OBSERVATION OF 40 fs SYNCHRONIZATION OF ELECTRON BUNCHES FOR FELs

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Abstract

State of the art XUV- and X-ray light sources like FLASH, the free-electron laser in Hamburg, or the planned European XFEL produce light pulses with durations down to a few femtoseconds. To fully exploit the experimental opportunities offered by these light pulses, synchronization of the FEL facility on the same time scale is required. To meet these high demands, which cannot be fulfilled by conventional, coaxial RF distribution schemes, optical synchronization systems have been developed at different laboratories. At FLASH, a prototype system has been recently installed and tested. It consists of a mode-locked, erbium-doped fiber laser, two fiber links which are stabilized by optical cross-correlation to better than 10 fs, and two electro-optical bunch arrival-time monitors with resolutions below 10 fs. We report on our experience with the system and describe its use for an intra-bunch-train arrival-time feedback with which we could improve the arrival-time stability of the electron bunches from above 200 fs for the unstabilized case to 40 fs with the feedback active.

INTRODUCTION

High-gain free-electron lasers (FELs) operating in the ultraviolet, soft and hard X-ray regimes are capable of generating light pulses with gigawatt peak power and pulse durations below $10\,\mathrm{fs}$ [1]. The high peak-power enables single-shot measurements and the short pulse durations offer the potential for time-resolved experiments.

To fully exploit the experimental opportunities offered by the ultra-short FEL pulses, demanding requirements on the synchronization of various devices have to be fulfilled, especially, when pump-probe experiments between an external laser and the FEL pulses must be carried out. For these sorts of experiments, however, it is sufficient to precisely measure the relative timing between the two light pulses and to remove the arrival-time jitter between the two lasers by sorting the data according to the timing measurement.

There are many measurement schemes, in which the electron beam is manipulated with an external laser. One example is the so-called optical replica synthesizer [2], in which an electron bunch is energy modulated by a laser pulse inside a first undulator. The energy modulation is transferred into a density modulation in a magnetic chicane and the coherent radiation emitted in a second undulator can be used to determine the longitudinal properties of the electron bunch. Another example is seeding of the FEL with an external laser field [3, 4] produced with a high power laser by high harmonic generation in either a gas jet or on a surface. Seeding of the FEL with such an external source has many advantages compared to the self-amplified spontaneous emission (SASE) mode of operation. The statistical spectral fluctuations can be removed and amplitude fluctuations can potentially be reduced. Furthermore, the FEL pulse duration can be adjusted by the length of the seed pulse.

All these schemes require a highly precise temporal overlap between the electron bunches and the laser pulses, and post-sorting data according to timing measurements is not sufficient anymore. A timing stabilization of the electron bunches is required and the level to which this is possible strongly influences the performance of the manipulation schemes described above. In the case of seeding, timing changes between seed pulses and the electron bunches convert directly into amplitude fluctuations of the amplified seed pulses, since the electron density and transverse properties along the electron bunch may vary.

The electron bunch arrival-time at the end of the machine is very sensitive to many parameters of the machine. Not only the generation of the electron bunches is affecting the arrival-time. Due to strong space charge effects in the low energy injector section, the bunches cannot be generated with the required charge density right in the beginning. Therefore, the bunches are longitudinally further compressed at higher energies using magnetic chicanes. The longitudinal dispersion of the chicanes, which is needed for the bunch compression process, is at the same time transforming energy changes in front of the chicane into arrival-time changes downstream of it. At FLASH, two magnetic bunch compressor chicanes are installed with longitudinal dispersions of $R_{56} = -180\,\mathrm{mm}$ and $R_{56} = -50\,\mathrm{mm}$, respectively. The large R_{56}, especially of the first chicane, has the consequence that demanding energy stabilities are required in order to keep the electron bunch arrival-time jitter low. An energy change of 0.01% corresponds to around $60\,\mathrm{fs}$ of timing change making the energy stability the most important parameter for the arrival-time stability. At the planned European XFEL, the situation is about a factor of two less critical with chi-

