SUB-PS TIMING AND SYNCHRONIZATION SYSTEMS FOR LONGITUDINAL ELECTRON BUNCH PROFILE MEASUREMENTS

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Abstract

Precise timing and synchronization systems have become an increasingly important topic for next generation light sources. Particularly free electron lasers can emit X-ray pulses with pulse durations down to the few-tens of femtoseconds level. In order to utilize this potential temporal resolution for pump-probe experiments, a precise synchronization of the experimental laser to the X-ray pulse and stabilization of the electron beam arrival time at the undulators are mandatory. This requires a timing and synchronization system which can supply ultra-stable phase references over long distances, thus enabling the temporal stabilization of the electron beam to a sub-100 fs level. Furthermore, a precise timing and synchronization system renders possible extremely accurate measurements of the longitudinal electron bunch profile. This talk will give an overview of the status of existing sub-ps timing and synchronization systems and of systems currently under construction.

INTRODUCTION

One of the key challenges for the linac-based FEL sources such as the European XFEL or FERMI at Elettra is to implement a timing stabilization and distribution system that allows the full exploitation of the ultra-short x-ray pulse for pump-probe experiments. The important factor at the end of the day is the temporal jitter and drift between the FEL pulse and the experimental laser used for the pump-probe experiments. The current effort evolving around optical timing and synchronization systems is to distribute signals to various end stations along the machine with varying distances ranging from around 100 meters to several kilometers with a stability of around 10 fs. This however, will eventually lead to a sub-100 fs arrival time stability of the electron bunch with respect to the main machine reference. With future development, another factor of two improvement seems feasible, however 10 fs arrival time stability of the electron bunch does not seem within reach in the next few years. A way to circumvent this problem is a seeded machine, for instance using high harmonic generation (HHG). Here, a femtosecond laser pulse is used to generate light at a particular harmonic of the optical frequency which modulates the electron bunch energy. This energy modulation is converted into a density modulation in a dispersive section and this part of the electron bunch emits radiation in a second undulator. This puts the load on the synchronization between seed laser and experimental laser. The electron bunch arrival time however still needs to be reasonably stable to guarantee overlap with the ultra-short seed laser pulse.

In the following sections, an overview of the present development of optical synchronization systems, which are key components for a sub-100 fs electron bunch arrival time stability, followed by a description of measurement techniques and possibilities making use of the optical synchronization systems will be given.

OPTICAL SYNCHRONIZATION SYSTEMS

A comment needs to be made regarding jitter and drift. Whenever a 10-fs stabilization is mentioned, this refers to the relative jitter between different components in the linear accelerator. Since all machine systems are synchronized to a common reference (usually done with a Phase-locked-loop), they follow this reference up to the PLL bandwidth. Hence only the relative jitter between the subsystems is important up to this bandwidth, which is usually in the 1 to 10 kHz range. The absolute phase noise is usually significantly higher. For faster fluctuations, which cannot be corrected by the PLL, the intrinsic absolute timing jitter becomes important. It is therefore reasonable to identify two different frequency regimes; one for frequencies above 1 kHz where the absolute phase noise is important and a second one for slower fluctuations where the relative phase noise compared to the common machine reference is relevant.

So why is a new approach for the synchronization system needed in next generation light sources?

Traditional coaxial cable based systems can deliver very stable signals from microwave oscillators over short timescales. For long distances however, the attenuation of cables for high-frequency signals is substantial. To compensate, high-power amplifiers are needed, which introduce additional jitter and drifts. RF cables are also susceptible to drifts caused by temperature fluctuations along the machine. Even if extremely stable RF cables are used, they still exhibit a temperature coefficient of 0.5 ppm/deg C. This can easily amount to several picoseconds per degree C for a kilometer-long facility. Optical fibers exhibit an even larger temperature coefficient (5 ppm/deg

C), but can be actively stabilized. These stabilized links can deliver signals to remote locations with femtosecond stability over long timescales. If one only takes the signal transmission capabilities into account, the cost/benefit ratio of optical synchronization systems vs. cable based systems becomes debatable. With passive stabilization techniques employed, RF cables can also deliver signals with low drift performance over short distances. However, as soon as length scales are in excess on a few hundred meters, the optical synchronization systems are clearly advantageous.

