

# DESIGN AND OPERATION OF THE INTEGRATED 1.3 GHz OPTICAL REFERENCE MODULE WITH FEMTOSECOND PRECISION

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## Abstract

In modern Free-Electron Lasers like FLASH or the European XFEL, the short and long-term stability of RF reference signals gains in importance. The requirements are driven by the demand for short FEL pulses and low-jitter FEL operation. In previous publications, a novel, integrated Mach-Zehnder Interferometer based scheme for a phase detector between the optical and the electrical domain was presented and evaluated. This Laser-to-RF phase detector is the key component of the integrated 1.3 GHz Optical Reference Module (REFM-OPT) for FLASH and the European XFEL. The REFM-OPT will phase-stabilize 1.3 GHz RF reference signals to the pulsed optical synchronization systems in these accelerators. Design choices in the final hardware configuration are presented together with measurement results and a performance evaluation from the first operation period in the European XFEL.

## INTRODUCTION

A key technology to achieve femtosecond stability in large scale free-electron lasers (FELs) is the generation and supply of femtosecond stable radio frequency (RF) reference signals along the accelerator. The field stability in the accelerating modules and therefore also the stability and accuracy of the low-level RF (LLRF) system and its reference signals have a significant influence on the energy stability and thereby also on the electron bunch arrival time stability [1].

Conventional RF transport suffers from temperature and humidity induced cable length drifts which easily exceed the envisioned femtosecond stability. Different methods for a phase stable RF distribution system have been evaluated at DESY in the past but did not provide the desired stability [2]. In the newly built European X-ray Free-Electron Laser (XFEL), the phase of the RF reference signals will therefore be measured and corrected with respect to the pulsed optical synchronization system [3] in the so-called optical reference module (REFM-OPT).

The master laser oscillator (MLO) of the optical synchronization system provides an optical pulse train with 4.1 fs timing jitter in the frequency range of 1 kHz to 1 MHz [4]. The laser pulses are distributed by fiberlinks to various end stations throughout the accelerator. The fiberlinks are actively stabilized in order to compensate length changes of the transport fibers and to provide the desired femtosecond stable laser pulses at each end station – like for example the REFM-OPT [3].

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## THE REFM-OPT

The REFM-OPT is the interface between the pulsed optical synchronization system and the RF reference distribution system. It is an engineered and fully integrated, remote controllable 19" unit. At the European XFEL for example the REFM-OPT is installed within the LLRF racks in the accelerator tunnel. A total of ten REFM-OPTs are foreseen for the European XFEL of which seven have already been commissioned. The internal components of the REFM-OPT will be briefly presented in the following sections.

### *The Laser-to-RF Phase Detector*

The central component of the REFM-OPT is the laser-to-RF (L2RF) phase detector, which has been invented at DESY and presented for the first time in [5]. The whole L2RF scheme has been mathematically analyzed and proven to be robust and insensitive to multiple typical error sources like bias voltage drifts and optical power variations [2].

The L2RF phase detector consist of an integrated read-out unit and an optical setup with both free-space and fiber components. The optical setup is based on a custom aluminum baseplate. The baseplate itself is temperature stabilized by Peltier elements while its housing is thermally isolated and sealed against humidity variations. A commercial temperature controller is used to actively stabilize the temperature of the baseplate.

The stabilized fiberlink ends directly on the optical base plate. The temperature and humidity stabilization are required in order to prevent environmentally induced drifts between the end of the stabilized fiberlink and the fiber-coupled Mach-Zehnder modulator (MZM) in which the phase measurement between the RF and the optical reference signal takes place. Details concerning the engineering of the optical baseplate can be found in [2]. A photo of the final version of the optical baseplate is depicted in Figure 1. The optical unit is mounted on vibration damping rubber bumpers within the 19" REFM-OPT and occupies about half of the available space.