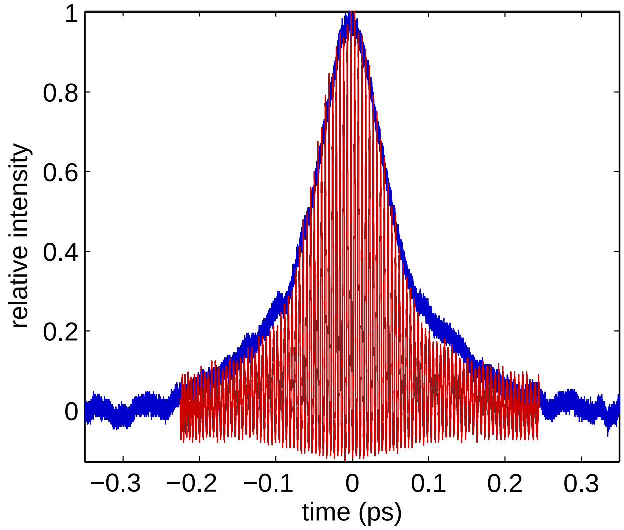

Figure 1: Autocorrelation trace of the soliton fiber laser with (red) and without (blue) resolving the interference fringes.

canes of $R_{56} = -100\,\mathrm{mm}$ and $R_{56} = -20\,\mathrm{mm}$. In the Linac Coherent Light Source (LCLS) in Stanford, the longitudinal dispersion of the chicanes is further reduced with $R_{56} = -36\,\mathrm{mm}$ and $R_{56} = -22\,\mathrm{mm}$. In the normal conducting accelerator, the energy chirp, which has to be imprinted onto the electron beam for the bunch compression process, is compensated by longitudinal wakefields. This allows using a stronger energy chirp than in a superconducting accelerator without deteriorating the energy distribution at the end of the accelerator.

THE OPTICAL SYNCHRONIZATION SYSTEM

At FLASH and the European XFEL, the stringent timing demands are addressed with an optical synchronization system which is 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 [5].

The reference laser at FLASH, also referred to as master laser oscillator (MLO), is a $216\,\mathrm{MHz}$ soliton laser. An autocorrelation trace of the pulses from the laser oscillator is depicted in Fig. 1, showing a pulse duration of $75\,\mathrm{fs}$ FWHM. The timing stability of the optical pulse train from such a laser was measured to be better than $6\,\mathrm{fs}$ in the frequency range from $10\,\mathrm{kHz}$ to $40\,\mathrm{MHz}$ [7]. To ensure the timing stability at lower frequencies, the laser repetition rate is locked to the reference microwave oscillator of the machine. Some of the end stations which utilize the laser pulses are sensitive to laser amplitude noise. This is especially the case when single laser pulses are used to perform measurements as it is for example the case in the bunch arrival-time monitors (BAMs). Most of these single shot

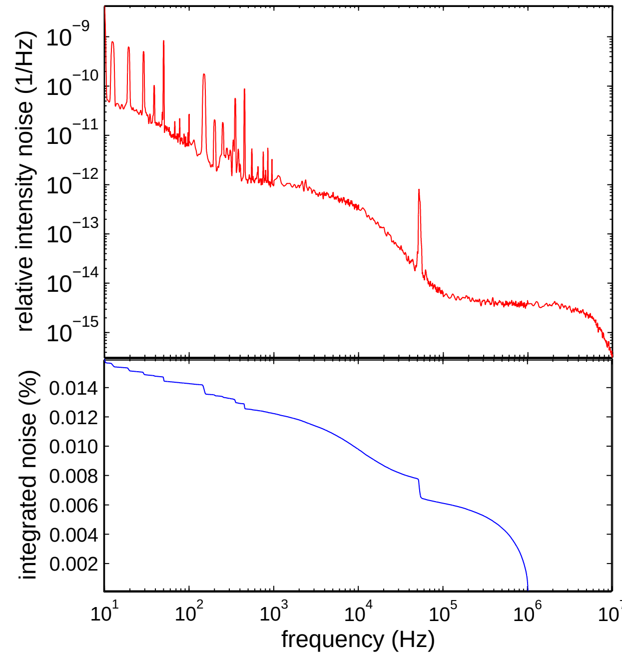

Figure 2: Relative intensity noise of the soliton fiber laser. The integrated noise in the frequency range from $10\,\mathrm{Hz}$ to $1\,\mathrm{MHz}$ is 0.016%.

measurements can be established in a way that a previous laser pulse is used for normalization purposes. If this is possible, only the high frequency noise of the laser is affecting the measurements. Figure 2 shows the relative laser amplitude noise measured in a frequency range from 10 Hz to 5 MHz. The decrease of the noise level above 5 MHz is due to the limited bandwidth of an amplifier in the noise measurement setup. It can be seen that with a relative intensity noise of only $4 \cdot 10^{-15}\,\mathrm{Hz}^{-1}$ at frequencies above a few hundred kHz, the noise level is very low. Integrating the noise from $1\,\mathrm{MHz}$ to $10\,\mathrm{Hz}$ yields a value of 0.016% which still contains significant contributions from the measurement devices.

