LLRF SYSTEM UPGRADE FOR THE SLAC LINAC*

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Abstract

The Linac Coherent Light Source (LCLS) at SLAC is in full user operation and has met the stability goals for stable lasing. The 250pC bunch can be compressed to below 100fS before passing through an undulator. In a new mode of operation a 20pC bunch is compressed to about 10fS. Experimenters are regularly using this shorter X-ray pulse and getting pristine data. The 10fS bunch has timing jitter on the order of 100fS. Physicists are requesting that the RF system achieve better stability to reduce timing jitter. Drifts in the RF system require longitudinal feedbacks to work over large ranges and errors result in reduced performance of the LCLS. A new RF system is being designed to help diagnose and reduce jitter and drift in the SLAC linac.

INTRODUCTION

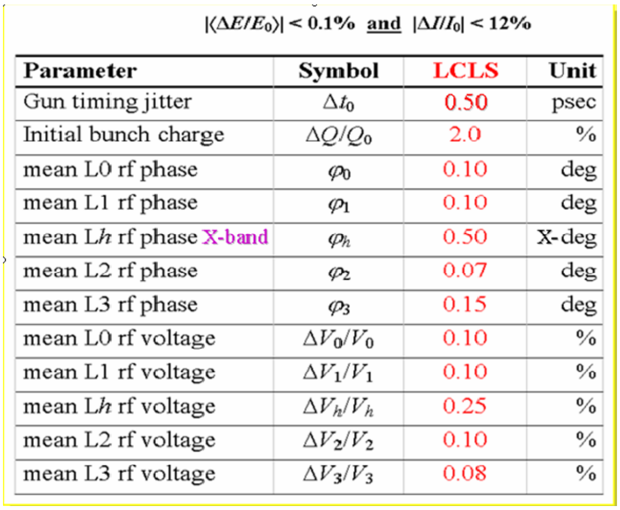
LCLS at SLAC has been delivering the brightest hard X-ray laser to users since September 2009. The SLAC Linac produces sub 100fS length electron bunches which pass through the undulators. Recently, the low charge mode of operation with 20pC rather than 250pC allows X-ray pulse lengths to be compressed down to the 10fS level. The actual pulse length is difficult to measure in this regime. Since the experimenters can now receive pulse lengths on the order of 10fS, there is a desire to push the timing jitter of the pulse down to the 10fS level. This will reduce errors in data sets taken by the experimenters. To achieve this goal, more precise timing synchronization and better diagnostics are required. The stability of the RF system is critical in setting up the position to energy correlation for the stable bunch length. The original specifications derived from simulations require the RF system to be stable to below 100fS in several critical injector stations.[1] Looking toward the future, the new LLRF upgrade should push the stability and accuracy of the RF system to limits which will temporarily satisfy the experimenters.

LCLS RF REQUIREMENTS

LCLS specifications require RF stability of 0.1%rms in amplitude and 100fSrms in an 850nS fill time S-Band structure, Table 1. These numbers are for time intervals of up to 2 seconds. Beyond that the long term drift requirements must be held, Table 2.

There are several factors which have been associated with short term jitter. White noise in the RF system, originating from the thermal noise floor adds to the jitter at the 35fS level. This noise is typically stable and sets a lower limit on the capability of the RF system. Jitter in the high power klystron modulators is one of the leading factors adding to noise in the RF system. The thyratrons which trigger the line type modulators require often ranging of the hydrogen reservoir to maintain the stability required by LCLS. When properly adjusted, the modulator stability is down at the 0.01% rms level. Jitter is also seen as a result of RF instabilities in the high power system. Breakdown in high power loads and the SLAC Energy Doubling "SLED" cavities in the form of arcing or multipactoring can be correlated to RF stability. The new LLRF system will assist in reduction of the above noise sources.

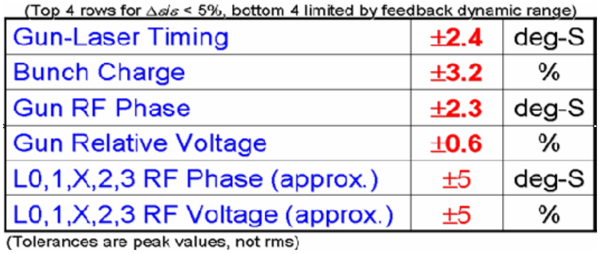
Table 1: RF Jitter (< 2 Seconds) Specifications



