

PAST, PRESENT AND FUTURE ASPECTS OF LASER-BASED SYNCHRONIZATION AT FLASH

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Abstract

In this paper we report on the present status and performance of the laser-optical synchronization system at FLASH, as well as its upcoming upgrades and new installations. These include the connection of the FLASH II extension, high-resolution electron bunch arrival time monitors for low charges, an improved master laser pulse distribution scheme, sub-10 fs jitter synchronization of the pump-probe laser and arrival time measurements of the UV pulses on the e-gun photocathode. Together with the planned connections of the acceleration modules to the optical master laser and the migration of the low-level hardware to the MTCA.4 platform, an outlook to slow and fast feedback strategies is given.

INTRODUCTION

Fourth-generation linac-based light sources, like the free-electron laser in Hamburg (FLASH) and the upcoming European XFEL, are capable of producing XUV and X-ray pulses with a duration of a few femtoseconds. For time-resolved pump-probe experiments and the externally seeded operation mode it is crucial not only to stabilize the arrival time of the electron bunches, but also to achieve a synchronization accuracy of external lasers on the same timescale. This can only be realized with a laser-optical femtosecond-precision synchronization infrastructure [1]. At FLASH, this is realized by transmission of a highly stable periodic train of laser pulses to the critical subsystems over actively stabilized optical fibers. Compared to other synchronization schemes, for instance based on cw laser signals, the use of laser pulses has a number of advantages. The laser pulse train can be utilized directly in special beam diagnostics, like in the bunch arrival time monitors, or external pulsed laser systems can be synchronized by means of optical cross-correlation techniques with high precision. Beginning in 2005 with the investigation and design of fiber lasers suitable as timing reference and first prototype measurements at FLASH in 2007, the system is in development for many years now and has quite matured.

ARCHITECTURE OVERVIEW

The timing reference of the optical synchronization system is a passively mode-locked erbium laser oscillator, emitting 200 fs long pulses at a 216.667 MHz repetition

rate at the telecom wavelength of 1550 nm. The distribution of the timing information over actively length and by that transit-time stabilized optical fibers is laid out in a star topology network, where all end-stations are referenced to a single point – the master laser oscillator (MLO). A sketch of the optical synchronization infrastructure at FLASH in its projected fully expanded state is depicted in Fig. 1, while Table 1 gives an overview of all presently installed and planned connection to timing-critical subsystems.

Connection of FLASH II

Most notably, the figure shows the connection of the FLASH II extension¹, which was built and installed during the recent shutdown of FLASH. In the FLASH2 beamline, a variable gap undulator is installed to allow for SASE operation at different wavelengths than FLASH1 although the same linac is being used. Furthermore, it is foreseen to operate FLASH2 as seeded FEL either using the HGHG (high-gain harmonic generation) or the EEHG (echo-enabled harmonic generation) scheme. In addition to the existing and permanently operational eight fiber links and connected subsystems at FLASH1 (Table 1, upper half), four additional fiber links and end-stations will be installed: two electron bunch-arrival time monitors, as well as the synchronization of the laser system for pump-probe user experiments and for the seed laser. In 2015, a third beamline will be installed in the FLASH II tunnel for the FLASHForward project.² It is dedicated to experiments in the relatively new field of laser- and beam-driven plasma wakefield acceleration. This also requires the connection of an external laser to the optical synchronization system, as well as another electron bunch arrival time monitor for sub-10 fs synchronization between an optical laser pulse and the electron bunch.

Synchronization Laboratory Infrastructure

Since the optical synchronization system was planned for 16 clients from the beginning, the additional end-stations can be added easily to the existing installation. While the optical fibers to the new stations are presently being installed alongside with the accelerator components, the synchronization laboratory is already equipped with the required infrastructure. This includes digital control and diagnostics hardware, piezo- and laser diode drivers etc., as

