RF KICKS IN THE SUPER CONDUCTING LINAC OF LCLS-II*

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Abstract

RF kicks are produced by misalignments between an electron beam in the acceleration structure. By analyzing these kicks, produced by the super conducting standing wave accelerator for the Linac Coherent Light Source (LCLS-II), a few unexpected observations were recognized. Initially, an out-of-phase (90 deg away from the accelerating phase) component was observed, which is similar in size to the expected by theory in-phase component. Then other observations like modeling errors (e.g.: not closed three-corrector bumps) led to a deeper analysis of the currently used model.

INTRODUCTION

Oscillation data along the LCLS-II beam path revealed quite some coupling terms from the Super Conduction (SC) RF Cryo-Modules (CM). In the example in Fig. 1 the coupled oscillation is closed in CM03 (BPM #28) after tuning for best FEL performance.

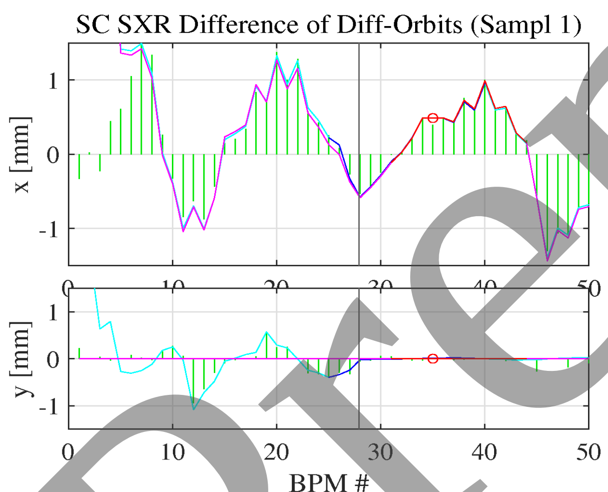

Figure 1: Oscillation data analysis. Trajectory oscillations are combined so that there is only an x offset, but no x' or y or y' at a certain location (red circle). The vertical black line is chosen where an unexpected kick occurs which corresponds to a skew quad of -0.25 kG. The start of the coupled part originates between BPM # 8 and 9 in the heater chicane and is a skew term of -0.21 kG [1].

During phasing the CM cavities, it was recognized that they kick the beam quite a bit transversely. Fitting the angle the kicks were quantified for most of the 8 cavities of all working cryogenic modules. Figure 2 shows the results of a part of L2B from CM04 to CM10. A focussing strength of -0.3 kG is quite reasonable (see below), but the out-of-phase component lags a good explanation.

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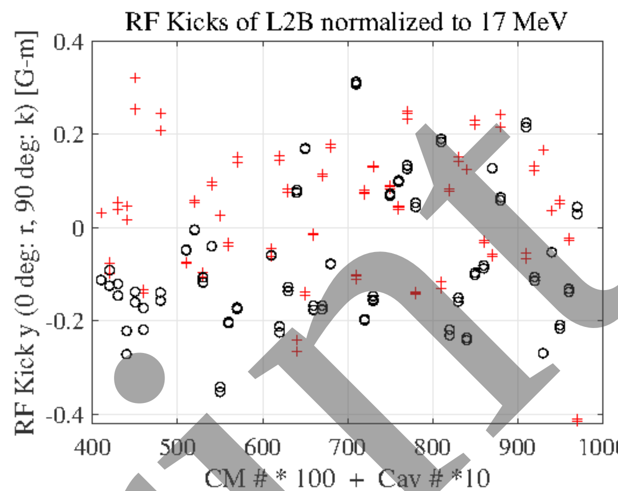

Figure 2: RF kicks measurements from two data sets. They are of the order of 0.3 kG-mm. Besides the expected in-phase (with the energy gain) component (red crosses) there is quite some out-of-phase part (black circles).

Measurement Accuracy

The accuracy of the measurements is very precise as see in Fig. 3 at around 0.01 G-m rms.

