

ALL-OPTICAL SYNCHRONIZATION OF DISTRIBUTED LASER SYSTEMS AT FLASH

S. Schulz, L. Wissmann, J. Zemella - Hamburg University, Germany; M. K. Bock, M. Felber, P. Gessler, F. Ludwig, K.-H. Matthiesen, H. Schlarb, B. Schmidt - DESY, Hamburg, Germany; F. Loehl - Cornell University, Ithaca, USA; V. Arsov - PSI, Villigen, Switzerland; A. Winter - ITER, Cadarache, France

Abstract

The free-electron laser FLASH and the planned European XFEL generate X-ray light pulses with durations that are below 30 fs. The feasibility of time-resolved pump-probe experiments, special diagnostic measurements and future operation modes by means of laser seeding [1] depends crucially on the long-term stability of the synchronization of various laser systems within the facility. For this purpose, an optical synchronization system is being installed and tested at FLASH.

In this paper, we report on the development and the performance of a background-free optical cross-correlation scheme to synchronize two individual mode-locked lasers of different center wavelengths and repetition rates with an accuracy of better than 10 fs. The scheme was tested by linking a Ti:sapphire oscillator, used for electro-optical diagnostics at FLASH, to a locally installed erbium-doped fiber laser and it will be used at the end-point of an actively length-stabilized fiber link which distributes the pulses from a master laser oscillator, after this has been commissioned. Then the diagnostic laser can be synchronized to the electron beam and first accelerator-based measurements on the performance of the system will be carried out.

THE OPTICAL SYNCHRONIZATION SYSTEM OF FLASH

The optical synchronization system for FLASH [2, 3] and for the European XFEL is based on an ultra-stable, mode-locked erbium-doped fiber laser generating sub-ps light pulses at the telecommunication wavelength of 1550 nm. This master laser (MLO) is phase-locked to the low-noise RF master oscillator of the accelerator to ensure stable operation and small jitter at low frequencies. The timing information is contained in the precise repetition rate of 216.66 MHz of the optical pulse train, which is the 6th sub-harmonic of FLASH's 1.3 GHz reference frequency. The pulses are distributed via actively length-stabilized fiber links to the remote locations along the accelerator. At these locations, low-level RF signals can be extracted using photo diodes and bandpass filters, Sagnac loops or interferometric methods to pick a harmonic of the MLO's repetition rate [4]. Other types of end-stations include bunch arrival-time monitors (BAM) or large horizontal aperture beam position monitors, and possibly di-

rect seeding of Ti:sapphire amplifiers. Another key component of the synchronization system is the optical cross-correlator, providing a mechanism to lock various laser systems to the optical reference with femtosecond accuracy. The laser systems include those used for electron beam generation, diagnostics and pump-probe experiments, as well as the laser system, which will be used to seed the FEL in the sFLASH experiment.

TWO-COLOR BALANCED OPTICAL CROSS-CORRELATOR

The operation of the balanced optical cross-correlator is based on the sum frequency generation (SFG) in a type-I phase-matched nonlinear crystal and, using a dispersive material, the generation of a group-delay difference between the two input pulses with the same polarization but different center wavelength. In this way, it is similar to the scheme described in [5]. A schematic view of the optical

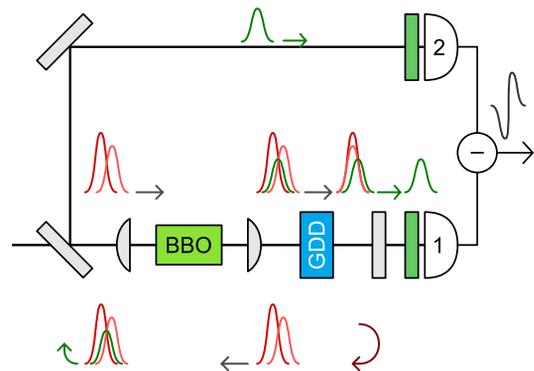


Figure 1: Schematic setup of a balanced optical cross-correlator and sketched propagation of the optical pulses inside the device. See text for details.

