

LCLS Undulator Fiducialization Plan

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Abstract

This note presents the LCLS undulator fiducialization plan. The undulators will be fiducialized in the Magnetic Measurement Facility at SLAC. The note begins by summarizing the requirements for the fiducialization. A brief discussion of the measurement equipment is presented, followed by the methods used to perform the fiducialization and check the results. This is followed by the detailed fiducialization plan in which each step is enumerated. Finally, the measurement results and data storage format are presented.

1 Introduction¹

The LCLS is made up of 33 assemblies consisting of an undulator, quadrupole, beam finder wire, and other components mounted on a girder. 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 ideal beam axis in the undulator have been described in a previous note². In this note, we describe in detail how the ideal beam axis is related to tooling balls on the undulator. This step, called fiducialization, is necessary because the ideal beam axis is determined magnetically and is intangible, whereas tangible objects must be used to locate the undulator.

The note begins with the list of fiducialization requirements. The laboratory in which the work will be performed and the relevant equipment is then briefly described. This is followed by a discussion of the method used to perform the fiducialization and the methods used to check the results. A detailed fiducialization plan is presented in which all the steps of fiducialization are enumerated. A discussion of the resulting data files and directory structure concludes the note.

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

²Z. Wolf, et al, "LCLS Undulator Test Plan", LCLS-TN-06-17, December, 2006.

2 Requirements

The LCLS undulator fiducialization requirements come from an undulator Physics Requirements Document³. The list of fiducialization requirements is given below.

1. The position of the line along which K has a specified value must be known in both x and y relative to tooling balls on the undulator to $50\ \mu\text{m}$ in x and $40\ \mu\text{m}$ in y at both ends of the undulator.
2. The roll of the undulator, the angle between the undulator midplane and the horizontal, must be known to $0.5\ \text{mrad}$.
3. The longitudinal position of the magnetic center of the undulator must be known in z relative to tooling balls to $0.5\ \text{mm}$.

3 Equipment

The undulators will be fiducialized in the Magnetic Measurement Facility (MMF) at SLAC. Most of the fiducialization will take place at the fine tuning bench, where final tuning of the undulators is performed. A number of checks of the fiducialization will also take place at the fine tuning bench. In a final step to locate tooling balls, the undulator will be moved to a coordinate measuring machine (CMM). Relative tooling ball locations will be measured and a mechanical check of the fiducialization will be performed.

The equipment for fiducialization in the MMF is illustrated in figure 1. At the fine tuning bench, capacitive sensors are used to align the undulator to the bench. An initial set of capacitive sensor measurements are made in a reference pole. The undulator is moved using a cam mover system until the capacitive sensor measurements through the undulator agree with the measurements in the reference pole. At this point, the horizontal, x , and vertical, y , mechanical position of the undulator is the same as the reference pole, the roll is the same as the reference pole, namely zero, and the undulator mechanical assembly has no pitch or yaw relative to the bench. A magnetic alignment is then performed. The magnetic field measurement probe is aligned to the magnetic undulator axis by performing horizontal and vertical scans of the field at a number of poles. The magnetic center is found at each scan location and a fit is made of the magnetic center positions *vs* z . The probe is moved to the average magnetic center position and the undulator is moved to take out the pitch and yaw of the magnetic axis. The magnetic field measurement probe then moves down a line along the magnetic undulator axis.

After alignment to the bench, the undulator will be tuned so that the electron beam will pass through the undulator with specified properties. After tuning, a Hall probe will be positioned so that it is measuring along the ideal beam axis. The location of this line along which the Hall probe measurements are made must be determined relative to tooling balls on the undulator so that the undulator can be positioned for the electron beam to move along that same line.

³H. D. Nuhn et al., "General Undulator System Requirements", LCLS Physics Requirements Document 1.4-001.

