IDENTIFYING JITTER SOURCES IN THE LCLS LINAC*

F.-J. Decker, R. Akre, A. Brachmann, W. Colocho, Y. Ding, D. Dowell, P. Emma, J. Frisch, S. Gilevich, G. Hays, P. Hering, Z. Huang, R. Iverson, K.D. Kotturi, A. Krasnykh, C. Limborg-Deprey, H. Loos, S.D. Molloy, H.-D. Nuhn, D. Ratner, J. Turner, J. Welch, W. White, J. Wu,
SLAC, Stanford, CA 94025, USA

Abstract

The beam stability for the Linac Coherent Light Source (LCLS) Free-Electron Laser (FEL) at Stanford Linear Accelerator Center (SLAC) is critical for good X-Ray operation. Although stability tolerances are met or very close to the specification [1,2], there is some transverse and longitudinal jitter in the beam [3]. Here we discuss identifying these jitter sources by different methods like correlations, frequency spectrum analysis or other methods for finally eliminating or reducing them.

MECHANICAL SOURCES

Understanding some of the jitter sources for the LCLS requires going back in history and looking at the sources and their solutions, which played out during running the SLC (SLAC Linac Collider) [4-7]. There was 10 Hz structural quadrupole vibration, which coupled from the longitudinal to the vertical 100 times stronger, since the quadrupole was mounted not below its center of gravity [4,5]. Additional clamps stiffened that motion and eliminated this frequency. Early frequency checks on the LCLS motion indicated some jitter power at 10 Hz, which could be traced to some clamps fallen in disrepair, like not be tightened down or even missing altogether, which was quickly fixed. The main sources, which drive this motion with mainly white noise jitter, are big accelerator structure water pumps. The asynchronous motors run at 3540 rpm 59 Hz [6,7], which when unbalanced, can be directly seen, or with 30 Hz beam rate aliased down at 1 Hz (see Fig. 1). 12% of the jitter power is at 1 Hz (8% at 4.4, 5% at 7 Hz).

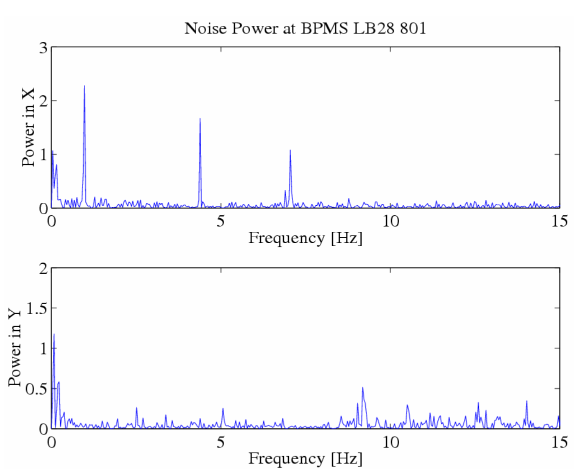

Figure 1: Power spectrum of a Beam Position Monitor (BPM) in the Linac indicates noise at 1.0, 4.4 and 7.0 Hz.

* Work supported by US DOE contract DE-AC02-76SF00515.

By plotting just the power at 1 Hz versus the length of the Linac *z* [6], we can pinpoint the location where a pump might be bad. Direct vibration data measured on top of the quadrupole can confirm this, and excessive variations of the pump water pressure can be even measured during running the beam.

Quantitative Analysis

A more quantitative approach is achieved in the following way. Only the 1-Hz-component of the FFT power spectrum (Fig. 1) is selected and the inverse FFT is taken. This gives a cleaned up 1-Hz sin curve (with some modulation, if more than one frequency bin was chosen). Now we take the peak-to-peak (p-p) difference (max – min) and plot this 1-Hz-difference orbit for all BPMs versus *z* or versus the BPM number (Fig. 2).

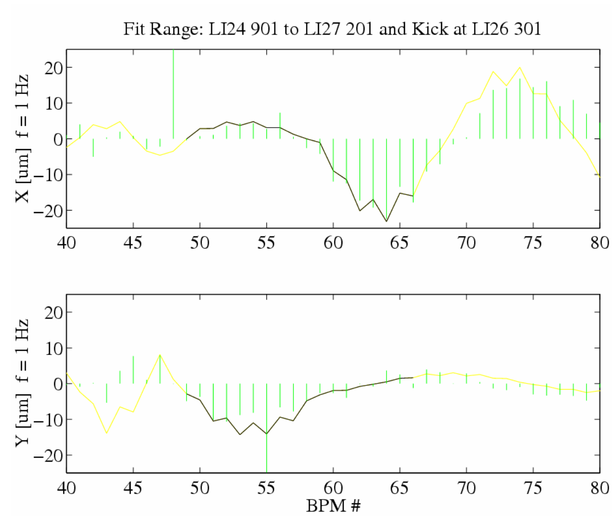

Figure 2: BPM orbit difference for only the 1 Hz component. A part (black curve) was fitted to the data allowing a kick at BPM # 59 (Li26 301).

