REFERENCE DISTRIBUTION AND SYNCHRONIZATION SYSTEM FOR SwissFEL: CONCEPT AND FIRST RESULTS

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Abstract

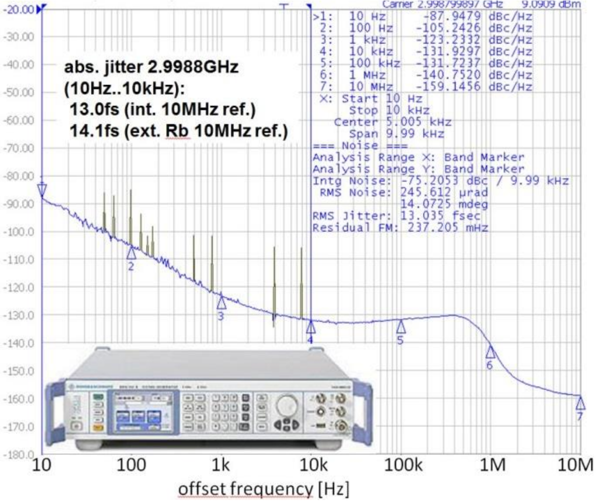
The development of the SwissFEL [1] reference distribution and synchronization system is driven by demanding stability specs of LLRF-, beam arrival time monitors (BAM) and laser systems on one and cost issues, high reliability/availability and flexibility on the other hand. Key requirements for the reference signals are $<10fs_{rms}$ jitter well as down to $10fs_{pp}$ temporal drift stability (goal) for the most critical clients (BAM, pulsed lasers). The system essentially consists of a phase locked optical master oscillator (OMO) with an optical power amplifier/splitter, from which mutually phase locked optical reference pulses as well as RF reference signals are derived. Optical pulses will be transmitted to pulsed laser and BAM clients over stabilized fiber-optic links whereas the RF signals are transmitted over newly developed stabilized cw fiber-optic links. Both s- and c-band reference signals use s-band links, whereupon the C band receiver incorporates an additional ultra-low jitter/drift frequency doubler. Furthermore, ultra-low noise analog laser PLLs have been built. We are presenting concepts and first results of sub-$10fs_{rms}$ jitter and $20fs_{pp}$ long term drift cw links, tested in the SwissFEL Injector Test Facility (SITF).

REFERENCE DISTRIBUTION CONCEPT

Generation of Mutually Stable Reference Signals

High mutual short as well as long-term stability is required between all clients of the reference distribution system. On the other hand the SwissFEL RF system uses three different RF frequencies ($f_{s\ band}$ = 2998.800MHz, $f_{C\ band}$ = 5712.000MHz and $f_{X\ band}$ = 11'995.200MHz = 4x2998.800MHz). The S and X band frequencies are very close to the European standards, whereas 5712.000MHz is a US C band frequency. $f_{C\ band} \neq 2xf_{S\ band}$, which complicates fs-stable electrical reference generation, i.e. mutual stability between C band, S band, X band and various pulsed lasers and BAMs. The European standard S band frequency has been slightly detuned to the above mentioned value in order to find an as high as possible common subharmonic base frequency (f_b = 142.800MHz).

The idea of the SwissFEL reference system is to start with this base frequency and derive laser reference pulses as well as RF reference frequencies from it. It has been shown that a mode locked laser OMO (f_{rep} = f_b = 142.800MHz), synchronized to a stable microwave source, can provide reference signals with extremely high temporal stability, pulses as well as RF harmonics, where the latter can be extracted from the OMO's pulse train (Fig. 2) or are delivered by a microwave oscillator synchronized to the latter [2]. Carefully deriving all reference signals from the OMO laser pulses yields high mutual stability.



