FEMTOSECOND SYNCHRONIZATION OF LASER SYSTEMS FOR THE LCLS*

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Abstract

The scientific potential of femtosecond x-ray pulses at linac-driven free-electron lasers such as the Linac Coherent Light Source is tremendous. Time-resolved pump-probe experiments require a measure of the relative arrival time of each x-ray pulse with respect to the experimental pump laser. An optical timing system based on stabilized fiber links has been developed for the LCLS to provide this synchronization. Preliminary results show synchronization of the installed stabilized links at the sub-20-femtosecond level. We present details of the implementation at LCLS and potential for future development.

INTRODUCTION

The next generation of accelerator-driven light sources will produce sub-100-fs high brightness x-ray pulses[1]. In particular, pump-probe experiments at these facilities require synchronization of pulsed lasers and x-rays from electron beam on sub-100 fs time scales over distances of a few hundred meters to several kilometers[2,3]. Pump-probe experiments at these facilities plan to use an x-ray "probe" to produce snapshots of atomic positions within a sample some time after it is excited with a laser "pump."

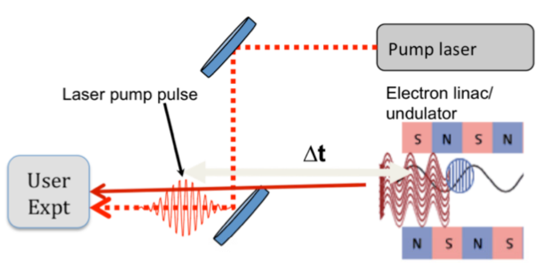

Figure 1: Layout for pump-probe timing.

Varying the time between pump and probe enables the recording of a "movie" of the dynamics in the sample, with a time resolution determined by the x-ray pulse length and the relative timing jitter and drift of pump and probe. For experiments that require minutes to hours to collect data, the relative drift of the pump and probe should be less than the x-ray pulse length.

One of the main challenges in reaching the level of synchronization required for pump-probe experiments is transmission of a timing signal over a relatively large facility. For example, in a facility of a kilometer in length, diurnal temperature variation results in cable length variation from several hundred ps to a nanosecond.

For the LCLS, the jitter of the electron beam with respect to the laser pump is unacceptably large. Therefore, the goal is to measure the arrival time of each electron pulse with respect to the laser pump and allow the proper ordering of the "frames" of the movie. In this case, it is critical to synchronize the electron arrival time diagnostic with the pump laser.

STABILIZED RF SIGNAL DISTRIBUTION

One of the key features in any synchronization scheme is the ability to stably transmit a master clock signal to the remote clients with negligible uncontrolled relative timing drift between the clients. A schematic view of this distribution is shown in Fig. 2. The master oscillator signal is distributed over the accelerator to remote clients in a star configuration. Each link consists of a stabilized optical fiber with a second fiber carrying the error signal, a receiver for RF signal processing (RX), a synchronization head (S/H), and a remote client. The phase of the master signal is corrected at the end of each fiber link for the length variation of that link. Thus the relative timing drift of clients locked the master signal on independent fiber links does is minimized over many hours and even days.

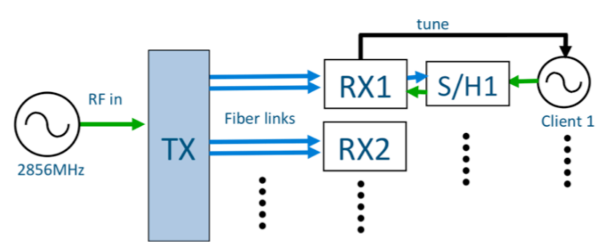

Figure 2: Schematic view of the distribution of the master clock over optical fiber. Each receiver consists of an RF signal processor (RX) and synchronization head (S/H).

Several approaches have been implemented to send stable signals over fiber optic links [4-8]. In our approach[9], each fiber link is an optical interferometer that precisely senses the delay variations in the link due to variations of the fiber.

A schematic diagram of one of the stabilized RF transmission links is shown in Fig. 3. The fiber used for transmission is one arm of an interferometer, which tracks

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changes in the optical phase delay through the fiber. Variations in optical phase are observed at the receiver, along with the amplitude-modulated RF signals to be stabilized. The measured optical phase shift is used to correct the detected RF phase. To compensate for the difference between phase and group delay in the fiber, an additional correction is applied.

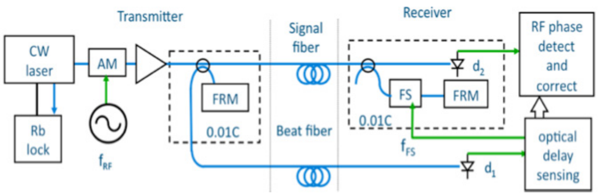

Figure 3: Schematic layout of a single channel RF transmission over an optical link. FRM: Faraday rotator mirror; FS: optical frequency shifter. Dotted rectangles indicate components temperature controlled to ±0.01 C.

