

# A SUB-50 FEMTOSECOND BUNCH ARRIVAL TIME MONITOR SYSTEM FOR FLASH

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## Abstract

A bunch arrival time monitor using the future laser based synchronization system at FLASH has been developed. The signal of a beam pick-up with several GHz bandwidth is sampled by a sub-ps laser pulse using a broadband electro-optical modulator. Bunch arrival time deviations are converted into amplitude modulations of the sampling laser pulses which are then detected by a photo-detector. A resolution of 30 fs could be reached with the capability towards sub-10 fs level. In this paper we describe the design of the optical system and present recent results.

## INTRODUCTION

The operation of ultra-violet and X-ray free electron lasers like FLASH (Free electron LASer in Hamburg) or the planned European XFEL requires an arrival-time stability on the order of several tens of femtoseconds between the X-ray pulses and laser pulses of external probe lasers, to be able to take full advantage of the fs-short X-ray pulses in pump-probe experiments.

A fs-stable synchronization system and monitor systems for the bunch arrival time with resolutions on the order of 10 fs are needed to establish a high level of stability. To distinguish accelerating gradient changes upstream of the dispersive sections from timing changes of the photo-injector laser, precise monitor systems for the beam energy in the dispersive sections are needed in addition.

Long-term, femtosecond-stable synchronization cannot be achieved by conventional coaxial distribution systems. At FLASH and the XFEL an optical synchronization system, developed in collaboration with MIT (see [1]), will be used. The system uses a mode-locked Erbium doped fiber laser as an optical master oscillator. It is locked to a microwave RF oscillator. For the FLASH synchronization system, two different types of fiber lasers are under investigation: one operates in the stretched-pulse regime at a repetition rate of 54 MHz [2], and the other one is a soliton laser with a repetition rate of 216 MHz [3]. The light pulses generated by these lasers are distributed to the remote locations via actively length-stabilized, dispersion compensated fiber links ([4], [5]). There, the light pulses are converted either into RF signals, used to synchronize external lasers by optical cross-correlation or seeding, or used to drive opto-diagnostic devices such as the bunch arrival time monitors (BAMs) presented here.

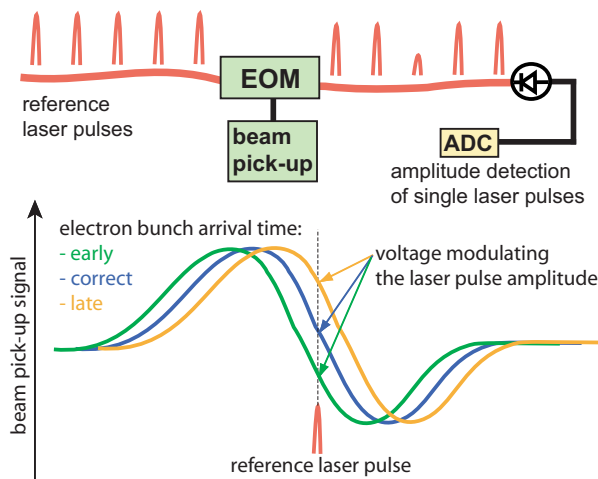


Figure 1: Principle of the arrival time detection. Reference laser pulses traverse an electro-optical modulator which is driven by the signal of a beam pick-up (top). Arrival time changes of the electron beam cause different modulation voltages at the laser pulse arrival time (bottom), leading to laser amplitude changes that are detected by a photo detector.

## MEASUREMENT SETUP

The system of the bunch arrival time monitor is described in [6], the principle of the arrival time detection is shown in Fig. 1. Reference laser pulses are fed into an electro-optical modulator (EOM) where the laser amplitude is modulated by the fast transient of a beam pick-up signal. The laser amplitude changes, which are a measure of the bunch arrival time, are detected by a photo-detector and recorded by a fast ADC. By using laser pulses from actively stabilized fiber-links and installing the EOM directly next to the beam pick-up to reduce cable-drifts, the realization of an almost drift-free arrival time detection with respect to the master laser will become feasible.

