SLAC-PUB-12593
June 2007

TIMING AND SYNCHRONIZATION AT THE LCLS*

P. Krejcik#, R. Akre, S. Allison, M. Browne, L. Dalesio, J. Dusatko, J. Frisch, R. Fuller, A. Gromme, K. Kotturi, S. Norum, D. Rogind, W. White, M. Zelazny

SLAC, Menlo Park, CA, 94025, U.S.A.

Abstract

Timing and synchronization in the LCLS is a three tier process: At level 1 an event generator broadcasts timing fiducials to event receivers over a fiber network. Hardware and software triggers are created in the event receiver according to the digital pattern broadcast at 360 Hz by the event generator. Beam synchronous data acquisition driven by these triggers allows time-stamped acquisition of all diagnostic devices simultaneously on every pulse. Timing fiducials are phase synchronized to the low level RF reference system with 10 ps precision. Level 2 synchronization ensures that individual klystrons powering gun and accelerating sections remain within a few tenths of a degree S-band to the phase reference distribution scheme. The gun laser system is also phase locked to this reference to within 0.5 ps. Level 3 provides synchronization at the 10 fs level between the electron beam and pump-probe laser systems in the end station experiments. This will be achieved with electro-optic sampling of the electron bunch and by synchronizing the laser systems over a stabilized fiber distribution system. A fiber stabilization scheme is currently under test at Lawrence Berkeley Laboratory.

INTRODUCTION

The Linac Coherent Light Source project, LCLS, is a 4th generation X-ray light source using the SLAC linac to deliver 14 GeV single bunch electrons to an undulator FEL operating at 1.5 Å. Linac based FELs are single pass machines where each pulse uses a fresh electron bunch from the gun. Stability of operation requires tight tolerances on the timing and synchronization of the production and acceleration of these bunches. Ultrafast science can be done with the femtosecond bunches from the LCLS and requires femtosecond clocking of the bunches.

Timing and synchronization incorporates several levels of the accelerator control system. It includes the programmable triggers that drive hardware functions. A synchronous data acquisition scheme to record data from devices on a single beam pulse throughout the machine is coupled with the broadcasting of event triggers. The timing triggers and synchronous acquisition systems have been programmed onto Micro-Research™ event generator and event receiver modules.

Synchronization with the beam also requires that the RF system be phase locked the beam. The low level RF (LLRF) distribution is based on a low noise master oscillator and a temperature stabilized copper coaxial cable phase reference distribution system.

Both the LCLS timing system and the LLRF are constrained by the requirement to be compatible with the existing SLAC systems and remain in synchronism with other beams in the SLAC linac. The LCLS system is built on top of the existing SLAC systems and to provide greater precision and stability for LCLS beams.

A new requirement for the LCLS is the need to synchronize laser systems at the femtosecond level. Many experiments at the LCLS rely on pump-probe systems where femtosecond phenomena are only revealed if the pump laser synchronization is known with this precision.

THE TIMING EVENT SYSTEM

A feature of the SLAC timing system is that the triggers are phase locked to the LLRF distribution system. A main drive line (MDL) running the length of the 3 km linac carries a 476 MHz reference signal. Superimposed on the RF are 360 Hz fiducials in the form of double amplitude pulses. A receiver attached to the MDL detects these fiducials and outputs both a 119 MHz reference RF signal plus a 360 Hz clock signal, as shown in Figure 1.

The clock signal and the reference RF are fed into an event generator (EVG), supplied by MicroResearch™[1]. The EVG has been programmed at SLAC to broadcast event codes at 360 Hz out to each of the event receivers (EVRs). The EVRs, also manufactured by Micro-Research™, are linked to the EVG over optical fiber through a fanout module. The EVG must pay heed to the pattern broadcast by the existing SLAC master pattern generator (MPG) which sets up beam codes in a 360 Hz pattern for the other accelerator systems. Eventually the EVG will take over the role of the MPG for all SLAC timing systems, but for now it receives the digital pattern broadcast over a pattern network (PNET). This allows the existing SLC timing network infrastructure to be used for the klystron modulator triggers and remain in synchronism with the new LCLS timing system.

