HXU Half Gap Encoder ABC Test

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Abstract

The LCLS-II hard x-ray undulators have three mounting positions, labeled A, B, and C. If the half gap encoders are used to control the undulator, the undulator behaves differently in the three positions. In particular, the K value changes for given gap settings and the phase errors increase as the undulator is moved from A to C. In this note we compare magnetic and mechanical measurements made in the three mounting positions when the half gap encoders are used to set the undulator gap.

1 Introduction[1]

The LCLS-II hard x-ray undulators (HXU) have two sets of encoders. Full gap encoders directly measure the gap, and half gap encoders measure the position of each strongback relative to the girder. The full gap encoders were not specified correctly to control the undulator within tolerance[2]. It wasn't until the first production undulator arrived at SLAC for calibration that the problem was found. Replacing these encoders now that production has begun will have a large impact on the project schedule and cost. The half gap encoders do not measure the gap, but perhaps their values can be correlated with the gap well enough to allow a calibration for setting the K value. This possibility relies on the mechanics of the undulator and how well the half gap encoders are correlated to the gap in spite of mechanical deformations of the undulator. The purpose of this note is to explore the consequences of using the half gap encoders to calibrate the undulators.

As noted, a primary concern when using the half gap encoders is deformations of the undulator. The undulators have three mounting positions and the deformations in the three positions may not be accurately accounted for by the half gap encoders. The purpose of the three positions is to allow the undulators to be equally spaced in the tunnel without moving the LCLS-I mounting pedestals. (The undulators in LCLS-I were not equally spaced as there were long and short break sections.) If the undulators behave differently in the three mounting positions, then each undulator will need to be calibrated and potentially tuned in its final mounting position. On the other hand, if the mounting position doesn't matter, then all undulators can be tuned and calibrated in the same position, simplifying the logistics of the production measurements. We demonstrate below that indeed the undulator deformations are not accurately accounted for by the half gap encoders and that each undulator would need to be tuned and calibrated in its final mounting position. We also show that the undulators are not stable and that the K value varies from dataset to dataset. Further investigation is needed to determine if this is a result of using the half gap encoders or whether the undulator strongbacks are changing shape as the gap is changed.

[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, Y. Levashov, and V. Vranković, "A Problem With The HXU Full Gap Encoders", LCLS-TN-19-1, January, 2019.

2 Requirements

The requirements for the hard x-ray undulators are specified in a Physics Requirements Document[3]. Two requirements are of interest for this note. The first is that the tolerance for setting the K value is

$$\frac{\Delta K}{K} = \pm 2.3 \times 10^{-4} \tag{1}$$

Using data from HXU-001, the relative change in K with gap at 7.2 mm gap is

$$\frac{1}{K}\frac{dK}{dg} = -1.67 \times 10^{-4}\ \frac{1}{\mu\text{m}} \tag{2}$$

This means that a gap error of only

$$\Delta g = 1.4\ \mu\text{m} \tag{3}$$

will cause a K change at the tolerance level.

The second requirement of interest is that the rms phase error must be below 4 degrees.

$$\Delta\phi_{rms} = 4.0\ \text{deg}$$

3 HXU Encoders

The hard x-ray undulators have two sets of encoders. The full gap encoders measure the actual gap at the beam height. The half gap encoders measure the position of each strongback relative to the girder. The encoders on the upstream end are shown in figure 1. There is a similar set of encoders on the downstream end.

