DEVELOPMENT STATUS OF OPTICAL SYNCHRONIZATION FOR THE EUROPEAN XFEL

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Abstract

Precise timing synchronization on the femtosecond timescale is a crucial asset for time resolved experiments at free-electron lasers (FELs) like FLASH and the upcoming European XFEL. The required precision can only be achieved by a laser-based synchronization system. The synchronization at FLASH is based on the distribution of femtosecond laser pulses over actively stabilized optical fibers and has evolved over the years from a prototype setup to a mature and reliable system. At the same time, the present implementation serves as prototype for the synchronization infrastructure at the European XFEL. Due to a factor of ten increase in length of the accelerator and an larger number of timing-critical subsystems, new challenges arise. This paper reports on the current development progress of the XFEL optical synchronization, discusses major complications and their solutions.

INTRODUCTION

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 timing synchronization system.

A schematic representation of the synchronization system is shown in Figure 1. 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. While this MLO lock at FLASH employs a homodyne scheme, the locking of the MLO at XFEL will benefit from a more robust and drift-free approach [1]. 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). The latest status of the LSUs deployed at FLASH is described in [2]. Each LSU actively stabilizes the effective length of its assigned optical link fiber. The optical link fibers can be conveniently guided through the entire FEL to stations obliged to femtosecond timing synchronization. The optical synchronization stabilizes the RF reference fot 12 stations [1] for Linacs, two laser-to-laser locking stations (L2L) [3] for the photoinjector lasers and uses of the pulse train directly for seven bunch arrival-time measurement stations (BAM) [4]. One notable feature in this optical synchronization system is the slave laser-oscillator (SLO). 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 3.5 km links 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 meaningful numbers for the actual synchronization accuracy. One more LSUs is included in this planning to reserve space for later use yielding 24 LSUs in total for the main synchronization.

REALIZATION

The optical synchronization scheme is dependent on a drift-free locking of the MLO to the MO. This locking method [1] will be implemented close to the laser to achieve best possible performance. As the MO will be localized in the vicinity, but in a different room, about 20 m of coaxial cable is required. To overcome potential drift of this cable a reflectometer set-up will be employed [5]. The LSUs will actively stabilize the optical fiber link to their stations. However, the FSD, between the MLO and the LSU, leaves a gap in active stabilization demanding a considerate design.

The current version of the LSU [2] occupies an area of approximately 30 cm by 40 cm and the final state of expansion will hold 24 LSUs in the master synchronization. Apparently, the required space would lead to quite large dimensions of an optical table leading to various problems. Furthermore, two MLOs - for redundancy - as well as the FSD with diagnostics will also significantly contribute to the space requirements. Moreover, the built-in motorized delay stage of the LSU is capable of compensating a timing change of up to ±0.5 ns which is insufficient for the increased optical lengths of the European XFEL with an expected timing variation of a few nanoseconds. Consequently, the LSU design had to be revised with respect to its size and its dynamic range of compensation.

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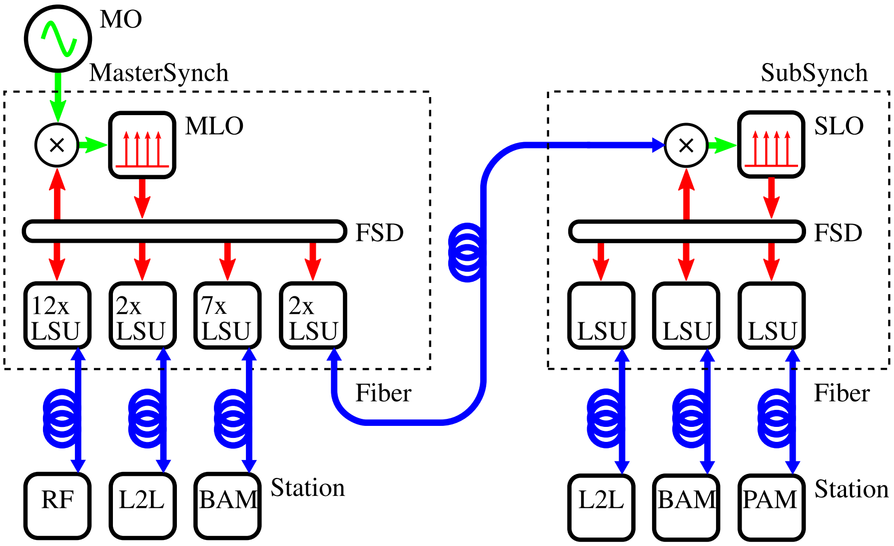

Figure 1: Schematic representation of the optical synchronization system for the European XFEL. The master synchronization will be located close to the injector and stabilize all stations up to 2.1 km. Also the slave laser oscillator of the sub-synchronization will be synchronized in the experimental hall 3.5 km downstream. All the stations between 2 km and the experimental hall will be synchronized from there.

