32nd Linear Accelerator Conference (LINAC2024),Chicago, IL, USA JACoW Publishing
ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-WEXA002

ADVANCES IN FS SYNCHRONIZATION

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Abstract

Linear accelerators for FELs have very high requirements for the accuracy of synchronization. The long and short term stability is influenced by various sources of interference. In this paper it will be shown which methods of stabilization exist and how synchronization accuracy up to the single-digit femtosecond-level can be achieved.

INTRODUCTION

High precision applications at Free-Electron Lasers (FEL) pose demanding requirements on the involved reference distribution and control systems of the Linear electron accelerators (Linac). Stability requirements for the Linac are derived from the needs of user experiments, concerning photon energy stability, and the desired temporal resolution when observing dynamics on the femtosecond scale. Advanced FEL schemes as the hard x-ray self seeding, are highly sensitive to deviations from the ideal electron bunch properties in both, the transverse and longitudinal phase space. All large-scale FEL facilities require some sort of synchronization system to reach sufficient time and phase stability. Experiments in pump-probe configuration with two or more radiation sources (x-ray photons, optical laser, THz) are limited in achievable measurement resolution by pulse widths and relative timing stability in between the pump and probe pulses.

All phase-critical subsystems at a Linac are susceptible for environmental changes, including variation of the ambient temperature, changes in relative humidity and air pressure (in case of laser systems), as well as micro-phonics and other types of vibrations and ground motions. In addition to the performance demands, at user facilities also the robustness and reliability of the critical subsystems is a vital property to guarantee a long mean time between failures and high availability. Costs for installation, operation and maintenance are additional criteria. When selecting a type of synchronization system, it makes sense to consider all of the mentioned aspects. Therefore, at most facilities a hybrid solution has been realized, providing a combination of an RF-based distribution for shorter distances, and a long-haul laser-based synchronization system to fulfill the needs of the most timing critical client systems at an FEL.

SYNCHRONIZATION TECHNIQUES

Each of the possible synchronization techniques comes with its own challenges, advantages and drawbacks. For example, RF-based distribution systems have relatively low costs for small facilities and can provide many reference tap points for the RF cavity control. However, their critical parameters concern phase drift in cables, phase uncertainties of frequency dividers and ability to recover phase offsets after power cycling of the system [1]. To improve the stability of a passive RF distribution system one has to carefully choose cabling type with temperature coefficients of <20 fs m^{-1} K^{-1} and an optimal ambient operation temperature to minimize drifts induced by temperature variation [2]. In addition, it might be needed to actively reduce overall temperature fluctuation in the whole accelerator tunnel during operation. Passive RF-distribution systems can achieve a long-term stability of about 50 fs/day/100m [3]. However, compared to telecom optical cables, RF cables suffer with typically 3 dB/100m from power loss. For long-haul distribution systems, this requires a lower distribution frequency with local frequency and phase reconstruction, to reduce distortions along the accelerator. A purely RF-based synchronization with an interferometric phase reference line and active stabilization is under development and has demonstrated already a phase error as good as ±200 fs over several days for short links of <200 m [4, 5].

Another approach are pure continuous wave (CW) optical links for distributing a microwave reference frequency over optical fiber, either as amplitude modulated (AM) or frequency modulated (FM) signal. As alternative to RF oscillators also CW optical lasers or atomic clocks can serve as ultra-low noise phase reference system. CW optical systems come with the advantage of usually lower costs while still reaching timing jitter performance as good as 10 fs level. For mitigating long-term timing drifts to below <1 ps over days, a more complex implementation has to be considered, e.g. by using multiple fibers for the same link (one uni-directional and a bi-directional link) for re-calibration purpose [6,7]. An RF-over-fiber reference distribution system has been developed for LCSL as described in [8]. It achieved an integrated residual jitter of 17.5 fs (10 Hz to 10 MHz) for a transmitted 476 MHz reference frequency. The limitation of CW reference sources in general are given by the fact that they deliver only a single frequency, reducing the variety and also the performance when phase-locking client systems to the reference source.

