# PROGRESS TOWARDS A PERMANENT OPTICAL SYNCHRONIZATION INFRASTRUCTURE AT FLASH

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*Abstract*

The optical synchronization system at FLASH has recently progressed from a bread-board/test-bench implementation to a more permanent engineered infrastructure. We report on the master laser oscillator, its lock to the master RF oscillator, the free-space pulse train distribution unit, the commissioning of the stabilized fiber links, bunch arrival-time monitors, an optical cross-correlator and the controls development. We also discuss a couple of design issues we identified while commissioning the devices.

## INTRODUCTION AND MOTIVATION

Free-electron lasers like FLASH and the planned European XFEL generate X-ray light pulses with durations in the order of a few 10 fs. For these next-generation light sources, an optical synchronization system has been proposed [1, 2] to enable time-resolved measurements with sub-10 fs resolution and the laser-driven seeded operation mode of the FEL. The system is based on the timing-stabilized distribution of an optical pulse train, from which RF signals can be generated or to which other laser systems can be synchronized. Furthermore, it facilitates several special diagnostic measurements on the sub-10 fs timescale.

Several proof-of-principle measurements and experiments have been carried out to further the development of the optical synchronization system. Their results were promising – like the construction of low-jitter fiber lasers, the fiber link stabilization, bunch arrival-time correlation measurements and even intra-bunch train arrival-time stabilization. All these experiments relied on their own, mainly breadboard, setups and required special knowledge to make them work – in some cases only for just a few days.

The challenge now is to expand the system and implement it in a low-maintenance and operator-friendly way, not only to provide standard diagnostic methods, but also to synchronize the pump-probe laser to the electron beam with a timing jitter of below 30 fs for user experiments. This requires a concert of highly integrated electronics, software and mechanically engineered optical devices.

## LAYOUT OF THE OPTICAL SYNCHRONIZATION SYSTEM AT FLASH

Figure 1 is a sketch of the overall design of the optical synchronization system and its location in the FLASH accelerator facility. Components depicted in color represent the devices which are currently operational, including two master laser oscillators, four stabilized fiber links, three bunch arrival-time monitors, a large horizontal aperture beam position monitor and two optical cross-correlators. The components shown in light gray will be installed in the future – most of them during the 6-month shutdown of FLASH beginning this year.

The master lasers and the free-space and fiber distribution are located in a temperature stabilized and EMI-shielded hutch inside the main accelerator building in the vicinity of the photo-injector laser [3]. The optical components are installed on a completely covered optical table to minimize temperature fluctuations and influences of air-flow. The base of the table is decoupled from the accelerator hall ground to reduce vibrational effects, e.g. from the klystrons. A lot of effort has been put into the proper installation of approximately 280 cables from the optical table to four racks containing the control electronics. Optical fibers with up to 300 m length have been installed to connect various locations in the linac tunnel and external laboratories.

## MASTER LASER OSCILLATOR

The timing reference for the optical synchronization system is a mode-locked erbium-doped soliton fiber laser (see e.g. [4]) with a repetition rate of 216.67 MHz which is the 6th sub-harmonic of the accelerator's reference frequency of 1.3 GHz. Two redundant lasers with integrated diagnostics are planned to minimize the downtime in case of one laser fails. Two identical lasers had been engineered and constructed, but during their assembly it became apparent that especially the optics could not be suitably aligned, preventing the operation of these lasers. As a fallback solution, we recommissioned a breadboard/experimental laser which was used for previous experiments [4]. However, due to several transports this laser could not be operated in its original state. It was running in a double-pulse regime for a long time, which was very challenging to detect with either a 8 GHz oscilloscope, an RF spectrum analyzer nor with an auto-correlator. Only the first optical cross-correlator inside the fiber link revealed the second pulse. In a single-

