LCLS-II HXR Undulator Fiducialization And Girder Alignment Plan

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July 12, 2018

Abstract

This note presents the LCLS-II HXR undulator fiducialization and girder alignment plan. The undulators will be fiducialized and the beam pipe and interspace components installed and aligned in the Magnetic Measurement Facility at SLAC. The note begins by summarizing the requirements for the fiducialization and alignment. A brief overview of the plan is presented, followed by the a discussion of the coordinate systems in which the results will be presented. This is followed by the detailed fiducialization and assembly plan in which each step is enumerated.

1 Introduction[1]

The LCLS-II hard x-ray undulator (HXR undulator) is made up of 33 assemblies, each consisting of an undulator segment (hereafter referred to as an undulator) with its beam pipe and a quadrupole, phase shifter, and other components mounted on a plate attached to the undulator. The components must be mounted in such a way that the beam passes down the axis of each component. The procedure and magnetic measurements for defining the beam axis in the undulator have been described in a previous note[2]. In this note, we describe in detail how the beam axis is related to tooling balls on the undulator. This step, called fiducialization, is necessary because the beam axis is determined magnetically and is intangible, whereas tangible objects must be used to locate the undulator. In addition, the magnetic axis must be very close to the mechanical axis because of force compensation springs and the limited range of beam pipe adjustment. This adds a complication compared to similar work for the LCLS undulator fiducialization[3] and girder alignment[4]. The complications of the HXR undulator warrant a separate plan.

The note begins with the list of fiducialization and alignment requirements. The coordinate systems used for the measurements is then briefly described. This is followed by a detailed fiducialization plan in which all the steps of fiducialization are enumerated.

[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, et al, "LCLS-II Undulator Test Plan", LCLS-TN-17-1 Rev 1, July, 2017.

[3]Z. Wolf, et al, "LCLS Undulator Fiducialization Plan", LCLS-TN-07-2, April, 2007.

[4]Z. Wolf, et al, "Girder Alignment Plan", LCLS-TN-08-3, March, 2008.

2 Requirements

The LCLS-II HXR undulator fiducialization requirements and girder assembly requirements are derived from an undulator Physics Requirements Document[5]. The list of relevant requirements is given below.

1. The position of the line along which K has a specified value must be set in the tunnel in both x and y relative to the line between centers of adjacent quadrupoles to 70 μm in x and 290 μm in y. Only a fraction of this tolerance can be used for fiducialization. We take the fiducialization tolerance to be approximately one third of the overall tolerance, or 20 μm in x and 100 μm in y, leaving the remainder for positioning the downstream quadrupole on the girder and positioning the undulator relative to the upstream quadrupole in the tunnel.

2. The roll of the undulator, the angle between the undulator midplane and the horizontal, must be vertical in the tunnel to 0.5 mrad. We take the fiducialization tolerance to be 0.25 mrad, leaving the other half for positioning the undulator in the tunnel.

3. The longitudinal position of the magnetic center of the undulator must be set in z relative to tunnel coordinates to 0.3 mm. We take the fiducialization tolerance to be 0.15 mm, leaving the other half for positioning the undulator in the tunnel.

4. When the quadrupole is placed on the girder, the quadrupole center must be positioned relative to the undulator axis to 20 μm as determined in requirement 1.

5. The phase shifter axis must be positioned relative to the undulator axis to (tbd*)* mm.

6. With the undulator gap set to 7.2 mm, the load cells must read less than (tbd) pounds at all undulator gaps.

7. The undulator magnetic axis must agree with the mechanical axis to 0.250 mm in order to have the beam pipe within range of adjustment.

8. The beam pipe center must be positioned on the undulator fiducialized beam axis to within 0.100 mm.

3 Overview

The undulators will be fiducialized and aligned in the Magnetic Measurement Facility (MMF) at SLAC. In this section we give an overview of the fiducialization and alignment process. Detailed procedures are presented in a following section.

The fiducialization and alignment are done in the following steps:

1. Move the undulator into the temperature conditioning area for at least two days before measurements begin.

[5]H. D. Nuhn et al., "Undulator System", LCLS Physics Requirements Document LCLSII-3.2-PR-0038-R3.