The laser pulses are distributed to the remote locations using optical fibers. At the end of the fiber links, a fraction of the intensity is reflected and the timing of the returning pulses is measured by cross-correlating them with pulses directly from the laser [6]. 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 [7].

Two fiber links with lengths of $230\,\mathrm{m}$ and $300\,\mathrm{m}$ have been installed and tested inside the FLASH tunnel. Figure 3 shows the timing corrections applied with a piezo-electric fiber stretcher 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 two months, timing corrections of about $50\,\mathrm{ps}$ had to be applied to the $300\,\mathrm{m}$ long link in order to correct for the thermal expansion of the fiber.

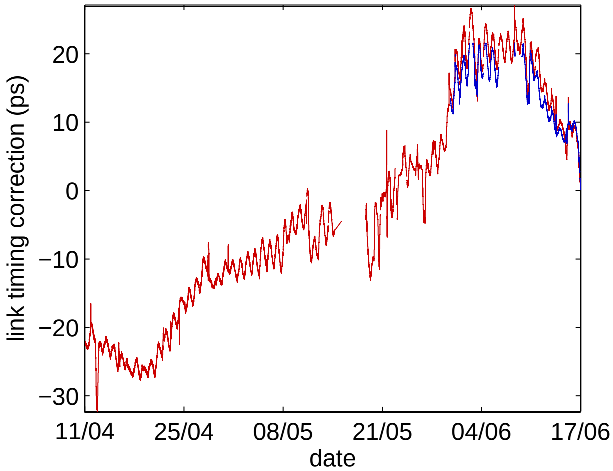

Figure 3: Corrections applied to compensate for the time variation of two fiber links over a duration of two months.

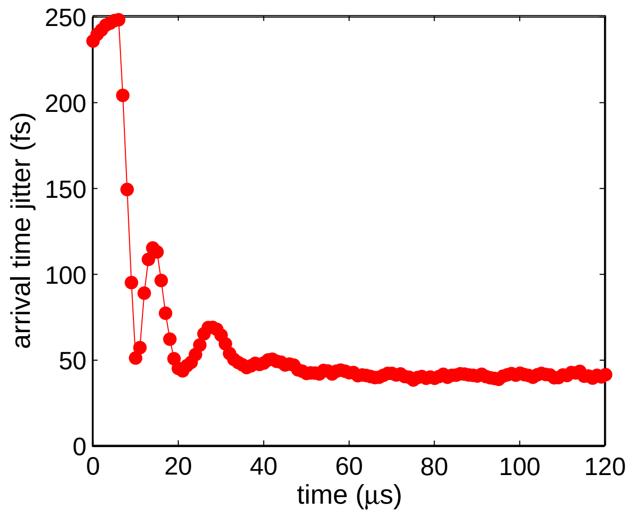

Figure 5: Effect of the intra bunch train feedback on the arrival-time stability.

At the end of the fiber links, there are a variety of devices foreseen which will utilize the precise timing signal. Figure 4 gives a schematic overview of the planned system at FLASH. Bunch arrival-time monitors, utilizing the pulses directly from the fiber links in an electro-optical detection scheme [8, 9], will be used at various positions to measure and control the arrival-times of the electron bunches. The resolution of these monitors was demonstrated to be better than $10\,\mathrm{fs}$ [10]. Beam position monitors in the magnetic chicanes using two BAMs to measure the beam position over a large aperture with micrometer-precision [11, 8] will be used for measurements and control of the beam energy. An electro-optical bunch profile monitor (EOSD) using a spectral decoding technique [12] 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 [13]. External lasers can be locked to the optical synchronization system by cross-correlation techniques. It was already demonstrated that two lasers of different central wavelength can be synchronized long-term stable to each other with sub-femtosecond precision [14]. To lock the lasers at FLASH 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 [15].

The electro-optical detection scheme of the BAMs is polarization 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 [8], slight amplitude changes occurring after a polarizer due to uncorrected polarization changes are strongly suppressed.

ARRIVAL-TIME CONTROL

The superconducting accelerator technique of FLASH allows to produce electron pulse trains consisting of up to 800 bunches separated by $1\,\mu\mathrm{s}$. Due to the high quality factor of the superconducting cavities, there are only very small changes of the accelerating fields from bunch to bunch. A BAM can measure the arrival-times of all bunches within the pulse train. The arrival-time information of an electron bunch can be used to calculate an arrival-time correction for a later bunch of the pulse train. We used the arrival-time information measured by a BAM to establish an intra-bunch-train arrival-time feedback acting on the amplitude of the first accelerating module, since here the influence on the arrival-time is largest. Figure 5 shows the effect of this feedback on the arrival-time stability. The first few bunches are not corrected by the feedback resulting in an arrival-time stability of around $240\,\mathrm{fs}$ (rms). The feedback needs about $20-30\,\mu\mathrm{s}$ to stabilize the arrival-time and a reduction of the timing jitter to $40\,\mathrm{fs}$ could be observed.