The relative phase between the RF signal and the laser pulse train is encoded in an amplitude modulation of the optical pulse train. This allows the detection and readout of the relative phase between both signals with conventional photodiodes without the usual performance degradation due to AM/PM effects of which direct phase measurements suffer [6]. The complete readout chain including the photodiodes has been implemented in the custom L2RF readout electronics. The L2RF readout electronics is fully remote



Figure 1: Final REFM-OPT module. On the right hand side the open optical compartment with free-space and fiber optics is visible. On the left hand side the TMCB is mounted on the frontpanel. The outputs from the RF splitter can be found below. The blue part of the front panel features the management and control unit FRED. The L2RF readout electronics, the REACT and the REFMPMS are stacked in the rear.

controllable and provides error signals for the phase and bias voltage control loops [7].

### *The REFM-OPT 1.3 GHz Actuator*

The REFM-OPT 1.3 GHz actuator (REACT) is the RF unit within the REFM-OPT. It contains a tunable attenuator used to actively stabilize the RF output power and a phase shifter used to feed back the 1.3 GHz phase in a phase-locked loop (PLL). The REACT also contains RF amplifiers, which are required to supply the specified RF output power of 21 dBm at all six RF outputs of the REFM-OPT. The REACT additionally features monitoring ports for the input and output RF power. Directional couplers are used for this purpose which also deliver signals to the module front panel for in situ phase noise measurements and to the internal machine protection module (REFMPMS).

The stability and integrity of the 1.3 GHz RF reference signal is crucial for the accelerator operation. The REFM-OPT therefore includes an internal supervision circuit (REFMPMS) which connects to the machine protection system (MPS). The output RF power is supervised together with the output phase stability. An error signal is sent out to the machine protection system in case an excessive output power drop of about 6 dB or a phase jump of about 5.3 ps/10s (hardware configurable) occur.

The output signal of the REACT is connected to a six-way custom made RF splitter<sup>1</sup> which is mounted directly to the front panel of the 19" REFM-OPT. It is a teflon free Wilkinson splitter which is sealed in order to be independent from environmental humidity changes. One splitter output is routed back into the 19" housing and fed through the MZM

in order to perform the phase measurement. Thereby, possible residual phase drifts of the RF splitter are detected and corrected by the active REFM-OPT phase stabilization. The relative stability between outputs is crucial for this kind of operation because only one output is actually stabilized. The splitter has therefore been carefully characterized and it has been verified that it meets the femtosecond requirements [8]. The internal RF cabling has been performed with phase stable Phasemaster 190E cables which are known to be robust against temperature and humidity variations.<sup>2</sup>

### *Management and Control*

The REFM-OPT is supplied by DC voltages from the 19" power supply module (PSM) which is used for all external units of the LLRF system. A power entry board called FRED has been developed at DESY for this purpose. It allows remote control over the REFM-OPT supply voltages. The FRED also includes fuses and allows to remotely monitor voltage and current consumption for all supply voltages.

The last component within the REFM-OPT is the TMCB which is the control system interface of the REFM-OPT. This is a DESY developed FPGA board with general purpose ADCs, DACs, GPIO and I<sup>2</sup>C interfaces. It gathers the monitoring data like temperatures, humidity, RF and optical powers, the status of the REFMPMS and it is used to implement the control loops for MZM bias voltage, RF power and RF phase. The data transmission and remote control are performed over Ethernet.

<sup>2</sup> Phasemaster 190E: measured 4.6 fs/m/%RH and 7 fs/(m K) at 1.3 GHz and 29 °C [2]

<sup>1</sup> MECA 806-4-1.500VWVWP-M01

## REFM-OPT PERFORMANCE

The performance of an installed REFM-OPT is presented in Figure 2. The detector noise floor (red curve) has been determined while the 1.3 GHz RF reference signal has been turned off. The measured voltage noise from the detector has been converted to its equivalent in fs using the previously determined calibration constant  $K_\phi$  of  $2.04 \text{ V ps}^{-1}$ . The integrated detector noise, which presents the achievable detection accuracy in the presented frequency range, amounts to 1.4 fs in a bandwidth of 1 Hz to 125 kHz.

