SLAC-PUB-14234

FEMTOSECOND OPERATION OF THE LCLS FOR USER EXPERIMENTS*

A. Brachmann, C. Bostedt, J. Bozek, R. Coffee, F.-J. Decker, Y. Ding, D. Dowell, P. Emma, J. Frisch, S. Gilevich, G. Haller, G. Hays, Ph. Hering, B. Hill, Z. Huang, R. Iverson, E. Kanter, B. Kraessig, H. Loos, A. Miahnahri, H.-D. Nuhn, A. Perazzo, M. Petree, D. Ratner, R. Santra, T. Smith, S. Southworth, J. Turner, J. Welch, W. White,, J. Wu, L. Young: SLAC National Laboratory, Stanford CA, USA

J. M. Byrd, G. Huang, R. Wilcox: LBNL, Berkley CA, USA

Abstract

In addition to its normal operation at 250pC, the LCLS has operated with 20pC bunches delivering X-ray beams to users with energies between 800eV and 2 keV and with bunch lengths below 10 fs FWHM. A bunch arrival time monitor and timing transmission system provide users with sub 50 fs synchronization between a laser and the X-rays for pump / probe experiments. We describe the performance and operational experience of the LCLS for short bunch experiments.

FEMTOSECOND OPERATION

In normal operation the LCLS uses 250 pC electron bunches to produce X-ray pulses with lengths between 50 and 500 femtoseconds. The LCLS can also be operated at 20pC to produce very short pulses. The pulse length is below the resolution of the accelerator instrumentation but based on indirect measurements it is believed to be less than 10fs FWHM [1].

For short pulse mode the the photo-cathode laser is apertured to a 0.6mm diameter spot on the cathode with a 3.6 ps FWHM pulse. The source laser is operated 15 degrees from the Schottky edge produce an electron beam out of the gun with a 700fs RMS bunch length. Typical emittance is 0.14 microns RMS in each plane.

The beam is compressed in two bunch compressors to near maximum peak current to produce a bunch length below the 20fs resolution of the transverse cavity. Simulations using measured beam paramters at 8.3 KeV photon energy give a pulse length around 5 femtoseconds FWHM.

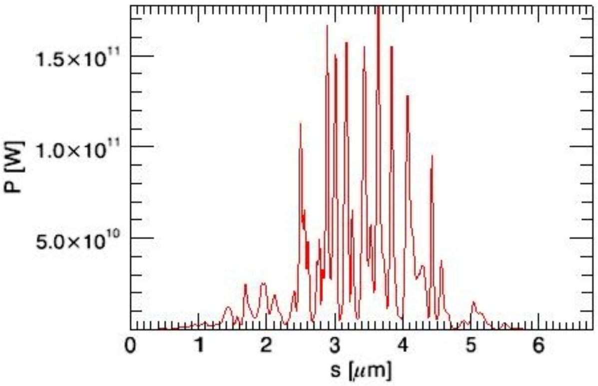

Figure 1: Simulated pulse length

In Figure 2 the FEL pulse energy and (uncalibrated) peak electron beam current are plotted as a function of the phase of the L2 compression section. The FEL does not lase well at full compression, probably due to a combination of slice energy spread and CSR induced emittance growth. Maximum compression is at -32.25 degrees, and the FEL lases well at +/- 1 degree from this peak. The bunch length when operating 1 degree from maximum compression can be calculated using a simple linear model and gives approximately 5 fs FWHM.