$|\langle\Delta E/E_0\rangle| < 0.1\%$ **and** $|\Delta I/I_0| < 12\%$

Parameter	**Symbol**	**LCLS**	**Unit**
Gun timing jitter	Δt_0	0.50	psec
Initial bunch charge	$\Delta Q/Q_0$	2.0	%
mean L0 rf phase	φ_0	0.10	deg
mean L1 rf phase	φ_1	0.10	deg
mean L*h* rf phase X-band	φ_h	0.50	X-deg
mean L2 rf phase	φ_2	0.07	deg
mean L3 rf phase	φ_3	0.15	deg
mean L0 rf voltage	$\Delta V_0/V_0$	0.10	%
mean L1 rf voltage	$\Delta V_1/V_1$	0.10	%
mean L*h* rf voltage	$\Delta V_h/V_h$	0.25	%
mean L2 rf voltage	$\Delta V_2/V_2$	0.10	%
mean L3 rf voltage	$\Delta V_3/V_3$	0.08	%

Table 2: RF Drift (> 2 Seconds) Specifications



(Top 4 rows for $\Delta\sigma/\sigma$ < 5%, bottom 4 limited by feedback dynamic range)

Gun-Laser Timing	**±2.4**	deg-S
Bunch Charge	**±3.2**	%
Gun RF Phase	**±2.3**	deg-S
Gun Relative Voltage	**±0.6**	%
L0,1,X,2,3 RF Phase (approx.)	±5	deg-S
L0,1,X,2,3 RF Voltage (approx.)	±5	%

(Tolerances are peak values, not rms)

Long term drifts are typically adjusted for by feedbacks. The feedbacks do have their limits. If several drifts occur simultaneously, the feedbacks will correct, but possibly not the parameter that drifted. The drifts are typically temperature related and are often seen to be correlated to outside temperature, diurnal, or cooling water temperature,

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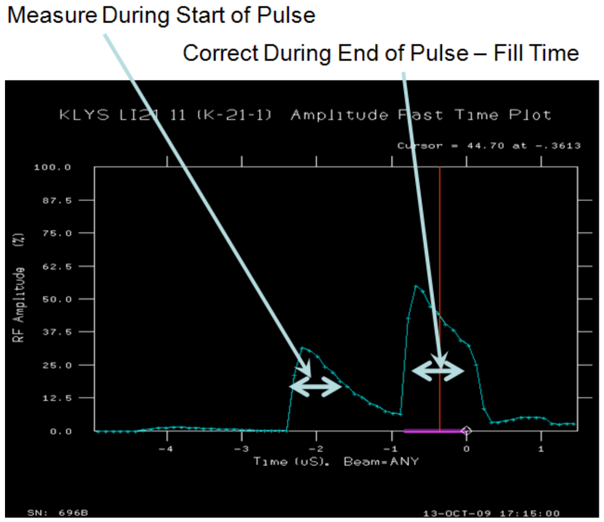
cycle time of minutes. The accelerator structure itself has a temperature coefficient of 8 degrees S-Band per degree F. A temperature change in the accelerator of 0.3 degrees F will put a system out of tolerance. The existing SLAC RF system only measures the RF at the input and output of the structure.

NEW LLRF CONTROL SYSTEM

Since operation, the jitter in L1S has been determined to be the major source of jitter in the FEL. A **new tolerance of 0.03 degrees** S-Band is determined to be necessary to reduce the FEL jitter contribution from L1S to below easily detectable levels [2]. The sources of the jitter at times are associated with modulator instabilities. To meet the new jitter tolerance, the new LLRF system will have the capability to do intra-pulse feedback. This will require data to be sampled over the initial part of the RF pulse and corrected during the last 1uS of the 3.5uS RF pulse. This is currently the requirement for L1S only, but as stability requirements for LCLS increase, this requirement may eventually be for all stations. A typical SLED output pulse is shown in Fig. 1.


Measure During Start of Pulse

Correct During End of Pulse – Fill Time

Figure 1: SCP plot of L1S PAD amplitude waveform.

The first part of the pulse shows RF reflected during the fill time of the SLED cavity. The second portion of the pulse shows the RF during the dumping of the energy in the SLED cavity. Feedback of this type will require low noise fast ADCs connected to an FPGA which is connected to fast low noise DACs. A block diagram of this portion of the RF system is shown in Fig. 2. The bandwidth of the system is on the order of 5MHz to implement the phase flip to dump the SLED cavity. The 5MHz bandwidth should be sufficient to do correction in 1uS.

The ADC being considered is a 16bit device that will be clocked at 102MHz. The SNR is listed at 81dBFS, but measurements have shown and SNR of 75dBFS, Fig. 3. The difference in SNR could be due to the test setup and further investigation is necessary.

