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LATEST ACHIEVEMENTS IN FEMTOSECOND SYNCHRONIZATION OF LARGE-SCALE FACILITIES

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Abstract

This overview addresses the realm of electrical, hybrid and specifically optical schemes for achieving a facility-wide synchronization on the femtosecond level at free-electron lasers (FELs). After a brief introduction to the fundamental principles behind FEL operation and the significance of synchronization for full utilization of their capabilities. Subsequently, it discusses various methods employed to achieve femtosecond-precision synchronization, including low-noise timing references, different active stabilization techniques, and advanced feedback algorithms. In addition, the tutorial provides an overview of the numerous challenges encountered in femtosecond optical synchronization and solutions developed to overcome them. It discusses technological developments, such as ultra-stable optical lasers or timing diagnostics both for optical pulses and electron beams. Moreover, practical considerations for implementing such systems in FEL facilities are addressed, including stability requirements, scalability, and integration with experimental setups. Results from recent studies highlighting successful synchronization implementations at prominent FEL facilities are presented.

THE FREE-ELECTRON LASER CONCEPT

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 [1].

It all begins with an electron source, where a photocathode is illuminated by a several picoseconds long optical laser pulse (often at UV wavelengths), which releases electrons via the photoelectric effect. These electrons are then accelerated to a few MeV by a radio-frequency (RF) cavity, resulting together with the focussing optics in a high-energy, low-emittance electron beam.

After this so-called injector, the electron beam enters a linear accelerator (linac, which can extend over several kilometers in total length), where the electrons are accelerated by a series of RF cavities to very high energies (up to several GeV, depending on the desired FEL radiation wavelength).

However, for efficient generation of extreme ultraviolet (XUV) or X-ray radiation, a high peak current of several kA is required, which is realized by shortening the electron bunches in time in several stages of bunch compressors. Basically, they consist of a magnetic chicane, which utilizes a particular time-energy correlation within the bunch imprinted by the acceleration process and causes the electrons at the tail of the bunch to travel a shorter path than those at the head, effectively compressing the bunch longitudinally.

After bunch compression and final acceleration, the electrons are directed into the undulator, which is a series of alternating magnetic poles. The magnetic field in the undulator forces the electrons to undergo sinusoidal motion, causing them to oscillate transversely, and emit synchrotron radiation to initiate the process of self-amplified spontaneous emission of radiation (SASE). The emitted radiation, in turn, interacts with the electron bunches, causing a microbunching effect where electrons group into smaller sub-bunches separated by the radiation wavelength. In high-gain FELs, this microbunching enhances the coherent emission of radiation exponentially leading to a high brightness, monochromatic and spatially coherent pulse of light, which is typically shorter than the electron bunch it was generated from.

The unique properties of FEL radiation compared to conventional lasers allow for investigating material properties on ultra-short dimensions and to observe dynamic processes happening on ultra-short time-scales. Experiments are often carried out in pump-probe geometry, involving additional radiation sources such as highly complex optical laser systems. One of the pulsed sources is used for initiating an excitation or modification in the sample of interest, and the mutually other pulse is used to probe the dynamics following this excitation. A "molecular movie" of these dynamics can be recorded by scanning the relative time delay of both pulses. The achievable resolution in this type of experiment strongly depends on widths of the pulses and on the precise knowledge of their relative time delay.

THE SYNCHRONIZATION MOTIVATION

Exploitation of the capabilities of state-of-the-art free-electron lasers (FELs) place demanding requirements on the timing reference distribution and control systems of the linear electron accelerators (linac) and to some extent the photon beam delivery systems. In the end, the requirements on the linac are driven by user experiments, for instance maintaining the photon energy and especially in terms of longitudinal stability for achieving femtosecond-level temporal resolution. Advanced FEL schemes like hard x-ray self-seeding, are even more sensitive to deviations in electron bunch properties, both transversely and longitudinally. Therefore, all large-scale FEL facilities require a synchronization system to ensure adequate time and phase stability. Additionally, pump-probe experiments involving multiple radiation sources (X-ray photons, optical lasers, THz radiation), the resolution is not only constrained by pulse duration, but in particular by the timing stability between the pump

