LASER-TO-RF SYNCHRONIZATION WITH FEMTOSECOND PRECISION

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Abstract

Optical synchronization systems are already in regular operation in many FELs, or they will eventually be implemented in the future. In FLASH and the European XFEL, phase-stable optical reference signals are provided by a pulsed optical synchronization system in order to achieve low timing jitter FEL performance. The generation of phase-stable RF signals from a pulsed optical synchronization system is still a field of active research. The optical reference module (REFM-OPT), designed at DESY for operation in both FELs, employs a laser-to-RF phase detector, based on an integrated Mach-Zehnder interferometer. The phase drift of the 1.3 GHz RF reference signals with respect to the optical pulses is measured and actively corrected within the REFM-OPT at multiple locations in the accelerator. Therefore the REFM-OPT provides phase stable 1.3 GHz RF reference signals at these locations. The short-term and long-term performance in the accelerator tunnel of the European XFEL is presented and carefully reviewed.

INTRODUCTION

Femtosecond stability has become a key requirement in modern large-scale free-electron lasers (FELs). Optical synchronization systems for femtosecond synchronization have been developed and built over the past years. The most recent application for such an optical synchronization system is the remote RF synchronization. RF reference signals are distributed and used as the phase reference for many accelerator sub-systems at the European XFEL and FLASH at DESY. Their performance requirements are driven by the low-level RF (LLRF) system, where the stability of the accelerating fields in the superconducting cavities depends on them. The field stability requirement of 0.01° at 1.3 GHz (or about 20 fs) leads to a stability requirement of the reference signals of about 10 fs [1].

An active system had to be implemented due to the size of the European XFEL and the number of devices connected. RF amplifiers are required to compensate cable losses.The phase stability of the RF reference signals is disturbed during their transport through the accelerator due to temperature and humidity induced drifts of the installed RF cables, amplifiers and auxiliary components. The 10 fs stability can therefore – especially in large scale FELs like the European XFEL – not be reached by conventional RF transport. The optical synchronization system however can supply laser pulse trains with femtosecond stability to any point in the accelerator. A Laser-to-RF phase detector within the REFM-OPT is used to measure the phase drift of the 1.3 GHz RF reference signals with respect to the optical reference at dedicated locations. These drifts are actively corrected and the REFM-OPT can therefore supply RF reference signals with femtosecond stability.

THE OPTICAL SYNCHRONIZATION SYSTEM

The central component of the optical synchronization system is the redundant master laser oscillator (MLO) which generates a low jitter, 216.66 MHz repetition rate optical pulse train at a wavelength of 1550 nm. It is tightly phase-locked to the RF master oscillator of the facility. The MLO is located in a central synchronization laboratory close to the injector laser. Environmental parameters like temperature and humidity are carefully controlled in this synchronization laboratory.

The laser pulses are subsequently distributed to individual link stabilization units (LSUs) from where the fiberlinks to the individual end stations launch. The fiberlink stabilization is based on balanced optical cross-correlation. The length changes of the optical fibers are compensated by a piezo driven fiber stretcher for fast changes and an optical delay line for slow long-term drift correction. Thirteen stabilized fiberlinks are currently in permanent operation at the European XFEL. More information on the optical synchronization system can be found in [2]. The optical synchronization system supplies reference signals to three different types of end stations.

The bunch arrival time monitors (BAMs) are used to measure the electron bunch arrival time with femtosecond precision at dedicated locations along the accelerator. A more detailed description of the BAM system can be found at [3]. A feedback system to the LLRF controllers allows to stabilize the electron bunch arrival time based on the BAM measurement.

Laser-to-Laser synchronization using balanced two-color optical cross-correlation is employed to synchronize laser systems along the FEL to the optical synchronization system. This is especially crucial for the pump-probe lasers which need to be tightly synchronized to the FEL but it is also foreseen for the injector lasers. Further details on Laser-to-Laser synchronization is available at [4].

