

LAYOUT OF THE OPTICAL SYNCHRONIZATION SYSTEM FOR FLASH

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Abstract

At FLASH, we observe an electron bunch arrival time jitter ~ 200 fs on a timescale of several minutes and drifts of picoseconds over the course of a day.. The short term jitter of 200 fs is mainly due to the amplitude stability of the first acceleration module. The long-term drifts however, are predominantly caused by the RF distribution and various front ends of the synchronization system. We propose a new type of synchronization system based on optical techniques. The optical synchronization system will satisfy 2 goals: Firstly to provide a high-stability local oscillator for low-level RF regulation, secondly to synchronize experimental lasers for the FEL users and for beam diagnostics which might also utilize the timing laser pulse train directly.

INTRODUCTION

One of the key challenges for the next generation synchronization systems is to provide a point-to-point stability of 10-20 femtoseconds. The arrival time stability of the electron bunch, however, is limited by path length changes in the magnetic chicanes used for bunch compression. In case of FLASH, an electron beam timing jitter of 60 fs translates into tight tolerances on the amplitude and phase stability of the RF in the most critical accelerating cavities of 10^{-4} and 0.03 deg, respectively. The synchronization system must provide the possibility for monitor systems enabling slow and intra-bunchtrain feedbacks (high bandwidth). Electron bunch manipulation by external fs-laser systems require these to be precisely locked. Synchronizing two individual lasers optically has been shown to be possible with extremely low jitter (sub-fs) [3]. Furthermore, the optical synchronization system at FLASH will serve as a test bed for the synchronization system for the XFEL.

The synchronization stability requirements are probably only achievable through an optical distribution of the timing signals, even though there is decades more experience with RF-based timing distribution through coaxial cables. This is because the sensitivity of optical phase-detectors by far exceeds the capability of RF phase-detection due to the great difference in carrier frequency and an active length-stabilization of the transmission line is possible. Due to the sensitivity of optical phase detectors ($\sim 1 \frac{fs}{mV}$), drifts of detectors and electronics used for the feedback are not an issue anymore as they can easily be kept in the sub-mV range.

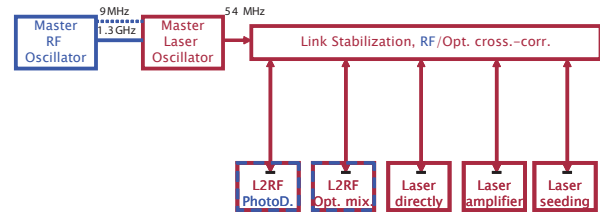


Figure 1: Schematic of an optical synchronization system.

A schematic layout of the proposed synchronization system is depicted in Figure 1. A periodic train of sub-picosecond light pulses is generated in a mode-locked fiber laser and distributed along the linac through fibers with optical length stabilization. The synchronization information is contained in the precise repetition frequency of the pulse train. At the remote locations, low-level RF signals are generated by using a photo diode and a bandpass filter to pick the desired harmonic of the laser repetition rate, or by phase locking an RF source to a harmonic of the pulse train [1].

SYNCHRONIZATION SYSTEM REQUIREMENTS

1. It should serve as a timing reference providing femtosecond stability between all significant points throughout the facility with small or negligible drifts over days and weeks.
2. It must provide RF signals or the possibility to lock ultra-low-noise RF local oscillators to the timing reference at different frequencies.
3. It must provide a mechanism to lock various laser systems, as in those used for electron beam generation, beam diagnostics, pump-probe experiments, seeding, and other applications.
4. The system stability, robustness, and maintenance should not limit machine availability.
5. The failure modes should be transparent and allow for rapid repair and start-up.

Besides the primary application of delivering an ultra-precise reference to the low-level RF, optical timing pulses are of great advantage for synchronizing various other laser systems used throughout the facility. For example, by frequency doubling the 1550nm to 775nm, a regenerative Titan-Sapphire amplifier can be seeded, the optical-replica synthesis experiment at FLASH [2] being one possible example. Laser-based diagnostic measurements can be carried out by directly using the optical pulse-stream of the timing system. Optical cross-correlation by sum-frequency

generation between the optical timing pulses and a laser system providing ultra-short laser pulses allows for precise monitoring or the operation of phase-lock-loops with femtosecond stability.