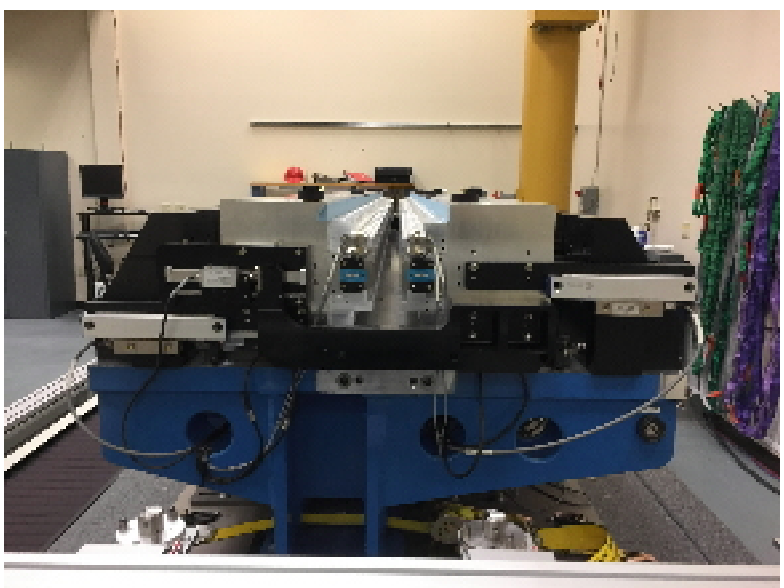

Figure 1: Photo showing the full gap encoder and the half gap encoders at the upstream end of HXU-017.

A schematic of the encoders is shown in figure 2. Looking at the undulator from the upstream

[3] H.-D. Nuhn, "Undulator System Physics Requirements Document", LCLSII-3.2-PR-0038-R3, June, 2017.

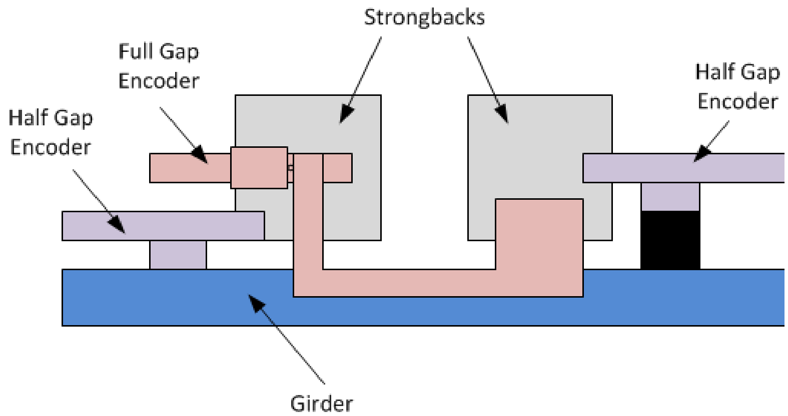

Figure 2: Schematic of the hard x-ray undulator and its encoders.

end, there is a half gap encoder on the right strongback. It is at the beam height. There is also a half gap encoder on the left side. It is at the bottom of the strongback. The half gap encoders do not measure the gap and they measure at different heights. The left encoder reading can be significantly different than a reading at the beam height if the strongback has roll. Both half gap encoders measure relative to the girder so that girder deformations which affect the gap are possibly not measured by the half gap encoders. For instance, the girder deforms when the magnetic forces on the strongbacks are large and bend the girder. A bend in the center of the girder affects the gap but is not seen by the half gap encoders.

The full gap encoders measure across the gap at the beam height. In principle, they provide a proper gap measurement. Of course, if the full gap encoders have errors, the errors will be reflected in the undulator gap when the control system uses the full gap encoders to set and read the gap.

There is a significant difference in the gap measurement by the full gap encoders and the value given by the sum of the half gap encoders. The plot in figure 3 shows the difference between the full gap encoder reading and the sum of the half gap encoder readings plotted as a function of gap. The plot shows a significant difference in the two gap measurements, over 30 μm at small gap. This is due to the girder bending and the strongbacks rolling due to the magnetic forces. This is expected since the half gap encoders do not accurately measure girder bending and strongback roll, so their sum should not give the true gap at the beam height. A smooth difference in the full gap and half gap readings in the plot is expected.

In addition to the smooth trend in the plot, however, there is significant noise in the points. The noise is large and it is this noise that made the full gap encoders unusable for setting K within tolerance.

If we neglect the full gap encoder noise and assume the half gap encoder values deviate from the gap in a smooth way, then the 30 μm error might be tolerated. The K value can be correlated with the half gap encoder reading. With this correlation, the half gap encoders might be used to set the K value.