The response time of the feedback is limited by the superconducting cavities which are used as an actuator. Although with a lot of RF power the effective regulation bandwidth could be significant enhanced, they are still extending the time needed for a correction to $20-30\,\mu\mathrm{s}$. A significant improvement could be reached by using a separate normal conducting cavity for the correction. For experiments which need arrival-time stability also for the first bunches, an option would be to perturb the first bunches of the bunch train with a fast kicker before they produce FEL radiation.

SUMMARY AND OUTLOOK

We have implemented an optical synchronization system and used it to measure the arrival-times of electron bunches with sub-$10\,\mathrm{fs}$ precision. This information was used to es-

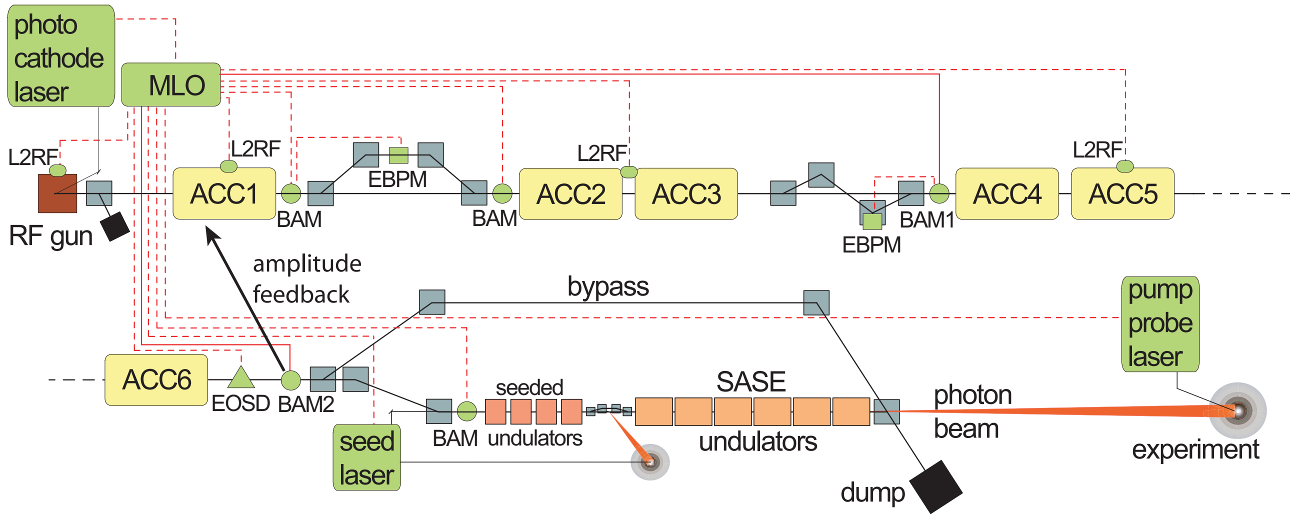

Figure 4: Schematic diagram of the optical synchronization system at FLASH. The red lines show the fiber links which are foreseen in a final setup (dashed) and already operational (solid). The end-stations, marked in green, which are linked to the master laser oscillator (MLO) are: BAM, bunch arrival-time monitor; L2RF, laser to RF conversion; EBPM, energy beam position monitor; EOSD, electro optical spectral decoding longitudinal profile monitor.

tablish a bunch arrival-time feedback with which we could reduce the bunch arrival-time jitter from 240 fs (rms) for the unstabilized case to 40 fs (rms) with the feedback active. The feedback uses the arrival-time information from a single BAM to act on the amplitude of a superconducting acceleration module upstream a magnetic chicane. With the demonstrated feedback, all sources of arrival-time jitter are compensated by a single actuator. For an optimized overall performance, the different jitter sources in the machine have to be measured and controlled separately which requires additional timing monitors for the photo cathode laser pulses, as well as for the electron beam. A system capable of this is currently being installed at FLASH.

Despite the bunch timing, another important parameter is the bunch compression process. The next step to further extend the longitudinal feedback system will be to control in addition to the amplitude also the phase of the first acceleration module on the basis of beam based measurements using a bunch compression monitor.

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