Laser Master Oscillator System The centerpiece of the optical synchronization system is a mode-locked Erbium-doped fiber laser. One requirement for this laser is, that its temporal stability (=phase noise) at high offset frequencies (>1 kHz) must be extremely low (~ 10 fs). This is due to the fact, that all accelerator subsystems can follow a common reference using a phase lock loop (PLL) with a certain speed (=bandwidth). Thus the absolute timing jitter of the reference within that bandwidth is not important. Only the relative timing jitter between the various subsystems matters. However, a PLL will not cut the frequency response immediately but usually with a first or second-order low-pass filter characteristic. This means that the residual high-frequency phase noise of the reference will be attenuated, but it must be small enough to be a negligible contribution to the total locking accuracy of the slave system. However, before these lasers can be implemented into machine operation, their reliability must be ensured. Effort is presently undertaken to construct such a system. For further details, see reference [5].

Stabilized Fiber Links To stabilize the optical path-length of the fibers used to distribute the pulse train throughout the machine, a combination of two feedbacks is foreseen. A percentage of the pulse train is reflected back through the transmitting fiber and correlated with a pulses directly from the LMO. An optical cross correlator can have a very high sensitivity, but lacks the dynamic range needed for long term operation, as it is proportional to the optical pulse width used in the cross correlator (~ 200 fs in our case). A conventional RF feedback using a microwave signal obtained by photo detection of the laser pulse train and subsequent filtering has a dynamic range on the order of several hundred picoseconds, but is susceptible to long-term drifts. A prototype of the RF-based feedback system has been tested in an accelerator environment and has shown extremely promising results, see [5]. Implementing the optical cross correlators requires a dispersion compensated fiber link. There is commercial dispersion compensating fiber available, but has not been tested yet. Different possible schemes of optical cross correlators (crystal-based signal generation vs. two-photon absorption) need to be tested with regard to signal quality and reliability.

Synchronization and measurement of the temporal stability of the injector laser It is necessary to synchronize and monitor the timing jitter of the injector laser so that it is possible to correlate the arrival time jitter of the injector laser pulse at the photo cathode with other diagnostic systems. The FLASH injector laser system consists of a frequency quadrupled actively mode-locked Nd:YLF laser system, running at a repetition rate of 27 MHz. Before

amplification and frequency conversion, the required pulse pattern is gated by a Pockels cell. The frequencies used to drive the amplitude modulators for the active mode-locking (at frequencies of 13 MHz, 108 MHz and 1.3 GHz) can be generated directly from an output of the LMO. If further stabilization is required, an optical cross correlation between the injector laser pulses and the LMO could be constructed and use either a fast phase shifter on the 1.3 GHz. A measurement of the stability of the injector laser pulse (in the UV) relative to the LMO is desirable. To measure the timing stability of the laser, a similar scheme as described in the section below could be employed by using an RF signal from photo detection of the injector laser pulses. The synchronization of the injector laser to the LMO and the measurement of its stability has not yet been implemented, but will be one of the main objectives for the first stage of the construction of the optical synchronization system.

Diagnostics The performance gain obtained by the optical synchronization system is primarily the temporal stability of the electron beam/X-ray pulse. To measure any improvement over the present state, a high-resolution arrival time monitor is required. A possible scheme making direct use of laser pulses from the timing system consists of an electro-optic modulator in which the amplitude of the timing system laser pulses is modulated by an electronic signal, e.g. from a high-bandwidth pick up [6]. This system has a potential resolution on the order of 10 fs, which is sufficient to detect any improvement in the fast timing jitter of the machine (intra-bunchtrain or from shot to shot) and has the advantage of intra-bunchtrain measurement capability and - if fed with timing laser pulses - intrinsic synchronization. Present day laser-based diagnostics installed at FLASH (temporal, spectral and spatial decoding) have a resolution on the order of 50 fs and are also well capable to measure improvement in machine jitter and drifts, but have separate laser systems requiring external synchronization to the timing system.

INSTALLATION OF THE FLASH SYNCHRONIZATION SYSTEM

The first version of the optical synchronization system will be installed at the FLASH facility at DESY beginning the latter half of 2006, so first results can be expected early 2007. The system will be installed in three steps: (1) Installation of the LMO system and two optical path length stabilized fiber links (2) Supply of ultra-stable reference to ACC1 and the experimental hall (3) Installation of the remaining fiber links and long-term tests of the system.

