# LARGE-SCALE TIMING DISTRIBUTION AND RF-SYNCHRONIZATION FOR FEL FACILITIES

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*Abstract*

For future advances in accelerator physics in general and seeding of free electron lasers (FELs) in particular, precise synchronization between low-level RF-systems, photo-injector laser, seed radiation as well as potential probe lasers at the FEL output is required. In this paper, we propose a modular system that is capable of achieving synchronization of various RF- and optical sub-systems with femtosecond precision over distance of several hundreds meters. Typical synchronization methods based on direct photo-detection are limited by detector nonlinearities, which lead to amplitude-to-phase conversion and introduce excess timing jitter. A new synchronization scheme for extraction of low jitter RF-signals from optical pulse trains distributed by mode-locked lasers is demonstrated. It is robust against photo-detector nonlinearities. The scheme is based on a transfer of timing information into an intensity imbalance between the two output beams from a Sagnac-loop interferometer. As a first experimental demonstration, sub-100 fs timing jitter between the extracted 2-GHz RF-signal and the 100 MHz optical pulse train from a mode-locked Ti:sapphire laser is demonstrated. Numerical simulations show the scaling to sub-femtosecond precision is possible. Together with low-jitter mode-locked lasers and timing stabilized fiber links, this scheme can be applied for large-scale femtosecond timing distribution and synchronization of RF- and optical sub-systems in accelerator and free electron laser facilities.

## INTRODUCTION AND MOTIVATION

Seeding of free electron lasers operating in the EUV and soft X-ray regime with radiation generated via high harmonics from noble gases may result in a fully coherent X-ray laser. For seeding of such large-scale facilities spanning over several hundreds meters, it is critical to synchronize lasers and RF-systems with low (preferably sub-femtosecond range) timing jitter in a long-term stable arrangement. Figure 1 shows the schematic outline of timing distribution and synchronization for such a facility. The pulse repetition rate of an optical master oscillator implemented as a mode-locked laser is stabilized to a frequency standard or a low noise microwave oscillator. The pulse train is distributed to all critical sub-systems by use of timing stabilized fiber links, i.e., the pulse trains leaving different fiber links are highly synchronous. The RF- or optical sub-systems are then synchronized to the pulse trains at the fiber outputs.

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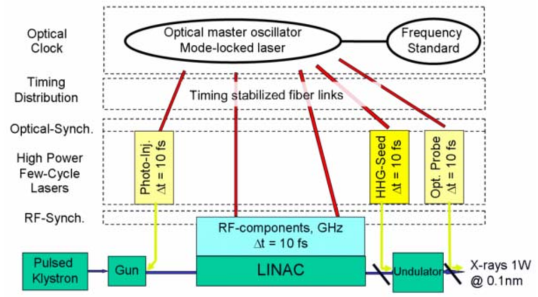


Figure 1: Schematic outline of timing distribution and synchronization for FEL facility.

It has been shown recently that the extraction of a microwave signal from an optical pulse train emitted by a mode-locked laser using direct photo-detection is limited in precision by excess phase noise [1]. The origin of this excess noise has been identified to be amplitude-to-phase conversion in the photo-detection process, beam-pointing variations, and pulse distortions by photo-detector nonlinearities [1]. In addition to this excess phase noise and timing jitter by photo-detector nonlinearities, the long-term synchronization stability is limited by the temperature dependence of semiconductor photodiodes. Thus, a new synchronization scheme to avoid these problems is highly desirable.

In the next section, a module for the synchronization between RF-signal and optical pulse train from a mode-locked laser is experimentally demonstrated and discussed in detail. The same module can also be used for the optical-to-optical synchronization between various lasers. The required technical criteria for timing stabilized fiber links and optical master oscillators are addressed in the last sections.

