A Conceptual Plan For The SLAC Superconducting Undulator Magnetic Measurements

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Abstract

Superconducting undulator magnetic measurements for free electron lasers pose many challenges because of the tight tolerances and the inaccessibility of the undulator fields. In this note a conceptual plan is presented for doing the magnetic measurements for a superconducting undulator being built at SLAC.

1 Introduction[1]

SLAC is building a superconducting undulator (SCU) which will be placed at the end of the LCLS-II HXR line. The SCU is a feasibility test on the way toward a full superconducting undulator free electron laser. There are many challenges to building and commissioning the SCU, and one of the major challenges is meeting the magnetic measurement requirements. This note proposes a conceptual plan for doing the magnetic measurements.

The techniques used to tune and calibrate the hybrid permanent magnet LCLS undulators have worked well. We wish to use as many of these techniques as possible for the SCU measurements. This note briefly describes the LCLS undulator magnetic measurement techniques, but then describes the new techniques required to do the SCU measurements.

2 Overview

2.1 SCU Key Features

An important feature of the SLAC SCU is that the gap is horizontal and the undulator poles are vertical. The poles are tall so the undulator fields do not change significantly vertically, but they do change rapidly in the horizontal direction. This allows the use of a stretched tube to guide our probes: the tube can sag in the vertical direction, but must be straight in the horizontal direction. Another important feature of the SLAC SCU is that the undulator is on movers inside the cryostat. This allows the undulator to be moved to the measurement probe, instead of the probe moved to the undulator in a very confined space. We exploit these features in the plan presented below.

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

2.2 Transition From Hybrid Permanent Magnet To Superconducting Magnet Undulators

The hybrid permanent magnet LCLS undulators have access to the gap from a side. This allows Hall probe measurements by inserting the probe from the side using a precision bench that moves the probe in a straight line along the undulator. An encoder on the bench gives the longitudinal position of the probe. The probe is moved transversely to the magnetic axis of the undulator by stages on the bench.

The tuning and calibration of the undulators are primarily done with a Hall probe, although long coil measurements are also required. Small offset errors in the Hall probe measurements are taken out by using a long coil. The long coil measures field integrals, and the Hall probe field integrals are made to agree with the coil measurements by adding a small correction to the fields measured by the Hall probe. The undulator side access allows the coil to come in from the side of the undulator.

The SCU has no side access. In fact the only access to the SCU magnetic field is through the end of the beam pipe. The long coil can be replaced by a single stretched wire for field integral measurements. We have demonstrated this and details of the measurements will be given in a forthcoming note. A Hall probe is the only way at present to characterize the field along the undulator axis with the required accuracy. Hall probe measurements must be done by inserting the probe through the end of the beam pipe. Making Hall probe measurements with the required accuracy but with so little control over the probe is very challenging.

As demonstrated in the next section, the good field region of the short period SCU is very small, so the Hall probe must move on a line straight at the few 10's of microns level to stay within the flat bottom of the hyperbolic cosine field profile. A technique must be invented to move the probe in a straight line on the undulator axis, and this is a major theme of what follows in this note. The probe must not rotate as it moves down the undulator in order that the horizontal and vertical components of the field can be independently measured. This necessitates pulling the probe through the undulator with a tube which is rotationally stiff. The longitudinal position of the probe must be accurately determined. If the system that moves the probe is stiff enough, an encoder on that system can be used to give the longitudinal position. Otherwise, an interferometer must be used. To achieve the required accuracy of the undulator K value, the Hall probe must be well calibrated and a system to check the calibration at regular intervals must be in place. Hall probe temperature and available space for the probe are major concerns. The beam pipe temperature is near 4 K, so if the measurements are not done in vacuum, an intermediate tube, a warm tube that guides the Hall probe, must be used whose inside surface is at room temperature to prevent ice from forming. The insulating vacuum outside the warm guide tube uses up space inside the beam pipe constraining the space for the Hall probe. In addition, the warm guide tube is likely not at a constant temperature to the required precision. Hall probes are sensitive to temperature, so the temperature changes of the probe must be measured and a temperature dependent Hall probe calibration must be used.