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and probe pulses. While all phase-critical subsystems at a linac are susceptible to environmental influence, microphonics and other types of vibrations and seismic activity, especially all involved laser systems are in particular sensitive to variation of ambient temperature, as well as changes in relative humidity and air pressure. Notably, while temperature and relative humidity can be controlled quite well with corresponding air conditioning systems in the laboratories, the influence of air pressure changes are non-negligible in free-space laser propagation and ideally should passively be mitigated. For instance, by realizing equal laser beam path lengths to two timing-critical subsystems, such changes would only induce a common error euqal for both paths.

THE SYNCHRONIZATION TECHNIQUES

At user facilities the robustness and reliability of critical subsystems is as crucial as fulfilling the demands on performance to ensure a long mean time between failures and high availability. In addition, costs for installation, operation and maintenance have to be considered. The choice of synchronization system needs therefore be based on all of these aspects. As a result, most facilities employ a hybrid solution, and normally implement a combination of an established, cost-effective RF-based distributions for shorter distances or less critical systems, augmented with a laser-based synchronization system to fulfill the needs of the most timing critical clients at the accelerator and for user experiments. Each of the possible synchronization techniques comes with its distinct challenges, advantages, and drawbacks.

RF Electrical Reference Distribution

RF-based 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. To improve the stability of passive RF distribution systems one has to choose cable types with low-temperature coefficients ideally at about 10 fs/m/K or below operated at their optimum ambient temperature to minimize phase drifts [2, 3]. In addition, it might be needed to actively reduce overall temperature fluctuation in the whole accelerator tunnel during operation, or at least enclosed passages for cable routing, adding additional cost in auxiliary systems like the air and water conditioning system. Nonetheless, passive RF distribution systems can achieve a long-term stability of about 50 fs/day/100m, as shown in [4]. However, compared to standard telecom-grade optical fibers, RF cables suffer with typically 3 dB/100m from signal attenuation, depending on the signal frequency. For large-scale distribution, this would require either a lower distribution frequency with local frequency and phase reconstruction to reduce distortions along the accelerator, and/or additional amplifiers along the distribution lines which may add jitter and phase drift. A completely RF-based synchronization with an interferometric phase reference line and active stabilization is under development and has demonstrated already a phase error as good as ±200fs over several days for short cable length of less than 200 m [5, 6]. Limitations may result for instance from unwanted reflections in the dristribution line.

Continuous Wave Optical Systems

A second approach involves using continuous wave (cw) optical links to distribute a microwave reference frequency over optical fiber, either as an amplitude-modulated (AM) or frequency-modulated (FM) signal. Instead of RF oscillators, cw optical lasers or atomic clocks can serve as ultra-low noise phase reference systems. Crucially, cw optical systems offer the advantage of lower costs while still achieving timing jitter performance as good as 10 fs. For mitigation of long-term timing drifts to below 1 ps over several days, more complex implementations are needed, such as using multiple fibers for the same link, including both uni-directional and bi-directional paths for re-calibration.

For the LCLS, an RF-over-fiber reference distribution system had been developed and implemented, achieving an integrated residual jitter of 17.5 fs rms in a bandwidth from 10 Hz to 10 MHz at a 476 MHz reference frequency. The main limitation of cw reference sources is their deliver of only a single optical frequency, which reduces the variety and performance when phase-locking client systems to the reference. At SwissFEL, however, a cw-optical system was chosen for connecting most systems (remote microwave oscillators), exhibiting less than 40 fs peak-to-peak timing drift over 24 hours and less than 10 fs rms integrated jitter in the frequency range from 10 Hz to 10 MHz [7].

Based on techniques described in the following section, a few pulsed optical links were added for the use of electro-optical bunch arrival time monitors, and for applying all-optical laser-to-laser timing measurements for highest temporal resolution in user experiments.

