FEMTOSECOND RESOLUTION BUNCH ARRIVAL TIME MONITOR

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Abstract

A need for femtosecond resolution beam arrival time measurements has arisen with the transition from many-picosecond-long bunches in ring-based accelerators to a few femtosecond-long bunches in high-gain free-electron lasers. Here we present an electro-optical detection scheme that uses the signal of a beam pick-up to modulate the intensity of a femtosecond laser pulse train. By detecting the energies of the laser pulses, the bunch arrival time can be deduced. We tested this scheme by distributing a laser pulse train to two locations in the FLASH linac, separated by 60 m, using length-stabilized optical fibers. By measuring the arrival times of the same electron bunches at these two locations, we determined an rms bunch arrival time resolution of 6 fs. This unprecedented monitor resolution allowed us to reduce the beam arrival time jitter from almost 200 fs down to 25 fs with an intra-bunch train feedback. In combination with a beam pick-up with a position dependent time-response, the same electro-optical detection scheme can be applied for micrometer resolution beam position measurements.

INTRODUCTION

High-gain free-electron lasers (FELs) operating in the soft and hard x-ray regimes are capable of generating light pulses with durations below 10 fs [1,2]. Even shorter light pulse durations are envisioned using schemes in which a part of the electron bunch is manipulated using a few cycle laser pulse (see, e.g., [3,4]).

In order to take full advantage of the sub-10-fs light pulses presently available (e.g., in two-color pump-probe experiments), precise measurements and eventually control of the electron bunch arrival time are required. The desired measurement resolution is on the same order as the photon pulse duration–ideally, a small fraction of it. The abovementioned manipulation schemes as well as FEL seeding schemes require a stable longitudinal overlap between the electron bunch and the laser pulse. Many of these schemes require a timing stability between the laser pulses and the electron bunches of around 30 fs or better.

In this work we present electro-optical synchronization schemes which allow for a bunch arrival-time measurement and stabilization with the before-mentioned resolution.

OPTICAL SYNCHRONIZATION SYSTEM

In collaboration with F.X. Kaertner's group at MIT, we developed an optical synchronization system to address the stringent timing requirements of FELs. Figure 1 depicts the schematic principle of the system. A mode-locked laser – the master laser oscillator (MLO) – is used as a time-reference. Its laser pulse train is distributed to the remote locations via length-stabilized optical fibers, where the respective subsystems are synchronized to the time-markers provided by the laser. These subsystems can, for example, be laser systems, which can be synchronized by optical cross-correlation techniques [5,6]; RF systems (for schemes on how to extract stable RF signals from the optical pulse train, see, e.g., [7,8]); or beam diagnostics systems such as the bunch arrival-time monitor discussed in this paper.

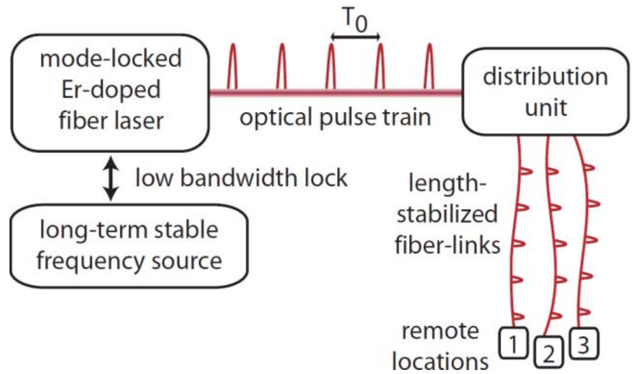

Figure 1: Schematic principle of the optical synchronization system [11].

Master Laser Oscillator

We used an erbium fiber laser operating in the soliton regime as the MLO [9,11]. It produces a train of sub-100 fs long laser pulses and operates at a repetition rate of 216.7 MHz, which is the sixth sub-harmonic of the 1.3 GHz frequency of the superconducting TESLA-type cavities used at FLASH. In order to compensate for length changes of the laser resonator due to thermal expansion or contraction, as well as due to microphonics, the laser repetition frequency is locked to a long-term stable RF oscillator. The phase lock loop (PLL) stabilizes the laser repetition rate up to frequencies of several kHz using a digital feedback loop acting on a fast piezo-mirror inside of the laser resonator. Laser timing changes occurring at frequencies larger than a few kHz are very small–significantly less than 10 fs [11]–and therefore do not need active correction. When all critical timing signals are derived from the MLO, slow timing changes below a few kHz are not critical for most applications, since most subsystems are able to follow these timing changes at a sufficiently high rate. The accuracy of the PLL is therefore not of highest importance. In our case, the timing jitter between the laser and the RF source was around 40 fs. The long-term frequency stability of the RF source is, however, of great importance when fiber links of different lengths are used. The reason is that the electron beam travel time between two locations in the