Meeting all these requirements is a major challenge and this note describes a possible technique for accurately making the measurements. The note also provides a roadmap to the development work that is needed to implement the measurement system.

3 Requirements

3.1 Calibration Requirements

The SCU tolerances come from an undulator Physics Requirements Document.[2] The list of requirements relevant to this note are briefly summarized below.

1. The K value must be known to $\pm 2.3 \times 10^{-4}$ at all operational SCU current settings.
2. The phase shake must be less than 5 degrees.
3. The total phase advance in the cell must be known to ±10 degrees.
4. The first field integral of B_x and B_y must be within $\pm 40 \times 10^{-6}$ Tm of zero.
5. The second field integral of B_x and B_y must within $\pm 150 \times 10^{-6}$ Tm^2 of zero.

It should be noted that these requirements are typical FEL undulator requirements. Having access to the undulator field only through the end of the beam pipe makes magnetic measurements very challenging and the requirements difficult to achieve.

3.2 An Important Requirement

An important requirement for undulator magnetic measurements is that they be done on the magnetic axis. This requirement results from the hyperbolic cosine dependence of the magnetic field. The center of the hyperbolic cosine field profile defines the magnetic axis. The field profile is relatively flat in this region so alignment errors are best tolerated. If a quantity like the undulator K value is measured on the magnetic axis and an alignment error puts the beam axis at a slightly different position, the difference between the K value the beam sees and the calibrated value is minimized.

The SCU will have vertical poles which produce a horizontal magnetic field in the gap. Figure 1 shows the calculated horizontal position dependence of the horizontal field B_x in the 21 mm period SCU. If the undulator is calibrated on the magnetic axis, the $x = 0$ position marked A in the figure, the beam can be within ±50 μm of $x = 0$ and the field will be within 10^{-4} of its on-axis calibrated value. If the measurements were done off the magnetic axis, say at $x = 0.08$ mm marked B in the figure, then misalignments of the beam from this position of only ±15 μm would place the beam in a position where the field and K value are different by 10^{-4} than the calibrated value. This difference is due to the steep slope of the field dependence away from the magnetic axis. We thus need to have a way to move our measurement probe onto the magnetic axis to within a fraction of the ±50 μm width where the field profile is relatively flat. In this way the sensitivity to alignment errors is minimized and the beam will see the K value, phase errors, field integrals, etc. that were measured in the calibration.

The vertical SCU poles are tall and the magnetic field is vertically uniform enough that vertical alignment of the Hall probe is not critical at the millimeter level. This feature will be exploited in the measurement scheme below.

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[2] H.-D. Nuhn., "LCLS SCU System", Physics Requirements Document SLAC-I-120-154-R0, December, 2022.

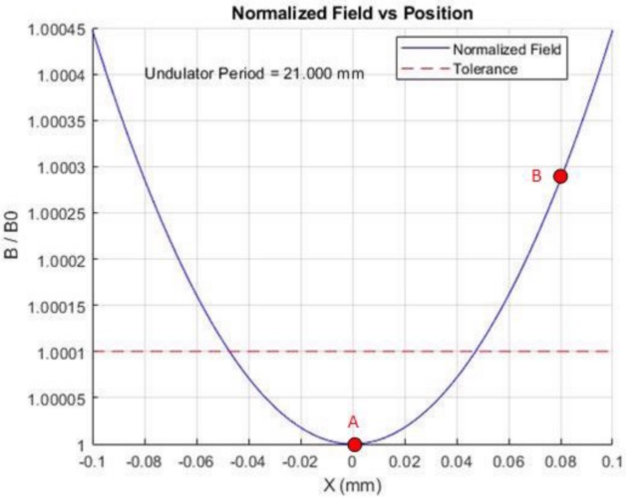

Figure 1: Calculated x-position dependence of the SCU magnetic field.