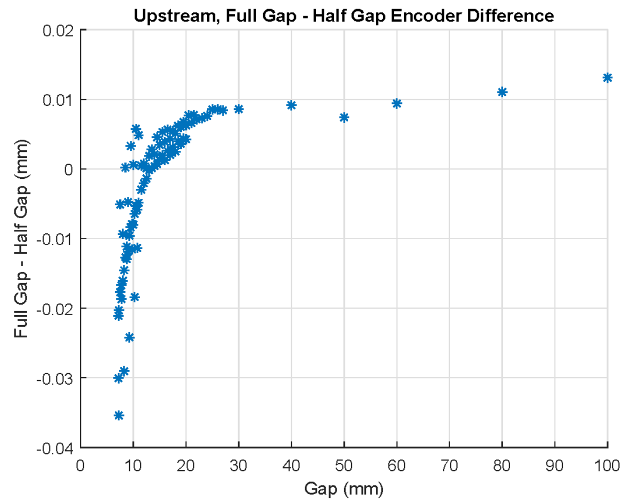

Figure 3: Difference between the full gap encoder reading and the sum of the half gap encoder readings as a function of gap.

4 ABC Mounting Positions

Figure 4 shows the HXU girder from the bottom. The mounting surfaces for the kinematic mount are labeled. The mounting surfaces are shown in the C position, with the B position in the middle, and the A position at the right of each set of three mounting locations. The C position places the undulator downstream for fixed mounting pedestal locations. This makes the largest overhang from the mounts to the end of the undulator. In the C position, there is more of the undulator extending past the support points, and the shelf with the interspace components extends further past the support points.

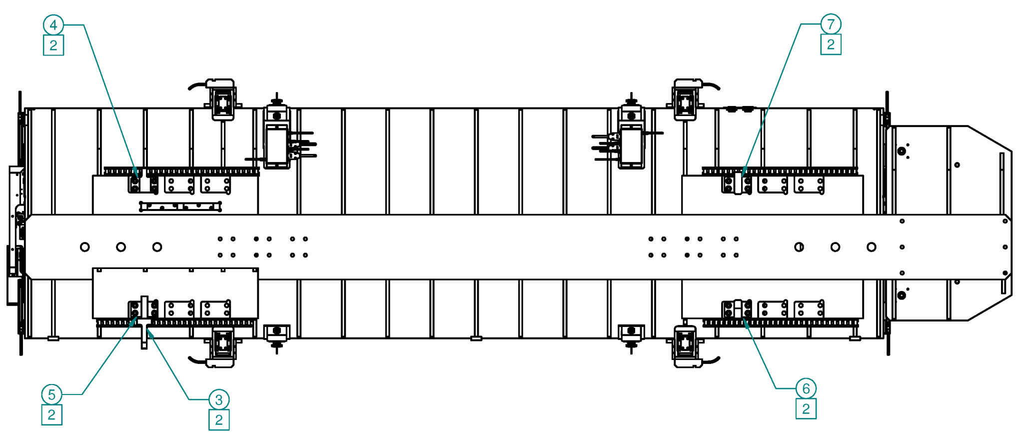

Figure 4: Bottom view of the HXU girder. The surfaces that go into the kinematic mount are labeled. The drawing shows the mounting surfaces in the C position.

The HXU mounting surfaces mate to a kinematic mount. This is illustrated in figure 5. The upstream end, to the left in the drawing, sits on a V and a flat. The downstream end, to the right in the drawing, sits on a wide V. The upstream end cannot rotate, but the downstream end can rotate in the wide V. Rotational moments can twist and distort the undulator at the downstream end. At the far right of the drawing is the shelf that the interspace components sit on. The interspace components weigh about 180 pounds and their weight has been simulated for the measurements by adding a stainless steel plate on top of the shelf.

