STATUS OF THE LCLS EXPERIMENT TIMING SYSTEM*

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Abstract

X-ray / optical laser pump - probe experiments are used for a significant fraction of the scientific work performed at LCLS[1]. The experimental laser systems are locked to the timing of the electron beam through a combination of RF and optical fiber based systems. The remaining ~100 femtosecond RMS jitter of the X-rays relative to the optical laser is measured shot-to-shot by both a RF timing detector, and by direct X-ray to optical cross-correlation, and the result is used to correct the experiment timing to 10s of femtoseconds. We present the present status of the system and plans for future upgrades.

SYSTEM OVERVIEW

The experiment timing system locks the RF reference for the experimental laser (typically used as a pump in pump / probe measurement) to the average beam time from the accelerator. The timing system also measures the shot-to-shot electron beam time relative to the RF reference and provides this data to the experiment for offline jitter correction. In addition, where practical a direct X-ray to laser cross correlator is used to measure the relative beam times for offline correction. A simplified block diagram of the system is shown in Figure 1.

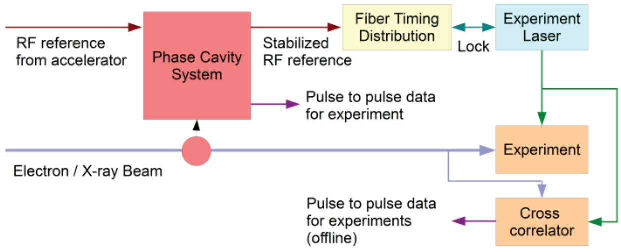

Figure 1: System Overview.

ACCELERATOR TIMING

The LCLS operates at a repetition rate of 120Hz, typical for room temperature accelerators. Since the RF fields completely decay between pulses there is significant pulse-to-pulse timing jitter that cannot be corrected with feedback; for LCLS this is on the order of 100fs RMS. Experiments which require better timing resolution rely on measuring the beam time on each pulse and correcting the data offline.

RF SYSTEMS FOR TIMING

RF systems provide a convenient method for providing timing synchronization. The timing noise of an RF system is given approximately as: $\Delta T = \frac{\sqrt{BW\cdot P_{n(1Hz)}/P}}{\omega}$. Where P is the RF power, BW the system bandwidth $P_{n(1Hz)}$ is the noise power in a 1 Hz bandwidth, ω the RF frequency in rad/sec and ΔT the RMS timing jitter. Most RF systems can operate near (a few dB) the thermal noise limit $\sim 4\times 10^{-21} W/Hz^{1/2}$ with transmission powers of a few millwatts.

For fiber systems the receiver noise is typically $\sim 10^{-11} W/Hz^{1/2}$optical (limited by the noise in the pre-amplifier)[2]. Since the detector output voltage typically scales linearly with optical power, the phase sensitivity varies inversely with optical power (rather than inverse square root for RF systems).

Oscillators have phase noise that increases with decreasing frequency since they are measured relative to an absolute clock. Most high quality commercial oscillators are based on quartz resonators, however there exist some lower phase noise (but more expensive) oscillators based on microwave sapphire resonators.

A comparison of the phase noise of RF systems is given in Figures 2 and 3. Figure 2 shows the phase noise density in femtoseconds /Hz$^{1/2}$, Figure 3 shows the phase noise integrated down from 10KHz (a typical feedback bandwidth) in femtoseconds. Phase noise for 2 fiber system is also shown, representing examples of simple and high performance fiber systems.

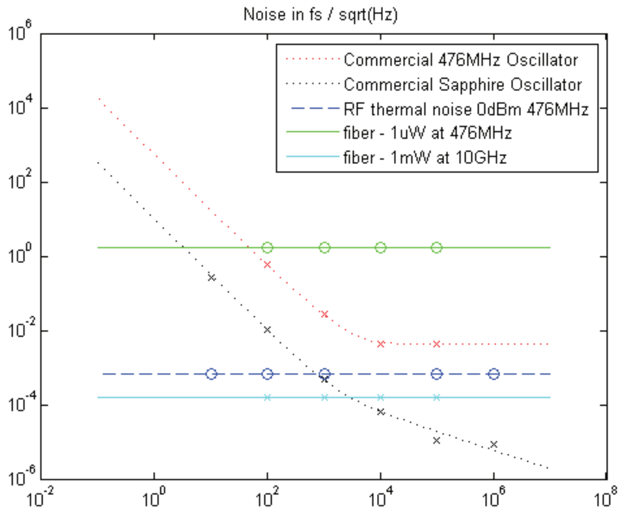

Figure 2: Phase noise in fs/Hz$^{1/2}$ for various RF and fiber systems.

