

# LARGE-SCALE OPTICAL SYNCHRONIZATION SYSTEM OF THE EUROPEAN XFEL

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## Abstract

At the European XFEL, a facility-wide optical synchronization system providing a femtosecond-stable timing reference at more than 40 end-stations had been developed and installed. The system is based on an ultra-stable, low-noise laser oscillator, whose signals are distributed via actively length-stabilized optical fibers to the different locations across the accelerator and experimental areas. There, it is used to locally re-synchronize radio frequency signals, to precisely measure the arrival time of the electron beam for fast beam-based feedbacks, and to phase-lock optical laser systems for electron bunch generation, beam diagnostics and user pump-probe experiments with femtosecond temporal resolution. In this paper, we present the system's architecture and discuss design choices to realize an extensible, large-scale synchronization infrastructure for accelerators that meets reliability, maintainability as well as the performance requirements. Furthermore, the latest performance result of an all-optically synchronized laser oscillator is shown.

## INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) is a fourth-generation linac-based light source being capable of producing X-ray pulses with a duration of only a few to tens of femtoseconds. In particular for time-resolved pump-probe experiments it is crucial to achieve a synchronization between the FEL and the pump-probe laser systems with an accuracy on the same timescale. Accordingly, the synchronization system for the European XFEL was designed and built [1] to achieve a point-to-point timing jitter of 10 fs.

The foundation of the system is a low-noise laser oscillator synchronized to the master radio-frequency (RF) oscillator (MO) of the facility to provide a long- and short-term stable timing reference to critical subsystems using optical fiber links (see Fig. 1). For this, an active fiber length stabilization scheme [2] is employed to compensate optical path length changes, and by this keeping the laser pulse arrival time at the fiber link end stable with a jitter of less than 1 fs (rms) [3]. Since in a large-scale accelerator like the European XFEL the radio-frequency signals, which are the reference signals for the accelerating modules, are distributed over kilometers of cables and amplified several times, phase drift and jitter contributions can add up significantly. To achieve low-drift and low-timing jitter FEL performance, optical reference modules ("REFM-OPT") are installed along the

accelerator to re-synchronize the degraded LLRF signals. These modules provide a femtosecond-precise, low-drift and amplitude-insensitive laser-to-RF phase detection based on an integrated Mach-Zehnder interferometer [4]. Another end-station type is the electron bunch arrival-time monitor [5] which, with its femtosecond temporal resolution, is used for diagnostic purposes as well as within a fast feedback loop on the electron arrival time. In addition to a well stabilized accelerator and thus low-timing jitter X-ray pulses, external laser systems are required to be synchronized with femtosecond precision for time-resolved pump-probe user experiments. Therefore, an all-optical scheme based on two-color balanced optical cross-correlation [6] is applied to precisely measure the timing error between two pulsed laser sources and keep their relative timing jitter at a minimum.

Key requirement for all subsystems relevant for operation of the European XFEL as a facility with over 8000 hours yearly for user experiments is reliability and high availability to ensure minimum amount of downtime. Therefore, strong focus had been laid on development of mechanically, electronically and optically robust systems with large amount of automation, monitoring and redundancy [7, 8].

## OPTICAL REFERENCE DISTRIBUTION

### Master Laser Oscillator

A commercial, passively mode-locked SESAM-based master laser oscillator (MLO) with a repetition rate of 216.7 MHz (one-sixth of the main RF cavity resonance frequency of 1.3 GHz) provides the main optical reference pulse train. The laser is synchronized to the MO at the 7th harmonic of its repetition rate (1516.7 MHz) in a PLL-type scheme, such that the phase detection is realized at an intermediate frequency. This kind of down-conversion instead of applying a conventional DC phase detection scheme bypasses problems like DC offsets, electromagnetic interference at low-frequencies as well as 1/f noise related jitter contributions. Furthermore, this scheme allows for choosing an arbitrary phase set point and thus enabling the possibility to electronically shift the timing of the laser pulses. To achieve the highest level of availability a second, redundant laser oscillator of the same type is installed while an automated and fast switching procedure ensures the possibility of an uninterrupted switching in case of a failure. At the same time the MLOs, together with the complete optical synchronization infrastructure and the MO, are connected to an uninterruptible power supply for maximum uptime.