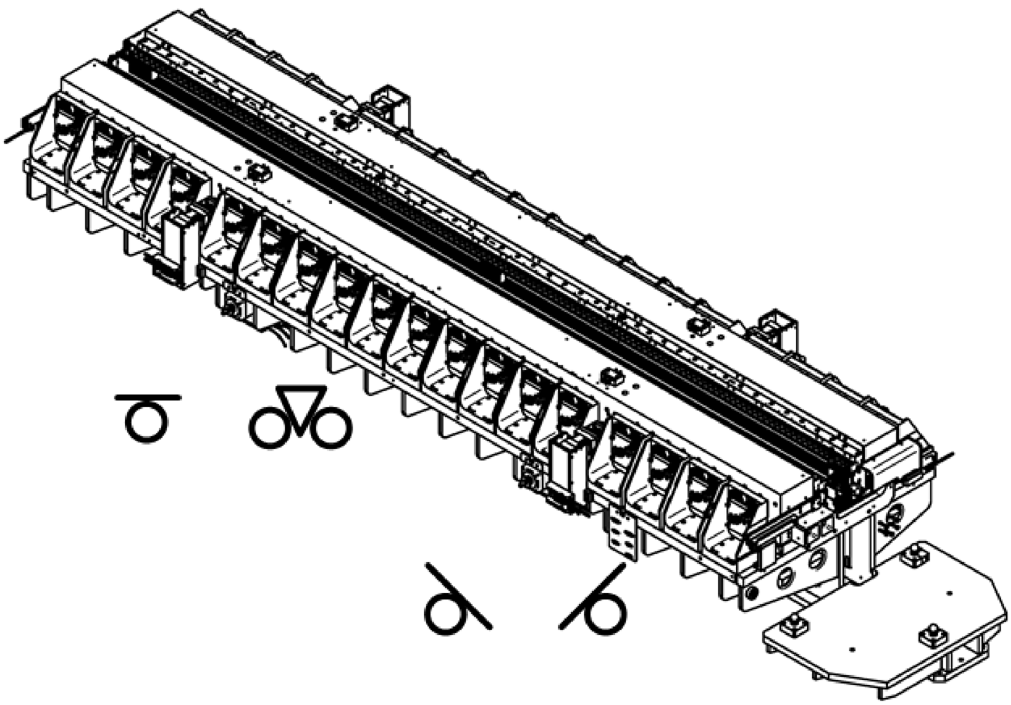

Figure 5: The HXU rests on a kinematic mount. This is illustrated by the V's and flat below the undulator.

An end view of the undulator is shown in figure 6. The strongbacks and spring cages are symmetric on the top of the undulator. There is a box beam that extends the length of the undulator which is offset from the center. The weight of the interspace components is coupled to the undulator through the offset box beam. This puts a rotational moment on the beam which tends to bend the left side of the girder down.

The supports for the kinematic mount are centered on the beam as shown in figure 4. The weight of the strongbacks on top of the undulator is offset sideways from the downstream V. This puts a moment on the girder which tends to bend the left side down. In the C position the moments bending the left side of the girder down are the largest. The moments are trying to bend the top of the girder which tends to open the gap of the undulator. The half gap encoders move with the top of the girder and are insensitive to this girder deformation and the resultant change in gap. This motivates the results which we will see below.

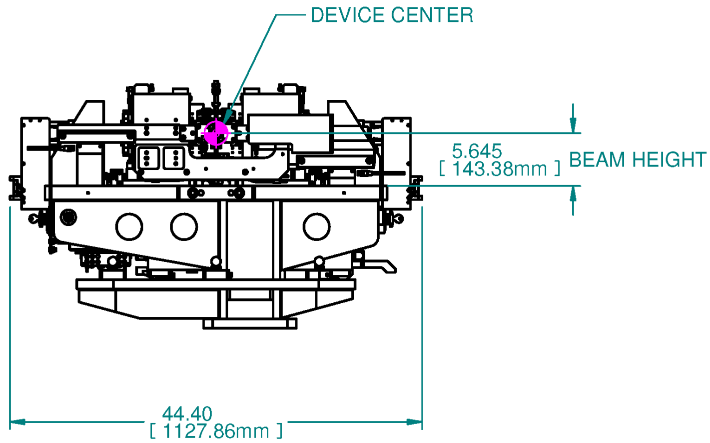

Figure 6: Drawing of the undulator as seen from the downstream end.

5 Magnetic Measurements In The A, B, And C Positions

5.1 Repeatability Of The Measurement System

The magnetic measurement results shown below are not repeatable. We must establish that it is the undulator that is not repeatable and not the measurement system. In order to do this, we repeated a magnetic measurement of the undulator seven times without changing the gap. The K value calculated from each measurement is shown in figure 7. The K value repeatability is $\left(\frac{\Delta K}{K}\right)_{rms} = 2 \times 10^{-6}$, which is much smaller than the tolerance, and much smaller than the repeatability of the measurements when we change the gap. The non-repeatability that is shown in what follows comes from the undulator and not from the measurement system.

5.2 Measurements In The A Position

Two sets of measurements were made in the A position. We use one of these measurements as the reference for all following measurements. The difference in K vs gap between the two measurements in the A position is shown in figure 8. The non-repeatability uses up about half the tolerance at small gap.

Also of interest is to compare the peak fields and the phase errors in the A position to measurements in the B and C positions. The amplitude of the peak fields at 7.2 mm gap is shown in figure 9. The slope of the line fitted to the peak fields is 1.5×10^{-4} T/m. We will compare this slope to the value in the different mounting positions.