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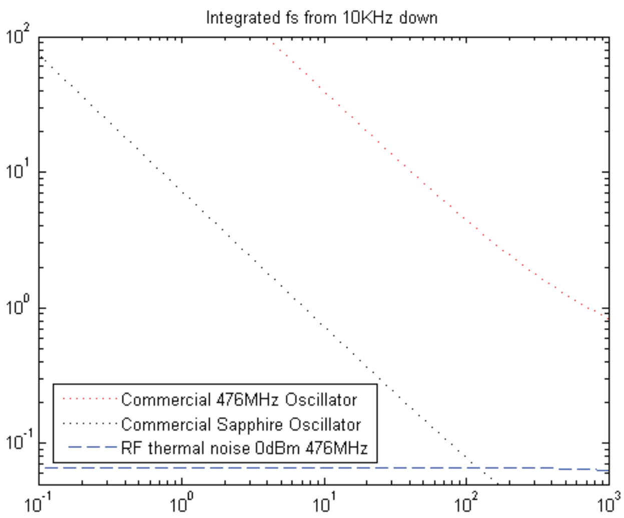


Figure 3: Integrated phase noise in femtoseconds from 10kHz for various RF systems.

From the indicated curves, it is clear that the theoretical noise limits for both RF and fiber systems are suitable for femtosecond timing systems. Timing drift of the systems is generally the more difficult problem, with typical RF cables and fibers changing delay by 30fs/m/ºC.

FIBER TIMING DISTRIBUTION

Precision timing systems, including the LCLS system, typically use a fiber for long distance timing transmission. The fiber length is measured and the signal timing is corrected by a feedback. Three different types of systems are in use at accelerator laboratories:

RF reflectometer: The optical signal is modulated at RF and detected at the far end of the fiber. A fiber mirror returns some of the light to the transmission end where a directional coupler samples the reflected signal. The phase of the RF modulation of the reflected signal is measured and the fiber length adjusted to stabilize the round trip length. This system is simple and robust but has only demonstrated 100s of femtosecond long term stability[3].

Optical interferometer: The optical signal is modulated with RF to transmit timing in the same manner as in the RF reflectometer. An optical interferometer measures the length of the optical fiber and the RF phase is shifted to compensate for the calculated delay time. The use of an optical interferometer provides <<1fs resolution on the fiber length. The overall stability of this systems is ~20 femtoseconds[4].

Pulsed laser: A ~picosecond pulsed laser is used to carry the timing information on the fiber. The timing of the pulses reflected from the fiber end is used to measure the round trip delay, and the fiber length is corrected. The high bandwidth and high power optical pulses allow direct optical phase detection with ~10 femtosecond stability[5].

There is also ongoing R&D on a fiber system based on "comb" lasers where the envelope modulation of the laser is locked to the optical phase. For this type of system it would be possible to use the optical phase rather than the envelop modulation to carry timing information, possibly allowing sub-femtosecond stability[6].

BEAM TIMING MEASUREMENT

The LCLS uses two S-band RF phase cavities to measure the beam time relative to a RF reference with a RMS noise of ~10 fs RMS and a drift of ~100fs/day. Other accelerator projects have used electro-optical beam pickups to measure with <10fs RMS noise[7].

The most serious limitation of both cavity and electro-optical pickups is that they measure the electron beam time, not the X-ray time. In normal operation the X-ray timing can jitter relative to the electron beam by a significant fraction of the bunch length, and when the LCLS is operated in ultra-short bunch mode using the slotted foil[8], the timing jitter of the X-rays relative to the electrons can be several times the X-ray bunch length.

LASER LOCKING

The mode-locked oscillators for the LCLS lasers are locked to the reference time from the fiber system using photodiodes and RF phase detectors with timing jitters of 50-100fs RMS. There is no direct measurement of the timing drift from the oscillator or of additional jitter and drift introduced by the laser amplifier and pulse compression system.

Pulsed fiber distribution systems offer the possibility of using optical cross correlation to directly measure the amplified and compressed pulses from the experiment laser.