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accelerator is defined by the speed of light, which is thought to be a constant, while, as we will see later, the length of the fiber links depends on the laser frequency. For a length difference of 100 m between two fiber links, a frequency change of $\Delta f / f = 10^{-8}$ causes a timing shift of around 5 fs [11]. While this can still be achieved by common quartz oscillators, large accelerators with length differences of a few kilometers between the fiber links will require an RF source with better long-term stability– for example, a clock based on a rubidium standard.

Fiber-Link Stabilization

In order to distribute the time-reference signal of the MLO without deteriorating its stability, active stabilization of the fiber link is required to in order compensate for optical length changes of the fiber blank?– for example, due to thermal effects, vibrations, or changes in the air humidity, which affect the mechanical properties of the fiber coating.

To measure the optical length of the fiber with femtosecond precision, we developed the scheme depicted in Fig. 2. Here, laser pulses from the MLO are transmitted through a dispersion compensated optical fiber. At the end of the fiber, the optical pulse train is amplified in an erbium-doped fiber amplifier, which is optimized to add a minimum amount of timing jitter to the optical pulse train [10]. While part of the laser intensity is then used for synchronization purposes, another part of the intensity is reflected by a Faraday rotating mirror and sent back to the MLO using the same optical fiber. There, the returning laser pulses are combined with pulses coming directly from the laser. In a balanced optical cross-correlator, based on a single periodically poled KTP crystal, the temporal overlap between both pulse trains is measured with sub-femtosecond resolution and length changes are compensated for with a feedback loop acting on a piezo fiber stretcher and an optical delay stage [11,12,13].

For configurations that do not require the ultimate resolution provided by the previously described scheme, we also developed an RF based scheme to detect the overlap between two optical pulse trains [14].

BUNCH ARRIVAL TIME MONITOR

A major difficulty with bunch arrival-time measurements at various locations within the accelerator against a common time reference–the transport of the reference signals–can be overcome with the system described earlier. In order to avoid deteriorating the precise timing information provided by the optical fiber links, an ideal bunch arrival-time detection scheme should directly use the laser pulses from the fiber links, and should not require any additional conversion process (e.g., from the optical signal to an RF signal) between the arrival time monitor and the fiber link.

We developed such a scheme, which uses a commercial Mach-Zehnder-type electro-optical modulator (EOM) as a key component. This is shown in Fig. 3. The modulator is driven by the transient voltage signal that the electron bunches induce in a beam pick-up. In order to be able to observe both destructive and constructive amplitude modulation, a constant phase shift is applied between both arms of the Mach-Zehnder interferometer by an additional bias voltage. The arrival-time of a reference laser pulse is adjusted such that it coincides with the zero-crossing of the pick-up signal for the nominal bunch arrival time. Variations of the electron bunch arrival time lead to variations of the modulation voltage experienced by the reference laser pulse. By detecting the amplitude of this reference laser pulse, the bunch arrival time can then be derived. This bunch arrival-time monitor (BAM) scheme was first proposed in [15].

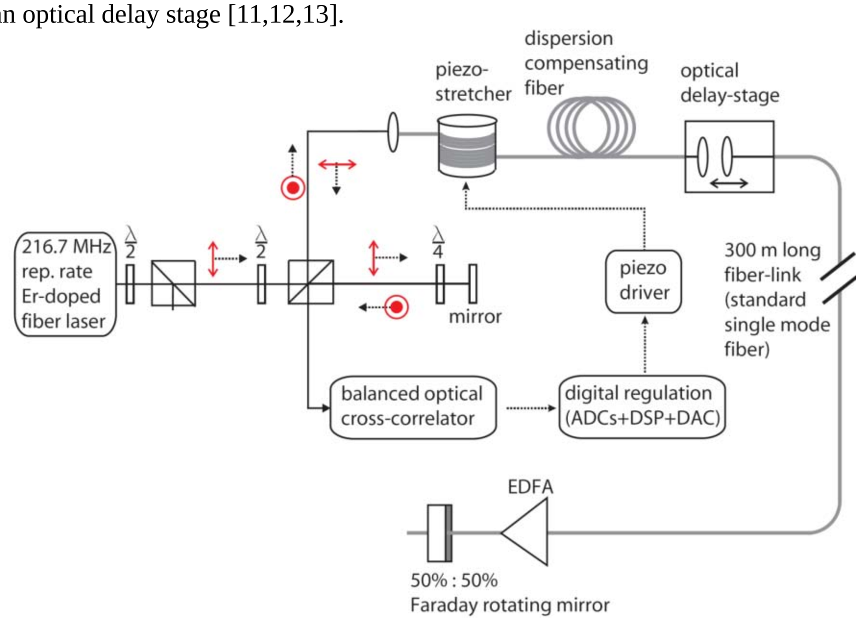

Figure 2: Principle of the fiber-link length stabilization based on an optical cross-correlator [11,12,13].