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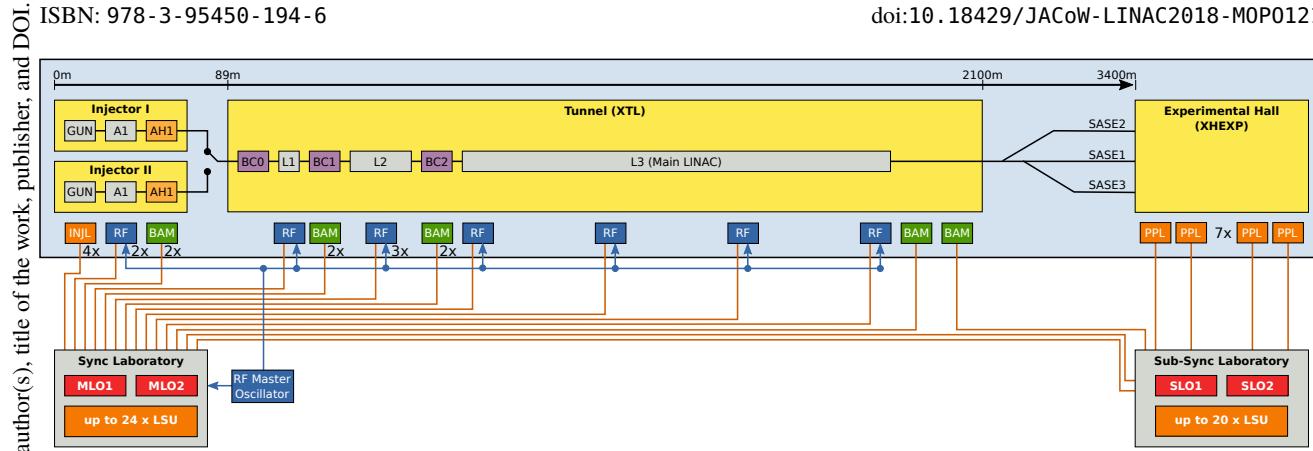


Figure 1: Schematic overview of the optical synchronization system at the European XFEL.

### Free-Space Distribution

The beam of the MLO is split up in a free-space distribution system based on half-wave plates and polarizing beam splitters to serve for a total of 24 end stations. To minimize drifts caused by a change of the optical beam path a custom optical table with both sides made from SuperInvar and by this eliminating bi-metallic effects was chosen, and, moreover, the path length between laser source and LSUs is identical for all 24 end stations resulting in identical beam parameters. Taking into account the beam path length between the MLO and the link stabilization units (LSU, see below), the thermal expansion coefficient of SuperInvar (1 fs/K/m) and the temperature stability of the laboaratory ( $\ll 0.1$  K) the residual drift due to thermal expansion of the optical table can be estimated as less than 300 as [1]. Another drift source on the non-stabilized beam path to the LSUs is the change of the refractive index of air with temperature, relative humidity and air pressure. This problem can be solved by synchronizing the MLO to a reference point with a distance equal to the LSU beam path length. As a result, all residual drifts are common mode and do not degrade the overall stability.

### Sub-Distribution System

The main synchronization laboratory at the European XFEL is located in the injector building between the MO room and the photocathode laser laboratory. Additionally, a secondary synchronization system (see Fig. 1, "sub-sync") was located close to the scientific instruments in the so-called experimental hall to provide the optical reference signals to a further 20 end stations. This sub-distribution system is operated with another laser oscillator (of the same type as the MLO) in a master-slave configuration, where the slave laser oscillator is tightly synchronized to the optical reference pulse train provided by a stabilized fiber link from the MLO. In fact, two stabilized fiber links connect the secondary synchronization system to the main optical reference, while also a second SLO is installed for redundancy reasons.

### FIBER LINK STABILIZATION UNITS

The basic principle of the LSUs is an all-optical measurement of arrival time changes between a laser pulse which had traveled forth and back through the optical fiber to the end station and fresh ones from the MLO. This measurement is based on a twofold non-linear optical frequency conversion process (sum-frequency generation, SFG) in a balanced configuration to eliminate deterioration of the timing error detection due to amplitude fluctuations [3]. For the LSUs installed at the European XFEL a type-II phase-matched PP-KTP<sup>1</sup> crystal was chosen for maximum conversion efficiency at low optical power levels. Additionally, the required back reflection for the balanced operation is realized by coating the crystal with a dichroic layer at its back surface. The two SFG signals are detected using a low-noise balanced photo detector, digitized and fed into a feedback loop to keep the optical path length to the end station constant utilizing two actuators as part of the overall link path. A piezo-based fiber stretcher is used for compensation of fast timing errors while a 4 ns (single-pass) optical delay line is used to cover larger drifts once the fiber stretcher reaches its limit. Under realistic conditions, drift compensation of up to 200 ps/km had been required. All fiber links at the European XFEL, being up to 3.6 km long, are based on polarization maintaining fiber to mitigate the effect of polarization mode dispersion which would in particular for longer links degenerate timing detection.

### LASER SYNCHRONIZATION

An essential feature of the optical synchronization system based on the distribution of pulsed laser radiation is the ability of synchronizing external laser systems to the optical reference by a direct all-optical technique. Similar to the scheme for fiber link stabilization, it is based on a two-color balanced optical cross correlation (see Fig. 2 and [6]), which provides high-resolution measurement of the timing error between the reference and the external laser. Again, a twofold sum-frequency generation process in a nonlinear crystal re-

<sup>1</sup> periodically-poled potassium titanyl phosphate

sults in a pure timing-sensitive error signal not affected by amplitude fluctuations of the two input signals. To lock the

however, strongly suppresses low-frequency contributions to the phase noise.

