Phase Matching The LCLS-II Undulators

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Abstract

This note describes a technique for ensuring the proper phase relation between the electron beam and the light wave in the LCLS-II adjustable gap undulators. It describes how to determine the phase shifter settings. It also describes how the undulators can be tuned so that no phase shifters are needed at a particular K value, which will provide a simplification when commissioning the undulators.

1 Introduction[1]

Adjustable gap undulators require phase shifters to account for the varying free space phase advance as the undulator gap is changed[2]. A method must be devised for setting the strength of the phase shifters to ensure that the electron motion has the proper phase relationship to the radiation wave in the center of each undulator. This note describes a procedure to determine the phase shifter settings. It also describes a way to commission the undulator line with all phase shifters turned off as a way to simplify the commissioning.

2 Ideal Phase

In order to formulate a procedure for setting the phase shifters, it is useful to employ the idea of the ideal phase. The ideal phase is one particular solution to the phase matching problem, but with other solutions easily found by adding multiples of 2π to the ideal phase. With the ideal phase solution, we imagine phase shifters at the entrance and exit of each undulator correcting deviations from the ideal phase solution. These conceptual phase shifters are then combined into the physical phase shifters at the end of the process. Additionally, the concept of ideal phase lets us add phase shims at the entrance and exit of each undulator in order to need no phase shifter correction at a particular K value. This will be beneficial when commissioning the undulators. We now proceed to define the ideal phase.

We first divide the undulator line into cells, one cell per undulator. We choose each cell to extend from the center of the interspace at the entrance of the undulator to the center of the interspace at the exit of the undulator. The ideal phase advance in the cell we require to be a multiple of 2π which we denote by Φ_c. Later, multiples of 2π can be added to Φ_c and the proper phase relationship will be maintained. When considering an individual undulator, we take the phase at the cell entrance to be $\Phi = 0$, and the ideal phase at the cell exit to be $\Phi = \Phi_c$.

The undulator has an entrance end region in which the magnets have varying strength in order to launch the trajectory without steering and without an offset. Although we ignore the light

[1] Work supported in part by the DOE Contract DE-AC02-76SF00515. This work was performed in support of the LCLS project at SLAC.

[2] Z. Wolf, "A PPM Phase Shifter Design", LCLS-TN-11-2, July, 2011.

produced in this end region, there is a phase advance in the end region and the free space leading up to it. After the end region, the electron motion must be in phase with the light and this must remain true through the center of the undulator. At the exit, there is another end region which makes the beam leave the undulator without a slope or offset. The exit end region and free space leading to the cell boundary contributes to the phase advance. At the exit end cell boundary, the ideal phase advance is Φ_c.

Suppose the end region is made of N_e poles. The first pole in the center is number $N_e + 1$. There are the same number N_e poles making up the end region at the exit. If the undulator has N_p poles total, the central region has $N_p - 2N_e$ poles. This is illustrated in figure 1.