Pulsed Optical Systems

Synchronization systems based on a pulsed optical laser can provide the best performance in terms of jitter and drift stability, but also typically require highest investment costs for infrastructure and components. In particular, polarization-maintaining fibers are required for both short- and long-haul connections to remote systems at the accelerator facility to ensure best long-term performance and the lowest uncertainty..

Typically, a passively mode-locked laser oscillator 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, when carefully designed and engineered, exhibit outstanding phase and respectively timing jitter stability, especially in the higher frequency range above a few hundred Hz.

Incorporating optical references into timing-critical subsystems, such as other laser systems (photocathode, pump-probe), allows for complete optical detection of time differences, leading to exceptionally high temporal resolution.

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The pulse train whose arrival time is of interest is overlapped with the highly stable optical reference in nonlinear materials such as BBO (beta-barium borate). This process of mixing, which is in this case based on a second order process, of both pulse trains gives birth to a new signal with a different wavelength, which in turn can be detected with conventional photodiodes. The conversion process is efficient when a specific relationship between the mixed frequencies and the material properties are fulfilled, called the (optical) phase-matching condition. Such a signal can then be used as error input to an electronic phase locked loop (PLL) circuit. Using a fast actuator, for instance based on piezo-electric materials, fast phase corrections can mitigate residual timing jitter between two pulsed laser sources to below 1 fs [2]. Moreover, contrary to RF phase detection schemes, these all-optical schemes can be implemented relatively easy to be insensitive to AM-to-PM detection errors. This nowadays well-established technique still undergoes continuous improvement and has been implemented in the optical synchronization system at FERMI, FLASH, the European XFEL, SwissFEL, and will be employed at upcoming facilities like LCLS-II, SXFEL and SHINE for stabilizing fiber-optical links as well as for optical locking of client laser systems. As an example, in 2018 a residual timing jitter of less than 2 fs rms in a bandwidth of 10 Hz to 10 MHz has been shown for locking a laser oscillator to a 3.5 km long fiber link [8]. The short and low-noise optical pulses of the (distributed) reference can also be used for other applications where in the time domain precise time markers are required, such as for arrival time monitors to detect the timing behavior of either electron bunches, optical or X-ray photon pulses [9]. Moreover the mode-locked, short laser pulses can also be used for generating low phase noise RF frequency signals by direct conversion and selecting harmonics of the laser repetition rate, or by more advanced schemes as descibed below. Such RF signals are suited for heterodyne mixing techniques when, for instance synchronizing RF oscillators to the optical reference.

Additionally, there are various optical-to-RF timing measurement techniques, many involving Sagnac-type interferometers as phase detector to retrieve high accuracy microwave signals in the multiple GHz range from an optical pulse train. However, at lower microwave frequencies (in the order of 1 GHz), such as those typically used in conventional linacs, performance decreases. Residual jitter can be around 10 fs rms, with even worse long-term stability at 1.3 GHz. Furthermore, such schemes can also be sensitive to AM-to-PM conversion errors.

In 2011, a novel approach was introduced using ultrashort laser pulses to sample a CW microwave signal. This phase detector uses a Mach-Zehnder-type electro-optical modulator (MZM) to couple the microwave and laser. RF phase variations cause a relative amplitude modulation of the laser pulses, which is detected by a photoreceiver. By using this as an error input to a PLL, a long-term stable performance with 3.8 fs rms residual jitter and less than 15 fs peak-to-peak drift was demonstrated [10].

THE BENCHMARK: THE LASER-BASED SYNCHRONIZATION SYSTEMS AT FLASH AND THE EUROPEAN XFEL

At the FEL facilities operated at DESY, i.e. the Free-Electron Laser at Hamburg (FLASH), as well as the European X-ray Free-electron Laser (EuXFEL), hybrid solutions for synchronization have been implemented. A large-scale pulsed optical synchronization system with multiple point-to-point connections of individually length-stabilized, polarization maintaining fiber links to connect around 40 timing-critical sub-systems and to provide the optical reference for femtosecond-precision time-resolved diagnostics. In addition, a passively stable RF distribution as backbone system, to deliver the 1.3 GHz to around 250 clients, including the main acceleration sections and further standard beam diagnostics.