Each fiber link is one arm of a heterodyne Michelson interferometer. The reference arm is a short fiber (about 1m) on the transmitter side with its temperature stabilized to ±0.01 C. An acousto-optic frequency shifter at the receiver end of the long arm shifts the optical frequency by 100 MHz in two passes by adding the input 50 MHz RF phase to the optical phase. The beat between the reference and reflected optical carrier is detected as a 100 MHz RF signal is sent back to the receiver over an unstabilized fiber. The receiver then adjusts the frequency shifter RF phase to correct the optical phase providing the ability to deliver a stable optical frequency over fiber.

For stable RF transmission, the CW laser used in the interferometer must have a frequency stability less than the desired temporal stability of the transmission delay. For a 2 km link with 10 fs stability, this corresponds to $\Delta\lambda/\lambda=10^{-9}$. The CW laser frequency is locked to a hyperfine absorption line in Rb vapor, achieving a stability of $\Delta\lambda/\lambda=5x10^{-10}$.

A 2850 MHz RF signal is amplitude modulated onto the optical carrier by a lithium niobate modulator. One issue with photodiode detection is amplitude modulation to phase modulation (AM-to-PM) conversion, where changes in the average optical power modulate the phase of the detected RF signal. The optical power level is set to a local maximum in the AM-to-PM photodiode response, where there is zero slope and minimal sensitivity to fluctuations in optical power. At this peak, a ±10% variation in average photocurrent causes less than 10 fs delay variation in the detected RF signal.

The receiver is a digital RF phase comparator used to compare the transmitted RF signal with a local signal to be controlled. Since the delay through coaxial cables and other RF components is temperature dependent, variations are corrected by subtracting a local calibration signal simultaneously sent through both comparison paths. All processing of RF signals is done at an intermediate frequency of 50 MHz, after mixing down with a 2800 MHz local oscillator.

We initially characterized the performance of this system in our lab by measuring the relative time difference between long and short stabilized links. Results from this system are described in detail elsewhere[9]. In summary, we measured an RMS deviation of <10 fs on a 200 m fiber for over 20 hours and <20 fs on a 2.2 km fiber over 60 hours. The results of this system installed in the LCLS are described in the next section.

LCLS RESULTS

A schematic of the installation of a 2-channel synchronization system is shown in Fig. 4. The aim of this system is to synchronize the arrival time of the x-ray pulse with the user laser pulse. In the LCLS, the arrival time of each electron bunch is measured by . Note that the arrival time of the x-ray pulse is not necessarily the same as that of the electron bunch.

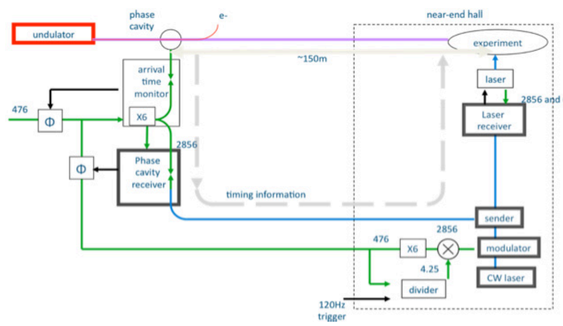

Figure 4. Detailed schematic of the signal path for synchronizing the user laser with the arrival time diagnostic (phase cavity.)

The phase cavity is a resonant cavity with a frequency of 2805 MHz and a Q of a few thousand. As the beam passes through the cavity, it excites a transient oscillation. The relative phase of this oscillation is compared with the phase of a 2856 MHz clock multiplied up from the 476 master oscillator signal for the LCLS. A servo loop adjusts the phase of the 2856 MHz signal such that the average beam arrival time is at the zero crossing of this clock. The relative timing of each electron bunch is measured with respect to the average arrival and reported to the user for post-processing of their data.

The fiber link transmitter is located in the first of the LCLS user areas (Near End Hall), a few meters from the user laser system. The entire transmitter and one of the receivers occupy about 2/3 of a standard 19-inch rack. One of the fiber links runs a few meters to the nearby laser. The other link runs ~150 m to the phase cavity in the linac tunnel just downstream from the undulator.

To lock the fiber links to the phase reference provided by the phase cavity, the fiber receiver adjusts the relative phase of the master clock so that the transmitted signal on the fiber links maintains a constant relative phase to the master clock.

To measure the relative stability of the two fiber links, we looped the fiber to the phase cavity back to the transmitter and compared the relative phase of the two receivers as shown in Fig. 5. The RMS relative drift of the two links over a half-day period was 16 fs. The slow drift seen in Fig. 5 is fully accounted for by the 0.5 m unstabilized cable connecting the two receivers.