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 2:  100 Hz    -105.2426 dBc/Hz
 3:  1 kHz     -123.2332 dBc/Hz
 4:  10 kHz    -131.9297 dBc/Hz
 5:  100 kHz   -131.7237 dBc/Hz
 6:  1 MHz     -140.7520 dBc/Hz
 7:  10 MHz    -159.1456 dBc/Hz
 X: Start 10 Hz
     Stop 10 kHz
   Center 5.005 kHz
     Span 9.99 kHz
=== Noise ===
Analysis Range X: Band Marker
Analysis Range Y: Band Marker
Intg Noise: -75.2053 dBc / 9.99 kHz
 RMS Noise: 245.612 µrad
            14.0725 mdeg
RMS Jitter: 13.035 fsec
Residual FM: 237.205 mHz
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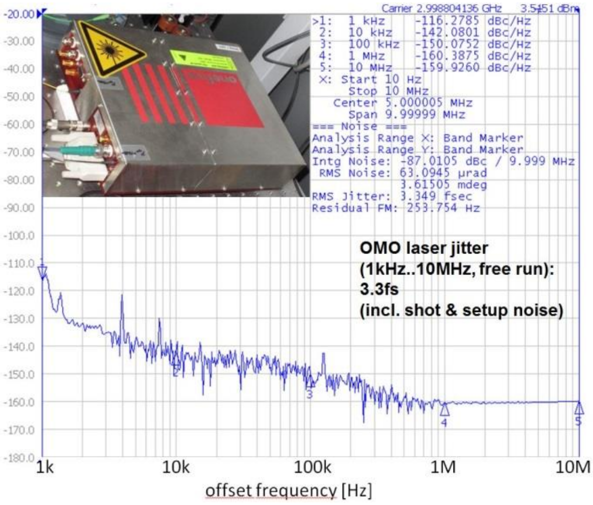
Figure 1: Measured phase noise spectrum timing jitter of the SwissFEL RF MO (Rohde + Schwarz SMA 100A.) Locking with a 10MHz Rb frequency standard (SRS FS725) slightly increases jitter from 13.0 fs to 14.1fs.



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 2:  10 kHz    -142.0801 dBc/Hz
 3:  100 kHz   -150.0752 dBc/Hz
 4:  1 MHz     -160.3875 dBc/Hz
 5:  10 MHz    -159.9260 dBc/Hz
 X: Start 10 Hz
     Stop 10 MHz
   Center 5.000005 MHz
     Span 9.99999 MHz
=== Noise ===
Analysis Range X: Band Marker
Analysis Range Y: Band Marker
Intg Noise: -87.0105 dBc / 9.999 MHz
 RMS Noise: 63.0945 µrad
            3.61505 mdeg
RMS Jitter: 3.349 fsec
Residual FM: 253.754 Hz
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Figure 2: Measured phase noise spectrum and timing jitter of the free running SwissFEL OMO laser (Onefive Origami 15, 1560nm, 142.8MHz repetition rate; Discovery DSC50 photodiode).

Figure 3 shows a schematic overview of the system. The OMO laser is locked on the 10th harmonic to the RF master oscillator (RF MO, Fig. 1), which is itself locked

ISBN 978-3-95450-141-0

to a 10MHz Rb standard to achieve high long-term frequency stability. Phase noise spectrum and jitter of the 21^{st} harmonic of the free running OMO (1kHz … 10MHz) are given in Fig. 2. It confirms that extremely clean RF signals can be derived by extracting harmonics using direct photodetection from the laser pulse train. Potential phase drifts due to amplitude variations can be supressed using a voltage variable optical attenuator with constant optical path length and a control loop keeping the photocurrent constant.

For the RF reference distribution 4 RF frequencies are required: $f_{S\ band}$ = 2998.800MHz, $f_{C\ band}$ = 5712.000MHz, $f_{X\ band}$ - $f_{S\ band}$ = 8996.400MHz (for LLRF X band downconverter LO), $f_{X\ band}$ = 11'995.200MHz. $f_{S\ band}$ and ½$f_{C\ band}$ = are extracted and transmitted via group delay stabilized radio-over-fiber links described below. C band signals require subsequent frequency doubling. SwissFEL requires 6 S band and 27 C band links. X band reference, X band downconverter LO and an S band reference signal, all required by the X band LLRF system are extracted from the photodetected pulse train of a stabilized pulsed link in the X band LLRF station. Alternatively the extracted harmonics could be used to lock low noise floor VCOs or a balanced optical to microwave phase detector based PLLs, fed directly with the optical pulses as reference, could lock VCOs [2].

