PERFORMANCE OF THE FLASH OPTICAL SYNCHRONIZATION SYSTEM WITH A COMMERCIAL SESAM-BASED ERBIUM LASER

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Abstract

The optical synchronization system of the free-electron laser in Hamburg (FLASH) is based on the pulse train generated by a passively mode-locked laser. In this paper we report on the commissioning, the characterization and the long-term stability of a commercial SESAM[1]-based laser which was recently installed in addition to the existing, self-built erbium-doped fiber laser. Accelerator-based measurements allow for first conclusions on the suitability of this type of laser systems as master clock for the optical synchronization system.

INTRODUCTION

Next generation light sources like FLASH and the planned European XFEL generate deep UV and x-ray pulses of a few femtosecond duration. To fully exploit these short pulses in pump-probe experiments or for the operation of an FEL by an external seed laser an optical synchronization system has been proposed [1] and is being installed at FLASH. The reference laser pulse train emitted by the master laser oscillator (MLO) is distributed to the remote locations at the accelerator using transit-time-stabilized fiber links, which in turn are based on optical cross-correlation. Electron bunch arrival time monitors (BAMs) modulate the amplitude of this train, which is then detected by digital hardware to extract the arrival time information [2, 3]. Another important aspect of the system is the synchronization of various other laser systems at the accelerator, like the pump-probe- and seed-Ti:sapphire oscillators. This can be achieved by either extracting RF signals from the pulse train and applying an RF-based PLL scheme [4], or with two-color optical cross-correlators which is particularly relevant for the photo injector laser [5].

It is evident that the master laser oscillator has to meet demanding requirements in terms of reliability, uninterrupted operation, timing jitter of the pulse train and amplitude stability. For nonlinear optical processes as the cross-correlations in various devices also spectral properties, pulse energy and duration become important. Besides the continuous improvement of our EDFLs (erbium-doped fiber lasers) we recently integrated a commercial “Origami-15” SESAM-based erbium laser [6], which promises to meet our specifications, into the established system.

CHARACTERIZATION & INTEGRATION

The free-space distribution (FSD) optics, which splits and delivers the reference pulse train to the individual link stabilization units and other devices using polarizing beam cubes and half-wave retarders, was designed for redundant operation of two lasers from the outset. That made the mechanical integration of the Origami laser system straightforward. Due to its small footprint it will be even possible to install a second laser into the space which was foreseen for one EDFL initially (see fig. 1), making room on the optical table for additional devices, like RF-based link stabilization units. After the required adaptation of the imaging

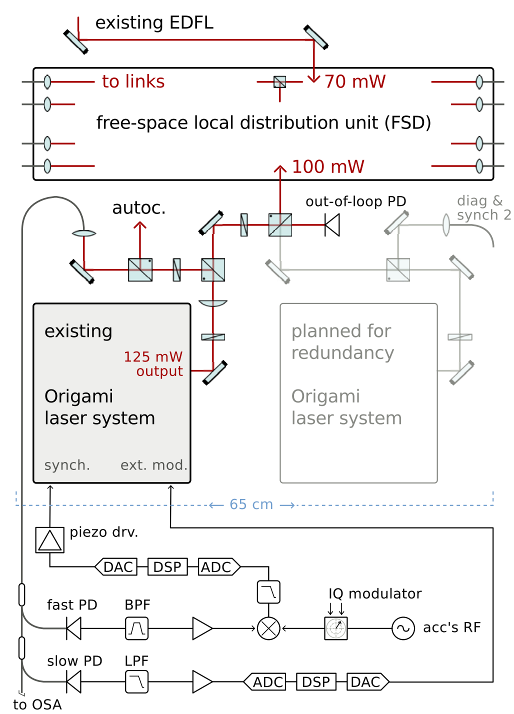

Figure 1: Sketch of the integration of the Origami laser system on the optical table (top half) and the two control loops for RF synchronization and amplitude feedback.

optics for the new laser we were able to achieve an average of 74% efficiency for coupling into the fiber collimators in the FSD, in comparison to 82% with the existing fiber laser. However, the distribution unit was optimized for the EDFL operation and our particular Origami unit shows a slightly more divergent beam than expected which makes us optimistic to achieve higher efficiency with improved optics.