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¹<http://flash2.desy.de>

²<http://laola.desy.de>

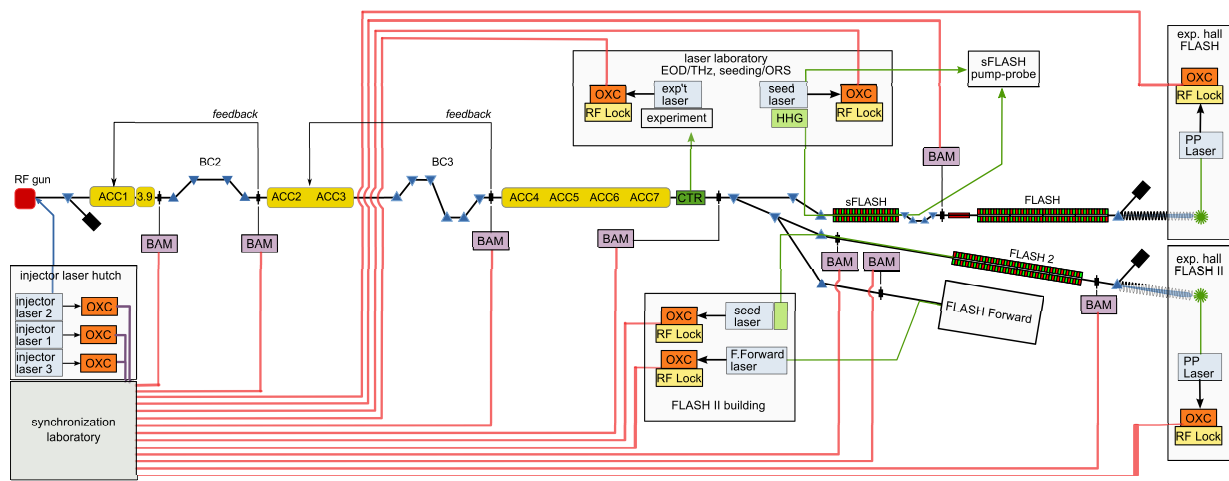


Figure 1: Schematic layout of the optical synchronization infrastructure at its full expansion state for FLASH, the currently built FLASH2 beamline and the future FLASH Forward project. The connection of the LLRF system for the acceleration modules (ACC1 ... ACC7) to the synchronization laboratory is not shown in the picture.

well as a proper cabling from the optical table to the electronics racks. The optical table is equipped with a rigid cover to minimize the influence of environmental changes. Recently, another layer of thermal insulation was added to the cover, resulting in a temperature stability of 0.007°C (rms, measured over 12 h; 0.089°C peak-to-peak) on the table while the room temperature fluctuated by 0.044°C (rms). In this period, the relative humidity was stabilized to 3.0% (peak-to-peak) or 0.6% (rms).

TIMING DISTRIBUTION

The best possible stabilization of temperature and relative humidity is essential, as, due to the star-like nature of the system, the MLO pulse train is split on the table and amplified for the individual fiber links. In the current implementation, the erbium-doped fiber amplifiers (EDFAs) used for the connection of the link to the MLO are not actively stabilized, which leads to a worst-case timing drift of 15 fs for the observed conditions and total fiber length of 1.4 m. However, since all EDFAs are built with an equal length only a common mode error is introduced and the mutual timing of the connected subsystems remains fixed.

Local Free-Space Distribution

The actual splitting of the MLO pulse train is realized in a free-space optical setup (FSD) based on polarizing beam splitters. A second version of this setup had been constructed and was commissioned during the recent shutdown of FLASH. It is based on a single Invar plate with compact custom-designed mounts for optics and optomechanical components. Due to the low thermal expansion of Invar, the additional timing error is below 1 fs. For redundancy, the setup includes two identical commercial³ SESAM-based erbium lasers as MLOs, which are also mounted on the

Invar base. Each of them is equipped with motorized polarization control, two optical power monitors (one internal mounted by the manufacturer and one low-pass filtered free-space photodiode) and phase-locked independently to the accelerator's RF oscillator. While one laser serves as actual timing reference, the relative timing of both can be measured by balanced optical cross-correlation and adjusted with a high-precision optical delay line. In case of failure of the MLO, the spare laser can take over without the need for timing scans. The common beam path for both lasers starts with a port for the connection of the three injector lasers via passively stabilized fibers to the adjacent laboratories. Then the light is split in a symmetric configuration for the connections of 2×8 fiber link stabilization units (LSUs, [2, 3]). The geometric path length of these 16 ports is differs by less than 0.1% with respect to the lasers' exit apertures, which has two advantages. First, thermal expansion affects all ports equally. Secondly, a Galilean telescope ensures maximum and equal coupling efficiency

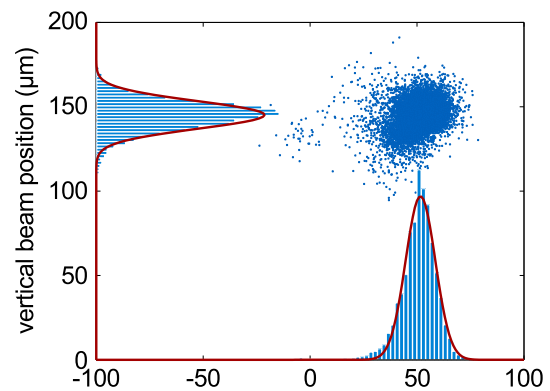


Figure 2: Master laser oscillator beam position measurement in the new free-space distribution unit.

