

LATEST ACHIEVEMENTS IN FEMTOSECOND SYNCHRONIZATION OF LARGE SCALE FACILITIES

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Abstract

The laser-based synchronization systems for the European XFEL and FLASH provide femtosecond-stable timing references for tens of clients along the accelerator and the experiment halls over many kilometers of optical fiber. Recently, benchmarking experiments revealed a point-to-point timing stability with sub-femtosecond rms timing jitter. At the same time geophysical effects like ocean waves and earthquakes do not only affect the performance of the system, but their impact can clearly be identified. To improve the temporal resolution in X-ray/optical pump-probe experiments, additional arrival time monitors for both the electrons and the optical laser pulses are currently being installed, allowing for a posteriori data sorting and eventually active feedbacks. Further, the optical reference oscillators and advanced synchronization schemes are being developed, resulting in timing jitter on the sub-hundred attoseconds level.

INTRODUCTION AND MOTIVATION

Free-electron lasers (FELs) can generate high-intensity radiation with narrow bandwidth and high brightness which is tuneable over a broad range of the electromagnetic spectrum, including X-rays. In particular, the current high-gain FELs like LCLS, SACLA, SwissFEL, PAL-XFEL, FLASH and the European XFEL are based on ultra-relativistic electron beams passing through long undulators to generate coherent, high-brightness X-ray pulses with typical durations of 10 fs to tens of femtoseconds, in special operating modes even attoseconds.

To fully utilize the capabilities of those and upcoming FEL facilities, demanding requirements are imposed on the timing reference and control systems of linear accelerators (linacs), and to a lesser extent, the photon delivery systems, as well as involved optical lasers (photoinjector laser, external seed lasers, pump-probe lasers). Moreover, advanced FEL modes, such as hard X-ray self-seeding, are especially sensitive to variations in electron bunch properties.

These requirements are ultimately driven by user experiments, which are often carried out in pump-probe geometries. Therein, not only longitudinal stability of the linac and the generated photon beams, but also the arrival time stability of optical laser pulses is crucial to achieve the best temporal resolution.

All phase-critical subsystems are vulnerable to environmental disturbances such as microphonics, vibrations, and seismic noise, with laser systems being particularly sensitive

to changes in temperature, humidity, and air pressure. While temperature and humidity can typically be well-controlled locally in laboratories and even in long accelerator tunnels, air pressure fluctuations can impact free-space laser propagation and should ideally be accounted for. For example, equalizing optical path lengths to timing-critical subsystems can ensure such pressure-induced shifts result in common-mode errors, minimizing their impact. This, however, is not possible for the typically complex laser delivery schemes at the experimental end stations or scientific instruments.

Therefore, large-scale FEL facilities rely on high-precision synchronization systems for phase stability of the linac itself, as well as for arrival time control and stability of external laser systems.

At the same time, the robustness and reliability of critical subsystems are as essential as performance to ensure high availability and long mean time between failures. Additionally, installation, operational, and maintenance costs should also be considered. Hence, synchronization systems are chosen based on a balance of these factors, with most facilities adopting hybrid approaches—using RF-based distribution for less critical and/or shorter-range connections, and laser-based systems for the most timing-sensitive components at the accelerator and in user experiments.

SYNCHRONIZATION SYSTEM TOPOLOGY AND IMPLEMENTATION

RF-based reference signal distribution systems exhibit relatively low cost for small facilities and can provide many reference tap points for instance for RF cavity control. However, their critical parameters concern phase drift in cables, phase uncertainties of frequency dividers and the ability to recover phase offsets after power cycling of the system. Nonetheless, all accelerator facilities are based on a low-noise, high power RF oscillator as ultimate reference, and have developed different strategies and measures to at least mitigate these issues.

For the FELs at DESY, this main oscillator (MO, sometimes “master oscillator”) had been developed with collaboration partners [1], providing a redundancy concept, high reliability and excellent absolute phase noise characteristic, which is of high importance when aiming at sub-femtosecond overall stability. The 1.3 GHz microwave signal required for the accelerating cavities is derived from a GPS-disciplined 9 MHz OCXO (oven-controlled crystal oscillator), being amplified to high power levels (> 40 dBm) and distributed using low-drift cables along the linac.