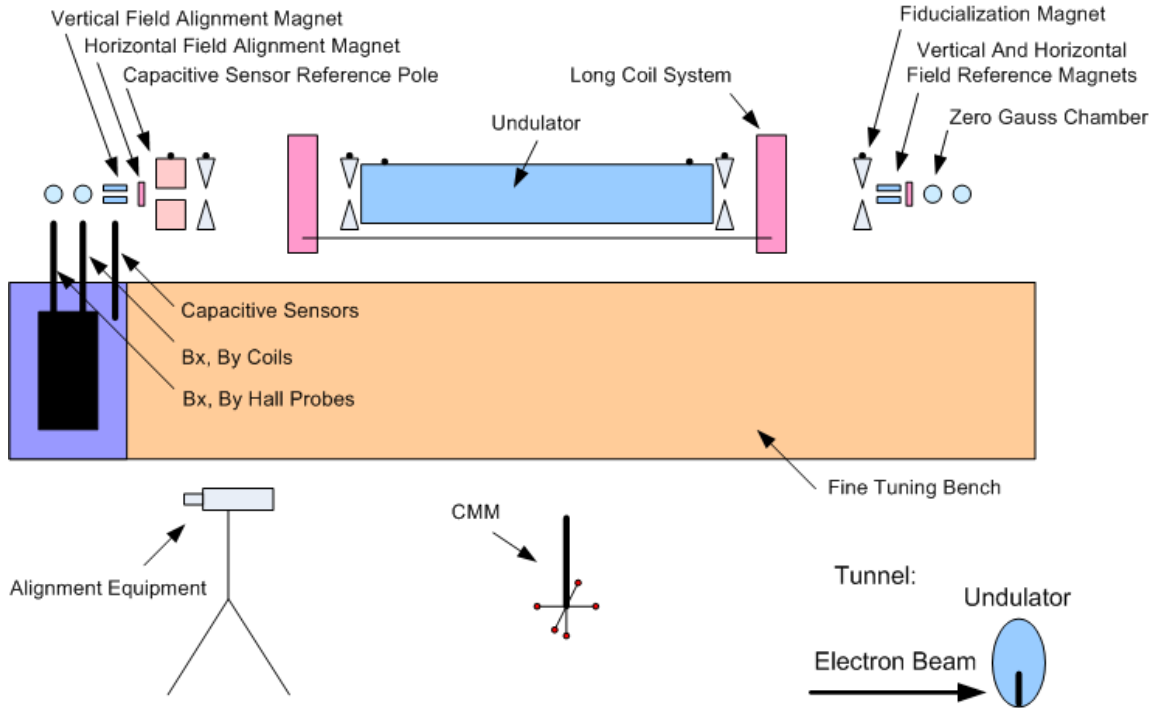


Figure 1: The undulator fiducialization will be done using the fine tuning bench and a CMM in the MMF. Checks will be done using optical alignment equipment.

The key to transferring from a location defined by where magnetic measurements are made to tooling balls is the use of special magnets which have a field pattern well defined relative to tooling balls. These magnets will be called fiducialization magnets. Each magnet has a point in the magnetic field which can be found with high repeatability with the Hall probe. This point can be located relative to tooling balls through a calibration procedure.

After the undulator is tuned, fiducialization magnets are bolted to each end of the undulator. The transfer from magnetic tuning axis to fiducialization magnet center is made.

To locate tooling balls, the undulator plus attached fiducialization magnets must be moved to the CMM. The CMM is located in another laboratory in the MMF.

There is potential to bump a fiducialization magnet during the move. Because of this potential source of error, and because of potential measurement errors, a number of checks will be made both at the fine tuning bench and on the CMM.

4 Method

In order to carry out the fiducialization process, a coordinate system must be defined and rigorously adhered to. Our coordinate system is given explicitly in figure 2. It is a right handed, orthogonal system. z is along the beam direction. y is up, referenced to gravity.

x is into the gap of the undulator. In positive roll of the undulator, a point on the $+x$ axis moves up toward the $+y$ axis. Each end of the undulator has a flat which is used to measure roll. Figure 2 illustrates how positive roll moves the flat when viewed from each end of the undulator.

