A SUB 100 FS ELECTRON BUNCH ARRIVAL-TIME MONITOR SYSTEM FOR FLASH

F. Loehl, K. Hacker, F. Ludwig, H. Schlarb, B. Schmidt, DESY, Hamburg, Germany
A. Winter, Hamburg University, Germany

Abstract

The stability of free-electron lasers and experiments carried out in pump-probe configurations depends sensitively on precise synchronization between the photo-injector laser, low-level RF-systems, probe lasers, and other components in the FEL. A precise measurement of the arrival-time of the electron bunch with respect to the clock signal of a master oscillator is, therefore, of special importance. For this task, we propose an arrival-time monitor based on a beam pick-up with several GHz bandwidth which permits measurements in the sub 100 fs regime. The RF-signal from the beam pick-up is sampled by an ultra-short laser pulse using a broadband electro-optical modulator. The modulator converts the deviation of the electron bunch arrival-time from a reference into an amplitude modulation of the laser pulse. This modulation is detected by a photo detector and sampled by a fast ADC. By directly using the laser pulses from the future master laser oscillator of the machine, any additional timing jitter is avoided. In this paper we present the layout of the system and first experimental results.

EXPERIMENTAL SETUP

The concept of the phase monitor system uses the upcoming laser based timing system developed in collaboration with MIT (see [1]). A mode-locked Erbium-doped fiber laser [2] is locked to a microwave RF master oscillator. Using dispersion compensated, optical length stabilized fiber links, the ultra-short laser pulses ($\sim$ 200 fs) from this master laser oscillator are distributed to the devices to be synchronized. There the laser pulses are either reconverted into a RF signal or used directly for diagnostic devices like the phase monitor system.

Since the timing system is not installed yet, we used the experimental setup shown in Fig. 1. A mode-locked Erbium-doped fiber laser operating at a repetition rate of 40.625 MHz is locked to the 1.3 GHz reference frequency of the machine. The laser pulses are fed into a 12 GHz electro-optical modulator (EOM) where the RF signal of a broadband beam pick-up modulates the amplitude of the laser pulses: inside the EOM, the laser signal is split in two waveguides which traverse $LiNBO_3$. The $LiNBO_3$ becomes birefrigent in the presence of an electrical field. The RF signal of the beam pick-up is applied to the waveguides with opposite polarity, causing a phase shift between the laser light in the two waveguides. Recombining the two signals transfers this phase modulation into an amplitude modulation.

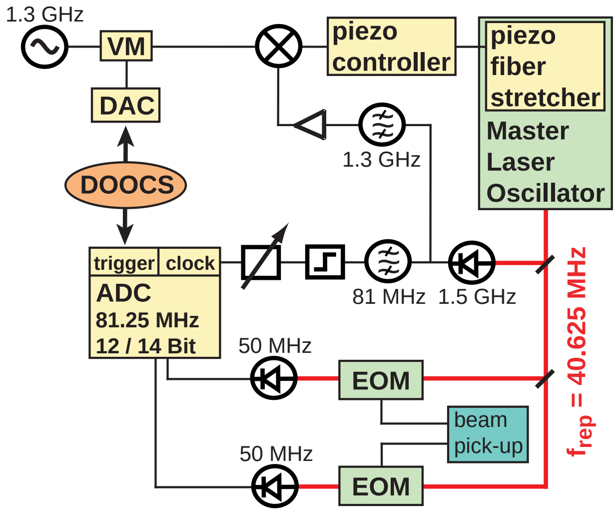

Figure 1: Schematic diagram of the test bench for the phase monitor system.

After passing through the EOM, the laser pulses are detected by a >50 MHz photo detector and sampled by a fast ADC. The ADC is clocked at twice the repetition rate of the laser in order to provide the possibility to sample both the signal and the baseline. Since the signal from the photo detector has a width of only $\sim 3\,\mathrm{ns}$, the detection of the laser amplitude is sensitive to a jitter of the ADC clock. To minimize this jitter, the ADC clock is generated directly from the laser by feeding the second harmonic into a limiting amplifier. The phase between the ADC clock and the laser pulses is adjusted by a trombone. With a vector modulator the laser phase can be shifted relative to the 1.3 GHz.

