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Girder Support Scheme for the LCLS Undulator System

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Abstract

Differential settlement of the foundation of the LCLS Undulator Hall will cause quadrupoles to move and the electron beam trajectory to distort. The resulting phase errors will decrease the FEL power and require time consuming beam-based alignment sessions to correct. By supporting quadrupoles on girders, with three quadrupoles to a girder, the foundation-motion induced phase error between the beam and the X Ray radiation can be reduced by a factor of 5 compared with supporting each quadrupole with a separate column. This comes about because the motions of three quadrupoles on a girder are linearly correlated so their effect on the beam is largely canceled out. Thus a girder support scheme can significantly help to extend the time between required beam based alignments and contribute to a more stable operation of the LCLS FEL beam.

Introduction

The production of FEL coherent X Ray radiation at 0.15 nm wavelength requires the transverse motion of the electron bunches to stay closely in step with the oscillations of the X Ray radiation that is generated by the electrons. Once established through careful beam based alignment, this close phase relationship will be lost if the path length of the electron beam trajectory changes by an amount comparable to the X Ray wavelength. For example, if the trajectory in the LCLS Undulator deviates by just 4 μm in one quadrupole the resulting increase in path length would generate 10 degrees of phase shift.

Changes to the electron beam trajectory in the Undulator will come about primarily through fluctuations in the incoming beam position and angle and changes in the mechanical alignment of the undulator quadrupoles. Feedback will be used to control the incoming electron beam position and angle so as to stabilize X Ray beam direction. However there is no known method of applying feedback on the phase error between the electron beam undulation and the X Ray beam phase, so outstanding mechanical stability of the quadrupole alignment is needed.

Quadrupole alignment stability is determined by the stack-up of the stability of several intermediate supporting structures and the stability of the foundation. While there are engineering means available to help stabilize the intermediate supporting structures (low coefficient of expansion materials and tightly controlled temperatures for example) the Undulator Hall foundation is in direct contact with the uncontrolled 'outside world', and so for the most part, the sources of motion of the foundation cannot be engineered away. Differential settlement of the foundation has been observed at several major accelerator laboratories and is expected to be present in the Undulator Hall at a a rate of up to 1–3 μm per day based on measurements in the nearby PEP II tunnel.[1], [2]

The effects of foundation motion on FEL performance can be substantially mitigated by using girders to support multiple quadrupoles. The concept of using girders to support multiple quadrupoles is in contrast to supporting each quadrupole independently with one pillar or column per quadrupole. (See figure 1). A girder will move with the motion of the

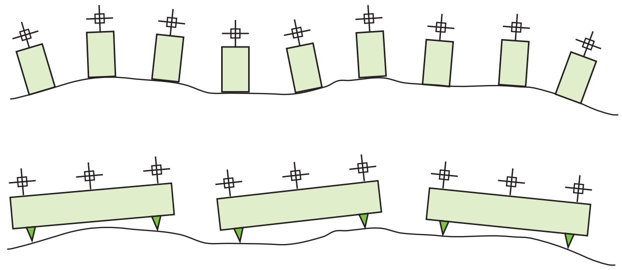

Figure 1: The upper figure depicts quadrupoles independently supported on columns mounted on the Undulator Hall foundation. The lower figure depicts quadrupoles supported three to a girder supported on the same (microscopically distorted) foundation.

foundation, just as a column would. However, the motion of quadrupoles on each girder will be highly correlated even though the motion of the girder is random. This correlation of the quadrupole motions can greatly reduce the sensitivity of the orbit and the resulting phase errors that would otherwise result from independent quadrupole support. Conceptually the multiple quadrupoles on a girder act as a doublet, triplet, etc., depending on how many quadrupoles are on the girder, whose effective focal length is much greater than that of individual quadrupoles. Motions of the quadrupole array as a whole have therefore less effect on the beam trajectory compared to motions of individual quadrupoles.

Simulation

Two models were created to analyze the effect of foundation motion on the accumulated phase error: one to represent the column support concept, and one to represent the girder concept with three quadrupoles to a girder. For simplicity only vertical motion was allowed. In the column model the deviation of the height of each quadrupole center from ideal was assumed to be equal to the vertical deviation of the foundation height at the location of the quadrupole. In the girder model the girders were assumed to be perfectly rigid objects whose motion was controlled by the foundation motion at two support points a distance L apart. The quadrupole height deviations were then calculated from the girder angle and position changes. For both models the height deviations of the foundation were random variables from a uniform probability distribution centered at zero with total width g_{tol}.