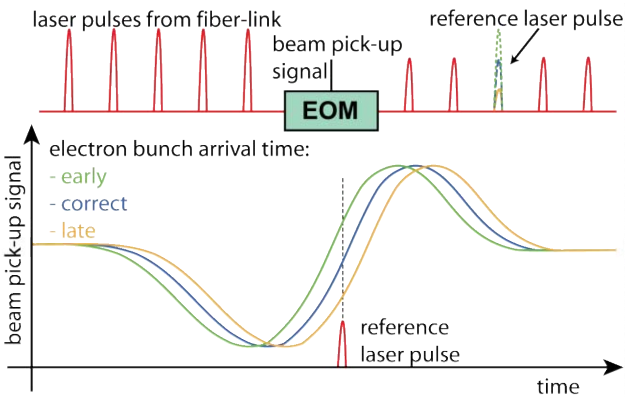

Figure 3: Principle of the bunch arrival-time monitor (BAM) [16,17].

The experimental setup of the first BAM prototypes used at FLASH is depicted in Fig. 4. The light pulses are sent through an optical delay line in which the temporal overlap between the laser pulses and the zero-crossing of the beam pick-up signal can be established. A slow feedback loop acting on the delay line ensures that the sampling time remains at the pick-up signal's zero-crossing even when the arrival-time of the electron beam changes. For that purpose and also to calibrate the BAM, the delay stage is equipped with an absolute position encoder. The beam arrival-time is then determined from the combination of the delay line position and the laser pulse amplitude after the EOM.

After the laser beam passes the first optical delay stage, a small fraction of the intensity is split and used to generate a sub-picosecond stable sampling clock for a 16 bit ADC which operates at a sampling frequency of 108 MHz (half the laser repetition rate). The remaining light is split a second time and sent to EOM1, which provides a high resolution bunch arrival-time measurement. To protect the EOM from damage, the beam pick-up signal is limited to ±5V by using a broadband limiting diode (> 26 GHz bandwidth). Since the dynamic range of this measurement is limited to around 5 ps, a second EOM is installed and driven by a strongly attenuated pick-up signal. A second optical delay stage is used to adjust the timing with respect to the first high resolution measurement.

The modulated laser pulse trains are detected with photo detectors, and in order to allow for a precise detection of the laser pulse energies, each photo detector signal is sampled by two ADCs in a particular way: one ADC samples the base line and another samples the peak of the detector signal. A large ADC analog bandwidth of around 700 MHz allows for a clean detection of single laser pulse energies.

In order to reduce the influence of laser amplitude variations as well as of noise and disturbances from electro-magnetic interferences on the beam pick-up signal, the energy of the laser pulse, which was modulated by the electron bunch, is normalized to the energy of a previous laser pulse, which arrives prior to the electron bunch. This scheme acts like a high-pass filter and strongly suppresses all disturbances from DC to frequencies of several MHz.

For bunch arrival-time measurements, a dependence of the beam pick-up signal on the position of the electron beam is undesirable and, therefore, a BPM-like button pick-up is utilized [18]. The beam position dependence is further reduced by combining the two horizontal and vertical signals, before sending them to the EOMs [11].

Figure 5 shows the normalized laser pulse energy as a function of the delay between the laser pulse arrival-time and the zero-crossing of the beam pick-up signal. The blue and the red curve show the high resolution signal of two independent bunch arrival-time monitors. The green curve depicts the response of the coarse measurement, in which the beam pick-up signal is attenuated by 26 dB.