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[1] semiconductor saturable absorber mirror

Spectral Properties and Pulse Duration

The optical set-up features three diagnostic ports where a fraction of the beam is tapped off. The light from one of the ports can be guided to an autocorrelator and the measured pulse duration is shown in fig. 2 (upper plot, red curve). The laser has, as expected, a significantly larger pulse duration of $\tau_{\mathrm{fwhm}} = 317$ fs (FWHM) than the EDFL (148 fs), but with a perfect sech^2 shape whereas the temporal profile of the EDFL pulse shows some deviations from that. The

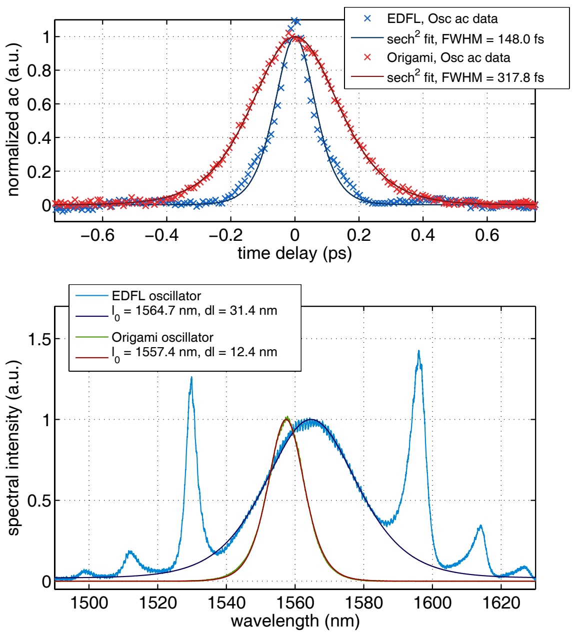

Figure 2: Comparison of the pulse duration and the optical spectra of both the EDFL and the Origami oscillator.

corresponding optical spectra of both oscillators are shown in the lower plot of fig. 2. In case of the Origami the optical spectrum analyzer (OSA) is connected with a 10 m long SMF patch cord to the fiber coupled diagnostics port (see fig. 1). The bandwidth of the Origami's sech^2-shaped optical spectrum amounts to $\Delta\lambda = 12.4$ nm which is approximately 2 nm less than measured by the manufacturer of the laser, and a measurement using a second OSA confirmed this. The spectral bandwidth also depends on the voltage applied to the synchronization piezo element. Influences of these spectral properties to the system have to be investigated, since the EDFL's spectrum has a much larger bandwidth of $\Delta\lambda = 31.4$ nm determined from a fit of the soliton shape, and its center is more than 7 nm red-shifted in comparison to the Origami. The observed sidebands are well understood for these type of lasers based on nonlinear polarization rotation (NPR) mode-locking, and their strong formation indicates that the pulse duration is near the minimum value possible before the soliton becomes unstable. This is the case when the laser is driven in excess of approximately 80 mW average output power which is appropriate for the current state of the synchronization system. For further expansion, however, a higher power is required and this can be fulfilled by the $\approx$ 125 mW delivered by Origami laser system.

Timing Jitter and Synchronization

The RF circuit for the independent synchronization of two laser systems to the accelerator's master RF oscillator is assembled in a rack-mounted chassis with active temperature stabilization ($\delta T < 0.1$ deg, [7]) and allowed for an uncomplicated establishment of the phase-locked loop. The regulation is based on the down-mixing of the master RF signal and a frequency extracted from the laser's Fourier comb. This error signal is sampled with an ADC, processed by a DSP and fed back to a piezo actuator in the laser cavity via a DAC and a self-developed fast piezo driver to stabilize the repetition rate (see fig. 1). The photo

