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OPERATIONAL MODEL OF THE ATHOS UNDULATOR BEAMLINE

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Abstract

Athos, the new Soft X-ray beamline of SwissFEL, operates 16 Apple X undulators and 15 compact chicanes to implement novel lasing schemes. With the data available after the end of the magnetic measurement campaign (middle 2020), a self-consistent set of equations will be used to summarize all the relevant properties of those devices to start their commissioning. The analytic approach planned will be discussed in great detail and tested with the preliminary experimental data available. Finally, the accuracy of this approach will be evaluated and critically compared to the requirements of the new FEL beamline.

INTRODUCTION

In Apple X undulators [1] synchrotron radiation can be produced with any polarization. Also the deflection parameter K can be changed by radially moving the arrays in and out, defining the gap (pole tip to central axis) of the undulator, also called radius (r). We differentiate between the standard cases: Linear Horizontal (*LH*), Linear Vertical (*LV*), Circular plus/minus (*Circ*+/-) and plus/minus 45 degrees (+/-45°). Moreover, elliptical polarization angles are possible, but not specifically detailed in this article.

All previous mentioned polarizations but +/-45° can be produced by shifting two opposite magnetic arrays (e.g. No. 1 and No. 3) parallel against their neighboring arrays (e.g. No. 2 and No. 4) [1]. Linear polarization of any angle however can be produced by shifting two opposite magnetic arrays anti-parallel to each other, against their neighboring arrays.

In the following sections we are deducing models from measurement data, in order to predict the undulator positions for any given K and polarization angle α. We are not looking into the Energy mode [1] nor the transverse gradient undulator (TGU) mode in this paper,

In order to allow for a proper set up of the different operational modes, the models should predict K with an error of a few $\frac{\Delta K}{K} = 10^{-4}$.

PARALLEL MODES

Assuming the magnetic field is equal in strength in x and y dimension the parallel modes should be easy to predict. In this case the effective K does not depend on the phase shift of the two moving arrays. However, in the case of a real undulator we have to correct for the slight variation between the magnetic field for the transverse dimensions, B_x and B_y. When moving the arrays in a parallel way, the K-value varies on a 1% level (see blue points in Fig. 1), which had to be taken into account in order to achieve the requested prediction error. Thus to predict the dependencies of the overall gap and the parallel shift needed for a given K-value a universal model based on the magnetic model was developed.With the magnetic model of sinusoidal form, a variation of K_{eff} (background) can be described by a difference between B_x and B_y, see red line in Fig. 1. For a single gap it can be expressed by Eq. (1), which is discussed in more detail in [2].

$$K(\phi) = 2\sqrt{2}\kappa\sqrt{B_x^2 + B_y^2 - \cos(\phi_p)(B_x^2 - B_y^2)} \qquad (1)$$

Here ϕ_p is the shift defined as a relative phase difference of two neighboring arrays and $\kappa = \frac{e\lambda_U}{2\pi m_e c}$. A result can be seen in Fig. 1, where it is fitted for a single gap (red line).

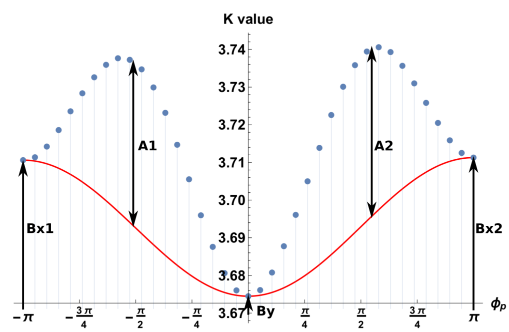

Figure 1: Measured points for a single gap (blue points), background (red line) and model coefficients (black).

Furthermore a second correction has to be added on top to describe the variation probably caused by mechanical deformation due to strong magnetic forces, especially at small gap sizes. It can be described empirically by Eq. (2).

$$K(\phi_p) = A\sin^2(\phi_p) \qquad (2)$$

For the data of the same gap as shown in Fig. 1, but with the background removed, the K-correction can now be fitted depending also on the parallel shift ϕ_p (see Fig. 2).

An asymmetry was observed when shifting the arrays in one direction with respect to the opposite direction. Therefore the model coefficients need to be calculated separately for each direction. This helped to minimize the errors at the five points of the dedicated modes ($LH, LV_1, LV_2, Circ+, Circ-$) to below $\frac{\Delta K}{K} = 2 * 10^{-4}$. For all measured gaps the fitting errors can be seen in Fig. 3.

With the above mentioned corrections five coefficients are needed to fit K for each gap (B_{x1}, A_1, B_y, A_2, B_{x2}). Doing

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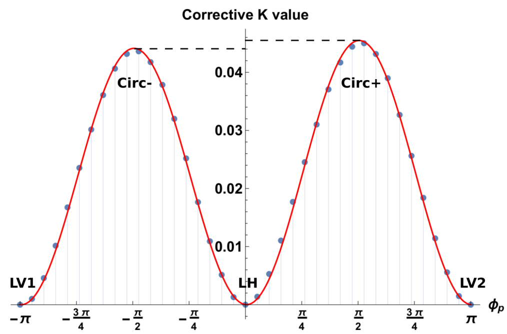

Figure 2: Measured points for a single gap with background subtracted (blue points), fitting their correction (red line) and operational modes indicated (black).

