FAST BEAM-BASED BPM CALIBRATION*

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Abstract

The Alignment Diagnostic System (ADS) of the LCLS undulator system indicates that the 33 undulator quadrupoles have extremely high position stability over many weeks. However, beam trajectory straightness and lasing efficiency degrade more quickly than this. A lengthy Beam Based Alignment (BBA) procedure must be executed every two to four weeks to re-optimize the X-ray beam parameters.

The undulator system includes RF cavity Beam Position Monitors (RFBPMs), several of which are utilized by an automatic feedback system to align the incoming electron-beam trajectory to the undulator axis. The beam trajectory straightness degradation has been traced to electronic drifts of the gain and offset of the BPMs used in the beam feedback system. To quickly recover the trajectory straightness, we have developed a fast beam-based procedure to recalibrate the BPMs. This procedure takes advantage of the high-precision monitoring capability of the ADS, which allows highly repeatable positioning of undulator quadrupoles.

This report describes the ADS, the position stability of the LCLS undulator quadrupoles, and some results of the new recovery procedure.

ADS SYSTEM

The ADS system has two major components, a wire position monitor (WPM) system, and a hydrostatic leveling system (HLS). [1]

The WPM [2] consists of two stretched wires running parallel to the beam, each 140 m in length. Wire position monitors attached to the undulator girders sense the girder position with respect to the wires. This allows better than 1 μm position determination in x (the transverse direction). Position in y (vertical) is nearly as well determined, in spite of the sag of the wire.

The HLS consists of a system of water pipes running parallel to the beam, extending for 140 m. Capacitive and ultrasonic sensors on the girders sense the water level. This provides an independent measurement of the vertical position of the girders, which is not subject to wire sag.

The ADS system has shown that quadrupole positions are quite stable long-term. Early characterizations showed stability to within about 2 μm over a 2-3 day period [3,4]. More recent measurements over a period of 19 days in August 2011 have showed quadrupole positions to be stable to better than 2 μm RMS [Fig. 1].

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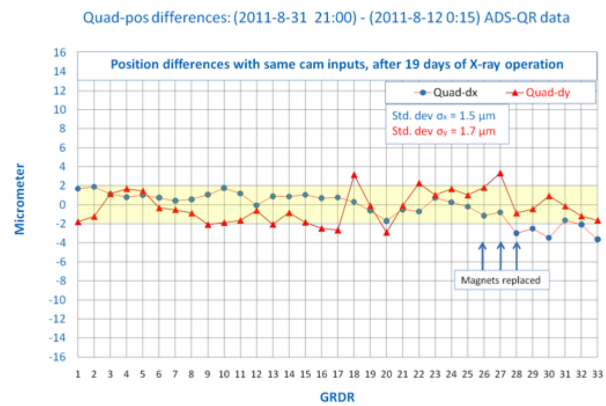

Figure 1: Quadrupole position stability over a 19-day period.

BEAM BASED ALIGNMENT (BBA)

Although the mechanical positions of the quadrupoles are quite stable over many weeks, the straightness of the electron beam trajectory and the FEL lasing efficiency degrade more quickly than this. A BBA procedure must be executed every two to four weeks to straighten the trajectory. This entails operating the linac at four different energies and fitting the trajectories for betatron oscillations, initial beam position and angle, and quadrupole and BPM offsets. Quadrupole magnets are moved to eliminate first and second magnetic field integrals between magnets, and BPM offsets are changed in software to reflect their true positions. This procedure is frequently repeated two or three times to ensure convergence. A full BBA typically takes three to four hours; much of this time involves re-establishing linac configurations for the four energies. [3,5]

BPM DRIFT

The RFBPMs used in the undulator provide high precision beam position measurements. However, they are subject to long-term electronic drift of both their gain and offset. Gain calibrations are typically done at the beginning of each BBA. (This accounts for about 30 minutes of the BBA time.) Over a period of a few weeks, the BPM gain change is on the order of 1%. Long-term BPM offset stability appears to be similar.

Changes in BPM offset do not directly affect the *actual* electron beam position in the undulators. But they directly affect the *apparent* beam position. These apparent beam positions indirectly affect the actual beam positions through a launch feedback system. This launch feedback system attempts to straighten the beam as much as possible, by looking at the apparent beam position as

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reported by the BPMs on girders 4-10. If the apparent beam positions are erroneous, the launch feedback system will introduce betatron oscillations in the undulator.