The phase errors are shown in figure 10. The rms phase error is 1.8 degrees.

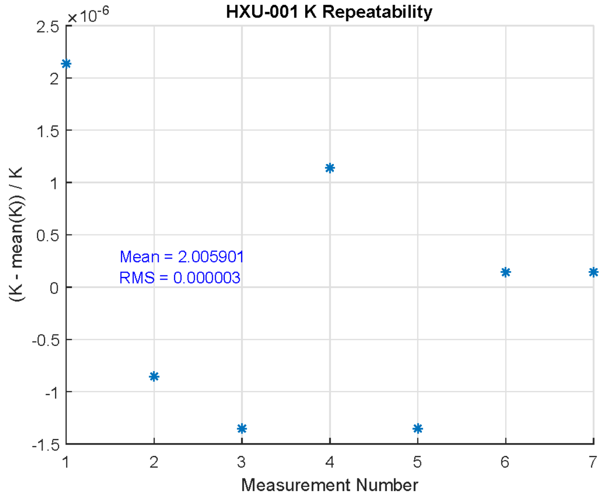

Figure 7: This plot shows the repeatability of the K value calculated from seven measurements taken without changing the undulator gap.

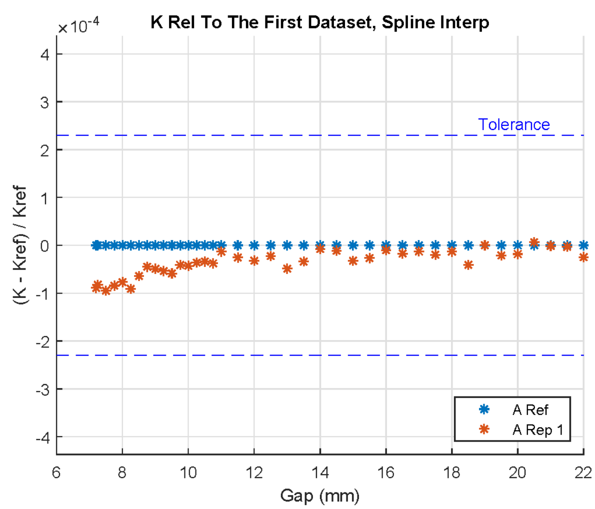

Figure 8: The two measurements in the A position repeated within tolerance.

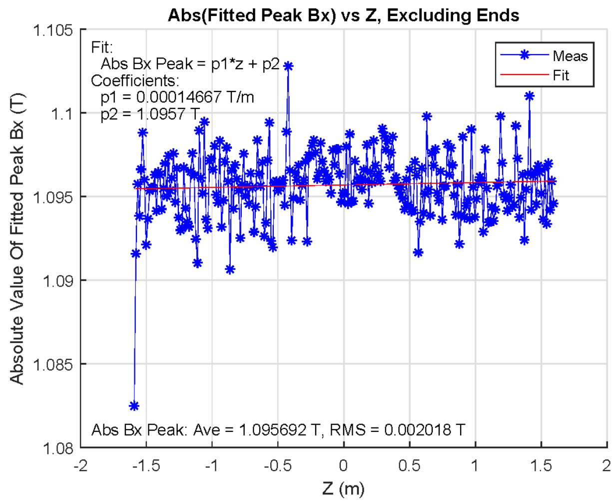

Figure 9: The magnitude of the peak fields at 7.2 mm gap in the A mounting position.

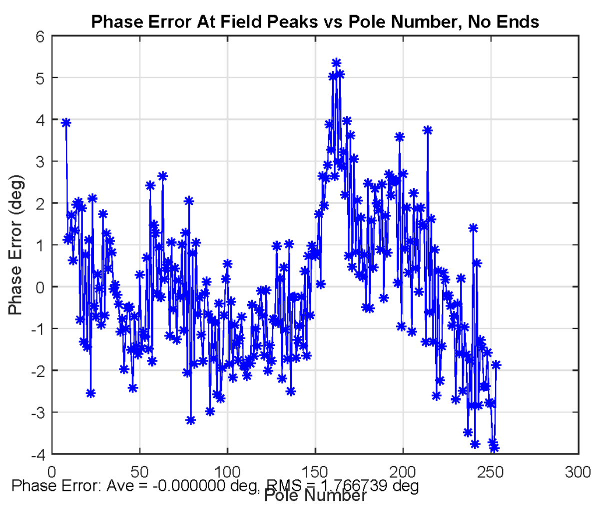

Figure 10: Phase errors at 7.2 mm gap in the A mounting position.