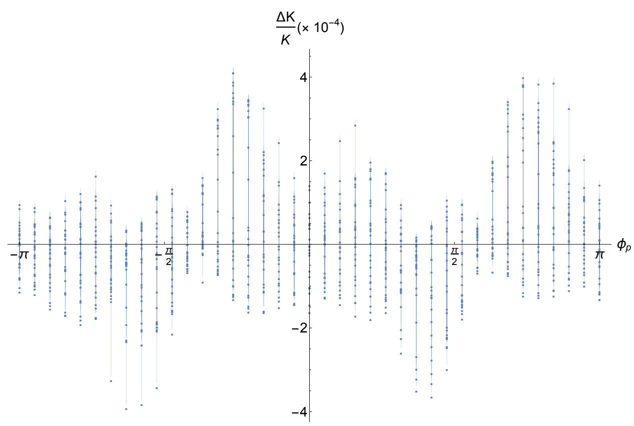

Figure 3: Relative errors when both fits are applied for all measured gaps.

this for all the measured gaps yields a coefficient table. That way each coefficient can be fitted with an exponential gap dependence. For example the resulting expression for B_y is shown in Eq. (3).

$$B_y(g) = \exp(a + bg + cg^2 + dg^3 + eg^4) \tag{3}$$

where all the parameters (a, b, c, d, e) need to be fitted for a particular mode. The same approach can be repeated for the other coefficients, which yields in total five equations. Combining them all into one expression results in the final model. The resulting equation for the case $\phi_p < 0$ is shown in Eq. (4). In case $\phi_p > 0$ two parameters have to be replaced by B_{x2} and A_2.

$$K(g, \phi_p) = 2\sqrt{2}\kappa[B_{x1}^2(g) + B_y^2(g) - \cos(\phi_p)(B_{x1}^2(g) - B_y^2(g))]^{\frac{1}{2}} + A_1(g)\sin^2(\phi_p) \tag{4}$$

NEW ANTI-PARALLEL MODE

To achieve any given, linear polarization angle, the anti-parallel mode is used. In contrast to the usual, pure anti-parallel shift of two opposing arrays, the Apple X allows also another scheme, which we will describe here. Starting by first opening the two opposing gaps, the polarization angle starts changing, and only then shift the same two arrays in opposite directions, moving the polarization angle beyond 45°. For polarization angles close to 90 degrees, the gaps can then be closed again. This new mode has in comparison with the legacy mode the advantage of avoiding spurious contribution of longitudinal magnetic forces.

However, there are also certain drawbacks going along with it. The most important ones are:

1. *The partial invalidation of previous shimming campaigns during these movements.* The shimming is currently optimized for the magnetic arrays having equal gap positions. More sophisticated shimming techniques could potentially be developed to comprise also these cases. Though it was not part this study.
2. *The complication of the modeling.* Moving the gap of two out of four arrays adds two new parameters: r_0 the initial gap of all arrays and $r_{1,3}$ the gap of the two arrays which are shifted in anti-parallel directions. This makes it more difficult to use drastic simplifications of the magnetic model. A possible method for mitigation is presented below.

The measurement results for different r_0 are presented in Figs. 4 and 5. The black lines indicate the different domains of movement. Here $gap_{1,3}$ indicates the gap opening of array 1 and 3, respectively closing, while ↑↓ $shift_{1,3}$ indicates the anti-parallel shift of array 1 and 3.

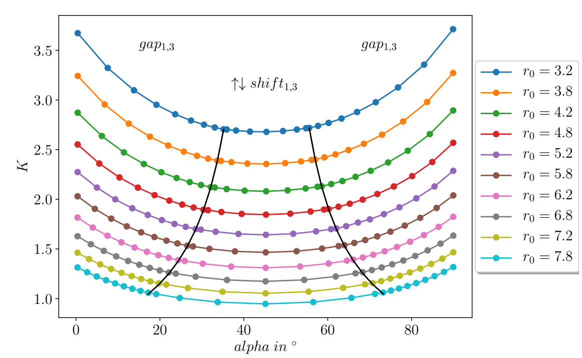

Figure 4: Measurement results of anti-parallel shifts at different r_0, black lines indicate model domain borders.

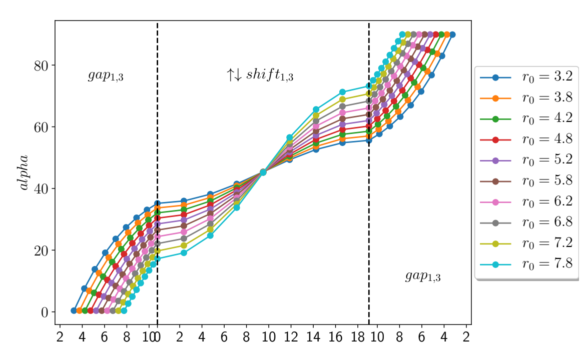

Figure 5: Measurement results of anti-parallel shifts at different r_0, black lines indicate model domain borders.

