# DEVELOPMENT OF AN ALTERNATIVE, PHOTODIODE-BASED, FEMTOSECOND STABLE DETECTION PRINCIPLE FOR THE LINK STABILIZATION IN THE OPTICAL SYNCHRONIZATION SYSTEMS AT FLASH AND XFEL

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*Abstract*

The fs-stable timing information in the optical synchronization system at FLASH and the upcoming European XFEL is based on the distribution of laser pulses in optical fibers. The optical length of the fibers is continuously monitored and drifts in signal propagation time are actively compensated in order to provide a phase stable pulse train at the end of the fiber link. At present, optical cross-correlation is used to measure the optical length changes. To overcome some of the disadvantages of the current scheme, a different approach for the detection of the optical fiber link length variation was developed. This new scheme uses 10 GHz photodiodes to measure the amplitude modulation of harmonics created by overlapping two pulse trains. The long-term stability of the prototype of this detector over 33 h was demonstrated to be below 5 fs (peak-to-peak) with a rms jitter of about 0.86 fs. The detection principle itself is practically insensitive to environmental influences and needs only about 10 % of the optical power, compared to the optical cross-correlator.

## INTRODUCTION

Today optical synchronization systems become more and more crucial to the operation of FELs, due to the fact, that different components of the machines have to be synchronized on a sub-10 fs scale or even below [1]. Fibers are used to transport the pulse train from the master laser oscillator (MLO) to the various end-stations. The optical cross-correlation is currently the only established scheme to measure the optical link length variation. While showing an excellent performance, in terms of timing jitter and drifts, this scheme has some disadvantages, which are in particular:

- The optical power levels, needed in the optical cross-correlator, can cause pulse shape distortion and self-phase modulation in the fibers.
- A precise dispersion compensation is needed to provide short pulses to the cross-correlator.
- To guarantee the temporal overlap in the detector, the link fiber has to be cut down to the precision of 1 cm.
- Outside of the small temporal overlap window of about 200 fs, no signal is visible on the detector.

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The development of an alternative detection principle was already presented in [2]. This experiment was now successfully evolved to a breadboard prototype [3], using a similar approach. In this paper, most recent measurements are presented, together with an outlook on the engineered version, which is currently under development.

## THE OPTICAL SETUP

Figure 1 shows the optical part of the breadboard detector. This setup consists mostly of free-space optics and has some additional components to allow for an out-of-loop measurement. For the active stabilization of the optical fiber length, a motorized delay line for coarse adjustments and a piezo stretcher for the fast feedback (not shown here) are used. One retarder plate is mounted in a motorized rotation table, offering remote control over the splitting ratio at the following polarizing beamsplitter cube (PBC).

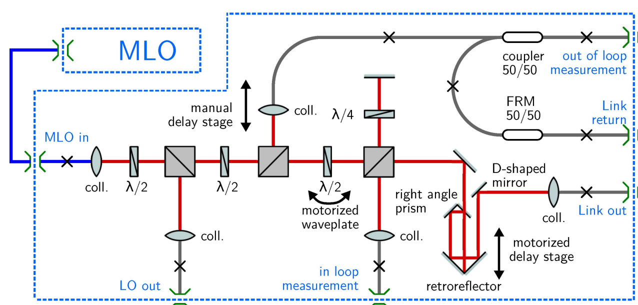


Figure 1: Sketch of the optical part of the prototype.

The pulse train originating from the MLO is split up at several PBCs for different purposes. The leftmost PBC separates a fraction of the pulse train, which is later used as a reference for the generation of the local oscillator (LO) signal for the RF mixer. The middle PBC splits up some light for the out-of-loop measurement, which is used to verify the measurement results. In the right PBC the remaining laser light is split up into a reference part, directly guided onto a fast photodiode (bandwidth > 10 GHz), while the other part is coupled into the fiber link. A faraday rotating mirror (FRM) at the link end reflects a fraction of the light back to this PBC, where it is guided onto the same photodiode. The out-of-loop measurement is realized by combining the pulses after the FRM with the reference signal in a fiber optic coupler. The two pulse trains are then guided onto a second detector.

# DETECTION PRINCIPLE AND READOUT ELECTRONICS

The detection principle relies on the amplitude modulation of the RF spectrum created by two laser pulse trains impinging onto one photodiode. The RF spectrum of a laser pulse train after detection with a photodiode consists of the pulse repetition rate (in our case $f_0 = 216.6$ MHz) and all harmonics of this frequency up to the bandwidth of the photodiode. If two laser pulse trains of the same repetition rate are combined on one photodiode, the amplitude of the harmonics is modulated depending on the delay $\Delta t$ between the two pulse trains. Certain harmonics can even vanish completely for specific delays.