4 Finding The Undulator Magnetic Axis

4.1 Hybrid Undulator Technique

The measurement techniques used for calibrating the existing hybrid LCLS undulators work well. We wish to use as many of these techniques for the SCU measurements as possible. The LCLS-II HXR undulators have a horizontal gap, the same as the SCU. Figure 2 shows an HXR undulator at its measurement bench. A Hall probe is mounted on stages which move the probe horizontally (x-direction) and vertically (y-direction), and the stage assembly moves down the undulator on an air bearing on the granite bench (z-direction).

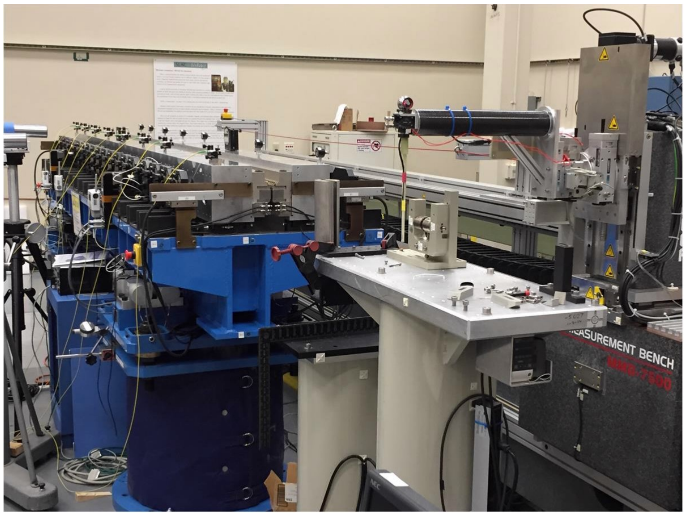

Figure 2: LCLS-II HXR undulator at its measurement bench.

To find the undulator magnetic axis, the Hall probe is moved to many poles down the undulator, and at each pole, the probe is moved in the x-direction to map out the hyperbolic cosine field dependence. A plot of the magnetic field Bx vs X is shown in figure 3. A fit gives the magnetic center position X_{center} at the Z position of the pole. A map is also made as the Hall probe is moved in the y-direction. Because of the large height of the poles, the field does not vary significantly in Y near the center. A plot of Bx vs Y is shown in figure 4. A fit gives the magnetic center position Y_{center} at the Z position of the pole. When the magnetic center is found at many poles down the undulator, a linear fit is made to the center positions X_{center} vs Z, and Y_{center} vs Z. The undulator is moved in pitch and yaw so the fitted line is parallel to the bench. The Hall probe is moved in X and Y so it moves down the magnetic axis.

4.2 SCU Technique

It is possible to perform a similar procedure with the SCU. The superconducting undulator will be mounted on a strongback which is held from the cryostat by 5 linear actuators. Figure 5 shows a schematic of the strongback supported by three actuators at the quadrupole

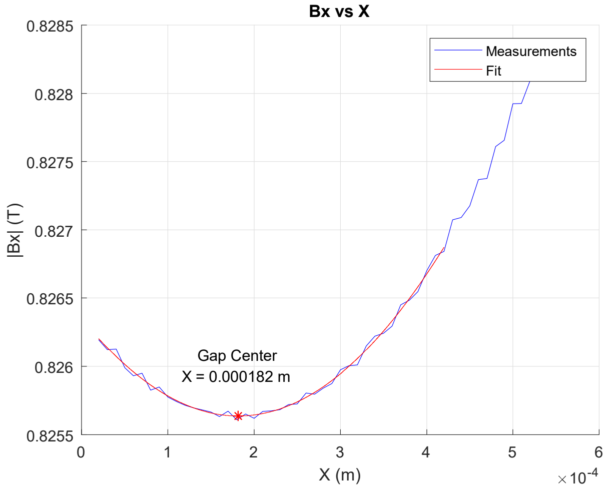

Figure 3: Hall probe scan of Bx vs X in an LCLS HXR undulator.

