LINAC TIMING, SYNCHRONIZATION, AND ACTIVE STABILIZATION

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Abstract

Femtosecond stability is required in an increasing number of linear accelerators, especially in free-electron laser facilities, but also in future light sources based on energy-recovery linear accelerators, as well as in future linear collider projects. This paper discusses schemes to synchronize and stabilize the most critical accelerator components in order to obtain such a stability.

INTRODUCTION

Many needs for femtosecond-stability are very similar in the three types of accelerators which are discussed in the following: free-electron laser (FEL) facilities, future x-ray light sources based on energy-recovery linear accelerators (ERLs), and future linear colliders. We therefore discuss timing requirements in FELs in more detail, and then briefly mention differences for the other two accelerator types.

Timing Requirements in Free-Electron Lasers

Single-pass FELs, operated in the vacuum ultra violet (VUV) and x-ray regime, require low emittance beams with peak currents in the kiloampere range in order to obtain tolerable FEL gain lengths. At the electron source, where the beam energy is low, however, the peak current has to be low (typically well below 100 A), to minimize a degradation of the beam emittance due to space charge forces. The electron bunches are therefore longitudinally compressed using magnetic bunch compressor chicanes after they have been accelerated to higher beam energies. These compressed electron bunches are further accelerated to their final beam energy and then sent through long undulator magnets in which they produce ultra-bright light pulses.

Depending on the duration of the electron bunches and the scheme with which the FEL radiation is generated, the light pulses have durations ranging from a few hundred femtoseconds to below 1 fs. Time resolved experiments use these short duration and highly energetic light pulses to resolve the evolution of physical and chemical processes on the femtosecond scale. In terms of the required stability, the most demanding sub-class of these experiments uses a two-color pump-probe configuration comprising, in addition to the FEL, a second (optical) laser to trigger or probe the process to be explored. The ultimate goal in these experiments is to achieve a synchronization of both light pulses to better than a small fraction of the pulse duration. For some of these experiments, the knowledge of the temporal delay between both laser pulses is sufficient, leading to less stringent requirements on the arrival-time jitter of both pulses. In this case, high resolution arrival-time detectors for both lasers are required, and the recorded data is corrected for arrival-time variations based on the monitor readings after the experiment. This is not possible in experiments that require averaging over multiple consecutive laser pulses, in which case both lasers have to be tightly stabilized with respect to one another.

Due to the large accelerator length of several hundred meters or even a few kilometers, as well as due to the complicated dynamics of the bunch compression and FEL process, stabilizing the arrival times of the FEL pulses to the femtosecond level is a challenging task. Most critical for the arrival-time stability of the electron bunches is the accelerator section in which the electron bunches are generated and compressed.

In order to compress the electron bunches using longitudinal dispersion generated in magnetic chicanes, the electron bunches are accelerated off-crest in the cavities in order to imprint an energy chirp along the bunch, causing different longitudinal positions in the bunch to experience different travel times through the magnetic chicane. If we assume a linear bunch compression process – i.e. both the curvature of the imprinted energy chirp as well as higher order time-of-flight terms of the transport matrix through the chicane are negligible – the bunch arrival-time jitter after a single compressor is given by

$$\sigma_t^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_V}{V}\right)^2 + \left(\frac{C-1}{C}\frac{\sigma_\phi}{2\pi f_{\mathrm{RF}}}\right)^2 + \frac{\sigma_{i,t}^2}{C^2}\,. \qquad (1)$$

Here, c_0 is the speed of light, C the bunch compression factor, and $\sigma_{i,t}$ the bunch arrival-time jitter from the injector. This further assumes that the beam energy after the injector is small compared to the energy at the chicane location and that the entire energy chirp is imprinted by the subsequent accelerator section, operating at an RF frequency f_{RF}. The peak accelerating voltage in the cavities is V, and the fluctuation of this voltage as well as of the cavity phase is σ_V and σ_ϕ respectively.