The detector presented here is working at the $n = 45^{th}$ harmonic (9.75 GHz) of the repetition rate, which is filtered out of the spectrum with band pass filters. The amplitude of this harmonic is taken as a measure for the phase shift between the two pulse trains. The steepest response from the detector can be observed when this monitored harmonic has vanished. The amplitude of one harmonic $\omega_n$ is given by Eq. 1, where $\omega_n = n \cdot 2\pi f_0$ and both pulse trains have the same optical power $P$. This formula is derived from a simple model where the laser pulses are shaped like dirac pulses.

$$A(\omega_n) \;\propto\; P\sqrt{\frac{2}{\pi}}\left|\cos\left(\frac{\Delta t\omega_n}{2}\right)\right| \qquad (1)$$

According to Eq. 1 the advantage of this detection principle compared to the optical cross-correlator is, that one finds up to 45 working points, where the $45^{th}$ harmonic vanishes. Each of them has a linear range of operation of a few picoseconds. Thus the link length does not need to be cut very precise. Low optical power levels (0.5 - 2 mW) are convenient to achieve a sensitivity of about 5 mV/fs depending on the RF amplification. These values were achieved without compensating the dispersion of the fiber link, which leads in this prototype to a pulse width of about 50 ps. The dispersion slightly influences the sensitivity of the detector, but apparently a precise compensation is not necessary.

The typical problems arising from the use of photodiodes, like temperature drifts and AM/PM effects [4], are well suppressed here, as they act on both pulse trains simultaneously. Amplitude fluctuations are suppressed additionally by the use of a high harmonic of the repetition rate and by choosing the correct optical power level, in order to operate the photodiode in saturation. Figure 2 shows the response from a ET-3500F photodiode for different harmonics of the laser repetition rate. From an optical power of 1 mW onwards and for harmonics in the 10 GHz range, amplitude fluctuations are well suppressed.

The amplitude of the monitored harmonic in the working point is zero and rises for delay variations in both directions. In order to encode the direction, the output signal is mixed down to the baseband with another reference signal in an RF mixer. The mixing process generates the prefix for the measurement signal, because the phase of the signal flips by 180 degrees in the working point depending on the direction of the timing drift. The mixer output is low pass filtered and amplified once more. Figure 3 shows a schematic of the readout electronics. Apart from the vanished amplitude of the harmonic an additional condition keeps the mixer output signal in the working point at zero. In this point, not only the amplitude, but also the phase (90 degrees-mixer-condition) of the harmonic let the output signal vanish. If, for example, the timing is stable and the amplitude would drift, the output signal would still be correct because of this condition.

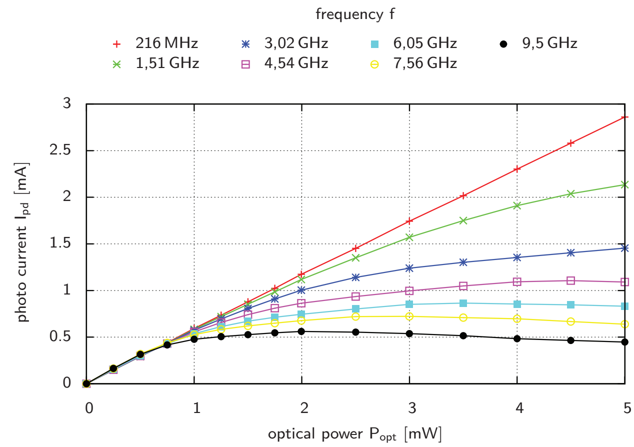


Figure 2: Frequency dependent saturation of a 10 GHz photodiode (type: ET-3500F, company: EOTech).

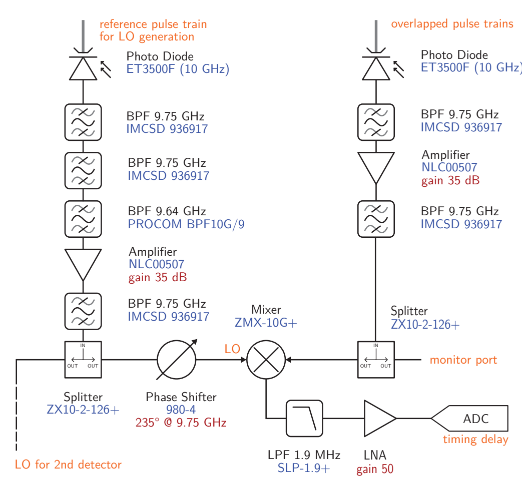


Figure 3: Sketch of the electronic part of the detector.