A 142.8MHz reference signal is also extracted for the BPM reference distribution. The latter is based on a non-phase-stabilized low cost fiber-optic links with coaxial sub-distribution inside the accelerator tunnel.

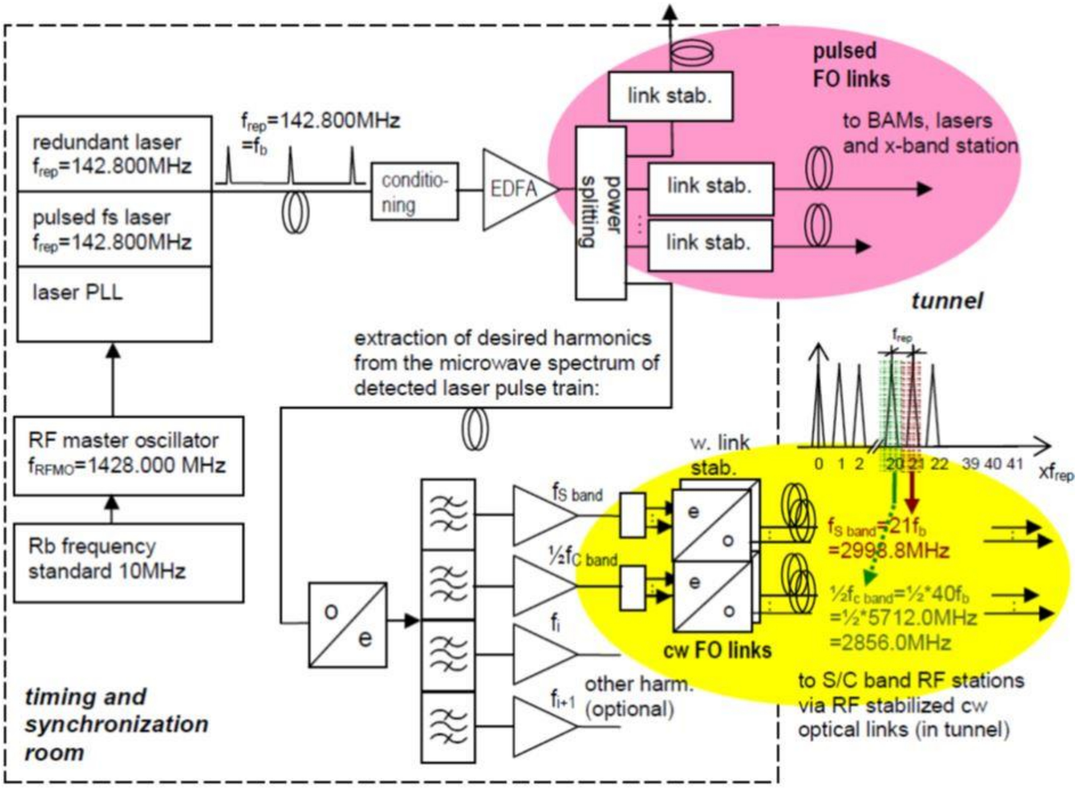

Figure 3: Concept of the SwissFEL reference generation, distribution and synchronization system.

CW FIBER-OPTIC LINKS FOR RF REFERENCE DISTRIBUTION

In the past, basically two approaches have been presented to achieve fs-stability in the distribution of reference signals: 1) Transmission of mode-locked fs-laser pulses and group delay stabilization by means of a balanced optical cross-correlator (BOC) [3]. 2) Intensity modulation and optical phase stabilization [4]. Both technologies potentially yield extremely high long-term timing stability (<10fs_{pp}/d) for link length up to 1km or even more. Particularly 1) has been optimized, ruggedized and even commercialized [5] over the last years. This type of link transmits laser pulses, but not RF signals, which makes it - together with its exceptional short and long term stability - the first choice for direct optical synchronization of stability-critical pulsed lasers, to derive stable RF signals from the pulses, requires additional effort. Drawbacks of this link type are that it requires relatively complicated optics, components that are expensive and operated in modes for which they were not manufactured and qualified and for many critical components no second source exists. Running the system reliably requires qualified personnel. Moreover the fibers need careful dispersion compensation and the system is rather sensitive. Using group delay stabilized radio-over-fiber links (RF input, RF output) was considered to be a straight forward and promising approach to distribute RF