The fitted kick angle was θ = -0.52 μrad in *x* and -0.18 μrad in *y* for a problem at Li26 301 BPM. The observed quadrupole vibration on top of the magnet was 2.3 μm RMS. These two numbers can be compared using the following equation

$$\theta = \frac{0.03}{E\,[\mathrm{GeV}]} * BL\,[\mathrm{kG - m}] \quad (1)$$

where E (6.2 GeV) is the energy at that point and BL is the integrated field strength of an effective dipole kick. This kick is assumed to be produced by a nearby quadrupole B (-9.4 kG) and a vibration offset Δy. Using the above numbers Δy results to 11.4 μm (p-p).

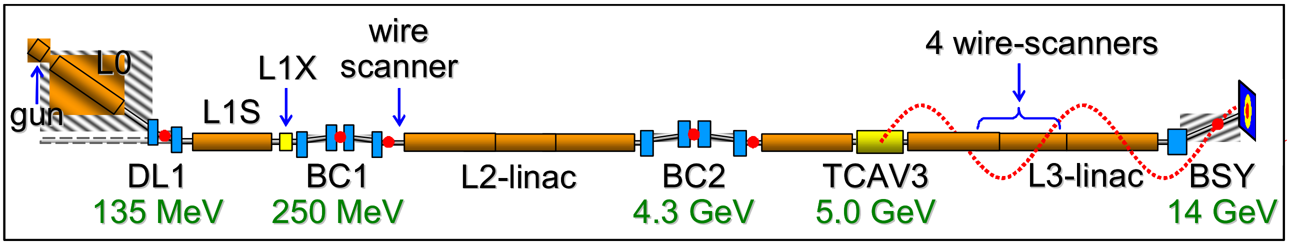

Figure 3: LCLS schematic layout of Linac sections L0, L1, L2, and L3 with the two bunch compressors (BC). There are four energy BPMs in the four dispersive sections: DL1 (Dog Leg), BC1, BC2, and BSY (Beam Switch Yard).

To get the amplitude of the 1 Hz sin wave we have to divide the p-p number by two (5.7 μm), and finally the RMS of a sin wave is still $1/\sqrt{2}$ smaller resulting in 4.0 μm RMS. For sin wave we have:

$$2.0\ (\text{p-p}) \equiv 1.0\ (\text{ampl.}) \equiv 0.707\ (\text{RMS}) \qquad (2)$$

This is still a factor of 1.7 higher than 2.3 μm. The quadrupoles in Sector 26 showed an average vibration level of 1.2 μm, while a "good" Sector can have an average below 0.5 μm RMS in x and 0.15 μm RMS in y [8]. The quadrupoles next to 301, namely 201 and 401, had 0.7 and 1.5 μm RMS quadrupole vibration which could have added coherently to 4.0 μm RMS. This is especially likely since the power cables of only Quad 301 were found resting on a vibrating rectangular waveguide.

Normally it could be argued in the opposite direction that the eight quadrupoles per Sector (driven by one pump) should cancel partly their motion due to focusing and defocusing quadrupoles and about half a betatron oscillation over a Sector. The incoherent addition of 8 quads with 0.1 μm gives 0.28 μm, while coherently four times: +0.10 and -0.06 μm gives 0.16 μm and the phase advance reduces this further to 0.12 μm. So a coherent motion of all eight magnets loosens the jitter tolerance by 2.3, so a 0.10 μm tolerance becomes 0.23 μm. There is still a discrepancy of about a factor of two between this tolerance [1] and the measured beam jitter (15% in x, 10% in y [3]) and the vibration measurement on top of the quadrupoles (0.5 μm RMS in x, 0.15 μm RMS in y). It could be explained by the center of the quadrupoles (beam axis) moving about half of the on top of magnet vibration numbers, making the different measurement nearly consistent.