Figure 1 schematically shows the overall layout of the European XFEL with its synchronization system. Laser systems at the facility are all-optically locked, including the photo-injector laser (INJL) with active drift stabilization, the subsidiary laser oscillator (SLO) for the synchronization sub-distribution in the experimental hall, as well as the laser oscillators at the experiments (PPL). Notably, no cables from the RF distribution are installed further than the main linac section L3, such that all timing-critical systems depend on the operation of the pulsed optical synchronization system.

Main RF Oscillator

The main RF oscillator (MO) as ultimate reference of the accelerator facility has been developed at DESY together with collaboration partners [11], providing a redundancy concept, extremely 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 is derived from a GPS-disciplined 9 MHz OCXO (oven-controlled crystal oscillator), being amplified to high power levels (> 40 dBm) and distributed to the RF acceleration modules along the linac. Crucially, continuous improvements over the past decades reduced the absolute phase noise of the RF reference from initially 35 fs rms in the bandwidth [10 Hz, 1 MHz] [12] by an order of magnitude to approximately 2 fs rms in [100 Hz, 10 MHz] [13], being the critical bandwidth for the phase lock of optical lasers to the MO.

Main Laser Oscillator

To guarantee long-term stable conditions for the core systems of the optical reference, environmental conditions inside the synchronization laser laboratories are controlled precisely to reach sub-0.1 K temperature and approx. 3% peak-to-peak relative humidity stability. The reference laser oscillators (MLO, SLO) are commercially available passively mode-locked oscillators [14]. For redundancy, in both the main and the sub-distribution laboratories two laser systems are installed as hot spare and can be taken into operation within minutes in case the active laser fails. The main lasers

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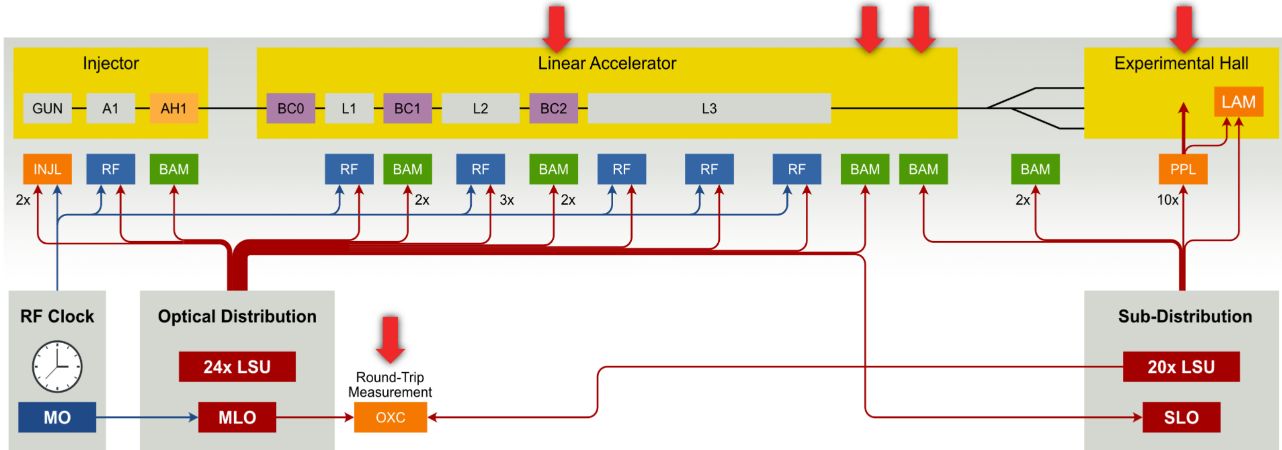

Figure 1: Sketch of the European XFEL accelerator facility and components of its pulsed optical synchronization system, with RF signal paths depicted as blue and optical fiber connections in red lines, main RF oscillator (MO), main laser oscillator (MLO), subsidiary reference laser oscillator (SLO), 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.