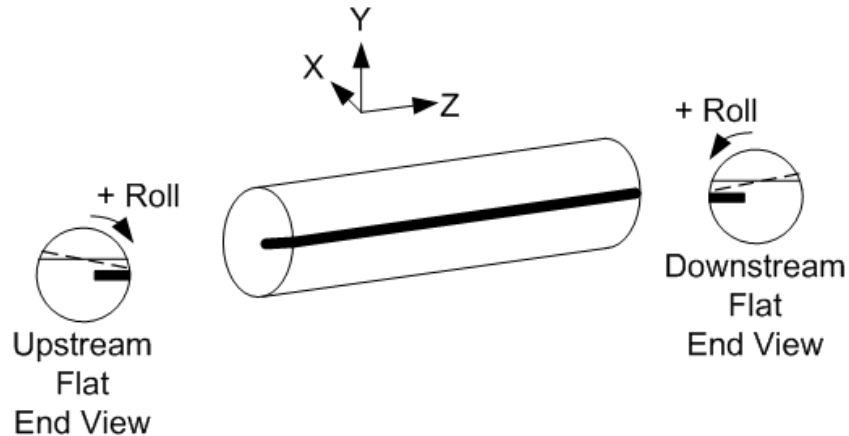


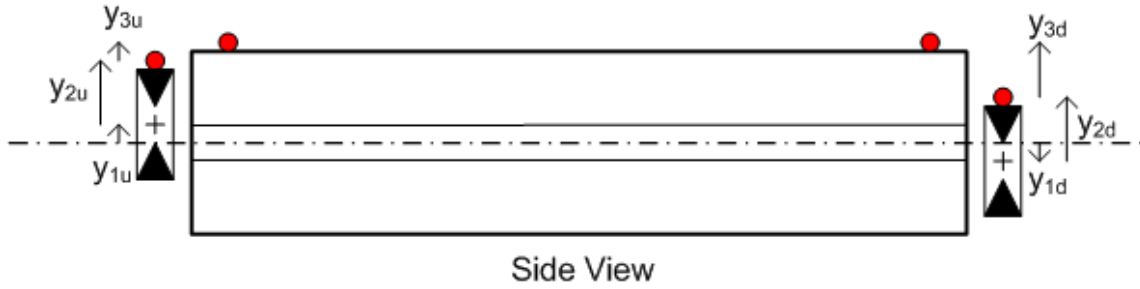
Figure 2: The coordinate system used to tune and fiducialize the undulator.

After the undulator is aligned to the bench and tuned, the steps to fiducialize the undulator proceed as follows. First, measure the offset from the ideal beam axis to the field point in the fiducialization magnet placed on each end of the undulator. This process is illustrated in figure 3. Second, measure the offset from the fiducialization magnet field point to tooling balls on the fiducialization magnet. Third, measure the offset from the tooling balls on the fiducialization magnet to the tooling balls on the undulator. The sum of these three offsets at each end of the undulator gives the offset from the ideal beam axis to the undulator tooling balls.

Quantitatively, the fiducialization is carried out as follows. Consider the x direction on the upstream end. The stage holding the Hall probe is moved a distance x_{1u} from the ideal beam axis to the center of the fiducialization magnet. The value of x_{1u} is determined from an electronic scale on the stage. The fiducialization magnet is placed in a calibration fixture to determine x_{2u} , the distance from the center of the fiducialization magnet to a tooling ball on the outside of the magnet in the x direction. This is a separate step prior to use. The calibration of the fiducialization magnets is described in an LCLS Technical Note⁴. The CMM, measures the distance from the tooling ball on the fiducialization magnet to the tooling ball on the undulator, x_{3u} . The fiducialization for the upstream end in the x direction, x_u , and similarly for the y direction, y_u , and downstream end, x_d and y_d , is

⁴Y. Levashov, Z. Wolf, "Tests of Coordinate Transfer from Magnetic to Mechanical Reference for LCLS Undulator Fiducialization", April, 2005.