The beam pick-up used for the measurements consists of a thin metal ring with an inner diameter of $34\,\mathrm{mm}$. With two feed-throughs mounted in opposite directions in the horizontal plane, the inductively shaped beam transient is coupled out. After about $30\,\mathrm{m}$ cable, the signal has a peak-peak voltage of more than $30\,\mathrm{V}$ and a bandwidth of more than 5 GHz. In the zero-crossing the slope is about 0.25 V/ps.

MEASUREMENT RESULTS

Measurement Principle

Using the vector modulator, the sampling laser pulse can be shifted over the beam pick-up signal. Figure 2 shows the measured laser amplitude at different sampling positions along the beam pick-up signal. The shape of the beam pick-up signal is mapped inversely to the laser amplitude. At large negative beam pick-up voltages the laser intensity is increased to a level where the photo detector saturates. Without attenuation of the beam pick-up signal the phase shift in the two waveguides of the EOM becomes larger than 180°, yielding over-rotation.

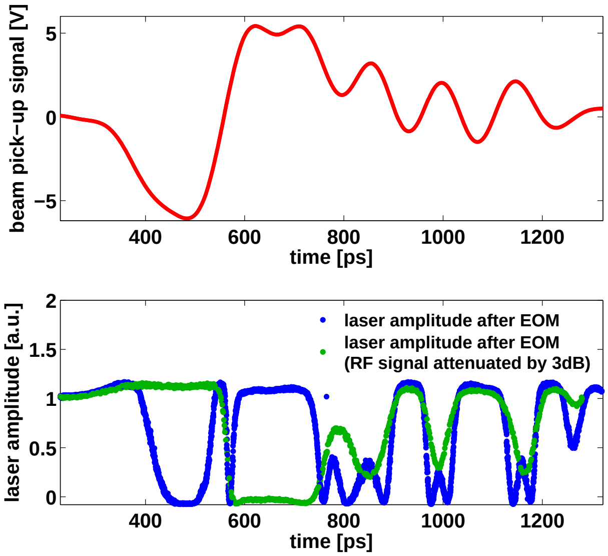

Figure 2: Top: Beam pick-up signal limited to 25 dBm. Bottom: Measured laser amplitude at different sample positions along the beam pick-up signal with (green) and without (blue) attenuation by 3dB.

In order to measure the beam arrival-time, the timing of the sampling laser pulse is adjusted such that it samples the steep slope at the zero-crossing of the beam pick-up signal. A change in the beam arrival-time is then transformed into an amplitude modulation of the laser pulse. The resolution of the system then is basically limited by the steepness of the slope and the accuracy with which the laser amplitude can be detected. The slope at the zero-crossing of the beam pick-up signal depends linearly on the bunch charge which can easily be corrected with charge monitor readings.

A big advantage of the high repetition rate of the laser and the ADC is that many disturbances in the measurement can be removed. The laser amplitude is determined from the difference of the sampling on top of the photo detector signal and the following sample on the baseline. Since the electron bunch spacing is $1\,\mu$s, only a small fraction of laser pulses is modulated. The amplitude of the modulated laser pulses can, therefore, be normalized to the previous unmodulated laser pulse. This has the advantage that all kinds of drifts and disturbances in the detection electronics, such as baseline or gain changes of the photo detectors, drifts and noise picked up by the ADCs and EOMs which are slower than several MHz, can be removed.

Calibration and Resolution

The conversion factor between laser intensity change and arrival-time change is determined by sampling the slope of the beam pick-up signal around the zero-crossing. Typical values are around $60 - 100\,\mathrm{fs}$ / (% laser amplitude modulation) when using the beam pick-up signal without attenuation. The laser amplitude is determined with an accuracy of $0.2 - 0.4\%$. The normalization of the laser amplitude to the amplitude of the previous laser pulse degrades this resolution by $\sqrt{2}$. This limits the resolution of the detectors in the present configuration to $20 - 50\,\mathrm{fs}$.