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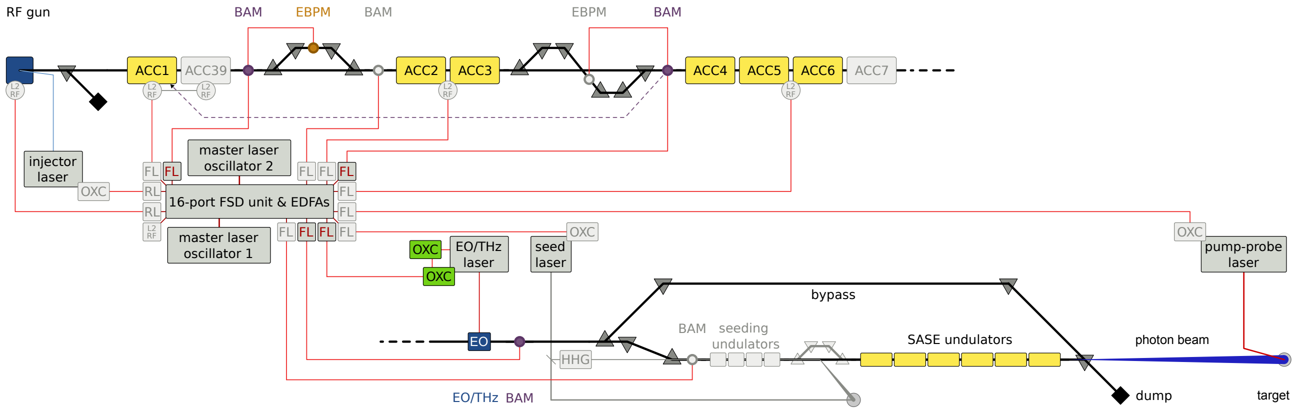

Figure 1: (color online) Overview of the FLASH optical synchronization system. The colored components represent operational devices at the time of this writing, and the light gray depicted components will be installed in the future. Abbreviations are BAM: bunch arrival-time monitor, EBPM: larger aperture beam-position monitor, L2RF: laser-to-RF conversion, OXC: optical cross-correlator, FL: fiber link, RL: RF-based link [5]. The red lines represent the already installed optical fibers to the various locations across the facility.

pulse regime it did not deliver enough optical power for all components. This lead to the decision to build a new laser system as a breadboard version which has a better mechanical stability and is more easily maintainable than the previous laser. The new laser emits a maximum of 215 mW of cw optical power which is reduced to approximately 65 mW in the case of a stable single-pulse operation, which is sufficient for the current state of the synchronization system. We assume that higher output power is achievable by further optimization. These types of lasers seem always to need careful tuning to reach the desired operating point with high output power and at the same time low timing jitter. Figure 2 shows the measured phase noise and integrated timing jitter which amounts to 15.9 fs in the offset frequency range from 1 kHz to 10 MHz and limited by the photo-detector. Lower frequency noise is compensated for by the phase lock loop to the RF master oscillator based on a down-mixing scheme described in detail in [6].

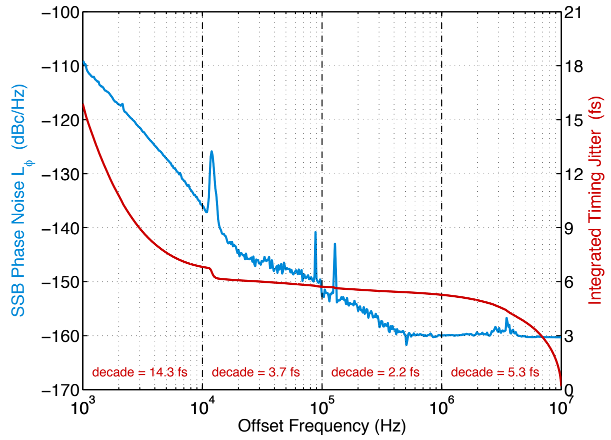

Figure 2: Single-sideband phase noise $L_\phi$ of the free-running oscillator at a carrier frequency of $f_c = 1.3$ GHz and corresponding timing jitter. It amounts to 15.9 fs from 1 kHz to 10 MHz.

## DISTRIBUTION OF THE REFERENCE LASER PULSE TRAIN

We decided to use free-space optics to minimize the problem of dispersive pulse broadening and drifts due to temperature or humidity changes which would occur in an unstabilized optical fiber distribution to16 devices. Furthermore, a free-space distribution (FSD, sketched in fig. 3) allows for the adjustment of the optical power levels on a device-by-device basis. It is constructed with an Invar base plate which eliminates thermal expansion effects. Custom-designed beamcube and waveplate mounts for the required 16 polarizing beamcubes and 32 half-waveplates are used.