Y Fiducializaion



X Fiducialization

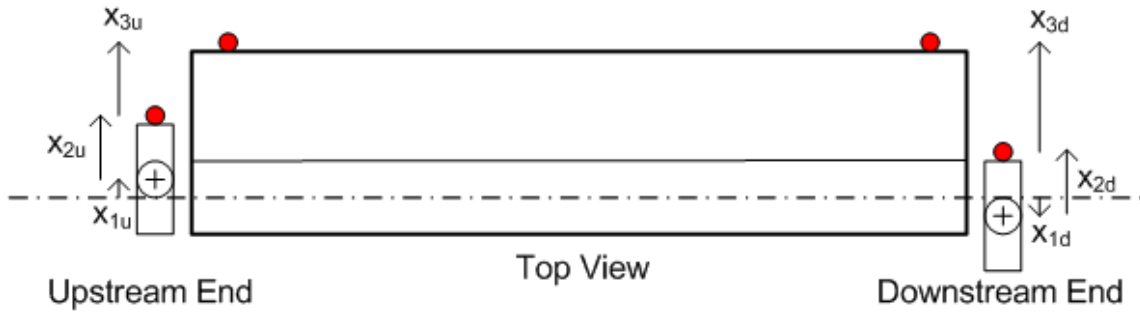


Figure 3: Three measured offsets add to give the total offset from the beam axis to tooling balls on the undulator. These three offsets are required at both ends of the undulator, in both the horizontal and vertical directions.

calculated as follows.

$$\begin{aligned}
 x_u &= x_{1u} + x_{2u} + x_{3u} \\
 y_u &= y_{1u} + y_{2u} + y_{3u} \\
 x_d &= x_{1d} + x_{2d} + x_{3d} \\
 y_d &= y_{1d} + y_{2d} + y_{3d}
 \end{aligned} \tag{1}$$

The fiducialization of the undulator in z will be done entirely on the CMM. Because of the loose tolerance on the z position of the undulator, magnetic measurements are not required. The z positions of the outside faces of the first and last poles will be measured by the CMM. The midpoint will be determined. The z position of the midpoint will be related to the tooling balls.

5 Checks

As noted previously, the tolerances on the fiducialization are fairly tight. As also noted, certain steps of the fiducialization have significant potential to introduce errors, such as

moving the undulator to the CMM with the fiducialization magnets attached. Because of the high accuracy required and significant risk for error involved, checks play an important part of the fiducialization.

Several checks have been implemented. A reference fiducialization magnet, the reference poles, a laser distance gauge, optical survey equipment, and the CMM are used in the checks. The checks taking place at the fine tuning test bench are illustrated in figure 4. The checks taking place on the CMM are illustrated in figure 5. The checks are enumerated below.