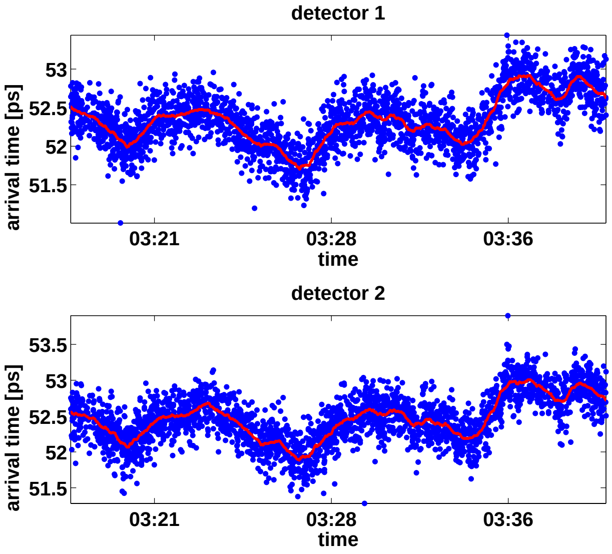

Figure 3: Arrival time measurements with two independent detectors for a long sequence of electron bunches. The pick-up signal was split so that both detectors should in principle deliver the same time readings. The difference signal between the two measured arrival-times has a rms width of $139\,\mathrm{fs}$.

To validate the resolution expected from the slope of the laser amplitude signal and the noise on the laser amplitude, the beam pick-up signal was split and connected to the two EOMs. The splitting leads to a smaller RF amplitude at both EOMs such that the expected rms resolutions are $99\,\mathrm{fs}$ and $114\,\mathrm{fs}$. Figure 3 shows the arrival-time measured by the two detectors for a long sequence of electron bunches. The difference of the two signals has a rms width of $139\,\mathrm{fs}$ which is in good agreement with the expected $151\,\mathrm{fs}$.

Position Dependence of the Beam Pick-up Signal

In order to improve the resolution of the detectors, the two outputs on opposite sides of the beam pick-up were connected to the two detectors. In this configuration the expected resolutions amounts to $33\,\mathrm{fs}$ for the two EOM systems. The difference signal between the two detectors, however, has a rms width of more than $1.5\,\mathrm{ps}$. The reason is that the zero-crossing of the beam pick-up signal depends on the transverse position of the electron beam in the beam pick-up. The attempt to remove this position dependence with the beam position monitor (BPM) readings by correlation methods failed, because the orbit fluctuations are mainly due to energy jitter upstream of the first bunch compressor chicane. This energy change also causes an arrival-time change such that the BPM and the EOM detector readings are no longer statistically independent.

Hence, the dependence on the beam position was experimentally investigated changing the horizontal and vertical orbit offset with corrector coils by $\pm 0.5\,\mathrm{mm}$. This yields an orbit dependence of the two detector signals of

$$a_{x,1} = (-6.94 \pm 0.05)\frac{\mathrm{fs}}{\mu\mathrm{m}} \quad a_{x,2} = (10.7 \pm 0.02)\frac{\mathrm{fs}}{\mu\mathrm{m}}$$
$$a_{y,1} = (-0.16 \pm 0.07)\frac{\mathrm{fs}}{\mu\mathrm{m}} \quad a_{y,2} = (0.29 \pm 0.02)\frac{\mathrm{fs}}{\mu\mathrm{m}}.$$

With these values the arrival-time, t, can be calculated from the times t_1 and t_2 measured at the two EOM detectors and the independent measured beam positions x and y:

$$t = t_1 + a_{1,x}x + a_{1,y}y \qquad (1)$$
$$t = t_2 + a_{2,x}x + a_{2,y}y. \qquad (2)$$

After applying these corrections, the rms width of the difference signal between the two phase detectors is reduced to $300\,\mathrm{fs}$ which is dominated by the limited BPM resolution of around $20\,\mu\mathrm{m}$.