end and two actuators at the other end. The quadrupole is shown in red. An auxiliary quadrupole used for alignment is not shown. The undulator is represented by the long object in the middle of the strongback. The basic idea to find the undulator axis is to move the Hall probe on a straight line through the undulator from pole to pole, and then at many poles, move the undulator in X and Y to find the magnetic center at the poles. The procedure is identical to that used for the hybrid undulators, but here the undulator is moved instead of the Hall probe. Linear fits to X_{center} vs Z and Y_{center} vs Z allow the strongback to be moved so that the Hall probe is always on the magnetic axis of the undulator.

4.3 Alternate Plan

As noted in the Overview, the plan to move the Hall probe in a horizontally straight line using a stretched warm guide tube, and then move the undulator to the probe using the linear actuators, is currently being developed and tested. If this plan does not work, our backup plan is to position the warm guide tube using the beam pipe. An insulator would thermally separate the beam pipe and guide tube, yet bring them into mechanical contact. In this way, the beam pipe will position the guide tube and guide the probe. This method to guide the probe by the beam pipe was used to measure the Delta undulator[3] and has been used at ANL for superconducting undulators.[4]

This technique has been demonstrated to work, but has its limitations. The main

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[3] H.-D. Nuhn, et. al., "Commissioning The Delta Polarizing Undulator At LCLS", SLAC-PUB-16404, presented at the 37'th International Free Electron Conference FEL15, Daejeon, Korea.

[4] C. Doose and M. Kasa, "Magnetic Measurements Of The First Superconducting Undulator At The Advanced Photon Source", proceedings of PAC2013, Pasadena, CA, THPBA06.

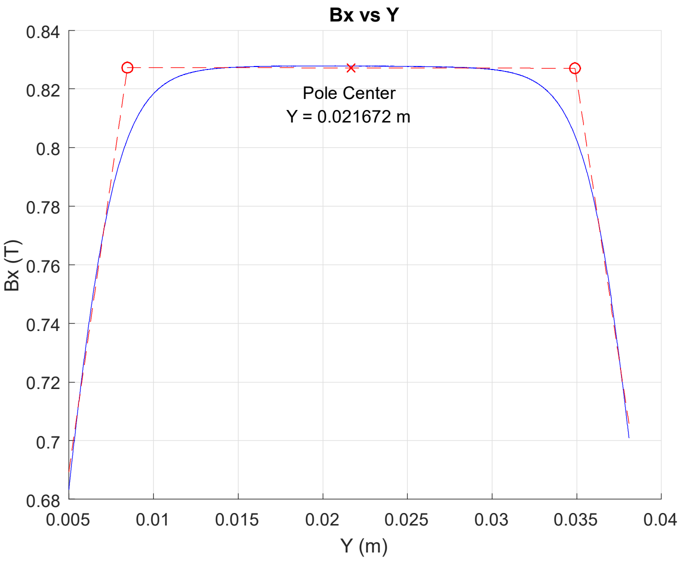

Figure 4: Hall probe scan of Bx vs Y in an LCLS HXR undulator.

limitation is that the beam pipe must be straight at the 10's of microns level in order to guide the Hall probe in a straight line at the required level. The only requirement on the beam pipe straightness is that it be straight to 100 microns in order to not affect the electron beam. If the beam pipe guides the Hall probe on a curved path, the K value the electrons see on a straight line will not be measured correctly. Another limitation is that the Hall probe must be shimmed to move it to the path that minimizes K. This handling of the fragile Hall probe has caused calibration errors in our studies of this technique. The measurements will likely be good enough for an afterburner, but a better technique is desired for a complete FEL undulator line.