The girder geometry is shown in figure 2. The quadrupole heights h_j, ($j = 1, 33$), on 11 girders, ($n = 1, 11$), are calculated from the foundation heights g_i, ($i = 1, 22$), and quadrupole to quadrupole spacing l according to equations of the form,

$$\begin{aligned} h_{3n} &= h_{3n-1} + (g_{2n} - g_{2n-1})(l/L) \\ h_{3n-1} &= (g_{2n} + g_{2n-1})/2 \\ h_{3n-2} &= h_{3n-1} - (g_{2n} - g_{2n-1})(l/L) \end{aligned}$$

The resulting orbit is calculated assuming the incoming trajectory is perfect and the only steering elements are due to the quadrupole positions h_i. The phase error is 2π times the change in length of the electron trajectory divided by the X Ray wavelength, 0.15 nm.

The spacing between the quadrupoles l was assumed to be uniform and the quadrupole gradients were assumed to have an integrated gradient of 3.0 T, alternating between horizontally and vertically focussing. The actual LCLS optics design differs in some of the details from these assumptions but the differences do not have significant affect on the comparison between the column support and the girder support.

Typical output of the simulations of column support and girder support are shown in figure 3 and figure 4, respectively. In these simulations the quadrupole to quadrupole spacing was 4.0 m and the spacing between the girder support points was 6.0 m. For both simulations the foundation height deviation g_{tol} was 20 μm. Note the much large trajectory deviation and phase error for the column supported quadrupoles. By averaging over 1000 different sets of foundation deviations, we find the average total phase error for the column supported quadrupoles is 360 degrees while for the girder supported quadrupoles it is only 76 degrees.

The dependence of total phase error at the end of the Undulator on the foundation deviation is shown

