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OSCILLATION DATA ANALYSIS DURING THE LCLS-II COMMISSIONING AT SLAC*

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Abstract

Analyzing the betatron oscillation of a beam is mainly used to find focusing errors in the lattice, like quadrupole errors. The generated trajectory differences can be compared with the design lattice or the current machine lattice where some magnets have been changed for different purposes or accidentally. Each method has different advantages and disadvantages like finding a quadrupole which got turned off by mistake won't be discovered with the current lattice method, while matching quadrupoles errors (which get tuned away from design) are harder to identify with the design lattice comparison. Besides lattice errors BPM (Beam Position Monitor) problems can be found too. Interpreting the data can have many pitfalls, some will be explained.

INTRODUCTION

Data Taking

The data taking is done by changing corrector magnets early in the beam path for a transverse trajectory in x and y, and RF (Radio Frequency) amplitude and phase for a longitudinal change, e.g. an energy E change. All BPMs (Beam Position Monitors) are recorded for a few (5) different settings. Since the phase advance between two correctors might be too small (or too close to a 180° phase advance) three x and three y correctors are used together with two energy changes generating a data set of 40 orbits (or trajectories to be correct) with around 175 BPMs taking about 3 minutes.

Data Analysis

To get the best signal to noise the difference orbit of the first and fifth corrector setting should be analysed. When there was any beam loss (or gain) involved, the data might be compromised near the loss area. This can be mitigated by choosing for instance the second and fifth corrector setting difference orbit. The raw difference orbits are often a good start to look for problems but are also often "messy" with coupled x and y behaviour. With good data five different orbits can be orthogonalized then at any chosen downstream location where there is only ONE of the five parameters (x, x', y, y', E) not equal to zero. There is no need for getting additional data further downstream. Figure 1 shows the orbit difference for the third parameter (Sample 3) for y being non-zero at the BPM # 110. From the corresponding y-kick θ a quadrupole error ΔQ is calculated via:

$$\theta = \frac{0.03}{E} \cdot \Delta Q \cdot y$$

with the energy E in GeV and the BPM y.

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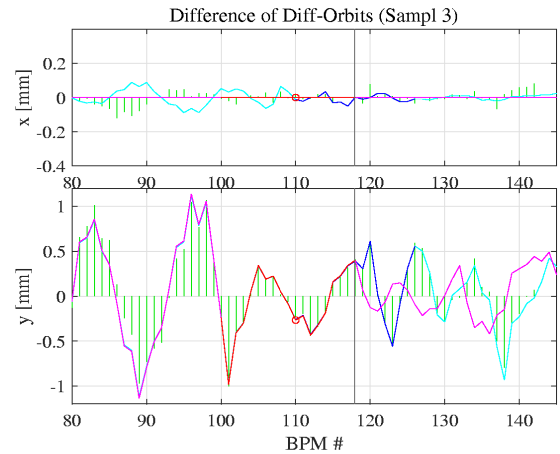

Figure 1: The data show the measured beam oscillations in green bars. It is a combination of a few orbits so there is only a y-offset at BPM # 110. In red is a fit which then extrapolates as magenta. Since it deviates near BPM # 118 (vertical line) a second fit including a kick at the nearest quadrupole is fitted in blue and extrapolated in cyan.

The quadrupole error was -66% of the quadrupole value making it three times weaker. The root cause was that the current transducer was configured for 300 A instead of 100 A.

IDENTIFYING PROBLEMS

More than ten problems were identified via this analysis, but often it was not as clear as in the case above. We go from the strong easy cases to the more complicated ones and discuss the signatures of the problems.

Easy Problems

The easiest were two -200% problems where the quadrupoles had just the wrong polarity. Then it looked we were down to 20% to 40% problems but suddenly two -100% cases occurred where a quadrupole was just off. One was where a quadrupole tripped before midnight, and the next crew saved a "SCORE" configuration which saves the current setup which then can be restored in the future. It stayed in there for about two months. Similar smaller variations are often not easily detected. The second one should have been found even quicker. The BDES (desired magnetic field B) had the right value, but the power supply was tripped and did not turn red indicating a wrong state.

