tunnel position "1932 m" with a separation of less than 1 m, have been commissioned together with their corresponding fiber links from the two phase-locked reference laser oscillators in the Hamburg and Schenefeld synchronization labs. Figure 3 shows the correlation of the electron bunch arrival time measured with the two monitors over 600 FEL shots or a period of 1 minute. In this graph,

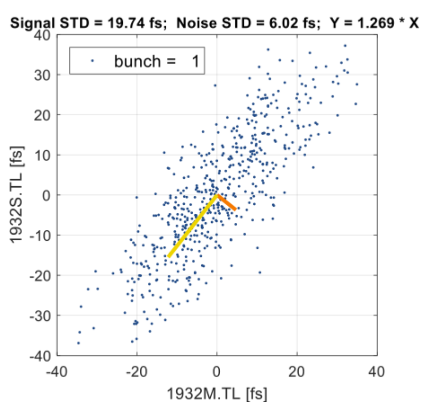

Figure 3: Correlation of the measured electron bunch arrival time with two adjacent BAMs at the end of the linac.

where the first of 195 electron bunches per 10 Hz train is shown, the width along the principal axis of the distribution represents the width of the arrival time distribution (indicated by the yellow line), such that the projection yields an electron bunch arrival time jitter of approx. 12 fs rms at each of the monitors. The width of the correlation in this preliminary analysis in the perpendicular direction (orange line) is approximately 6 fs rms and includes the resolution of the BAMs, the timing stability of the three fiber links to the BAMs and between the two reference lasers, the timing jitter of the synchronization of the SLO to the link, as well as the high-frequency noise of the lasers themselves. A more rigorous, on-going analysis of the data suggests an even lower timing jitter performance of 2 fs rms for the overall synchronization system on short timescales. A long-term

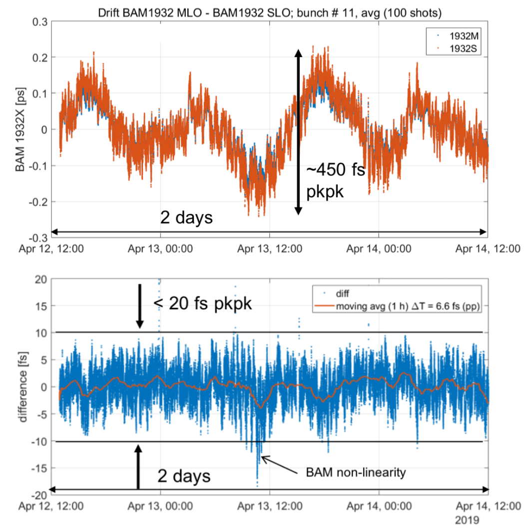

Figure 4: Peak-to-peak (top) and residual long-term drift (bottom) between the two BAMs at the end of the linac.

measurement over two days without any longitudinal feedbacks active revealed a slow arrival time drift of 450 fs peak-to-peak with a characteristic period of approx. 12 h (Fig. 4, upper panel). There are indications that this drift may arise from tidal movement, and consequently more long-term data is presently being acquired and analyzed. The residual drift between the two monitors amounts to 20 fs peak-to-peak over the measurement period (Fig. 4, lower panel). Further investigation on the source of this drift and possible mitigation measures are also presently on-going.

SUMMARY AND OUTLOOK

In conclusion, we demonstrated a performance of the optical synchronization infrastructure at the European XFEL accelerator on the single-digit femtosecond timescale when measured with two independent electron bunch arrival time monitors. Independent measurement campaigns at both scientific instruments at the SASE1 beamline resulted agreeingly in an X-ray/optical relative arrival time jitter of approx. 30 fs rms [22], comparable to newest measurements at another hard X-ray facility [23]. In the future, we plan to further improve the stabilization of the photoinjector laser and hence the whole injector section of the linac, and to commission advanced beam-based feedbacks such that long-term low-drift operation with few femtosecond timing jitter can be achieved.

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REFERENCES

[1] C. Sydlo *et al.*, "Development Status of Optical Synchronization for the European XFEL", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper MOPC32, pp. 135–138.

[2] C. Sydlo *et al.*, "Femtosecond Timing Distribution at the European XFEL", in *Proc. FEL'15*, Daejeon, Korea, Aug. 2015, paper WEP047, pp. 669–671.