The event codes are setup through an EPICS input output controller (IOC) interface. The EVR IOC has a user interface for setting up individual trigger characteristics (delay, width, polarity) and assigning them to an event code from the EVG.

The stability of the timing triggers has been measured by comparing them with triggers from the standard timing buffer (STB) in Figure 1. For the VME based EVR we measured a RMS timing jitter of less that 10 ps over a 30 minute period.

*Work supported by DOE contract number DE-AC02-76SF00515
#pkr@slac.stanford.edu

Presented at 8th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators,

5/20/2007-5/23/2007, Venice, Italy

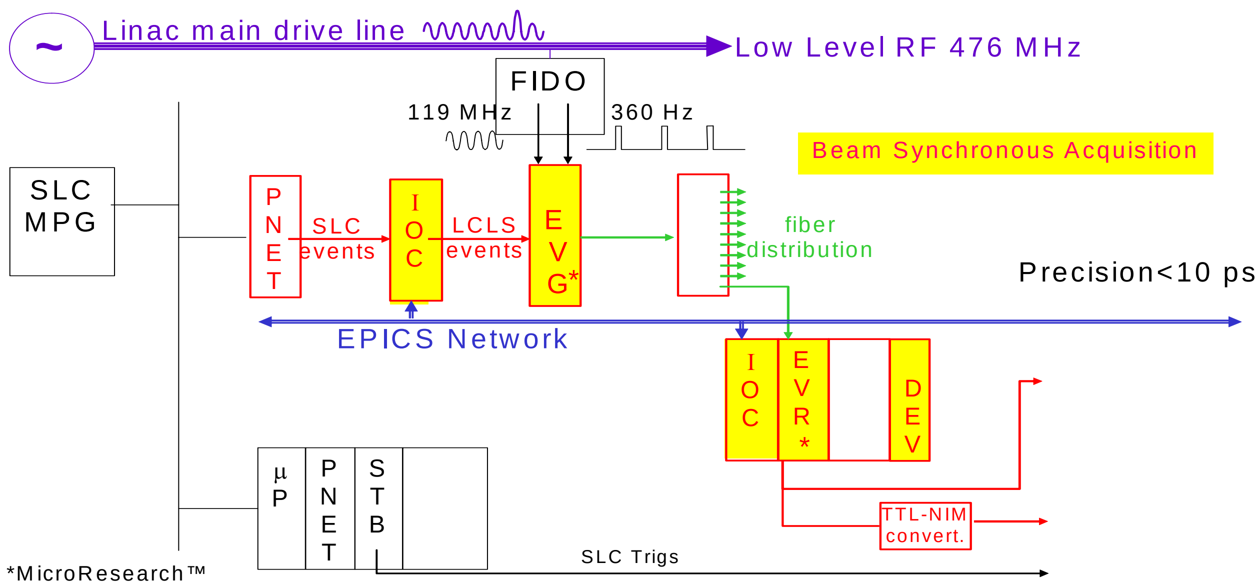

Figure 1: Block diagram of the major timing system components synchronized to the low level RF.

Beam Synchronous Acquisition

The EVR supplies triggers to the measurement devices such as beam position monitors (BPMs) as well as supplying time stamp data to the IOC for the data acquisition. Every measurement record taken on a single beam pulse through out the machine can be correlated by this common time stamp. Further more, each IOC connected with an EVR has a number of data buffers set up to receive data from beam synchronous acquisition devices. These buffers can be programmed to accept beam data in unison across the machine with any prescribed pulse pattern, which we call an event definition. Buffered data for all devices can be recorded up to the full machine rate of 120 Hz for as many as 2800 pulses. Thus all devices in the machine can be correlated on a single beam pulse measurement and all devices can be read for up to 2800 consecutive pulses.