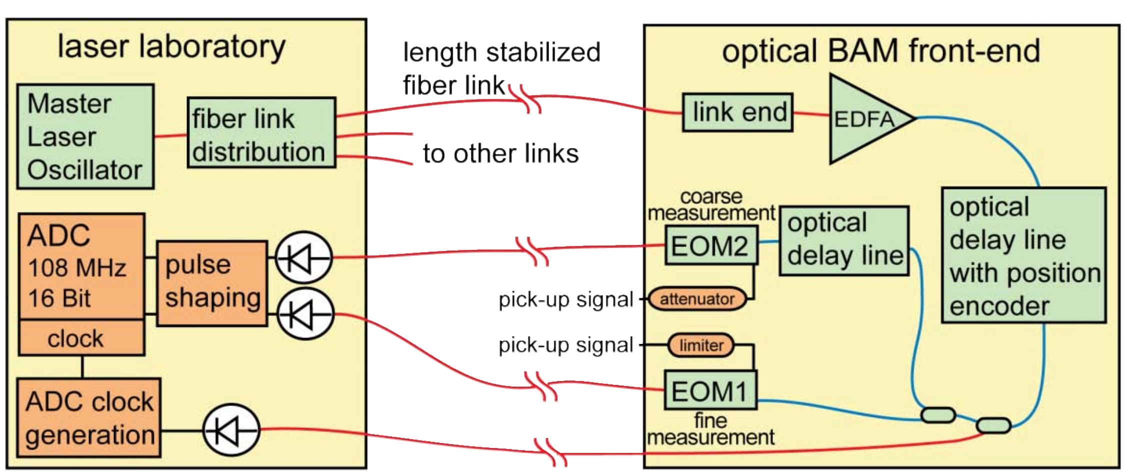

Figure 4: Simplified experimental setup as used for the first BAM prototypes at FLASH [11,17].

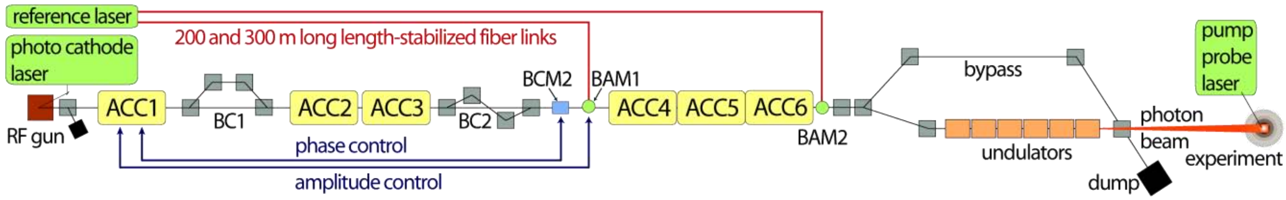

Figure 6: Installation of the BAMs in the FLASH accelerator for BAM resolution measurements. The feedback path for initial bunch arrival-time and bunch compression feedbacks is indicated as well (adapted from [16]).

While the coarse measurement nicely resembles the signal from the button pick-up, the two high resolution measurements show an over-rotation at very high and low modulation voltages which are caused by a phase shift of larger than 180° between both arms of the Mach-Zehnder interferometer in the EOM.

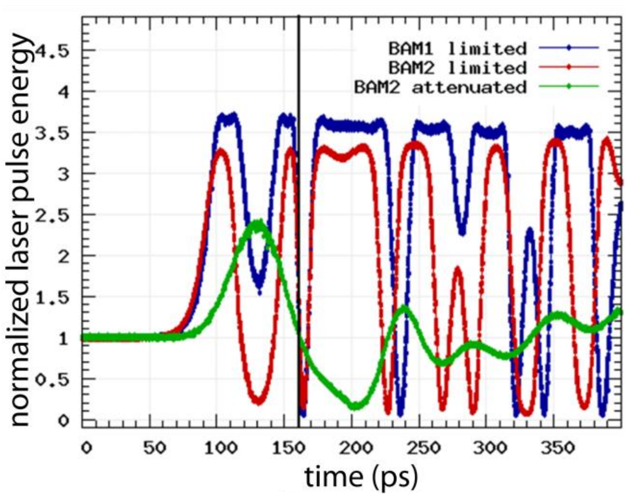

Figure 5: Normalized laser pulse energy as a function of the delay between laser pulse arrival and beam pick-up zero-crossing. The operating point is indicated as a dashed line and corresponds to an unmodulated laser pulse ([11]).

BAM Resolution

The resolution of the bunch arrival-time monitors can be evaluated from the precision with which the laser pulse energies are determined (since only a small fraction of the laser pulses is modulated by the electron beam, this value is available at all times without the need for interrupting the arrival-time measurements), and the steepness with which the normalized pulse energy changes with the delay between laser pulse and beam pick-up zero-crossing. A resolution as good as 3-5 fs could be determined for optimized settings.