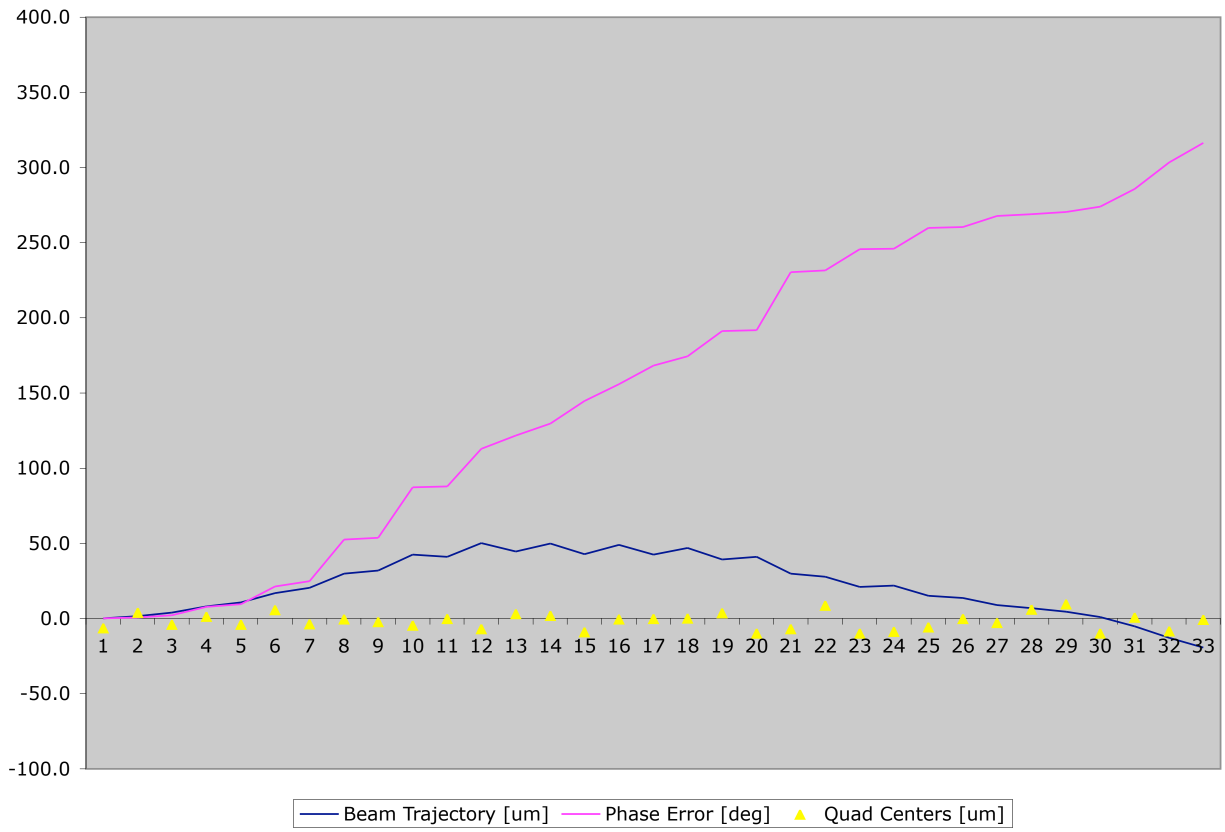

Figure 3: Trajectory, phase error and quadrupole position, assuming quadrupoles are supported independently, one to a column, are shown plotted against the quadrupole number along the Undulator.

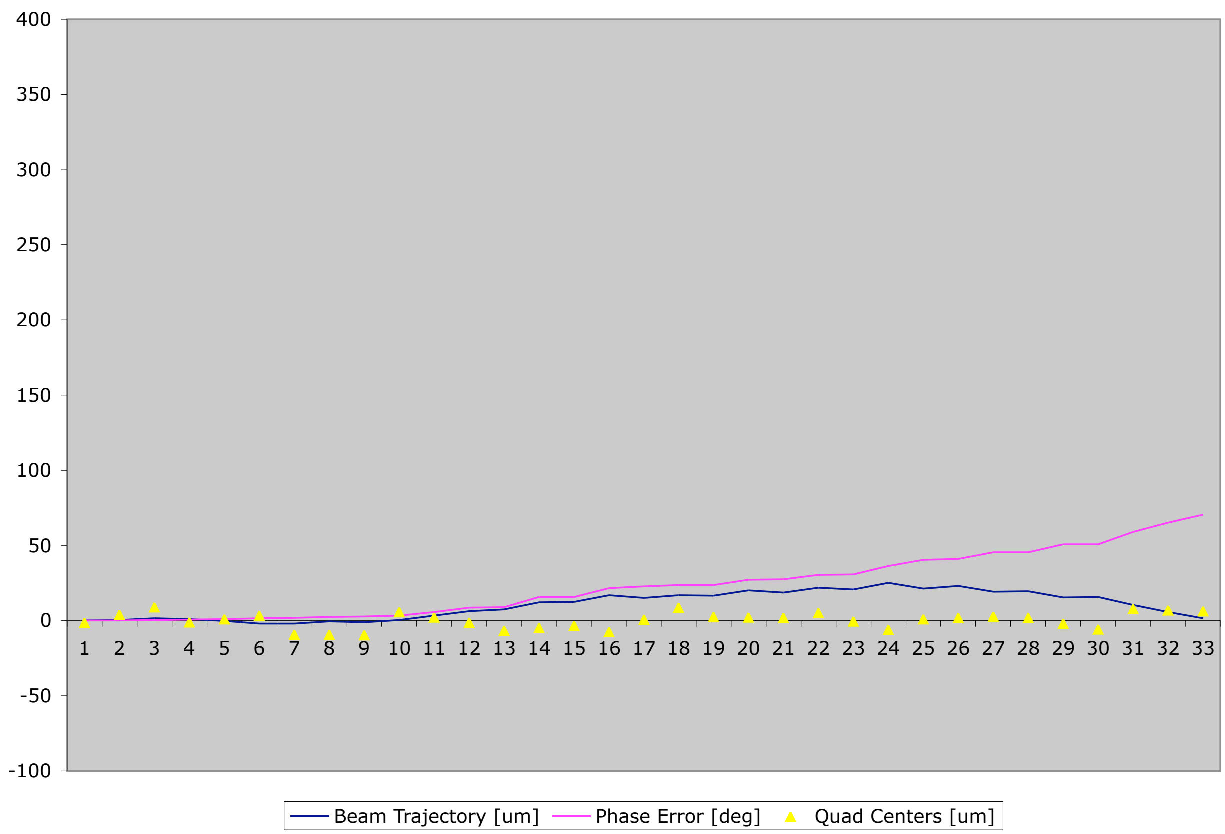

Figure 4: Trajectory, phase error, and quadrupole position, assuming quadrupoles are supported three to a girder, are shown plotted against the quadrupole number along the Undulator. The quadrupole centers (yellow points) can be seen to be grouped in lines of three corresponding to individual girders.