2. Move the undulator onto the CMM for initial mechanical measurements. In this step we wish to determine the following:
   (a) the position of the centerline of the jaws relative to the nominal beam pipe position
   (b) the force on the load cells as a check that the magnetic forces are being compensated by the spring forces
   (c) the positions of all the magnet poles to look for the straightness of the pole assemblies and whether any poles are misplaced
   (d) the positions of all the magnets to make sure they have the proper recess and alignment relative to the poles
   (e) the positions of accessible fiducials relative to the undulator features
3. Move the undulator to the Kugler bench. The following steps will be performed:
   (a) the undulator will be aligned using the fiducials determined in the previous step
   (b) any required tuning will be performed
   (c) all magnetic measurements will be performed including the final dataset
   (d) the magnetic centerline will be found relative to fiducialization magnets attached to the undulator
4. Move the undulator to the CMM
   (a) locate the fiducialization magnets relative to undulator fiducials, this locates the beam axis
   (b) locate a set of fiducials relative to the beam axis for future alignment of the undulator
   (c) check for any poles moved too far into the gap during tuning
5. Move the undulator to the assembly area. Using a laser tracker for alignment,
   (a) install the beam pipe
   (b) align the beam pipe to the beam axis
   (c) install the interspace components
   (d) align the interspace components to the beam axis
6. Move the undulator to the CMM
   (a) check that the beam pipe is properly installed on the beam axis
   (b) check that the quadrupole is properly installed on the beam axis
7. Move the undulator to storage

The HXR undulator is expected to deform as the gap is changed. Thus the initial CMM measurements will establish a coordinate system related to the girder at a fixed gap. That fixed coordinate system will be used to locate components at other gaps. It will also be used to place the undulator at the Kugler bench. Afterward, a new fiducialized beam axis will be determined, again at a single fixed undulator gap. The fiducialized beam axis will be the basis of all future alignment work.

After the final dataset of the magnetic measurements is complete, special fiducialization magnets are bolted to the undulator. It is essential that these magnets do not get bumped on the way to the CMM. Work must be planned so that the undulator goes straight from the Kugler bench onto the CMM at this stage. This is a critical step.

4 Coordinate Systems

Data will be presented in two coordinate systems. Initially, the girder will be mechanically measured and the nominal beam axis will define a coordinate system for the mechanical measurements. After the undulator is fiducialized, the fiducialized beam axis will be used for all final measurements and alignment.

In order to initially locate components on the undulator, a coordinate system must be established. We wish the coordinates of an object to be related to undulator features. The primary undulator features are the nominal beam axis and the roll about that axis. Because the undulator can distort due to the magnetic forces, we must choose a fixed gap in order to establish the coordinate system. We choose the tuning gap of 9 mm.

Figure 1 shows a schematic of the undulator. The beam pipe is positioned by two pins

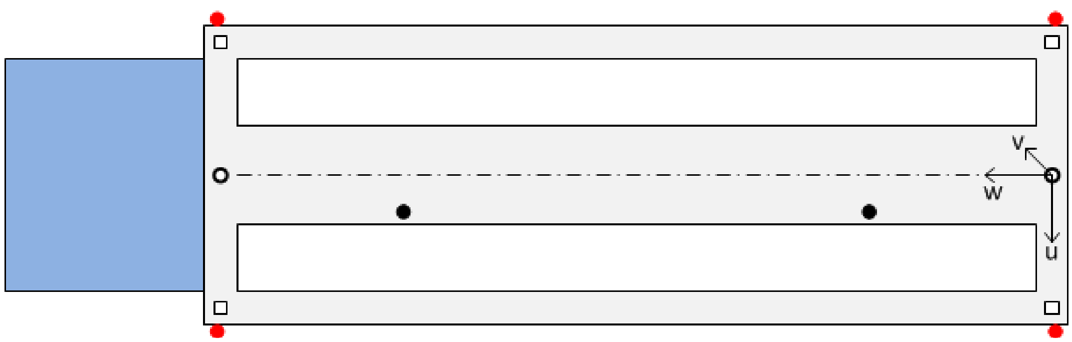

Figure 1: Girder features are used to establish the girder coordinate system.

shown as solid black circles. The beam pipe has a clearance of 250 μm around the pins so the final magnetic beam axis must be within this 250 μm range of adjustment. The pins are difficult for the CMM to reach, so they are not desirable components to use for alignment. In fact, the pins are not accessible in the operating gap range.