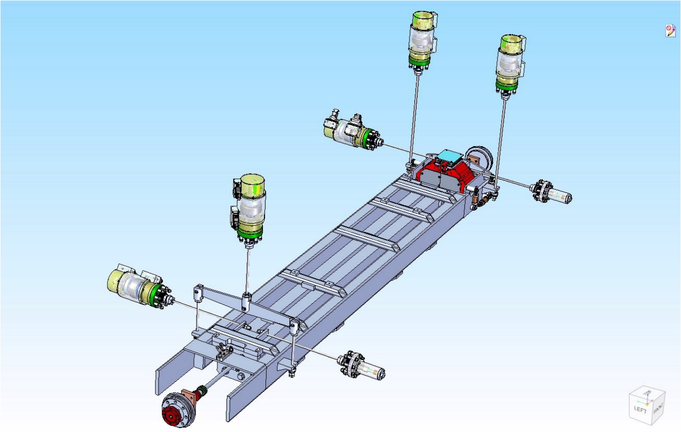

Figure 5: The SCU undulator will be held in a strongback supported by five linear actuators.

5 Moving The Hall Probe Along A Straight Line

As noted above, we wish to pull the Hall probe through the undulator using a tube, a probe tube, because of its rotational stiffness. We also need a second tube, a guide tube, to guide the path of the Hall probe. The guide tube also is used to make the transition from the beam pipe at a temperature of 4 K to the Hall probe at room temperature. The guide tube is supported by the ends and it must not touch any components inside the cryostat to avoid a large heat leak. An evacuated space fills the gap between the guide tube and the undulator beam pipe. Electric current flows in the guide tube to heat it by resistive heating. The heat is taken out by the refrigeration system. Tests are underway to make sure the current in the guide tube does not affect the magnetic measurements.

The guide tube must guide the Hall probe on a horizontally straight line. The tube can sag a small amount without changing the Hall probe reading because the undulator poles have a large extent in the vertical direction. The guide tube is stretched to make it straight in the horizontal direction. Tests are underway to stretch a tube to verify that it can be made horizontally straight to better than ±20 microns. Results of these tests are encouraging and will be documented in a subsequent note.

One must determine the tube sizes to meet the space constraints. Figure 6 shows a cross section of the beam pipe. The beam aperture has an oval shape and is 5.7 mm wide horizontally. The beam pipe is only required to be straight to ±100 microns. The straight line clear path inside the vacuum chamber is then only 5.5 mm wide. There must be a space between the beam pipe and the guide tube. If we choose the space to be 0.5 mm on either side of the guide tube, the guide tube OD must be 4.5 mm or smaller. This is illustrated in figure 7. The Hall probe has a maximum diameter of 3.0 mm. This means the probe tube must have an ID larger than this, say 3.1 mm.

Figure 8 shows the constraints on the tube dimensions. The guide tube must have an outer diameter smaller then 4.5 mm. The probe tube must have an inner diameter larger than 3.1 mm. Some clearance must be provided between the tubes so that the probe tube can slide inside the guide tube. If the clearance is 0.1 mm on each side of the probe tube, the maximum wall thickness of the tubes is 0.3 mm if both tubes have the same thickness. A way to keep the probe centered in the guide tube must be developed. Studies have been performed at SLAC with non-magnetic stainless steel tubes with 0.25 mm thick walls. More development work is needed to choose tubes with good magnetic properties, thin walls, proper diameters, and available in long lengths.