## RF-SYNCHRONIZATION

### *Outline of the Scheme*

The general idea for suppression of excess noise due to the photo-detection process is shown in Figure 2. While still in the optical domain, the timing information is transferred into an intensity imbalance between two beams by sending the pulse train through a pair of amplitude modulators. The modulators are driven by the output signal from a voltage-controlled oscillator (VCO) with $180^{o}$ phase difference. The intensity difference is detected with a balanced detector and this signal controls the input to the VCO via a loop filter. With this step, we shift the problem of photo-detector nonlinearities on the electronics side to the realization of amplitude modulators with drift-free bias points on the optical side. The $180^{o}$

out-of-phase amplitude modulators can be realized by a Mach-Zehnder interferometer with a phase modulator in one arm. However, this scheme will suffer from the phase drifts in the interferometer arms due to temperature fluctuations, air currents, and mirror vibrations. To remove these problems, the interferometer is implemented in a Sagnac-loop configuration with a phase modulator inside the loop.

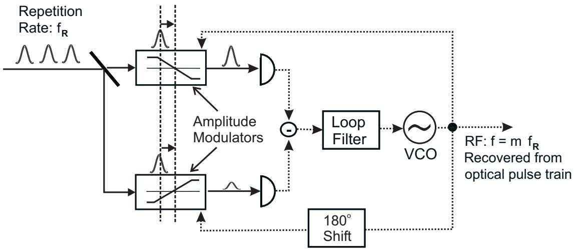


Figure 2: General idea of synchronization scheme based on a transfer of timing information into an intensity imbalance in the optical domain.

## *Experiments*

Figure 3 shows the synchronization scheme.

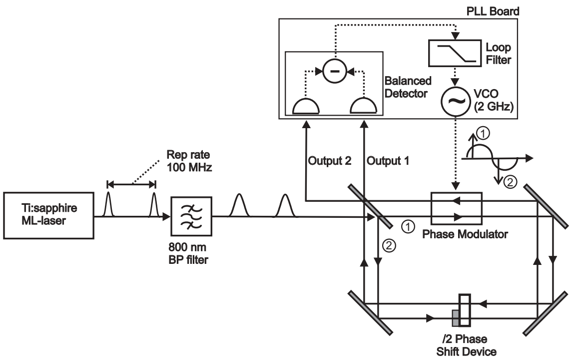


Figure 3: The synchronization scheme for extraction of a 2 GHz signal from a 100 MHz repetition rate Ti:sapphire laser.

A 100 MHz repetition rate mode-locked Ti:sapphire laser is used as the pulse source. After passing a bandpass filter at 800 nm to limit the pulsewidth to about 100 fs, the input optical pulse train is sent into the Sagnac-loop. A resonant phase modulator at 2 GHz is positioned in the Sagnac-loop in such a way that the optical delay between counter-propagating pulses at the phase modulator is set to half of the RF-signal period. This assures that the two pulses experience opposite phase modulation. The output beams are detected by a balanced detector that generates a difference signal between the two photocurrents from the two Si pin-photodiodes. The output current from the balanced detector is transferred to a passive loop filter (type II, order 2 topology [2]) for proper filtering. The passive loop filter structure is advantageous over an active counterpart since it allows a simple circuit and also ensures excellent noise performance. The loop filter output signal drives the VCO and changes the driving frequency of the phase modulator until it reaches a phase-locked state by balancing the two output powers from the interferometer. This closes the phase-locked loop operation. For a stable and drift-free biasing of the interferometer, an effective quarter-wave plate is inserted in one of the beams using a thin-film coating covering only half of the substrate. A very stable and drift-free phase-locked operation is achieved with this scheme.

## *Phase Noise Measurement Set-up*

The phase noise of the RF-output signal from the VCO is characterized in two ways: (i) by the frequency discriminator technique using a commercial phase noise measurement setup PN9000 from Aeroflex; (ii) by mixing the output signal of the VCO in quadrature with the 2 GHz component of the directly detected pulse train in order to measure the relative phase noise between the optical pulse train and the extracted RF-signal. Figure 4 shows the measurement set-up. Using method (i), the input is delayed and mixed with itself in quadrature to extract the phase noise of the input [3]. Method (ii) is a standard technique to measure the residual phase noise between two locked RF-signals [4] where an oscilloscope is used to monitor that the two RF-signals are in quadrature, and a vector signal analyzer is used to measure the noise spectrum.

