OPTICAL SYNCHRONIZATION OF THE SwissFEL 250 MeV TEST INJECTOR GUN LASER WITH THE OPTICAL MASTER OSCILLATOR*

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Abstract

The stability of the SwissFEL photoinjector laser is crucial for stable FEL operation in the hard X-ray regime. In the 10 pC operation mode, in which sub-10 fs photon pulses will be generated for the users, the arrival time jitter of the laser pulse at the photocathode should not exceed 40 fs (rms). Therefore, it is foreseen that the titanium-sapphire gun laser oscillator (Ti:Sa) is stabilized by optical cross-correlation with the pulses from the laser master oscillator, which is an erbium-doped fiber laser (Er:FL). In this paper, we demonstrate a stable optical lock for 60 min. between two such mode-locked oscillators, which were placed on different optical tables and connected optically but not mechanically via a 5 m long free-space transfer line. Furthermore, we make a comparison between the RF- and the optical lock stability of the slave laser in the frequency range from 10 Hz to 10 MHz.

INTRODUCTION AND MOTIVATION

Beam dynamics simulations for the SwissFEL indicate that the photoinjector laser stability is highly critical for stable SASE operation in the hard X-ray regime. Specifically in the 10 pC operation mode, in which sub-10 fs photon pulses are produced, the arrival time jitter of the photoinjector laser at the cathode should be on the order of 40 fs (rms) or less. This stringent tolerance is required to meet the specifications for stable SASE user operation in order to fulfill the planned experimental program of the SwissFEL [2]. Thus, the level of allowed peak current fluctuations is limited to 5%, the bunch arrival time jitter at the undulator - depending on the operation mode - to 20 fs or 5 fs, and the bunch mean energy stability to 0.05%. While the bunch arrival time jitter is assumed to be on the order of the photon pulse length (20 fs or 5 fs), the tolerance of 0.05% bunch mean energy jitter follows from the requirement to preserve the resonance condition within the FEL bandwidth [1, 3].

In order to meet the SwissFEL stability demands, a hybrid electrical / optical reference distribution system is planned to be implemented [1]. As part of this system and in order to secure highest phase stability, several mode-locked lasers, such as the photoinjector laser, the seed laser and the pump-probe laser, are planned to be synchronized with the pulsed optical reference distribution via optical cross-correlation [4, 5].

According to the present conceptual design the titanium-sapphire (Ti:Sa) photoinjector oscillator will be stabilized optically, but several other components upstream the photocathode are expected to cause phase instabilities. Such are the photoinjector laser amplifiers, the crystals for the generation of the photoinjector UV pulses, and the optical transfer line towards the cathode. Recently at FLASH, a few ps change of the electron pulse arrival time across the macropulse could be traced back to heat load induced in the BBO crystal by the photoinjector laser [6].

As a step towards the fulfillment of the jitter and stability goals for SwissFEL, we demonstrate in this paper a stable optical cross-correlation between two mode-locked lasers of different wavelengths and repetition rates. In addition, the stability of the combination of laser oscillator and a transfer line is measured with an optical reference.

EXPERIMENTAL SET-UP

Laser Systems and Laser Beam Transport

The laser oscillator of the SwissFEL photoinjector is a mode-locked titanium-sapphire (Ti:Sa), type Rainbow from Femto Laser with a repetition rate of 83.275MHz, central wavelength of 800 nm, and bandwidth >100 nm. In our current measurements, it has been used as a master laser oscillator. The client, a mode-locked erbium-fiber laser (Er:FL), type M-Fiber-Synch from Menlo Systems, with a repetition rate of 214.136 MHz, a central wavelength of 1565 nm and a bandwidth of 20 nm, has been installed on another optical table together with the two-wavelength balanced optical cross-correlator (OCC) (Figure 1).