The data has been read out remotely via Ethernet from the TMCB. The ADC sampling rate is  $250 \text{ kS s}^{-1}$ . The presented curves have been obtained in two steps. Above a frequency of 2 kHz the fast Fourier transform (FFT) of the raw data is presented. Below 2 kHz the sampling rate has been decimated by a factor of six such that a continuous readout of the ADC data is available. Obtaining 1 s of data allows the FFT to resolve frequencies down to 1 Hz.

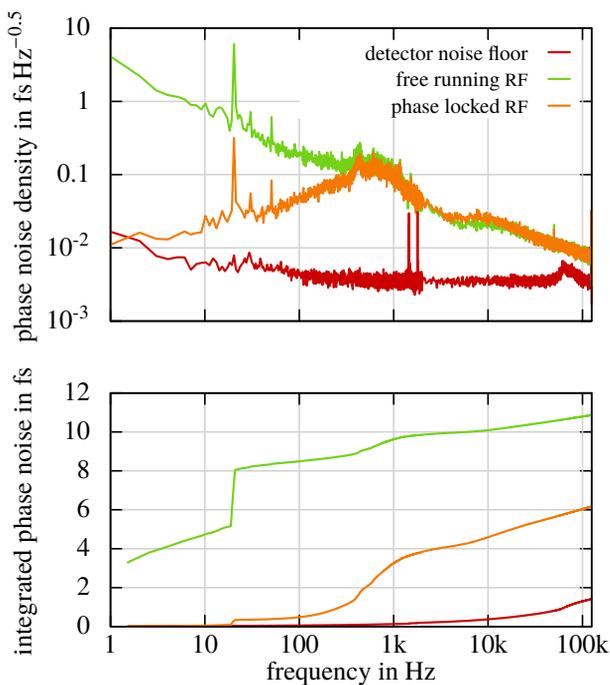


Figure 2: Short term performance of a REFM-OPT measured directly in the accelerator tunnel.

After switching back on the RF (green curve) the jitter between the reference pulse train from the optical fiberlink and the 1.3 GHz RF signal is measured. The relative integrated jitter amounts to 10.8 fs between 1 Hz and 125 kHz. The spurious signal at 20 Hz is currently under investigation. The two bumps around 1 kHz and 10 kHz originate from the MLO and the RF MO. Details can be found in [4].

The orange curve shows the situation after the feedback has been closed. The RF is now phase-locked to the optical reference. Drifts and low frequency jitter are corrected. The integrated jitter drops to 6.2 fs in-loop. The locking bandwidth has been set such that the noise bump around 1 kHz is not fed back onto the RF.

## CONCLUSION AND OUTLOOK

For the first time, the newly invented L2RF phase detector has been implemented in a particle accelerator. The laboratory prototypes have successfully evolved into an integrated device. Many details like the humidity and temperature sensitivity of the used components have been carefully taken into account during the engineering of the REFM-OPT in order to achieve the envisioned performance. Only a few off the shelf commercial components could be used while the presented subcomponents needed to be custom made in order to meet the stability requirements and to fit into the limited available space.

The commissioning of seven REFM-OPTs is a huge milestone towards the required 1.3 GHz RF reference phase stability. The REFM-OPTs serve as femtosecond stable phase reference but also present highly sensitive phase detectors directly in the accelerator tunnel which allow to measure and monitor the RF quality and performance during accelerator operation on a femtosecond level.

The detector accuracy of 1.4 fs and the short term performance of 6.2 fs (both in a bandwidth of 1 Hz to 125 kHz) have been successfully proven in this paper.

As a next step the spurious signals which are still visible in the measured data need to be investigated and the long-term drift stability in the accelerator tunnel will be verified.

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