FEMTOSECOND TIMING DISTRIBUTION AT THE EUROPEAN XFEL

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Abstract

Accurate timing synchronization on the femtosecond timescale is an essential installation for time-resolved experiments at free-electron lasers (FELs) such as FLASH and the upcoming European XFEL. To date the required precision levels can only be achieved by a laser-based synchronization system. Such a system has been successfully deployed at FLASH and is based on the distribution of femtosecond laser pulses over actively stabilized optical fibers. For time-resolved experiments and for special diagnostics it is crucial to synchronize various laser systems to the electron beam with a long-term stability of better than 10 fs.

The upcoming European XFEL has raised the demands due to its large number of stabilized optical fibers and a length of 3400 m. Specifically, the increased lengths for the stabilized fibers had necessitated major advancement in precision to achieve the requirement of less than 10 fs precision. This extensive rework of the active fiber stabilization has led to a system exceeding the current existing requirements and is even prepared for increasing demands in the future. This paper reports on the laser-based synchronization system focusing on the active fiber stabilization for the European XFEL, discusses major complications, their solutions and the most recent performance results.

INTRODUCTION

For the European XFEL a very strong emphasis is put on accurate timing and on the optical timing distribution. Already in the very first expansion stage 27 stations will receive optical synchronization with the option to extend this number to 44 stations. Additionally, the length of the accelerator increases by an order of magnitude compared to FLASH, which has a length of 300 m. This has necessitated a thorough planning and redesign of the existing optical synchronizationn system at FLASH. In the following an overview is given.

The master-oscillator (MO) distributes a stabilized 1.3 GHz reference to which the master laser-oscillator (MLO), with a repetition rate of 216.7 MHz (a sixth of the MO frequency), is locked. The stabilized pulse train from the MLO is split into multiple channels and guided to the individual link stabilization units (LSUs) through the free-space distribution (FSD). Each LSU actively stabilizes the effective length of its assigned optical link fiber, which can conveniently be guided through the entire FEL to stations obliged to femtosecond timing stability. One notable feature in this optical synchronization system is the slave laser-oscillator (SLO) at the end of the FEL. A sub-synchronization will be located in the experimental hall at the end of the beamlines to facilitate all the synchronization needs for the pump-probe lasers on-site. Additionally, it will stabilize all stations between 2.1 km and the end of the experimental hall. Hence, two more links with a length of 3.6 km are provided for SLO to MLO locking. On the one hand, this serves as a redundancy improving reliability and robustness. On the other hand, these two long links can be cross-correlated in-situ for diagnostics providing numbers for the actual synchronization accuracy.

CONCEPT

The optical synchronization system for the European XFEL will adopt to the greatest possible extent the proven and reliable system from FLASH. The long term experience with the optical synchronization system at FLASH has led to numerous enhancements and deeper understanding of the issues involved in such a complex and sensitive precision arrangement. Consequently, for the European XFEL an inimitable possibility arises to incorporate all the gathered knowledge from the bottom up into a new benchmark setting synchronization system.

The distribution of a highly stable optical pulse train to different stations along the complete European XFEL is divided into multiple steps which need individual attention.

The key system of the optical reference distribution is the master laser oscillator (MLO) which is stabilized by a phase-locked loop against the master oscillator (MO), which again is frequency stabilized by a Global Positioning System receiver to ensure best possible long term performance. The locking of the optical pulse train of the MLO against the RF signal of the MO requires a photodiode to convert the optical signal to an electrical for phase comparison. The phase difference is fed back by a feedback loop into the MLO. However, a conventional photodiode set-up is subjected to the AM-to-PM effect [1–3], where amplitude variations convert into phase variations. Despite the very high optical power stability of the deployed MLO minimising the degradation of phase variation due to the aforementioned effect, a more sophisticated method will be introduced for MLO locking. This method is inherently free of the AM-to-PM effect and has already proven high performance [4].

The stabilized optical pulse train is split free space by polarizing beam splitters into multiple channels to feed all link stabilization units (LSU). To accommodate the large number of LSUs - up to 24 LSUs are used on one optical table - they need to be placed efficiently. The optical free space path for each individual channel reaches a certain length. The lengths are kept identical to maintain identical beam parameters for each LSU. However, a distance of about 2 m has to be covered in free space on the optical table.