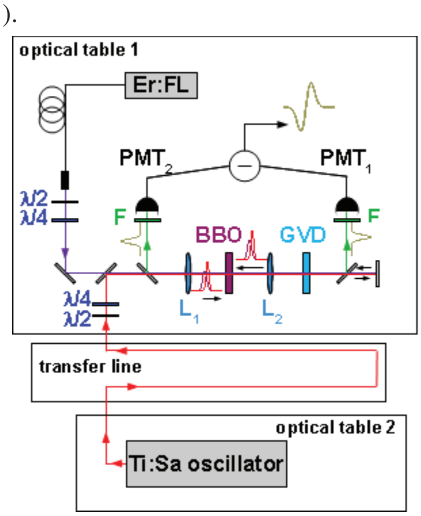

Figure 1: Scheme of the optical set-up and the two-wavelength balanced optical cross-correlator: λ/2, λ/4 - waveplates; BBO - 0.5 mm crystal; $L_{1,2}$ - lenses; GVD - group velocity control; F - band-pass filter at 529 nm; $PMT_{1,2}$ - photomultipliers.

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The reference Ti:Sa oscillator pulses are delivered to the second optical table through a not evacuated, not length-stabilized free space optical transfer line with an approximate length of 5 m, which consists of four plane silver-coated mirrors for beam steering and a double lens telescope at its end for beam size control. The vertical support elements are 1 m long OWIS profiles, type SYS-65, to which standard OWIS cube mounts with mirror holders are attached. The two optical tables do not have mechanical contact through the transfer line. A horizontal pipe is loosely attached to the upper cube mounts to provide environmental insulation. All other optical components in the set-up are also air flow shielded.

Optical Phase Detector

The optical phase locking is achieved via two-wavelength balanced optical cross-correlation (OCC) [4] in a collinear geometry and Type-I phase matching for sum frequency generation (SFG) between 800 nm and 1565 nm in a single 0.5 mm thick BBO crystal (Figure 1). The set-up is assembled from standard Thorlabs 30 mm cage components, similarly to [5]. The pulse lengths are 200 fs (FWHM) for the Ti:Sa laser and 400 fs (FWHM) for the Er:FL. Assuming a Gaussian shape, the theoretical optimal pulse swap in the OCC for these pulse widths is 380 fs, achieved with a double pass through a 6 mm thick BK7 lens and two 2 mm thick silica slabs. The two plano-convex lenses for the forward and the backward OCC branches have focal lengths of 40 mm and a curvature optimized for the median wavelength between the Ti:Sa and the Er:FL at 1183 nm. The photodetectors are two photomultipliers (PMT), type H6780 from Hamamatsu. The balanced differential voltage signal is acquired with two precise 10 kΩ resistors connected to a differential voltage amplifier, type DLPVA-100 from Femto with 20 dB gain and 100 kHz bandwidth (Figure 2).

Phase Locking and Data Acquisition Schemes

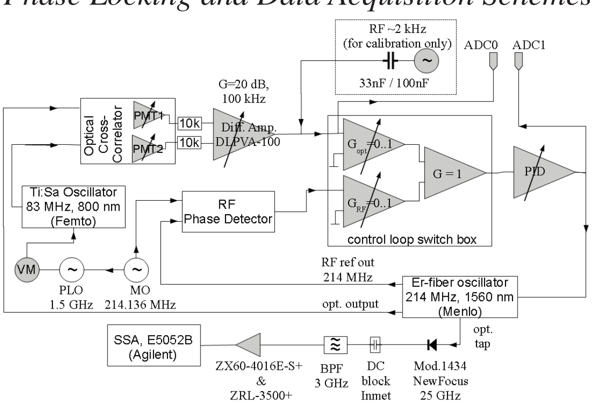

Figure 2: Scheme for the RF and optical phase-locking, for data acquisition, calibration, and phase noise stability measurements.

A prerequisite for the optical cross-correlation is a stable RF-reference. For the Er:FL this is the RF-master oscillator (MO) from Inwave at 214.136 MHz. For the Ti:Sa oscillator the RF reference is a phase locked oscillator (PLO) from Ralab at 1.5 GHz (Figure 2). A vector modulator (VM) between the PLO and the Ti:Sa laser allows shifting of its pulses with 160 fs steps. The pulse overlap occurs at 11.897 MHz (each 18th Ti:Sa with each 7th Er:FL pulse). A home made analog repeater box with variable gains allows switching between the optical and the RF loops with arbitrary gain-ratios.