are tightly phase-locked to the 1.3 GHz RF reference signal from the MO (approx. 20 m of low-drift cable), achieving a residual jitter of 3 fs rms in [10 Hz, 100 kHz] and practically drift-free because of the utilization of the aforementioned MZM-based RF-to-optical phase detector [14]. The same type of detector is also incorporated into the so-called optical reference modules (REFM-OPT), indicated in Fig. 1 by the symbol ”RF”. The REFM-OPT modules are the first element in the reference signal chain of the low-level RF (LLRF) control system, removing locally all temperature and relative humidity induced phase drifts, by re-synchronizing the 1.3 GHz RF reference signal to the sub-femtosecond stable optical reference with a locking bandwidth of several 100 Hz [15].

Such a stable reference enables the regulation stability of the LLRF system [16] within the design values of 0.01% in amplitude and 0.01 degree in phase [17, 18]. All subcomponents of the LLRF system have been optimized for adding only little or no noise to the phase noise budget.

Beam-Based Measurement and Stabilization

At EuXFEL and FLASH, conventional bunch compressors as descibed above are used for reducing the bunch length from initially few picoseconds at the RF gun in multiple stages to a final length of 5 fs to 10 fs rms [19]. These sections with longitudinal dispersion are used for applying beam-based feedbacks for mitigating arrival jitter by applying energy corrections to the upstream RF modules. For reaching highest stability, corresponding to lowest arrival time jitter of the electron bunches, a longitudinal intra-train feedback (L-IBFB) has been implemented exploiting the burst mode operation of the machines (at 10 Hz, with up to 27000 electron bunches within 600 µs corresponding to an intra-train repetition rate of 4.5 MHz). The electron bunch arrival time monitors (BAMs) downstream of the bunch compressors transmit the arrival time information for each electron bunch directly via a low-latency link to the digital LLRF controls of the upstream RF station. The method uses an error combination and weighting of RF field-based and beam-based measurement in the LLRF system for calculating required amplitude and phase correction to minimize the error signal. With the L-IBFB a bunch-train to bunch-train stability in the few single-digit femtosecond regime can be reached which is close to the resolution limit of the arrival-time monitors (typically 5 fs at 250 pC bunch charge), keeping this performance over days during user operation [9].

After acceleration to final beam energy in the main linac, at EuXFEL the electron bunches are distributed within a switch yard consisting of several kickers to the three SASE beamlines [20]. The RF pulse is separated into several sections, called beam regions (BR), according to the bunch pattern which is distributed by the timing system. Bunches for the different SASE beamlines can be located in different BRs, which allows for relatively flexible tailoring the linac parameters in the regions for the needs of the different SASE photon pulse requirements, and in addition for the application of corresponding (slow) feedbacks. At FLASH, a very similar concept is employed to distribute the electron bunches between the SASE-based FLASH2, and the future seeded FLASH1 beamlines [21].

Benchmarks and Validation Experiments

Several validation experiments had been carried out to benchmark the performance of the synchronization system, the electron bunch arrival time feedbacks and auxiliary systems. In one example, by using photon arrival-time monitors (PAMs, [22]), a nearly perfect correlation was observed in

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the short-term timing of X-ray photon pulses and the electron bunches from which the photons were generated in the SASE process [9]. In addition to the application in beam-based feedbacks, the bunch arrival-time monitors deliver the single-shot information to user experiments, allowing to correct the time delays in pump-probe measurements for keeping time overlap and improving the overall time resolution, under the assumption that the SASE process does not add substantial amount of timing jitter. In this mode of operation, and using feed forward modification of the acceleration fields, custom arrival time patterns can be imprinted on the X-ray pulse arrival time, for instance a linear slope, which enables pump-probe experiments within the burst.