The third and newest application is the Laser-to-RF synchronization. The key component of the REFM-OPT is the Laser-to-RF phase detector. It is based on a commercial integrated Mach-Zehnder modulator in which the phase dif-

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ference between the 1.3 GHz RF signal and the phase stable laser pulses from the optical synchronization system leads to a proportional amplitude modulation of the optical pulse train. The principle of the Laser-to-RF phase detector has been evaluated and analyzed in [5].

The REFM-OPT is an engineered and fully integrated, remote controllable 19" unit built to be operated directly in the accelerator tunnel. Requirements for the REFM-OPT were driven by the architecture of the RF distribution system. The REFM-OPT for example includes six RF outputs with an output power level of 21 dBm each, such that all local components of the LLRF system plus the neighboring stations can be connected without requiring any further external components. An overview over the internals of the REFM-OPT and its engineering has been published in [6].

THE RF REFERENCE DISTRIBUTION SYSTEM

The conventional RF distribution system of the European XFEL is based on heliax cables. It starts at the 1.3 GHz RF master oscillator (RF-MO) in the injector building. The layout is presented in Figure 1. The fiberlinks which provide the optical reference signals with femtosecond precision to the REFM-OPTs are shown in red.

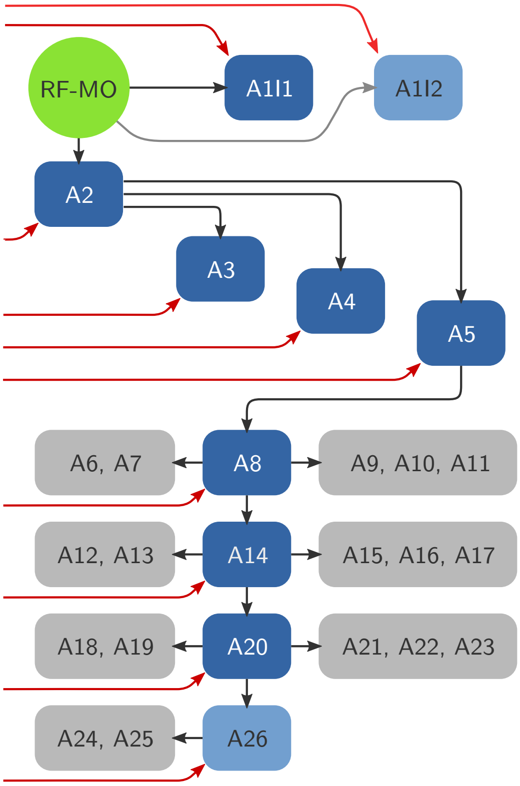

Figure 1: Layout of the RF reference distribution system including the optical reference signals (red). LLRF stations equipped with a REFM-OPT are presented in blue.

The RF distribution system is currently stabilized by a total of eight (final expansion stage is ten) REFM-OPTs within dedicated LLRF stations (printed in blue). Each REFM-OPT delivers femtosecond-stable RF signals to the connected systems. Every LLRF master station up to the third magnetic chicane, which is located downstream of the LLRF station A5, is equipped with a REFM-OPT. These are the LLRF stations with the most demanding phase stability requirements. Further downstream of the bunch compressor the stability requirements are relaxed such that a single REFM-OPT supplies up to six LLRF stations with a local subdistribution. LLRF stations without a REFM-OPT are printed in gray. As a future upgrade, it is planned to stabilize this subdistribution (up to 150 m of distance) with RF interferometers for residual cable drift suppression [7].

The injector LLRF system (A1I1) is connected directly to the RF-MO and also phase stabilized by a REFM-OPT. The second injector (A1I2) has not been built yet and the REFM-OPT at the LLRF station A26 has not been installed up to now (both shown in light blue).

