ELECTRO-OPTIC BUNCH ARRIVAL TIME MEASUREMENT AT FLASH

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Abstract

Optical synchronization systems, based on mode-locked erbium-doped fiber lasers whose pulses are distributed over length stabilized fiber links, are expected to be drift free and to provide femtosecond stability for the next generation of free electron lasers. In this paper we provide a comparison between the stability of two bunch arrival time monitors working on different principles. In the first type the bunch-induced signal in a broad-band beam pick-up invokes an amplitude modulation in a train of short laser pulses, which are detected with a photo diode and a fast ADC. The second type utilizes the electro-optic effect in a 175 µm thick GaP crystal, placed 3 mm away from the electron beam. Both methods show excellent correlation over a change in the bunch compression and acceleration. The achieved arrival time jitter is 80 fs over 20 s, which is near the limit of the present RF stabilization at FLASH.

INTRODUCTION

Bright electron beam sources, producing short, intense relativistic bunches with less than 100 fs duration, require robust, single-shot bunch length and arrival time monitors. The gain of a FEL based on the self-amplified spontaneous emission (SASE) depends strongly on the bunch compression and peak current. For the soft X-ray FEL FLASH at DESY, it is important to have an online feedback for the longitudinal bunch profiles. Ideally the diagnostic would be non-destructive and monitor each electron bunch. Further parameters of interest, e.g. for pump-probe experiments, are the bunch arrival time and jitter.

The electro-optic (EO) techniques are suitable for both bunch longitudinal profile and arrival time diagnostics. The methods are based on encoding the bunch electric field into the polarization of a co-propagating laser pulse by a non-linear interaction in an electro optical crystal. Since the beam orbit does not intercept the crystal, the method is non-invasive. In the most simple arrangement, the sampling laser pulse is chirped linearly, so that there is a known time-frequency relationship, which is then resolved with a spectrometer [1-4]. This technique has an intrinsic limit of the temporal resolution due to the modulation of the chirped pulse by the THz field [2-3].

Better temporal resolution is obtained by cross-correlation of the chirped pulse with a short gate pulse from the same laser in a non-linear crystal [2-3]. With this technique, known as temporal decoding, the shortest EO signals of 60 fs have recently been measured [5]. The temporal resolution is limited entirely by the lattice resonances in the EO crystal [6].

The electron bunches at FLASH have a sharp leading spike due to the few degrees off-crest acceleration preceding the compression. This spike can also be used for arrival time measurements [4], e.g. using the spectral decoding method.

A technical limit of the present EO methods is the imaging device (CCD camera or line array with a fast shutter), which cannot be read out with the 1 MHz repetition rate of the electron bunches at FLASH. This prevents continuous monitoring within a bunch train. A new bunch arrival time monitor (BAM) has been installed at FLASH [7, 8]. The RF-signal from a fast beam pick-up enters an electro-optical modulator and induces an amplitude modulation in a train of infrared laser pulses. Any deviation in the bunch arrival time changes the amplitude of the laser pulses. The readout is performed with a photodiode and a fast ADC, which allows monitoring of each bunch in a train with a sub-10 fs accuracy [8].

The present paper provides a comparison between the arrival times determined with the EO spectral decoding and with the BAM system.

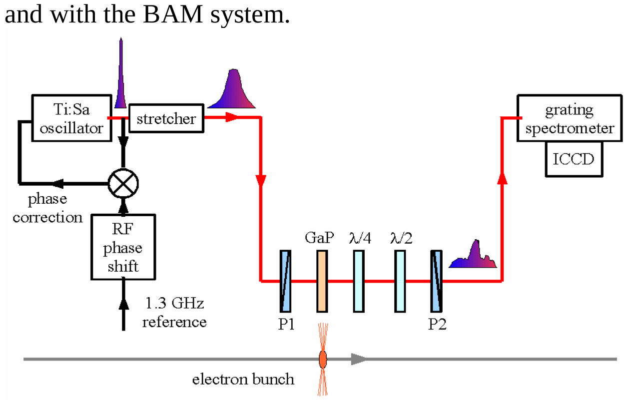

Figure 1: Schematic layout of the electro-optic spectral decoding setup.

EXPERIMENTAL SETUP

The electro-optic diagnostic (EO) and the beam arrival time monitor (BAM) are installed shortly before the linac collimator and are separated by about 2 m. A detailed description of the BAM can be found in [7, 8].

The EO-spectral decoding setup is shown schematically on Fig. 1.

The laser, the synchronization electronics and the spectrometer are situated in a laboratory outside the FLASH tunnel. The laser beam is transported to the optical table holding the polarization elements by using imaging optics and a 15 m long evacuated transfer line. Only the EO crystal (GaP) is in the linac vacuum. Its distance to the electron beam is controlled remotely with a motorised translation stage. The encoded laser pulse is transported back to the spectrometer in the laboratory with a multimode fiber. The acquisition is performed at -2° off crossed polarizers.

