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FEMTOSECOND LASER-TO-RF SYNCHRONIZATION AND RF REFERENCE DISTRIBUTION AT THE EUROPEAN XFEL

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Abstract

At the European XFEL, optical pulses from a mode-locked laser are distributed in an optical fiber network providing femtosecond stability throughout the accelerator facility. Due to the large number of RF reference clients and because of the expected higher reliability, the 1.3 GHz RF reference signals are distributed by a conventional coaxial RF distribution system. However, the provided ultra-low phase noise 1.3 GHz RF reference signals may drift over time. To remove these drifts, an optical reference module (REFM-OPT) has been developed to detect and correct environmentally induced phase errors of the RF reference. It uses a femtosecond long-term stable laser-to-RF phase detector, based on an integrated Mach-Zehnder amplitude modulator (MZM), to measure and resynchronize the RF phase with respect to the laser pulses from the optical synchronization system with high accuracy. Currently nine REFM-OPTs are permanently operated at the European XFEL, delivering femtosecond stable RF reference signals for critical accelerating field control stations. The operation experience will be reported together with a detailed evaluation of the REFM-OPT performance.

INTRODUCTION

The European X-ray Free-Electron Laser (XFEL) uses a 1.7 km long superconducting linear accelerator (linac) to drive the FEL. A pulsed optical synchronization system has been built and is operated 24/7 at the European XFEL in order to meet various synchronization requirements [1]. For example the synchronization between the FEL and the pump-probe laser systems needs to be in the femtosecond range in order to make time-resolved, ultra-fast pump-probe experiments possible. This synchronization system also allows to provide RF reference signals with femtosecond stability throughout the linac [2] in order to meet the stability requirement for the accelerating field stability of 0.01° at 1.3 GHz ($\approx$ 20 fs) [3]. See Fig. 1 for a schematic overview of the complete system.

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OPTICAL SYNCHRONIZATION SYSTEM

The master laser oscillator (MLO) of the optical synchronization system is a redundant, low jitter, commercial laser system with a repetition rate of 216.66 MHz at a wavelength of 1553 nm. The MLO is precisely phase-locked to the 1.3 GHz RF master oscillator (RF-MO) of the accelerator facility. The laser pulse train from the MLO is split up and distributed in polarization maintaining optical fibers to numerous end stations throughout the accelerator facility. Optical length changes of these fibers are permanently measured and actively corrected. Three different types of end stations are currently supplied by the optical synchronization system and all end stations are synchronized with femtosecond precision [4]. The system is used to precisely synchronize laser systems like the photoinjector laser [5] or the pump-probe laser systems, to operate the bunch arrival time monitors (BAMs) [6, 7], and to provide femtosecond stable RF reference signals to dedicated end stations along the linac via the optical reference module (REFM-OPT).

RF REFERENCE DISTRIBUTION

The conventional RF reference distribution system installed at the European XFEL is a highly reliable system. It is however susceptible to temperature and humidity variations. The RF cables installed along the accelerator tunnel

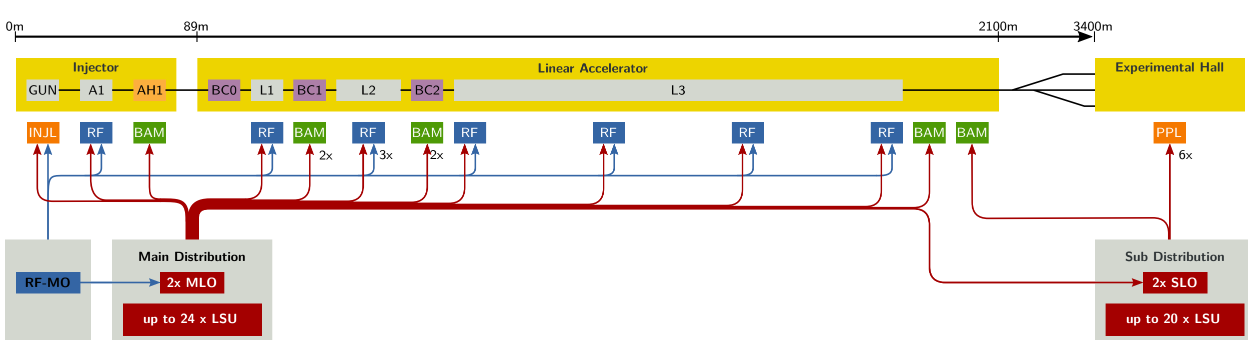

Figure 1: Layout of the RF reference distribution and the pulsed optical synchronization systems of the European XFEL. The RF reference distribution system including the RF-MO and the REFM-OPTs is shown in blue. Stabilized fiber links, MLO/SLO and FSD are presented in red. BAMs are illustrated in green and external laser systems in orange.