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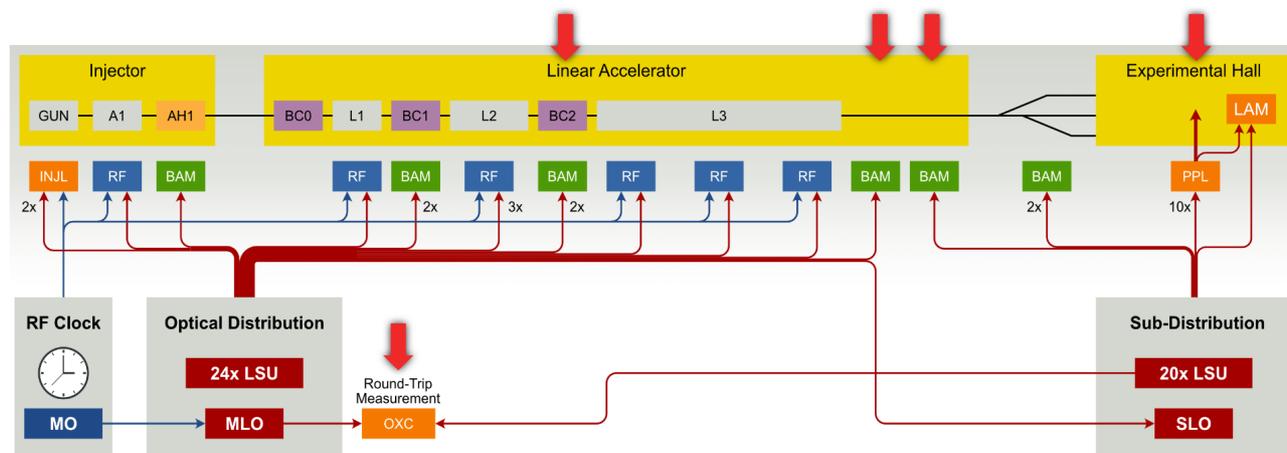


Figure 1: Sketch of the European XFEL accelerator facility and components of its pulsed optical synchronization system, with RF signal paths depicted as blue and optical fiber connections in red lines, main RF oscillator (MO), main laser oscillator (MLO), subsidiary reference laser oscillator (SLO), bunch arrival time monitors (BAM) around the bunch compressors (BC) and at the end of the linac, the "RF" re-synchronization along the accelerating stations along the linac, the laser systems of the injector (INJL) and for pump-probe experiments (PPL), and its arrival time diagnostic (LAM). The large red arrows indicate locations which are relevant for benchmark and validation experiments. Reproduced from [2].

Pulsed Optical Systems

For FLASH and the European XFEL, the RF distribution is augmented by an all-optical scheme, where a pulsed optical laser can provide the best performance in terms of jitter and drift stability. For signal distribution, actively length-stabilized polarization-maintaining fibers (PMF) are employed for the connections to remote systems at the accelerator facility to ensure best long-term performance. The use of PMF is mitigating signal-deteriorating effects like polarization mode dispersion therein. Typically, a passively mode-locked laser oscillator (MLO) with a center wavelength in the telecom C-band (1550 nm) and comparatively short laser pulses of few 100 fs duration serves as optical reference. Such laser oscillators can exhibit outstanding phase noise and respectively timing jitter stability, especially in the higher frequency range above a few hundred Hz. In contrast to RF phase detection methods, these all-optical schemes can be implemented relatively easy to be insensitive to AM-to-PM detection errors. Nowadays, this all-optical technique has been implemented in the optical synchronization system at FERMI, FLASH, the European XFEL (depicted schematically in Fig. 1), SwissFEL, and will at least in parts be employed at upcoming facilities like LCLS-II for stabilizing fiber-optical links as well as for optical locking of client laser systems. As mentioned above, at FLASH and the European XFEL the RF signal quality deterioration after distribution from the MO along the accelerator over kilometers of cables, including amplification, is being addressed by a re-synchronization of the signal to the optical reference ("RF" in Fig. 1, with RF and optical input, see also [3]).

Crucially, the scheme is undergoing continued improvements, based on both accelerator-based and purely laser-based benchmarking experiments and measurement cam-

paigns, as well as more theoretical work and simulation-based approaches.

BENCHMARKS, IMPROVEMENTS AND FUTURE CHALLENGES

Beam-based Measurement and Linac Stabilization

Electron bunch arrival time monitors (BAMs) are capable of measuring the fluctuations of the arrival time of the accelerated electron bunches with femtosecond resolution with respect to the optical reference signal. By acting on the phase and the amplitude of the RF field of the accelerating modules preceding the BAM, a feedback loop is closed to stabilize the arrival time of the electron bunches to typically 5 fs rms (for 250 pC bunch charge [4, 5]). As a result, the generated X-ray pulses are expected to exhibit a short-term arrival time jitter at the scientific instruments at the same level, benefiting the temporal resolution in user experiments.

Additionally, the BAMs can be utilized for benchmarking the synchronization system performance itself.