Medium Problems

The 20% to 40% problems were in a location where we adjust quadrupoles to measure and match the beam's alpha and beta functions to the design lattice values. The same strong quadrupoles which are used for a 1500 MeV beam are also used where the beam energy is only 75 MeV or 20-

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times lower making the magnet hysteresis problem that much more problematic. Figure 2 shows the hysteresis curves going up in blue and down in red for this 20 kG magnet. The typical hysteresis gap of 2% of the maximum value is visible and of the same order of the quadrupole settings (stars) in this area. If not carefully “staying on the curve” of going up a problem up to 50% can easily occur.

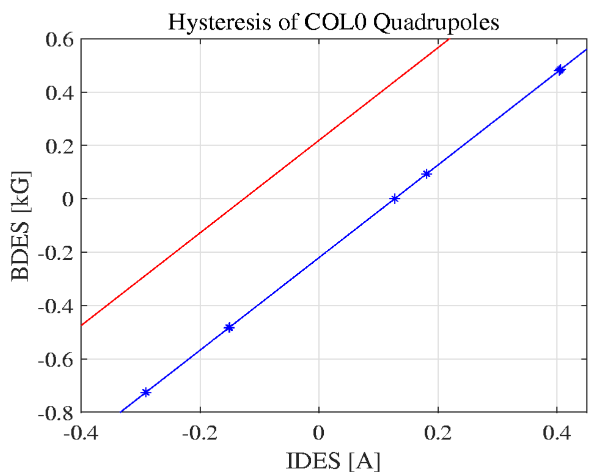

Figure 2: Hysteresis curve of a 20 kG quadrupole in the Collimator region COL0. The desired integrated magnetic field (BDES) is plotted versus the current (IDES).

Harder Problems

Harder problems to identify are either quite small, or in places with hysteresis, or near matching quadrupoles and required hints from other observations.

When a three-corrector bump isn’t closed it might be a strong hint of a problem. Analysing the non-closed orbit in a similar fashion with quantifying the kick pointed to a bad corrector or a much weaker quadrupole. The quadrupoles have an actual current reading IACT and a monitor reading IMON which was about a factor of 4 lower but was the real current. Since the power supply stabilises IACT the monitoring current reading was changing over time and not turning red which would indicate something is wrong (Fig. 3).

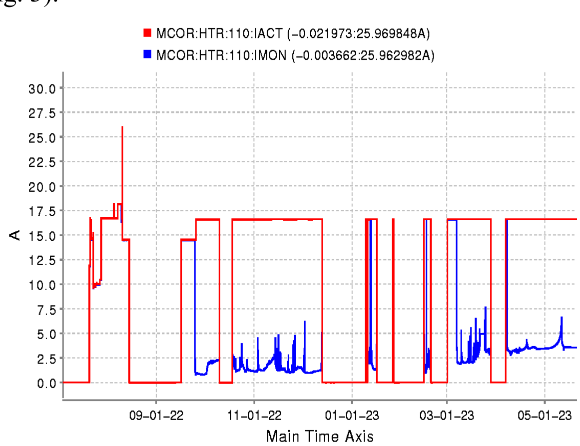

Figure 3: IACT and IMON quadrupole current versus time. After the initial setup and checks the monitor current drifts away from the IACT value.

An even tricker problem evaded us for years. A mayor hint was that when tuning the matching quadrupoles in the LTUS (Linac To Undulator Soft) area to maximized FEL performance we ended up always with a similar strong mismatch measured with the downstream wire scanner (Fig. 4). Propagating this mismatch in x and y predicted a very unrealistic beta beat in the undulator region (Fig. 5).