The main feature which makes optical synchronization systems unique, is the possibility to optically phase-lock different laser systems with an actively stabilized fiber-link used to transport the reference signal. This has been demonstrated with a stability of sub-10 fs over short and long timescales. This is a significant advantage compared to the traditional locking of lasers to a microwave reference, which has been demonstrated to a 60 fs level [5]

At present, there are two different schemes to employ a synchronization system based on the distribution of laser radiation in development. One approach, being investigated at Berkeley National Lab (LBL), is based on the interferometric stabilization of optical fiber and will be called frequency domain approach in this paper. The second option, suggested by MIT [6] and presently developed by a collaboration between DESY, MIT and Trieste, distributes femtosecond laser pulses and makes use of the timing information contained in the repetition rate of the laser pulses. It will be called time-domain approach.

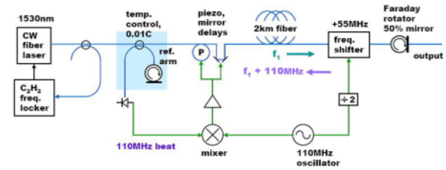

Figure 1: Schematic setup of the setup of the frequency domain stabilization scheme.[7]

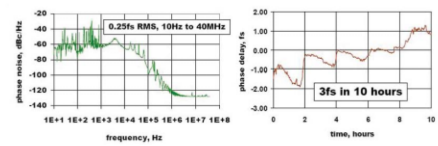

Figure 2: left: Jitter Power spectral density (250 as rms); right: drift over several hours (3 fs).[7]

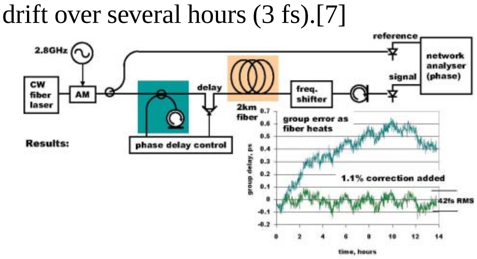

Figure 3: Measurement setup and results of group vs. phase velocity drifts.[10]

Frequency Domain Approach

A schematic of the stabilization setup is depicted in figure 1. A continuous-wave single-frequency erbium-doped fiber laser at a wavelength of 1550 nm is sent down the fiber link. As this scheme relies on a sufficiently long coherence length of the fiber laser used, it is stabilized to an aceltylence resonance, which results in 10^{-9} frequency stability. At the end of the link, the optical frequency is upshifted by 55 MHz using an acousto-optic modulator and a portion of the light is reflected back and passes the modulator again for a total upshift of 110 MHz. A microwave signal at 110 MHz is obtained at the start of the link by a heterodyne beat between reflected and original signal. This is compared to the microwave signal used to upshift the optical radiation in a phase detector. This resulting dc error signal is fed via a Controller to a piezo-based fiber stretcher which closes the stabilization loop. Results for an out-of-loop measurement, where a link of 2 km length is compared to a 1 meter long link. The stability obtained is 250 as rms for short term fluctuations (10 Hz ... 40 MHz) and drifts amount to 3 fs over 10 hours (see figure 2). It must be noted, that only the phase velocity of the light propagating down the fiber is stabilized. However, any signals being transmitted travel at the group velocity. The proposed scheme to bring RF signals to the end stations is to amplitude modulate the cw light with the frequency of choice using an electro-optic modulator. The temperature coefficient of group velocity and phase velocity differ on the order of 10^{-2}. That means for a total correction applied to the piezo-stretcher of say 100 ps (which is a typical value for a km-long link over the course of one day), the transmitted RF signal will have drifted by 1 ps. At present, a 1.1% fixed correction is applied to the phase velocity error signal. This brings the error down to around 40 fs rms over the course of several hours. A schematic of the measurement setup and results are shown in figure 3. This work is ongoing and improvements are to be expected. It will remain to be seen if a long-term stability on the order of 10 fs rms can be achieved. Remote lasers can be phase locked by stabilizing two cw lasers operating at slightly different wavelengths to two different lines of the frequency comb of a mode-locked laser. This phase information is transmitted over the stabilized link and a slave laser is locked to these two incoming signals using a PLL. Here, the scheme does not suffer the problems of group velocity vs. phase velocity, since the only phase information of the cw signals propagating down the link is relevant. Further details regarding the stabilization scheme can be found in references [7, 8, 9].