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suffer mostly from environmental temperature variations. Electronics, like RF amplifiers, which are installed in the tunnel in temperature stabilized racks are additionally susceptible to humidity variations. These effects could regularly cause several tens of picoseconds of RF phase drifts along the linac if they were not measured and directly corrected in a phase-locked-loop (PLL) by the REFM-OPT. The REFM-OPT operates by locally re-synchronizing the 1.3 GHz RF reference signals in order to meet the low-level RF (LLRF) phase stability requirement.

In the L1 and L2 sections of the linac a star topology has been implemented in the RF distribution system in order to achieve the ultimate performance. A dedicated REFM-OPT is installed at each master RF station in these sections. The main linac (L3) is connected by daisy chained modules, where one REFM-OPT supplies several RF stations.

OPTICAL REFERENCE MODULE

A drift-free laser-to-RF phase detector has been specifically developed in order to make use of the femtosecond optical pulse trains provided by the optical synchronization system [8]. It allows to measure the phase drifts and jitter of the 1.3 GHz RF reference signals with respect to the optical reference and correct them up to the locking bandwidth with femtosecond precision in a PLL. The laser-to-RF phase detector is based on a Mach-Zehnder amplitude modulator (MZM). The optical pulse train is modulated proportionally to the phase difference between the two signals and the amplitude modulation is used for detection. All nine planned REFM-OPTs are installed and permanently operated. Phase corrections of tens of picoseconds are routinely applied after maintenance days or accelerator operation interruptions in order to maintain stable RF reference phases for the accelerating field control [2].

PERFORMANCE EVALUATION

In order to particularly evaluate the performance of the REFM-OPT in the accelerator tunnel under operation conditions, several of out-of-loop measurements were performed, using a commercial Rohde & Schwarz FSWP phase noise analyzer. A set of absolute phase noise measurements is presented in Fig. 2 to show the overall performance at the RF station A2M in the L1 section of the linac. The phase noise of the RF reference signal at the input of the REFM-OPT is depicted by the green curve. This signal is provided by the RF-MO in the injector building, it is transmitted by RF cables to the accelerator tunnel and amplified in a so-called reference module (REFM) in order to provide the required RF power. The integrated jitter of this signal in a bandwidth of 10 Hz to 1 MHz amounts to 17.3 fs rms with a large contribution from the 50 Hz spike of about 7 fs. This signal is connected to the input of the REFM-OPT.

Two additional measurements were carried out in the same offset frequency range at the output of the REFM-OPT. For the first measurement (red curve) the phase and RF power feedbacks in the REFM-OPT were switched off. The REFM-

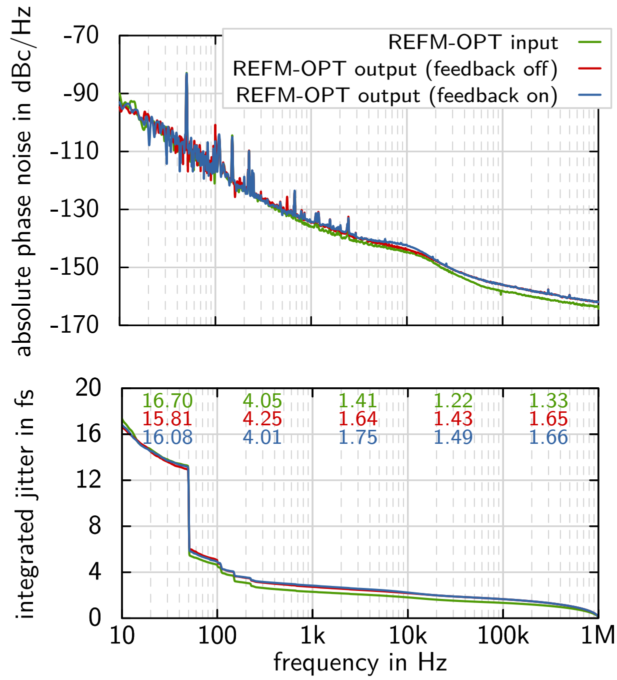

Figure 2: Absolute phase noise measured at the input and the output of the REFM-OPT at the RF station A2M. The measurement was obtained in the accelerator tunnel under operation conditions.