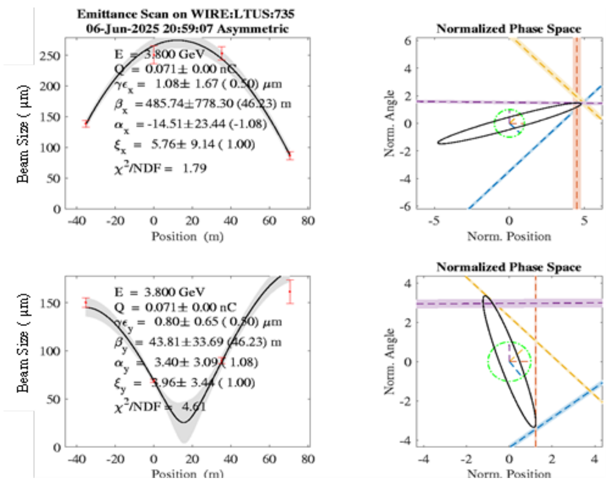

Figure 4: Emittance scan using four wire scanners.

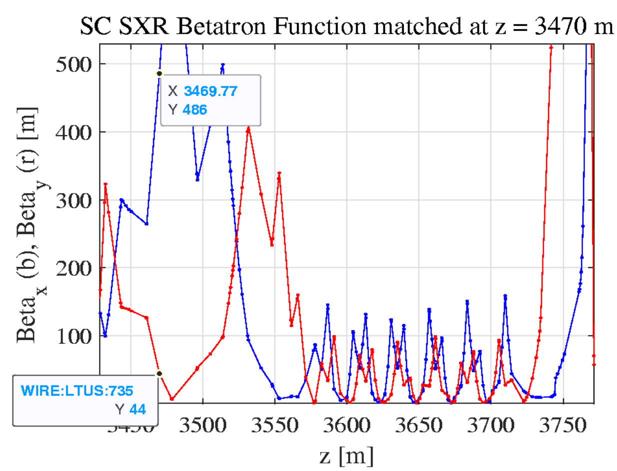

Figure 5: Propagating the measured alpha and beta functions from the wire scanner at z = 3470 m predicted a strong beta beat in the undulator (z ~ 3600 to 3700 m) hinting to a problem somewhere in between.

Quantifying the fitted kicks with a more recent data set indicated a -8 kG quadrupole problem for the x-orbit while being +8 kG for the y-orbit (Fig. 6). This inconsistency of ±8 kG pointed to at least two problems which were finally tracked down to four quadrupoles just before the undulator being too weak by a factor of three, like the problem of Fig. 1, but much harder to find since four magnets with opposing strengths were involved.

The Power of Tuning

It should be mentioned here that we allow tuning of the matching quadrupoles along the beamline to increase performance. This counteracts problems like the one above for some time but also hides problems.

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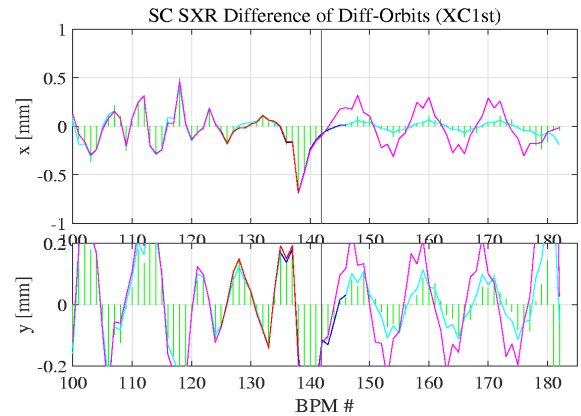

Figure 6: The fit to the data with a kick at the vertical line predicts an inconsistent result corresponding to -8 kG quadrupole in x and +8 kG in y pointing to at least two problems.

OTHER ANALYSIS

Instead of analysing one trajectory like in Fig. 1 and looking for deviations, we can take a local fit over a few BPMs and get *x, x', y, y'*. With orthogonal orbits we can generate all points on a phase space ellipse at that location. Assuming a matched beam there, which is a circle in normalized phase space, we can now use the measured orbit combinations to plot the ellipses upstream and downstream of that location generating a Rosetta picture (Fig. 7).