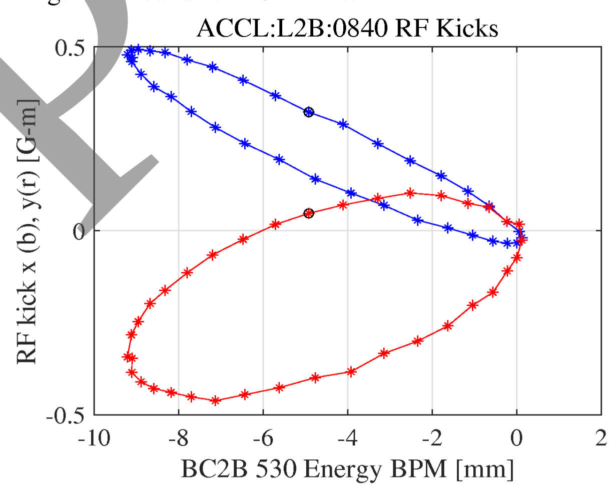

Figure 3: The fitted kick strength in x and y is plotted against the energy BPM (Beam Position Monitor) in BC2B (Bunch Compressor 2). [The reference orbit is subtracted therefore the on-crest phase is close to zero, while typically the range is centered around zero (±5 mm)].

THEORY AND CODES

After going through lots of theoretical papers [2-4] searching for an out-of-phase component one of us (CEA) pointed out his small simulation code which integrates motion along an accelerator structure. Fig. 4. shows an output of a standing wave 9 cell cavity with 18 MeV/m at 900 MeV beam energy.

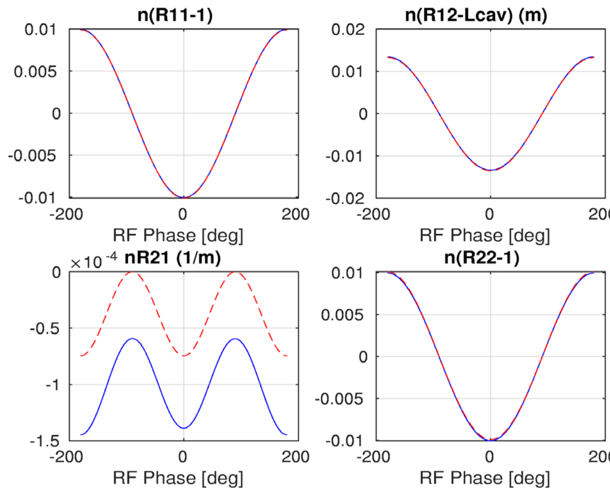

Figure 4: R-matrix versus phase for standing wave (blue) and traveling wave (dashed red) 1.34 m long cavity. The paraments where chosen that the maximum values are at 1% (= 18/2*900) and stretched / compressed by the length value of 1.34 m. The R21 term of the standing wave gets an additional focussing from the backward propagating wave which is independent of phase since over one cell (π-mode) the forward going beam and the backward wave add up to 2π.

The overlayed traveling wave structure is just the formula of eq. (3) of [5], using $\log(1+x) = x - x^2/2 + \ldots$:

$$R_A = R_{out} R_{acc} R_{in} = \tag{1}$$

$$\begin{pmatrix} 1 - {}^{dE}/_{2E} & L(1 - {}^{dE}/_{2E}) \\ -dE^2/(4LE(E+dE)) & E/(E+dE)\cdot(1+dE/(2E)) \end{pmatrix}$$

There is no out-of-phase component, but a hint of where it may come from can be achieved by looking at the separate components of the transverse kicks from E_r and B_ϕ in the code (Fig. 5).

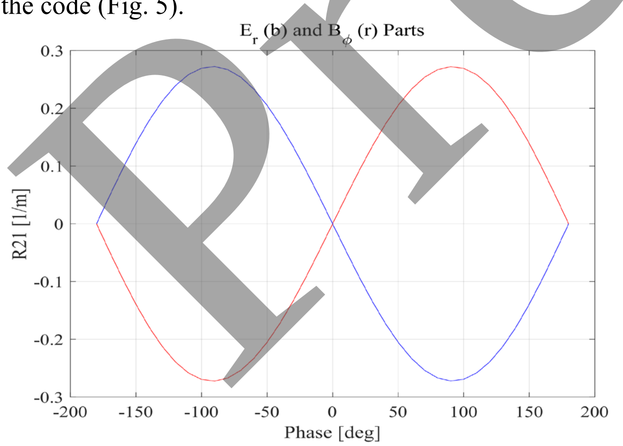

Figure 5: The separate parts of the transverse forces of the electrical and magnetic components are about 2000 times stronger than their sum (0.27 / 1.34E-4). Any non-perfect cancelation by cavity deformations or higher order mode (HOM) couplers might wash out the 2*f* harmonic feature in favour of the out-of-phase component.