³OneFive Origami-15 with LP Linear Driver, <http://www.onefive.com>

Table 1: Summary of present and future clients of the laser-optical synchronization system and fiber link connections at FLASH. Dates printed in a bold typeface mark upgrades and modifications since 2011 [4], while an italic typeface indicates future installations. Items containing a question mark do not have a fixed schedule yet.

station	installation (planned)	latest upgrade (planned upgrade)	connection	latest modification (planned)
BAM 1 (“1UBC2”)	2009	<i>2014</i>	LSU	2013
BAM 2 (“3DBC2”)	2010	<i>2014</i>	LSU	2013
BAM 3 (“4DBC3”)	late 2007	<i>2014</i>	LSU	2012
BAM 4 (“15ACC7”)	late 2007	<i>late 2013</i>	LSU	<i>late 2013</i>
BAM 5/test stand	2013	–	LSU	2013
injector laser 2	late 2009	<i>2014</i>	passive from FSD	2012
pump-probe laser (FIPP)	2010, RF-based	2013, OXC	LSU	2012
seed laser	2010, RF-based	2013, OXC text	LSU	2013
EO experiment laser	2009, RF-based	2012, OXC test	LSU	<i>early 2014</i>
laser for THz experiments	2013	–	passive from FIPP	2013
injector laser 1	<i>mid 2014</i>	–	passive from FSD	2013
injector laser 3	-not decided-	–	passive from FSD	–
LLRF for ACC1	<i>late 2013</i>	–	RF-LSU	<i>late 2013</i>
LLRF for ACC23	<i>early 2014</i>	–	RF-LSU	<i>late 2013</i>
LLRF for ACC4567	-not decided-	–	-not decided-	–
BAM (“F2EXTR”)	<i>early 2014</i>	–	LSU	<i>late 2013</i>
BAM (“F2BURN”)	<i>early 2014</i>	–	LSU	<i>late 2013</i>
FLASH 2 pump-probe laser	<i>mid 2014 (?)</i>	–	LSU	<i>mid 2014 (?)</i>
FLASH 2 seed laser	<i>mid 2014 (?)</i>	–	LSU	<i>mid 2014 (?)</i>
BAM for FLASH Forward	<i>2015 (?)</i>	–	passive from F2EXTR (?)	<i>2015 (?)</i>
FLASH Forward laser	<i>2015 (?)</i>	–	LSU	<i>2015 (?)</i>

into the fiber collimators, which has been measured to be 80%. In the former setup, the path lengths varied by more than 100 mm preventing such an optimization. Additional ports are available for providing the RF-based stabilized fiber links [5] with the optical reference signal. These links will be installed for referencing the LLRF system of the acceleration modules to the MLO in late 2013/early 2014 [6]. Finally, the beam position is measured using a four-quadrant detector. The result of a 12-hour measurement period is shown in Fig. 2. The pointing changes amount to $\sigma_x = 6.80 \mu\text{rad}$ and $\sigma_y = 7.97 \mu\text{rad}$ for the horizontal and vertical dimension. Since the fiber collimators were measured to accept several tens of micrometer deviation from their center position, the pointing stability of the actual setup is sufficient not to deteriorate the coupling into the fibers. This is a big improvement from the former setup [7] where the MLOs and the FSD were mounted independently on the optical table. Taking all fiber links and diagnostics into account, the master laser pulse train is split for 24 ports, requiring appropriate distribution of the available optical power. For this the previously underestimated loss in all optical components was considered thoroughly.

Actively Stabilized Fiber Links

Recently, a dedicated test stand has been set up for further development of active stabilization schemes for fiber links. The result of an out-of-loop evaluation of the present link scheme is shown in Fig. 3. While fast fluctuations,

i.e. the timing jitter, is 0.8 fs on average over 22 h and well within the jitter budget of the system, a drift with a worst-case slope of 13 fs/h of the absolute timing can be observed. Although the total fiber drift is suppressed by a factor of approximately a factor of 800, an improvement by a factor of at least 10 is desirable. Beside small thermal effects and minor imperfections in the balanced measurement the main reason for the residual drift was found to

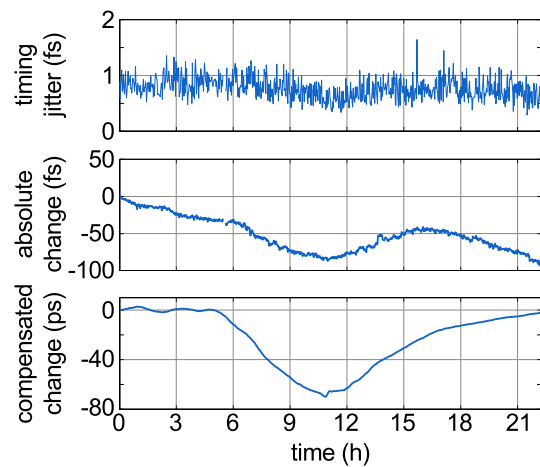


Figure 3: Performance of the current link stabilization scheme measured out-of-loop by optical cross-correlation with the reference at the test stand.

be polarization mode dispersion (PMD), which is an inherent effect in optical fibers. Since the present link design is sensitive to PMD a new fiber link stabilization scheme was invented and is presently under investigation.