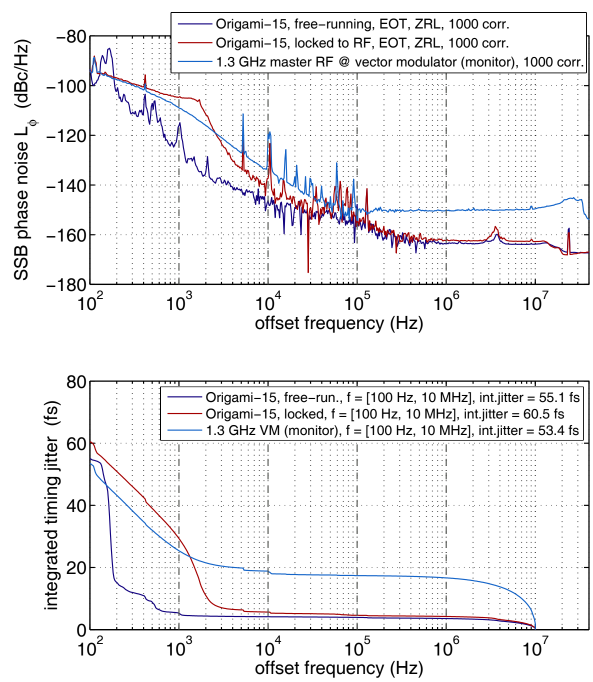

Figure 3: Phase noise measurements (top) and integrated timing jitter (bottom) of the free-running and the locked oscillator, and the RF reference after the phase shifter.

diode with a bandwidth of 10 GHz used for RF generation from the laser pulse train is located on the optical table and connected to the fiber coupled diagnostics port. The master RF is connected to the mixer through a vector (IQ) modulator, required e.g. for bunch arrival time monitor timing scans. A second fast photo diode is installed at the third diagnostics port of the optical set-up for out-of-loop measurements. As an important figure of merit the phase noise at the RF lock carrier frequency of 1.3 GHz and the calculated timing jitter is shown in fig. 3. For the free-running oscillator the integral amounts to 5.2 fs in the frequency range [1 kHz, 10 MHz], but from the corresponding phase noise data it can be concluded that the measurement is limited from around 600 kHz upwards by the photo detection process. With the mitigation of the known EMI problems in the synchronization laboratory and the use of better photo diodes we assume to corroborate the timing jitter in the order of 3 fs measured at PSI [8, 6]. The blue curves show the phase noise and the timing jitter of the RF reference measured at a monitor port of the vector modulator, which is a 20 dB coupler from the actual output. It is obvious that the laser system performs better than the RF reference down to a frequency of around 200 Hz. The steep rise of the timing jitter at this frequency might be caused by the driver which controls the Origami's pump laser diode and could be reduced in cooperation with the manufacturer. For the closed phase-locked loop the data shown in red is acquired. From its characteristics a locking bandwidth in the range of 1 kHz to 2 kHz can be deduced which was adequate for the EDFLs. The Origami laser, however, should be locked with a much lower bandwidth and we are currently optimizing the loop parameters. Other investigations concerning the direct conversion of the laser pulse train to an RF signal with different types of photo diodes and operating conditions are ongoing to improve the RF synchronization of laser systems or the future connection of the accelerating modules to the optical synchronization system, which definitely will require a highly stable master laser oscillator.