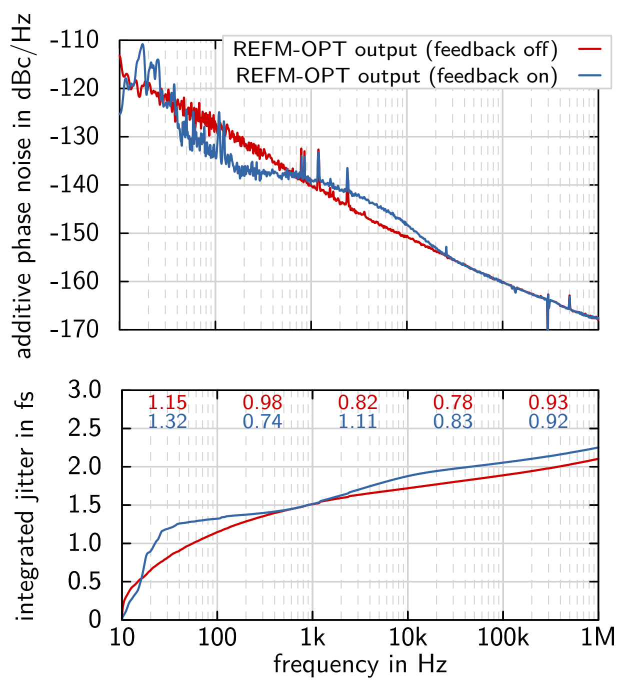

Figure 3: Additive phase noise of the REFM-OPT at the RF station A2M. The measurement was obtained in the accelerator tunnel under operation conditions.

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OPT acts in this state like an RF amplifier. For the next measurements the feedbacks were switched on (blue curve) such that the RF signal at the output of the REFM-OPT was actively amplitude and phase stabilized. The curves show two distinct changes. The general phase noise level is slightly elevated by the REFM-OPT in the frequency range of 1 kHz to 1 MHz (from the green to the red curve). One can furthermore see, that the noise bump at 10 kHz is increased when the feedback is switched on (from the red to the blue curve). This noise bump originates from the RF-MO and is transmitted across both the optical and the RF reference distribution system as it is just outside the bandwidth of the involved control loops.

In order to be able to better quantify these effects and to study the actual phase noise contribution of the REFM-OPT, additive phase noise measurements were additionally performed. They are presented in Fig. 3. A reference measurement was carried out, where the REFM-OPT phase and amplitude feedbacks were switched off (blue curve). The integrated additive jitter of the REFM-OPT (without active feedback) in a bandwidth of 10 Hz to 1 MHz amounts to 2.1 fs rms. With active feedbacks the additive jitter is slightly increased (2.3 fs rms) as expected. The REFM-OPT with active feedback is correcting RF phase jitter and drifts which the RF signal accumulated during transmission into the tunnel. One can clearly see low frequency phase drift corrections up to 30 Hz but also how up to the controller bandwidth of 500 Hz the RF amplifier noise is partially suppressed by the phase feedback.

The additive jitter contribution from the REFM-OPT amounts to 2.1 fs rms without active feedback and 2.3 fs with feedback in a bandwidth of 10 Hz to 1 MHz. This out-of-loop measurement proves that there is only little phase noise added by the REFM-OPT while drifts and phase jitter is actively corrected in the same time in the locking bandwidth of up to 500 Hz.

CONCLUSION

Absolute phase noise of the 1.3 GHz RF reference signal amounts to 17.3 fs rms in a bandwidth of 10 Hz to 1 MHz at the input of the REFM-OPT. This measurement was carried out in the accelerator tunnel with no significant contribution from the REFM-OPT when repeated at its output. This measurement shows the low phase noise RF reference signal provided by the RF-MO. It has been shown hereby that the performance of the RF reference signals in the accelerator tunnel fulfill the requirement for the accelerating field stability.

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