We can use Eq. 1 to get an estimate of the stability requirements for the accelerating RF and the injection time. In the example of FLASH at DESY, Hamburg, the longitudinal dispersion of the first bunch compressor chicane is $R_{56} \approx 180\,\mathrm{mm}$ and $f_{\mathrm{RF}} = 1.3\,\mathrm{GHz}$, yielding a required field amplitude stability of $\sigma_V/V \approx 1 \times 10^{-5}$ and a phase

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stability of $\sigma_\phi < 0.005\,\mathrm{deg}$ in order to achieve a bunch arrival-time stability of 10 fs. Most FEL facilities utilize more than a single bunch compression chicane, and they also apply higher harmonic accelerating cavities operating at a frequency $3f_{\mathrm{RF}}$ or $4f_{\mathrm{RF}}$ to linearize the energy chirp along the bunch. Due to this, combined with the fact that longitudinal space charge and coherent synchrotron radiation effects as well as wake-field effects alter the longitudinal charge distribution, a more sophisticated analysis is required to determine the acceptable tolerances on the various accelerator parameters for a given operation condition. A more detailed analysis for FLASH is described in ref. [1].

Due to the nature of the FEL process, even a stable electron-bunch arrival time does not necessarily lead to the same arrival-time stability of the photon pulses. The reason is that the exponential growth of the light fields along the FEL undulator depends strongly on the details of the charge distributions, and any variation of the latter can affect the photon pulse arrival-time, even if the arrival-time of the bunch centroid does not change. A second fundamental mechanism causing additional arrival-time variations between the electron bunches and the x-ray pulses is due to the fact that the interaction time between the light field and the electron bunch is limited to the so called *cooperation time*, which, depending on how many longitudinal modes the FEL pulses possess, can lead to additional jitter between electrons and photons of a few femtoseconds for soft x-ray wavelengths, and much less than 1 fs in the hard x-ray case.

Many schemes have been proposed to increase the longitudinal coherence, or to shorten the duration of the FEL pulses, or both (see refs. [2, 3] for examples). A common element in many of these schemes is the application of ultra-short laser pulses which in the simplest case are used as a seed for the FEL radiation, or, in more advanced schemes, to manipulate the electron bunch phase space distribution in order to select only a small part of the bunch which then will contribute to the lasing process. Such schemes offer a great potential to improve the arrival-time stability of the photon pulses because the FEL pulses are intrinsically synchronized to the manipulating laser pulses, the stability of which is easier to control. However, the synchronization of the electron bunches with the manipulating laser pulses is still a major task in these schemes.

Timing Requirements in X-Ray Energy Recovery Light Sources

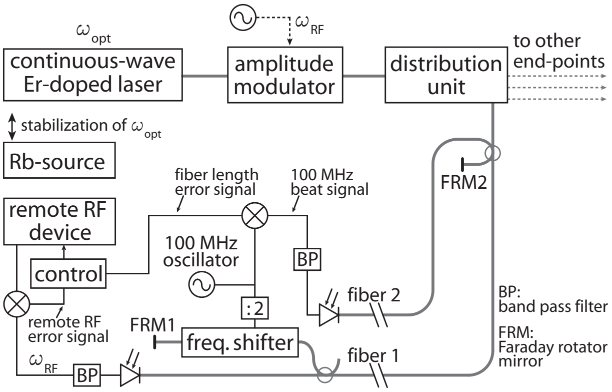

Figure 1: Schematic concept of the continuous wave optical synchronization scheme (adapted from [10]).

Future x-ray ERLs such as the Cornell ERL project [4] offer the possibility to incorporate conventional FELs in a non-energy recovery mode and thus the stability requirements are identical to the ones discussed for FELs. A major difference is that these machines also offer the possibility to generate ultra-short x-ray pulses at GHz repetition rates running high beam currents which can be much larger than 1 mA. At such high beam currents, it can be preferable to perform the bunch compression (and decompression) at full beam energy to reduce the higher order mode power the beam induces into various accelerator components. The consequence is that the number of cavities upstream of the bunch compressor chicane is significantly larger than in an conventional FEL.

Timing Requirements in Future Linear Colliders

The main driver for femtosecond stability in future linear collider projects like ILC [5] or CLIC [6] is the fact that arrival-time fluctuations between the two colliding beams, as well as cavity phase fluctuations (which cause the beam energy spread to change), deteriorate the achievable luminosity (see ref. [7] for a tolerance study for CLIC). A major complication in a collider compared to a light source facility is the large extent of the accelerator of several tens of kilometers, while both accelerator types have similar stability demands. Furthermore, the number of cavities in such colliders is significantly larger, and is has to be seen, if identical synchronization concepts as in light source facilities can be applied.