Therefore, the existing LSU design is split into two separate units. One - the secondary unit - will contain the comparably uncritical actively compensated part of the LSU which comprises the motorized delay stage, dispersion compensation, fast piezo-based delay change and an optical amplifier. The other - the primary unit - is the critical element, as it implements the timing detection which has to be as close as possible to the MLO. Due to the reduced distance between the MLO and the LSUs the timing drift susceptibility caused by enviromental changes is significantly reduced. Such a prototype has been designed and its primary unit - the timing detection - is shown in Figure 2 in comparison to the existing design. This new prototype has a length of 32 cm and a width of 12 cm enabling a close spacing of all needed LSUs on the optical table and a reduction of required space by a factor of about 2. This reduction already includes the additional space required for two lasers and the FSD. The layout for the primary optical table occupies about 1.3 m by 2.2 m and is shown in Figure 3.

As a result of this development a secondary table is required to hold the secondary units of the LSUs. Nevertheless, their connection to the primary units with optical fibers are already within the compensated path and therefore comparably uncritical.

Albeit the reduced dimensions of the primary optical table a passive stabilization is compulsory requiring a closer look at used materials and their properties.

Table 1 contains temperature and relative humidity coefficients of materials which are used in the optics set-up. Aluminum is comfortable to work with, but has a large temperature coefficient. Hence, it is only used for small components like posts. The standard material for optical tables is steel. Excellent stability and stiffness are its most complimented benefits. However, the thermal expansion coefficient of steel is not suited for the required timing precision. Guiding the pulse train by optical fibers is not adequate as well. Even phase stabilized optical fibers (PSOF) exhibit a pronounced effective length change with temperature and - to make things worse - even with relative humidity. It is worth being noted, that even air shows a significant effective length change by varying temperature as its refractive

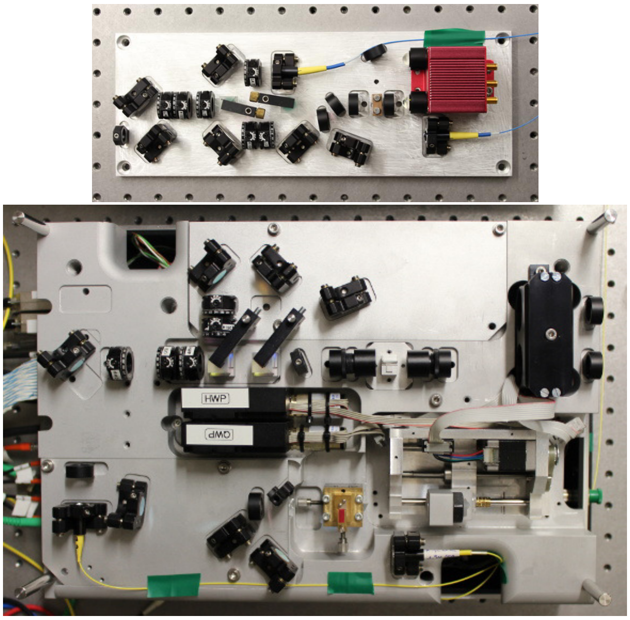

Figure 2: The prototype of the new link stabilization primary unit (top) has a size of 32 cm by 12 cm. The existing design (bottom) used in FLASH has a size of 42 cm by 30 cm.

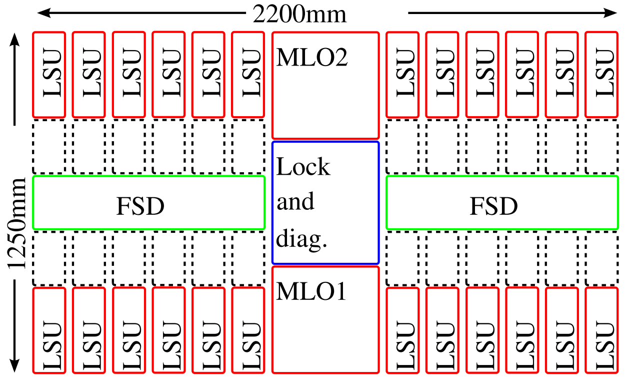

Figure 3: Layout plan for the primary optical table. The new prototype LSU notably reduces space requirements and accordingly potential drift sources.