LOW LEVEL RF SYNCHRONIZATION

A low-noise microwave oscillator is phase locked to the MDL at a pick off point near the LCLS injector, as shown in Figure 2. We therefore remain synchronous with the other accelerator users but we use its output as the new phase reference for LCLS LLRF and for locking the photoinjector laser. Copper coaxial cable provides the phase reference distribution. Critical components are housed in a temperature stabilized room and the reference line passes through the accelerator tunnel which maintains a temperature stability of a few tenths of a degree during normal operation.

Experience was gained at the Sub-Picosecond Pulsed Source (SPPS) project[2] at SLAC in locking a Ti:Sapphire laser to a low noise oscillator. The new oscillators have a measured noise floor of -157dBc/Hz at 476MHz, corresponding to 11fS RMS Jitter in 5MHz BW or 31fS RMS Jitter in 40MHz BW.

Each klystron in the LCLS injector is driven by a solid state sub-booster stage (SSSB) so that the phase and amplitude can be individually controlled by an electronic I&Q modulator. The output of the accelerating structures is coupled to a phase and amplitude detector so that the phase of the RF as seen by the beam can be compared to the reference RF.

Low Level RF Control

Digital I&Q control of the LLRF uses LCLS phase and amplitude control (PAC) modules and phase and amplitude detector (PAD) modules throughout. A local oscillator (LO) signal operating at 2830.5 MHz is derived from the reference 2856 MHz and is mixed with the RF detected in the PAD. This gives an IF of 25.5 MHz which is digitized in the PAD ADC. The ADC clock signal of 104 MHz is also derived from the LO module.

Software feedback loops between the PAD and the PAC compensate for slow drifts in the klystron and laser systems. In figure 2 only the laser feedback is shown. An optical diode detects part of the light output from the laser and the feedback maintains the laser phase with respect to the RF reference.

Performance requirements for the low level RF

The longitudinal beam dynamics requirements for the bunch compression in the LCLS dictate that the phase stability of the RF is within very tight tolerances. The laser phase stability is to be better than 0.8 ps. The S-band phase stability is given as 0.10° S-band and the higher harmonic cavity has a stability requirement of 0.50° X-band. A beam based feedback using the measured energy and bunch length of the electron beam will provide final control of the injector LLRF settings.

