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ALL-OPTICAL SYNCHRONIZATION OF PULSED LASER SYSTEMS AT FLASH AND XFEL

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Abstract

The all-optical laser synchronization at FLASH and XFEL provides femtosecond-stable timing of the FEL X-ray photon pulses and associated optical laser pulses (photo-injector laser, seed laser, pump-probe laser, etc.). Based on a two-color balanced optical cross-correlation scheme a high-precision measure of the laser pulse arrival time is delivered, which is used for diagnostic purposes as well as for the active stabilization of the laser systems. In this paper, we present the latest installations of our all-optical synchronization systems at FLASH and the recent developments for the upcoming European XFEL that will ensure a reliable femtosecond-stable timing of FEL and related pulsed laser systems.

INTRODUCTION

The free-electron laser in Hamburg (FLASH) and the upcoming European XFEL as fourth-generation linac-based light sources are capable of producing X-ray pulses with a duration of a few femtoseconds. Particulary for time-resolved pump-probe experiments and the externally seeded operation mode it is mandatory to achieve a synchronization of the external laser systems with an accuracy on the same timescale. One possibility to fullfill the requirements of a femtosecond-precise synchronization is a laser-based infrastructure [1]. Already in operation at FLASH and currently in the installation phase at XFEL the transmission of a highly stable periodic train of laser pulses to the critical subsystems over actively stabilized optical fibers is used and provides a time-stable reference signal to the corresponding end-stations [2]. This laser pulse train can be utilized directly for diagnostic purposes like in the bunch arrival time monitors [3]. Another application is the high-precision synchronization of external pulsed laser systems using a two-color balanced optical cross-correlation scheme [4]. The first prototypes for the actual system at FLASH were installed in 2007. Meanwhile, this optical synchronization system has grown to a key part of the facility. Further improvements of the system, particulary with regard to the European XFEL, focus on reliability and maintainablity of the subsystems. As one result we show here the first version of a new engineered design for laser-to-laser synchronization that is based on the well-proven all-optical laser synchronization setup currently running at several locations at FLASH.

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LASER-TO-LASER SYNCHRONIZATION

One essential key feature of the optical synchronization systems at FLASH and XFEL is the laser-to-laser (L2L) synchronization of external pulsed laser systems. This is based on a two-color balanced optical cross correlation scheme [4] that delivers a high-precision measure of the timing error between the reference and the laser pulse. Here, a twofold sum-frequency generation process in a nonlinear crystal provides a pure timing-sensitive error signal that is not affected by amplitude fluctuations of the two input signals. The principle of the balanced optical cross-correlation is shown in Fig. 1. To lock the laser repetition rate to the reference the error signal can be fed back within an electronic control loop that tunes the laser cavity length. The initialization of the synchronization process requires an additional RF-based pre-locking with a locking stability in the order of the used pulse widths.

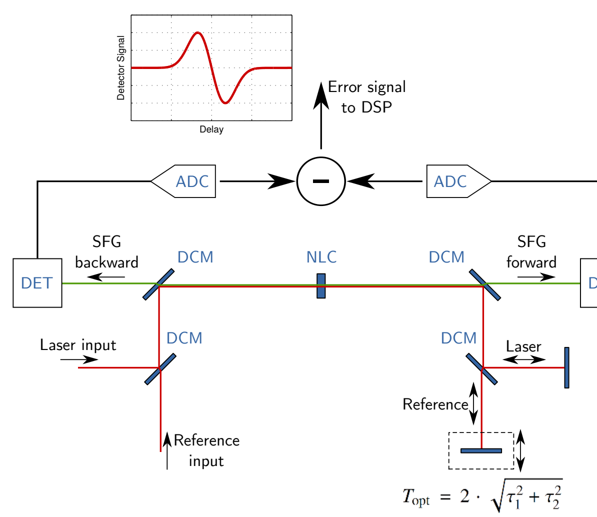

Figure 1: Principle of the balanced optical cross-correlator.

Current & Future Installations

So far we are operating three L2L-based synchronization setups at FLASH. The all-optical synchronization of the pump-probe laser system has brought great improvement regarding the jitter performance between pump-probe and FEL pulses [5]. A facility-wide timing jitter between pump-probe and FEL pulses could be shown to be below 30 fs (rms) [5]. Beside this, the injector laser system at FLASH is also equipped with an optical cross-correlator whereat no fast synchronization but a slow drift feedback is used to lock the laser to the optical reference. And meanwhile we also upgraded the synchronization system of the Ti:Sapphire