The performance of the BAM system, was evaluated using the pulses from a 40.625 MHz stretched-pulse laser as a reference. The laser was phase-locked to the accelerator RF and, by using a vector-modulator, the laser pulses could be shifted in time. In [6] we found a strong electron-orbit dependence of the ring electrode used as a beam pick-up. This could be used to determine the beam position with high resolution from the difference signal of two arrival time measurements. With a special beam pick-up this method will be used for beam position measurements inside the mag-

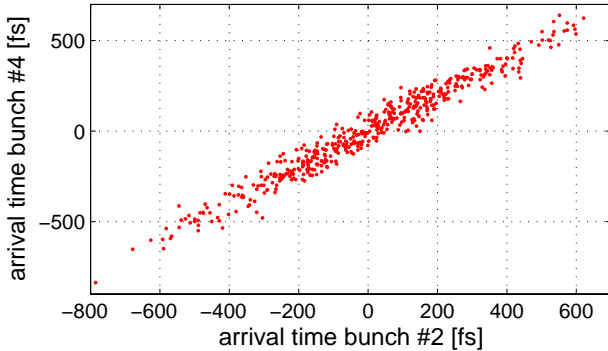


Figure 2: Correlation between the measured bunch arrival time of two bunches inside the same bunch train for 500 bunch trains. From the arrival time difference a single bunch resolution around 30 fs can be estimated.

netic chicanes of FLASH [7]. Since the orbit dependence complicates the arrival time measurement, a new pick-up design [7] with a smaller orbit dependence, based on buttons, will be used for FLASH.

All measurements presented here have been carried out with the ring electrode. In order to reduce the orbit dependence, two outputs on opposite sides of the pick-up were combined, resulting in an orbit dependence smaller than 200 fs/mm. This could be corrected by beam position monitor readings.

The resolution of the system is limited by two sources: the accuracy with which the amplitude of the single laser pulses can be detected and the beam pick-up signal slope. The signal slope defines the degree of laser amplitude modulation for a given timing change. Since in the test setup the EOM was connected to the beam pick-up by a 30 m long cable, high frequency components of the pick-up signal were damped out, resulting in a voltage slope around 0.25 V/ps. This gives a time-to-optical amplitude conversion factor of around 60 – 80 fs/(% laser amplitude modulation) in the optical setup. Being able to read out the laser amplitude with an accuracy of about 0.3% gives a resolution of 20 – 25 fs for this set-up. The amplitude read-out was mainly limited by ADC clock-jitter, and with a better ADC 0.08% detection accuracy could be reached in a laboratory setup. Measurements of the beam pick-up signal with a fast oscilloscope installed directly in the tunnel gave a voltage slope of around 1 V/ps for the ring-electrode and also for the new button design. We are, therefore, optimistic that a monitor resolution below 10 fs is feasible with the setup installed directly in the tunnel.

## MEASUREMENTS

An upper limit of the resolution achieved with the monitor system can be estimated using the special time structure of the superconducting FLASH linac. With a repetition rate of 5 Hz, trains of up to 800 bunches with 1  $\mu$ s spacing are produced. Due to the short bunch spacing, fluctuations of

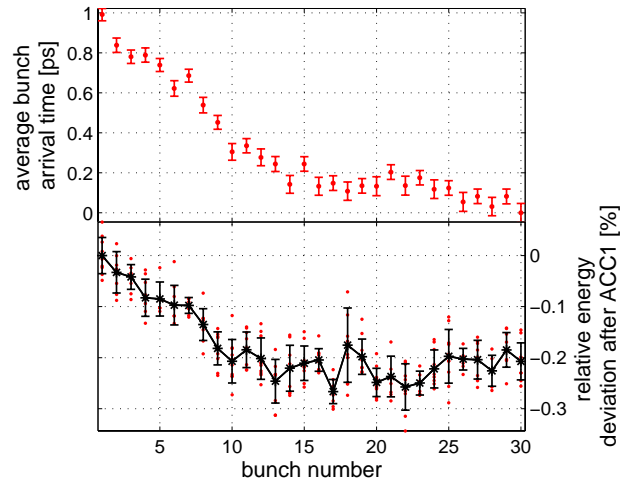


Figure 3: Comparison of the average bunch arrival time over the bunch train at the end of the machine with the average beam energy after the first accelerating module ACC1.

the accelerating fields experienced by adjacent bunches are small. The correlation of the arrival time of two bunches in the bunch train for many different shots gives an upper resolution limit, since amplitude changes of the accelerating fields are experienced by both bunches. The limiting factor is only the shot-to-shot change of the amplitude slope of the accelerating fields.

Figure 2 shows the correlation between the arrival time of two bunches inside the bunch train for 500 shots. The jitter of the arrival time difference is around 40 fs over 100 and 50 fs over 500 shots. The resolution of a single bunch measurement is smaller by a factor of  $1/\sqrt{2}$  leading to around 30 fs single bunch accuracy. This confirms the resolution estimated before.

