EXPERIMENTAL DETERMINATION OF THE TIMING STABILITY OF THE OPTICAL SYNCHRONIZATION SYSTEM AT FLASH

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Abstract

An optical, long-term stable synchronization system with an accuracy of better than $10\,\mathrm{fs}$ is presently being installed at the free electron laser FLASH. A periodic laser pulse train from a mode-locked, erbium-doped fiber laser is distributed via length stabilized fiber links. In this paper, we present measurements of the timing stability of the optical distribution system. Two bunch arrival time monitors (BAMs) are used to measure the electron bunch arrival times at two positions in the linac, separated by $60\,\mathrm{m}$. Each BAM is supplied with fiber laser pulses by its own fiber link. By correlating the measured arrival times of the same electron bunches, the overall performance of the optical distribution system and the BAMs can be evaluated. A resolution and timing stability of better than $10\,\mathrm{fs}$ has been achieved.

INTRODUCTION

FLASH, the Free electron LASer in Hamburg, is a FEL user facility producing laser pulses based on the SASE process with fundamental wavelengths ranging from $48\,\mathrm{nm}$ down to $6.5\,\mathrm{nm}$. Typical pulse durations are on the order of few tens of femtoseconds and in a short pulse mode, sub-$10\,\mathrm{fs}$ long laser pulses can be produced [1].

These ultra-short laser pulses lead to demanding requirements on the synchronization of various devices within the machine. At FLASH, this challenge is addressed with an optical synchronization system based on the distribution of ultra-short laser pulses of a mode-locked laser within the facility, using actively length stabilized fiber links. This scheme was first proposed at MIT in 2004 [2].

At FLASH, the reference laser, also referred to as master laser oscillator (MLO), is a $216\,\mathrm{MHz}$ soliton laser producing pulses of approx. $100\,\mathrm{fs}$ duration. The timing stability of the optical pulse train from such a laser was measured to be about $10\,\mathrm{fs}$ in the frequency range from $1\,\mathrm{kHz}$ to $40\,\mathrm{MHz}$ [3]. At lower frequencies, the timing stability is ensured by locking the laser repetition rate to the reference microwave oscillator of the machine.

The laser pulses are distributed to the remote locations using optical fibers. At the end of the fiber links, part of the intensity is reflected and the timing of the returning pulses is measured by cross-correlating them with pulses directly from the laser [4]. Timing changes of the fiber link are corrected using piezo-electric transducers and delay stages. Using this scheme, we have achieved sub-$10\,\mathrm{fs}$ stabilization over many hours of operation [3].

Figure 1 gives a schematic overview of the optical synchronization system at FLASH. Various end-stations are foreseen. Bunch arrival time monitors, utilizing the pulses directly from the fiber links in an electro-optical detection scheme [5, 6], will be used at various positions to measure and control the arrival time of the electron bunches [7]. Beam positions monitors in the magnetic chicanes using two BAMs to measure the beam position over a large aperture with $\mu\mathrm{m}$-precision [8, 5] will be used for measurements and control of the beam energy. An electro-optical bunch profile monitor (EOSD) using a spectral decoding technique [9] will provide, in addition to the charge profile, information about the arrival time of the high charge density part of the electron bunch. First comparisons of the arrival times measured by a BAM and EOSD are presented in [10]. In order to tightly lock external lasers to the optical synchronization system, robust cross-correlation schemes are under development. They will be applied for the EOSD laser, the photo cathode laser, the pump-probe laser, and the upcoming seed laser. First results are shown in [11].

EXPERIMENTAL DETERMINATION OF THE STABILITY OF THE OPTICAL SYNCHRONIZATION SYSTEM

In order to evaluate the performance of the optical synchronization system, a setup consisting of the MLO, two stabilized fiber links, and two BAMs was utilized to measure the electron bunch arrival time at two positions within the machine.

The MLO is synchronized to the $1.3\,\mathrm{GHz}$ reference signal of the machine using conventional RF techniques and a digital feedback controller. The in-loop timing jitter between the microwave reference and the laser pulses is about $50-60\,\mathrm{fs}$. This result is in good agreement with the measured timing differences between a BAM and the EOSD setup, which uses a Ti:sapphire-laser that is synchronized to about the same accuracy as the MLO [10].

The fiber links have a length of $230\,\mathrm{m}$ and $300\,\mathrm{m}$, respectively. Figure 2 shows the timing corrections applied with a piezo element and an optical delay stage, which are needed to keep the optical length of the fiber links constant. Within a day-night cycle, more than $10\,\mathrm{ps}$ timing correction can occur for the $300\,\mathrm{m}$ long link. Over the entire week, timing corrections of more than $20\,\mathrm{ps}$ are applied.