[3] C. Sydlo *et al.*, "Femtosecond Optical Synchronization System for the European XFEL", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3969–3971. doi:10.18429/JACoW-IPAC2017-THPAB108

[4] J. M. Mueller *et al.*, "Large-Scale Optical Synchronization System of the European XFEL", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 253–256. doi:10.18429/JACoW-LINAC2018-MOPO121

[5] T. Lamb *et al.*, "Large-Scale Optical Synchronization System of the European XFEL with Femtosecond Precision", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3835–3838. doi:10.18429/JACoW-IPAC2019-THPRB018

[6] S. Schulz *et al.*, "Past, Present and Future Aspects of Laser-Based Synchronization at FLASH", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper WEPC32, pp. 753–756.

[7] S. Schulz, I. Grguraš, C. Behrens, H. Bromberger, J. T. Costello *et al.*, "Femtosecond all-optical synchroniza-tion of an X-ray free-electron laser", *Nat. Commun.*, 6:5938 (2015). doi:10.1038/ncomms6938

[8] F. Löhl, V. Arsov, M. Felber, K. Hacker, W. Jalmuzna *et al.*, "Electron Bunch Timing with Femtosecond Precision in a Superconducting Free-Electron Laser", *Phys. Rev. Lett.*, vol. 104, p. 144801 (2010). doi:10.1103/PhysRevLett. 104.144801

[9] M. Felber *et al.*, "Implementation of MTCA.4-based Controls for the Pulsed Optical Synchronization Systems at DESY", in *Proc. FEL'15*, Daejeon, Korea, Aug. 2015, paper MOP040, pp. 115–117.

[10] M. Felber, E. P. Felber, M. Fenner, T. Kozak, T. Lamb *et al.*, "Usage of the MicroTCA.4 Electronics Platform for Femtosecond Synchronization Systems", in Proc. FEL19, Hamburg, Germany, Aug. 2019, paper WEB007 (this conference).

[11] L. Z. Zembala *et al.*, "Master Oscillator for the European XFEL", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 2771–2773. doi:10.18429/JACoW-IPAC2014-WEPRI116

[12] M. Felber, M. Hoffmann, U. Mavric, H. Schlarb, S. Schulz, and W. Jalmuzna, "Laser Synchronization at REGAE using Phase Detection at an Intermediate Frequency", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper WEPPD048, pp. 2624–2626.

[13] A. Angelovski, A. Kuhl, M. Hansli, A. Penirschke, S. M. Schnepp *et al.*, "High Bandwidth Pickup Design for Bunch Arrival-time Monitors forFree-Electron Laser", *Phys. Rev.*, 15, 112803 (2012), 8 pages. doi:10.1103/PhysRevSTAB.15.112803

[14] 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. FEL'15*, Daejeon, Korea, Aug. 2015, paper TUP049, pp. 478–482.

[15] 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. IBIC'13*, Oxford, UK, Sep. 2013, paper WEPC31, pp. 749–752.

[16] M. Viti *et al.*, "The Bunch Arrival Time Monitor at FLASH and European XFEL", in *Proc. ICALEPCS'17*, Barcelona, Spain, Oct. 2017, pp. 701–705. doi:10.18429/JACoW-ICALEPCS2017-TUPHA125

[17] M. Omet *et al.*, "LLRF Operation and Performance at the European XFEL", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1934–1936. doi:10.18429/JACoW-IPAC2018-WEPAF051

[18] 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, 2017. doi:10.3204/PUBDB-2017-02117

[19] T. Lamb *et al.*, "Laser-to-RF Synchronization with Femtosecond Precision", in *Proc. FEL'17*, Santa Fe, NM, USA, Aug. 2017, pp. 407–410. doi:10.18429/JACoW-FEL2017-WEB04

[20] J. M. Mueller *et al.*, "All-Optical Synchronization of Pulsed Laser Systems at FLASH and XFEL", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 854–856. doi:10.18429/JACoW-IPAC2015-MOPHA032

[21] J. Müller, S. Schulz, L. Winkelmann, M. K. Czwalinna, I. Hartl, and H. Schlarb, "Arrival Time Stabilization of the Photocathode Laser at the European XFEL", *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

[22] T. Sato, R. Letrun, H. J. Kirkwood, J. Liu, P. Vagovic *et al.* "Femtosecond timing synchronisation at megahertz repetition rates for an X-ray Free-Electron Laser", *submitted*, 2019.

[23] M. Kim, C.-K. Min, and I. Eom "Laser systems for time-resolved experiments at the Pohang Accelerator Laboratory X-ray Free-Electron Laser beamlines", *J. Synchrotron Rad.*, 26, 868–873 (2019). doi:10.1107/S1600577519003515