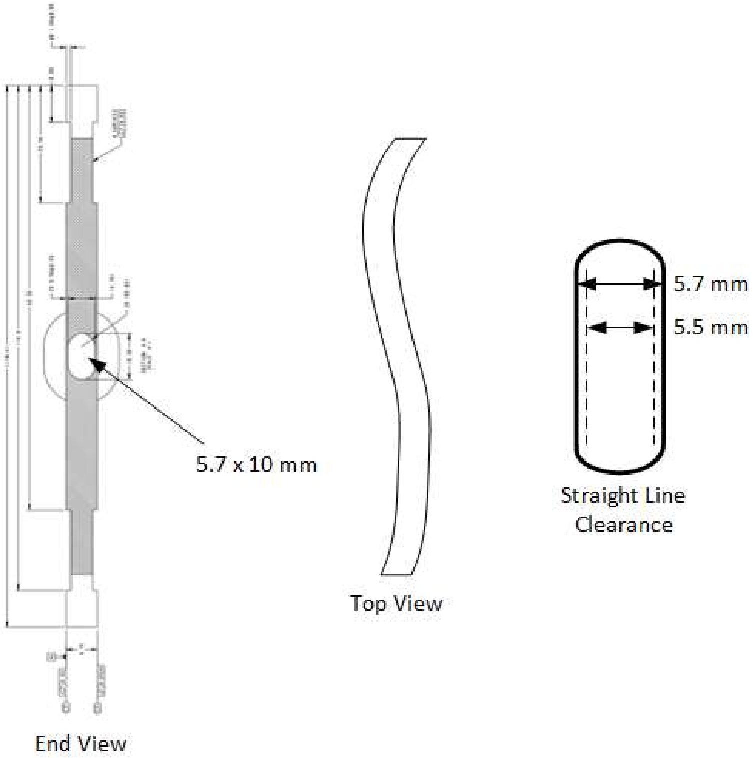

Figure 6: A cross section of the undulator beam pipe is shown on the left. The beam pipe can bend by up to ±100 microns using up the straight line clearance region as shown in the middle and right.

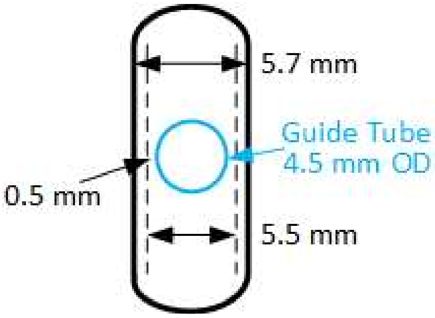

Figure 7: Space must be left between the guide tube and the beam pipe to provide thermal insulation.

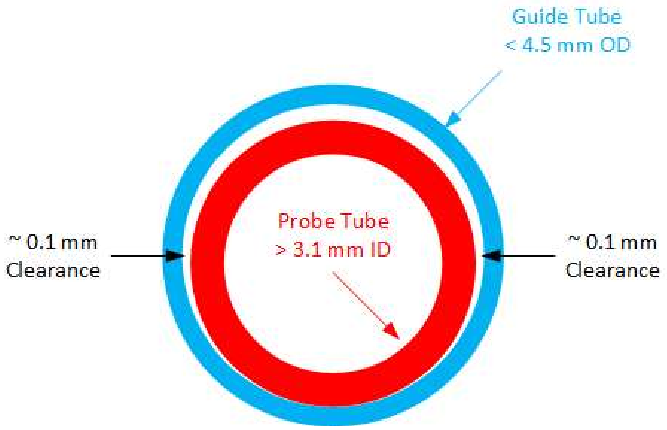

Figure 8: The tube dimensions are constrained by the size of the Hall probe and the size of the beam pipe.

6 Magnetic Measurement System Overview

The key components of the measurement system are the stretched wire system and the Hall probe system. The stretched wire needs stages at each end of the undulator. These stages are moved out of the way when doing Hall probe measurements. The Hall probe system needs a guide tube, a probe tube, and a long stage to pull the probe tube through the undulator. In addition, a reference magnet must be available to check the calibration of the Hall probe. An alignment magnet is needed so the probe can be rotated to correctly measure B_x and B_y. Zero Gauss chambers are required to remove Hall probe offsets. A linear encoder is required on the measurement bench to measure the z-position of the probe and provide triggers, although a laser interferometer may be required for the z-position instead. A separate Hall probe calibration system is also required. A schematic of the measurement system is shown in figure 9.