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Conventional optical tables are composed of 4.8 mm thick steel plates as top and bottom sheet. Steel has a thermal expansion coefficient of about 10 ppm/K or about 33 fs/K/m [5]. For a climatization environment a thermal stability of 0.1 K is ambitious, but realistic. That would result in more than 6 fs drift for the optical table alone. Clearly, this is outside the acceptable range. Therefore, the optical table supporting the MLO and the LSUs - more specifically the top and bottom sheet - are made from Superinvar, which has a very low thermal expansion coefficient resulting in less than 1 fs/K/m [5]. Both sheets have been manufactured from Superinvar to avoid a bimetallic effect among other details. The most dominant contribution for drift is now the change of refractive index of air which is about 3 fs/K/m [6]. This issue can easily be overcome by placing the aforementioned laser locking scheme at the same distance from the MLO as the LSUs and exploiting common mode drift. While the temperature distribution on an optical table is usually not uniformly distributed due to the finite thermal conductivity, the temperature distribution of air is governed by movement. Consequently, this optical table incorporates dedicated holes for this purpose and a ventilation system is integrated into the climatization system.

The choice of Superinvar as top and bottom sheet demands to take great care with mounting optics and systems on it. The superior thermal performance of this material must not be degraded. Consequently, the classical clamping forks are banned as they apply mechanical stress and occupy a lot of valuable space. All the optics are mounted directly onto the optical table by cylindrical optical post which have been specifically designed to match the mechanical requirements. The small footprint of these post with a diameter of 24 mm is sufficiently small not to degrade the mechanical properties of the table. As a side effect the optical paths are kept in the 25 mm grid of the metric optical table simplifying optical alignment and diagnostics.

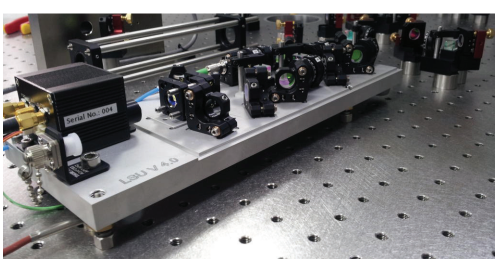

Figure 1: First link stabilization unit on optical table in the European XFEL.

Larger components required on this table - like the LSUs and MLO - received special feet for accurate placing. They are derived from the classical 3-point support which is commonly found on kinematic optical mounts. This is also a beneficial factor for the LSUs. While it sounds logical to also make the LSUs out of Superinvar to avoid thermal expansion and therefore resulting drift, we have chosen another approach. Superinvar is an expensive material and has a high lead time. However, a careful placing of the 3-point supports in the LSUs results in zero drift if a uniformly distributed temperature can be assumed. As the maximum dimension of the LSUs is 31 cm with a thickness of 15 mm, a material with reasonable thermal conductance is sufficient. In our case, we have chosen aluminum to avoid the aforementioned disadvantages, which provides a decent thermal conduction. Figure 1 presents an opened LSU made from aluminum on the Superinvar optical table in the European XFEL. One of the three 3-point supports is visible between the top sheet of the table and the LSU plate in the lower left corner of the photography. Additional rubber bumps are mounted for convenient assembly and storage; they do not touch the optical table when placed. Also, some of the custom mounts for optics are shown in the top right corner.

To complete the design concept logically consistent, all the optical delay stages and the supplementary fibers are also banned from this optical table. The optical delay lines are placed on a second optical table which is made from conventional steel. The frequent movement of this coarse delay correction introduces vibrations which must be kept away from the MLO. All the supplementary fibers - for amplification and dispersion compensation etc. - are placed in a compact 19 inch rack under the second optical table. This allows parallel working, commissioning and simplified maintenance.

EXPERIMENTAL RESULTS

The finalized design of the LSU has been manufactured in a small quantity for final tests before a large number has been sent to production. This test environment is kept identical to the previous experiments [7] and only the LSU itself has been replaced by the finalized production version. It should be noted that the used laboratory does neither feature a Superinvar table nor the new control electronics which is based on MTCA.4 [8]. The identical environment allows a concentrated test on the LSU alone.

Figure 2 presents the results of these test and confirms that the performance is identical to the previous test with a demonstrator set-up [7]. This result has released the large volume manufacturing for the European XFEL.

