LCLS-II Technical Note

Possible improvements to the LCLS-II experiment timing

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Motivation: A significant fraction of X-ray science experiments rely on optical pump / X-ray probe for femtosecond time resolution measurements. Improving the timing resolution of these experiments will increase the science reach of the machine.

Noise Spectrum: Timing noise cannot be described as a single number, but must be viewed as a noise spectral density. In practice the absolute time difference between laser and X-rays can only be measured by the experiment itself with some sort of T0 finding procedure. For most experiments what matters is the total noise in the time between T0 measurements.

Laser / X-ray cross-correlator: For some experiments a laser / X-ray cross-correlator similar to the LCLS "Time Tool" can be used to measure the relative timing of the laser and x-rays in the experiment. This can be used for offline correction of the experiment data, or for feedback on the timing at rates slower than the readout rate of the cross-correlator. In some experiments the timing resolution is set by the cross-correlator resolution.

Single vs multi-pulse experiments: In experiments where every pulse is an independent measurement, the cross-correlator can be used to tag pulses with time delay for offline sorting. The science resolution is set by the cross-correlator resolution.

Accelerator timing:

Timing Chain: The relative timing of the experiment lasers and the X-rays is determined by

X-rays:

- Accelerator: The accelerator produces an electron beam with some jitter relative to the phase reference line. This is controlled by the LLRF system. In LCLS-II the LLRF spec is to be less than 20 fs rms for systematic errors; better performance is expected for random LLRF errors which is expected. Note that only jitter faster than both the ~KHz locking frequency of the experiment system lasers and the beam rate is important, slower jitter and drifts are corrected by feedback.
- X-ray transport: The X-rays are transported several hundred meters through a series of small angle mirrors to the experimental hutches. Due to the small angles, the mirrors do not introduced significant jitter, however ground motion may produce femtosecond level path length changes.

Laser:

- Beam Arrival Time Monitor: This measures the electron beam arrival time at the end of the undulator and provides a timing reference for the experiments. This is measured at full beam rate.
- Timing transport: This transports the timing information from the Bunch Arrival Time monitor to the experimental hutches, a distance of several hundred meters
- Laser locking system: This locks the laser mode-locked oscillators to the timing transport system.
- Laser amplifier and Transport: This is the combination of regenerative amplifiers, single pass amplifiers, non-linear frequency generation and transport lines from the laser oscillators to the experimental chambers.

Cross-Correlator:

- The Laser/ X-ray cross-correlator is located near the experimental chamber in the hutch. It uses a nonlinear interaction in some material between the X-rays and the optical laser to measure the relative timing. This measurement is independent of the laser and X-ray transport systems. In addition to any measurement jitter and drift, there is the potential for drift in the meter-scale optical transport between the experimental chamber and the cross correlator.

Baseline System

The planned baseline system is very similar to that used for LCLS-I.

- Accelerator: The LCLS-I accelerator has 70-100fs RMS jitter relative to the RF reference line. Drift is corrected by the arrival time monitor.
- Beam arrival time monitor: Copper RF cavities. LCLS-I has ~15fs RMS single shot noise and ~100fs 1-day drift in normal operation. An experimental algorithm that will be implemented in production soon has given 10fs RMS noise, 100fs 1-day drift.
- Timing Transport: The existing system uses a reflection stabilized coaxial cable. The added noise is <25 fs (consistent with zero) however drifts are ~1ps 1-day. An improved system is under development that is expected to reduce drift to ~100fs 1-day.
- Laser locker: A RF based laser locker provides 25fs RMS locking, drift has not been measured but is <<1ps 1-day.
- Laser amplifier and transport: The laser transport is not stabilized. Jitter is < 100fs RMS, consistent with zero, and drift is <1ps, consistent with zero.

The majority of precision timing experiments at LCLS use an X-ray / optical cross-correlator for offline correction of timing. This allows experiments with ~10fs RMS resolution. For experiments where the cross-correlator is not available, typical resolutions are ~100fs.

LCLS-II changes from LCLS-I:

- The superconducting LCLS-II accelerator is expected to have substantially lower jitter than the copper LCLS-I linac. The jitter will be the result of the RF and beam feedbacks correcting the low frequency noise created by microphonics. The microphonic spectrum and amplitude is not

known, but estimates suggest 10fs of femtosecond jitter, mostly at low frequencies that can be tracked by the laser locking system.

- The mode-locked lasers will be fiber lasers instead of Ti:Sapphire lasers. Fiber lasers have substantially lower timing noise, so the overall system performance is expected to be substantially better. Best estimates are 5-10fs RMS.

It is expected that baseline LCLS-II will be able to perform 20-100fs RMS timing experiments (depending on the time between T0 measurements) without the use of a cross-correlator. With existing cross-correlator designs, the experimental resolution will be <10fs RMS.

Possible timing improvements:

Note that these are new systems and it is not possibly to reliably predict their performance without more R&D and/or measurements on the hardware.

<u>Cross-correlator</u>: For experiments where it can be used, an X-ray / optical cross-correlator provides the best timing performance. If the cross-correlator can be used at high rate, it can provide direct laser feedback in addition to re-sorting experimental data. A high frequency general purpose cross-correlator will provide timing performance to the limit of the measurement resolution. There are a variety of possibly approaches to high frequency cross-correlators and substantial R&D is required.

Estimated experimental resolution <5fs RMS (for the subset of experiments that can use the cross-correlator). $5M

<u>Optical timing system</u>: A fiber based timing system will improve the performance of all of the subsystems except the laser transport. Experiments at other labs have demonstrated long distance laser locking with noise of a few femtoseconds. Several sub-systems are required

- Optical bunch arrival time monitor
- Optical timing transport
- Optical Laser Amplifier and Transport systems

This is a complex system with multiple fiber lasers. In order to be useful, this needs to include fiber stabilization links around the Laser Amplifier and Transport Systems. Substantial engineering and controls integration work is required.

Estimated experimental resolution <5fs RMS. $5-10M