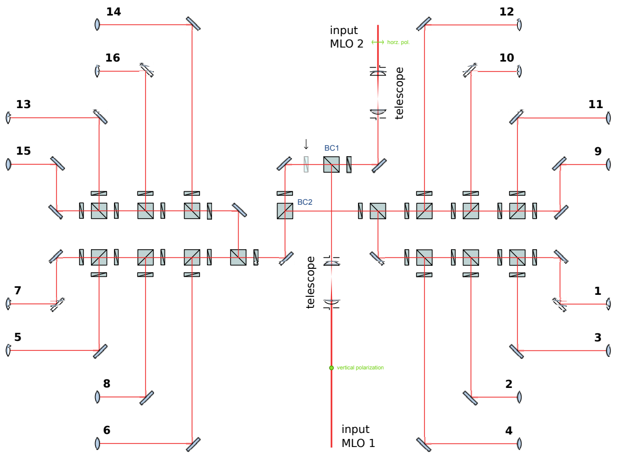

Figure 3: Schematic setup of the free-space unit to distribute the light from the two redundant laser systems to up to 16 individual devices, all of which is connected by a dispersion compensated EDFA to this unit.

The lens symbols in the picture denote the input collimators of dispersion compensated erbium-doped fiber amplifiers (EDFA) boosting the laser power from 4 mW to about 60 mW for the link stabilization unit. During commissioning we observed that a redesign of the telescopes is required to meet the tight tolerances (longitudinal 100 $\mu$m, transversal $< 5\ \mu$m) for efficient incoupling into these collimators. Additionally, another lens inside each laser system is required to image the output collimator of the new lasers to the design positions of the not operable laser's position. Taking into account that the optical beam path is designed to be roughly the same for all ports, we are now able to couple light into all installed collimators with an efficiency between 80% and 95% for both laser systems. The loss from the various optical components amounts to about 25% and was initially underestimated. Figure 4 (bottom plot) shows the amplitude drift of the FSD over 14 hours measured using the low-pass ($< 5$ MHz) filtered photodiode signal from collimators in three ports of the unit. Since the curves are normalized to the MLO amplitude drift (middle plot, blue curve) the FSD-induced drift amounts 0.3% (peak-to-peak), most likely due to Poynting instability. The MLO amplitude stability also shows only a drift of 0.3% with the largest contribution from the first two hours of measurement. This arises from a temperature changes by 0.05 deg C of the pumpdiodes (red curve) which is also visible in the temperature of the rack containing the electronics for the laser systems (top plot, red curve).

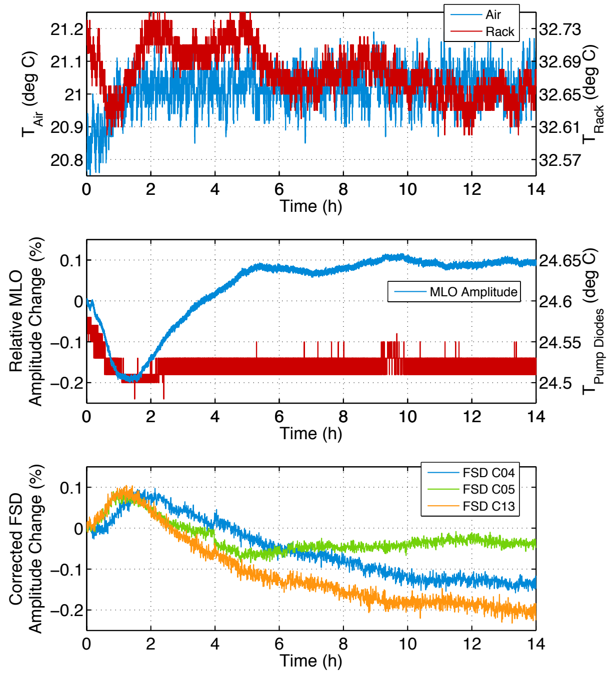

Figure 4: Amplitude stability over 14 hours of the free-space distribution (bottom) and the master oscillator (middle), and comparision to temperature changes (top).

