BEAM-BASED ALIGNMENT OF C-SHAPED QUADRUPOLE MAGNETS[*]

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Abstract

Many storage rings have implemented a method of finding the positional offset between the electrical center of the beam position monitors (BPM) and the magnetic center of the adjacent quadrupole magnets. The algorithm for accomplishing this is usually based on modulating the current in the quadrupole magnet and finding the beam position that minimizes the orbit perturbation. When the quadrupole magnet is C-shaped, as it is for many light sources, the modulation method can produce an erroneous measurement of the magnetic center in the horizontal plane. When the current in a C-shaped quadrupole is changed, there is an additional dipole component in the vertical field. Due to nonlinearities in the hysteresis cycle of the C-magnet geometry, the beam-based alignment technique at the Advanced Light Source (ALS) deviated horizontally by .5 mm from the actual magnetic center. By modifying the technique, the offsets were measured to an accuracy of better than 50 μm.

1 INTRODUCTION

Maintaining accurate control of the particle beam orbit in a storage ring light source is critical for user operation. The optimal closed orbit for an accelerator is usually referenced to the magnetic centers of the quadrupole and sextupole families. Placing the beam in the magnetic center minimizes orbit distortions, spurious dispersion, and beam motion caused by power supply jitter. Often BPMs are located adjacent to the quadrupoles, however, the zero reading of the BPM does not always correspond to the magnetic center of the quadrupole. First, the electrical offset of the BPM center can be large due to impedance differences in the buttons and cables. Second, the BPM buttons are mounted in vacuum chambers which are often "floating" in the magnets. This makes accurate survey and alignment of the BPM center relative to the quadrupole quite difficult. At the ALS, these two problems produce .25-1.25 mm BPM to quadrupole offsets. To accurately determine this offset, many accelerators have implemented a beam-based alignment method, [1], [2], [3], and [4].

The objective of beam-based alignment is to find the orbit in the quadrupole where modulating the quadrupole field does not steer the beam. At the ALS, this experiment has been done on the 48 quadrupole magnets that are independently powered, [3]. Vertically, the measured quadrupole to BPM offsets are typically .25-1.25 mm and roughly centered around zero. Horizontally, the offsets are about the same magnitude but are not centered around zero. Instead, the mean of the horizontal offsets is approximately .5 mm. Therefore, 1) the quadrupoles and/or vacuum chambers are misaligned (however, survey and alignment of the magnets and vacuum chambers should be much better than .5 mm), 2) the BPM electrical offsets happened to be systematically directional in the horizontal plane, 3) the quadrupole modulation method is flawed in the horizontal plane for the ALS. Since the first two options are unlikely, a closer look was taken at finding the magnetic center of a C-shaped quadrupole magnet.

Further experiments revealed that changing the modulation amplitude produced a different measured "center" location for the horizontal plane. This led to a modified approach, which we call the directional current sweep method.

Section 2 compares three beam-based alignment methods (on/off modulation, sine wave modulation, and the directional current sweep) on the same quadrupole magnet in the ALS. Section 3 discusses beam-based alignment of C-shaped quadrupole.

2 BEAM-BASED ALIGNMENT TECHNIQUES

This section will compare the results for three beam-based alignment techniques. The first two are modulation methods and are commonly used at a number of accelerators. The first method is geared toward shunts and the second is geared toward backleg windings. The third method was originally devised as a "sanity" check on the other two methods and turned out to be a viable method of finding the center of C-shaped quadrupoles. All three methods will be tested and compared on the same ALS quadrupole magnet—the first focusing quadrupole in sector 7, QF(7,1). The BPM adjacent to this quadrupole is BPM(7,1).

2.1 On/Off Modulation

On/Off modulation method originated as a way to find the quadrupole center using shunts, [1]. By comparing the difference orbit at two different quadrupole settings for different beam positions in the quadrupole, one can quickly find the magnetic center. Fig. 1 shows the horizontal difference orbits for all 96 BPMs when QF(7,1) is varied by 1 percent. One horizontal corrector

magnet is used to change the position of the electron beam at five locations in the quadrupole. The zero crossing occurs at approximately .360 mm in BPM(7,1). For more detailed analysis of this method, see [3].
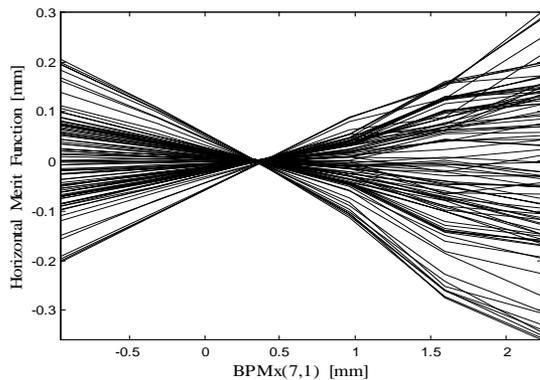
Fig. 1. The On/Off Modulation Method—Horizontal.