TIMING DISTRIBUTION

While conventional microwave oscillators are capable of offering excellent stability in the (sub-) femtosecond range (see, e.g. [8]), the stable distribution of these reference signals is a major challenge. Coaxial distribution systems suffer from thermal expansion and contraction of the cables, and for larger cable lengths and high frequencies also from extensive distribution loss. An alternative is an optical system, in which the time reference signal is distributed via optical fibers. Two different approaches are commonly used.

The first scheme [9, 10] (see Fig. 1) uses a narrow band continuous wave (CW) laser operating at $1560.49\,\mathrm{nm}$. The RF signal which is to be transmitted is amplitude modulated onto the optical carrier signal. The optical signal then is sent through an optical fiber (*fiber 1*) to the remote location, where the RF signal is extracted. Part of the laser power is split and sent through an optical frequency shifter, in which the optical frequency ($\sim 200\,\mathrm{THz}$) is up-shifted

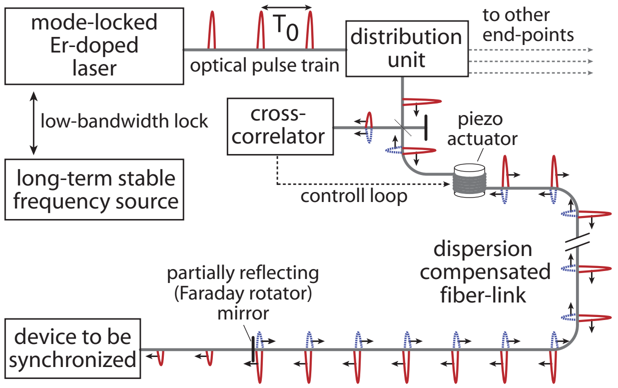

Figure 2: Schematic concept of the pulsed optical synchronization scheme.

by $\Delta f_s = 100\,\mathrm{MHz}$, before the laser beam is sent back through the same fiber. Back at the distribution unit, the returning signal is combined with a laser signal which did not travel through the optical fiber (reflected by the Faraday rotating mirror *FRM2*). The two superimposed signals propagate through a second fiber (*fiber 2*) back to the remote location, where the 100 MHz heterodyne beat signal between both laser beams is detected. The phase of this beat signal changes by π when the phase of the returning (frequency shifted) optical signal changes by π, which corresponds to a travel time difference of around 2.5 fs. A phase detection between the beat signal and the original 100 MHz RF signal therefore yields a very sensitive measurement of *fiber 1* length variations. A digital control loop keeps track of the fiber length changes and adds a corresponding phase correction to the distributed RF signal. One difficulty in this scheme is that the phase velocity of the optical carrier differs from the group velocity of the RF signal due to chromatic dispersion. The control loop compensates for this by adding an additional correction. Using a 200 m long optical fiber, sub-10 fs rms stability for the transmitted RF signal could be achieved [10] over many hours of operation.

The second scheme was first proposed in ref. [11] and is depicted in Fig. 2. It uses a mode-locked, Er-doped laser as a timing reference, which is phase-locked to a long-term stable RF source. The timing information is encoded in the highly accurate repetition rate of the laser. The laser pulses are transmitted through a dispersion compensated optical fiber to the remote location. There, part of the optical power is used to synchronize the remote device, while another part is reflected and returns through the same fiber. Back at the distribution unit, the returning pulses are superimposed with laser pulses which did not travel through the optical fiber, and are sent into a cross-correlator which measures changes of the temporal overlap between both pulse trains. By using a balanced optical cross-correlator as in ref. [12], a dependency of the measured temporal overlap on laser power variations is suppressed and sub-femtosecond resolution is achieved. The information from the cross-correlator is used as the input of a feedback system to correct for group delay variations of the optical pulses in the fiber by acting onto a piezo actuator. Sub-10 fs stability of the distributed optical signal was achieved over many hours of operation [13, 16].