The following tests will concentrate on the fusion with the enhanced electronic performance of the MTCA.4 based system. While the most evident improvements are increased ADC and DAC sampling rates and resolutions for detection and regulation, here, another uniqueness will be introduced. The balanced detector - which is also an in-house development - will read out both photodiodes individually as this technique has a couple of advantages. First, the EMI situation is improved, as both photodiode signals are guided by two closely spaced low-crosstalk cables to two ADCs. The difference signal for locking is generated inside the regulation algorithm. This way any potential EMI will affect both cables highly identical which can be considered like a common mode distortion. The two single-ended ADC inputs can be regarded as a differential input. Any imbalance or offset error can be canceled out by the algorithms running on the

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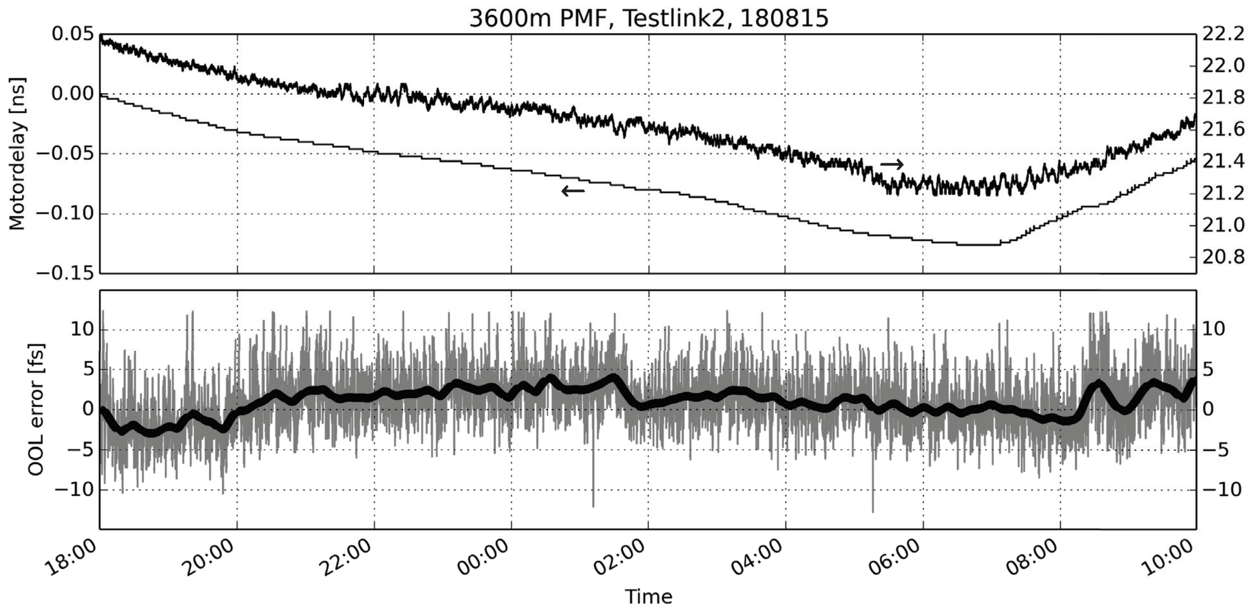

Figure 2: In the top graph the compensated length change of the fiber and the corresponding temperature is shown. The delay is given for one-way and therefore represents the drift of 3.6 km polarization maintaining fiber. The lower graph presents the measured residual out-of-loop timing error at the end of the stabilized fiber. Gray color shows the raw data, while the black line is a convolution with a Hanning-window of 1 h full length to distinguish between jitter and drift.

MTCA.4 system. Also, this technique features an inherent lock detection as both photodiodes carry some DC part in a locked state. This DC value provides additional relevant information of the link situation.

CURRENT STATUS

The main synchronization room in the European XFEL is ready for installations and the first optical set-ups are already built up. By the time of writing, the first MTCA.4 systems for the optical reference distribution are finalized and placed into their designated places. About 5 km of polarization maintaining fibers are already inserted which is about 25 %. These fibers serve the injector area, the photoinjector laser and the first LLRF station of the 2 km long LINAC. These fibers received a special custom jacket suitable for underground installations and complying with fire safety rules. To the best of our knowledge this is a unique feature in the accelerator community.

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