At SwissFEL, a CW-optical system for connecting most systems (remote microwave oscillators) has been chosen, showing less than 40 fs drift peak-to-peak over 24 h and less than 10 fs rms (10 Hz to 10 MHz) integrated jitter [9, 10]. A few pulsed optical links were added for the use of electro-optical bunch arrival time monitors, and for applying a direct laser-to-laser synchronization for the user experiments.

Such pulsed optical synchronization systems are required to fulfill highest demands on timing stability, in terms of jitter and drift, but also typically require highest investment

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costs for infrastructure and components, especially if using polarisation-maintaining fibers for best long-term performance. Typically, a mode-locked laser oscillator with center wavelength in the infrared region (1.5 µm) and ultra-short laser pulses of few 100 fs pulse width serve as optical reference, with outstanding phase stability especially in the higher frequency range. The optical frequency bandwidth and pulse energies in few nano-Joule range allow for highly resolved phase detection by means of all-optical non-linear mixing techniques. Dependent on the time difference between two laser pulses (reference and measurement system) a third pulse is generated in a non-linear crystal and detected in a photo receiver, converting to a voltage signal which can be used as error input to a phase locked loop (PLL). Using a fast actuator, based on Piezo-electric material fast phase corrections can mitigate residual timing jitter between two pulsed laser sources to below 1 fs [1]. Contrary to a microwave phase detector this all-optical approach is immune to AM-to-PM detection errors.

A synchronization network can achieve under optimal conditions <1 fs [11] link stability. Even under realistic conditions of an FEL facility, already in 2018, a residual integrated timing jitter of less than 1.5 fs rms (10 Hz - 10 MHz) has been shown for locking a laser oscillator to a 3.5 km long fiber link [12].

The ultrashort optical pulses can also be used for other applications where in time domain precise time markers are required, such as for arrival time monitors to detect the timing behaviour of either electron bunches or photon pulses with respect to the optical reference [13]. Moreover the mode-locked, ultra-short laser pulses can also be used for generating ultra-low phase noise RF frequencies, by direct conversion and selecting harmonics of the laser repetition rate. These RF signals are suited for heterodyne mixing techniques when, e.g. synchronizing RF oscillators to the optical reference.

There are a variety of optical-to-RF timing measurement techniques, many of them involving some sort of Sagnac interferometer-type phase detectors [14]. Utilising such phase detectors for an RF-to-Laser synchronization setup can reach excellent levels of accuracy for microwave signals in the higher GHz regime [15]. However, at lower microwave frequencies, as usually used at conventional Linacs, the performance is reduced with residual jitter in the range of 10 fs rms and worse long-term stability (at 1.3 GHz [16]). But also these phase detectors are sensitive to AM-to-PM conversion errors.

Therefore, a novel approach utilising ultra-short laser pulses for sampling a CW microwave signal had been introduced. This type of phase detector incorporates a Mach-Zehnder-type electro-optical modulator (MZM) as a balanced coupling device between microwave and laser. RF phase variations introduce a relative amplitude modulation of laser pulses which are detected in a photo receiver. Using this as error input to a PLL, an excellent long-term stable performance of 3.8 fs rms residual jitter and less than 15 fs peak-to-peak drift has been demonstrated in 2011 [17].

FEMTOSECOND SYNCHRONIZATION AT THE EUROPEAN XFEL

For the FEL facilities operated at DESY, i.e. the Free-Electron Laser at Hamburg (FLASH), as well as the European X-ray Free-electron Laser (EuXFEL), the decision was taken to implement a hybrid solution: a large-scale pulsed optical synchronization system with multiple point-to-point connections of individually length-stabilised, polarisation maintaining links to synchronize all critical sub-systems and to provide the optical reference for time-resolved diagnostics. In addition, a passively stable RF distribution as backbone system, to deliver the 1.3 GHz to the main acceleration sections.