5.3 Measurements In The B Position

Four measurements were made in the B position. The difference between the four measurements and the reference measurement in the A position is shown in figure 11. In general, the measurements in the B position are systematically lower than the reference measurement in the A position. The systematic difference uses up about half the tolerance. The scatter in the measurements uses up the full tolerance at small gap.

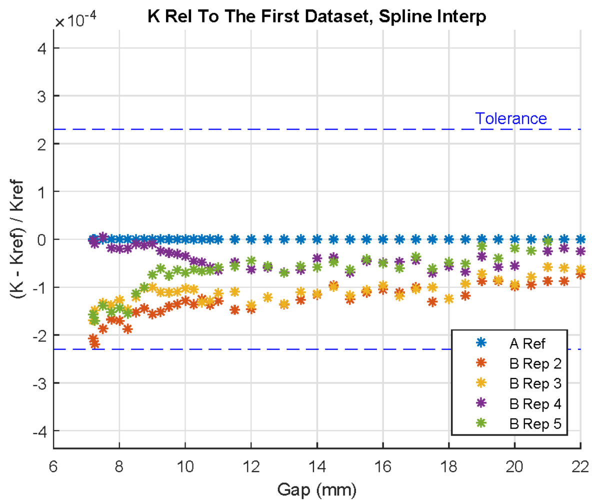

Figure 11: Comparison of measurements made in the B position to the reference measurement made in the A position.

The amplitude of the peak fields at 7.2 mm gap in the B mounting position are shown in figure 12. The slope of the line fitted to the peak fields is -3.2×10^{-5} T/m. This is lower than the slope in the A position so the fields are getting weaker as one goes down the undulator. It implies that the gap is opening as one goes down the undulator.

The phase errors are shown in figure 13. The rms phase error is 2.4 degrees. The change in the rms phase error compared to the A position is due to the taper change in the magnetic field.

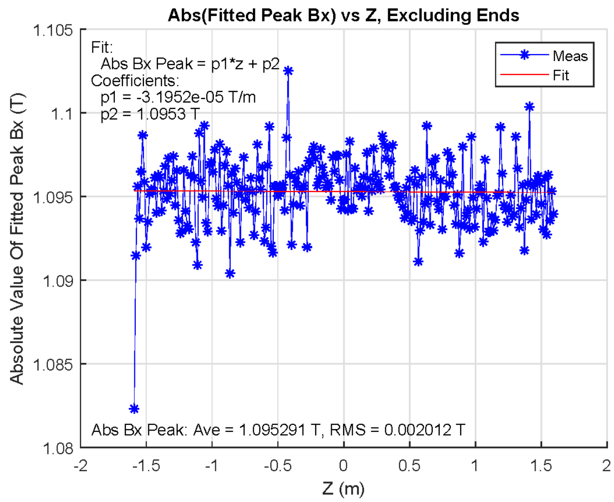

Figure 12: The magnitude of the peak fields at 7.2 mm gap in the B mounting position.

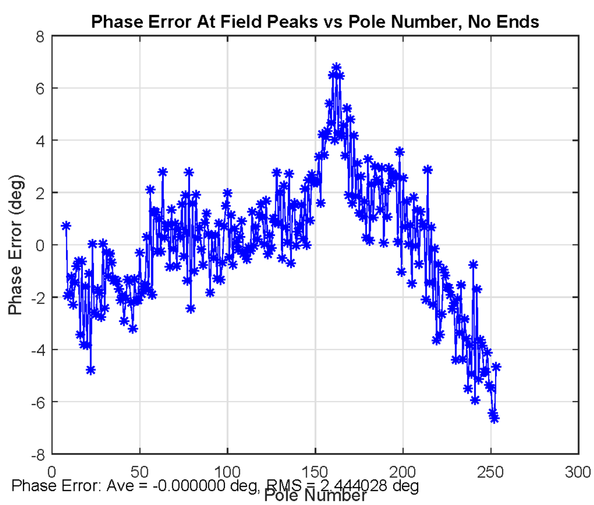

Figure 13: Phase errors at 7.2 mm gap in the B mounting position.