X-RAY / OPTICAL CROSS CORRELATION

Pump – Probe experiments are sensitive to the relative timing of the optical pulse and the X-ray pulse. Techniques are being developed to measure this directly. The techniques at use at SLAC are based on the X-ray beam changing the real and imaginary parts of the index of refraction of a material, and detecting those changes with the experiment laser. Two different techniques based on this principal are under development:

Spatial Cross Correlation[9]

The X-rays and laser cross at an angle in a thin (100nm) Si_3N_4 Film. The crossing angle causes the relative arrival times of the beams to vary across the film. The reflected optical beam is then imaged onto a camera.

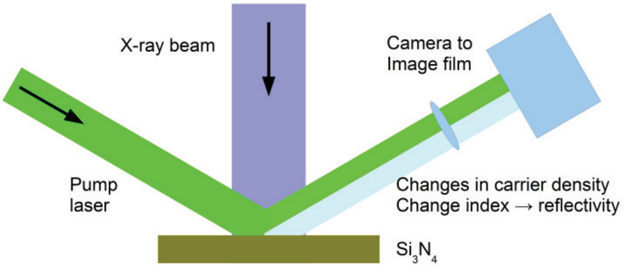


Figure 4: Spatial Cross Correlator.

The resulting images for different time delays are shown in Figure 5,and a comparison with Nitrogen ionization data is shown in Figure 6 [10]. The nitrogen ionization data has an 83fs FWHM, consistent with the 50fs width of the laser pulse and the expected 50-100fs X-ray pulse width.

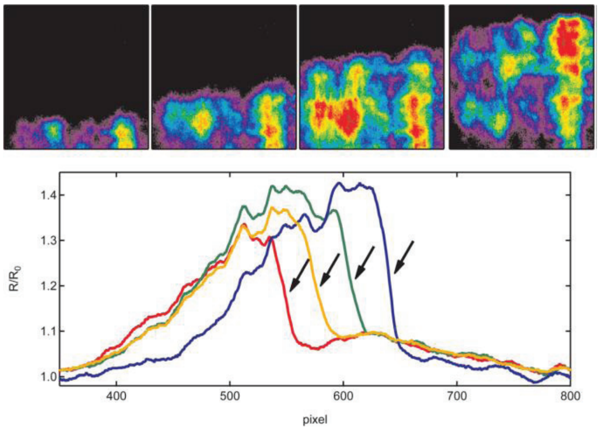


Figure 5: Spatial cross-correlator images.

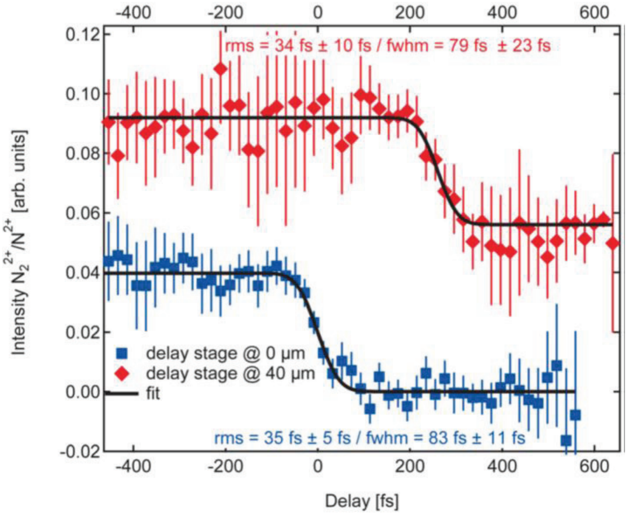


Figure 6: Comparison of Nitrogen ionization data with spatial cross-correlator.

The change in reflection from the thin film is believed to be primarily due to X-ray induced changes in the real part of the index of refraction and subsequent changes in the interference between the front and back surfaces of the film.

Spectral Cross Correlation[10]

The amplified and compressed laser is passed through a continuum generator to create a very broadband (~550-650nm) pulse. This pulse is then frequency dispersed and transmitted through a thin Si_3N_4 film. The dispersion maps time onto optical wavelength and the resulting step in transmission can be read in the spectrum. Figure 7 shows the spectral step after dividing out a background (no X-ray) pulse. The full spectral width with the dispersion represents approximately 1 picosecond. The fit is an empirical fit to the edge of the step. The statistics based noise of the fit is a few femtoseconds, but there is not yet data available for comparison with an independent timing measurement.