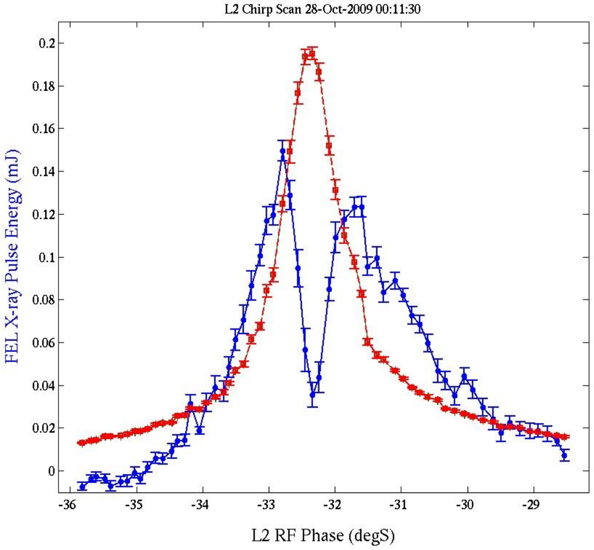

Figure 2: FEL power (blue) and Ipk(red) vs. compression

PUMP-PROBE EXPERIMENTS

A variety of experiments can be preformed by pumping the sample with a visible laser and after a variable delay probing with a X-ray pulse. This requires synchronization of the FEL and a conventional laser and a system to measure their relative timing. The LCLS uses S-band RF cavities to measure the pulse to pulse beam time relative to a phase reference line. A slow feedback adjusts the timing of a signal that is transmitted to the experiment pump laser through an interferometrically stabilized fiber link [2]. A block diagram of the timing system is shown in figure 3.

The electron beam timing jitter measured at the phase cavities relative to the 476 MHz phase reference line was 130 fs RMS for the 2009 run and 60 fs RMS for the 2010 run. The improvement was due to using a different source for the phase reference as shown in figure 3. The phase

Work supported in part by US Department of Energy contract DE-AC02-76SF00515.

SLAC National Accelerator Laboratory, Menlo Park, CA 94025

cavity system reports the pulse to pulse relative timing of the electron beam and phase reference to allow offline improvement of the experimental data.

The RF based beam arrival time measurement sytstm is described here. The fiber and laser locking systems are described in XXX

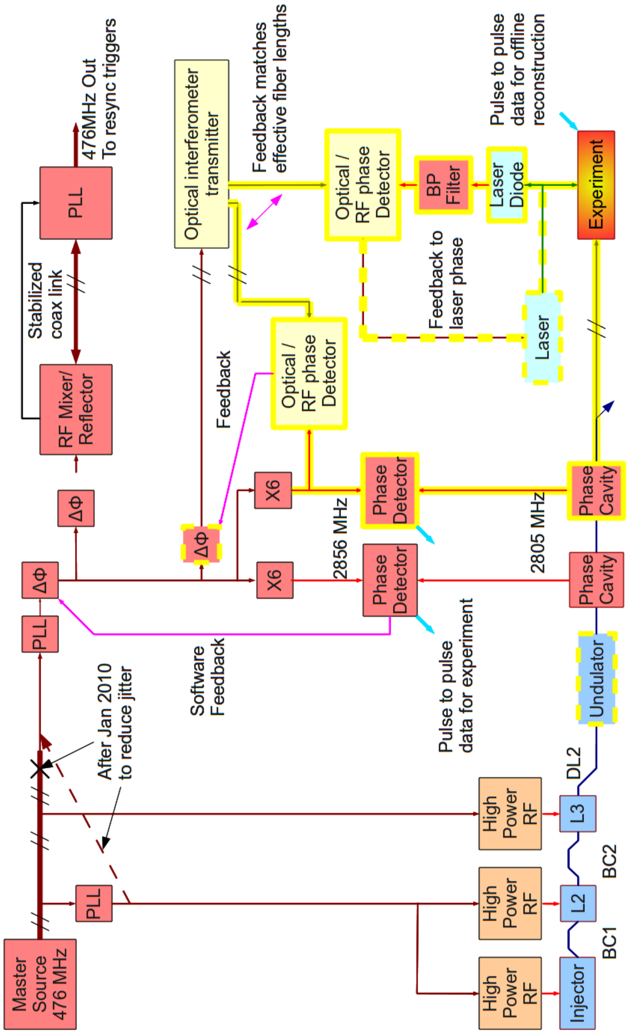

Figure 3: Timing system

BEAM ARRIVAL TIME MONITOR

The Beam Arrival Time system uses single cell resonant cavities operating at 2805MHz which are excited by the bunch passage. This produces a decaying exponential tone which is mixed with the 2856 MHz 6th harmonics of the 476 MHz reference line to produce a 51MHz IF. That signal is digitized with the 119MHz 4th subharmonic of the 476 MHz. Figure 4.