SYNCHRONIZATION SUBSYSTEM'S PERFORMANCE

As the Origami laser serves as master laser oscillator for the synchronization system the long-term amplitude stability and timing drift become important. The blue curve in the upper plot of fig. 4 shows the amplitude drift of the Origami over nearly seven days, measured as the low-pass filtered signal of a slow photo diode while the laser is locked to the RF oscillator. The amplitude changes peak-to-peak by 7.6%, but this is highly correlated to the voltage applied to the piezo actuator as clearly can be seen from the gray curve. Since the laser provides an external modulation input, an amplitude feedback also based on a DSP-controller has been commissioned and the measured drift is shown in the red curve. The peak-to-peak change significantly drops to 0.1% and the jitter amounts to 1.1×10^{-4} in the 160 hours; in the first 24 hours to 5.6×10^{-5}. For comparison the amplitude change of the unstabilized EDFL is also shown (green curve). It amounts to 1.8% peak-to-peak, suggesting a lesser influence of the applied piezo voltage. This is supported by the observed steps in the curve which occur when the translation stage for coarse repetition rate tuning moves, and hence the piezo voltage reached one of its limits. From the piezo voltage of the Origami laser, on the other hand, it can be seen that the limits were not reached in the measurement period because of the intrinsic stability of the laser and a coarse tuning was not necessary. The lower plot of fig. 4 shows the timing change of the Origami acquired from an out-of-loop phase detector. If the laser is not amplitude stabilized the maximum timing change amounts to 5.47 ps, but this is clearly

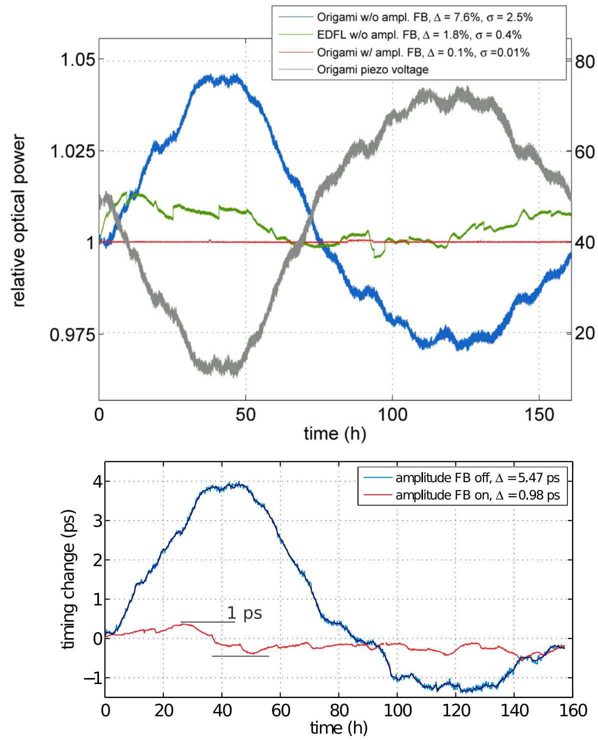

Figure 4: Long-term amplitude stability of both lasers (top) and timing drift of the SESAM-based laser (bottom).

governed by AM-to-PM conversion when the large amplitude change is taken into account. The amplitude feedback strongly suppresses this process and the timing change over 160 h reduces to less than 1 ps. The cause for this residual drift needs to be further investigated.

Distribution-EDFA

Each fiber link stabilization unit is connected to the free-space distribution unit with an individual, dispersion compensated erbium-doped fiber amplifier (EDFA). It boosts the optical power from around 5 mW to levels in the order of 60 mW which is then split for the optical cross-correlator and the fiber link itself. These power levels are necessary to overcome noise limits, e.g. due to large splice losses in the dispersion compensated fiber of the link. During the commissioning of the laser the pulse duration and the optical spectra after the EDFA have been recorded and the latter are shown in fig. 5 for different pump current setpoints. The spectrum becomes broader at higher wavelengths and a second peak is formed, while at the same time the center wavelength is blue-shifted. The reason for this behavior, which is not observed with the EDFL, is most likely self-phase modulation and/or intrapulse Raman-scattering and is currently under investigation. It should also be noted that the pulse duration is not only influenced by the EDFA, but also by the oscillator itself, for example as a function of the applied piezo voltage. A variation of the pulse duration could degrade the performance of the optical links and the synchronization of external lasers, since the pulse du-