5.4 Measurements In The C Position

Two measurements were made in the C position. The difference between the two measurements and the reference measurement in the A position is shown in figure 14. The full set of measurements labeled C in the figure are systematically below the A measurements by more than the tolerance limit. They are also below the B measurements. After this set of measurements was made, a two week lifetime test was performed on the undulator in the C position. After the lifetime test, a check of three measurements was made. These three measurements are labeled "C Rep" in the figure. They are systematically different than the initial C measurements by more than the tolerance limit. It seems that the lifetime test changed the undulator. Further investigation is required to determine whether the change is due to using the half gap encoders, or whether the change is due to the strongbacks changing shape, for instance bowing.

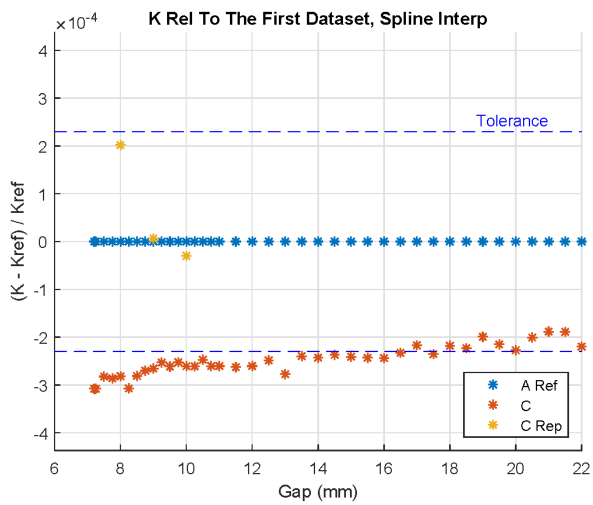

Figure 14: Measurements in the C position relative to the reference measurement in the A position.

The amplitude of the peak fields at 7.2 mm gap in the C mounting position are shown in figure 15. The slope of the line fitted to the peak fields is -3.4×10^{-4} T/m. This is lower than the slope in the A and B positions. The peak fields are getting smaller as one goes down the undulator. It implies that the gap is opening as one goes down the undulator and the amount of gap opening increases systematically from mounting position A to B to C.

The phase errors are shown in figure 16. The rms phase error is 4.4 degrees. The change in the rms phase error compared to the A and B positions is due to the taper change in the magnetic field. The rms phase error in the C position exceeds the tolerance.

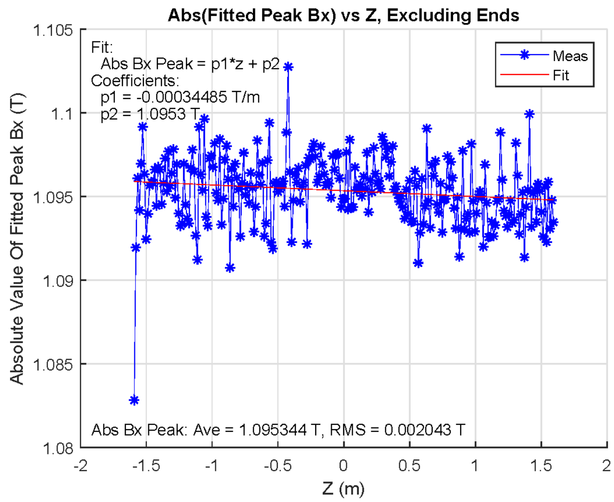

Figure 15: The magnitude of the peak fields at 7.2 mm gap in the C mounting position.

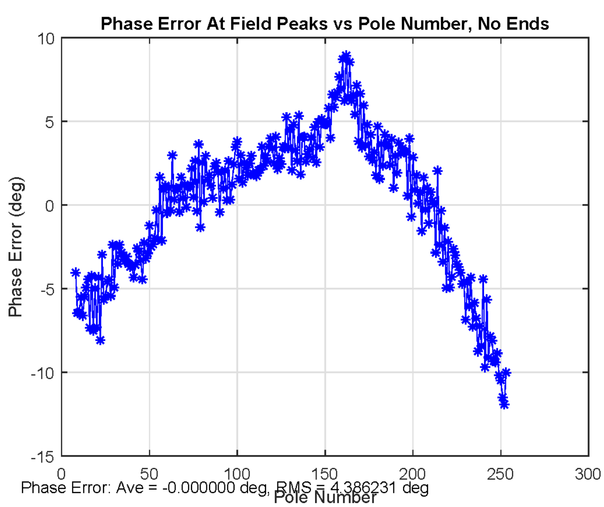

Figure 16: Phase errors at 7.2 mm gap in the C mounting position.