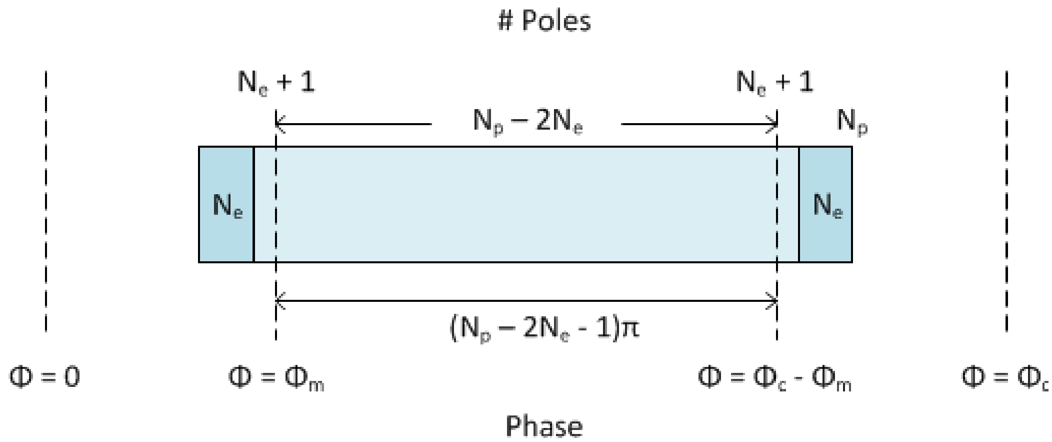

Figure 1: Figure showing the number of poles and the phase advance through the undulator to the cell boundary.

In the central part of the undulator, the ideal phase advance is π per pole. We are assuming the K value is set correctly and we are considering phase calculated with the radiation wavelength of this undulator. There are $N_p - 2N_e$ poles in the central region, so there are $N_p - 2N_e - 1$ phase shifts of π between poles. The phase shift in the central region is

$$\Phi_{center} = (N_p - 2N_e - 1)\pi \tag{1}$$

Suppose the ideal phase is Φ_m at the first center pole, number $N_e + 1$. This is the matching phase to bring the electron motion in phase with the light wave in the center of the undulator. We assume symmetry of the cell about the center of the undulator, so the ideal phase advance to go from the last pole in the center to the cell boundary is also Φ_m. The cell phase is the sum of the matching phase at the entrance, the phase advance through the center, and the phase advance through the exit.

$$\Phi_c = 2\Phi_m + (N_p - 2N_e - 1)\pi \tag{2}$$

This relationship lets us solve for Φ_m.

$$\Phi_m = \frac{1}{2}\left[\Phi_c - (N_p - 2N_e - 1)\pi\right] \tag{3}$$

Once we specify the ideal phase advance in the cell Φ_c, and we choose a number of end poles N_e out of a total number of poles N_p, we calculate Φ_m which is the ideal phase at the first pole after the end poles.

Knowing Φ_m, we can calculate the ideal phase of every pole in the center of the undulator. For pole number n in the center, the ideal phase is

$$\Phi_n = \Phi_m + [n - (N_e + 1)]\,\pi \tag{4}$$

We choose a cell phase, calculate Φ_m, and get this ideal phase at every pole in the center to compare the measured phase against.

3 Phase Matching Error

By measuring the magnetic field in the undulator, we can calculate the slippage, the K value, the radiation wavelength, and the phase at each pole in the center region. Let ϕ_n be the measured phase at pole n. Regardless of the wavelength, the phase advance in the undulator center is still π per pole, and relation 4 still holds for the ideal phase at pole n. Taking the difference between the measured phase at pole n and the ideal phase at pole n, we get a plot like the one in figure 2. The

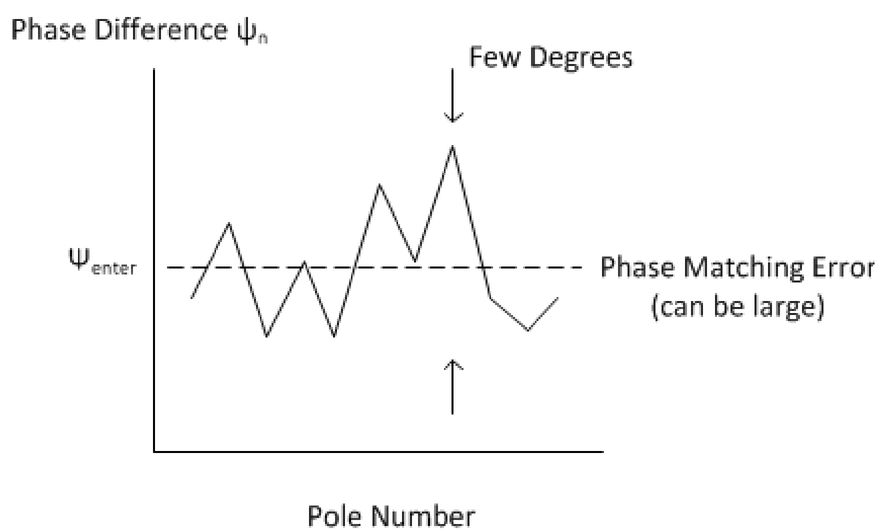

Figure 2: The average of the difference between the measured phase and the ideal phase in the center of the undulator is the phase matching error.