As the BPMs drift, the actual launch conditions gradually deteriorate. This adversely affects the beam trajectory straightness and the FEL lasing efficiency.

NEW CALIBRATION PROCEDURE

Description

The high repeatability of undulator position can be used to quickly recalibrate the offsets of the RFBPMs. After a BPM gain calibration, the undulators are returned to the same position they were in at the end of a previous full BBA. This is verified with the ADS and can be done to an accuracy of better than 1 micron. The electron beam trajectory should now be a straight line, as it was at the end of the previous BBA. But because erroneous BPM offsets affect the beam launch into the undulator through the launch feedback system, there will be also be some betatron component. And since offsets and tilts of the entire undulator system are frequently introduced to adjust the pointing of the X-ray beam, a linear component might also be present in the apparent beam trajectory. After fitting and subtracting a betatron oscillation and a linear component from the data [Fig. 2], the residual beam offsets are assumed to be the BPM offset errors. These are applied as offset corrections to recalibrate the BPMs.

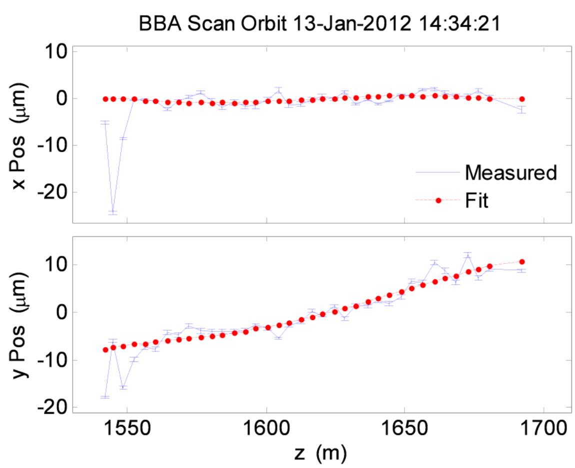

Figure 2: Trajectory data and fit from new calibration procedure (January 13, 2012).

A BPM offset error component at the betatron wavelength can mimic a betatron oscillation, which will be lost with this fitting procedure. Assuming the BPM offset errors to be uncorrelated, the amplitude of this component should be on average $4/\pi\sqrt{2/N}$ times the rms BPM offset error, where N is the number of BPMs. For the LCLS undulator this method might result in a remaining betatron oscillation of 30% of the BPM offset error.

Performance

The new fast calibration procedure does not require changing linac energy, so is significantly faster than the full BBA. The new procedure can be done in about 30 minutes, versus three to four hours for a full BBA.

The new procedure has been tested eight times over the past year. Its effectiveness in finding BPM offsets is generally good. Figs 3 and 4 show the BPM offset corrections calculated by both procedures in January 2012. The differences between the two procedures are about 10 times smaller than the actual corrections; the fast calibration procedure was about 90% accurate for this test.

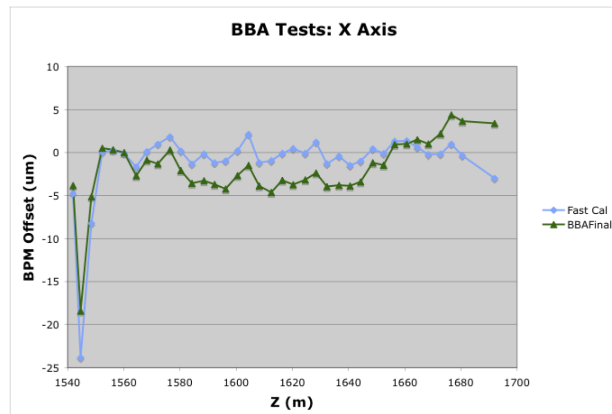

Figure 3: BPM offset corrections for X axis from Fast Cal and Full BBA (January 13, 2012).