Downstream of the main linac ("L3" in Fig. 1, approx. 2 km from the electron gun), two BAMs are installed adjacent to each other. One of them is provided with an optical reference signal from the main synchronization laboratory in the injector area of the accelerator facility, while the reference signal for the second one is provided from the subsidiary reference laser oscillator ("SLO" in Fig. 1, phase-locked to the MLO) located in the experimental hall, approx. 3.5 km away from the injector. Figure 2 shows the correlation of the measured arrival times in both detectors over a period of 10 minutes (i.e. 6000 macro-pulses), where each data point corresponds to an average of 400 individual electron bunches to reduce the high-frequency instrument noise. The correlation width of less than 1 fs rms can be interpreted

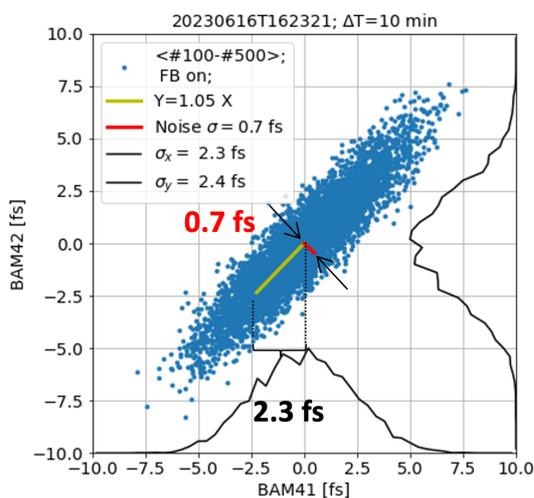


Figure 2: Correlation of electron bunch arrival time measured with two adjacent monitors downstream of the main linac of the European XFEL. The monitors are provided with an optical reference from the main laser oscillator of the facility, and the subsidiary reference laser oscillator of the facility, respectively, while the subsidiary reference laser oscillator is synchronized to the main one via another optical fiber link.

as an upper limit of the induced jitter from the optical synchronization system itself, which includes three stabilized fiber links covering a total length of more than 7 km, and the synchronization of the SLO.

Laser-based Measurements and Stabilization

Achieving temporal resolutions below 10 fs FWHM, and potentially even sub-femtosecond in the future, advancements in arrival time monitoring and active stabilization are essential, particularly for maintaining the temporal stability of pump-probe laser pulses close to the experiment's interaction point (IP). While placing a laser pulse arrival monitor (PAM) at, or ideally with multiple PAMs upstream and downstream around the IP, would offer optimal correlation between X-ray and optical pulses, such a setup is only feasible in specific, limited experimental geometries. Moreover, in the XUV, soft X-ray, and some hard X-ray regimes, PAM implementation is often impractical, if not impossible. To measure and mitigate timing drift and jitter of optical laser pulses, the development of laser pulse arrival time monitors (LAMs) has recently been initiated. These monitors, ideally installed as close as possible to the interaction point (IP) will measure the arrival time of the optical pump-probe laser pulses relative to the ultra-stable optical reference of the laser-based synchronization system, rather than to the X-ray pulse. By this, potential jitter and drift of the pump-probe laser system and the beam transport of the laser radiation starting from the synchronized seed laser oscillator to the IP can be measured, and, utilizing another feedback loop, stabilized.

In a recent benchmark experiment, such a LAM (in this case for the pump-probe laser wavelength of 1030 nm, utilizing multipass cell, or MPC, spectral broadening and compression [6]) had been installed at the FL23 beamline at FLASH to evaluate the laser pulse arrival time characteristics with respect to the optical reference close to the experiment [7]. Figure 3 shows the measured timing drift, with the slow arrival time feedback active (approx. 1 Hz bandwidth), acting on a delay line to stabilize the arrival time at the experiment based on the measured LAM data.

The compensated drift (not shown) amounts to approx. 1 ps over several hours, which corresponds well with previous benchmark and user experiments carried out at FLASH [8, 9]. During those measurement campaigns, laser delivery was based on OPCPA technology at a different wavelength of 800 nm. With the laser system being located in the same laboratory, comparable amount of corrected drift indicates that the major contributions is caused by the transport from the lab to the experiment. Based on the findings of those studies, during the on-going and upcoming maintenance and upgrade periods of both FLASH and the European XFEL, LAMs will be deployed at almost all experiments and scientific instruments to not only measure the laser pulse arrival pulse-resolved for post-sorting experimental data, but stabilizing the arrival time of the laser close to the IP. However, in this first stage, only wavelengths of 800 nm and 1030 nm will be supported, while more advanced monitors covering a broad wavelength range will be available in the future.