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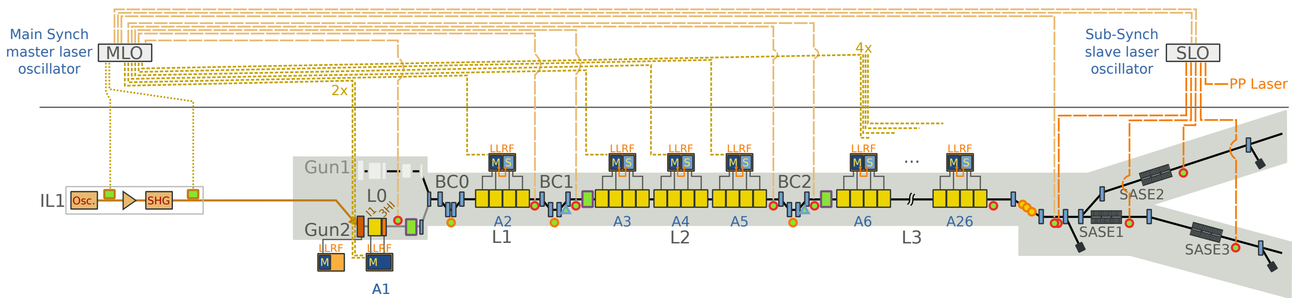

Figure 2: Schematic of the laser-based synchronization system at XFEL.

seed laser with an optical cross-correlator similar to the pump-probe system. An identical setup is also planned for another Ti:Sapphire system that serves as a source for EO-experiments.

More optical laser synchronization installations are planned for the FLASH II extension. These are for the 2nd injector laser system, a common setup for both injector lasers in the UV range, a laser system for the seeding mode and the pump-probe system for the FLASH2 beamline as well as a laser system for the upcoming wakefield-accelerator project FLASHforward [6]. Furthermore, the complete new laser-based synchronization system at the XFEL facility foresees in total 6 optical laser synchronization systems. As shown in Fig. 2 this again concerns the two injector as well three pump-probe laser systems. Table 1 gives an overview of the current and future installations of laser systems with L2L-based synchronization scheme at FLASH and XFEL.

The increasing number of systems reveals the demand for a new common design for all optical laser synchronization systems at FLASH and XFEL to obtain the highest degree of maintainability. Thus, a new engineered setup based on the so far collected experience from our existing systems was built up and is now ready for installation in our facilities. Beside a better maintainability we focussed on the development of a compact and mechanically high-stable design that covers the requirements for the synchronization of all different laser systems at FLASH and XFEL.

Table 1: Current & Future Laser Systems with L2L-based Synchronization Scheme at FLASH and XFEL

FLASH	
Location	**Type/Wavelength/Rep. Rate**
Injector 1 (IR)	Nd:YLF, 1047 nm, 1 MHz 10 Hz bursts
Injector 2 (IR)	Nd:YLF, 1047 nm, 1 MHz 10 Hz bursts
Injector (UV)	Nd:YLF (4xf), 262 nm, 1 MHz 10 Hz bursts
EO	Ti:Sa, 800 nm, 108.33 MHz
Seed F1	Ti:Sa, 800 nm, 81.25 MHz
Seed F2	not specified yet
Pump-Probe F1	Ti:Sa, 800 nm, 108.33 MHz
Pump-Probe F2	not specified yet
FLASHforward	Ti:Sa, 800 nm, 108.33 MHz
XFEL	
Location	**Type/Wavelength/Rep. Rate**
Injector 1 (IR)	Yb:KGW, 1028 nm, 54 MHz
Injector 1 (UV)	Yb:KGW (4xf), 257 nm, 4.5 MHz 10 Hz bursts
Injector 2 (IR)	not specified yet
Pump-Probe 1	Yb:YAG, 1030 nm, 108.33 MHz
Pump-Probe 2	Yb:YAG, 1030 nm, 108.33 MHz
Pump-Probe 3	Yb:YAG, 1030 nm, 108.33 MHz

A New Engineered L2L Design

Fig. 3 shows a picture of the new common L2L design. The entrance of the reference pulses via the length-stabilized link is located on the upper right corner. The link fiber type is either SMF (current installations at FLASH) or PMF (upcoming installations at XFEL). For SMF a polarization control is needed to compensate for polarization changes during the operation to keep the optical power behind polarizing elements constant. For this reason the L2L base plate can be optionally equipped with motorized rotation mounts.

The end of the actively-stablized optical link is defined by a Faraday rotator and a partially reflecting mirror that leads part of the incoming pulse train back to the link-stabilizing unit in the synchronization hutch. Current installations are based on a fiber-based Faraday-rotating mirror (FRM). However, shifting the link end as far as possible to the non-linear crystal includes more potentially drifting parts into the length-stabilized path. Thus, the L2L setup can be optionally equipped with a Faraday rotator and a partially reflecting mirror for a further improvement regarding the total drift of the reference pulses at the optical cross-correlator. A perfectly aligned setup completely reflects the reference beam at the end-mirror back to the non-linear crystal and thus, also to the optical link. The portion of this unwanted reflections can easily exceed the power that is fed back by the FRM. Since this could cause the link to be locked to the wrong pulse train, an isolator supresses pulses that are reflected by the end mirror to prohibit propagation back to the link.

Two $\lambda/2$-waveplate/beamsplitter sets were used to extract part of the beam for the generation of the 1.3 GHz reference

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signal for the RF synchronization as well as a power monitor signal. After combination of the two input beams another beam sampler taps part of the beam to a fast photodetector that reveals the timing information between reference and laser pulses. As mentioned before a number of different laser systems have to be handled by the L2L design. Thus, different wavelengths, input pulse energies and laser modes lead to individual configurations regarding the nonlinear crystal, dichroic mirrors and detectors. As crystal types we either use BBO or PPLN. Depending on the available pulse energy the detection is done by either a balanced photodetector or two high-sensitive photomultiplier tubes each followed by a low-noise amplifier. The two SFG signals are then digitized for the subtraction and further processing in our digital control system.