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ISBN 978-3-95450-141-0

reference signals. The basic technology has already been established for decades [6] and high quality reliable cots components designed for telecom and sensing applications are available from various suppliers at reasonable cost.

Group Delay Stabilized Radio-Over-Fiber Links

A radio-over-fiber type fiber-optic link, named “Libera Sync 3” has been developed in collaboration between PSI and Instrumentation Technologies d.d. The idea was to develop a fiber-optic link, based on classical intensity modulation of (cw) telecom laser diode light (“cw link”) but with additional group delay stabilization. It is conceptually based on the detection of the RF phase between the transmitter input signal and the photo-detected light reflected at the link end. . The operating frequency for the first prototype is 2998.8MHz (SwissFEL S band frequency).

Even in a carefully designed bi-directional fiber-optic link Rayleigh scattering [7] causes a weak noise floor (uncritical in telecom applications), significantly increasing the jitter in the received signal, still at 1550nm wavelength. Therefore the system incorporates two distinct fibers. One fiber is operated in a bi-directional mode providing a stable medium … long term (>seconds) phase, whereas the other is uni-directional. RF phase detectors are also key components, the performance of which has been optimized by taking care of high symmetry and temperature stabilization. As opposed to pulsed optical links phase noise and drift due to AM-PM conversion in the photodetector can be eliminated in RF intensity modulated cw light by operating it at an optimum photocurrent, as many photodiodes exhibit sweet spots in the phase-vs.-photocurrent characteristic for this type of modulation. An optimized prototype of the Libera Sync 3 has been tested recently at PSI and results are presented here. Details on the system architecture can be found in [8,9,10]. Transmitter (TX) and receiver (RX) units are in compact 19”/2HU housings and can be remote controlled and monitored via Ethernet (Fig. 1). After installation, the units can be tuned-on and the link automatically phase-locks after a warm-up phase of <2h.

Figure 4: Libera Sync 3 cw fiber-optic link receiver (top) and transmitter (bottom).

The TX Input power level is +15dBm. The RX has two outputs with +15dBm each and a tapped output for testing.

Libera Sync 3 Prototype Measurement Results

Measurements of phase noise, timing jitter, long term timing drift and link gain drift have been made. Two 453m (max. SwissFEL RF reference link span is ≈500m) long meandering fiber loops installed on a cable tray have been spliced in the 65m long SITF tunnel to establish a realistic environment for the tests. TX and RX units were located in the SITF gun laser hutch, which is temperature and relative humidity controlled (typ. ±<0.25°C, ±<1%RH) and was usually rather crowded during all tests. The tunnel temperature is stabilized during operation but not its relative humidity.

The phase noise/jitter contribution of the link was measured by tapping part of the reference signal that feeds the TX input and mixing it in quadrature with the RX output. This relative phase noise measurement carries the risk of adding phase noise from the reference source at offset frequencies >10kHz, as the output noise higher spectral components’ correlation decreases after transmission over a certain distance. Therefore a Poseidon/Raytheon DRO with a low noise floor of -170dBc/Hz has been chosen as reference source to reduce this overestimation of phase noise.