The laser is a commercial titan-sapphire oscillator (Micra-5 from Coherent) with a typical output power of 460 mW at the central wavelength of 800 nm, 50 nm bandwidth and a repetition rate of 81 MHz. A 10 cm long block of heavy flint glass (SF11) is used for chirping. The chirp coefficient is 0.55 fs/mm.nm. The Fourier limited pulse length is τ_0 = 20 fs (FWHM); the length of the stretched pulse is τ_c = 2.8 ps. The chirp was deliberately chosen long to compensate for possible long time drifts. The signal broadening, imposed by the chirp is $\sqrt{\tau_0 \tau_c} \approx$ 240 fs (FWHM). The time resolution, determined by the EO crystal (175 µm GaP) is ~200 fs (FWHM) [6]. The overall resolution is 500 fs which is at the order of the measured FWHMs (Fig. 3).

The spectra are resolved with a 150 mm spectrometer and a 600 l/mm grating. The images are recorded with a 1280x1024 intensified CCD camera. A calibration with an Ar discharge lamp provides a spectral resolution of 0.12 nm/pix. Thus the calibration constant for the EO spectra is 6.8 fs/pix and the temporal resolution is 57 fs/nm. Instead of the above "static" method, which does not account for the laser spectral and intensity fluctuations, the calibration was performed before each measurement, by shifting the phase between the laser and the 1.3 GHz reference with 10 fs steps. With this method a typical EO calibration, which is also used in the presented arrival time measurements, is 6.7 fs/pix.

RESULTS AND DISCUSSION

The estimated arrival time jitter in the present BAM-EO comparison is 70 fs. This is the limit imposed by the RF synchronisation between the two lasers, which are independently locked to the RF-mater clock reference with 50 fs accuracy. Since 1 nm shift of the central wavelength of the EO laser results in a 55 fs shift, it is necessary to investigate its spectral fluctuations over extended periods (Fig. 2).

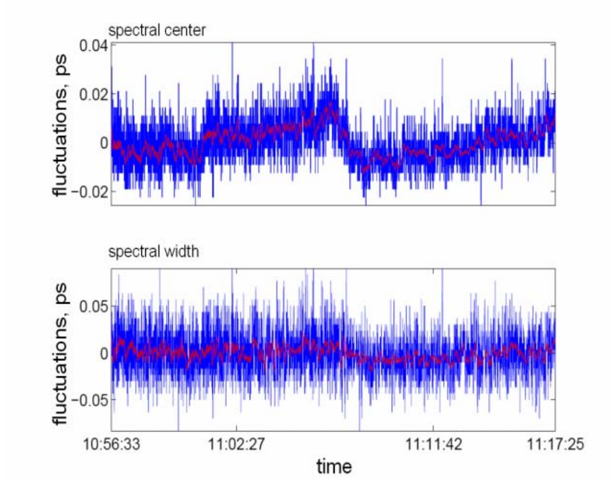

Figure 2: Time jitter, induced by the fluctuations of the spectral center (top) and spectral width (bottom) of the EO laser.

The measurement is performed at crossed polarizers without electron beam. The jitter of the spectral center (Fig 2, top) is 5.4 fs (rms) and the one of the spectral width (Fig 2, bottom) is 7.1 fs (rms). The mutual jitter of 22 fs between both indicates slight intensity and pulse shape fluctuations. This is a systematic error in the arrival time measurements.