MEASUREMENT DATA

Until now only the REFM-OPTs in the injector (A1I1) and at the LLRF stations A3, A4 and A8 have been operated permanently. The remaining stations have already been commissioned but not regularly operated because their Firmware can only be updated to the newest version after a cabling modification which requires hardware access. The tunnel positions of the operated stations are 247 m for A3 and 295 m for A4. The station A8 is located at 611 m. The phase-locked-loops (PLL) within the REFM-OPTs have been established with a bandwidth of a few hundred Hz in order to correct slow drifts of the 1.3 GHz RF reference signals.

The measurement presented in Figure 2 has been started at the end of a maintenance day and it lasts one week. The bottom plot shows temperatures which were measured within the accelerator tunnel. The tunnel heats up after operation has been resumed. The LLRF stations A3 and A4 are located in the L2 area while the station A8 is located in the L3 area. The RF cables from the RF-MO are guided two stories down through media shafts and along the accelerator tunnel from L1 over L2 to L3. The peak-to-peak RF phase drift which was corrected at the station A8 amounts to 14.2 ps. The plot shows that the majority of the corrected phase drift of all three stations is common mode which indicates that it is induced already upstream of A3.

The largest temperature change after the maintenance occurs during the first 3 days. The temperature variations afterwards are much smaller. The peak-to-peak corrected phase change at A8 from day four to the end of the measurement amounts for example only to 2.9 ps while the stations A3 corrects in this time period already 2.2 ps of peak-to-peak phase drifts. The peak-to-peak temperature variation in this time in L2 is 0.26 °C while the temperature in L3 only varies about 0.18 °C. It is only an approximation to correlate single point temperature measurements with the phase drifts of the long RF connections. One can however estimate that even during the last four days of the measurement about 1 ps of

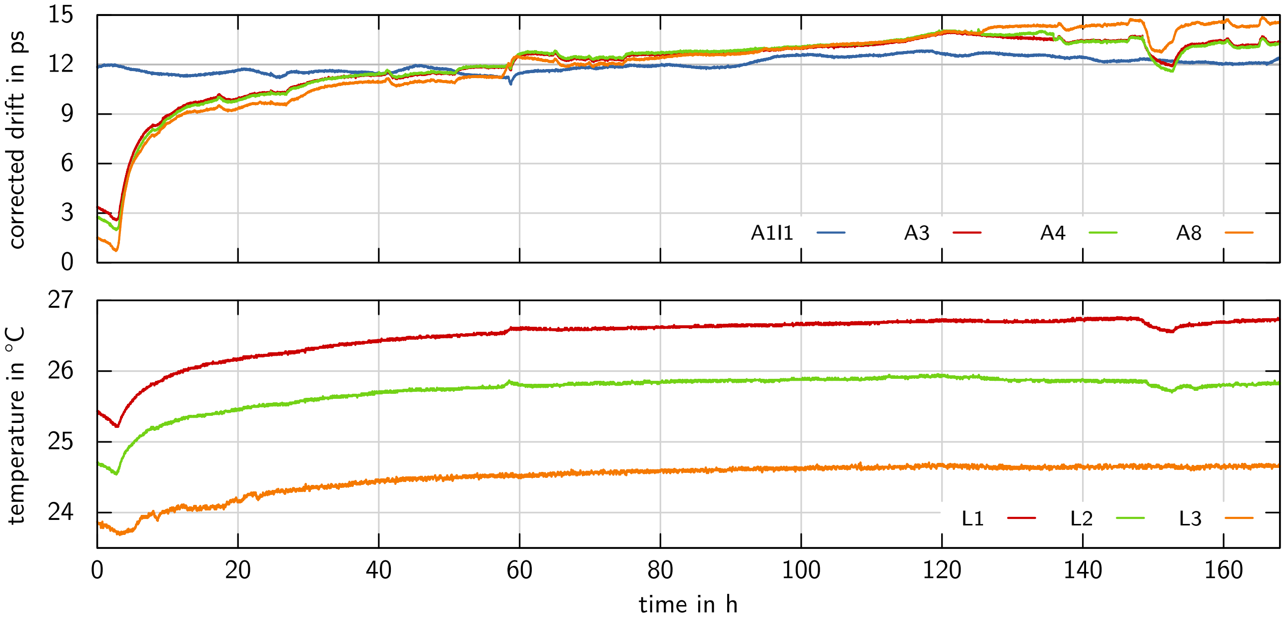

Figure 2: Cable drifts corrected by REFM-OPTs during regular FEL operation following a maintenance day. The remaining in-loop jitter amounts to 9.5 fs (1 Hz to 125 kHz).