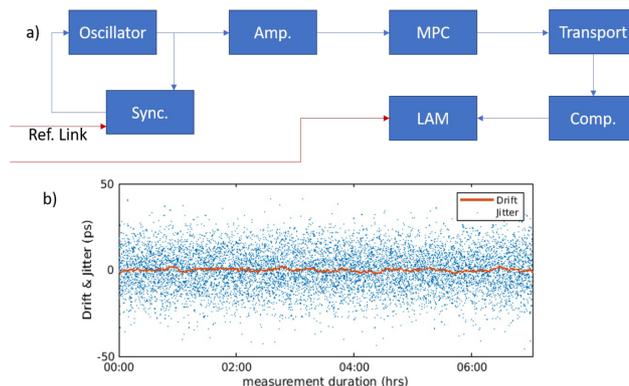


Figure 3: Laser pulse arrival time measurement at FLASH FL23. a) Schematics of the setup. The pump-probe laser's seed oscillator is synchronized (Sync.) to the optical reference (Ref. Link), while the laser amplifier, transport, compression scheme (MPC, transport, Comp.) may introduce timing jitter and drift, measured using a laser pulse arrival time monitor (LAM), which is also referenced to the optical reference. b) With a active feedback, the peak-to-peak arrival time drift (red line, moving average) is determined to be less than femtosecond over the measurement period of 7 hours. Reproduced from [7].

Model-based Timing Jitter Budget Analysis

Supporting the experimental approaches, theoretical and simulation-based approaches are being employed to improve the performance in our system. For this it is essential to understand how timing jitter between the synchronization client, for instance a pump-probe laser system, and the main oscillator (MO) is cumulatively influenced by the different system components and noise sources.

Adopting white-box, i.e. physics-informed modeling, wherein we explicitly model the physical behavior of each relevant component contributing to timing jitter. The model equations, representing the physical processes underlying those jitter contribution are generally reusable across different stations. However, local identification of model parameters is necessary, particularly for components with inherent variability such as the complex laser systems and certain electronic subsystems. Most commercial electronic components only require a single characterization. By systematically measuring the noise contributions at the system input, such as oscillator phase noise, thermal instabilities, and detector noise the model can be used to quantitatively predict each source's impact on the resulting residual jitter. Even with approximate or coarsely estimated input noise parameters, the model enables inference of the dominant contributors to jitter in specific frequency bands. As a result, this additional diagnostic enables targeted research efforts, focusing on the system components and noise sources that significantly degrade timing performance.

Besides the beam-based measurements, a self-contained, laser-based benchmark experiment had been implemented within the synchronization system at the European XFEL. For this, another stabilized fiber link had been commissioned from the subsidiary reference laser oscillator back to the main synchronization laboratory (depicted by "round-trip measurement OXC" in Fig. 1). Latest measurements suggest already a very good agreement between the model-based jitter analysis and experimentally determined short-term jitter. Those investigations are an on-going effort, alongside extension and implementation of more detailed simulations.

INFLUENCE OF SEISMIC EFFECTS

Analysis of the input-output data of phase-locked loops (PLLs) of the length-stabilized optical fiber links revealed their response to environmental disturbances such as earthquakes, ocean-generated microseism, and civilization-induced noise. By correlating PLL control signals with external seismic and environmental data, specific disturbances can be identified and their impact on loop stability can be assessed. Even earthquakes approx. 5000 km away from the European XFEL site induce notable fluctuations in the in-loop signals. Especially ocean-wave generated microseism, exhibits a particularly strong influence, with varying magnitude depending on the season. The high sensitivity of the optical synchronization system also enables the detection of local vibrations from human activity, including road traffic and large public events such as concerts or soccer games

in the stadium located in the vicinity of the accelerator site. Figure 4, reproduced from [10], shows the analysis of the feedback controller output signal fiber link at the European XFEL, with a compensated length of more than 3.5 km. The spectrogram (panel a) clearly shows all three categories of seismic activities. Noise induced by ocean-generated microseism between 0.1 Hz and 0.3 Hz, and civilization noise between 0.9 Hz and 3.5 Hz, are visible. Notably, even the weekday/weekend pattern can be distinguished in the civilisation induced noise, which is believed to be mainly attributed to the number of cars passing on a street above the underground accelerator tunnel. Seismic activities triggered by earthquakes were also detected during the data period.

CONCLUSIONS AND OUTLOOK

Large-scale free-electron laser facilities require an outstanding level of synchronization accuracy. Presently, laser-based schemes, based on the distribution of the pulse train of a low-noise femtosecond laser oscillator via actively length and by this transit time stabilized optical fibers are state of the art. Such systems typically augment RF-based, or other laser-based approaches such as RF-over-fiber (see e.g. [11]). However, only the pulsed optical systems presently allow for advanced electron beam diagnostics, low-jitter laser oscillator and RF signal synchronization, as well as laser pulse arrival time measurement close to the actual experiment.