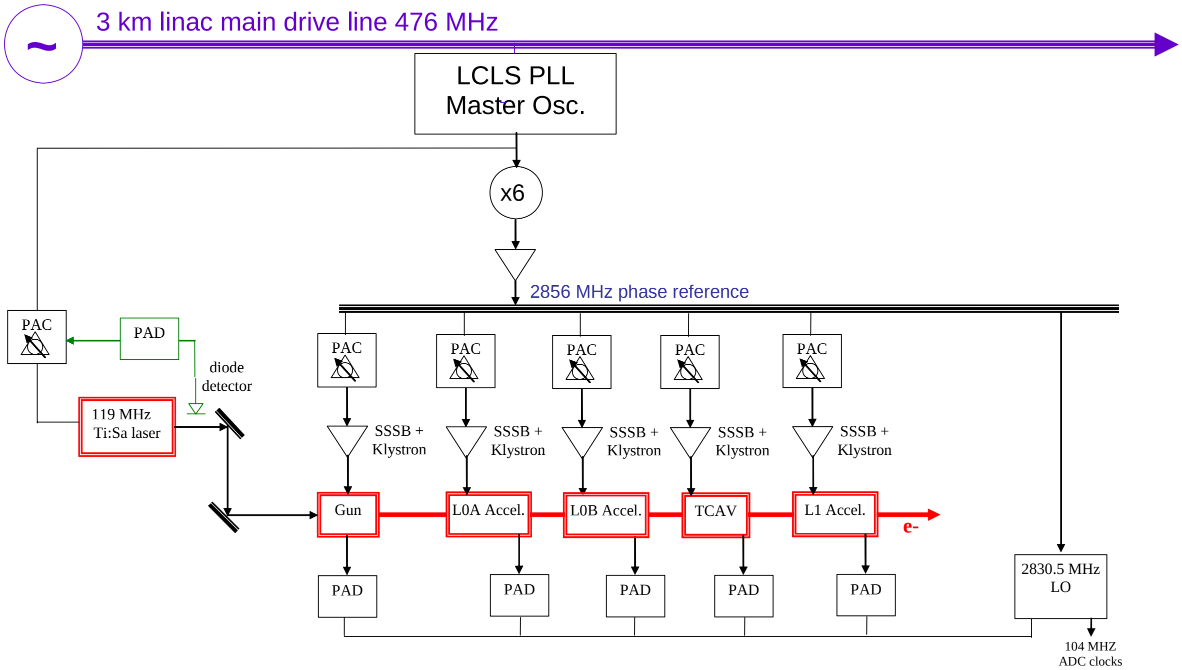

Figure 2: Low level RF for the LCLS photoinjector.

OPTICAL SYNCHRONIZATION

The stability of a state-of-the-art microwave phase reference scheme is of the order of hundreds of femto seconds. To move beyond this level requires different technologies. Two schemes are pursued at the LCLS. One is distribute a lower noise reference signal to the laser and klystron system via an optical distribution scheme. The other is to accept a certain amount of jitter in the electron beam arrival time, but to measure it with respect to a reference laser in conjunction with a pump-probe experiment. Both schemes rely on sending signals down a stabilized optical fiber.

Two optical fiber schemes are being studied. In one scheme a CW laser allows the optical length of a fiber to be regulated at one wavelength using a heterodyne detection method[3]. This technique offers great precision since the fiber length can be maintained to within one optical wavelength. However, difficulties arise when the optical carrier is modulated in order to transmit the RF signal. The modulation sidebands have a group velocity deviation because of the dispersion in the fiber so that the stabilization at the carrier frequency is no longer as precise.

A second scheme uses a pulsed laser to measure and stabilize the fiber[4]. The fiber is stabilized at the wavelength of the modulation envelope of the pulsed signal, so it cannot approach the precision of the optical wavelength stabilization scheme described above. However, it is simpler to implement because the LLRF signal is already carried by the fiber. For this reason it is an attractive solution for a staged approach to providing femtosecond synchronization.

The final challenge is to synchronize two remote lasers with femtosecond precision. It is desirable to lock a pump-probe laser to the master laser of the photoinjector. Even greater precision is called for to lock the pump-probe laser to a diagnostic laser for measuring the electron bunch arrival time. At the SPPS an electro optic (EO) detection scheme was used to clock the electron bunch arrival time with respect to the laser[5]. This method relies on the EO laser being synchronized to the pump-probe laser at the femtosecond level.

While many parts of optical synchronization have been demonstrated it still remains to put them together in a workable system for use at a facility like the LCLS.

REFERENCES

[1] MicroResearch, http://www.micro-researchfinland.fi/
[2] P. Krejcik et al, Commissioning of the SPPS linac bunch compressor**,** Proc. Particle Accelerator Conference, Portland, Oregon, 12-16 May 2003, pp. 423-425.
[3] J. W. Staples and R. Wilcox, Fiber Transmission Stabilization By Optical Heterodyning Techniques And Synchronization Of Mode-Locked Lasers Using Two Spectral Lines, Proc. of the 27th International Free Electron Laser Conference, Stanford, California, August 2005, pp. 686-689.
[4] A. Winter et al, High-Precision Optical Synchro-nization Systems For X-Ray Free Electron Lasers, Proc. of the 27th International Free Electron Laser Conference, Stanford, California, August 2005, pp. 677-681.
[5] A. Cavalieri et al, Clocking Femtosecond X Rays, Phys. Rev. Lett. **94**, 114801 (2005).