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MEASUREMENT AND CORRECTION OF RF KICKS IN THE LCLS ACCELERATOR TO IMPROVE TWO-BUNCH OPERATION*

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Abstract

RF kicks, caused by a misalignment of an electron beam and acceleration structure, produce an electron orbit in the accelerator which decreases the final energy of the accelerated electron beam and is detrimental to lasing electron bunches in an X-ray Free Electron Laser (XFEL). RF kicks can depend on the RF waveform of the accelerating structure, so controlling this effect is particularly important when two or more electron bunches are accelerated within an RF fill time. Multibunch modes have been successfully developed for the Linac Coherent Light Source (LCLS) accelerator at SLAC, and are being continually improved to accommodate new experiments. One such experiment, the Cavity-Based XFEL (CBXFEL) project will require two electron bunches separated by 218.5 ns which must be identical in energy and orbit. To reduce variation in energy and orbit between the two bunches, we studied the RF kicks produced by each of 75 accelerator segments in the LCLS linac at several RF timings. Here, we discuss these measurements and propose a method to correct RF kicks in the LCLS accelerator using corrector dipoles and quadrupoles.

INTRODUCTION

The LCLS accelerator is made up of 75 accelerating segments divided into ten sectors of up to 8 segments each. These accelerator segments are aligned carefully through a beam-based alignment procedure, but small misalignments or defects (such as bowing) in accelerator cavities can remain, causing RF kicks [1]. When the LCLS electron beam passes through a misaligned cavity, there are three kicks which occur, as illustrated in Fig. 1.

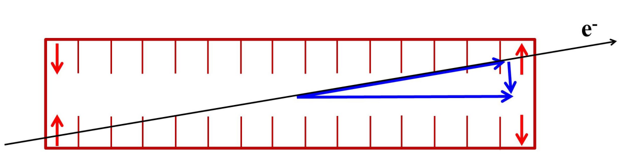

Figure 1: RF Kicks. The effects of R_{in} and R_{out} are illustrated in red, and R_{acc} is illustrated in blue.

There is a kick, R_{acc} caused due to the misalignment of the accelerating field with the electron beam trajectory, and there are two kicks, R_{in} and R_{out} which occur as the cavity RF enters and leaves the cavity structure. For the resonant RF accelerating phase, these kicks can be represented by R matrices given in Eq. (1) and Eq. (2), and the combined R matrix for these kicks is given in Eq. (3) [2]. L_s is the length of the accelerating cavity, E is the energy of the electron beam, and dE is the energy gain in a single accelerator segment. All three kicks are roughly the same in magnitude, so in the example in Fig. 1, R_{in} and R_{out} kick up, and R_{acc} kicks down, so the the net result is a kick up.

$$R_{acc} = \begin{pmatrix} 1 & \frac{L_s E}{dE} ln(1 + \frac{dE}{E}) \\ 0 & \frac{E}{E+dE} \end{pmatrix} \tag{1}$$

$$R_{in} = \begin{pmatrix} 1 & 0 \\ \frac{-dE}{2L_s E} & 1 \end{pmatrix}, R_{out} = \begin{pmatrix} 1 & 0 \\ \frac{dE}{2L_s(E+dE)} & 1 \end{pmatrix} \tag{2}$$

$$R_A = R_{out} R_{acc} R_{in} \tag{3}$$

Generally, the effects of RF kicks can be reduced using corrector magnets along the beamline, producing a beam orbit which is relatively flat. However, when two bunches are injected into the accelerator, RF kicks can be different for the two bunches. This is because the strength of the LCLS SLEDed RF varies over a time of 1 µs [3].

The CBXFEL project will rely on a two-bunch LCLS mode, with bunches separated by 624 RF buckets, or ~218.5 ns [4]. Four Bragg-reflecting diamond mirrors will be installed in the LCLS Hard X-ray Undulator line to return X-rays produced in seven undulator segments by the first electron bunch back to the beginning of the hall to interact with the second bunch. In order for the second electron bunch to lase with X-rays produced by the first bunch, the electron bunch energy and orbit must be identical between the two bunches.

We studied how RF kicks in the LCLS linac vary with different times on the SLED RF waveform to understand how we can reduce the differential RF kicks experienced by two electron bunches spaced 218.5 ns apart for CBXFEL.

EXPERIMENT

We used a single-bunch mode to characterize the RF kicks in the LCLS linac. To do this, we varied a Phase-Shift Keying (PSK) value to vary the time between the arrival of RF pulse from the accelerator klystrons and a 180° phase shift which dumps RF cavities which fill the accelerator. Different PSK cause the electron bunch to see different parts of the SLED accelerator waveform, so this is equivalent to scanning the arrival time of the electron bunch with respect to the RF waveform.