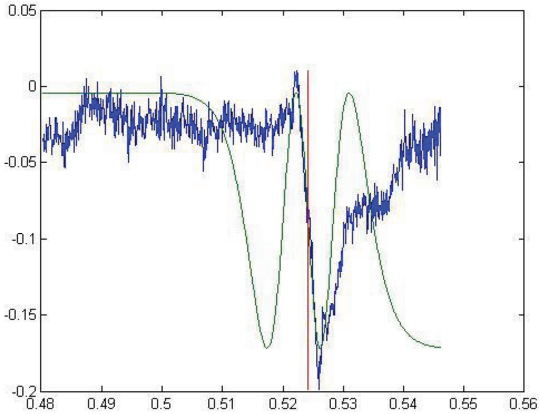


Figure 7: Spectral cross-correlator, change in transmission vs. optical frequency in PHz. Emperical fit.

The changes in index of refraction of the film in combination with interference between the front and back surfaces create ripples in the spectral transmission. Work is underway to compare the data with a physical model of the interaction.

Limitations of cross-correlators

For both cross-correlator designs the change in optical signal may not be linear in the X-ray power, possibly resulting in an incorrect measurement of the centroid of the X-ray pulse. This can also generate intensity related errors on the timescale of the pulse width, or film response timescale. Fortunately for the majority of experiments determining the arrival time of the X-rays to less than the pulse width is sufficient.

Both cross-correlators rely on the X-rays interacting with a solid film. In some experiments the target is opaque to X-rays and the film must be located upstream. The X-ray transmission of a 100nm Si_3N_4 film decreases from 90% at 1000eV to 50% at 400eV, limiting its usefulness for soft X-ray experiments.

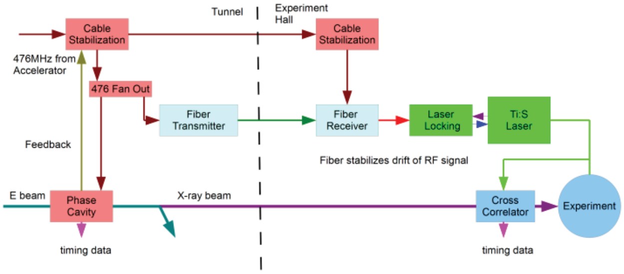
Both cross-correlators are X-ray pump / optical probe systems and cannot work with very low X-ray intensities. Unfortunately the shortest pulses in LCLS and other XFELS are expected to be produced with low X-ray fluxes. The minimum flux required for the cross correlators has not yet been determined.

NEW LCLS TMING SYSTEM

The LCLS timing system is currently being modified to provide improved performance and reliability. The new design has two key features:

- Primary timing is derived from the X-ray / optical cross correlator.
- Modular design to allow upgrades of individual components.

The overall design is based on using an X-ray / optical cross correlator as the most direct way to measure relative timing of the X-rays and pump laser. When this data is available for offline data correction, there is minimal advantage to improving the performance of the rest of the timing system below the ~50-100fs RMS jitter of the accelerator. The subsystems are shown in Figure 8.



Red=RF, Cyan = fiber, Green = laser, Blue = X-ray
Figure 8: Timing Subsystems.

RF Subsystem

The phase cavity design is essentially unchanged from the existing LCLS system[7]. Two 2805MHz cavities are used to measure the electron beam time relative to the RF reference.

RF at 476MHz is transmitted from the phase cavity system to the experimental hutches. The design has been modified relative to the previous LCLS design to eliminate the phase locked loop between the phase cavity signal and the hutches by integrating its function into the cable system.

The cable system operates by locking a VCO at the receive end of the cable to the phase measured at the transmit end. At the receive end the average of the phase of the forward and reflected signals in the cable is then first order independent of cable length. Laboratory tests indicate a long term stability of a few picoseconds for this system. The hardware block diagram is shown in Figure 9.