2.2 Sine Wave Modulation

By modulating the main quadrupole field with a small amplitude sine wave, one can find the beam position in the quadrupole that minimizes the orbit distortions that correlate with the input sine wave. This method is used at LEP for continuous orbit correction in the interaction region, [1].
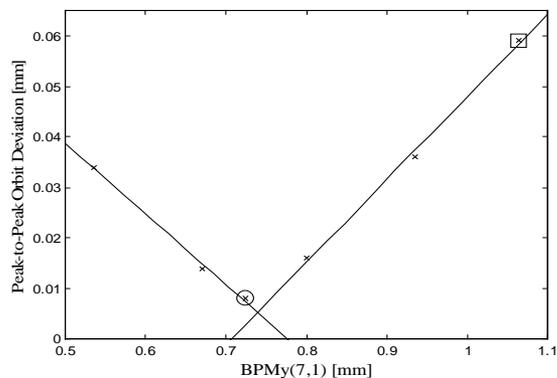
Fig. 2. QF(7,1) Sine Modulation Method—Vertical.
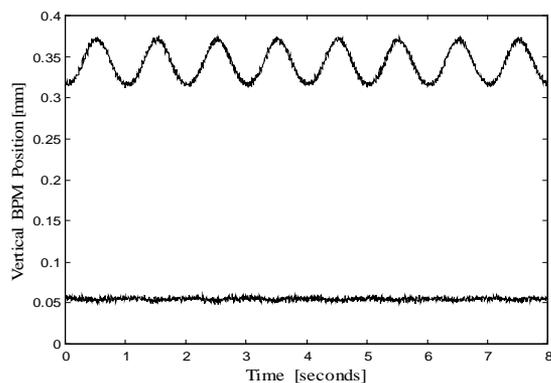
Fig. 3. Time Domain Signals for QF(7,1)—Vertical.

Fig. 2 shows the results for the vertical plane when QF(7,1) is modulated by .9 percent. The ordinate is the peak-to-peak change in the orbit at straight section BPM(7,2). The time domain signals for two of the data points (labeled with a square and circle) in Fig. 2 are shown in Fig. 3.

The two linear curve fit lines in Fig. 2 do not intersect at zero. This is because the peak-to-peak beam motion in the BPM is approximately 5 microns. The corresponding plot for the horizontal plane is shown in Fig. 4. The projection of the linear fit linear would put the horizontal center at 7.125 mm, which is almost impossible.
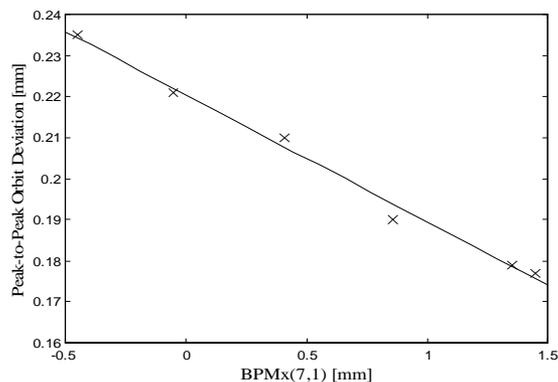
Fig. 4. QF(7,1) Sine Modulation Method—Horizontal.

2.3 Directional Current Sweep

Since the ALS has independent power supplies on 48 of the quadrupole magnets, the magnetic center can be verified by sweeping the current in the quadrupole and monitoring the orbit change. When the beam is in the center, no change in the closed orbit should occur. Fig. 5 shows the results for the horizontal plane. For each line, QF(7,1) is first cycled to the lower hysteresis branch, the orbit is selected, and QF(7,1) is swept up until the beam becomes unstable. By inspection, the magnetic center is at approximately -.5 mm.
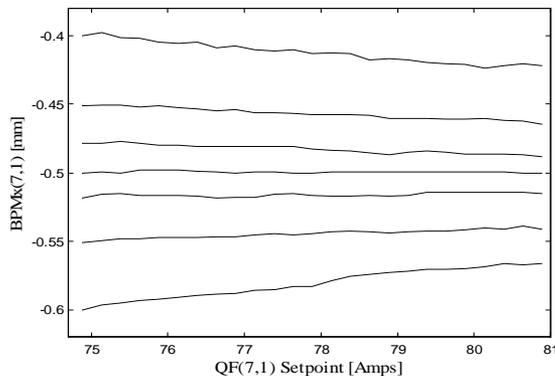
Fig. 5. QF(7,1) Horizontal Orbit vs. QF(7,1) Current.