At the SQS scientific instrument located at the soft X-ray beamline SASE3 the the EuXFEL, user experiments have shown that a time resolution of 16 fs ± 2 fs FWHM (fit error the data) can routinely be achieved, which is important for femtosecond pump-probe spectroscopy for rsolving photo-induced structural changes in molecules. The time delay between the x-ray photons and an optical pump laser at the location of the interaction region was scanned by changing an optical delay line (ODL). The expected relative time delay in between both pulses was corrected using the information of the electron bunch arrival times. The temporal resolution in such kind of experiments is limited by the X-ray pulse duration and the residual temporal jitter in between pump and probe pulses, where from the data both parameters have been estimated to be approximately 10 fs FWHM each [23].

The Novelty: Laser Pulse Arrival Time Monitors

Achieving temporal resolution in the sub-10 fs FWHM regime, or even on the sub-femtosecod level in the farther future, improvements for the arrival time monitoring and active stabilization are inevitable, particularly for the temporal stability of the pump-probe laser pulses close to the location of the interaction region (IP). Although a PAM close to the IP (or multiple PAMs down- and upstream of the IP for improved correlation) measuring the X-ray photon pulse arrival time with respect to the optical pump-probe laser pulse would be ideal, such a configuration is practically only realizable in a select number of experimental geometries. Furthermore, in the XUV and soft X-ray regions, but also for certain hard X-ray experiments, implementing a PAM is often not feasible. To measure and mitigate the influence of optical laser pulse timing drift and jitter, development of laser pulse arrival time monitors (LAMs) had been initiated recently. Such monitors, installed as close as possible to (or when multiple devices are involved, around) the IP and will be used to measure the arrival time of the optical pump-probe laser pulses with respect to the ultra-stable optical reference of the laser-based synchronization system, instead of the X-ray pulse. Naturally, the monitor is based on the balanced optical cross-correlation scheme, where, as explained above, the optical mixing process in nonlinear medium strongly depends on the matched wavelengths. This imposes a challenge for the technical implementation of such a device, as in user experiments often the fundamental

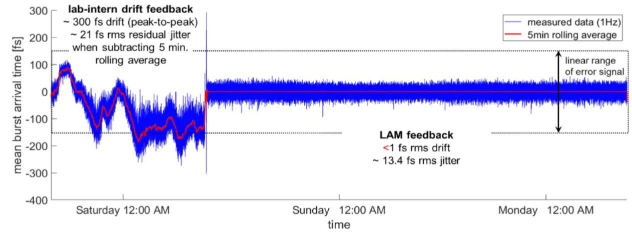

Figure 2: Laser pulse arrival time drift at the FL26 beamline at FLASH withount and with active feedback based on a LAM installed close to the experiment's interaction point. Figure reproduced with permission of N. Schirmel.

wavelength of the pump-probe laser system is converted to another one over a broad spectral region from the UV to the mid-IR, together with modifications of other parameters of the laser radiation (e.g. pulse duration, wavefront, etc.), depending on the actual scientific case. Even more, those changes may occur regularly and at any time during a user experiment, such that a LAM is required to cope with them in a mostly automated matter. Most crucially, the required broad wavelength range coverage will be addressed by altering the established collinear optical cross-correlator geometry [24] to non-collinear, allowing for large phase-matching with negligible loss of efficiency. At the same time, utilizing a LAM which is covering a broad optical wavelength range promises to even improve the temporal resolution in certain user expriments, as until now, the available PAMs are specifically tailored to the fundamental wavelengths provided from the pump-probe laser, such that negative influence from wavelength conversion and/or laser pulse manipulation are not taken into account, even if a PAM is available during the user experiment.

In a first benchmark and validation experiment, a LAM (in this case for the pump-probe laser wavelength of 800 nm) had been installed at the FL26 beamline at FLASH to evaluate the laser pulse arrival time characteristics with respect to the optical reference [25, 26] close to the experiment. Figure 2 shows the measured timing drift, where in the first few hours only the laser-internal (”SysDC”) arrival time feedback was active, while in the remaining time, a slow (approx. 1 Hz bandwidth) feedback acted on a delay line to stabilize the arrival time at the experiment based on the measured LAM data. Without the feedback active, a temporal drift of around 300 fs peak-to-peak had been measured, which results from approx. 40 m of in-vacuum beam transport and laser pulse compression at the experiment.