The optimal delay between reference and laser pulses for the backward SFG process $T_{\mathrm{opt}} = 2 \cdot \sqrt{\tau_1^2 + \tau_2^2}$ with pulse widths τ_1 and τ_2 can easily be set for high-bandwidth Ti:Sapphire laser systems by inserting a transmissive group delay dispersive (GDD) element into the common beam path before the end mirror. However, this configuration can not be applied for signals with pulsewidths in the ps-range (e.g. all injector laser systems) since too much glass would be needed to achieve the required delay. The most convenient and also here chosen way to set the delay for ps-pulses anyway is to split both beams with another dichroic mirror and vary the path length difference to the end mirrors (see Fig. 1). Since this difference depends on the exact pulse width combination one of the two end mirrors is mounted on a manual delay stage making the setting of the delay more flexible.

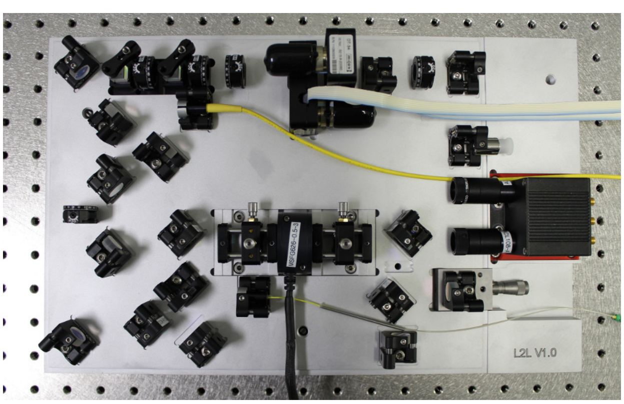

Figure 3: New engineered laser-to-laser synchronization setup. Outer dimensions: 375 mm x 235 mm.

Using the setup as shown in Fig. 3 assumes that the two input beams are already temporarily overlapping in the nonlinear cystal. Since this is usually not the case the functionality of a variable delay is required. This delay could principally be introduced in the reference or the laser path whereas we usually install a motorized delay stage in the reference beam path. The reason for this is mainly the better maintainability since we only need one type of delay stage system for all kind of L2L setups with its changing wavelength combinations. To install it in the L2L setup we simply remove the two mirror mounts on the most left side of the base plate and place our in-house made delay stage to the left of the setup. Beam entrance and output of this delay stage correspond exactly to the beam positions at the two removed mirrors making the combination of the L2L setup and the delay stage quite easy and comfortable. This delay stage provides a maximum possible length change of around 4 ns covering more than the required delay of half the reference laser period (=2.3 ns). Since an already existing RF-based pre-lock is required for the optical synchronization, a change of the timing of one of the two pulse trains could also be done with an electronic phase shifter for the RF synchronization signal. However, this is usually the way to set the timing of the corresponding laser with respect to the FEL and thus, can not be used for the timing when setting up the L2L synchronization.

The change of environmental conditions like temperature or humidity usually causes timing changes of the two input pulses at the SFG crystal position that can lead to timing errors of the synchronized laser. To avoid this, the L2L base plate has a special three-point mounting without a rigid connection to the optical table. One of these mounting point positions is fixed by a cone, the second can move within a V-groove and the third mounting point lays on a flat. This avoids twisting since the Al base plate can float on the optical table. On the other hand the fix point was calculated in such a way that an expansion of the base plate due to temperature changes does not affect the timing of the two input pulses at the SFG crystal.

CONCLUSION

We gave an overview of the current and future laser-to-laser synchronization systems at FLASH and the European XFEL and have presented an engineered version of our proven laser synchronization setup for a higher degree of reliability and maintainability. This synchronization scheme is planned to be installed at least for 15 Laser systems at FLASH and XFEL.

REFERENCES

[1] J. Kim et al. "Drift-free femtosecond timing synchronization of remote optical and microwave sources", Nature Photonic 2 (2008), 733–736.

[2] J. Kim et al. "Long-term femtosecond timing link stabilization using a single-crystal balanced cross correlator", Opt. Lett. 32 (2007), 1044–1046.

[3] M. K. Czwalinna et al. "New design of the 40GHz bunch arrival time monitor using MTCA.4 electronics at FLASH and for the European XFEL", Proc. IBIC2013, 749–752 (2013).

[4] T. R. Schibli et al. "Attosecond active synchronization of passively mode-locked lasers by balanced cross correlation", Opt. Lett. 28 (2003), 947–949.

[5] S. Schulz et al., "Femtosecond all-optical synchronization of an X-ray free-electron laser", Nature Communications 6 (2014).

[6] M. de la Ossa et al., "High-Quality Electron Beams from Beam-Driven Plasma Accelerators by Wakefield-Induced Ionization Injection", Phys. Rev. Lett. 111 (2013), 245003.