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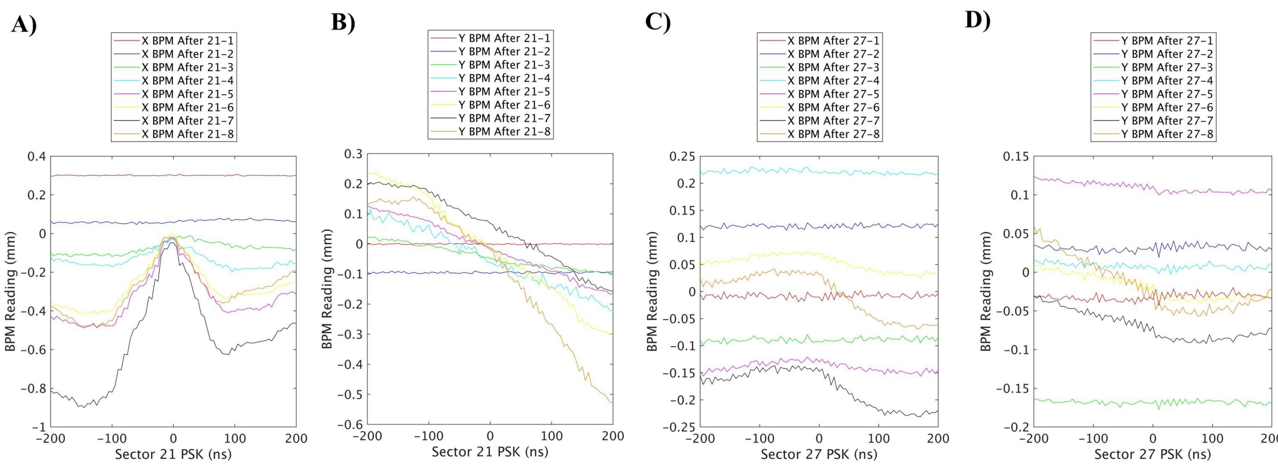

Figure 2: PSK scans for sector A-B) 21 and C-D) 27. BPM readings within the sector scanned are plotted for X and Y.

The PSK can be controlled independently for each of the accelerator sectors, labeled 21-30, or for the entire accelerator at once. Here, we performed two different studies. In the first, we varied the PSK of each sector, and in the second, we turned on/off individual klystron accelerator segments to measure RF kicks.

Scanning PSK of Klystron Sectors

We scanned the PSK for accelerator sectors 21-30, and recorded the beam position monitor (BPM) orbits. The BPM readings for scans of sectors 21 and 27 are shown in Fig. 2. Since it is important for CBXFEL bunches to also have equivalent electron energy and peak current, we also used a BPM in the middle of bunch compressor 2 (BC2), a chicane in sector 24, to plot the change in energy and peak current as PSK was scanned in sectors upstream of BC2. This is shown in Fig. 3.

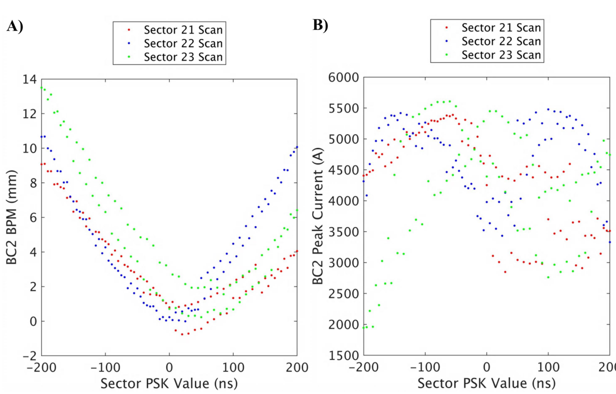

Figure 3: Plots of A) BPM in the BC2 chicane, which is proportional to electron beam energy, and B) peak current in BC2, for scanning the PSK in sectors 21, 22, and 23.

Turning on/off Individual Klystrons

We also turned on/off the klystrons attached to each of the 75 accelerator segments to measure RF kicks on the level of single accelerator segments. An example difference orbit and fit is given in Fig. 4.

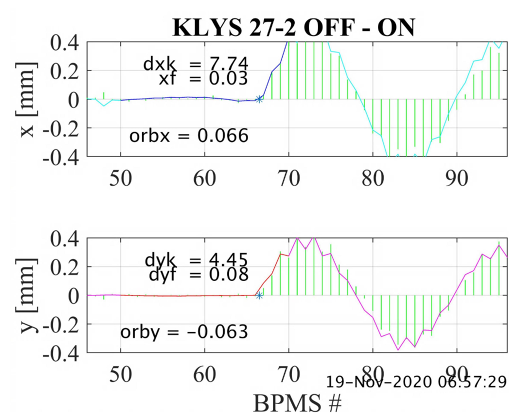

Figure 4: Difference orbit for turning on/off klystron 27-2. Orbx and Orby give the electron orbit (in mm) in section 27-2 when the klystron is on. dXk, dYk, dXf and dYf are fit parameters (units of mm).