setup is given in figure 1. The pulses from both lasers enter the cross-correlator through a first dichroic mirror, which is transmissive for these fundamental pulses, but reflective at the wavelength $\lambda_3 = (\lambda_1^{-1} + \lambda_2^{-1})^{-1}$ corresponding to the sum frequency. Then the pulses are focussed onto the phase-matched BBO crystal and collimated by a second lens. The resulting sum frequency is transmitted through a second dichroic mirror and an optical bandpass filter onto the first photo detector. Assuming Gaussian-shaped input

pulses with the intensities $I_1(t)$ and $I_2(t)$, the intensity $I_{+,I}(t)$ of the SFG component is given by the correlation function

$$I_{+,I}(t) \propto \int_{-\infty}^{\infty} I_1(\tau) I_2(t - \tau) d\tau$$

$$= \frac{1}{\sqrt{2\pi(\sigma_1^2 + \sigma_2^2)}} \exp\left\{-\frac{(t - \Delta t)^2}{2(\sigma_1^2 + \sigma_2^2)}\right\},$$

which is highly sensitive to the relative time delay Δt between the input pulses. In this way the amplitude change is a direct measure for a timing change. In the cross-correlator, the fundamental pulses are reflected by the second dichroic mirror and pass a small silica slab (depicted as GDD in 1). This results in a group delay because of the different indices of refraction for the different center wavelengths. The now swapped pulses are focussed again onto the BBO crystal, generating another SFG component, which is reflected by the first dichroic mirror into the second detector arm, filtered and measured by the second photo detector. With this balanced detection, the measured difference signal $I_{+,II} - I_{+,I}$ at the detector's output is, on the slope around the zero-crossing, proportional to the relative timing Δt and almost background free, i. e. if there is no temporal overlap, the also generated second harmonic is strongly suppressed. Furthermore, this detection scheme is insensitive to amplitude noise of the laser systems.

In order to keep the lasers synchronized to each other, the balanced detector's output signal is fed back into a digital control loop, whose operating point is the zero-crossing of slope mentioned above. In this way, the repetition rate of the experiment's laser is stabilized with a piezo transducer and a motorized translation stage inside the cavity relative to the optical reference.

MEASUREMENT RESULTS

For prototype research and development, we use a commercial ultra-short pulse 81.25 MHz Ti:sapphire oscillator with a center wavelength of 800 nm, which is also used for

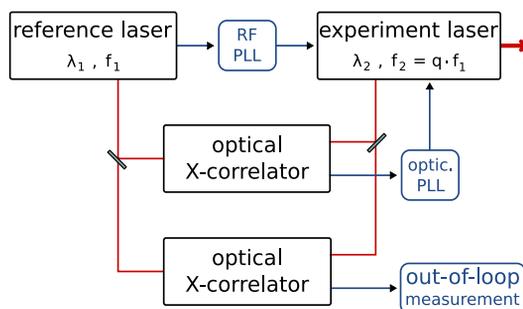


Figure 2: Schematic of the experimental setup for jitter and drift measurements. The second cross-correlator enables out-of-loop measurements.

electro-optic diagnostic measurements. The timing reference is a self-built 40.625 MHz erbium-doped fiber laser

Instrumentation

T23 - Timing and Synchronization

(EDFL) at the telecommunication wavelength of 1550 nm, resulting in a wavelength of 527.7 nm of the corresponding sum frequency. This local, free-running fiber laser is installed to be independent of the master laser during development, but after completion of the MLO and fiber link system it will be replaced by the optical reference pulse train. It emits 20 mW average power, which is moderately amplified in the already installed link-end to about 30 mW, split in the ratio of 1:2 and guided to both cross-correlators. A fraction of the Ti:sapphire's average power of 600 mW is tapped off by a beam splitter and also distributed to the cross-correlators after chirping the pulse to about 100 fs, providing approximately 50 mW at their input mirrors. The Ti:sapphire laser can be phase-locked to the EDFL with a digital control loop based on a traditional RF phase detection scheme, which is an important prerequisite to initially find temporal overlap inside the nonlinear crystal, thus generating the sum frequency components and the error signal, respectively. Only then can the SFG based control loop supersede the RF-lock.