## LENGTH-STABILIZED FIBER LINKS

The distribution of the reference laser pulse train is accomplished by actively stabilized fiber links to the individual remote locations. The stabilization units use optical cross-correlation signals which are fed back to a piezo stretcher. Further details can be fond in [4]. They have evolved from breadboard setups to mechanically stable engineered versions consisting of three layers integrated into one device. The electronic part includes a 2.6 GHz RF phase detector and amplitude monitors for the light entering the fiber link and for the light reflected at the link end. The components of the free-space balanced optical cross-correlator, the optical delay stage for coarse compensation of fiber link length changes and a telescope are mounted onto a stable base plate. The fiber part mounted from below to this plate consists of the piezo stretcher for fine and fast compensation of length changes and the dispersion compensating fiber (DCF). With the exception of the self-built delay stage and a redesign of the telescope we had no major problems commissioning now four of these link devices. There were minor design issues which are currently being addressed in a second iteration of the mechanical design. The delay stage turned out not to meet the requirements; moving it reduced the incoupling efficiency into the link fiber by 90% in the worst case. This could partly be fixed and a second version of the stage is currently on its way. Figure 5 shows the balanced optical cross-correlator signals of two links and the fitted slope around the zero-crossing of the curve which is the operating point of the control loop. The orange curve reveals a lower peak-to-peak value and more importantly a larger time difference between the extremal values. This indicates a worse dispersion compensation, i.e. the laser pulses reflected from the link end have a longer pulse duration than in the other case, resulting in a lower resolution. It should be noted that the steepness of the signal's slope is highly sensitive to the power ratio between the reference and the returning light pulses. In particular, the amplitude becomes larger for higher reference pulse power, but the reduced light coupled into the fiber link causes problems for the operation of the front-

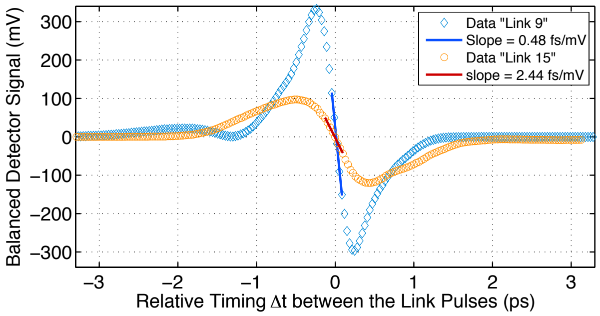

Figure 5: Balanced detector signal of the optical cross-correlators in two individual fiber links measured by scanning $\Delta t$ between the reference laser pulses and the pulses reflected at the end of the links used for in-loop calibration.

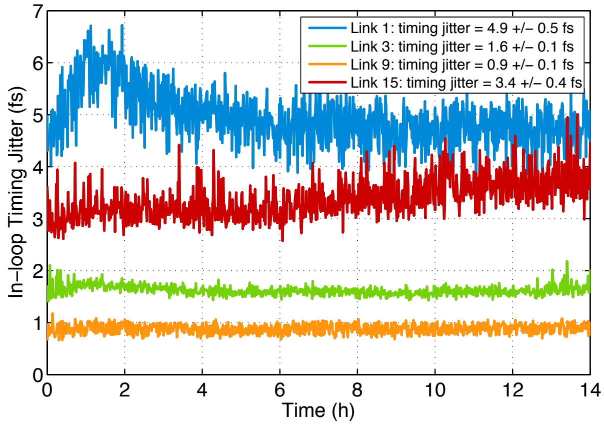

Figure 6: In-loop timing jitter of the four operational links over 14 hours.

ends. Hence, a careful adjustment between an improved slope and a sufficient amount of light at the link end has to be found. Using a digital feedback system (running on a DSP) the link stabilization is realized. Figure 6 shows the residual in-loop jitter over 14 hours. The timing stability varies between 0.9 fs and 4.9 fs (rms).