RF SOURCES

The new EPICS RF system for LCLS had many teething problems concerning jitter and many problems got already identified and fixed [3]. So we concentrate on some new findings. Besides the 1 Hz line in Fig. 1, there is a 4.4 Hz line which turned out to be mainly longitudinal. Looking at Fig. 3 we have four dispersive sections where energy BPMs can pick up any energy jitter. Figure 4 shows the 4.4 Hz line p-p orbit difference along the Linac. With the design dispersion the energy BPMs give the following p-p energy jitter (at 4.4 Hz): DL1: -0.45‰, BC1: -0.38‰, BC2: 0.70‰, BSY: 0.18‰.

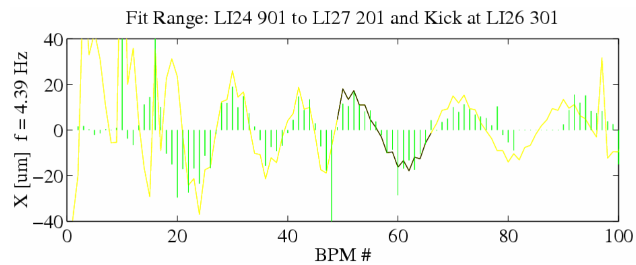

Figure 4: Horizontal p-p orbit difference for the 4.4 Hz line, indicating an energy jitter problem early in the Linac and non-matched dispersion after BC1 and BC2. Most energy BPMs are off-scale: DL1 (#10): 119 μm, BC1 (#16) 88μm, BC2 (#48) -256 μm, and BSY (#100) -15 μm.

Again, these numbers are $2\sqrt{2}$ bigger than RMS. The energy change is not the whole story, there was some phase jitter, but mainly the R56s of the chicanes (and dogleg) explain the energy ratios or even the sign flip after BC1. A lower energy of -0.38‰ in BC1 will give rise to a 17 μm longer path (R56 = -45mm), the effective L2 phase will move from -37° to -36.94° resulting in a +0.71‰ energy change at BC2, as measured. Figure 5 shows the culprit, mainly an amplitude jitter of the L0B klystron, although the jitter is 0.052%, below the tolerance of 0.1%.

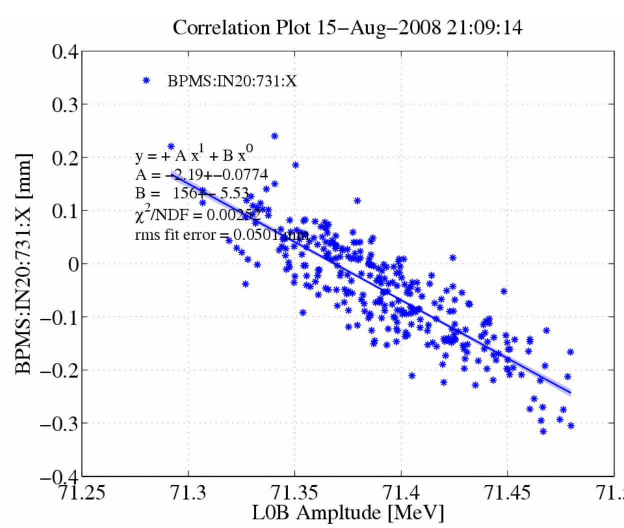

Figure 5: The BPM in DL1 (IN20:731) shows a strong correlation to the amplitude variation of the L0B klystron.

The square of the correlation coefficient (r = -0.85) is equal to the power (73%) in the correlation

$$r^2 = p, \qquad (3)$$

while the reduced jitter amplitude is

$$j_r = j_o * \sqrt{1-p}\,. \qquad (4)$$

So the jitter in the BPM x (RMS = 96 µm) could be reduced to 50 µm. Another way to get this reduced number is to look at the rms fit error (see Fig. 5), which is the projection along the fitted line. To compare how much jitter comes from different sources it is best look at the power fractions, since they just add (not add in quadrature like the amplitudes). Table 1 lists some jitter sources and their fraction of the jitter power, which correlates with energy, phase, bunch length (BL), and transverse measurements (73% of DL1 ΔE is from L0B).