5.5 Repeat Measurements In The B Position

After the C position, the undulator was moved back to the B position. The difference between the repeat measurements in the B position and the reference measurements in the A position is shown in figure 17. The difference is larger than for the previous B measurements. It is uncertain whether the change is due to using the half gap encoders or whether the change is due to the strongbacks changing shape during the lifetime test.

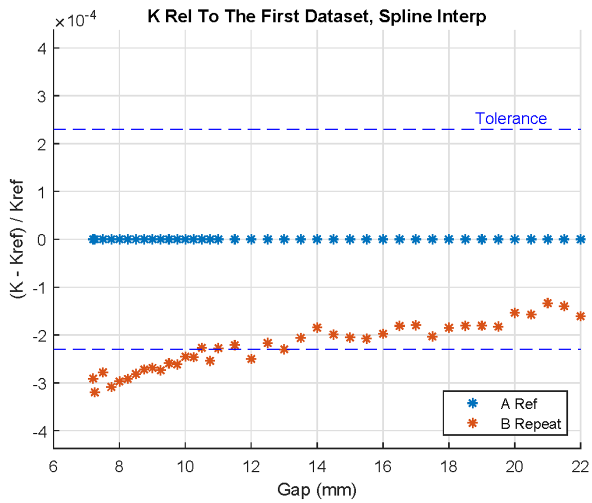

Figure 17: Repeat measurements in the B position compared to the reference measurements in the A position.

6 CMM Measurements In The A And C Positions

CMM measurements were made in the A and C positions. At a nominal 7.2 mm gap, the difference in gaps between the C and the reference A positions is shown in figure 18. The gap gets systematically larger as one moves down the undulator. This is consistent with the undulator having a lower K value in the C position compared to the A position.

The half gap encoders were used to set the gap and they had the same values in the A and C positions. The change in the actual gap is caused by girder deformations not seen by the half gap encoders.

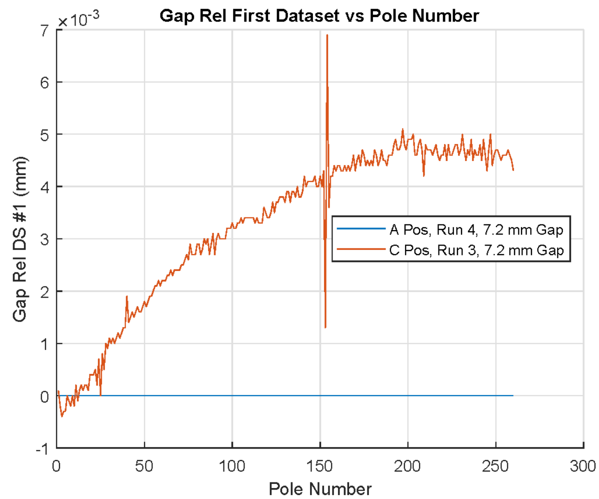

Figure 18: In the C position the gap gets systematically larger than in the A position for the same readings of the half gap encoders.

7 Conclusion

The half gap encoders do not see all deformations of the undulator girder. This causes errors in setting the gap using the half gap encoders. In particular, the K value changes at a given half gap encoder reading as the undulator is moved from one mounting position to another. The changes can exceed the tolerance on setting K. In addition the phase errors change and can exceed the rms phase error tolerance. Because of these changes, each undulator would have to be tuned and calibrated in its final mounting position if half gap encoders are used. This causes logistical problems, but is possible to do.

The measurements presented in this note had large variations from one measurement to the next with the same mounting position. This problem needs further investigation. It is uncertain whether the variation is due to using the half gap encoders, or whether the strongbacks are changing shape (for instance bowing) as the gap of the undulator is changed. If the strongbacks are changing shape, the non-repeatability of the field will persist when valid full gap measurements are made at the ends. Further measurements will tell whether this is the case.

Acknowledgements
We are grateful to Heinz-Dieter Nuhn for valuable discussions about this work.