Using beam-based longitudinal feedbacks, the electron bunch arrival time at the European XFEL and presumably at FLASH after its FLASH2020+ upgrade in 2025 can routinely be stabilized to the low-femtosecond level. However, especially for the large facilities like the European XFEL, where photon beam transport from the undulators to the actual scientific instruments can be as large as 1.5 km, arrival time variations may be induced, and seismic influence can not be excluded. Therefore, joint measurement campaigns are being planned, combining the synchronization system data, as well as photon beam and laser pulse arrival time diagnostics. Such investigations will give inside on whether and how additional feedforward or feedback systems can be implemented for photon pulse arrival time stabilization.

The stabilization of the laser pulse arrival time at the actual experiment had been proven necessary already, and therefore dedicated LAMs will be installed at almost all experimental stations. In the future, the spectral range of those devices will be extended from the current lasers' fundamental wavelengths to ideally cover the range users can request for their studies and improving the overall temporal resolution. Pushing towards attosecond synchronization precision remains a challenging pathway ahead.

ACKNOWLEDGMENTS

The authors acknowledge not only all valuable contributions to the manuscript and the accompanying slide deck by members of DESY's beam controls group (MSK), but would like to thank all members of DESY's and the European XFEL's operations teams, the optical laser groups, as well

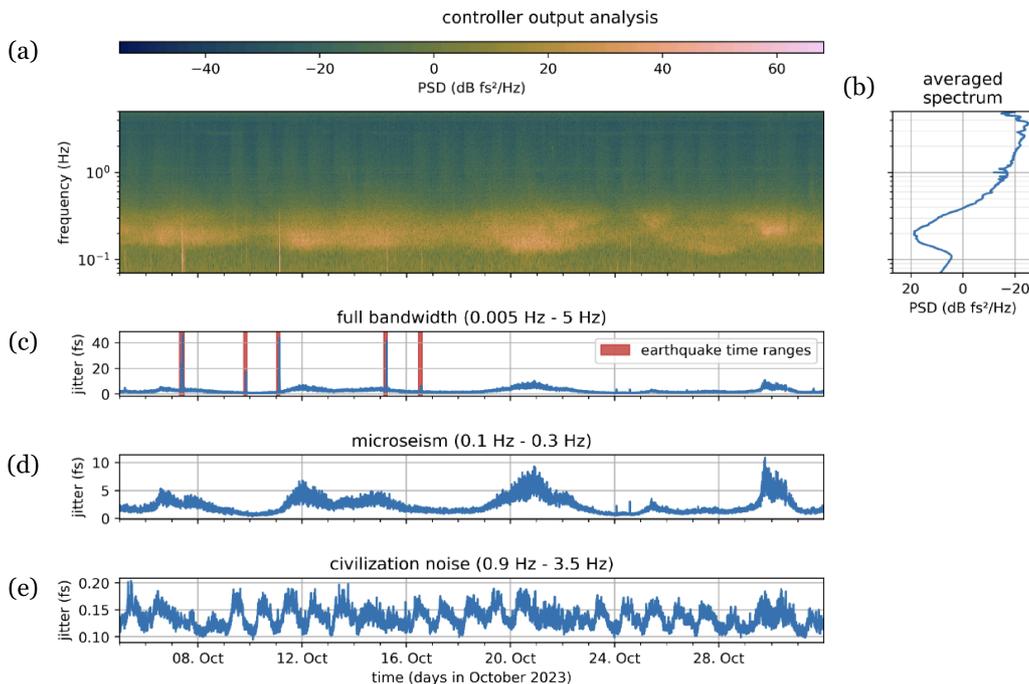


Figure 4: Results of analyzing controller output signal of the 3.5 km link. (a) Spectrogram as of October 2023. (b) Average power spectral density (PSD). (c) Integrated timing jitter over the frequency range 0.005 Hz to 5 Hz. (d) Integrated timing jitter over the frequency range 0.1 Hz to 0.3 Hz, with earthquake effects removed. (e) Integrated jitter over the frequency range 0.9 Hz to 3.5 Hz. Reproduced from [10].

as the members of FLASH's photon science department, the scientific instruments and beamlines at EuXFEL and FLASH, the user groups willing to dedicate their precious beamtime for benchmarking the synchronization system performance, contributions from the WAVE Collaboration and in particular also all the effort of everybody involved, who may not be named here but is essential to make the systems work!

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