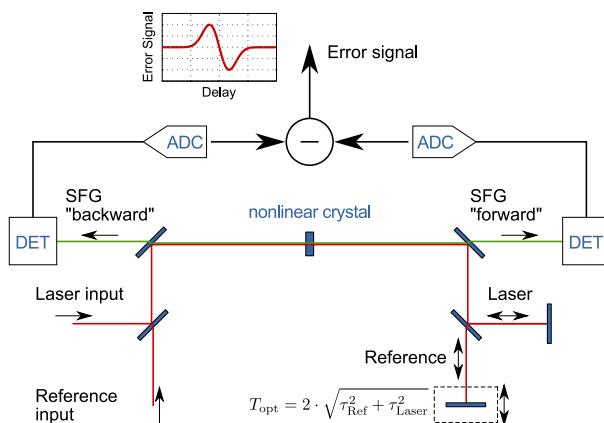


Figure 2: Balanced optical cross-correlation - principle.

laser repetition rate to the one of the reference, the error signal is fed back within an electronic control loop based on the MTCA.4 computing architecture that tunes the laser cavity length. The fast FPGA-based control system firmware allows for establishing of this optical synchronization loop even without prior locking to RF-based loops. At the European XFEL, different types of laser oscillator configurations need to be covered and supported by the synchronization system, in terms of parameters as wavelength, pulse duration or repetition rate as well as the type of cavity tuning. Therefore, the MTCA.4-based electronics provides drivers for multiple piezo actuators, stepper motors, piezo-based motors as well as temperature tuning.

### Measurement Results

In case of the synchronization of the slave laser oscillator to the reference laser pulse train two-color optical cross-correlation can not be applied, since both lasers operate at the same wavelength. Therefore, polarizing optics are used instead of dichroic mirrors for the combination of the two input beams, while the same type-II non-linear process in a PPKTP crystal as in the fiber link stabilization is employed and in fact realized on a only slightly modified mechanically engineered LSU optomechanical base plate. Figure 3 (upper panel) shows the result of the phase noise measurement while the SLO is optically locked to the reference pulse train with power levels of 20 mW and 11.3 mW, respectively. The in-loop differential signal was recorded from the balanced photo detector and evaluated using a baseband analyzer<sup>2</sup>. Integrating the phase noise in the lower panel of Fig. 3 in the measurement bandwidth (10 Hz - 10 MHz) yields a total rms jitter of 1.25 fs. The two main contributions can be identified at around 400 Hz as well as the superelevation between 1 kHz and 20 kHz. While the prominent distortion around 400 Hz is caused by acoustic coupling from rack cooling fans, the main contribution of approximately 1 fs to the total jitter is caused by the waterbed-related peak, which,

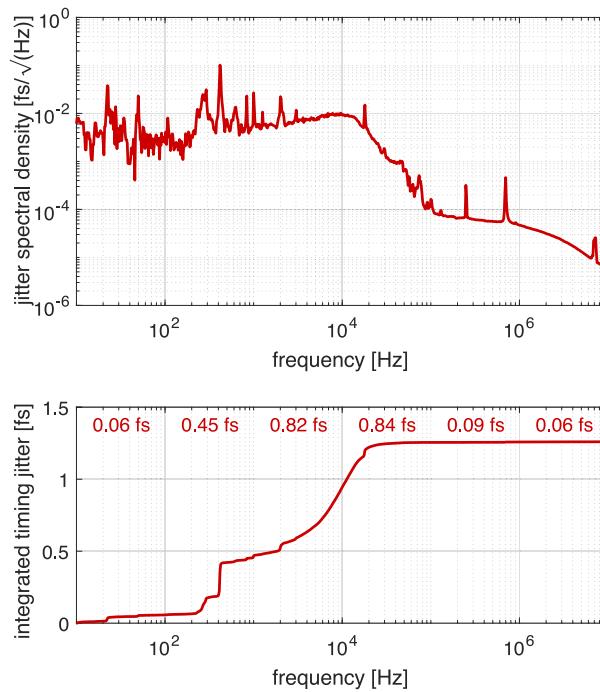


Figure 3: SLO phase noise and integrated rms timing jitter.

## CURRENT STATUS AND SUMMARY

The European XFEL started operation in 2016 and pump-probe experiments at the first beamline (SASE1) have been performed in September 2017 using the pump-probe laser phase-locked to the optical synchronization system. However, installation and commissioning of several further subsystems is still ongoing. This mainly concerns fiber links in the experimental hall as well as the corresponding laser synchronization systems for the upcoming scientific instruments at the beamlines SASE2 and SASE3, where just recently X-ray radiation had been produced. The total number of 8 fiber links within the sub-distribution system and 7 laser synchronization systems in the experimental hall will be in operation until early 2019, with 3 fiber links and 1 laser synchronization system already running. In the main synchronization laboratory all installations are finished and all required 18 length-stabilized optical fiber links are in operation. For the present status of the accelerator and in particular the experimental facilities, the optical synchronization system has practically reached its final state, but is at the same time prepared for future upgrades. In summary, an overview of the laser-based synchronization system at the European XFEL was presented, as well the current status of the latest installations. Recent performance studies of an all-optical laser-to-laser synchronization scheme with an integrated rms jitter below 1.3 fs have been shown.

<sup>2</sup> Agilent E5052B

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