Since both outputs of the beam pick-up see the same beam arrival-time, this offers the possibility to determine the horizontal beam position very accurately:

$$x = \frac{t_1 - t_2 + (a_{2,y} - a_{2,x})y}{a_{1,x} - a_{2,x}}. \qquad (3)$$

Using the errors given above and assuming a vertical orbit change of less than $\pm 100\,\mu\mathrm{m}$ this results in a horizontal resolution of $3\,\mu\mathrm{m}$ over a $1\,\mathrm{mm}$ range when using the two outputs as a beam position monitor. This can be considered as a proof of principle for the planned beam position monitors in the bunch compressor chicanes. They will use the same phase measurement technique to achieve sub $5\,\mu\mathrm{m}$ resolution over a 10 cm aperture [3].

This precise beam position information can be used to calculate the arrival-time with much higher precision than when using the BPM read-backs. Error propagation yields a rms timing error of $27\,\mathrm{fs}$.

For larger vertical orbit changes the resolution for both, the beam position and the arrival-time, are limited by the large error in $a_{y,1}$. For a vertical beam position change of $1\,\mathrm{mm}$ the resolutions are already reduced to $4.8\,\mu\mathrm{m}$ and $48\,\mathrm{fs}$, respectively. However, the error of the calibration constants could easily be reduced in a new calibration measurement.

Figure 4 shows an example for an arrival-time measurement using the method described above. Arrival-time changes have been produced by changing the path length in the first bunch compressor chicane. The different colors denote different bunches along the bunch train. The measurement shows that there is a systematic arrival-time difference of about $1\,\mathrm{ps}$ between the first and the last bunch inside the bunch trains. The rms bunch arrival-time jitter is about $200\,\mathrm{fs}$. The relative rms jitter of the timing between two adjacent bunches inside the same bunch train is between 40 to $60\,\mathrm{fs}$ along the bunch train, which is a confirmation of the high resolution of the arrival-time measurement.

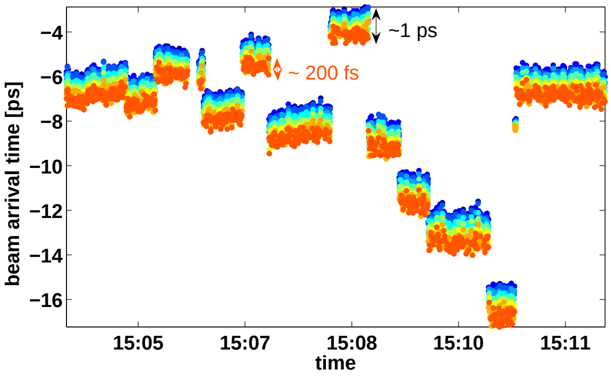

Figure 4: Measured beam arrival-time after corrections for the orbit dependence of the beam pick-up signal. The arrival-time was changed during the measurement several times by changing the path length through the bunch compressor chicane.

SUMMARY AND OUTLOOK

A new system to measure fast electrical transients with high accuracy has been demonstrated. The same principle is usable for all kinds of fast electrical transients such as beam pick-up signals for beam position and beam arrival-time measurements, photo detector signals in order to determine the arrival-time of laser pulses with respect to a reference, and also as an optical down-converter for phase and amplitude measurements of cavity signals.

The signal of the beam pick-up used for the demonstration of the measurement principle shows a strong orbit dependence. This enables us to measure not only the arrival-time with a precision of about $30\,\mathrm{fs}$ but also the beam position with an error of about $3\,\mu\mathrm{m}$ when no large changes in the vertical orbit are applied.

REFERENCES

[1] J. W. Kim et. al., “Large scale timing distribution and RF-synchronization for FEL facilities,” FEL Conference 2004, Trieste, Italy, 2004.

[2] A. Winter et. al., “High-precision Laser Master Oscillators for Optical Timing Distribution Systems in Future Light Sources,” this Conference, Edinburgh, UK, 2006.

[3] K. Hacker et. al., “Beam Position Monitor with Large Horizontal Aperture,” this Conference, Edinburgh, UK, 2006.