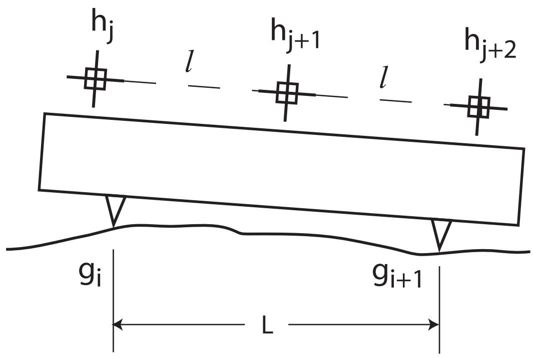

Figure 2: Definition of variables used to calculate the quadrupole motion from the foundation motion for the girder support concept.

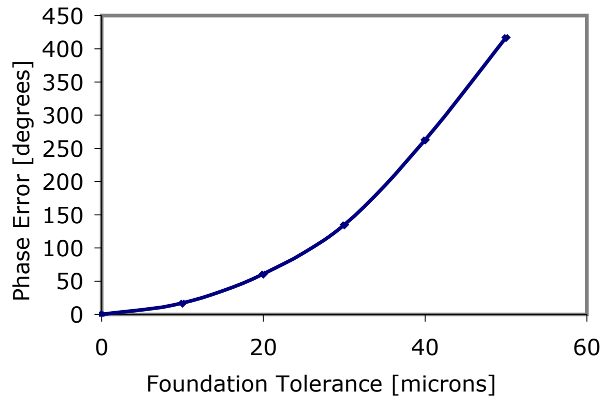

Figure 5: Total phase error as a function of the foundation tolerance.

in figure 5 for the girder case. As expected this is a purely quadratic dependence. A study of the dependence on the total phase error as a function of the spacing between the girder support points was done. The results are shown in figure 6.

Discussion

There are two key assumptions made in the previous analysis. One is that the girders are perfectly rigid bodies and the other is that the foundation motions are uncorrelated from one quadrupole to another.

Rigid Body Assumption

To the extent the girders do not behave as a perfectly stable rigid bodies the distortions of the girders will cause additional quadrupole motions. Nevertheless the beneficial effect of the girder in reducing the sensitivity to foundation motion is still there. Undesirable uncorrelated girder distortions would have to be at a level at least 2.5 times higher than similar column distortions before the net phase error for girders would be equal to that for columns. The total phase error starts to seriously affect FEL performance if it reaches roughly the level of 360 degrees. For the girder support scheme this corresponds to a g_{tol} of about 50 μm, so it is important that time vary-

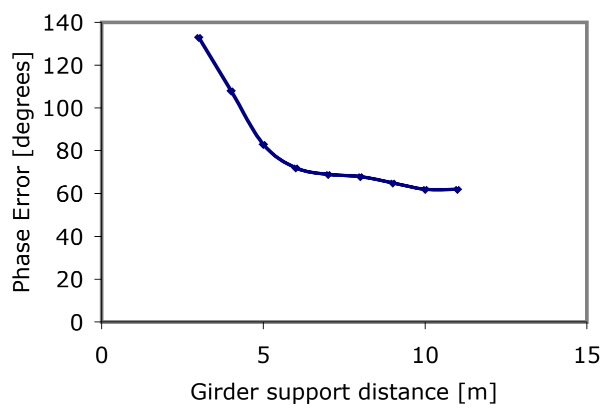

Figure 6: The dependence of the total phase error on the distance between the support points on the girder is shown in this figure. A constant foundation tolerance of 20 μm was assumed.

ing girder distortions be kept well below the 50 μm level. Distortions which do not change in time, such as bending due to gravity, have no effect on the beam trajectory or phase error once beam based alignment has been performed.

Correlation of Foundation Motion

The key result of the analysis presented in this paper is that correlated motions are much less important to the phase error than uncorrelated motions. Whether the correlations are because of an intervening girder or because the foundation stiffness tends to correlate nearby motions is immaterial — both are beneficial. In this sense the g_{tol} value should be interpreted as the uncorrelated part of the foundation motion. The correlated part will have little effect. In existing accelerators, level measurements typically show correlation of foundation settlement velocities for nearby measurements, but there are many exceptions as well. See,for example, ref [2].

References

[1] SLAC-PUB-95-7043, R. Pitthan, *Re-Alignment: It is the Tunnel Floor Which Moves, Isn't It*, p3. Settlement velocities of several monuments can be determined from the graph provided. They range from +1 to −1 mm/year, i.e., ±3 μm/day.

[2] PEP Technical Memo PTM-258, F. Linker, *Analysis of PEP Arc Surveying Data: 1984 and 1985*