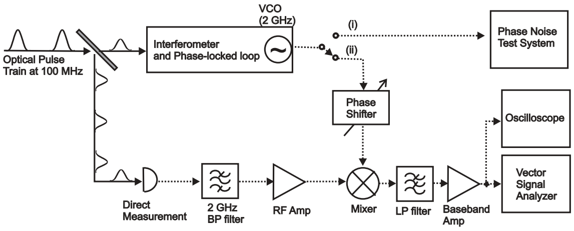


Figure 4: Phase noise measurement set-up: (i) frequency discriminator technique using a commercial phase noise instrument (PN9000, Aeroflex) and (ii) mixing the output signal of VCO in quadrature with the same frequency component of the directly detected pulse train.

## *Phase Noise Measurement Results*

The measured single-sideband (SSB) phase noise spectra from 1 Hz to 10 MHz are shown in Figure 5. Curve (1) shows the phase noise spectrum of the free-running VCO measured with the Aeroflex phase noise measurement system. Curve (2) shows the phase noise measured by the same method when the system is locked. The locking is clearly visible in the spectrum covering the range of 100 kHz to 10 MHz. At lower frequencies, the phase noise of the free-running Ti:sapphire pulse train dominates.

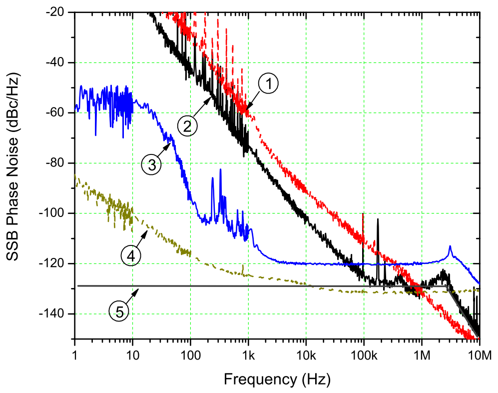


Figure 5: Single-sideband phase noise measurement result: (1) free-running VCO and (2) locked VCO using method (i); (3) measured phase noise between extracted RF-signal and the $20^{th}$ harmonic of directly detected pulse train using method (ii); (4) noise floor of vector signal analyzer; (5) estimated phase noise level of extracted RF-signal from result of curve (2).

In order to verify the assumption that the phase noise of the laser dominates at low frequencies in the frequency discriminator measurement results, we measured the relative phase noise between the pulse train and the RF-signal by using the second phase noise characterization method. The result is shown in curve (3) of Fig. 5. Due to the noise floor of the vector signal analyzer (curve (4) in Fig. 5) and excess noise in the photo-detector that generates the reference signal, the high frequency noise floor is increased in comparison to method (i). But this measurement clearly shows that the noise increase at low frequencies in curve (2) is the phase noise of the free-running Ti:sapphire laser. This result suggests that better shielding of the laser against environmental perturbations, higher pulse repetition rate as well as the use of a VCO with lower phase noise, will lead to drastic improvements in the timing jitter of the microwave signal extracted from the laser source.

Note that the origin of the enhanced phase fluctuations below 1 kHz may be due to either mechanical vibrations in the Sagnac-loop or excess phase noise in the photo-detection process resulting from converted laser amplitude fluctuations. These hypotheses will be further investigated in the near future by building two RF-synchronization systems and beating the two outputs against each other. Based on the current system and measurements, the relative timing jitter between the RF-signal and the pulse train integrated from 100 Hz to 10 MHz can be estimated by the area underneath curve (5), which lines up with the high frequency noise of the Aeroflex measurement (curve (2) in Fig. 5) and results in about 60 fs timing jitter.

The demonstrated timing jitter is not as low as using pure microwave techniques based on high-speed photo-detection [5,6] or using purely optical means [7] yet. However, with improved system design, this method will be able to reduce the relative jitter to the sub-femtosecond range over the full Nyquist bandwidth in the near future. For long-term stability, a fiber implementation of the Sagnac loop is preferable. This will eliminate a large part of the drift problems in the low frequency range. In addition, a lower-noise VCO combined with a higher phase detector gain of phase-locked loop will dramatically reduce the phase noise of high frequency range. Numerical simulations also show that scaling down to sub-femtosecond timing jitter is possible with the improved design.

