BEAM STABILITY STUDIES IN THE *LCLS* LINAC*

R. Akre, A. Brachmann, F.-J. Decker, Y. Ding, D. Dowell, P. Emma, J. Frisch, S. Gilevich, G. Hays, Ph. Hering, Z. Huang, R. Iverson, C. Limborg-Deprey, H. Loos, S. Molloy, A. Miahnahri, H.-D. Nuhn, D. Ratner, J. Turner[#], J. Welch, W. White, J. Wu, *SLAC*, *Stanford*, CA 94309, USA

Abstract

The beam stability specifications for the Linac Coherent Light Source (*LCLS*) Free-Electron Laser (FEL) at Stanford Linear Accelerator Center are critical for X-Ray power, pointing, and timing stability. Studies of the transverse, longitudinal, and intensity stability of the electron beam are presented. Some sources are identified, correlated, and quantified.

INTRODUCTION

Transverse centroid motion components in the pulse to pulse regime come from laser pointing stability, magnetic field stability, and quadrupole vibration. The injector is stable, at 250 MeV the transverse jitter is about 3.5% of beam sigma well below the 10% tolerance budget. By the end of the *LCLS* Linac it is 14% horizontal and 10% vertical (see Figure 1).

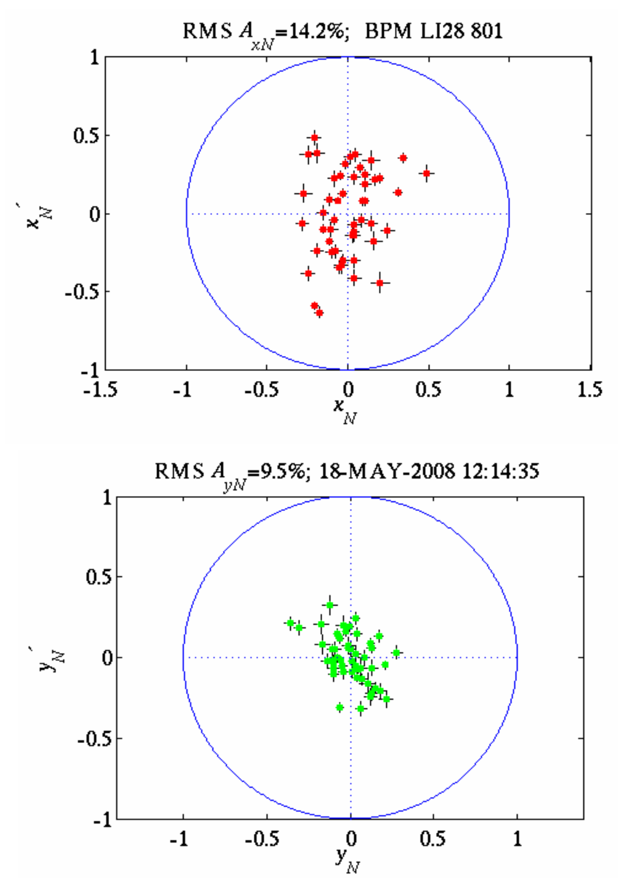

Figure 1: Data taken at 14 GeV near the end of the Linac. The blue circle is 1 sigma beam size. The goal is for the RMS amplitude to be less than 10% of beam sigma.

Longitudinal motion in the pulse to pulse regime comes from source laser timing jitter, locked to the RF, and RF phase and amplitude jitter.

TRANSVERSE JITTER AND QUADRUPOLE VIBRATION

The quadrupole magnet vibration in the Stanford Linear Accelerator was studied in the 1990s and found to correlate primarily with the accelerator structure cooling water [1][2]. The vertical motion was constrained to the 100-200 nanometer level from 2-100 Hz then by the combination of clamping the magnet support to another nearby support and by careful selection of water pumps. The horizontal vibration was not studied at that time. The *LCLS* is sensitive to vibrations in both planes above the 100 nm level [3]. This presents a challenge. For uncorrelated motion, a typical vibration budget has most of the Linac quadrupoles at 100 nm in both planes.