2.4 Experimental Summary

Table 1 shows the summary of the results for the three different beam-based alignment methods. The experiments were done on different days and data collection and reduction was not optimized, hence the error bars are likely ±.1 mm. However, measurement errors do not explain the huge discrepancies in the horizontal plane.

Table 1: QF(7,1) Magnetic Center Measurements

Methods	QF(7,1) Center	
	Horizontal	Vertical
On/Off Modulation	0.360 mm	0.695 mm
Sine Modulation	7.125 mm	0.730 mm
Current Sweep	-0.500 mm	0.680 mm

Fig. 6 shows the change in the horizontal "center" using the on/off modulation technique for different modulation amplitudes of QF(7,1). The same experiment on the vertical plane shows no change in the measured center that is greater than the measurement error.
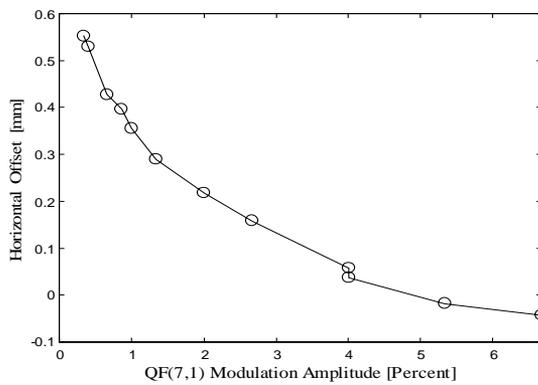
Fig. 6. QF(7,1) "Center" vs. Modulation Amplitude.

3 C-MAGNET QUADRUPOLES

The obvious difference between the horizontal and vertical planes in the ALS stems from the C-shaped geometry of the iron core of the quadrupole magnets. C-shaped magnets are common in light sources to allow clearance for the vacuum chamber containing the photon beam. The asymmetry of the iron produces a vertical field that is proportional to the current in the magnet. This extra dipole field component causes a shift in the magnetic center from the geometric center of the quadrupole. A simple shift in the magnetic center will not produce an error in the beam-based alignment techniques discussed in section 2. The problem is likely caused by nonlinearities between the quadrupole field component and the extra dipole field component.

The ideal vertical field, B_y, in a C-shaped quadrupole is

$$B_y(x, I) = K I x + D I$$

where, x is the horizontal position from the center, I is the excitation current, K is the proportionality constant for the quadrupole field component, and D is the proportionality constant for the dipole field component. The definition of center for this paper has been the horizontal position where the B-field is zero regardless of the excitation current, i.e., -D/K for an ideal C-shaped quadrupole. If D/K is constant, then all of the beam-based alignment techniques should produce the exact same center. If nonlinearities in the hysteresis cycle change the ratio of D to K, then finding the center is chasing a moving target.

The modulation methods clearly produce an incorrect measurement of the quadrupole center horizontally since the center depends on the modulation amplitude. The more difficult question is whether or not the directional current sweep method produces the optimal location? Intuitively, if the orbit does not change for an 8 percent change field strength, as in Fig. 5, then it is tempting to call that location the quadrupole center. However, this experiment is based on ramping the field along the lower hysteresis branch. If the power supply current is reversed, the orbit shift is quite large. What is likely happening is that when the field is increased along the lower hysteresis branch, the ratio of D to K is remaining constant.

4 CONCLUSION

The large discrepancy in the three beam-based alignment techniques in the horizontal plane is quite alarming. The fact that the sine wave modulation method fails so badly implies that it is impossible to locate a position in the quadrupole that removes orbit perturbations from power supply ripple. At the ALS, the beam is corrected to the location determined by the directional current sweep method. This method has been automated using the same algorithm as in on/off modulation method except that the quadrupole field is always stepped along the lower hysteresis branch. More magnetic field measurements need to be taken in order to understand the exact mechanism causing the problem.

ACKNOWLEDGMENTS

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