In a recent follow-up measurement campaign at the same beamline FL26 at FLASH, a user experiment had been carried out to benchmark the achievable time resolution based on laser-assisted Xe photo-ionization. The active arrival time feedback compensated practically all drift of about 500 fs peak-to-peak arrival time, leaving only a narrow jitter band of sub-20 fs rms [27]. To also mitigate this residual jitter, fast actuators will be implemented in the future for feedbacks with kHz bandwidth.

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THE DATA-DRIVEN APPROACHES

At free-electron laser user facilities not only the lowest timing jitter is essential for the success of user experiments, but also the reliability, robustness and in particular the availability of the given research infrastructure. Data-based condition monitoring (CM) is a predictive maintenance method where intelligent algorithms analyze system health data to detect deviations or anomalies at an early stage to avoid unplanned downtimes. It relies on a real-time data aquisition system, which in our case is directly integrated into the accelerator control system [28, 29]. The operationally relevant data is sent from the front-end servers that control the device to a central data server using ZeroMQ, an asynchronous message exchange library. A total of more than 47000 different data channels are collected from 37 different data sending servers, of which approx. 43000 are via publish-subscribe and 3700 via request-reply. From this central data server, all data is stored on a long-term data storage, following the dCache technology [30] in Apache Parquet [31] format.

To identify deviations from the healthy operating state, we primarily use the controller I/O data from the PLLs, which control the laser oscillators and the link units. The system is usually in a healthy operating state. Therefore, algorithms from the area of semi-supervised learning are particularly suitable for identifying any deviations from this normal state. In particular, the autoencoder with convolutional layers shows promising results. In addition, thanks to the data taking, we were able to determine the influence of environmental factors such as laboratory conditions (temperature, humidity, air pressure) and seismic movements at the particle accelerator [32].

CONCLUSION AND OUTLOOK

In summary, at FLASH and the European XFEL high reliability and an excellent stability in the RF field control has been achieved by combining an RF signal distribution with a precise, pulsed optical synchronization system, allowing for the implementation of precise electron bunch arrival time monitors, as well as all-optical schemes for laser synchronization and direct laser pulse arrival time measurement. The overall accelerator and FEL stability is routinely even further improved by applying additional beam-based regulations to the RF cavity control, enabling single-digit femtosecond timing jitter.

Several components and sub-systems at the accelerator have already been identified for further developments to approach the 100 attosecond stability regime in the future, which include improvements of the main RF oscillator and the RF field receivers in the LLRF regulation, as well as higher resolution of the electron bunch arrival time monitors as input for the longitudinal feedback systems. At the same time, laser pulse arrival time monitors will enable monitoring and correcting the pump-probe laser pulse arrival time over a broad wavelength range as close to the interaction point of the user experiment as possible. Sensitivity of those devices will be crucial to enhance feedback loops from slow drift-correcting ones to fast, potentially also pulse-by-pulse ones. Promising results have been obtained meanwhile during several user experiments at FLASH and dedicated measurement campaigns at the European XFEL.

The long-term timing drift behavior observed at European XFEL exhibits an interesting feature, which seems to be explainable from periodic earth movements and ocean tides. This effect of slow stretching and compressing is experienced by all components with large elongated dimensions (e.g. the accelerator tunnel, beam pipe and kilometer long cables). Since the regulation of the length-stabilized optical links corrects for all path length changes, the timing at the synchronized clients is not altered. However, due to actual path length changes for the electron bunches [33] and X-ray photon pulses, there is indeed a slow and periodic drift observed in experiments as delay between the X-ray photons and the synchronized pump-probe lasers. A dedicated project had been started to study this effect in more detail and investigate the possibility of a short-term prediction window and subsequently correction with a feed-forward control loop.