Another major concern is the phase noise of RF signals generated from the amplified light pulses at the link-end using direct conversion (see fig. 7). In case of a locked, i.e. stabilized, fiber link the integrated timing jitter amounts to 220 fs in the frequency range from 1 kHz to 10 MHz (orange and red curves in the figure). In case of an open loop, i.e. when there is no temporal overlap of the laser pulses inside the fiber link cross-correlator, the master laser's phase noise is almost recovered as expected (blue and green curves, see also fig. 2). This issue is currently being investigated carefully, because it has severe influence on the RF generation using direct conversion at the link end-stations.

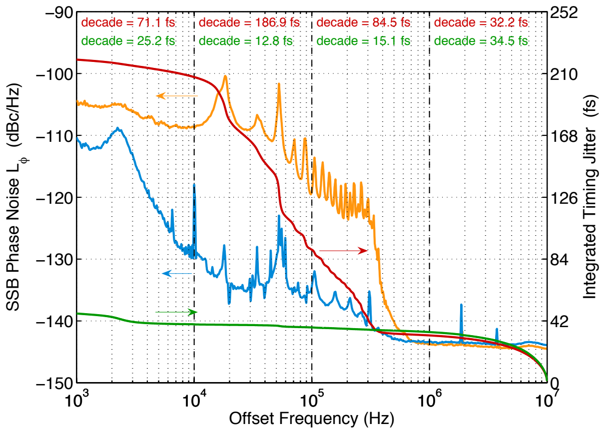

Figure 7: Comparision of the single-sideband phase noise $L_\phi$ at a carrier frequency of $f_c = 1.3\,\mathrm{GHz}$ generated from the laser pulses at the link-end and corresponding timing jitter for a closed (orange and red) and an open (blue and green) link control loop.

## SUMMARY AND OUTLOOK

The engineered infrastructure for permanent optical synchronization at FLASH has made a good progress. We built and commissioned a new master laser oscillator which has been operating for several weeks now. The reference pulse train is distributed in a free-space unit to four dispersion compensated EDFAs driving engineered fiber link stabilization devices. Substantial effort was put into the infrastructure of the synchronization hut in terms of cabling, temperature, air-flow and vibrational issues. We also managed to solve some severe electronic design and programming issues, mainly in the DSP-based control loops and the fast ADCs required for the BAMs.

With the new fiber links, we successfully commissioned two existing BAMs and one newly constructed BAM. After solving technical problems and with the use of new master laser they showed very good results which are presented in [7]. These also show that although only about 4 mW of the MLO's optical power is amplified in each distribution EDFA, we do not reach the shot-noise limit. There are also an optical and an RF-based front-end to the EBPM pickup installed in the synchronization hut, and the results of comparative measurements are discussed in [8]. Concluding from these references, all electro-optic-based devices have an intrinsic resolution of below 10 fs.

We could not lock a Ti:sapphire oscillator to the synchronization system using an optical cross-correlator since this relies on a low-jitter RF signal generated from the reference pulses at the link-end to RF-lock the oscillator initially [9]. Further components of the synchronization system will be commissioned in the next weeks, e.g. the BAM after the first bunch compressor, the optical EBPM front-end in the tunnel and the optical cross-correlator for a Ti:sapphire oscillator. The upcoming FLASH shutdown enables us to investigate the majority of the difficulties encountered in more detail.

## REFERENCES

[1] J. Kim *et al.*, FEL'04, Trieste, Italy, 2004, TUAOS03

[2] J. Kim *et al.*, Nature Photonics 225:733–736, 2008

[3] A. Winter, PhD Thesis, Hamburg University, 2008, DESY-THESIS 2008-010

[4] F. Loehl, PhD Thesis, Hamburg University, 2009, publication as DESY-THESIS in preparation

[5] J. Zemella *et al.*, FEL'09, Liverpool, UK, 2009, FROA05 (this conference)

[6] K. E. Hacker *et al.*, FEL'09, Liverpool, UK, 2009, WEPC69 (this conference)

[7] M. K. Bock, FEL'09, Liverpool, UK, 2009, WEPC66 (this conference)

[8] K. E. Hacker *et al.*, FEL'09, Liverpool, UK, 2009, WEPC70 (this conference)

[9] S. Schulz *et al.*, PAC'09, Vancouver, Canada, 2009, TH6REP091