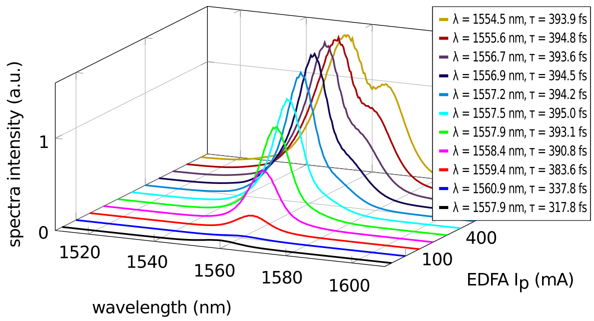

Figure 5: Optical spectra measured after the EDFA which connects a fiber link stabilization unit to the FSD. In the legend the corresponding center wavelengths and pulse durations are given.

ration change would be detected as relative arrival timing change of the pulses. Detailed studies on the performance of the links will be possible when a second Origami laser is available for dedicated measurements.

BAM and Injector Laser Cross-Correlator

To evaluate the performance of the bunch arrival time monitors numerous measurements have been carried out, one of which being the observation of drifts in the accelerator. Figure 6 shows the electron bunch arrival time up-

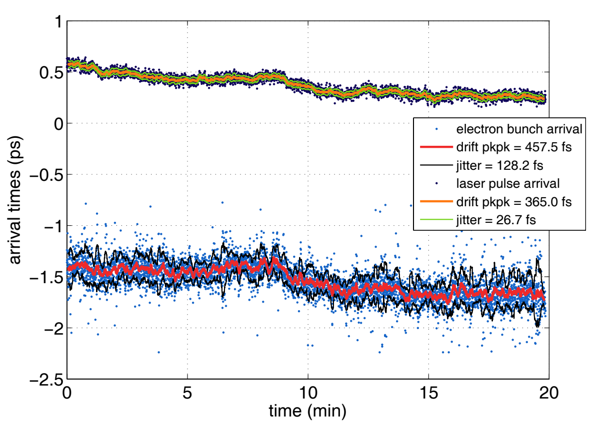

Figure 6: Measurement of the laser pulse arrival time on the photo cathode and the electron bunch arrival time after the booster.

stream of the first magnetic chicane (blue dots, see also [9]) and the arrival time of the injector laser pulses on the photo cathode (violet dots) measured with an optical cross-correlator. As the phase of the RF gun was set to $\phi_{\mathrm{nominal}} - 20$ deg in this measurement the timing jitter and drift of the photo cathode laser should be transported by the electron bunch through the booster modules. This correlation is observed and demonstrates the reasonable operation of both devices with the Origami as master laser. We would like to emphasize that the outliers and the relatively large jitter of the bunch arrival time results from minor issues with the BAM itself and not from the laser. Furthermore, the BAMs are to some extent insensitive to the spectral and temporal shape of the laser pulses, as only relative intensity changes are measured. We observed the same time resolution of all BAMs as with the EDFL in the order of 10 fs to 15 fs. The optical cross-correlator performs also very well and the longer Origami pulse duration seems to play only a minor role as the injector laser's pulse duration of $\mathcal{O}(10\,\mathrm{ps})$ is much larger. For precision measurements of this, however, and to generally benefit from the Origami's stability further investigations are required with this device.

CONCLUSIONS & OUTLOOK

In summary, the commissioning experiences, the properties determined from the characterization and first accelerator-based measurements show a great potential for SESAM-based lasers like the Origami as master clocks of pulsed optical synchronization systems. Some minor technical issues have been or will be resolved in cooperation with the manufacturer. There are, however, differences in the performance and behavior of several parts of the synchronization system when operated with the Origami laser system. These are mainly caused by the larger spectral bandwidth and shorter pulse length of the EDFL – which the system is currently optimized for. Especially the EDFAs and the optical cross-correlators need further research and some adaptation to the new type of laser. An enormous advantage compared to the self-built EDFL is the reliable and maintenance-free operation of the laser enabling to focus research on other components of the system, such as the implementation of the complete arrival time feedback and first measurements, which showed an arrival time jitter of < 40 fs [10, 11].

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