When the gain of the optical loop is increased, the initially random occurrence of the optical error signals observed on an oscilloscope orders itself into a periodic structure. Once both loops are enabled, the RF detector gain can be turned down. Initially the optical control loop starts to oscillate. By further reducing the PI gains of the optical-lock loop, the amplitude of these oscillations and the height of the spike observed in the phase noise spectra (Figure 5) can be minimized. At such conditions smallest jitter values are recorded.

MEASUREMENT RESULTS

An absolute measure for the quality of the RF- and the optical- phase lock stability of the Er:FL are the phase noise spectra acquired with a signal source analyzer (SSA), type E5052B (Agilent) (Figure 2). All active components from the synchronization chain are included in the measurement.

The jitter of the RF-MO to which the PLO and the Er:FL are locked is 67.4 fs (rms) in the range 10 Hz - 10 MHz (Figure 3) and 65.8 fs (rms) in 10 Hz - 1 kHz, the range corresponding roughly to the Er:FL control loop bandwidth.

The jitter of the PLO to which the Ti:Sa is locked is 76.8 fs (rms) in the range 10 Hz - 10 MHz and 75.7 fs (rms) in the range 10 Hz - 1 kHz.

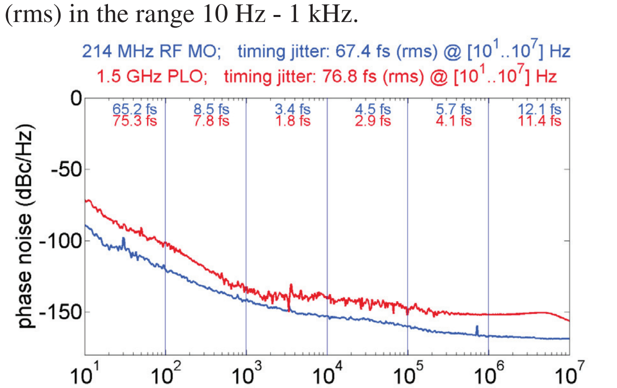

Figure 3: Phase noise spectra of the 214 MHz RF master oscillator and the 1.5 GHz phase locked oscillator.

The phase noise spectrum of the RF locked Ti:Sa measured after the transfer line is shown in Figure 4. The signal is acquired from the free space optical pulse train with a fiber coupled collimator and a photodiode with a bandwidth of 25 GHz (Figure 2). The jitter in the range 10 Hz - 1 kHz is 99.3 fs (rms). Although this is a typical value, also higher jitter was measured on different days and different environmental conditions, which indicates intrinsic phase instability of the RF locked Ti:Sa laser. In addition it is susceptible to different distinct external

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sources in the lab. For example a correlation with the operating frequency of the laboratory air conditioning at 70 Hz was observed. The measurements after the transfer line are limited by the pointing stability which causes coupling variations in the fiber collimator, and thus increases the amplitude jitter. To reduce this effect, the corresponding phase noise spectra have been averaged.

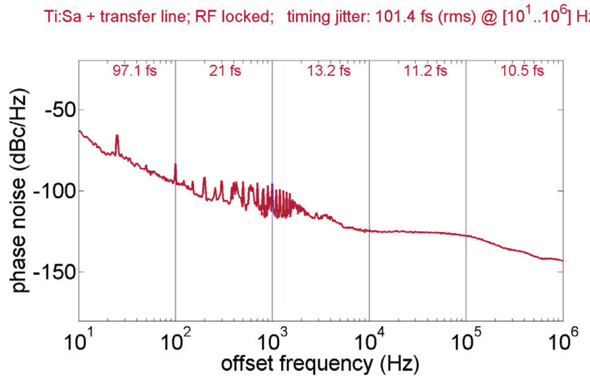

Figure 4: Phase noise spectrum of the RF-locked Ti:Sa oscillator after the transfer line.