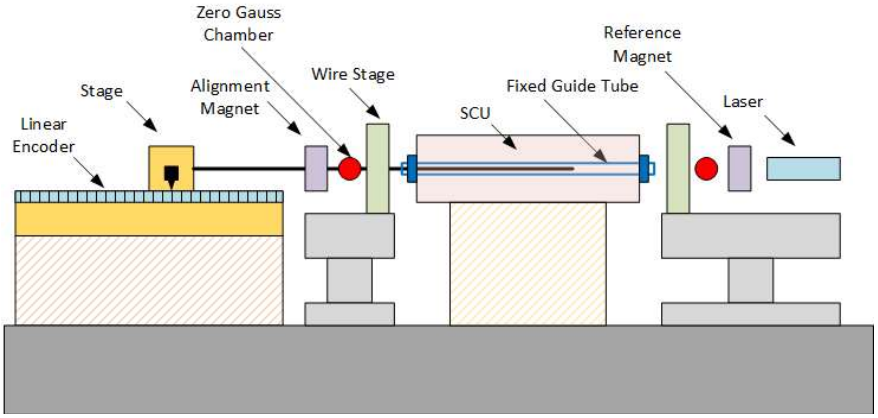

Figure 9: Schematic of the SCU measurement system.

7 SCU Alignment

We have discussed how to calibrate the undulator on its magnetic axis where the field dependence on position is flat. The problem now is to make the beam go down the line that the undulator was calibrated on. For this, our current techniques used at LCLS can be applied. The main idea is to align quadrupoles at each end of the undulator to the undulator axis. This can be done on a CMM assuming the undulator and quadrupoles are fiducialized. If the undulator axis is aligned to the quadrupole centers, beam based alignment techniques make the beam go near the quadrupole centers, and this makes the beam go down the undulator axis.

Since the undulator calibration is done on the magnetic axis where the field is flat, the alignment tolerance between the undulator axis and the quadrupole center is a few tens of microns. Aligning the quadrupoles to the undulator axis can be done mechanically at room temperature. We start by fiducializing the undulator cores on a CMM. When the undulator is assembled, the fiducials are used to determine the mechanical center line. Steel quadrupoles can be fiducialized to high accuracy using a vibrating wire technique.[5] Our plan is to initially use steel quadrupoles. A similar technique must be developed for superconducting quadrupoles if those are chosen in the future. The undulator and quadrupoles are mounted on a strongback and aligned relative to each other using the fiducials and a CMM. When the assembly is cooled, we assume the undulator and quadrupoles keep their relative alignment. This must be checked.

The check that the quadrupole centers are on the undulator magnetic axis proceeds as follows. During magnetic measurements, the field is mapped at many poles down the undulator. A line is fit to the magnetic center positions. The undulator is moved so that the Hall probe goes down the line fit to the magnetic centers. The Hall probe is then moved to the quadrupole longitudinal positions. The position of the magnetic center of the quadrupoles is measured by moving the strongback assembly which moves the quadrupole so its field can be mapped. The transverse magnetic center position of the quadrupoles is then compared to the undulator axis position. This measurement provides a check that the quadrupole center is on the undulator axis within tolerance. If a quadrupole is not on the undulator axis, the system must be warmed up and the quadrupole moved. This scheme is illustrated in figure 10.