RF SIGNAL GENERATION

As described above, the transmission of RF signals is inherently incorporated into the CW optical synchronization scheme. The pulsed synchronization scheme also provides easy access to RF signals. The spectrum of the transmitted optical pulse train contains integer multiples of the laser repetition frequency f_{rep}, which in the simplest case can be extracted by photo detection and subsequent band-pass filtering. While this already allows for sub-10 fs stability between the extracted RF signal and the optical carrier [14], a major difficulty, which is also present in the CW synchronization scheme, is a shift of the phase of the extracted RF signal when the optical power is varied. While it is possible to minimize this effect by using properly selected photo detectors and operating them at optical power levels at which this dependency is minimum, a second problem remains. The RF power extracted from the photo detector is rather low and most applications require additional RF amplifiers, which might deteriorate the stability of the RF signal (e.g. due to thermal drifts). For the pulsed optical synchronization system, schemes exist, in which this problem is overcome. One of these schemes is the application of a Sagnac loop interferometer, which acts as an optical phase detector, the signal of which is used to lock the phase of a low noise microwave oscillator to the optical pulse train [15, 16]. As an alternative to the external microwave oscillator, the phase of an amplified RF signal extracted from a photo detector can be detected with a Sagnac loop based phase detector and RF phase variations then are corrected by acting onto a RF phase shifter. Such a scheme allows for a stability of the RF signal with respect to the optical pulse train of only a few femtoseconds [17].

ELECTRON BUNCH ARRIVAL-TIME MONITORS

A few types of electron bunch arrival-time monitors exist that have have achieved sub-10 fs resolution, and several others have such potential.

One class of arrival-time monitors uses beam pick-ups and a subsequent RF based phase detection scheme. A high temporal precision can be achieved by performing the phase detection at very high RF frequencies. An example of such a monitor operating at a 30 GHz frequency is described in ref. [18]. When the required measurement bandwidth is low, averaging over many RF cycles is possible, which leads to high temporal resolutions even at lower frequencies of the RF phase detector. Such a scheme using a cavity with stabilized resonance frequency as a beam pick-up is used, for example, at the LCLS free-electron laser at SLAC [19].

A second class of bunch arrival-time detectors uses an electro-optic crystal inside of the beam pipe, the birefringent properties of which are altered in the presence of the electric field of a passing electron bunch. A laser pulse then is used to probe the birefringent properties of the crystal, which yields a measurement of the longitudinal bunch profile as well as of the arrival-time difference between the electron bunch and the probing laser pulse [20, 21, 22]. The arrival-time resolution of these monitors is limited by the accuracy with which the laser can be synchronized to the reference clock of the accelerator. Since the data acquisition in these schemes involves imaging the laser beam with a camera or a line array detector, the data analysis is less straight forward than in other arrival-time monitors, making these monitors less suited for fast feedback applications.

The scheme presented in ref. [21] can be applied to measure the arrival-time difference between the pulses of a pump-probe laser and the electron beam, by using the edge radiation the electron beam produces in an FEL undulator as the THz field to modulate the properties of the electro-optical crystal. Such a scheme was implemented at FLASH and achieved sub-10 fs arrival-time resolution between the laser and the electron beam (see ref. [23]).

A bunch arrival-time monitor which combines using a beam pick-up to extract a fast beam induced electrical transient signal with an electro-optic detection scheme was proposed in ref. [24] and is described in detail in refs. [1, 25]. The monitor uses laser pulses from the pulsed optical synchronization scheme as a timing reference, which avoids a potential degradation of the monitor resolution due to additional signal conversion steps like an RF signal generation or laser synchronization that are required for other arrival-time monitors. A resolution of 6 fs was demonstrated at a measurement bandwidth of more than 10 GHz (see ref. [26]).

In order to achieve even shorter electron and photon pulses, many FEL facilities are introducing operation modes with bunch charges of only a few (tens of) pico-Coulombs. This makes a high resolution arrival-time detection more difficult and might require additional research and development in the future in order to maintain the level of accuracy achieved at higher bunch charges of a few hundred pico-Coulombs.