A comparison of the phase noise stability of the free running, the RF-locked, and the optically locked Er:FL is shown in Figure 5. For all three types of lock conditions there are similar measurements made on different days. The noise floor in the case of the optical lock is always the lowest. Typically, the free running and the RF locked Er:FL has a broad noise peak at 7.5 kHz coming from its controller unit. In Figure 5 (green trace) the PI gains are such, that this peak is strongly suppressed. In the case of the optical synchronization, a peak at 5.4 kHz becomes dominant. Depending on the PI gains, this peak can be considerably reduced, but then the optical lock becomes more fragile. With a jitter variation between 80.9 fs and 217.8 fs (rms) in the range 10 Hz - 10 MHz on different days and for different PI gain settings, the optical synchronization provides better stability than the RF one, for which jitter values between 318 fs and 5.6 ps. (rms) in the same range have been measured. The wide span of measured jitter values in the case of an RF synchronization comes from the multiple noise spikes in the range 10 Hz - 1kHz which are always present in the phase noise spectra.

Their origin can not be conclusively resolved, since no occurrence pattern was observed. Most probably it is a combination of several sources. Base band measurements, which are purely electrical, exclude to a greater extent air flow and acoustics. There are other noise sources, among which are the pump of the laboratory air conditioning, the Pockels cells of the Ti:Sa amplifiers, some common laboratory electronics, a THz plasma source in the adjacent laboratory, and the linac operation.

Up to 1 kHz, the optical loop removes any disturbances almost completely. This became also evident when a sine signal with a few volts amplitude from an external frequency generator was used to calibrate the optical lock stability traces (Figures 6, 7). Therefore, no such peaks are observed in the phase noise spectra in the case of the optical lock.

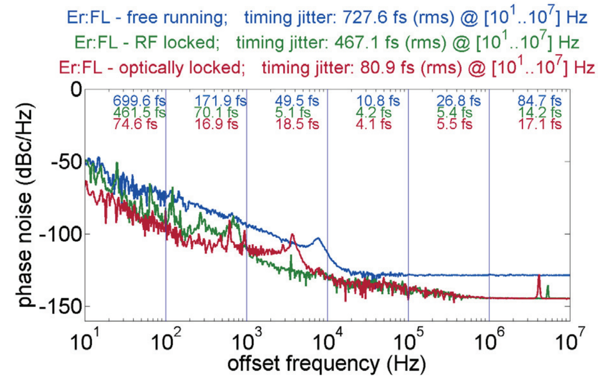

Figure 5: Comparison of the RF- and the optical lock stability of the Er:FL.

The measured jitter of the optically locked Er:FL contains also the phase noise of the PLO, to which the Ti:Sa is referenced and that of the transfer line. In the range 10 Hz - 1 kHz the optically locked Er:FL jitters between 76.5 fs and 118.5 fs (rms), measured on different days and under different environmental conditions. When the PLO contribution of 75.7 fs (rms) in this frequency range is quadratically subtracted, a remaining jitter between 11 fs and 91.2 fs (rms) is observed for the part of the transfer line and the optical phase detector.

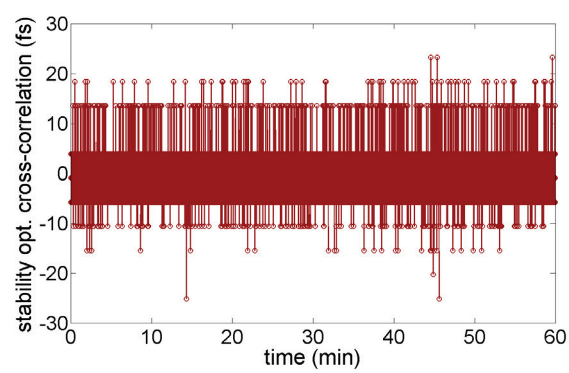

Figure 6: Long-term in-loop optical lock stability of the Er:FL. Integrated timing jitter over 60 min: 4.6 fs (rms) [1 Hz..100kHz].

The long-term in-loop optical lock stability of the Er:FL is shown in Figure 6. The integrated timing jitter over 60 min is 4.6 fs (rms). The ADC sampling rate is 10 samples/s with a bandwidth of 100 kHz. Since these are in-loop measurements, they do not incorporate the drifts. Therefore, the results have to be regarded only as a measure for the persistence of the optical lock. The integrated timing jitter can be reduced by varying the loop PI gains, but the set of values for which the optical lock remains stable is very narrow. High P gains increase the the width of the noise band, since the optical loop starts to oscillate. At low P gains, the measured integrated timing jitter decreases, but then the loop becomes more susceptible to acoustics and tends to break within minutes.