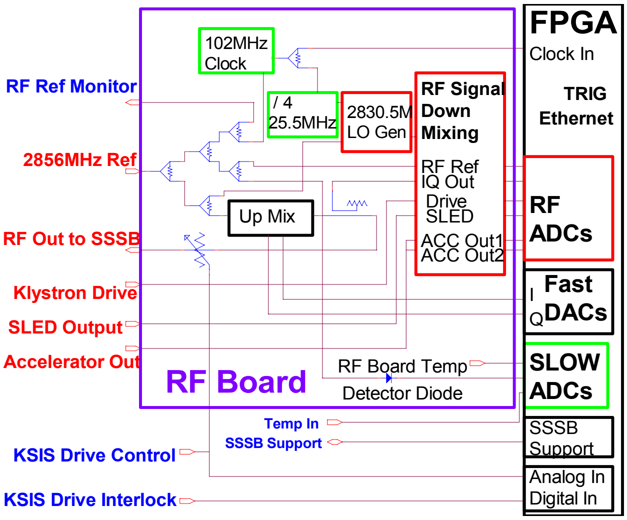


Figure 2: Block diagram of LLRF controller.

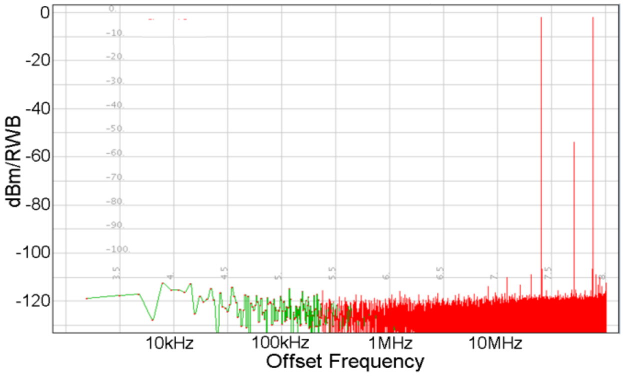


Figure 3: FFT of 25.5MHz carrier clocked in at 102MHz.

The large dynamic range of the ADC is useful in measuring the phase of the beam in the accelerator structure. Data has been taken at klystron station 24-5 in the SLAC main linac using an LCLS Phase and Amplitude Detector "PAD". To further increase the SNR of the RF measurement to beyond 75dB, two ADC channels were used as shown in Fig. 4. High powered RF is measured through a 60dB attenuator on one channel, while another channel measures low RF levels directly. A limiter on the low level channel is capable of handling 1kW of peak input power and is used to protect the electronics from the high power pulses.

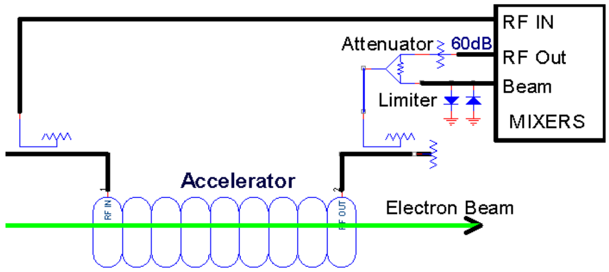


Figure 4: Beam phase measurement setup.

It is desired to use the beam induced RF signal at the output of the traveling wave accelerator to measure beam to klystron RF phase. Two measurements are done, one with the RF on and one with the RF off. The klystron RF signal amplitude is 2000 x higher than the beam signal at 250pC charge in a single bunch and the phase of the beam induced RF is desired to be measured to the 0.1 degree level. Both signals, high power RF in red, and beam induced in black, are shown in Figs. 5 and 6.

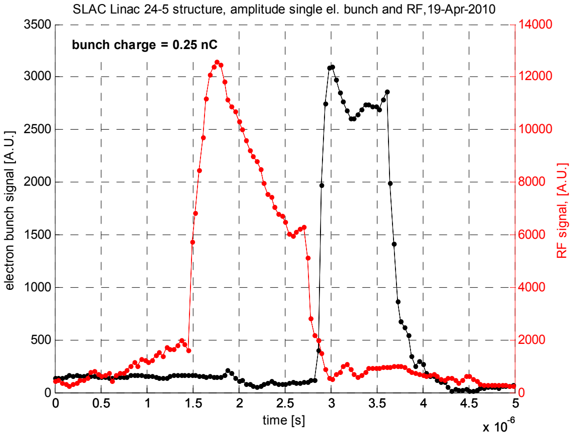


Figure 5: 24-5 Accelerator output RF amplitude in red and beam induced RF amplitude in black.