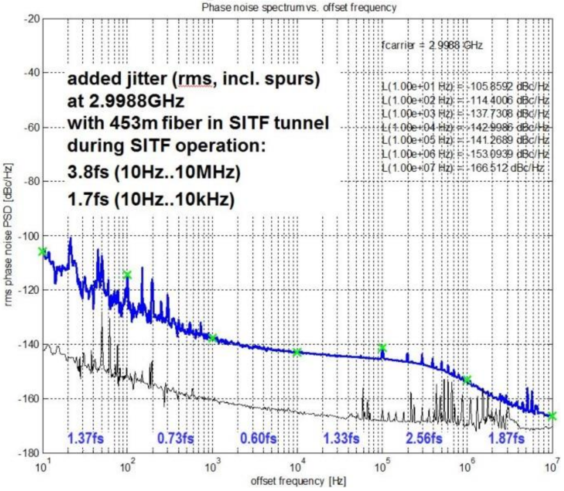

Figure 5: Libera Sync 3 measured phase noise and jitter at 2998.8MHz. Thin black curve: setup noise limit (mixer Pulsar ML-04-LC, SSA Agilent E5052B baseband).

Fig. 5 shows the measured phase noise and jitter as well as the jitter values for each decade between 10Hz and 10MHz. The added jitter of 3.8fs$_{rms}$ (10Hz … 10MHz) or 1.7fs$_{rms}$ in a smaller range relevant for many reference signals (10Hz … 10kHz) for this S band fiber-optic link in a realistic accelerator environment is below the envisaged ≈7fs$_{rms}$.

The link phase and gain drift measurement setup is shown in Fig. 6. The phase/gain detector is based on the well-known Analog Devices AD8302, which incorporates a Gilbert cell mixer and input log amps. With additional temperature stabilization this integrated detector is

ISBN 978-3-95450-141-0

extremely stable (given there are no significant differential input signal variations) as shown in Fig. 7. The cabling for this measurement has been laid out as symmetric as possible using low temperature drift RF cables (Micro Coax UT-85C-FORM). Two dummy couplers have been added to optimize cabling symmetry.

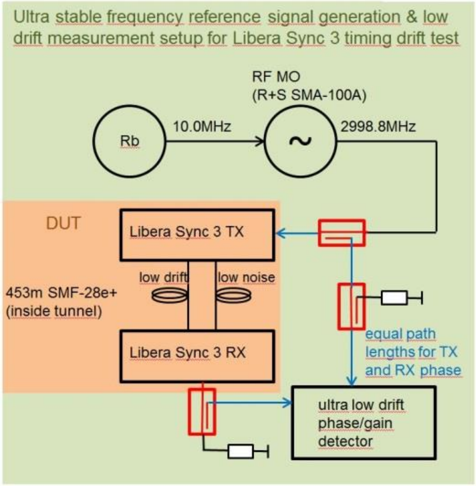

Figure 6: Setup for the link phase and gain drift measurements.

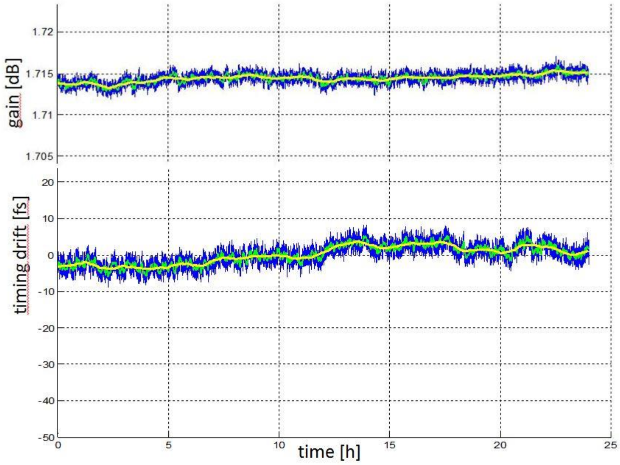

Figure 7: Phase/gain det. drift over 24h (f=2998.8MHz): Gain det. (top), phase det. (bottom). Blue: raw (2.2s sampling period); grn.: 2.2min avg.; yellow: 1h avg. Timing/gain drift:11.4fs$_{pp}$/0.003dB$_{pp}$ (2.2min avg.), 7.6fs$_{pp}$/0.002dB$_{pp}$ (1h avg.).