Expressed as a jitter amplitude in beam sigma from uncorrelated kicks, a tolerance budget is formed [4] using the sensitivities of each to a 10% centroid motion in the undulator.

$$A_i = y'_i \sqrt{\frac{\beta_i}{\epsilon_i}}$$ } Normalized invariant amplitude per item (*n*-sigma)

$$A_T^2 = \sum y_i'^2 \frac{\beta_i}{\epsilon_i}$$ } Total amplitude² for *N* uncorrelated kicks

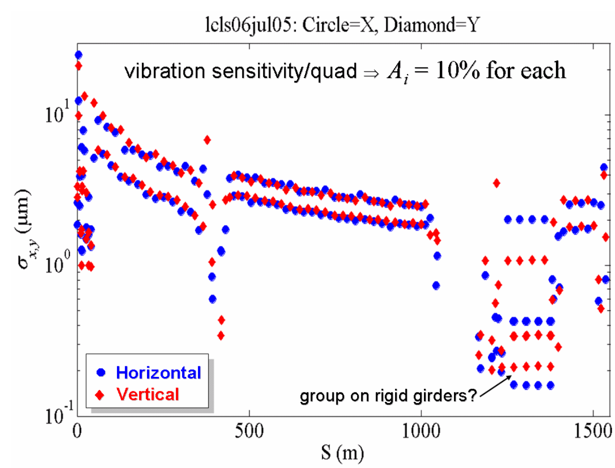

Figure 2: Vibration sensitivity is the displacement of a single quadrupole which will alone generate motion in the undulator which is 10% of the rms beam size.

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# jturner@SLAC.Stanford.edu

Measurements of the actual quadrupole magnet vibration have been recently done with seismometers read by a portable laptop data acquisition system the calibration of which has been checked with a laser interferometer at Stanford Linear Accelerator Center.

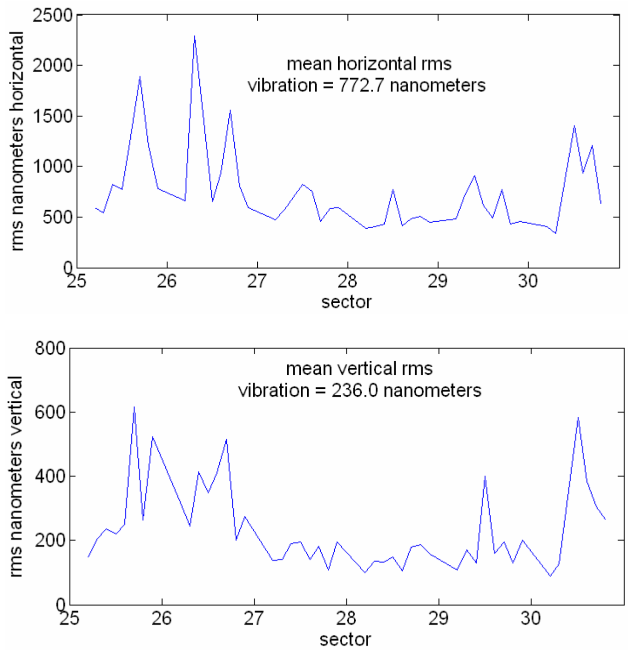

Figure 3: Horizontal RMS vibration of 48 of the *LCLS* Linac quadrupoles from 4 to 100 Hz on top graph, Vertical on the bottom.

Quadrupoles with large amplitude are measured to have dominant motion at 59 Hz coming from the water pumps running slightly below line frequency. The water pressure fluctuations can also be measured at 59 Hz. Where in sectors 25 and 26 large amplitude motion of quadrupoles is seen, the water pressure also shows power at 59 Hz above other sectors.