Table 1: Temperature and Humidity Influence

Material	**Temperature fs / K / m**	**Relative humidity fs / %RH / m**
Aluminum	≈77	-
Steel[6]	33	-
SMF28e[7]	40	2.5
Furukawa PSOF[7]	3.2	0.4
Air	3	0.03
Superinvar[6]	<1	-

index changes.

Fortunately, there is one material available featuring good machinability and low thermal susceptibility. Superinvar®(the further improved version of invar®) is the material of choice. Its excellent thermal insusceptibility even outperforms air. The free-space path from the MLO to a LSU is approximately 1.5 m and will be kept identical for all LSUs. This results in a thermally induced timing error below 1.5 fs/K for the FSD. The target climatization stability for the XFEL synchronization room below ±0.1 K and is already obtained in the FLASH synchronization hutch. The same applies to the stabilization of relative humidity which shows a variation of less than ±3%. These values are detoriated by the presense of persons due to their body radiation. To even further reduce climatization variations the same isolation concept as at FLASH will be incorporated. The optical table is thermally isolated and has a large mass. This reduces temperature and humidity variations even further down to the limit of the resolution (0.01 K) of the employed measurement equipment.

ENVIRONMENTAL CONDITIONS

In addition to stringent demands on the accuracy of temperature and relative humidity, several further environmental aspects need elaborated arrangements, too.

A indisputable source for synchronization performance degradation are vibrations. For femtosecond accuracy the demand for lateral displacements far below a micrometer is obvious. Here, the coupling from ground motion to the optical table is just one factor to be considered. The influence of vibrations on the optical table to synchronization errors predominantly depends on the quality of the employed opto-mechanics. The experience with the optical synchronization at FLASH, specifically its opto-mechanics, is invaluable for the XFEL design. In the case of the optical table accommodating the FLASH synchronization systems vibrations can be measured albeit standing on an own groundwork. Nevertheless, measurements revealed that the existing vibration levels are approximately 10 times below the threshold of synchronization error detectability. For the optical table employed for the synchronization of XFEL there is no possibility for an own groundwork. However, the concrete floor has a thickness of 1 m as it also serves as radiation shielding from the injector underneath. The level of vibrations cannot be assessed at this time, but has to be measured once all installations are complete and in operation.

Acoustics or (fast) barometric pressure variations primarily influence the MLO. While atmospheric pressure changes occur on a slow timescale and are effortlessly compensated by the laser-lock electronics, faster changes leave a small residual synchronization error. Such influence has been already observed in the synchronization at FLASH where vibrations had been transferred over the roof and led to a low frequency barometric pressure variation detected in the MLO phase noise and all LSU OXC signals. The overall concrete structure of the XFEL and the heavy fire doors should keep this influence low.

A widely underestimated aspect for the precision for a synchronization system is electromagnetic interference (EMI). As the system relies on sophisticated electronic regulation and controls, inherently EMI is deteriorating the signal-to-noise ratio (SNR) of all signals. Cables between the optical system and their corresponding regulation electronics lead to a sensitive set-up. While all sort of noise sources in electronic circuits can be calculated straightforward, the assessment of the EMI influence is a rather complicated topic. At the FLASH optical synchronization system the 50 Hz of mains and its harmonics can be detected all over the installations although the EMI precautions have been installed. Furthermore, a large number of electrical distortions arises from the electronics itself and from the proximity to other high-voltage and high-current FLASH installations. Magnetic fields have been measured to be 300 nT rms and electric fields up to 10 V/m rms.

Consequently, a considerate grounding and shielding approach needs to be implemented prior to the installation of optical and electronic systems. For the upcoming XFEL it will comprise a copper floor hidden under a raised floor as a central ground point for all electronics and electrics. Dedicated ferromagnetic cable channels with a low impedance connection to this copper floor will be separated by sensitive signals and potentially disturbing signals to reduce their coupling. As a matter of course racks and the optical tables will be grounded with low impedance copper bands in addition to safety grounding with cables only.

SUMMARY

The design of the European XFEL strongly benefits from the gathered experience by the daily operation of the FLASH accelerator. All the in-house experiences can flow directly into each system which will yield best possible performance from the planing up to operation.

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