Rather than use the pins, we use two precision holes in the girder below the nominal beam axis. They are shown as the two heavy open circles on the centerline near the ends of the undulator. The CMM can define a point at each precision hole by finding a line along the axis of the hole and the intersection point of the line with a plane found by fitting nearby points on the surface of the girder. These measurements can be done at the tuning gap of 9 mm. These points are measured in arbitrary CMM machine coordinates. A line is established between the two points to determine the w-axis of the undulator. We will first make the (u, v, w) coordinate system located in the girder, then we will translate up to the beam height to establish the (x, y, z) coordinate system where the z-axis is along the nominal beam path.

The four open squares in the drawing are machined surfaces on the top of the girder. The CMM can repeatably locate a point in each of these squares by fitting multiple measurements in each square. These four points are fit to a plane. The normal to this plane is along the v-axis.

We now have a line and the normal to a plane. We intersect the line and the normal at the center of the precision hole located at the entrance end of the undulator. The (u, v, w) coordinate system is now defined. The w-axis is along the line between the centers of the precision holes. The v-axis is along the normal determined by the plane fit to the four flats on the top of the undulator. The u-axis is along the perpendicular to v and w. The origin is at the location of the center of the precision hole which was used to define the w-axis on the upstream end. Note that in this intermediate coordinate system, the v-axis is not necessarily perpendicular to the w-axis. However, the u- axis is perpendicular to both the v and w axes.

In order to establish a coordinate system on the nominal beam axis, we translate the (u, v, w) coordinate system up along the v-axis by 143.76 mm to the nominal beam height. This nominal beam line coordinate system will be used for all initial measurements It is denoted as the nominal (x, y, z) coordinate system. The y-axis is parallel to the v-axis and it determines the roll and pitch of the undulator. The x-axis is parallel to the u-axis. The z-axis is perpendicular to both the x and y axes and it determines the yaw of the undulator. The (x, y, z) system is orthogonal. Tooling balls on the outside of the undulator are located in the (x, y, z) coordinate system when the gap is set to the nominal tuning gap. The tooling balls are a redundant set shown in red in the figure. They allow us to easily reestablish the nominal (x, y, z) system.

Once the undulator is fiducialized, the "nominal" designation will be dropped and we will use the fiducialized beam axis as the (x, y, z) coordinate system for all future work. In this system, the z-axis is along a line determined by magnetic measurements as the magnetic axis of the undulator. The z-axis now determines undulator pitch and yaw. The normal to the girder, the v-axis, is used to determine the roll direction of the y-axis. The y-axis is perpendicular to the z-axis. The x-axis is perpendicular to both z and y.

5 Fiducialization And Girder Alignment Plan

1. Preliminaries

   (a) Calibrate the fiducialization magnets which go on each end of the undulator.

   (b) Calibrate the reference poles used by the capacitive sensor system.

   (c) Install pedestals in the assembly area to hold the undulator during beam pipe installation.

2. Move the undulator to the temperature stabilization area

   (a) The undulator must remain in the temperature stabilization area for at least two days before measurements are performed.
   (b) Earthquake anchoring in the temperature stabilization area must be provided.
   (c) Final controls checkout should be performed in the temperature stabilized area.

3. Move the undulator to the CMM. Set up the nominal beam axis coordinate system. Fiducialize tooling balls on exterior part of the undulator so the nominal beam axis coordinate system can be reestablished.

4. Perform the following measurements at gaps of 7.2, 10, 15, 20, and 40 mm. Record the load cell readings and encoder readings for the dataset at each gap.