The beam induced RF has and amplitude of only 3000 on a 16 bit ADC, so we are still not using most of the dynamic range. One hundred measurements were done and resulted in a standard deviation of a 0.1degree rms error, which is partially measurement error and partially actual beam jitter. The beam induced RF phase error of 0.1 degrees rms gives a dynamic range of 55dB. This on top of the 2000:1, 63dB, signal ratio gives a total system dynamic range of 118dB.

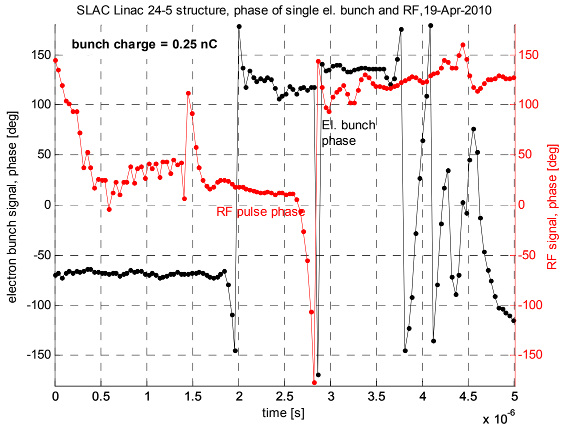


Figure 6: 24-5 Accelerator output RF phase in red and beam induced RF phase in black.

A plot of the RF phase measurement from the beam induced RF will show how the accelerator structure is tuned, black trace Fig. 6. A slope in this pulse would mean that the accelerator is not at the correct temperature. By use of the above method we will be able to keep stations phased to the 0.1degree level. The phasing will be done with respect to the beam which is what really counts and the tune of the structures will also be able to be monitored. The price of this information is a few stolen beam pulses during operation.

SSSB AMPLIFIER FOR KLYSTRONS

Most of the 240 S-band klystrons along SLAC Linac are driven by Sub-booster klystrons. One Sub-booster klystron drives 8 5045 klystrons at each sector. However, Solid-State Sub-booster (SSSB) amplifiers have been in service for the injector of LCLS and several other critical locations for more precise and faster phase and amplitude control of the Linac. 25 units of new 1KW SSSB amplifiers are planned to be installed at Sector 21-24 this June to July.

These 1KW SSSB amplifiers will use the Sub-Booster Klystrons as the pulsed input RF for the current control condition. But they are designed to adapt to the Beam Containment System Triggers, and integrated with PAC and PAD to establish the new LLRF control unit at each klystron station. Eventually the FOX phase shifter, High Power Attenuator and the old PAD will be removed from klystron stations. Figure 7 shows the current and the future klystron station RF system.

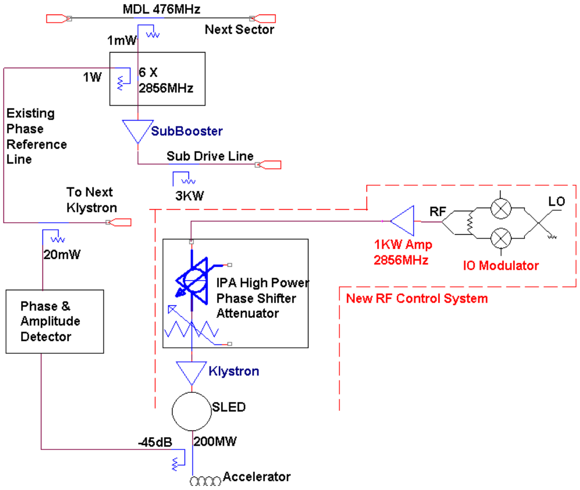


Figure 7: Current and future klystron station RF system.

The first 1KW SSSB amplifier has been measured with 5uS and 100Hz repetition rate. The output power has reached 1KW with the total gain of 30dB. The phase noise and amplitude error are measured with LCLS PAC and PAD on the test bench. The phase noise is less than 0.02 deg. Amplitude error is smaller than 0.02%.

REFERENCES

[1] P. Emma, "Issues and R&D Critical to the LCLS", Proceedings of the 2001 Particle Accelerator Conference, Chicago, http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/TOPA008.PDF.

[2] F-J Decker *et al.*, "Identifying Longitudinal Jitter Sources in the LCLS Linac" IPAC'10 these proceedings.

[3] R. Akre *et al.*, "LCLS LLRF Upgrades to the SLAC Linac" PAC'07 proceedings Albuquerque, New Mexico, http://www.jacow.org.