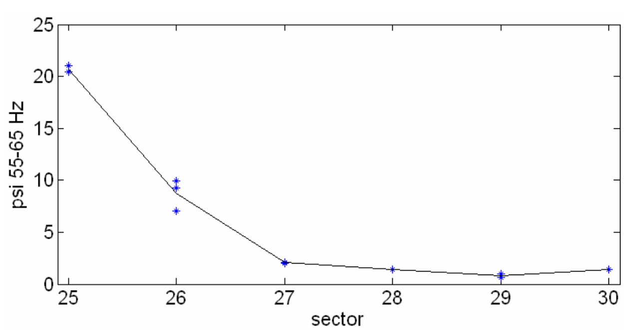

Figure 4: *LCLS* Linac accelerator cooling water pump pressure fluctuations at 55-65 Hz.

The spectrum of a quadrupole in sector 25 is illustrated in Figure 5 where there is a narrow band stripe at 59 Hz, and broadband noise elsewhere from 4 to about 70 Hz. The integrated motion is dominated by the narrow line however as shown on the top plot in Figure 5.

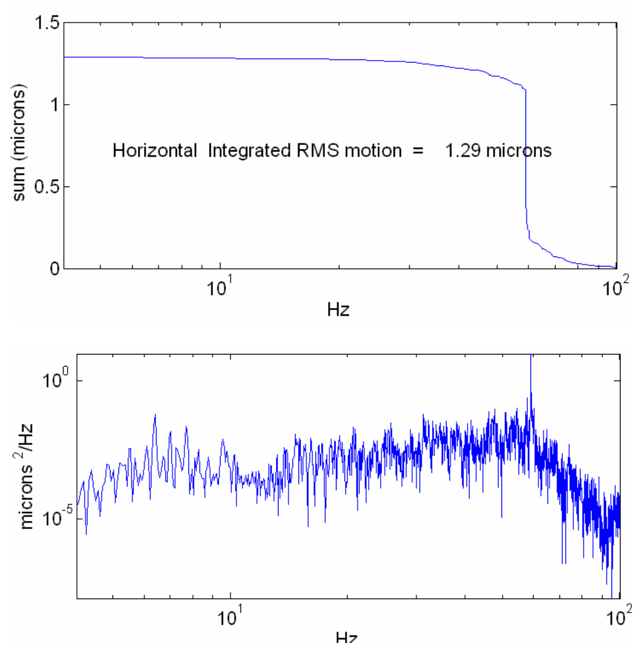

Figure 5: Quadrupole in sector 25 horizontal power spectral density from 4-100 Hz (bottom graph), top graph shows the integrated motion from 100 Hz to 4 Hz (high to low). Note the large step at 59 Hz.

LONGITUDINAL JITTER AND RF

The radio frequency (or RF) system drives the beam, its amplitude and phase has to be controlled to high precision (see Table. 1)[5].

Table 1 Longitudinal Jitter Tolerance Budget[5]

$|\langle \Delta E/E_0 \rangle| < 0.1\%$ **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	%

Early measurements with beam position monitors (BPMS) at high dispersion showed very high jitter numbers, which could be correlated to certain klystrons in the Linac (see Fig. 6).