The input attenuator is used to control the signal level sent to the mixer. The desired level is a trade-off between noise and nonlinearity that would convert bunch charge fluctuations into timing noise. A signal level of -10dBm into the mixer (Marki Microwave T3-03) gives good performance. The cavity produces signals larger than this for bunch charges above approximately 50 pC. The mixer output is followed by a 20dB gain low noise, high linearity amplifier (MiniCircuits ZHL-2010+) to match the signal to the digitizer input level.

The digitizer is a VME module constructed at SLAC based on a Linear Technology LTC2028 16 bit chip. The external trigger to the digitizer is synchronous with the beam so the waveform is reproducible shot to shot. If the divide-by-4 circuit jumps buckets it is reset by software.

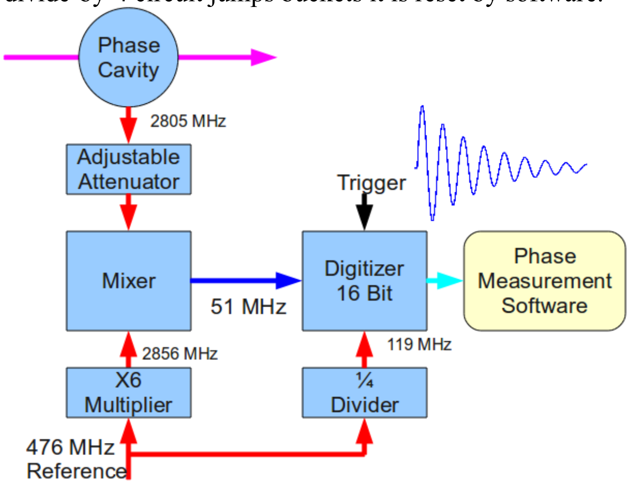

Figure 4: Bunch Arrival Time system block diagram

Phase Measurement Algorithm

The phase cavities are constructed from copper and will exhibit a temperature Dependant frequency shift that will result in a change in the average phase of the signal on the order of several picoseconds per degree C, much larger than the tolerance for the system. Fortunately the signal provides a direct measurement of the cavity frequency on each pulse which can be used to correct for the temperature coefficient.

The digitized signal is down-converted to provide a measurement of phase vs. time. The projection of this phase back to the beam arrival time provides a signal that is first order independent of of cavity frequency.

Beam Arrival Time Monitor Performance

Comparison of the 2 phase cavity systems provides a measure of their phase drift and noise. Note that while the systems use independent hardware after the reference line, they are exposed to similar environments so some drifts may not be seen in this comparison.

In addition drifts of the X6 multipliers will show up in the cavity to cavity comparison, but will not effect the operation in the real system: the fiber system is locked to the ouput of the X6 multiplier.

Figure 5 shows the difference between the times measured by the two systems and the 100 pulse shot-to-shot RMS difference plotted over 4 days of operation at the normal 250pC operating charge.

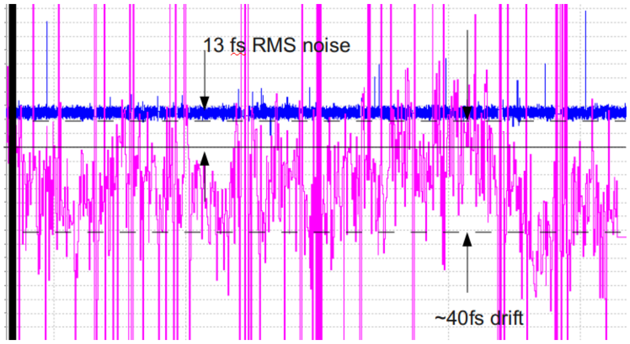

Figure 5: Phase cavity system performance over 4 days showing 13fs RMS noise (blue) and 40fs drift (magenta).