In terms of reliability and availability of the synchronization system itself, but also the accelerator and research infrastructure as a whole, machine learning based approaches are being evaluated and tested at present. At the same time, conventional measurement campaigns are being carried out at the European XFEL, FLASH and individual sub-systems of their synchronization system to identify further potential for improvement. As an example, a measurement is being set up at EuXFEL, where the stability of the laser pulse train traveling both to the experimental hall and back to main synchronization laboratory will be evaluated over a distance of more than 8 km of actively stabilized optical fiber. First results indicate already, that air pressure changes in the two laboratories can alter the stability on the single-digit femtosecond level, caused by a slight difference in optical path length.

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APPENDIX

Terminology and Glossary

Between the various implementations of optical synchronization systems, there are slight differences in terminology and acronyms. A (certainly) incomplete list includes:

BAM (Electron Bunch Arrival Time Monitor): apparatus to measure the arrival time of the electron bunch with respect to an optical pulse train based on electro-optic sampling of the transient electric field induced in a high-frequency pickup antenna installed in the beam pipe.

BCC (Balanced Cross-Correlator), **BOC** (Balanced Optical Cross-Correlator), **OXC** (Optical Cross-Correlator): normally refers to the optical implementation of a scheme based on nonlinear optical cross-correlation and usually realized in a balanced, i.e. amplitude fluctuation insensitive way. Depending on the specific implementation, application or related feedback systems, the acronym is extended, as in **TC-BOC** (Two-Color BOC), **cmBCC** (Common Mode BCC), **dmBCC** (Differential Mode BCC), **SysDC** (System Drift Correlator). The foundation of the **LAM** is also the balanced cross-correlation scheme. The acronym OXC is not to be confused with OCXO (Oven-Controlled Crystal Oscillator), which refers to a term in the RF domain.

FSD (Free-Space Distribution): refers to the optical setup to split and distribute the laser beam of the MLO to the individual LSUs, either realized in a TSP or inside a actively and passively designed environmentally very stable lab. Alternatively, splitting can be realized using optical fiber couplers.

LAM (Laser Pulse Arrival Time Monitor): opto-electronic implementation of an apparatus to measure the relative arrival time between two optical pulse trains, being usually the one of the pump-probe laser with respect to an optical reference and based on an OXC, with the goal to measure or provide feedback to stabilize the laser pulse arrival time. Depending on the context, either the whole implementation or only the optical part is referred to.

LSU (Link Stabilization Unit), **FLS** (Fiber Link Stabilizer): opto-electronic device to measure and compensate for changes of an optical fiber. Depending on the context, only the optical (i.e. mainly the optical cross-correlator), only the actuator part or the whole implementation is referred to.

MLO (Main Laser Oscillator), or **OMO** (Optical Main Oscillator): in pulsed optical synchronization systems, this oscillator provides the train of laser pulses with approx. 200 fs duration, where its repetition rate provides the timing reference for all connected subsystems.

MO (Main Oscillator), or **RMO** (RF Main Oscillator): The main radio frequency oscillator of the accelerator facility.

ODL (Optical Delay Line): device to precisely control and delay the arrival time of an optical laser pulse train. Depending on the implementation, a **FDL** (Fiber Delay Line) might be employed, where e.g. an optical fibre is altered in length by varying its temperature (**TC-FDL**, Temperature-Controlled FDL).

PAM (Photon Pulse Arrival Time Monitor), or **ATM** (Arrival Time Monitor): apparatus to measure the relative arrival time of a XUV or X-ray pulse with respect to an optical reference pulse. Numerous implementations of PAMs are deployed across the different accelerator facilities, where normally the pump-probe laser serves as reference. However, also the reference pulse train of the optical synchronization system is used in specific applications.

PFTS (Pulsed Fiber Timing System): mainly at LCLS, this term is used for the synchronization system based on a pulse optical laser oscillator as MLO. Note that other facilities use the term "timing system" also for the less precise, i.e. not with femtosecond resolution and stability, distribution of clock and trigger signals.

TSP (Temperature Stabilized Platform): In some implementations, the core components of the synchronization system (MLO, splitting, LSUs, ODLs) are installed in this well temperature and humidity controlled enclosure.

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