## OPTICAL-TO-OPTICAL SYNCHRONIZATION

Synchronization is necessary not only between optical and RF-subsystems but also between different optical systems, for example, the photo-injector laser and the master oscillator as shown in Fig. 1. Figure 6 shows how the optical-to-RF synchronization technique can be used to synchronize two pulsed lasers with each other. By use of the RF-synchronization module described in the previous section, we first lock the RF signal to the pulse train from one laser (ML-laser 1 in Fig. 6). This locked RF-signal drives the phase modulator of another RF-synchronization module. However, instead of driving VCO, the error signal from balanced detector drives the piezoelectric transducer (PZT) to control the repetition rate of the second laser (ML-laser 2 in Fig. 6). In this way, an effective synchronization of multiple lasers is also possible by locking lasers to the same RF signal synchronized to one laser.

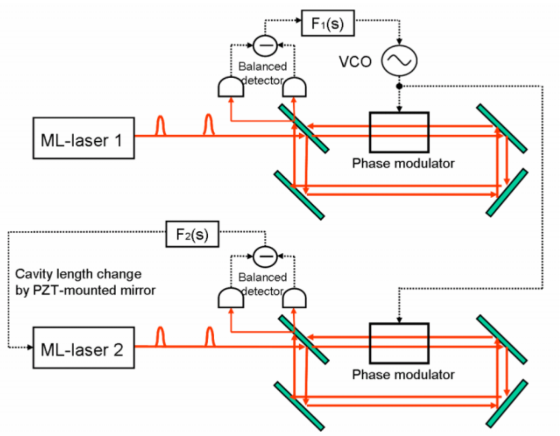


Figure 6: Possible optical-to-optical synchronization scheme with the proposed RF-synchronization technique.

## TIMING DISTRIBUTION

Precise transfer of RF-signals through fiber links has been demonstrated recently [8,9]. For timing distribution over a large-scale free electron laser facility, timing stabilized fiber links will be used. If the fiber length is L, we assume that no length fluctuations are faster than (2nL)/c, where n is the refractive index of the fiber and c is the vacuum velocity of light. Relative fiber expansion by temperature change is typically on the order of $10^{-7}$/K, which can be compensated for by a fiber length control loop as shown in Figure 7 by referencing the back reflected pulse from the fiber end with a later pulse from the mode-locked laser. This approach is applicable up to a precision fundamentally limited by the high frequency jitter of the laser from frequency of c/(2nL) up to the Nyquist frequency, i.e., half of the repetition rate. Therefore this jitter should be on the order of a few femtoseconds or below if 10-fs overall jitter needs to be achieved. This puts a serious constraint on the high frequency timing jitter of the optical master oscillator.

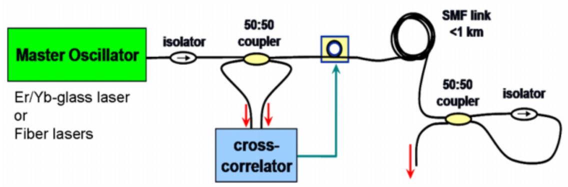


Figure 7: Timing stabilized fiber link.

## OPTICAL MASTER OSCILLATOR – LOW-JITTER MODE-LOCKED LASER

Currently the most promising candidates for ultra-low jitter optical master oscillators are Er/Yb-glass lasers [10], passively mode-locked Er-doped fiber lasers [11] and Yb-doped fiber lasers [12]. Particularly, Er/Yb-glass lasers with sub-20 fs timing jitter have been demonstrated recently [10]. The crucial performance indicator for such a source is the phase noise or timing jitter integrated from c/(2nL) to the Nyquist frequency. This jitter will set an inherent limitation to the precision in timing achievable with a given distribution system. Construction and evaluation of several of these lasers with respect to timing jitter requirements are currently in progress.

## CONCLUSION AND OUTLOOK

In summary, we introduce a scalable timing distribution and synchronization scheme for future accelerator and seeded free electron laser facilities. We demonstrate a modular RF-synchronization scheme between laser and RF-subsystem which is robust against photodiode nonlinearities. This technique can also be used for optical-to-optical synchronization. Together with timing stabilized fiber links driven by an ultra-low jitter mode-locked laser, we anticipate large-scale timing distribution and synchronization techniques with femtosecond precision in the near future.

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