Figure 1 shows the general layout of EuXFEL with its synchronization system. Laser systems at the facility are all-optically locked, including the photo-injector laser, the subsidiary laser oscillator (SLO) for the synchronization sub-distribution, as well as the laser oscillators at the experiments; no cables from the RF distribution are installed further than the main Linac section L3. To guarantee long-term stable conditions for the core systems of the optical reference, environmental conditions inside the laser lab are controlled precisely to reach < 0.1K temperature and $< 3\%$ relative humidity stability [18].

The main RF oscillator (MO) device for the European XFEL has been developed at DESY together with collaboration partners, providing a redundancy concept, extremely high reliability and excellent absolute phase noise characteristic, which is of high importance when aiming at sub-femtosecond stability. The 1.3 GHz microwave signal is derived from a GPS-disciplined 9 MHz OCXO, being amplified and distributed to the RF acceleration modules along the Linac. Continuous improvements over the past decade, reduced the phase noise of the RF reference from initially 35 fs rms (10 Hz - 1 MHz) [19] by an order of magnitude to <2 fs rms (100 Hz - 10 MHz) [20].

The 216 MHz main laser oscillator (MLO) is a commercially available mode-locked laser oscillator. It is tightly phase-locked to the 1.3 GHz MO with an in-loop jitter of 3 fs rms (10 Hz to 100 kHz) and practically drift-free [18], using the aforementioned MZM-based optical-to-RF phase detector. This type of detector is also incorporated into the so-called optical reference modules (REFMOpt), indicated in Fig. 1 by the abbreviation ”RF2L”. These modules are the first element in the reference signal chain of the low-level RF (LLRF) control system, removing locally all temperature and relative humidity induced phase drifts, by re-synchronizing the 1.3 GHz RF reference signal to the sub-femtosecond stable optical reference with a locking bandwidth of several 100 Hz as described in [21].

The Linac of EuXFEL is operated in pulsed mode with 10 Hz repetition rate and 650 µs duration. In the main Linac, individual RF stations consist of 4 cryo modules, each equipped with 8 TESLA type 1.3 GHz cavities. The LLRF system regulates the vector sum of the 4×8 cavities per RF station, driving the 10 MW multi-beam klystrons. The

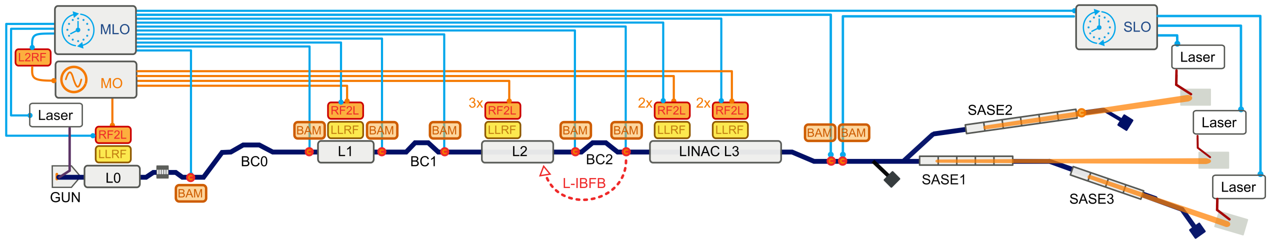

Figure 1: Schematic layout of the 3.5 km long European XFEL facility with some elements of the synchronisation system: the main RF oscillator (MO), the main laser oscillator (MLO), the subsidiary laser oscillator (SLO), bunch arrival time monitors (BAM) around the bunch compressors (BC), the RF-to-Laser re-synchronization (“RF2L”) using MZM-based balanced RF-to-optical phase detectors, and exemplary, the location of low-level RF (LLRF) controls of RF stations.

regulation stability is well within the design values of 0.01 % in amplitude and 0.01° in phase [22, 23]. Details on the implementation of the LLRF system at EuXFEL can be found in [24]. All sub-components of the LLRF system have been optimized for adding only little or no noise to the phase noise budget.