BUNCH COMPRESSION MONITORS

In a high gain FEL, typically only a fraction of the electron bunch with proper beam emittance and peak current contributes to the FEL interaction. A fluctuation of the longitudinal bunch shape leads therefore to a timing jitter between the emitted x-ray pulses and the centroids of the electron bunches, which is detected by most bunch arrival-time monitors (in addition to the statistical fluctuations caused by the self-amplified spontaneous emission process). A variety of monitors exists to measure longitudinal bunch properties, e.g. the laser based profile monitors mentioned above. A very useful monitor type for feedback applications is a monitor which measures the (integrated) power of beam induced coherent THz radiation. The source of this radiation can, for example, be coherent diffraction radiation (CDR), coherent synchrotron radiation (CSR), or coherent edge radiation (CER). Such monitors are routinely used for example at FLASH [27] and at LCLS [28] to monitor variations in the bunch compression process.

ARRIVAL-TIME AND BUNCH SHAPE STABILIZATION

In order to achieve stable bunch arrival-times and bunch shapes, a very good stability of both the injector emission time and cavity fields in the accelerating cavities upstream of bunch compressors is required. A stabilization of each single cavity to the required level is not alway necessary and might also be too expensive in cases where the number of cavities becomes very large. An alternative is to measure the beam arrival-time and to monitor the variations in the bunch compression process, and then to use these measurements as an input for a beam-based longitudinal feedback system, which applies corrections to the cavity amplitudes and phases. Such a feedback scheme applied in the superconducting FLASH Linac is described in ref. [26] and yielded a bunch arrival-time stability of 25 fs.

In accelerators with pulsed cavity fields, such a scheme is only possible if multiple bunches are accelerated within a single cavity field pulse. In normal-conducting accelerators, the duration of the cavity field pulses is typically very short, so feedback schemes become very challenging. The readings of the arrival-time and compression monitors are, however, very useful even if no feedback is applied, because they can be used to apply proper feed-forward corrections to minimize repetitive arrival-time and bunch compression errors.

SYNCHRONIZATION OF LASERS

The possibility to precisely synchronize mode-locked laser systems to the timing reference of the accelerator is very important in light source facilities. When using the pulsed optical synchronization scheme, this can be done with high accuracy using optical cross-correlator based schemes to measure the temporal overlap between both optical pulses trains. Such a scheme is described in ref. [29] and was also applied in ref. [16], which synchronizes two mode-locked lasers with a 0.4 fs rms jitter (measured in a 2.3 MHz bandwidth) over many hours of operation. The development of such schemes for the pulsed optical synchronization system for various types of laser systems is currently under way (see, for example, ref. [30]).

When using the CW optical synchronization scheme, lasers can be synchronized by locking a high harmonic of the laser repetition rate to the RF signal transmitted through the optical fiber (see ref. [19]). A higher accuracy can potentially be reached by phase-locking two optical comblines of the mode-locked laser to the optical signal distributed via the fiber. In the case of a carrier envelope phase stabilized laser system locking a single comb-line is sufficient.

X-RAY PULSE TIMING MEASUREMENTS

Due to the possibility of additional jitter between electron bunches and photon pulses, as discussed above, a high resolution arrival-time monitoring of the photon pulses is desired. Currently, there are only a few schemes of such monitors available. One possibility for realizing such an arrival-time detector is to use the effect that a high intense x-ray pulse leads to a change in the reflectivity of materials like GaAs, occuring on a sub-picosecond time scale. This change in reflectivity can be detected using a fast optical laser allowing a photon pulse arrival-time detection with a resolution of around 40 fs (see refs. [31, 32]).

SUMMARY AND OUTLOOK

The needs for femtosecond stable electron beams and accelerator subsystems have been summarized, and various technologies to achieve these kinds of stabilities have been discussed. Although many schemes to achieve sub-10 fs stability have already been demonstrated, it will still require some time until these kinds of stabilities will be available on a regular basis. Beam based feedback loops using high resolution monitors have the potential to play an important role in the realization of femtosecond beam stability, especially in superconducting accelerators. Although there are solutions for the femtosecond-stable distribution of reference signals over many hundreds of meters, research is still required to achieve the same level of stability over very long distances of many (tens of) kilometers that will be needed in large x-ray facilities, and especially in linear collider projects.

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