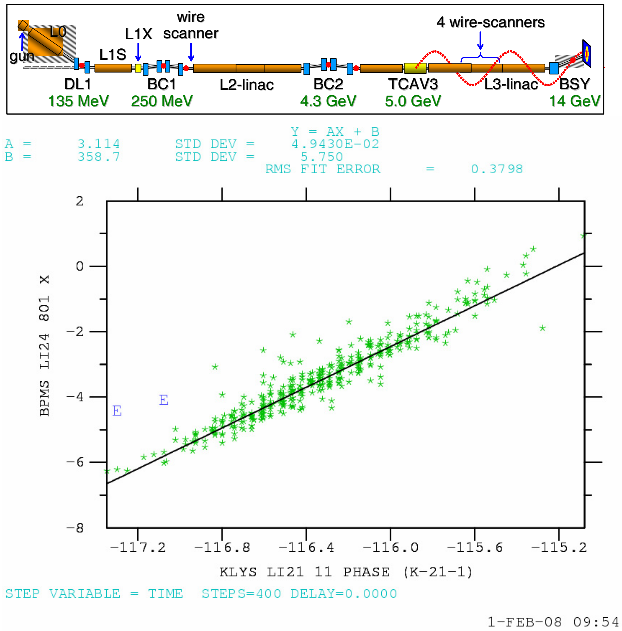

Figure 6 Top shows the layout of the LCLS and abbreviations of Linac sections (L), bunch compressors (BC). Bottom, energy BPM (Li24 801) in BC2 strongly correlates with L1S (KLYS Li21 11) phase.

At -366 mm dispersion the observed variation of about 6 mm (or 1.27 mm rms) corresponds to 0.35 % energy jitter. If this source could be eliminated, it would reduce to 0.104 % (=0.3798/366) about a factor 3.5.

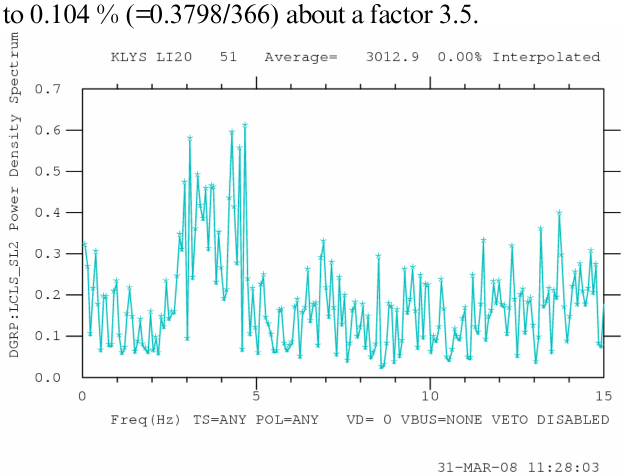

Figure 7 : Phase power spectra of one of the injector klystrons (Li20 51) an hour later the main jitter was between 6 and 8 Hz indicating a moving target.

For tracking this source down we looked at the power spectrum of the RF phases of several klystrons. An unexpected wandering frequency band between 3 and 5 Hz or a little later 6 to 8 Hz was visible (Fig. 7).

All klystrons with new Low Level RF (LLRF) showed this problem, so we started looking at their common source the LLRF distribution. The amplitude signal did not reveal any obvious structure, but an FFT (Fast Fourier Transform) showed a spectrum with a 2-Hz wide line at 17 Hz, giving a hint that the frequency might be higher and aliased down in earlier measurements. With further investigation we realized that this "line" is actually 325 Hz, varying from as low as 275 Hz to as high as 390 Hz (even 450 Hz when the module, which was finally replaced, was cold after being turned off). This Phase Lock Loop (PLL) waveform (Fig. 8) revealed two other problems. First, the lines at 180 and 300 Hz went away after disconnecting some pulsed phase shifters at the main RF distribution in Sector 0. Second, the "low" frequency components were reduced by narrowing the gate width of a measuring signal inside the LLRF module.