MEASUREMENT OBSERVATIONS

Here are some observations which might give some insight. The out-of-phase kicks are much more prevalent in the SC linac, while in the copper linac the 2*f* the feature is often observed after minimizing the angle (Fig. 6).

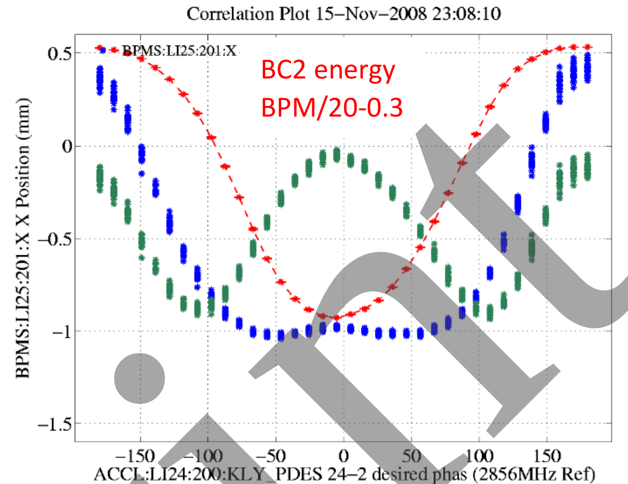

Figure 6: The mainly cos-term (in-phase) kick of a traveling wave copper structure (blue) is reduced by beam angle adjustments to the 2*f* harmonic behaviour (green).

Quantifying RF Kicks

To measure the change in RF kicks due to different beam offsets and angles the beam was bump up to ±6 mm and correspondingly to ±1 mrad (12 m apart) for two CMs. Figure 7 shows the in-phase response due to an angle change for CM08 Cavity 4.

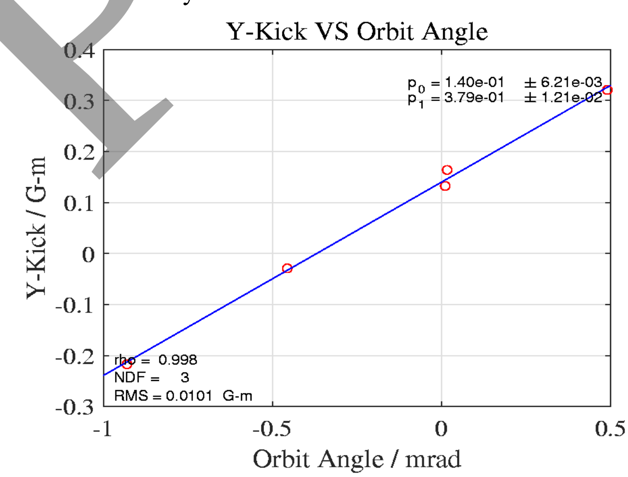

Figure 7: RF kick versus Angle change gives a response slope of 0.379 G-m/mrad for CM08 Cav #4.

All measurements in *x* and *y* were initially plotted in a similar way as Fig. 1 (see Fig. 8). The in-phase responses are typically 2-3 times higher than the out-of-phase responses. The range of these beam trajectory changes were nearly enough to find a value close to zero for individual cavities, but not for all at once. If misalignments would be the main cause of the RF kicks, values of 5 mm and 2 mrad per cavity would be necessary which is very unlikely by a factor of 10.