The electro-optical detection scheme of the BAMs is po-

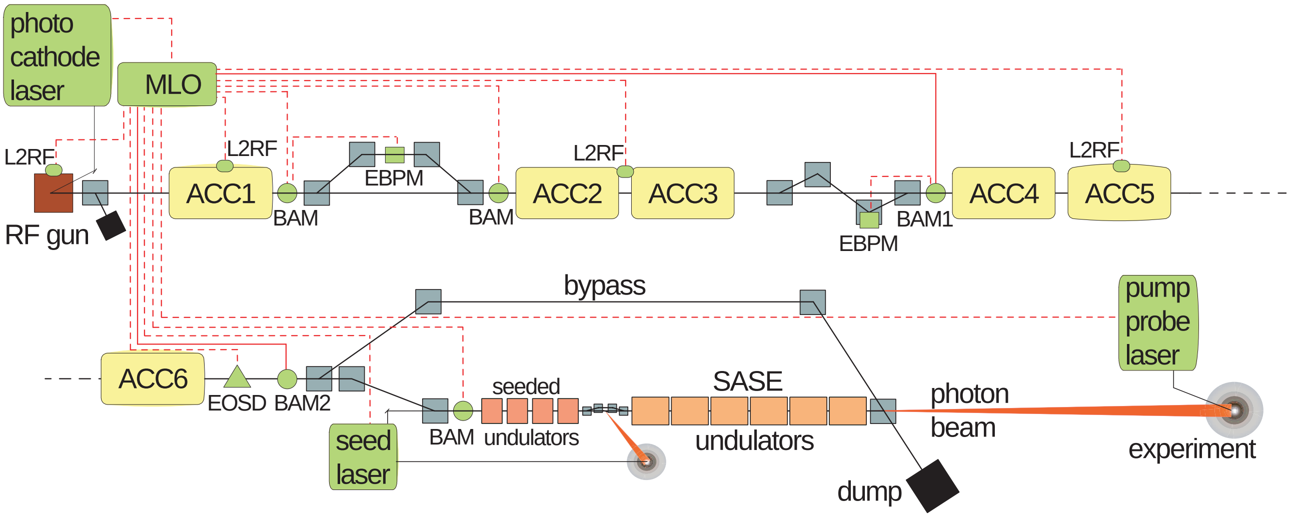

Figure 1: Schematic diagram of the optical synchronization system at FLASH. The red lines show the fiber links which are foreseen in a final setup (dashed) and already operational (solid). The end-stations, marked in green which are linked to the master laser oscillator (MLO) are: BAM, bunch arrival time monitor; L2RF, laser to RF conversion; EBPM, energy beam position monitor; EOSD, electro optical spectral decoding longitudinal profile monitor.

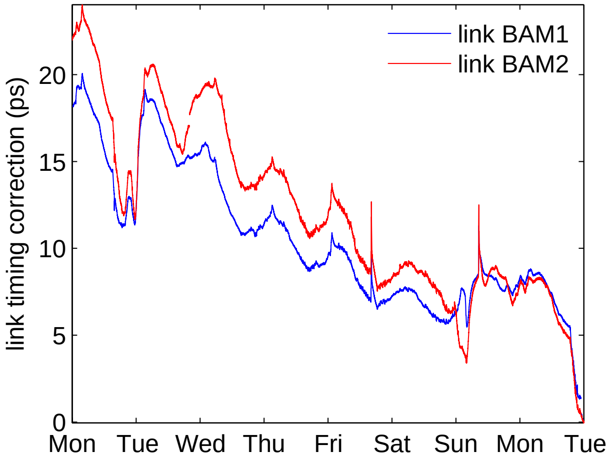

Figure 2: Corrections applied to compensate for the time variation of the two BAM fiber links over a duration of one week.

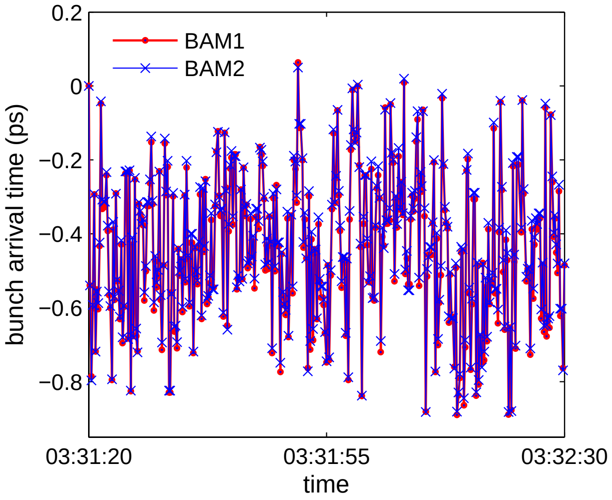

Figure 3: Bunch arrival time measured by two BAMs separated by a 60 m straight section for 350 shots.

larization dependent and the polarization within the links rotates with temperature changes. If the fibers are not touched, this is a very slow process and it is corrected for by changing the polarization of the light entering the link using motorized $\lambda/2$ and $\lambda/4$ wave-plates. Since the BAM detection scheme normalizes the laser intensity to a previous laser pulse [5], slight amplitude changes occurring after a polarizer due to not corrected polarization changes are strongly suppressed.