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In order to test the rigidity of the optical loop under the influence of an external perturbation, e.g. a drift, an offset voltage is added to the optical error signal and manually varied (left hand side of Figure 7). The PI gains are set such that the loop is more stable on the expense of relatively higher integrated timing jitter of 11 fs (rms). It follows the induced changes within a range of 95 fs peak-peak, then breaks. The left hand side of Figure 7 demonstrates how the optical lock is reestablished by taking the offset voltage away, by varying the PI gains and by driving the piezo motor of the Er:FL. At the right end of the trace the Er:FL is again in optical lock.

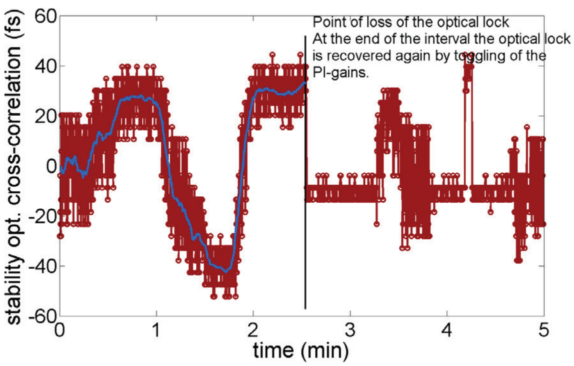

Figure 7: Artificially induced voltage offset added to the error signal to test the rigidity of the optical phase detector. Left hand side: stable operation within 95 fs (p-p). The integrated timing jitter is 11 fs (rms) [1 Hz..100kHz].

SUMMARY AND OUTLOOK

For stable SASE operation in the the 10 pC operation mode the arrival time jitter of the photoinjector laser pulses should be less than 40 fs (rms). We demonstrate the stability of an optical phase lock loop by using a Ti:Sa laser oscillator as a master laser. Its pulses are transported through an approximately 5 m long free space transfer line to optically synchronize an erbium-fiber laser via two-color balanced optical cross correlation in a 0.5 mm thick phase-matched BBO crystal. The two lasers are installed on different optical tables, which do not have a mechanical connection via the transfer line. All components are isolated from air flow. This arrangement simulates the transfer of the photoinjector laser pulses to the electron gun and allows to investigate the stability of the combination of laser oscillator and a transfer line.

The phase noise measurements show that in RF lock the Er:FL is susceptible to different noise sources, which in an usual accelerator environment might vary during the day and also from day to day. Thus, the measured short-term RF-lock stability in the range 10 Hz - 10 MHz varies between 318 fs and 5.6 ps (rms). In the same frequency range, the optical lock stability varies only between 80.9 fs and 217.8 fs (rms). Up to 1 kHz, the optical control loop suppresses external disturbances almost entirely. The loop is robust and follows a slow external offset within 95 fs peak-peak. The procedure for achieving an optical phase locking is reliable and the Er:FL was optically locked multiple times on different days and for long periods of time. We demonstrated a stable optical lock for 60 minutes, but longer periods are possible.

The Ti:Sa is RF-locked to the 1.5 GHz PLO, the phase noise stability of which is 75.7 fs (rms) in the range 10 Hz - 1 kHz. In this range, the phase noise stability of the optically locked erbium-fiber oscillator varies between 76.5 fs and 118.5 fs rms on different days. Thus, up to 11 fs (rms) remaining phase noise jitter for the combination of an optical phase detector and a transfer line is achieved in this frequency range when the PLO contribution is quadratically excluded. These results are an important milestone towards the achievement of the ultimate goal: it shows that a few tens of fs stability is achievable and the transfer line drift does not break the optical loop. A second, out-of-loop optical cross-correlator is set-up and in final preparation for measurement of the transfer line drift. The result also indicates, that in order to achieve less than 40 fs arrival time jitter of the laser pulses at the photocathode, measures should be undertaken to stabilize also the intermediate components upstream the cathode.

For SwissFEL an engineered version will be produced and installed close to the photoinjector oscillator. Since the optical phase detector is sensitive to acoustic disturbances, in the upcoming optical synchronization unit a good environmental insulation will be foreseen.

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