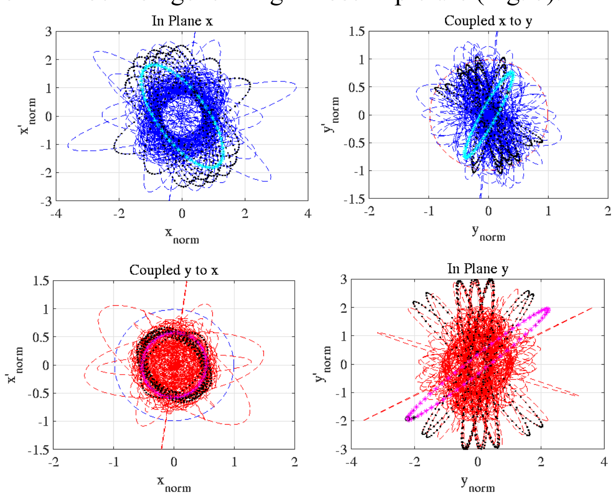

Figure 7: Rosetta like picture in normalized phase space. Starting with a circle of radius = 1 mismatches generate ellipses and coupling generate ellipses in the off-diagonal spaces x to y and y to x.

Plotting ellipse parameter versus *z* or the BPM # reveals locations where things happen. Initially this data representation looked quite noisy, but two problems identified later where already visible (Fig. 8). On the left just before BPM # 150 happens the mismatch describe near Fig. 5 and the five low values after BPM # 105 were due to a BPM radius scaling problem. Other deviations still need interpretations. The right shows determinant C (detC), it is up to about 40% and corresponds to an emittance growth due to coupling.

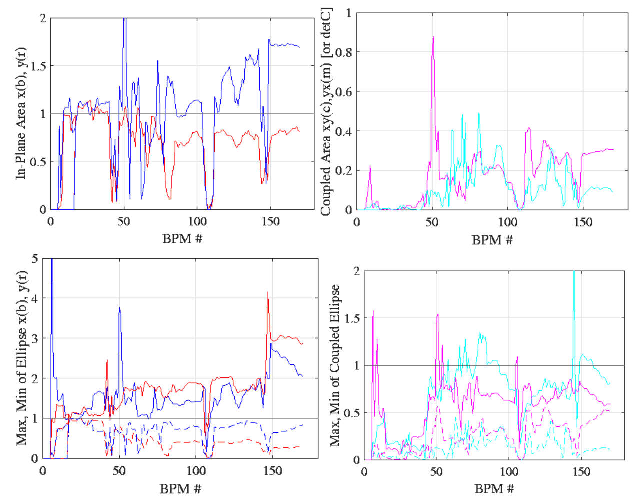

Figure 8: Area for in plane and coupled part (top), mismatch expressed in maximum and minimum of the ellipses (bottom).

Besides the coupling from cryogenic modules the heater undulator generates quite some coupling too (Fig. 9). Since the beam is round the emittance growth is small.

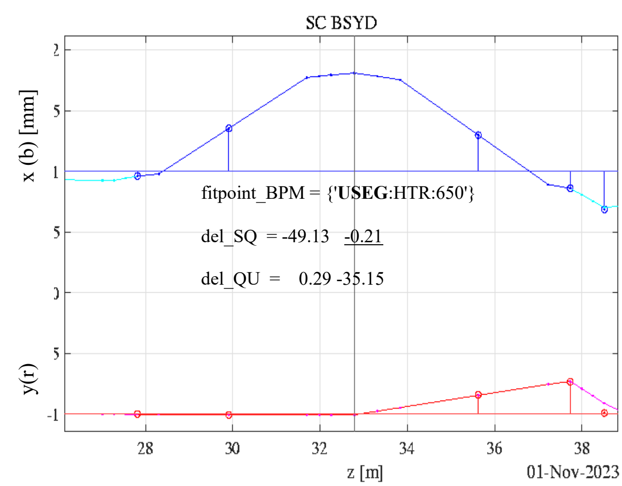

Figure 9: The undulator segment (USEG) in the heater chicane shows a skew quadrupole component of -0.21 kG.

SUMMARY

Many off-design quadrupole settings have been identified and fixed. The skew-quadrupoles terms from the superconducting accelerator modules cause up to 40% emittance growth. Tuning FEL performance can counteract some of these problems.

ACKNOWLEDGEMENTS

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