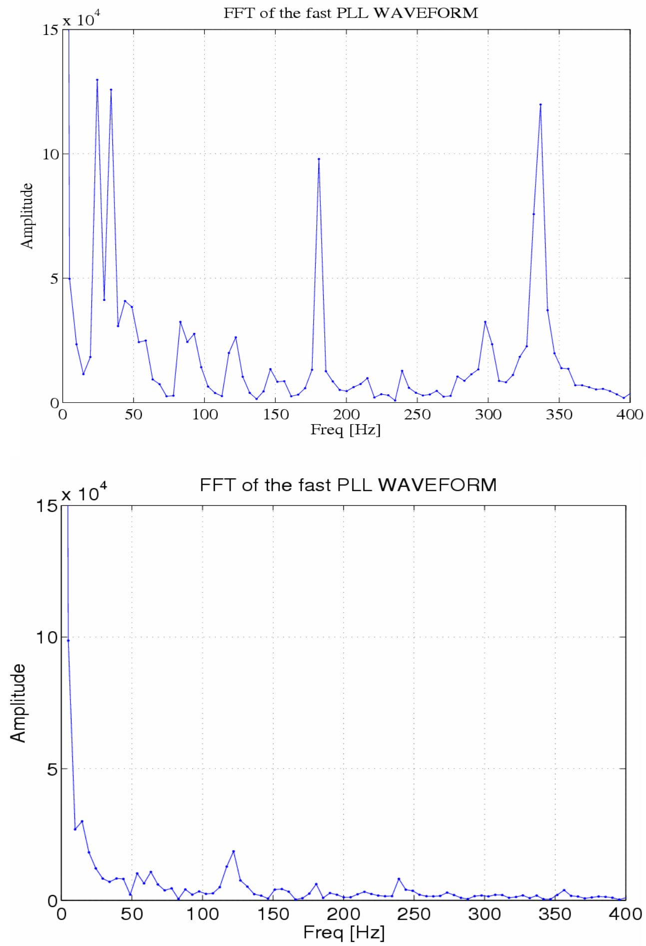

Figure 8: The amplitude of the FFT of the RF phase distribution signal up to high frequencies (here 400 of 19528 Hz) is shown on top before the fixes and at the bottom afterwards.

The LLRF module was the major problem after which the jitter reduced dramatically. To be correct the beam jitter was already reduced about a month earlier after feeding the L2 Linac with the same new (and jittery) RF. The problem was masked since in the last part (L3) the beam is close to the RF crest and therefore much less sensitive to phase jitter.

Other problems concerning amplitude and phase jitter were/are coming from the high power RF system, probably mainly the klystrons themselves. Figure 9 shows the phase jitter RMS distribution for all klystrons used for LCLS. The klystron for L1S showed one of the worst phase jitters above 0.12 deg at its typical running

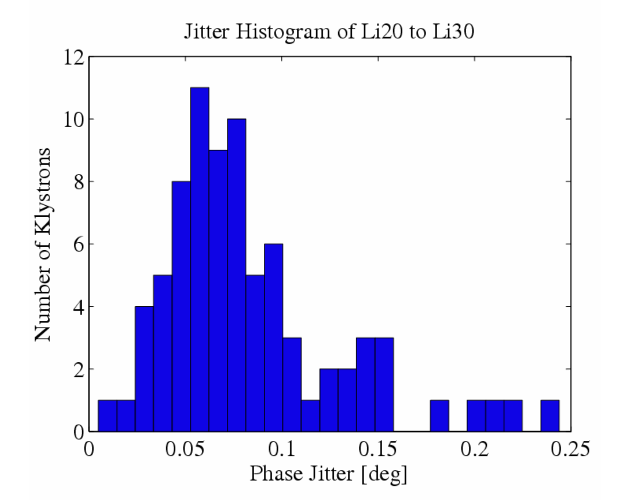

Figure 9: Phase jitter histogram of all klystrons used for LCLS. Most klystrons are around 0.07 deg, while a few show problematic behavior.

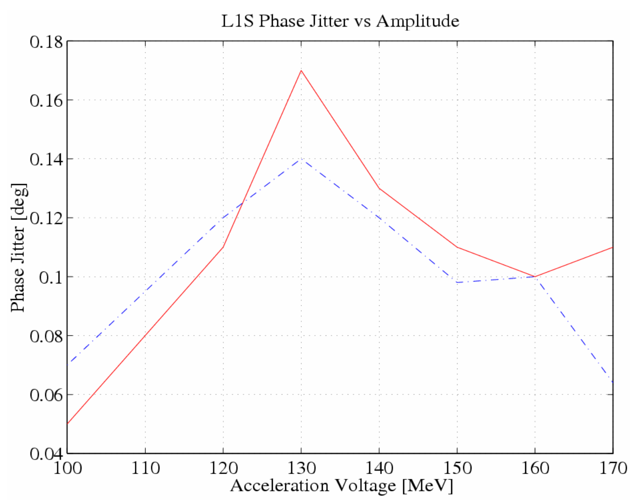

Figure 10: The L1S klystron exhibits more phase jitter just around its typical running range of 140 MeV.