Time Domain Approach

The centerpiece of the stabilization approach using ultra-short optical pulses is a passively mode-locked erbium-doped fiber laser. It not only supplies the pulses to stabilize the transmission lines using optical cross correlation, but the timing information is also encoded in the precise repetition rate of the oscillator. The intrinsic low phase noise of the fiber laser at frequencies above 1 kHz is combined with the low close-in phase noise of commercially available microwave oscillators using a PLL. Hence an optical frequency source is derived which combines the benefits of both microwave oscillators and lasers.

Mode-locked fiber lasers are a natural choice to realize an optical master oscillator, because of the ease of coupling to the fiber distribution system, their excellent long-term stability, and the well-developed and mature component base available at the optical communications wavelength of 1550 nm. Recently, their technical capabilities have also improved significantly [11, 12]. Yb-doped and Er-doped fiber lasers offer stable and practical platforms for short pulse generation, at $1\mu\mathrm{m}$ and $1.5\mu\mathrm{m}$, respectively. Fiber lasers can generate pulses from picosecond down to 35 fs in duration by simultaneous phase coherent lasing of multiple longitudinal modes spaced in frequency by the pulse repetition rate of the laser. During photodetection, these optical modes beat in the photodetector and generate all harmonics of the repetition rate within the bandwidth of the photodetector. A detailed description of the mode of operation of these lasers can be found in reference [13].

One of the most important features of these lasers is the low phase noise in the frequency range above 1 kHz. As mentioned above, this range cannot be compensated easily with a PLL, so the intrinsic noise performance is a key issue. At present, erbium-doped fiber lasers in both the soliton and stretched-pulse mode of operation are under consideration. A phase noise measurement for both laser types is shown in figure 4. I can be seen that the performance differences in the regime above 1 kHz are small so both lasers are potential candidates. The noise floor of the soliton laser is slightly lower, as the measurements are limited by the electrical power level in the filtered harmonic of the laser repetition rate after photodetection. Since the total output power of the photodiode is constant, there is more power in each spectral line of the higher repetition rate laser.

The stabilization of the optical links is done using optical cross correlation. A schematic of the stabilization scheme is depicted in figure 5. As a testbed, a 400 m long dispersion compensated fiber link is used, which is installed in a hall at DESY. A Faraday rotator mirror reflects part of the light intensity back at the end of the link. The returning pulses are combined with the pulses coming directly out of the laser in a balanced cross correlator (see lower right of figure 5). Two light pulses with orthogonal

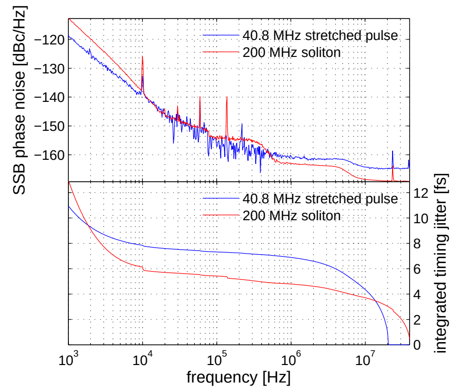

Figure 4: Phase noise comparision between a 40.8 MHz stretched-pulse laser and a 200 MHz soliton laser. Top: single-sideband phase noise measured at the harmonics at 980 MHz (stretched-pulse) and 1.2 GHz (soliton), respectively. Bottom: integrated timing jitter starting integration at 20.4MHz (stretched-pulse) and 40 MHz (soliton)[14].