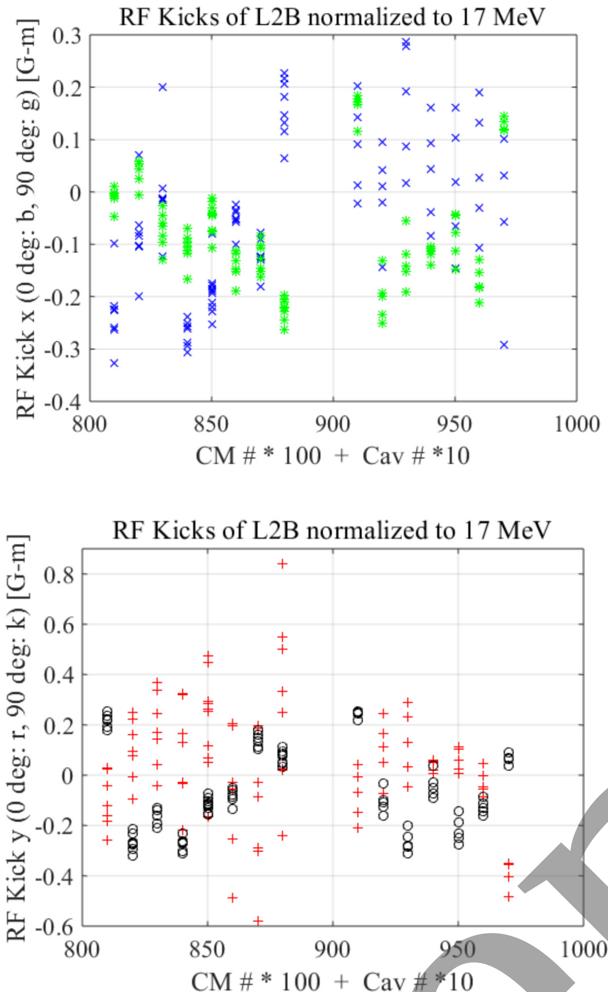

Figure 8: RF kicks measured for 93 phase scans during different orbits in the cavities, top for *x*, bottom for *y*. The in-phase (0 deg) and out-of-phase (90 deg) are plotted separately.

The variations per position or angle change look somewhat similar but plotting the slopes like from Fig. 7 for all measurement reveals quite a different picture, see Fig. 9. The values of 0.3 kG for an angle change are quite reasonable, while the 0.03 kG for a position change is about a for of ten higher than expected.

CONCLUSION

RF kicks of the super-conducting accelerator in LCLS-II were studied since they are higher than expected. The out-of-phase kicks might come from a not perfect cancelation of the transverse electric and azimuthal magnetic fields in the cavities. The measurements have a high precision of 0.01 G-m.

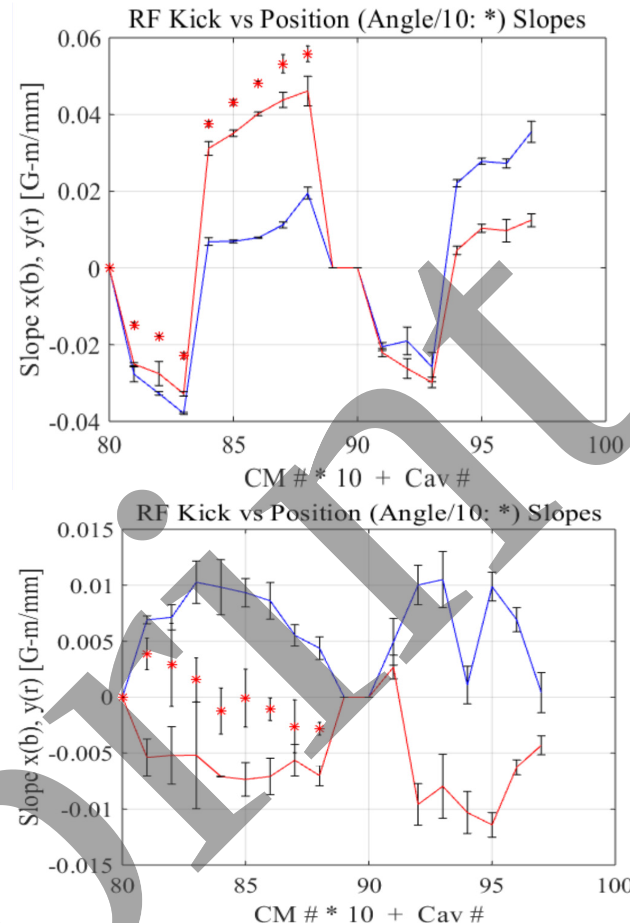

Figure 9: The slopes for the RF kick change versus beam position is show for 15 cavities in two CMs. On top is the in-phase measurements while on the bottom is the out-of-phase component. Additionally, the variation versus angle divided by 10 is shown in units of G-m/mrad.

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