difference in phase has some small fluctuations about an average value, but the average value may be very large. The average value, the phase matching error at the entrance, must be corrected to be a multiple of 2π for the undulator to contribute to the radiation wave.

Let

$$\psi_n = \phi_n - \Phi_n \tag{5}$$

be the difference between the measured phase at pole n and the ideal phase at pole n. Let

$$\Psi_{enter} = \langle \psi_n \rangle \tag{6}$$

be the average value of the phase difference through the center of the undulator. Ψ_{enter} is the phase matching error that must be corrected at the entrance of the undulator to be a multiple of 2π.

There is also a phase matching error at the exit. The measured phase of the cell may be different than Φ_c. In this case the phase at the undulator exit must be corrected. Let ϕ_c be the measured phase of the cell. The difference between the measured phase of the cell and the ideal phase of the cell we denote by ψ_c.

$$\psi_c = \phi_c - \Phi_c \tag{7}$$

The phase matching error that must be corrected at the exit is denoted by Ψ_{exit}.

$$\Psi_{exit} = \psi_c - \Psi_{enter} \tag{8}$$

Ψ_{exit} is the phase error of the cell minus the correction that has been made at the entrance.

Once the phase matching errors Ψ_{enter} and Ψ_{exit} have been corrected to be a multiple of 2π, both the phase through the entrance to reach the center of the undulator will be a multiple of 2π, and the phase through the cell will be a multiple of 2π. Note that in principle it is also acceptable to have the phase matching error be an odd multiple of π at the entrance and an odd multiple of π at the exit, but we choose not to use this strategy since it increases the possibility of a large error when setting up the undulator line.

4 Phase Matching Error Correction

The phase matching correction at the entrance and the exit can be done in two ways. A phase shifter can add phase until a multiple of 2π is reached, or a phase shim can subtract phase until a multiple of 2π is reached. Consider the plot in figure 3. In this plot the phase matching error at

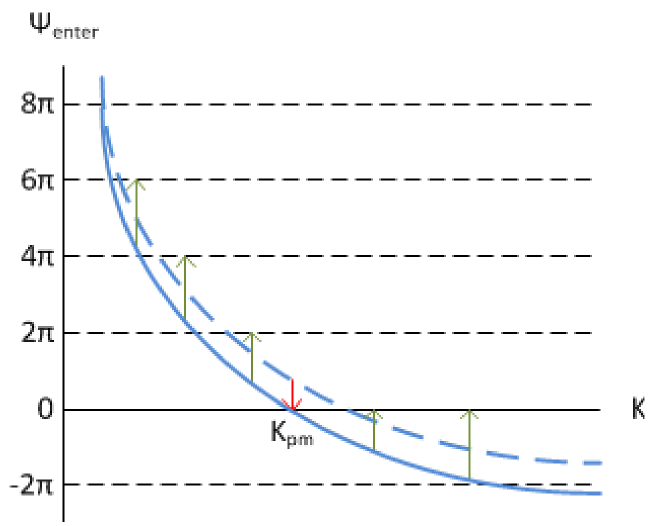

Figure 3: The dashed line of this plot shows the phase matching error at the entrance as a function of K value. The red line shows a negative phase correction from a phase shim which makes $\Psi_{enter} = 0$. This changes the phase matching error at all K values to the solid line. The green lines show positive phase corrections from phase shifters to get to a multiple of 2π at various K values.

the undulator entrance is plotted as the dashed line. A phase shim is added at the entrance which makes the phase matching error zero at a given K value, K_{pm}. This is shown by the red arrow. The phase matching error is then remeasured at all K values giving the solid line. At any given K value, a phase shifter adds phase to make the phase matching error a multiple of 2π. This is shown by the green arrows. The phase shim and phase shifter at the entrance are shown in figure 4.