Out-of-Loop Measurements

Figure 3 shows the measured error signal of the out-of-loop cross-correlator, while the Ti:sapphire oscillator is optically locked to the reference laser with the first cross-correlator. The relative timing Δt of the input laser

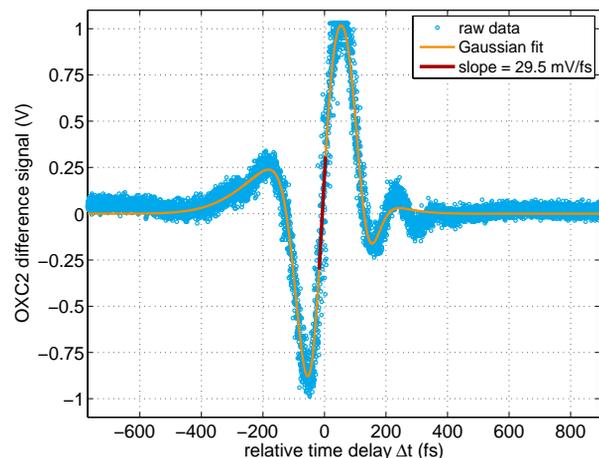


Figure 3: Measured difference signal of the out-of-loop optical cross correlator by varying the relative timing Δt .

pulses is changed with a motorized translation stage in the Ti:sapphire laser's beam path. The slope of 29.5 mV is calculated from the Gaussian fit in the range from -0.3 V to 0.3 V. The following measurements were performed after adjusting the delay Δt to zero and measuring the difference signal of the second cross-correlator. Figure 4 shows a drift measurement over 400 s (red curve). The timing jitter on that time-scale amounts to 7.9 fs (rms), and there is practically no drift observable. For comparison, the blue curve in the background shows the timing jitter of the RF phase-lock, which is a factor of 2.4 worse. It was mea-

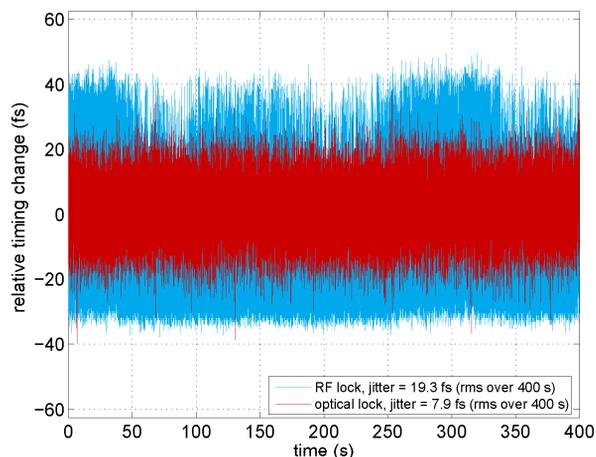


Figure 4: Out-of-loop drift measurement over 400 s of the optically locked (red), and the RF-locked Ti:sapphire laser (blue).

sured with the out-of-loop cross-correlator, right before the optical lock had been closed. We also measured the baseband noise with an Agilent E5052B signal source analyzer and figure 5 shows the calculated spectral density and integrated timing jitter of the out-of-loop signal. The decrease above 100 kHz corresponds to the bandwidth of the used differential amplifier. The largest contribution to the timing jitter arises from the peak at 9 kHz, indicating imperfect parameters of the control loop, especially a too high proportional gain. Curing the already above mentioned obvious deficiencies and detailed analysis of additional noise sources promises to reach the 1 fs (rms) jitter level, at least on short time-scales, and it should be emphasized, that the results presented here are obtained very recently and are not yet optimized for best performance.