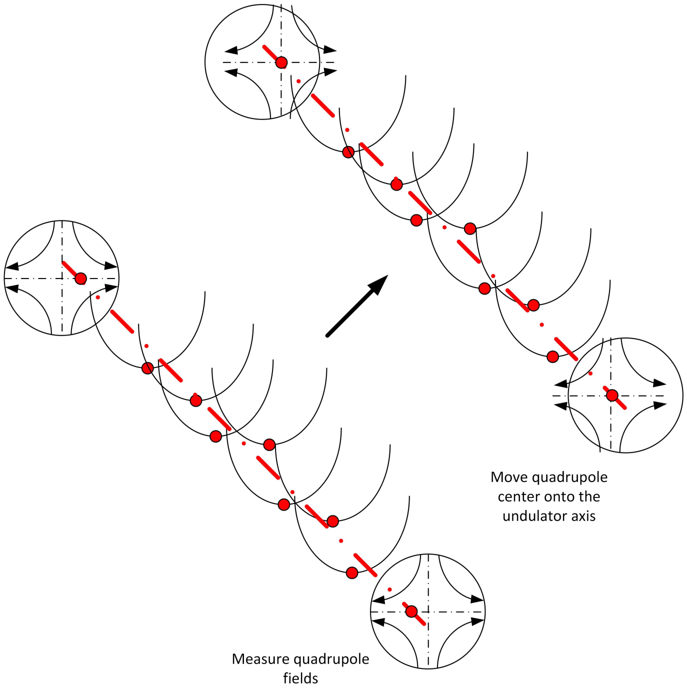

Figure 10: The quadrupole alignment to the undulator axis can be checked using magnetic measurements.

The overall alignment plan is to have alignment crews align the quadrupoles to the nominal beam axis in the tunnel, taking into account the nominal thermal contraction of

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[5] Z. Wolf, "A Vibrating Wire Technique For Quadrupole Fiducialization", LCLS-TN-05-11, May, 2005.

the components. This step must get the quadrupoles within the convergence range of beam based alignment which means the quadrupole centers must be within a few hundred microns of the beam axis. During beam based alignment, the primary quadrupole is moved to make a straight beam trajectory. The alignment of the undulator axis to the quadrupole center makes the beam go down the undulator axis at this end of the undulator. After this step, the alignment quadrupole at the other end is energized. The alignment quadrupole is moved until the beam trajectory is straight again. This step aligns the "loose end" of the undulator. Afterward, power to the alignment quadrupole is turned off for normal operation.

8 Summary Of Required Development Work

Many techniques used to measure the LCLS undulators can be incorporated into the SCU measurements. In particular, the Delta undulator measurements referenced above are very similar. However, a number of differences remain. In order to be ready for SCU magnetic measurements, development in several areas must be completed:

1. Field integral measurements with a single stretched wire must be established. The signal is very small, so a preamplifier must be used. Errors on the first integrals should be less than 2 μTm.

2. A method to make a guide tube horizontally straight to better than 20 μm must be established. The tube should be tensioned to reduce sag, although the exact amount of sag is not important. Non-contact measurements of the tube straightness must be made.

3. An algorithm must be established to make the guide tube not contact the beam pipe after the SCU is assembled.

4. Suitable tubes for the guide tube and probe tube must be found. The probe tube must have an ID greater than 3.1 mm. The guide tube must have an OD less than 4.5 mm. The tubes must have good magnetic properties, thin walls, proper diameters, and be available in long lengths.

5. Measurements must be made to establish that the electric current used to heat the guide tube does not affect the magnetic measurements.

6. Typically we use Senis Hall probes for undulator measurements because of their small planar Hall effect. The probe must be chosen and tested well in advance of the measurements in order to verify that it meets its published specifications.

7. A holder for the Hall probe must be designed. The holder should have a way to center the probe in the guide tube.

8. A Hall probe calibration as a function of both magnetic field and temperature must be developed.

9. A mechanical system to insert the probe tube and pull the probe tube through the undulator for measurements must be built. Safeguards for inserting the probe tube must be incorporated so it does not buckle in case ice forms in the guide tube, or in case there is stickiness for some reason.
10. A way to trigger the Hall probe measurements and determine the z-position of each measurement must be determined. An interferometer can be used as for the Delta undulator measurements, or a long linear scale can be used as for the hybrid undulator measurements.

9 Conclusion

SCU magnetic measurements pose difficult problems. The only access to the undulator gap is through the ends of the beam pipe. The undulator is cold, so space for a warm insert is required to bring the inner bore to room temperature. Very little space is left for a Hall probe. In spite of this, the same accuracy is required for the K value measurement as for a planar undulator with side access to the gap. This note presented a roadmap of development work required to come up with an adequate SCU measurement system.

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