Figure 3 shows a comparison between the average arrival-time measured by the BAM system at the end of the machine and the average energy deviation measured with a synchrotron radiation monitor [8] in the first bunch compressor. A large energy slope in the first part of the bunch train is visible. This is transformed inside the magnetic chicanes into arrival time differences. The arrival time change  $\Delta t$  is related to beam energy changes  $\delta E/E$  by

$$\Delta t = \frac{R_{56}}{c_0} \frac{\delta E}{E}, \quad (1)$$

where the momentum compaction factor  $R_{56} = 180$  mm for FLASH giving an arrival time change of 6 ps per % energy change. This is in good agreement with the measurements of the BAM.

This measurement shows the high potential for using the BAM or other devices that use this optical front end in beam based feedback systems. Being able to measure the arrival time over the entire bunch train together with the ease of the data acquisition makes the system ideally suited for fast intra bunch-train feedbacks.

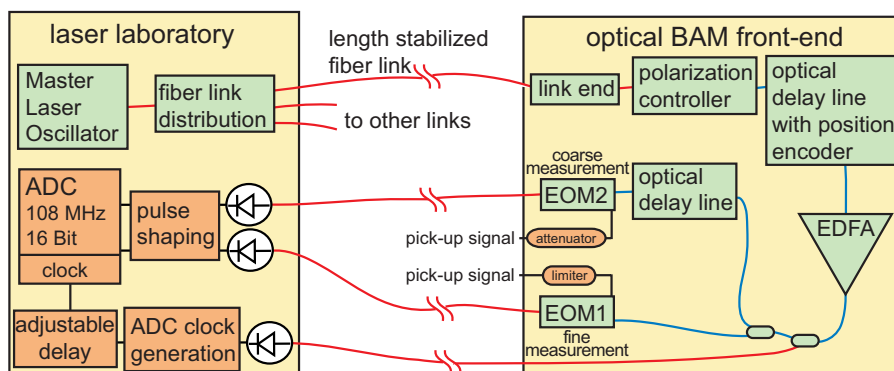


Figure 4: Schematic design of the BAM system for FLASH.

## DESIGN OF THE SYSTEM FOR FLASH

Figure 4 shows a schematic of the BAM design for FLASH. Optical front-ends installed directly next to the beam pick-ups will be used. The reference laser pulses from the master laser oscillator are supplied by actively length-stabilized fiber-links. Since the fiber-links do not use polarization maintaining fibers, a polarization feedback will be applied. It is not yet decided, whether the polarization adjustment will be done inside the fiber-link or at the exit. An optical delay line (ODL) will be used to adjust the timing of the reference laser pulses such that the pick-up signal is sampled at the zero-crossing in order to reduce the dependence on the signal amplitude. With a feedback on the ODL position, this timing adjustment will be stabilized. Since the timing of the reference laser pulses is changed by the ODL, a precise position readout of the ODL is required. We use absolute position encoders with a resolution of  $3\ \mu\text{m}$  over a 100 mm range. The bunch arrival time is determined from the combination of ODL position and laser amplitude modulation. Having an ODL installed, the dynamic range of the arrival time detection is limited only by the length of the ODL, which corresponds to a maximum timing change of 330 ps in our case. Without the ODL, the dynamic range is in the order of 1 ps and fast changes of machine parameters could be a problem. A second EOM is, therefore, foreseen which is modulated by a strongly attenuated pick-up signal. This gives a low resolution measurement with a dynamic range of several picoseconds which can be used to adjust the ODL in case the high resolution measurement is out of range. The timing adjustment between the two EOMs can be done using either accurate fiber- and cable lengths or a second delay line.

The modulated laser pulses are sent back to the laser laboratory where the master laser is also located. This has the advantage that changes in the readout system can be made without accessing the accelerator tunnel. With photo detectors, a pulse shaping unit, which in the easiest case is just a low pass filter, and a fast ADC, the amplitudes of the laser pulses are measured. The ADC is clocked with 108 MHz; this is twice the repetition rate of the 54 MHz master laser.

With a proper timing adjustment, the laser pulses and the base line of the photo detector signal can be sampled, allowing for offset-free amplitude detection. The ADC clock is generated directly out of the laser pulses that sample the pick-up signal. This makes sure that the sampling position remains the same when the ODL position is changed. To simplify the ADC sampling time adjustment, a clock-delay module will be used [9]. In case a 216 MHz laser will be used, either faster ADCs are needed, or the baseline and the laser amplitude have to be sampled by different ADC channels. In the latter case drifts of the ADC channels could become an error source.

## SUMMARY AND OUTLOOK

A monitor system to measure the arrival time of fast electrical transients with fs-resolution has been developed. A resolution below 30 fs could be reached with the capability towards sub-10 fs level. The system will be installed at FLASH for measurements of the bunch arrival time and for precise measurements of the beam position inside the magnetic chicanes.

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