common mode phase drifts might not have originated in the tunnel but elsewhere in the injector building.

The next REFM-OPT to be permanently operated is therefore the REFM-OPT at A2 in order to prove the above assumptions. The LLRF station A2 is located at 131 m. It should be possible to correct most of the phase drifts from Figure 2 at this station such that the consecutive REFM-OPTs see greatly reduced phase drifts.

The injector (A1I1) is connected by a dedicated cable directly from the RF-MO. It is shorter and guided through a different area. The peak-to-peak corrected phase drift at the REFM-OPT at A1I1 amounts to 2.1 ps. This is in the same order as the phase drifts in the accelerator tunnel - if one disregards the heat up after the maintenance day which is not applicable for the injector.

The short-term performance of the REFM-OPT at A3 is presented in Figure 3. Within the locking bandwidth of about 200 Hz the integrated detector noise floor amounts to 55 as while the in-loop jitter is 1 fs. There is still a large jitter contribution visible in the noise bump around 7 kHz which originates from the RF power-amplifier in the RF-MO and is outside the locking bandwidth of the REFM-OPT. This amplifier is about to be exchanged which should improve the performance of the 1.3 GHz RF reference signals by at least a few femtoseconds.

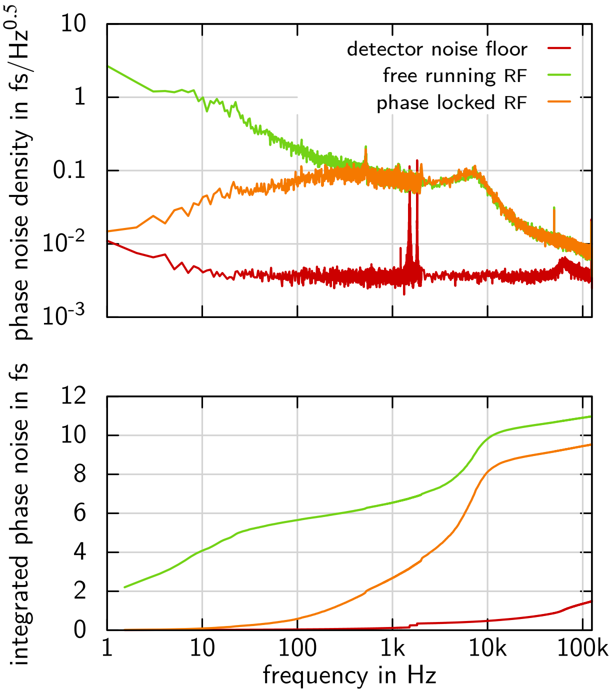

Figure 3: Short term performance of the REFM-OPT at A3.

CONCLUSION

The quality of the RF reference signals throughout the facility can now be analyzed and monitored online with femtosecond precision through the REFM-OPT. Without the REFM-OPT the RF reference phase stability at the European XFEL would be in the order of a few ps peak-to-peak during normal operation and more than 10 ps peak-to-peak after maintenance days. With the REFM-OPT in operation, the phase drifts are corrected and the residual phase jitter of the 1.3 GHz RF in a bandwidth from 1 Hz to 125 kHz amounts to 9.5 fs. The specification of 10 fs phase stability is therefore fulfilled.

The next crucial step is to finally establish permanent operation of all installed REFM-OPTs and to further improve their performance.

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