polarization pass through a type-II PPKTP crystal. Inside the crystal the two polarizations experience a different group delay. With a dichroic mirror the second harmonic generated in the crystal is sent to a first detector, while the fundamental is back-reflected, passing the crystal a second time. The second harmonic is separated by a second dichroic mirror and directed to a second detector. Using the difference signal of the two detectors, amplitude fluctuations of the incoming pulses can be suppressed by a large amount. Changes are corrected by a DSP based feedback system which drives a piezo stretcher inside the link. The bandwidth of the feedback loop is around 1 kHz. Larger timing changes are corrected by a motorized optical delay line. Results are shown in figure 6. The jitter over a timescale of 12 hours is (7.5 ± 1.8) fs rms with a timing drift of 25 fs. The red line indicates changes with a time constant of 100 s. The timing jitter faster than 100 s is (4.4 ± 1.1) fs. Further details can be found in reference [14].

The RF reconversion can be done in two different ways. The first possibility is using a regular photodiode, combined with a bandpass filter for frequency selection. This leads to results shown in figure 4, but suffers from changes of detected phase with temperature and the limited noise floor. The second option is locking a microwave oscillator to the optical pulse train using for instance a sagnac-type interferometer. Details regarding this method can be found in reference [15].

BEAM DIAGNOSTICS USING OPTICAL SYNCHRONIZATION SYSTEMS

The prime benefit of an optical synchronization system is the possibility to lock lasers to the optical reference with femtosecond precision using for instance optical

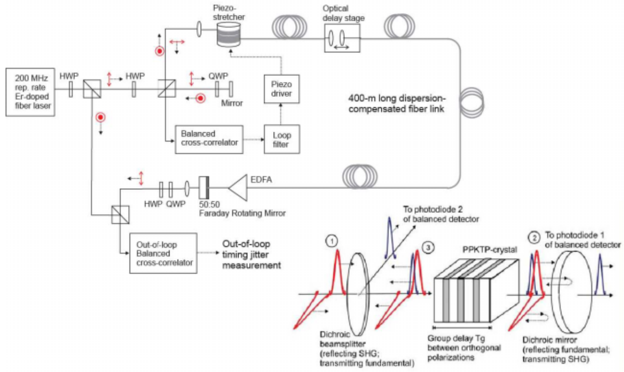

Figure 5: Experimental setup of the fiber link stabilization. lower right: Principle of the balanced optical cross-correlator [14].

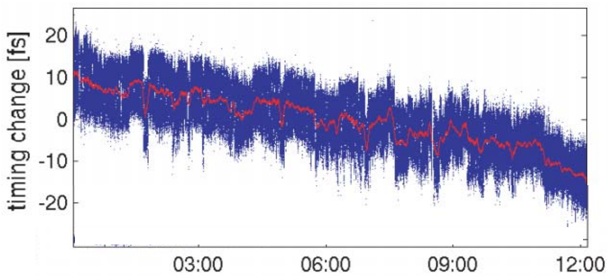

Figure 6: Out of loop drift measurement of a 400 m long fiberlink [14].

cross correlation techniques. So in prinpical any beam diagnostic system using lasers will benefit. For brevity, three examples will be treated in this paper. One is the so-called beam arrival monitor (BAM) [16], making use of the optical pulse train directly by converting the arrival time of the electron bunch into an amplitude modulation. The second example, which at a later stage will use the optical pulse train as a seed for a Ti:sapphire based amplifier system, is the Optical Replica Synthesizer [18]. Third, a brief description of electro-optical techniques will be given.