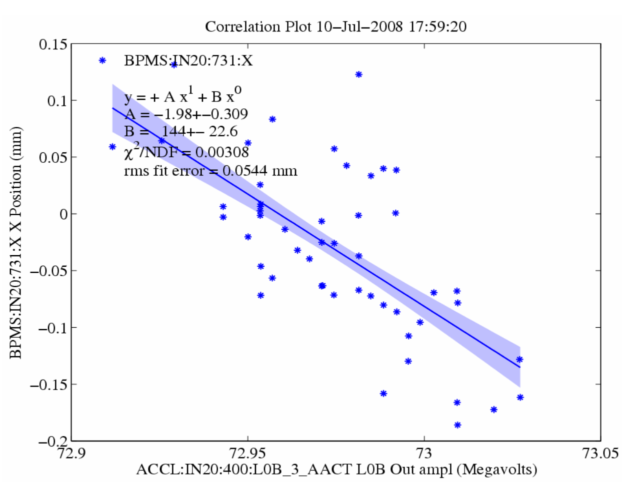

Figure 11: The energy in dogleg 1 (DL1) is strongly correlated with L0B klystron amplitude.

amplitude (140 MeV, see Fig. 10), it was reduced to 0.08 deg by only partly filling the SLED cavity with RF and avoiding an unresolved instability. We might exchange it again with a klystron capable of a jitter less than 0.05 deg.

Energy variation due to amplitude jitter is seen early in the Linac with correlation with the L0B klystron, which represents 48% of the power in the jitter (Fig.11). The charge jitter is correlated with the laser intensity onto the cathode, at least 60% of the intensity jitter power. Some uncorrected dispersion in the Linac can couple the longitudinal into the transverse (Fig. 12).

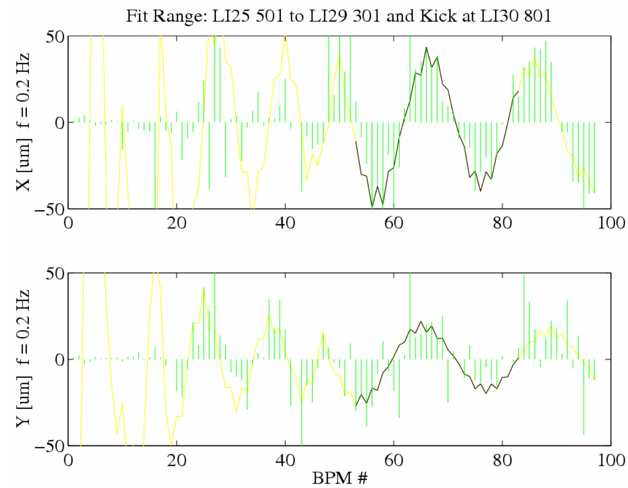

Figure 12: Looking only at a certain frequency in the FFT and performing the inverse FFT, and then plotting the resulting maximum orbit difference versus z, we can determine where this disturbance starts. In this case it is likely to be uncorrected dispersion in x just around BC2 (BPM #48) and in y after BC1 (BPM #20).

SUMMARY

All jitter numbers are below the specification except horizontal transverse which is slightly higher. Work nonetheless continues on jitter reduction. Although the measured quadrupole motion is quite large, the observed beam motion could be explained by correlated motion which cancels a major portion. Experience this run with ultra-low emittance, low charge beam while being easier from a collective effects point of view would increase the relative contribution in beam sigma for all jitter sources from 10% to 25%.

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