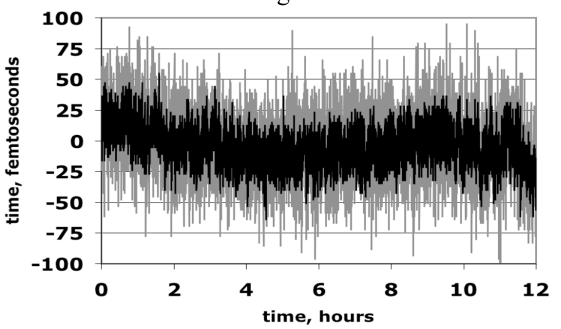

Figure 5: Relative drift of a 2856 MHz signal transmitted over the phase cavity link (2x150m) and the laser fiber (5 m) fiber. The relative time difference has an RMS deviation of 16 fsec in a 1 kHz bandwidth over 12 hours. The slow drift is due to a 0.5 m unstabilized cable between the two receivers.

The user laser is a mode-locked Ti:sapphire oscillator. A schematic of the layout for synchronizing the laser to the 2856 MHz reference phase is shown in Fig. 6. The phase of 7^{th} harmonic of the laser signal observed on a photodiode in the oscillator, multiplied by 6, is compared with the reference phase. The error signal is used to correct the laser phase by driving a piezo-controlled mirror in the laser cavity. The in-loop laser control error signal over a day is shown in Fig. 7. The RMS signal over a 125 kHz bandwidth was 120 fs and over a 1 kHz bandwidth the value was 25 fs.

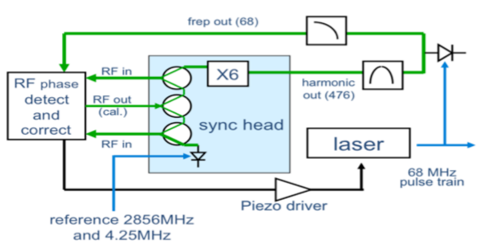

Figure 6: Schematic layout of synchronization to user laser oscillator.

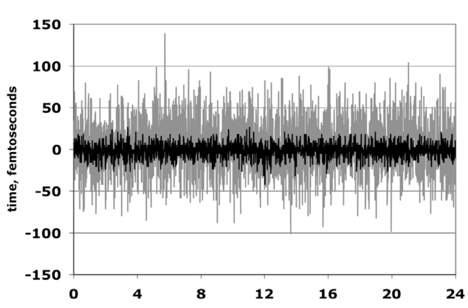

Figure 7: In-loop laser control error signal over a day. The RMS error signal was 120 fs over a 125 kHz bandwidth (gray), and 25 fs over a 1 kHz bandwidth (black).

This system was installed at the LCLS in September 2009 and ran continuously during the first LCLS user run in October 2009.

CONCLUSION

We have installed a fiber link system at the LCLS for high precision distribution of RF signals used for synchronization of a user laser with the average arrival time of the electron beam as measured with a phase cavity. We were able to regularly achieve an rms jitter and drift between two RF channels of less than 20 fs.

We locked one of the two links to the reference phase provided by the phase cavity and the other link to the mode-locked Ti:sapphire oscillator.

We achieved a 25 fs relative locking stability to the laser in a 1 kHz bandwidth. We expect to improve the stability by improving the laser pump stability and vibration isolation of the oscillator.

The fiber synchronization system operated continuously during the LCLS user run in Oct 2009 and is presently in use for the run that began in mid-April 2010. LCLS is engineering production receivers (8 channels) and upgrading the transmitter to 16-channel capability

This approach has several advantages for operation in an accelerator facility. It is easily manufacturable, expandable to many channels, and can be configured to lock to a wide variety of clients. Following the demonstration of this two-channel system, the first commercially produced subsystems are presently being tested.

We are planning improvements in the laser oscillator stability and control, transmitting higher frequencies for higher phase resolution. We also plan a full series of measurements to characterize the overall timing stability of the x-ray and laser pulses.

REFERENCES

[1] C. Pellegrini, in Proceedings of the 10th European Particle Accelerator Conference, Edinburgh, Scotland, 26-30 Jun 2006.
[2] A. M. Lindenberg, et al., Science 308, 392 (2005).
[3] A. L. Cavalieri, et al. Phys. Rev. Lett. 94, 114801 (2005).
[4] O. Lopez, A. Amy-Klein, C. Daussy, Ch. Chardonnet, F. Narbonneau, M. Lours, and G. Santarelli, "86-km optical link with a resolution of 2x10-18 for RF frequency transfer," Euro. Phys. J. D 48, 35 (2008).
[5] P. A. Williams, W. C. Swann, N. R. Newbury, J. Opt. Soc. Am. B 25 1284 (2008).
[6] H. Kiuchi, IEEE Trans. Microwave Theory and Tech., 56, 1493 (2008).
[7] D. D. Hudson, S. M. Foreman, S. T. Cundiff and J. Ye, Opt. Lett. 31, 1951 (2006).
[8] J. Kim, J. A. Cox, J. Chen, F. X. Kartner, Nature Photonics 2, 733 (2008).
[9] R. Wilcox, J. M. Byrd, L. Doolittle, G. Huang, and J. W. Staples, Opt. Lett. 34, 3050 (2009).