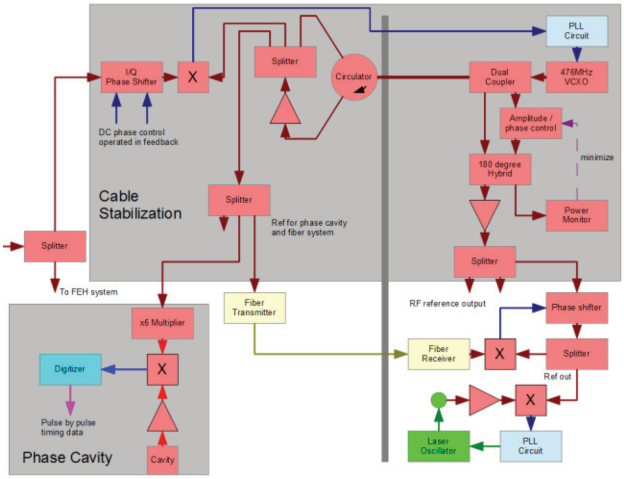


Figure 9: RF subsystem.

Fiber Subsystem

In the new LCLS design the fiber system is used to improve the timing stability of the RF from the cable stabilization system over long timescales. Initially the LBNL interferometer fiber system will be used, but other systems can be substituted as the technology develops.

A simplified RF based fiber system is being tested at SLAC for this application since the use of the cross-correlator reduces the long term stability requirements on the fiber system – and may even allow operation with just the RF system.

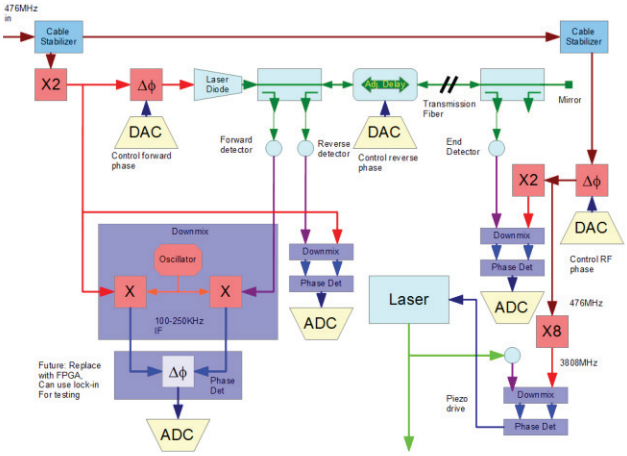


Figure 10: SLAC simplified fiber system.

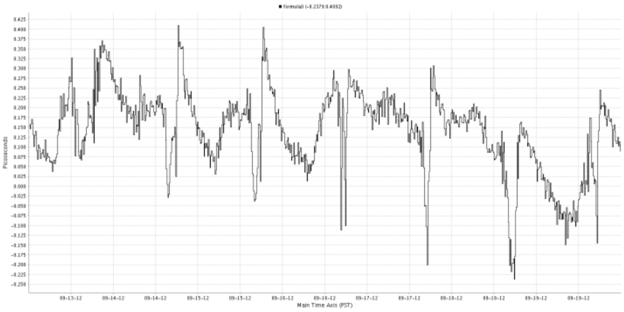


Figure 11: Simplified fiber system: 1 week test 600fs pk-pk for 1.8 ºC pk-pk, 500M fiber.

Laser Locking System

The laser locking system uses a photodiode to monitor the mode-locked oscillator and phase compare against the RF reference. Recent results at LBNL with high linearity diodes and an improved feedback algorithm have demonstrated 25fs RMS noise on the laser system[6].

Commercial laser locking systems can also be used if they can meet the stability and noise requirements.

FUTURE DEVELOPMENTS

We expect the "conventional" timing for the LCLS; the beam pickups, fiber system and laser locking to develop into a simple, high reliability system to provide jitter and stability below the ~100fs uncorrectable timing jitter of the accelerator. This should be sufficient to keep the beam within the dynamic range of the X-ray / Optical cross correlators which will be used for offline correction of the data.

The existing spatial and spectral cross-correlator concepts will be engineered to require minimal intervention by the experimenters. Data analysis systems are under development to provide near real-time timing information to allow experimenters to debug experiments during their beam time.

Ongoing developments in X-ray FELs suggest that pulse lengths below 5fs FWHM are readily available (though not yet directly measured)[11], and few-femtosecond optical pulses have been demonstrated at a number a laboratories [12]. In combination these could allow pump-probe experiments on few-femtosecond timescales. The existing X-ray / Optical cross correlators are expected to have single femtosecond resolution and new techniques will be needed for the ultra-fast regime.

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