   (a) Measure the shape of the girder.
      i. Measure the height of the girder along the beam pipe mounting surface every 200 mm.
      ii. Measure the height of the machined flats on the four corners of the girder.
   (b) Measure the x-position of each pole at several y-positions. Determine:
      i. The included angle between opposite poles.
      ii. The angle of the symmetry line of opposite poles.
      iii. The distance between opposite poles in the vertical center.
      iv. The x-position of the midpoint between opposite poles in the vertical center.
      v. At 7.2 mm, the x-position of each pole on both jaws showing the stay clear region for the beam pipe.
   (c) Measure the y-position of the top of each pole.
   (d) Measure the y-position of the top of the magnet keepers.
   (e) Measure the z-position of each magnet by touching it on both ends and finding the center point.
   (f) At 10 mm gap, measure the x-position of each magnet and determine the recess from the poles.
   (g) From these measurements, verify that the mechanical centerline between poles is within the adjustment range of the beam pipe from the mechanical centerline of the girder.
   (h) From the measurements, verify that the roll angle of the symmetry line between poles is within tolerance.
   (i) From the measured z-position of all the magnets, calculate the average z-position of all the magnets and use this as the z-position of the center of the undulator.

5. Move the undulator to the Kugler bench.

   (a) Have an alignment crew roughly place the undulator using the nominal beam axis fiducialization determined in step 3. Verify that the probes go through the undulator gap without touching.
   (b) Use capacitive sensors to measure the undulator position.
   (c) Use the cam movers to move the undulator into position parallel to the bench.

6. Magnetically align the Hall probe to the undulator
   (a) Measure along the undulator with the Hall probe to find the pole positions.
   (b) At every N'th pole ($N \simeq 5$), move the Hall probe in x and y and find the magnetic center. Fit the magnetic field centers as a function of z. Move the probe to the field center line.
   (c) Correct pitch and yaw of the magnetic center line with the cam movers, if necessary, and repeat step (b).
   (d) The magnetic center line defines $x = 0$, $y = 0$ for the Hall probe position.

7. Tune the undulator

   Tune the x trajectory, y trajectory, and the phase. Make the final data set characterizing the undulator. Leave the Hall probe on the magnetic center line.

8. Add fiducialization magnets
   (a) Add the fiducialization magnets to the undulator ends.
   (b) Record positions required to calculate the offset from the magnetic axis to the center of the fiducialization magnets.

9. Complete the fiducialization on the CMM
   (a) Move the undulator to the CMM.
   (b) Establish the nominal beam axis coordinate system.
   (c) Locate the tooling balls on the fiducialization magnet at each end of the undulator. Add offsets corresponding to the distance from the tooling balls to the fiducialization magnet center and from the fiducialization magnet center to the ideal beam axis as measured on the fine tuning bench. Using this information, set the $x = 0$, $y = 0$ line of the CMM along the undulator magnetic axis. This is the fiducialized beam axis.
   (d) Fiducialize tooling balls on the exterior of the undulator in the fiducialized beam axis coordinate system.

10. Repeat the measurements in step 4 in the fiducialized beam axis coordinate system.

11. Move the undulator to the assembly area.
   (a) Install the beam pipe.

(b) Align the beam pipe to the fiducialized beam axis using a laser tracker.

(c) Install the interspace components.

(d) Align the quadrupole center to the fiducialized beam axis.

12. Move the undulator with the beam pipe and interspace components to the CMM for a final check.

13. On the CMM, perform the following measurements at 20 mm gap so that there is access to the sides of the beam pipe and to the magnet poles

    (a) Measure the x-position of the midpoint of the beam pipe relative to the fiducialized beam axis.

    (b) Determine the y-position of the beam pipe chamber relative to the fiducialized beam axis.

    (c) Determine the x,y-position of the center of the quadrupole relative to the fiducialized beam axis.

    (d) Measure the x and y-position of each pole. Find the mechanical centerline of the undulator using the pole positions. Determine how far the mechanical centerline is from the fiducialized beam axis.

14. Move the undulator to the storage area.

    (a) Remove the phase shifter from the base plate and place it in storage.

    (b) Remove the undulator from the CMM and move it to the storage area.

    (c) Package the undulator for storage.

15. Complete the analysis of the data.