The Bunch Arrival Monitor

Laser pulses from a fiber link output are fed to an electro-optical modulator (EOM), where the laser amplitude is modulated by a fast transient of a beam pick-up signal. This way, the arrival time fluctuations of the electron bunch are transferred into an amplitude modulation of the laser pulses. These amplitude changes are now detected by a photo-detector and recorded by a fast ADC. The principal of the detection is illustrated in figure 7. Results from a test setup using a fiber laser at a repetition rate of 40.8 MHz synchronized to the machine RF with a conventional PLL are shown in figure 8. The arrival time measured at the end of the machine with the bunch arrival monitor is compared to the average energy deviation measured using

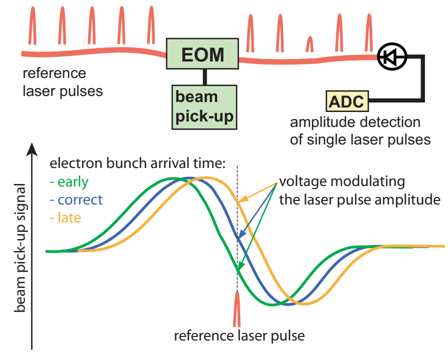

Figure 7: Principle of the arrival time detection. [16].

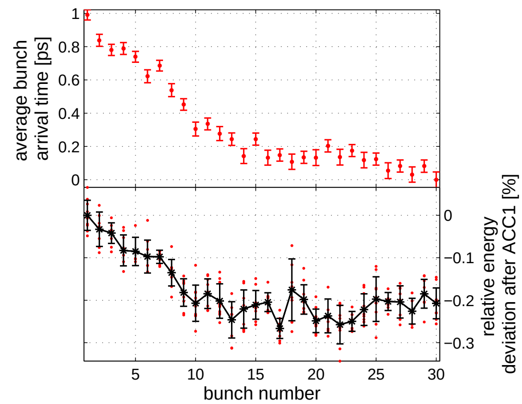

Figure 8: Comparison of the average bunch arrival time over the bunch train at the end of the machine with the average beam energy after the first accelerating module [16].

a synchrotron radiation monitor. in the first bunch compressor. The large energy slope visible in the first part of the bunch train is transformed into arrival time differences inside the magnetic chicanes. More details can be found in reference [16, 17].

The Optical Replica Synthesizer

Here, an amplified Ti:sapphire beam of sub-1 mJ energy is used to intensity modulate the electron bunch in an undulator. The intensity modulation is transferred into a density modulation in a chicane. This density modulation will radiate in a second undulator and emit an optical pulse at the laser wavelength onto which the electron bunch structure has been imprinted. The system is presently being set up at FLASH, for further details see reference [18]. The optical pulse length required is on the order of ps. Hence frequency doubled Er-doped fiber laser pulses can be used to seed the Ti:sapphire amplifier. This system is a natural candidate to be seeded by pulses coming from the output of a fiber link.

Electro-optical experiments

There are various electro-optical techniques under development at the moment ranging from spectral and temporal decoding [19] to spatial decoding [20], each having different laser requirements. The best resolution currently observed is 118 fs FWHM for the temporal decoding technique. Here, the time structure of the electric field of the electron bunch is encoded onto the intensity profile of a chirped laser pulse. In the electro-optic crystal the polarization of the stretched laser pulse is rotated such, that it is slightly elliptical. The ellipticity is proportional to the electric field of the electron bunch. A polarizer turns the elliptical polarization into an intensity modulation, which is then sampled by the gate pulse in a single-shot cross-correlator, using a second harmonic crystal (BBO). Further details may be found in references [19, 21].

Commonly used in all those techniques are Ti:sapphire lasers, either just the oscillator or paired with an amplifier. The oscillators can be synchronized to an optical synchronization system using cross-correlators. This would mean an improvement in terms of jitter from ~ 60 fs to the few-fs level and thus be very attractive.

CONCLUSION AND OUTLOOK

Optical synchronization systems will play a major role in order to meet the stringent stability requirements for next generation light sources, such as the European XFEL. An overview about the potential sources of jitter and ways to circumvent them has been given in this paper. Furthermore, an overview about the two concepts for optical synchronization systems that have been proposed and an update on their present state of development has been given. There are also various beam diagnostic systems that rely directly or indirectly on the optical synchronization system of which three examples were described.

Without the help and contributions of many people this review would not have been possible. I would like to thank R. Willcox, H. Schlarb, F. Loehl, F. Ö. Ilday, G. Angelova, L. Banchi, M. Ferianis, J. Mueller, B. Lorbeer, J. Byrd, J. Phillips for providing data and helpful discussions.

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