The software for the routine operation of the fiber link stabilization units underwent a significant revision [8]. After hardware commissioning, the newly implemented full automation includes signal search, periodical self-calibration, timing jitter and drift calculation as well as monitoring and error logging. At the same time, the implementation of algorithms and middle layer control system servers was done as portable as possible to reuse them in the upcoming MTCA.4 computing platform⁴. First tests on locking a fiber link based on MTCA can be carried out at the test stand, while the deployment for the synchronization system is planned for 2014. Before, the RF-based fiber links [5] solely rely on the new platform and the synchronization laboratory has already been prepared for this.

EXTERNAL LASER SYNCHRONIZATION

The phase-lock of external pulsed laser systems to the optical reference is one of the main applications of the synchronization system. For this, the pump-probe laser, the laser for FEL seeding and a laser used for diagnostics are equipped with RF-based phase detectors [9], where the RF signals are extracted from the laser's and the reference pulse trains using photodiodes. Recently, the pump-probe and the seed laser were equipped with balanced optical cross-correlators (OXC) allowing for all-optical timing detection. Preliminary measurements reveal the possibility to sustain sub-10 fs timing jitter over long time periods. This was only possible with a newly developed piezo driver and a much faster digital PID controller. Albeit being implemented still on the outdated VME platform, the possible locking bandwidth could be increased from below 10 kHz to theoretically 100 kHz. Using the more powerful MTCA computing platform, together with an optimized OXC design under investigation, it is feasible to achieve an even greater synchronization accuracy in the future. Like for the fiber links, automation and ease of use of the software has greatly been extended. Furthermore, a new control system server had been implemented for the optical cross-correlator installed at the photoinjector laser [10]. The measurement of the arrival time of the laser pulses and user friendly display are an anticipated tool for machine operation. Additionally, it is possible to stabilize the arrival time based on the OXC data with a low-bandwidth feedback. The measurement shown in Fig. 4 yields 63 fs (rms) stability while a drift of ~ 4 ps was compensated.

BUNCH ARRIVAL TIME MONITOR FOR LOW BUNCH CHARGES

To cope with bunch charges as low as 20 pC, the electron bunch arrival time monitors (BAMs) are presently being redesigned [11]. The RF front-end, with two of which

⁴<http://mtca.desy.de>

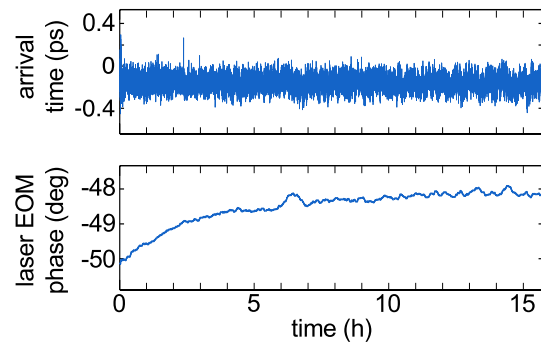


Figure 4: Long-term arrival time stabilization of the photoinjector laser oscillator pulses.

installed in the FLASH beamline for tests, is now based on new 40 GHz pickups. Because it is difficult to find suitable electro-optic modulators at these frequencies for pulsed lasers, a comparative study had been carried out [12]. Also, dedicated BAM electronics are developed for MTCA, promising a much higher reliability and performance due to faster ADCs and larger signal-to-noise ratio.

The BAM signals are then used for a fast intra-train arrival time stabilization via the LLRF control of the accelerating modules, which already are operated based on MTCA. An additional, slow feedback which also will include the injector laser arrival time data can be used to stabilize the accelerator on the long-term.

SUMMARY AND OUTLOOK

In the last years, the optical synchronization system matured and got easier to operate by more software automation. Impending upgrades include the connection of the FLASH2 beamline and the LLRF stations, while the system is prepared for further expansion. Although machine operation and user experiments rely more and more on the system, it serves well as development testbed for the upcoming European XFEL – including the step-by-step upgrade to the MTCA computing platform.

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