A subject of on-going development for the LLRF system are RF field receivers for detecting amplitude and phase of a microwave signal. Conventional solutions for RF field detection, using either frequency mixing into baseband with subsequent amplification, or IQ-demodulation techniques, are limited by internal noise of involved components. Recent results of a new carrier-suppression interferometer (CSI) for precision phase-noise detection in the sub-femtosecond regime has been demonstrated in 2022 [25]. Notably, these investigations also reveal that in systems with an imbalance of group delay from different cabling lengths (which is the case for the connection in between RF cavities and field receivers) the absolute phase noise of the MO reference signal does play a role, when aiming at highest precision into the attosecond regime.

BEAM-BASED MEASUREMENTS AND STABILISATION

At EuXFEL, conventional bunch compressors are used for reducing the bunch length from initially 4 – 6 ps rms at the RF gun in multiple stages to a final length of typically 5 – 15 fs rms (measured with a THz spectrometer [26]). Using the combination of bunch energy chirp introduced in the upstream RF modules and the negative R56 (momentum compaction factor) of a magnetic chicane, the charge density within an electron bunch is shaped to reach high peak currents; also incoming arrival time jitter is reduced by the compression factor. These sections with longitudinal dispersion are used for applying beam-based feedbacks for mitigating arrival jitter by applying energy corrections to the upstream RF modules. After acceleration to final beam energy in L3, the electron bunches are distributed within a switch yard consisting of several kickers to the 3 SASE beamlines, compare Fig. 1.

The RF pulse is separated into several sections, called beam regions (BR), according to the bunch pattern which is distributed by the timing system, shown in Fig. 2. Bunches for the different SASE beamlines can be located in separate BR. This has several advantages: RF chirp and sumvoltage can to some extent be tuned individually on the different BR, shaping the longitudinal electron-bunch properties to the needs of SASE photon pulses. In addition, the BR concept allows for applying static shapes to the RF field (usually in amplitude) to correct for repetitive errors (repeating with 10Hz). On top of this field correction, intra-train beam-based feedbacks can be applied acting within the duration of each BR. Later on in the switch yard those bunches which where located in the transient region of the feedbacks can be removed from the train, using only those electron bunches for SASE generation which are already located in the steady-state regime of the feedbacks [24]. The third advantage of the beam-region concept is, that also offsets in sumvoltage and chirp of the RF field within each BR can be regulated within certain limits individually, by applying slow beam-based feedbacks to remove slow drifts in arrival-time or beam energy, bunch compression and bunch charge [27].

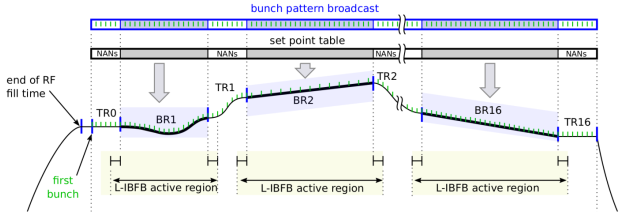

Figure 2: Illustration of the beam region (BR) concept: LLRF field regulations and beam-based feedbacks are active during the BR regions. Those are interrupted by transition regions (TR) with transient RF fields to accommodate to new set-values in the following BR. Only the stabilized electron bunches within the individual BR are distributed to the SASE beamlines, the others are removed from the train and directed into an electron beam dump by fast kickers.(Figure had been adapted from [24].)

Table 1 gives typical numbers of the measured arrival-time jitter along the Linac, downstream of each bunch compressor and without any additional beam-based feedback. For reaching highest stability in the arrival-time of the electron bunches, a longitudinal intra-train feedback (L-IBFB) has been implemented. Monitors downstream of the bunch compressors send the arrival-time information for each electron bunch directly via a low-latency link to the digital LLRF controls of the upstream RF station. The method uses an er-

Table 1: Arrival-time stability (rms jitter over 100 shots) at different locations in the European XFEL Linac without additional beam-based feedbacks. Compare also Fig. 1 for the location names.