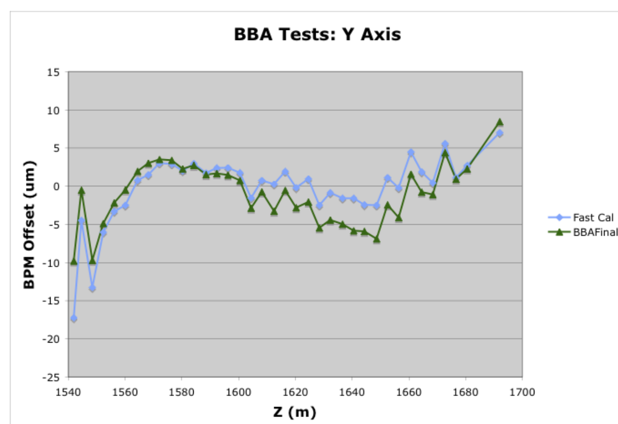

Figure 4: BPM offset corrections for Y axis from Fast Cal and Full BBA (January 13, 2012).

Figs 5 and 6 show the corrections calculated by both procedures in August 2012. Here both the total corrections and the differences between the two procedures were somewhat larger. However, FEL lasing performance was similar with the two procedures.

Problems and Drawbacks

This new procedure has two requirements if it is to work well. First, the undulators, quadrupole lenses, cams, translation stages, and software beam offsets must be returned to their positions at the previous full BBA.

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Second, there must be no change in remnant or stray magnetic fields along the undulator. So long as these requirements are met, the procedure works well. But we have seen a variety of instances where these requirements were *not* met, and the new procedure did not recover FEL performance.

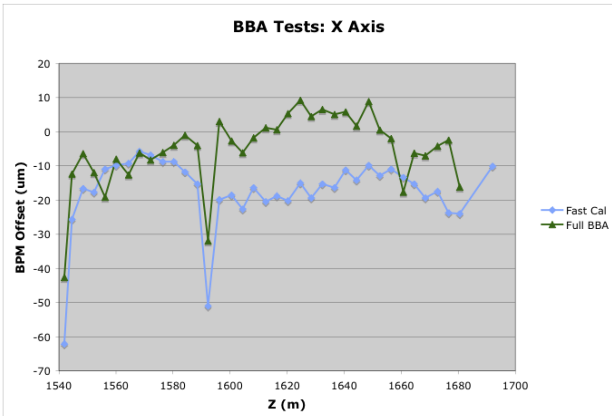

Figure 5: BPM offset corrections for X axis from Fast Cal and Full BBA (August 5, 2012).

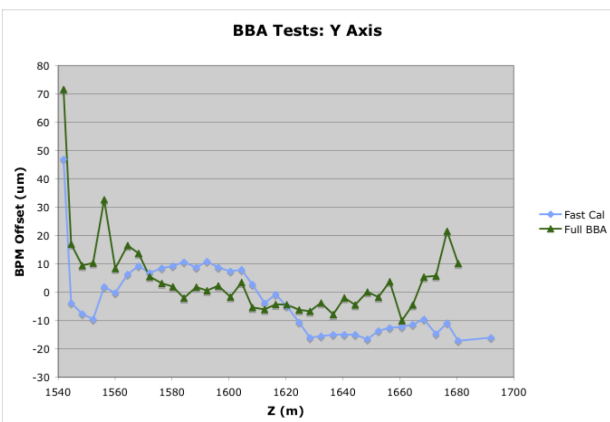

Figure 6: BPM offset corrections for Y axis from Fast Cal and Full BBA (August 5, 2012).

The ADS system allows accurate return of the undulator *girders* to the previous BBA. But other settings (e.g. translation stages and in-out corrections) have not always been recovered, causing poor results. These problems can be addressed pretty straightforwardly with more careful saving and restoring of the full machine state.

Remnant magnetic fields have been a bigger problem. This new procedure began to be used routinely in early 2012. But after installation of the Hard X-ray Self-Seeding (HXRSS) chicane, the new procedure gave poor results and adversely impacted FEL performance. This was traced to turnoff of the HXRSS chicane magnet power supplies, which left random fields of a few gauss on the magnets and introduced a beam kick at the location of the HXRSS.

Any similar magnetic field changes along the undulator line (i.e. only a few gauss) are enough to impact this new procedure. If a magnetic anomaly is suspected, a kick can be fitted to the data to correct for this. But small anomalies are likely to be missed and to adversely impact the BPM offset calibrations.

SUMMARY

A new fast beam-based BPM calibration procedure offers a much faster method (about 6x faster) of undulator re-alignment as compared to a full BBA procedure. However, it is not foolproof. So long as all mechanical settings and software offsets are returned to a known condition of a previous full BBA, and the magnetic field environment is identical to that of the previous full BBA, the method works well.

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