The LMO system will be situated in a separate hutch adjacent to the injector laser hutch (green dot in Figure 2). During the first phase, the goal is to achieve a proof-of-principle that a fiber-laser based LMO can be operated over long time scales in the accelerator environment and an evaluation of its performance by measuring the temporal stability of the machine. This will be done measuring the

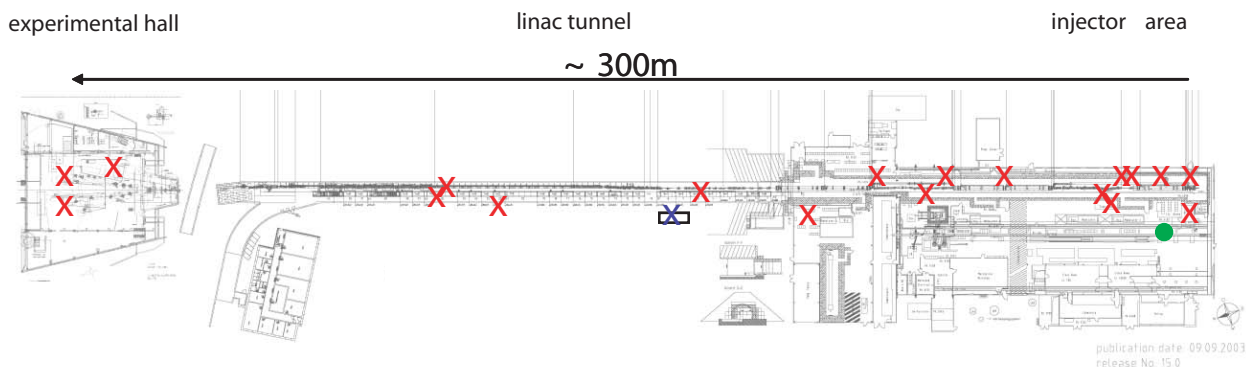


Figure 2: Layout of the FLASH synchronization system.

electron-bunch arrival time using two phase monitors (as described in [6]) ideally in two different positions along the machine only separated by drift space, so the electron bunch cannot pick up any timing jitter between the phase monitors (blue crosses in Figure 2). Further effort will be made to synchronize the laser used for the electro-optic experiments [7] to the transmitted LMO and compare the results from the EO-experiments and the phase monitors. Furthermore, an ultra-precise beam position monitor based on the same principle as the phase monitor will be installed during a shutdown late 2006 [8] and tested during this phase. The synchronization of the injector laser to the LMO will also be implemented during phase one. It is expected to have first results before the major FLASH shutdown in March 2007.

During the longer shutdown, the fibers needed for all remaining links will be installed in the FLASH tunnel. The supply of an ultra-stable reference from the LMO to the most critical components of the accelerator for timing stability of the electron bunch (low-level RF regulation of ACC1) in conjunction with a new version of the down converters is the main aim of phase two. Furthermore, the synchronization of the probe laser in the experimental hall will be a main focus. Phase two is expected to be completed by mid-2007. With these parts of the optical synchronization system in place, it should already be possible to measure a significant improvement in machine stability. Over the next few months, all remaining components will be installed, which makes it possible to run the complete machine from the optical synchronization system over long timescales. These tests are foreseen to commence by the end of 2007.

CONCLUSION AND OUTLOOK

In this paper, we have presented the layout of the optical synchronization system proposed for FLASH. It will consist of a Er-doped fiber laser as laser master oscillator, with actively length stabilized fiber links distributing the pulse train to various locations within the machine. The construction is foreseen to go in three stages between 2006 and late 2007. In stage one, the LMO will be set up in

the accelerator environment and three fiber links will be set up to diagnostic experiments to validate the functionality with measurements relative to the electron beam. In stage two, the most critical subsystem - the low-level RF of ACC1 - will be supplied from the optical synchronization system and the pump-probe lasers in the experimental hall will be synchronized. All remaining fiber links will be implemented in stage three and the machine should run using the optical synchronization system for long periods at a time.

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