# MEASUREMENT RESULTS

Before and after each drift measurement, the detector was calibrated with the use of the mechanical delay line. For each calibration, 20 data points were taken with the in-loop and the out-of-loop detector. The sensitivity can be adjusted in a wide range by varying the optical power or the RF amplification. For drift measurements a rather small $K_\varphi$ is useful to maximize the measurement range, which is limited by the maximum voltage of the ADC. Without feedback, the in-loop detector, compared to the out-of-loop detector, sees two times the timing drift in the fiber link. Therefor the sensitivity of the out-of-loop detector was adjusted by intention approximately twice as large as the in-loop sensitivity to provide similar measurement ranges.

Figure 4 shows a long term drift measurement over 33 h. The in-loop detector was calibrated to a sensitivity of $K_{\varphi,\mathrm{in}} = 2.17\,\mathrm{mV/fs}$, the out-of-loop detector to $K_{\varphi,\mathrm{out}} = 4.0\,\mathrm{mV/fs}$. For this test, the link fiber is 20 m long and drifting due to temperature and humidity variations in the laboratory. The optical power on the detector amounts to about 0.28 mW. After the initial cool down, the temperature in the laboratory is stable to the level of about 0.1 K. The values from the in-loop detector are divided by a factor of two because this signal passes the link twice. The peak-to-peak error, if both measurement traces are subtracted from each other, is for this measurement 4.8 fs, the standard deviation amounts to 0.86 fs.

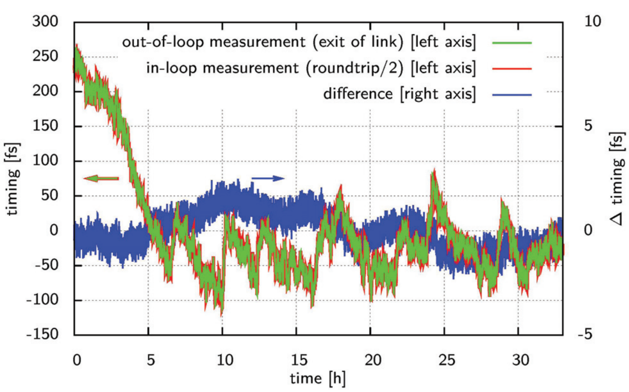


Figure 4: Long term drift measurement with the difference (error) between in-loop and out-of-loop detector.

The second measurement in Fig. 5 shows data from an actively compensated fiber link. A temperature step of 1 K is applied to the link fiber, while the digital control is running. The piezo stretcher compensates the sudden timing change in the fiber and the motorized delay line is moved, when the voltage applied to the stretcher comes close to its limits. The calibration constants for this measurement are $K_{\varphi,\mathrm{in}} = 1.5\,\mathrm{mV/fs}$ and $K_{\varphi,\mathrm{out}} = 4.4\,\mathrm{mV/fs}$. Due to the temperature step, the propagation time through the link changes by about 2 ps. The residual timing measured between the in-loop and the out-of-loop detector shows both a correlation with the piezo voltage and the delay line position. The deviance caused by the actuators amounts to 7 fs for a 2 ps drift of the fiber link. These errors are assumed to be caused by variations in the optical power and not perfectly adjusted working points. Further investigations on this issue will be performed.

The data for all measurements was taken with a 14-bit ADC, reading the first 2048 data points every second with

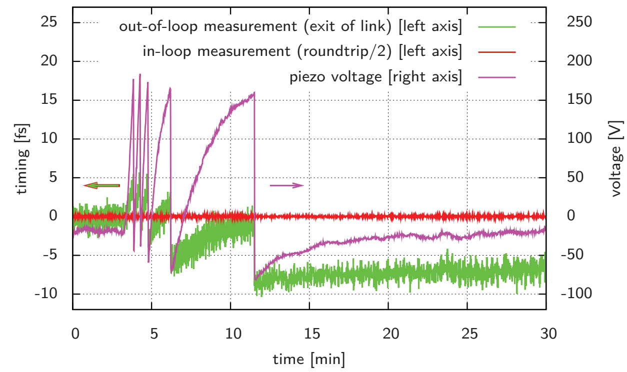


Figure 5: Measurement of a temperature step, applied to the link fiber of an actively compensated fiber link.

a sampling rate of 100 kHz. The average of those 2048 points was plotted and analyzed afterwards.

## CONCLUSIONS AND OUTLOOK

Various measurements were done with a prototype setup for an alternative detection principle for the stabilization of optical fiber links. The detector works very reliable with optical powers down to some tens of microwatt and up to the damage threshold of the photodiodes of a few milliwatt. In drift measurements, extremely good results below 5 fs (peak-to-peak) and 1 fs (rms) were achieved.

Currently a 4-channel engineered version of the detector is constructed. This includes an optimized and miniaturized version of the optomechanics as well as a compact printed circuit board, containing all the electronics for four channels. Further tests will be carried out with this engineered version to answer the open questions. In 2012 this prototype will be installed at FLASH to supply the RF-stations with a high precision optical synchronization signal.

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