Location	Typical Jitter [fs]rms
BC0	40-50
BC1	30-35
BC2	15-25

ror combination and weighting of RF field-based and beam-based measurement in the LLRF system for calculating required amplitude and phase corrections to minimize the error signal. With the L-IBFB a bunch-train to bunch-train stability in the few single-digit femtosecond regime can be reached which is close to the resolution limit of the arrival-time monitors (typically <5 fs at 250 pC bunch charge), keeping this performance over days during user operation [13]. By using photon arrival-time monitors, a nearly perfect correlation was observed in the short-term timing of x-ray photon pulses and the electron bunches from which the photons were generated in the SASE process [13]. In addition to the application in beam-based feedbacks, the bunch arrival-time monitors deliver the single-shot information to user experiments, allowing to correct the time delays in pump-probe measurements for keeping time overlap and improving the overall time resolution.

OVERALL STABILITY

User experiments have shown that a time resolution of 16 fs ±2 fs FWHM (fit error to the data) can routinely be achieved at the soft x-ray photon beamline SASE3. This is important for femtosecond pump-probe spectroscopy for resolving photo-induced structural changes in molecules. The time delay between the x-ray photons and an optical pump laser at the location of the interaction region was scanned by changing an optical delay line. The expected relative time delay in between both pulses was corrected using the information of the electron bunch arrival-times. The temporal resolution in such kind of experiments is limited by the x-ray pulse duration and the residual temporal jitter in between pump and probe pulses; from the obtained data both parameters have been estimated to be approximately 10 fs FWHM each [28].

To achieve temporal resolution in the <10 fs FWHM regime, improvements for the arrival-time monitoring and active stabilization are required, as well as for the temporal stability of the pump laser pulses close to the location of the interaction region. In this regard, recently a development for laser arrival-time monitors (LAM) has been initiated. Technical challenges concern especially the wide range of optical wavelengths and pulse lengths from the pump-probe laser system which have to be covered. The layout for arrival-time detection uses the nonlinear mixing for all-optical phase detection. In latest experiments at FLASH it was demonstrated that with a feedback loop using the LAM data, the laser pulse drift can basically be completely removed, leaving only a narrow jitter band of <20 fs rms [29]. To also mitigate this residual jitter, fast actuators are needed for implementation of PLLs with kHz bandwidth.

CONCLUSION AND OUTLOOK

To summarise, at European XFEL high reliability and an excellent stability in the RF field control has been achieved by combining an RF backbone distribution with a precise, pulsed optical synchronization system. Compared to an actively controlled CW RF distribution system, in a pulsed optical synchronization there are no hard limitations from reflections in the distribution line, and it allows for applying precise arrival time monitors. The overall accelerator and FEL stability is routinely even further improved by applying additional beam-based regulations to the RF cavity control, achieving single-digit femtoseconds timing jitter.

Some components and sub-systems have been identified for further developments to approach the few 100 attosecond stability regime:

- further improvements of the MO,
- ultra-low noise RF field receivers,
- higher resolution of the bunch arrival time monitors,
- development of laser arrival time monitors,

to mention the main on-going activities. It should be pointed out that for achieving highest levels of synchronization with active stabilization, both, a control of environmental conditions and a good passive stability of involved components are required.

The long-term timing drift behaviour at European XFEL, which should shortly be mentioned here, shows an interesting feature, which seems to be explainable from periodic earth movements by earth tide and ocean tides. This effect of slow stretching and compressing is experienced by all components with large elongated dimensions (e.g. accelerator tunnel, beam pipe and kilometer long cables). Since the regulation of the length-stabilised optical links corrects for all path length changes, the timing at the synchronized clients is not altered. But due to actual path length changes for the electron bunches [30] and x-ray photon pulses, there is indeed a slow and periodic drift observed in experiments as delay between the x-ray photons and the synchronized pump-probe lasers. A project is at the moment started to study this effect in more detail and investigate the possibility of a short-term prediction window and subsequently correction with a feed-forward control loop.

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