Table 1: Fractional Jitter Power [in %] of Four Sources

Source:→ Measurement ↓	L0B amplitude	L1S phase	L1S ampl.	L0A ampl.
DL1 energy	73	0	0	12
BC1 energy	10	4	1	
BC2 energy	12	26	5	
BSY energy	13	24	5	
Li21beamphase	4	9	2	
BL Li21_A	3	17	2	
BL Li21_B	11	31	5	
Li28 401 x	15	8	6	all
Li28 801 x	9	13	3	in %

The phase jitter of L1S (only 0.09° RMS) has no special frequency component. It is white noise, most likely a random instability in the klystron itself. It causes the highest down stream energy and bunch length jitter, and even contributes about the same amount to the transverse jitter (13%) compared to the 1 Hz pump jitter from Fig. 1 (12%). This is also an indication that the dispersion after the chicane is not perfectly canceled.

SVD Method

Besides the FFT approach, looking at the special frequency component and plotting it versus z, or correlating an observed jitter with a suspecting source, there is the singular value decomposition (or SVD):

$$[U, S, V] = \text{svd}\,(X), \qquad (5)$$

where X is a big matrix off about 400 variables at 400 to 800 consecutive time intervals. The variables were for 101 BPMs (x, y, charge) and about 100 RF klystron and sub-booster phases. This gives about 400 eigenvalues S, which are orthogonal to each other, and depending on the orientation of X, U is the time eigenvector and V is the variable eigenvector. Just plotting the first 100 elements (equals to x) of the four biggest eigenvectors V reveals big excursions at 10, 16, 48 (see Fig. 6), where the energy BPM are located, indicating at least 4 independent sources.

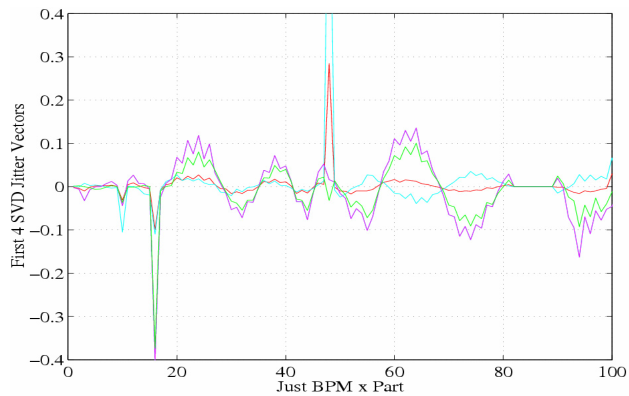

Figure 6: The first 4 eigen values using the SVD method point to different jitter sources, all concerning energy. Although they have the same sign at the energy BPMs and after BC1, the sign of one mode is opposite after BC2.

A small bump was also seen on L0B phase. The FFT of the time eigenvector U turned up one eigenvector with 4.4 Hz indicating the L0B problem (magenta V-vector in Fig. 6). The others mainly had a slow drift.

How to "scale" the data and get the most important jitter sources is still under investigation. For example the charge in units of number of particles (4E9 = 250 pC) had to be divided by 1E10, otherwise these eigenvector would have dominated. Maybe scaling by RMS jitter for each device is an option, but was not checked yet. The other problem is that the energy BPMs have more absolute jitter compared to transverse jitter say in Li28, so the 1 Hz line was not sticking out as a problem.

SUMMARY

Three methods to identify jitter sources were discussed: frequency content, correlation, and singular value decomposition. They helped to find vibrating pumps, phase noise in the RF system and trouble with certain klystrons, finally bringing the jitter numbers within spec.

REFERENCES

[1] P. Emma, J. Wu, "Trajectory Stability Modeling and Tolerances in the LCLS", EPAC06, Edinburgh, p. 151.

[2] P. McIntosh et al., "Overview of the RF Systems for LCLS", PAC'05, Knoxville, p. 2753.

[3] R. Akre et al., "Beam Stability Studies in the LCLS Linac", FEL08, Korea, Aug 2008.

[4] J.L. Turner et al., "Vibration Studies of the Stanford Linear Accelerator", PAC95, Dallas, 1995, p. 665.

[5] R.E. Stege, J.L. Turner, "Beam Jitter and Quadrupole Motion in the Stanford Linear Collider", BIW98, Palo Alto, May 1998.

[6] F.-J. Decker et al., "Characterizing Transverse Beam Jitter in the SLC Linac", EPAC 98, Stockholm, p. 457

[7] J.L. Turner, R. Stege, "Vibration of Linac Quadrupoles at 59-Hertz", SLAC-CN-399, Oct 1995.

[8] J. Turner et al., "LINAC Quadrupole Vibration Measurements", LCLS Engineering Note #1.0-003, May 2008.