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One way to fit the measured behavior while mitigating the additional complexity is to split the modeling task into the aforementioned domains of movement. A possible user scenario would be scanning the polarization angle from 0 to 90 degrees while maintaining a constant K. We propose to determine first for each pair of K, α which model is to be used. For that we fit $r_{0\alpha} = f(\alpha, K = const.)$, as well as $r_{0K} = f(\alpha = const., K)$ for now with a simple polynomial. Comparing these two initial gaps we can decide which model to use: if $r_{0\alpha} > r_{0K}$ we use the model for $gap_{1,3}$, otherwise the model for $\uparrow\downarrow$ $shift_{1,3}$. However, there are slight asymmetries between the opening and closing of the gap at different shift positions (e.g. LV_3 and LV_4). Thus it is necessary to decide additionally if $\alpha < 45°$ to use the dedicated gap model.

Once a model has been determined. The models themselves have to be broken down into two parts due to the higher number of parameters. First step would be to fit $r_0 = f(\alpha, K)$. Knowing r_0 we can fit $pos = f(\alpha, r_0)$, where pos is the gap or shift depending which model was chosen.

A simple two dimensional, 4th order polynomial fit of the first part to recover r_0 for each domain is shown in Fig. 6. The errors are still rather big and do not satisfy the operational needs of accuracy. Better fit functions need to be found, ideally based in physics.

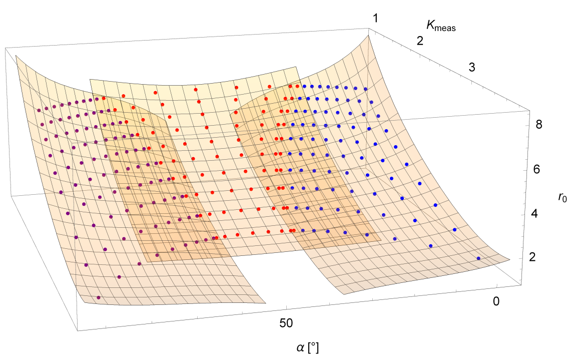

Figure 6: 2D fit results for each model domain.

MECHANICAL HYSTERESIS

We identified the mechanical hysteresis by measuring the magnetic field at 4.75 mm while approaching this value from each side. This was done by repeatedly opening and closing the gap between 3.25 and 10.75 mm, see figure 7 for a visualization.

The measurements were done at different shift positions of the magnetic arrays, representing different operational modes ($LH, LV, Circ$ +/-, 45° +/-). The results are shown in Fig. 8. It can be seen, that the mechanical hysteresis of the gap movement is around the level of 10^{-4} for LH, LV and 45° modes, while the hysteresis for circular polarization can be excluded above $2 * 10^{-5}$.

Similarly the magnetic arrays (Top Left and Bottom Right) were shifted in an anti-parallel way repeatedly between +/-19 mm, while the hysteresis was analyzed at +/-9.5 mm.

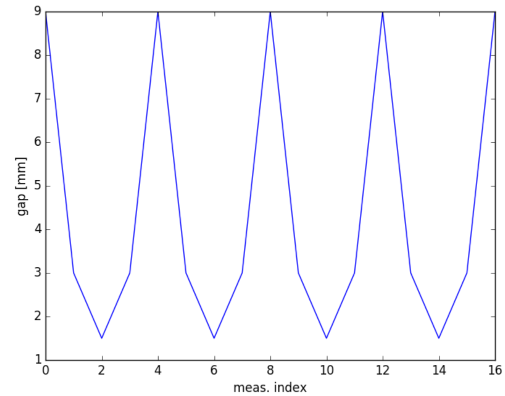

Figure 7: Measurement scheme to investigate hysteresis.

The measurements are not shown here, but yield a slightly bigger error of $2 * 10^{-4}$, which should still cause no problems for the operation.

Mixed gap and shift movements will have to be measured and analyzed next.

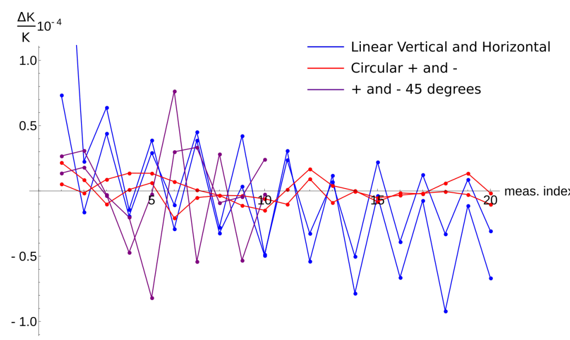

Figure 8: relative K-errors of mechanical hysteresis for different modes.

CONCLUSION

The mechanical hysteresis for gap, respectively shift movements have been investigated and shown to fulfill the required accuracy, with relative errors around 10^{-4} . A complete model to describe distinct parallel operational modes was developed with sufficient accuracy for current operation. Furthermore, a novel anti-parallel operational mode was proposed, which combines opening gaps and shifting arrays. Currently a model split into three domains is under development.

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