The reference source is the SwissFEL RF MO SMA 100A (Fig. 2), locked to a Rb standard. TX and RX units, reference source and phase detector were installed in a vibration damped rack, the front of which was partly covered to shield it from direct air flow and exposure to lamps that are frequently turned on and off.

Two typical link phase and gain drift measurements for relatively stable environmental conditions and crowded hutch during the measurement periods are shown in Figs. 8 and 9. RH in the tunnel is varying by 11.5% (Fig. 8)/9% (Fig. 9) and the temperature by about 0.4°C (Figs. 8 and 9). The measured drifts are well within the spec (<a few tens of fs$_{pp}$/d and <0.05dB$_{pp}$/d).

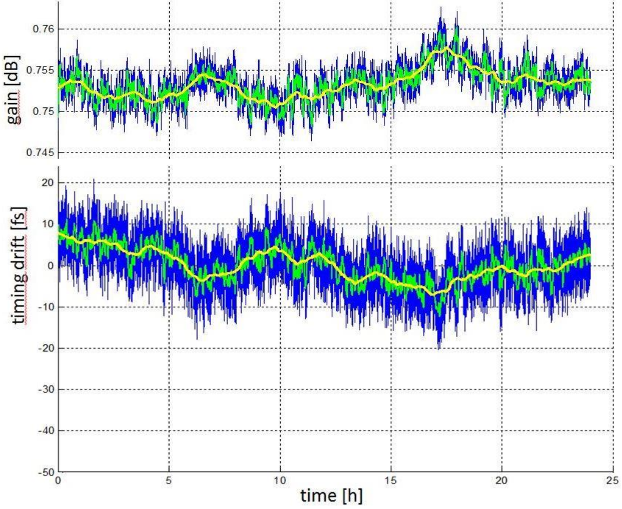

Figure 8: Libera Sync 3 phase/gain drift over 24h (453m link in SITF tunnel, f=2998.8MHz): Gain det. (top), phase det. (bottom). Blue: raw (2.2s s.p.); grn.: 2.2min avg.; yellow: 1h avg. Timing/gain drift: 23.7fs$_{pp}$/0.012dB$_{pp}$ (2.2min avg.), 15.0fs$_{pp}$/0.007dB$_{pp}$ (1h avg.).

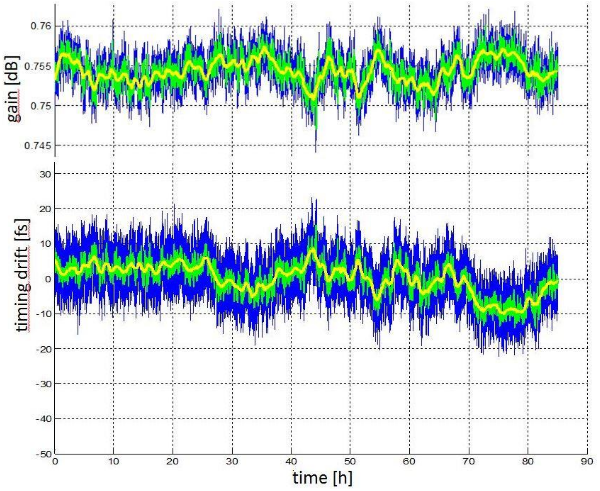

Figure 9: Libera Sync 3 phase/gain drift over 85h (453m link in SITF tunnel, f=2998.8MHz): Gain det. (top), phase det. (bottom). Blue: raw (2.2s s.p.); grn.: 2.2min avg.; yellow: 1h avg. Timing/gain drift: 29.5fs$_{pp}$/0.013dB$_{pp}$ (2.2min avg.), 18.6fs$_{pp}$/0.007dB$_{pp}$ (1h avg.).

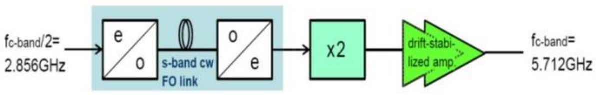

Figure 10: C band reference distribution using S band cw radio-over-fiber link Libera Sync 3.