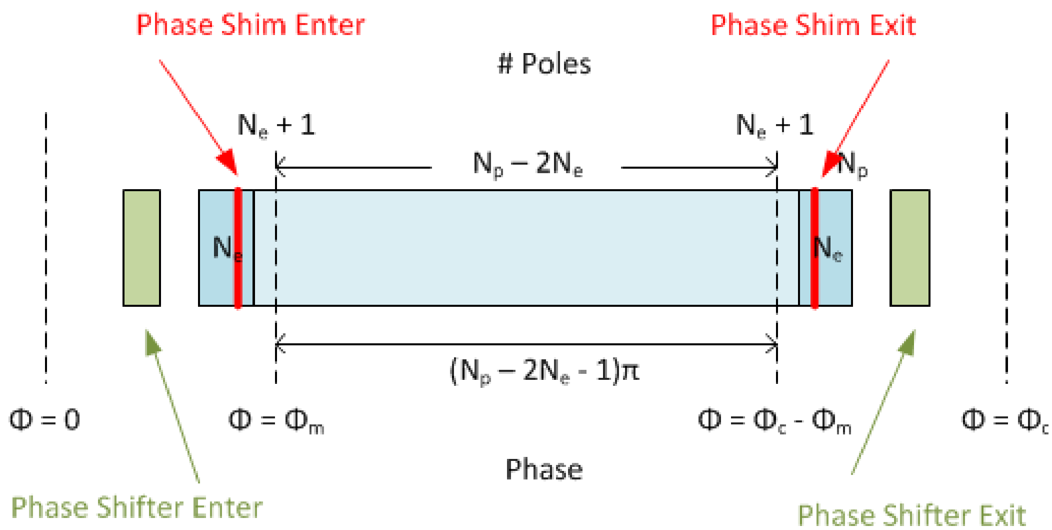

Figure 4: Phase shims are added at the entrance and exit to make the phase matching error zero at a certain K value, K_{pm}. A phase shifter at the entrance makes the phase matching error in the undulator center equal to a multiple of 2π at arbitrary K values. A phase shifter at the exit makes the phase error of the cell equal to a multiple of 2π at each K value.

A phase shim is also added at the undulator exit so that at K_{pm}, the phase error of the cell is zero. A phase shifter at the exit then makes the phase error of the cell equal to a multiple of 2π at arbitrary K values.

The undulator line does not have individual phase shifters at the entrance and exit of each undulator. One phase shifter is between each pair of undulators and its value is set to the exit phase matching correction of the previous undulator plus the entrance phase matching correction of the present undulator.

This scheme will be of great value during the undulator line commissioning. With the phase shims installed, all undulators can be set to K_{pm} and the correction from all the phase shifters will be zero. In this case the undulator line can be turned on without phase shifters, providing a significant simplification. This will make the initial turn on similar to that of LCLS-I.

Up to now, the cell phase Φ_c has been an arbitrary multiple of 2π. The procedure given above shows us how to determine its value. The undulators are tuned at a given mechanical gap value. Afterwards, the K value at each gap setting is determined. We choose an integer N, with $\Phi_c = 2\pi N$, so that at the tuning gap, the magnitude of the phase error of the cell is less than 2π. We then choose K_{pm} so that Ψ_{enter} and Ψ_{exit} both have a positive value on the order of 10 degrees. In this case we can add phase shims to make Ψ_{enter} and Ψ_{exit} equal to zero at K_{pm}.

5 Conclusion

This note presented an algorithm for setting the phase shifters in a line of adjustable gap undulators. In addition, it provided a way to commission the undulator line with all phase shifters turned off. This should provide a significant simplification to the commissioning.

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