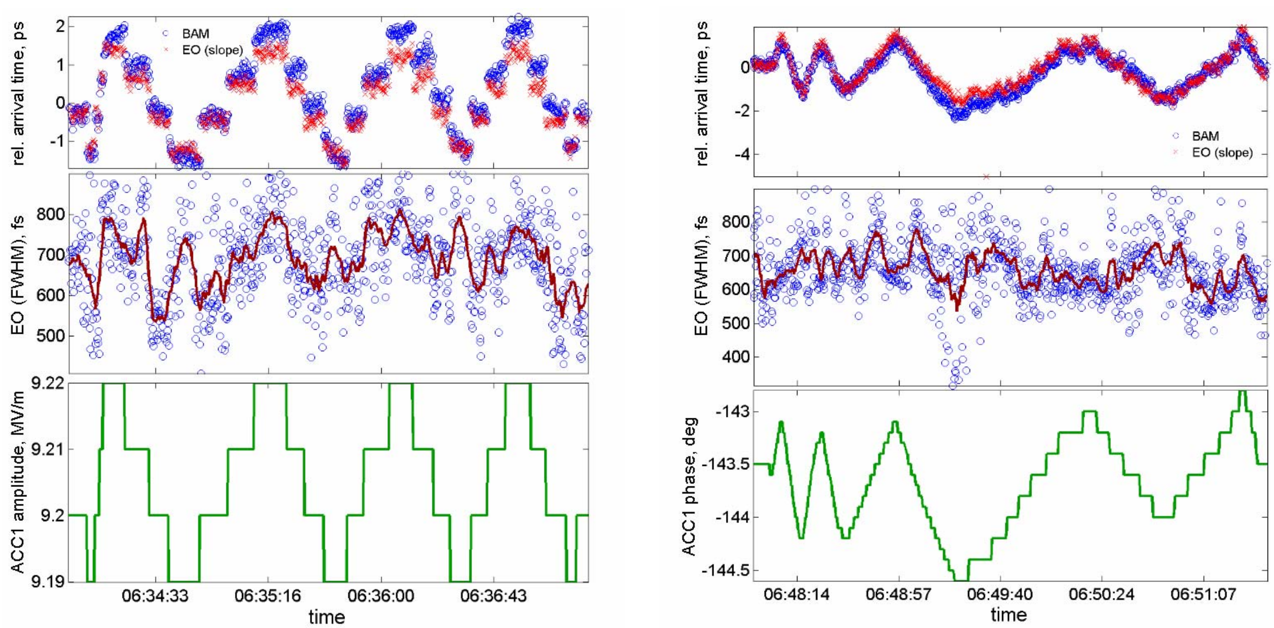

Figure 3: Left: Dependence of the EO arrival time, BAM arrival time (up) and EO (FWHM) (middle) on the ACC1 amplitude (down); Right: same dependence on the ACC1 phase.

Another source of systematic error is the way the arrival time is inferred from the EO signal. There are two possibilities: by the tangent at the half maximum of the leading EO edge (EO-slope), or by the center of the peak, determined through a Gauss fit (EO-peak). A typical jitter between the EO slope and peak over 20 min is 30 fs. This jitter depends not only on the laser spectral and intensity fluctuations, but also on other factors, which influence the EO signal shape and strength, such as the bunch compression, the number of bunches in the machine, the

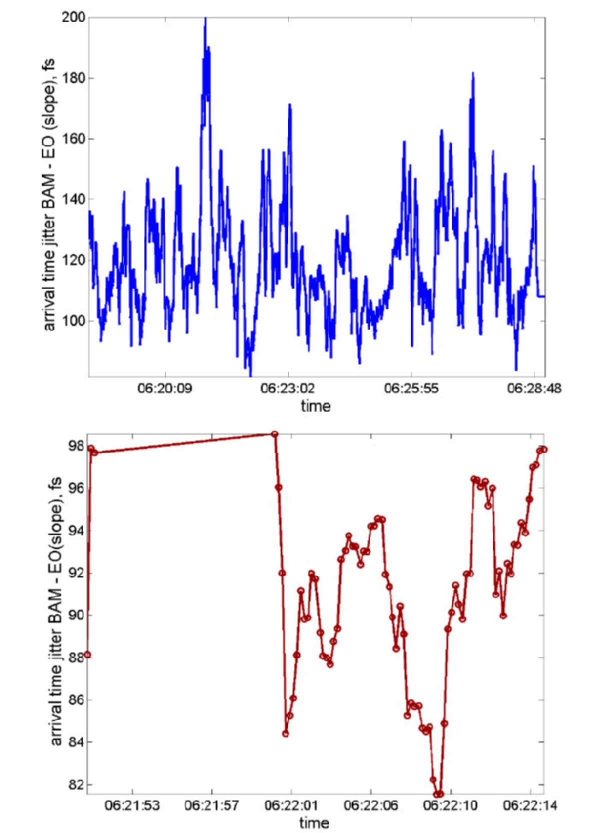

Figure 4: Arival time jitter between BAM and EO, calculated over 10 s at fixed ACC1 parameters. Each data point contains 50 arrival time events. Top: entire evolution of 3200 bunches; Bottom: data points with jitter below 100 fs.

bunch charge, the beam orbit and energy fluctuations etc. The source of this jitter is not fully understood and requires further investigation.

The arrival time jitter depends on the bunch compression, energy and energy spread. By varying the amplitude (Fig 3 left) and phase (Fig 3 right) of the linacs first acceleration module ACC1, a change in the arrival time is expected. Whereas the EO is sensitive to the peak charge, spread over 500-900 fs, the BAM measures the bunch center of mass. Both EO and BAM results show good correlation. For each set of parameters the evolution of the EO peak FWHM is also shown. The measured widths are in the range 500-900 fs, which are limited by the resolution of the EO-spectral decoding method. Nevertheless there is a good correlation with the ACC1 amplitude and phase (Fig. 3).

Fig. 4 represents the arrival time jitter between EO and BAM over 12 min acquisition. The average jitter is 120 fs. Each data point is the jitter over 10 s and is obtained by shifting the interval with 0.2 ms step over the entire evolution set of 3200 bunches. The bottom graphic shows the jitter below 100 fs. On average it is 90 fs. The absolute minimum is 81 fs over 20 s. This value is near the expected limit for the RF synchronisation, since each laser has ~50 fs RF stability. To achieve better stability it is necessary to lock the laser optically to a stabilized optical reference [9].

CONCLUSION AND OUTLOOK

Both EO and BAM follow the changes in the phase and amplitude of ACC1 in a consistent way. For a fixed acceleration (few degrees off-crest) the smallest relative jitter between the two diagnostics which has been achieved is 80 fs over 20 s. This value is near the limit of the RF synchronisation. An optical cross-correlator is under development, with which the diagnostic laser will be synchronized to an optical reference from a length stabilized link with 10 fs stability.

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