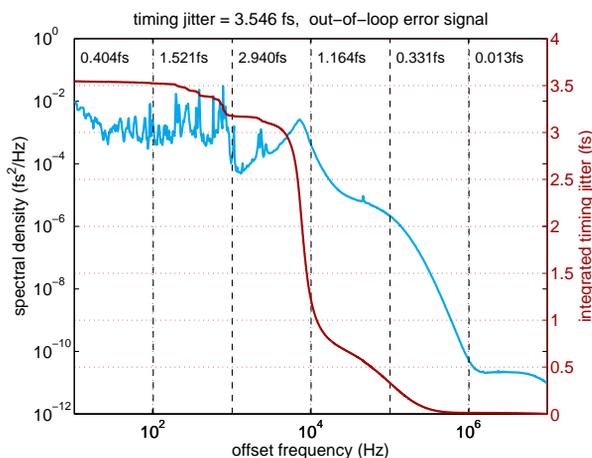


Figure 5: Baseband noise and integrated timing jitter of the out-of-loop error signal measured with an Agilent E5052B signal source analyzer and a 100 kHz bandwidth differential amplifier.

SUMMARY AND OUTLOOK

The optical synchronization system of FLASH is being reassembled and upgraded from breadboard setups to an extensible, professionally engineered version, which promises long-term stable, user-friendly operation and low maintenance. After the required infrastructure had been completed, the master laser oscillator was commissioned, together with its RF phase-lock and various online diagnostics. Then the first non-prototype fiber link with a recommissioned BAM [6] as end-station could be set up. Based on the BAM data, we were able to implement a slow amplitude feedback for the first acceleration module. This present state allows us to debug the complete system and identify possible design issues, while we simultaneously setup and commission the next components, including the fiber link to the laboratory, where the Ti:sapphire laser is located.

We managed to lock this Ti:sapphire oscillator to a local fiber laser already with an accuracy of less than 10 fs over a time-scale of 400 s. Recently we were able to close the control loop over 13 hours, which opens the possibility to carry out first accelerator-based measurements such as a comparison of the BAM data versus the EO-spectral decoding arrival time (see [7] for RF-lock based results).

ACKNOWLEDGEMENTS

We would like to thank many people of other DESY and Hamburg University groups for fruitful discussions and ideas, as well as the engineers and technicians of the FLA group for their great work.

REFERENCES

- [1] J. Boedewadt *et al.*, “Status of the XUV Seeding Experiment at FLASH”, PAC’09, Vancouver, Canada, 2009, TU5RFP072 (this conference), <http://www.jacow.org>
- [2] A. Winter *et al.*, “Layout of the Optical Synchronization System for FLASH”, EPAC’06, Edinburgh, UK, 2006, TUPCH028, <http://www.jacow.org>
- [3] J. Kim *et al.*, “Large-Scale Timing Distribution and RF-Synchronization for FEL Facilities”, FEL’04, Trieste, Italy, 2004, TUAOS03, <http://www.jacow.org>
- [4] M. Felber *et al.*, “Different Methods for Long-term Femtosecond Stable RF Signal Generation from Optical Pulse Trains”, PAC’09, Vancouver, Canada, 2009, TH6REP088 (this conference), <http://www.jacow.org>
- [5] T. R. Schibli *et al.*, “Attosecond active synchronization of passively mode-locked lasers by balanced cross correlation”, *Opt. Lett.* 28(11):947–949, 2003
- [6] F. Loehl *et al.*, “Measurement and Stabilization of the Bunch Arrival Time at FLASH”, EPAC’08, Genoa, Italy, 2008, THPC158, <http://www.jacow.org>
- [7] V. Arsov *et al.*, “Electro-Optic Bunch Arrival Time Measurement at FLASH”, EPAC’08, Genoa, Italy, 2008, THPC152, <http://www.jacow.org>