We repeated this measurement for scanning the PSK the entire accelerator to -70, -60, -50, 0, 110, 120, and 130 ns. Before turning on/off klystrons, we recorded beamline parameters to build a matrix model of the beamline at a PSK of 0 ns and 120 ns. The PSK of 120 ns model was used for comparison with all PSK values other than 0 ns, as the accelerator model was expected to be fairly similar for these PSK. We then modified the matrix to insert Eq. (3) at the acceleration location where the kick occurred. We used this matrix method to fit two parameters in X and Y, labeled dXf and dXk, and dYf and dYk. These parameters are proportional to the transverse (x) and angular (x') misalignment of the accelerator segment as defined in Eq. (4) and Eq. (5).

$$dXf = x_1 - x_0 \tag{4}$$

$$dXk = \frac{2L_s E}{dE}(x'_1 - x'_0) \tag{5}$$

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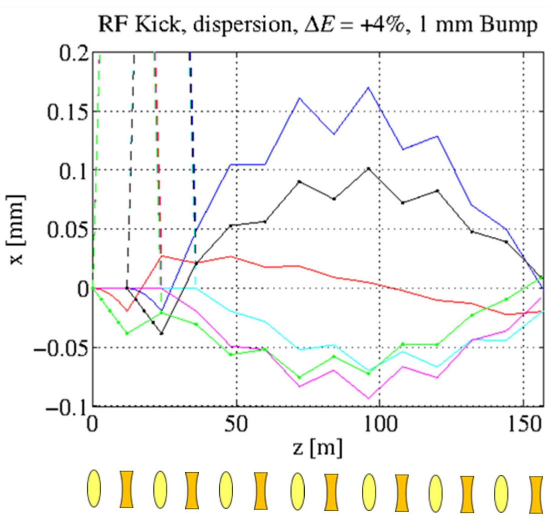
Generally, dXk has a larger effect than dXf. dXk can also be thought of as the height of the orbit bump which provides an equivalent kick to the RF kick.

The simulation in Fig. 5 inserts a 1 mm orbit bump in one of two locations, then inserts a matrix R_{acc} with $dE = 4\%$ (230 MeV / 5.75 GeV). The dispersion from the kick mimics R_{in}, and the beam is kicked. The magnitude of the kick depends on whether the accelerating segment was in the rising or falling part of the bump (mimicking a positive or negative angular misalignment), and whether the beta function at the end of the segment was large or small.

In the example in Fig. 4, the kick in Y occurs in a high-beta region, making it comparable to the blue and magenta curves, depending on the direction of the kick. For the magenta curve, the downstream orbit is 0.1 mm versus 0.4 mm experimentally. Thus, the experimental kick is equivalent to a 1 mm∗0.4 mm/0.1 mm = 4 mm kick.

In X, the kick occurs in a low-beta region, making it comparable to the red and cyan curves. For the cyan curve, the experimental kick is equivalent to a 1 mm∗0.5 mm/0.07 mm = 4 mm kick.



	dE before bump	dE in rising half of bump	dE in falling half of bump
Bump 0 m - 24 m	Green	Red	Magenta
Bump 12 m - 36 m	Black	Blue	Cyan

Figure 5: Simulation of a 1 mm bump in one of two locations, with an accelerating segment in one of three locations.

Figure 6 shows the fitted dXk and dYk for all 75 accelerator sections for for PSK = -60, 0, and 120 ns. We see there is a small amount of variation of dXk and dYk with PSK for each section.

FUTURE DIRECTIONS

With future work, we plan to establish a relationship between dXk and dYk for different PSK, so we can predict the PSK-dXk curve of a given accelerating segment by taking just a few dXk-PSK points. We plan to combine this information with our study of scanning the PSK of klystron sectors to decide at what times to place our two bunches 218.5 ns apart so that they receive similar RF kicks. If LCLS installs fast kickers which can kick bunches several ns apart, we can also use this study to predict the kicks that will be needed to correct the orbits of the two bunches to be similar.

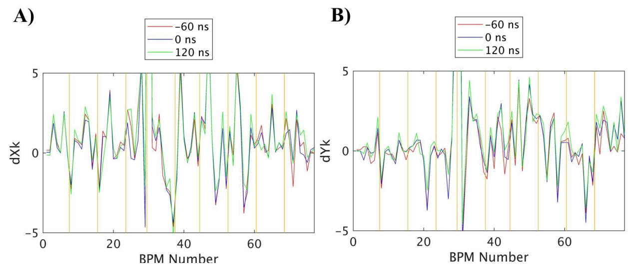


Figure 6: Fitted A) dXk and B) dYk for PSK = -60, 0, 120 ns. Yellow lines indicate the boundaries between accelerator sectors.

CONCLUSION

We measured the electron beam orbits in the LCLS accelerator for RF kicks caused by electrons arriving at different times on the SLED RF waveform. We did this by varying the PSK of accelerator sectors, and also by turning on/off individual accelerator sections for different values of accelerator PSK. With further study, we will use this measurement to inform the placement in time of two electron bunches so that they see the same RF kick in the LCLS accelerator.

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