The two BAMs are located in a straight section of the linac and are separated by $60\,\mathrm{m}$. Since there are no dispersive elements in this section, the arrival times of the ultra-relativistic electron bunches differ only by a constant value at the two monitor positions. An uncorrelated jitter between the two arrival time measurements will have three main contributions: Due to the difference in the fiber link lengths, different laser pulses are used for the arrival time detection. Therefore, timing jitter of the MLO in the frequency range from about $3\,\mathrm{MHz}$ up to the Nyquist frequency of $108\,\mathrm{MHz}$ will be seen in the correlation. The second contribution is the timing stability of both fiber links. The third contribution is the resolution of the BAMs.

Both BAMs have been calibrated by shifting the timing of their reference laser pulses with an optical delay stage which is part of each BAM. The position of the delay stage

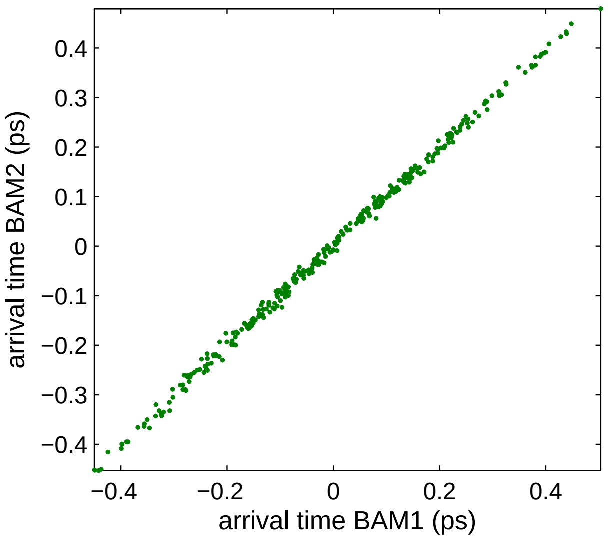

Figure 4: Correlation between the two arrival time measurements shown in Fig. 3. The correlation width is 9.5 fs (rms).

is monitored using an absolute position encoder with μm-precision. In the measurements presented here, the calibration factor of one BAM was corrected by 2%.

Figure 3 shows the bunch arrival times measured by both BAMs for a duration of about one minute (350 shots at a repetition rate of 5 Hz). The arrival time jitter over this period is $198.2\,\mathrm{fs}$ for BAM1 and $198.4\,\mathrm{fs}$ for BAM2.

Figure 4 shows the correlation of the two arrival time measurements. The correlation width is $9.5\,\mathrm{fs}$ (rms). Since these are two independent measurements, an entire synchronization branch consisting of a fiber link and an arrival time monitor has a timing stability and resolution of better than $9.5\,\mathrm{fs}/\sqrt{2} = 6.7\,\mathrm{fs}$ (rms) on a time scale of minutes integrated up the Nyquist frequency of the MLO.

From the noise on the laser amplitude in the BAM detection scheme and the BAM calibration constant, an independent estimation of the BAM resolution can be made, which excludes the contributions from the fiber link and the MLO. This estimate gives a BAM resolution of around $5-6\,\mathrm{fs}$ (rms) which shows that the BAM is the main limitation of the entire measurement chain. This is an indication that by a better laser amplitude detection of the BAM, the entire performance can be improved further.

In the final setup of the synchronization system, BAMs will be available up- and downstream of each magnetic chicane. The first chicane has a R_{56} of $180\,\mathrm{mm}$ and time of flight measurements using two BAMs with $6.7\,\mathrm{fs}$ rms resolution would provide single shot energy measurements with an rms resolution of $1.6 \cdot 10^{-5}$.

SUMMARY AND OUTLOOK

We used two independent electro-optical arrival time monitors each having its own stabilized fiber link to evaluate the stability of the distribution system of the optical synchronization system at FLASH as well as to determine the resolution of the bunch arrival time monitors. We found the stability and resolution of a complete measurement branch (fiber link and arrival time monitor) to be better than $6.7\,\mathrm{fs}$ (rms). Using the arrival time information in fast feedback systems to control the electron bunch arrival time, this high resolution opens the door to sub-10 fs arrival time stability of the electron bunches.

In this paper, the timing stability of the synchronization system has been studied on a timescale from a minute integrated to about $10\,\mathrm{ns}$ which is twice the distance between two laser pulses. An open point is the drift stability of the setups which is mainly given by the temperature stability of the corresponding devices. During the next FEL user study period, long-term measurements of the bunch arrival time will be possible and this topic will be addressed.

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