When the accelerator is operating at 20pC for short bunches, the phase cavity noise increases due to the small signal level. Figure 6 shows the performance over 3 hours. This is the longest run at 20pC with the present version of the phase cavity system.

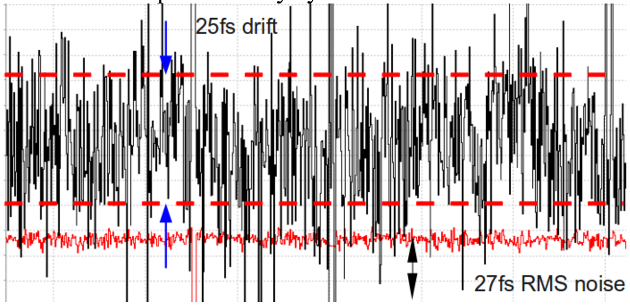

Figure 6: Operation at 20pC showing 27fs RMS noise and 25fs drift over 3 hours.

OVERALL SYSTEM PERFORMANCE

The noise and drift performance of the fiber system cannot be measured as installed – there is no alternate system for comparison. Based on measurements at LBNL the RMS noise and drift are believed to be below 10fs.

The experiment laser phase noise is 25fs RMS in a 1KHz bandwidth, but increases to 120fs RMS at broadband (up to 100 KHz), believed to be due to acoustic noise. There is no direct way to measure the laser timing drift.

Preliminary results from laser pump / X-ray probe experiments performed in 2009 indicate a beam timing jitter of approximately 150 fs between the pump laser and the X-rays. This is consistent with the electron beam measurements preformed at the same time. The reference line has been upgraded in 2010 (see figure 3), but new experiment results are not yet available.

The 2009 experiments indicated sub 50-femtosecond pump laser to X-ray timing noise and drift(after off-line correction). This was likely dominated by the noise of the pump laser relative to the fiber system reference. [3]

PERFORMANCE IMPROVEMENTS

The low frequency noise and drift performance of RF components is not generally specified by the manufacturer. Work is under way to test components to find improved performance substitutes.

The algorithm used is non-ideal as it does not make use of the fact that the cavity frequency varies slowly with time. It also discards some of the data due to phase ringing from components in the RF system. Initial tests indicate that a factor of 2 improvement in noise may be possible from algorithm improvements.

The existing fiber system includes some RF components that are outside of the stabilization loop and could probably be optimized.

The laser locking system is believed to be the largest contributor to timing noise. Work is underway to isolate the laser from acoustic noise and to use low drift and temperature stabilized cables and components in the locking system.

The low (68MHz) repetition rate of the laser mode locked oscillator limits the noise performance if its phase detection system. Experiments are underway to use an etalon system to multiply the beam rate on the photodiode to improve the measurement phase noise.

SYSTEM LIMITATIONS

The X-ray timing may not match the electron timing if not all of the bunch lases. This system also does not measure the X-ray path length from the undulator to the experimental chamber, or changes in path length from the pump laser oscillator to the chamber. These effects probably limit the performance of this type of system to a few femtoseconds or some fraction of the electron bunch length.

REFERENCES

[1] Y. Ding et. al. "Measurements and Simulations of Ultra-low Emittance and Ultra-short Electron Beams in the Linac Coherent Light Source", Phys Rev Lett. 102, 254801, (2009).

[2] J. M.Byrd et. al. "Femtosecond Synchronization of Laser Systems for the LCLS", This conference.

[3] J. M. Glowina et. al. "Time Resolved Pump Probe Experiments at the LCLS", To be published in Optics Express. (2010)