Using Libera Sync 3 for C Band Reference Signal Distribution

Apart from S band also C band reference signals have to be distributed (SwissFEL LINAC). The optics of the Libera Sync 3 system is designed for S and C band frequencies f>6GHz but the RF part would require a new design for direct C band transmission. As the long term stability requirements for the C band reference signals are somewhat relaxed in case of SwissFEL, we decided to use the S band link also for the C band reference signals but to transmit $f_{C\ band}/2$ = 2856.000MHz and use a stable RF frequency doubler and a drift stabilized amplifier at the end of the link (Fig. 7). Measurements have shown that low noise Schottky diode 3GHz→6GHz frequency doublers do not add measurable jitter to an ultra-low noise 3GHz signal as provided at the Libera Sync 3 RX output. Furthermore this type of switched frequency doubler is potentially relatively immune to AM-PM conversion (timing drift due to input amplitude variations, which are very low anyway with stabilized links) [11]. A frequency doubler/amplifier is currently under development at PSI.

PULSED OPTICAL LINKS

Some clients that require ultimate long term stability (<10fs_{pp}) will finally be fed with pulsed optical reference signals (SwissFEL phase 1: 4 BAMs, experiment and gun lasers, X band RF). Therefore 7 stabilized pulsed optical links will be installed as well. As this technology is commercially available today, the pulsed optical links including the optical pulse power amplifier/splitter system will be purchased from a commercial vendor.

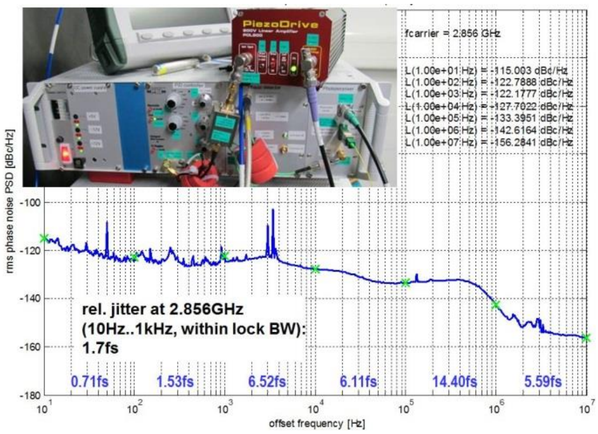

Figure 11: Relative phase noise/jitter of Onefive Origami 15 OMO, locked to a R+S SMA 100A with the analog PSI laser PLL vs. frequency doubled RF MO reference signal ($2xf_{ref\ RF,MO}$=1428MHz).

PULSED LASER SYNCHRONIZATION

The relative phase noise of the locked Origami 15 OMO (142.8MHz rep rate) is shown in Fig. 11. The reference signal is at 1428MHz (10x rep rate) from an SMA 100A and the relative phase noise is measured at the 20th harmonic vs. the frequency doubled reference signal. The analog ultra-low noise PLL locks a laser harmonic to an RF reference. The measurement shows that very tight lock is possible up to a few kHz. Above the loop bandwidth of few kHz the phase noise of the SMA 100A reference source dominates in this relative measurement. Vector modulator based superperiod lock and coarse frequency tuning are controlled via the EPICS control system. A versatile digital PLL incorporating these functionalities and sequentially locking the laser to superperiod, RF and optical pulses (BOC) is currently under development.

CONCLUSION

We have presented the core of the planned SwissFEL reference generation, distribution and synchronization system which provides high mutual phase and amplitude stability for all RF and optical reference signals. Test results for a radio-over-fiber link prototype (<4fs_{rms} jitter, <20fs_{pp} w. 1h avg. phase drift over 85h) as well as for RF MO (14fs_{rms} abs. jitter) and OMO harmonic (3.3fs_{rms} free run abs. jitter 1kHz..10MHz) have been reported.

ACKNOWLEDGMENT

Support by the SwissFEL project and discussions with colleagues from PSI, Elettra, Desy, PAL-FEL and SLAC (diagnostics, T&S, LLRF) are gratefully acknowledged.

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