In order to verify this resolution, two BAMs have been installed in a straight section of the FLASH accelerator, separated by 60 m. Each BAM was supplied by laser pulses from its own stabilized fiber link (see Fig. 6). By measuring the arrival-times of the same electron bunches with both monitors, the BAM resolution can be determined. Figure 7 shows the outcome of this measurement. The top graph presents the beam arrival-time variations measured by both monitors. The bottom graph represents the difference between both measurements. The rms noise of this difference signal is 8.4 fs, which shows that the resolution of a single BAM together with the stability of its fiber link is 6 fs or better, measured in the frequency range of around [0.00167 Hz, 15-20 GHz]. The higher cut-off frequency is determined by the bandwidth of the beam pick-up, the combiner, limiter, and the EOM.

Initial measurements on the long-term stability could be carried out yielding BAM resolutions of around 9 fs over a duration of 1.5 hours and 14 fs over a duration of 4.5 h. Since we observed steps in the difference signal between both BAMs during these long-term measurements, we believe that this is caused by changes in the electron bunch shape due to machine tuning, and slightly different response characteristics of the beam pick-ups used in both BAMs. This inherent interdependence of the BAMs on the longitudinal shape will be greatly attenuated by the linearized compression scheme (also used at LCLS) that is currently being commissioned at FLASH, which removes the picosecond-long tails in the charge distribution.

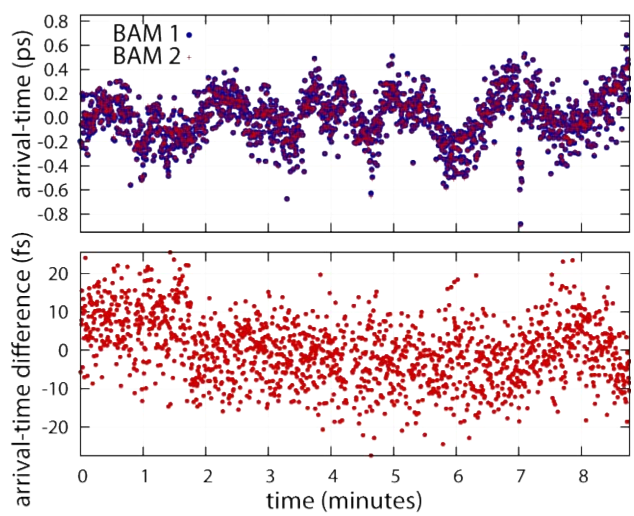

Figure 7: Electron bunch arrival time as measured with two independent BAMs. Top: readings of both BAMs. Bottom: difference signal of both BAMs (from [16]).

Bunch Arrival Time Feedback

The precise arrival-time information provided by the BAMs in combination with the ease of the required data processing makes the BAM an ideal tool for fast bunch arrival time feedbacks. The feedback scheme as depicted in Fig. 6 has been implemented at FLASH and has allowed for the stabilization of the bunch arrival-time as well as of the bunch compression process within the up to 800 µs long bunch trains. The arrival-time stability could be improved from around 180 fs to 25 fs for the later bunches in the bunch train (see [16,19,20] for more details).

Beam Position Measurements Using Electro-Optical Detection Scheme

Initial arrival time measurements have been performed with a ring-type beam pick-up, the signal of which possessed a very strong dependence on the electron beam orbit. By measuring the arrival-time of the pick-up signals at both sides of the pick-up, a measurement of the horizontal beam orbit with a 3 µm resolution was possible in addition to a precise bunch arrival-time measurement [15]. In combination with a transversely mounted strip-line pick-up, this scheme is planned to be used in the bunch compressor chicanes of FLASH to allow for measurements of the horizontal beam position with micrometer resolution over a many centimetre large dynamic range [21].

SUMMARY

A novel electro-optical detection scheme for femtosecond resolution bunch arrival time measurements was presented. In combination with an optical synchronization system, the arrival time with respect to a common time reference can be measured at distributed locations within the accelerator with a precision of better than 10 fs. This arrival time monitor provides a great tool to time-stamp events for pump-probe experiments and, due to its simplicity, can be used in fast feedback loops to stabilize the bunch arrival-time. In initial experiments we were able to improve the arrival-time stability from 180 fs to 25 fs with such a feedback.

Since the electro-optical detection scheme only requires a fast electrical transient, several other applications in addition to bunch arrival-time measurements are possible. One such application is a beam position measurement in bunch compressor chicanes with a several centimeter large dynamic range while delivering micrometer resolution [21]. Even more applications based on this scheme are imaginable, for example a laser arrival-time detection using the signal of a fast photo detector to drive the EOM, or a high resolution phase detection of RF signals.

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