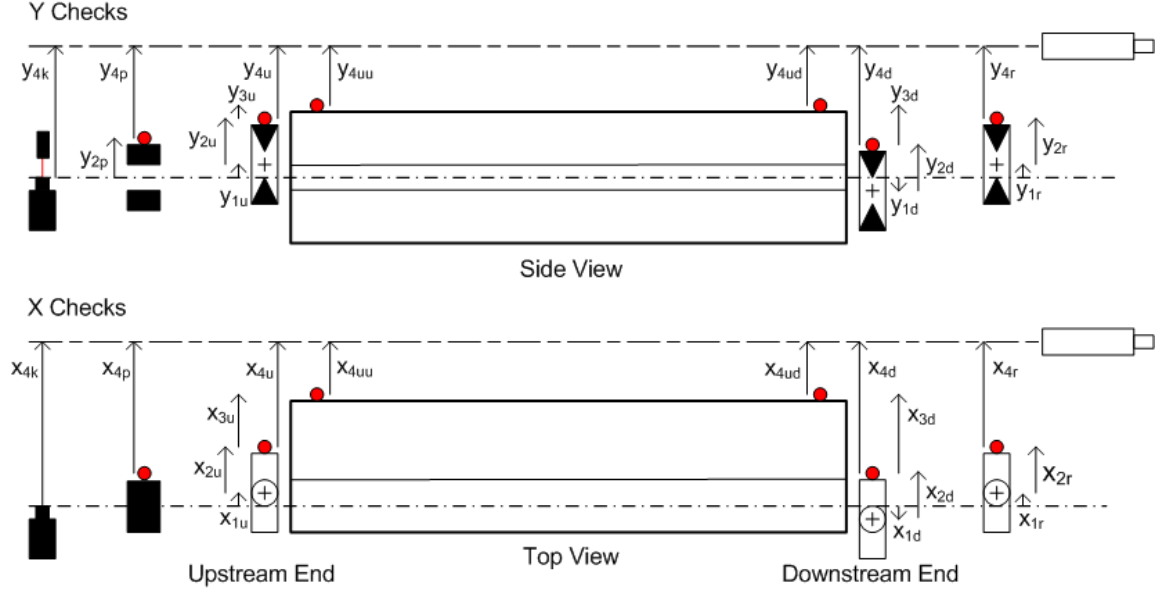


Figure 4: Additional measurements at the fine tuning bench are made to check for errors in the fiducialization process.

It should be noted that additional checks may be implemented and their methods will be similar to those discussed below.

5.1 Reference Fiducialization Magnet Check

The fiducialization magnet to the far right in figure 4 is permanently mounted on a pedestal. Its magnetic center does not move relative to the bench. Each undulator is moved so that it is mechanically in the same position relative to the bench as all the other undulators. We expect the magnetic center of the undulator to agree closely with the mechanical center determined by the capacitive sensors. We therefore expect the ideal beam axis in y to be at the same location relative to the reference fiducialization magnet for all the undulators. We expect y_{1r} to be the same for all the undulators.

The undulators are tuned to a specified K value by both adjusting the gap and moving the beam axis horizontally in the canted poles. The combination of two adjustments makes the x position of the ideal beam axis uncorrelated with the mechanical x position of the undulator. The reference fiducialization magnet can not be used for a check of the x position of the ideal beam axis.

5.2 Optical Alignment Check

Optical alignment equipment will be used to check for errors at the fine tuning bench. The accuracy of the optical measurements is roughly $100 \mu\text{m}$. This check will find any large errors, such as a fiducialization magnet being bumped during transport.

To check the y fiducialization, a sight level is used and referenced to the bench y tooling balls as illustrated in figure 4. The instrument resolution is $12.5 \mu\text{m}$, its repeatability is estimated to be $25 \mu\text{m}$ within the same setup and $50 \mu\text{m}$ otherwise. The measurements y_{4p} , y_{4u} , y_{4uu} , y_{4ud} , y_{4d} , and y_{4r} are made. In this notation, p refers to the reference poles, u refers to the upstream fiducialization magnet, uu refers to the upstream end of the undulator, ud refers to the undulator downstream end, d refers to the downstream fiducialization magnet, and r refers to the reference fiducialization magnet. The following quantities must all be equal. Any inequality of larger than approximately $100 \mu\text{m}$ indicates an error.

$$\begin{aligned}
 & y_{2p} + y_{4p} \\
 = & y_{1u} + y_{2u} + y_{4u} \\
 = & y_{1u} + y_{2u} + y_{3u} + y_{4uu} \\
 = & y_{1d} + y_{2d} + y_{3d} + y_{4ud} \\
 = & y_{1d} + y_{2d} + y_{4d} \\
 = & y_{1r} + y_{2r} + y_{4r}
 \end{aligned} \tag{2}$$

Note that not all terms in these expressions are directly measured. In particular, the terms labeled 1 and 3 are calculated from two position measurements. The terms labeled 1 are the difference between scale readings when the Hall probe is on the beam axis and when the Hall probe is centered in the fiducialization magnet. The terms labeled 3 are the difference between two tooling ball positions measured on the CMM. We use this notation to simplify the discussion, however, it must be remembered that some preliminary calculations are required to use these formulas.

To check the x fiducialization, a jig transit is bucked in to the bench as illustrated in figure 4. The instrument resolution is $12.5 \mu\text{m}$, its repeatability is estimated to be $25 \mu\text{m}$ within the same setup and $75 \mu\text{m}$ otherwise. The measurements x_{4u} , x_{4uu} , x_{4ud} , x_{4d} , and x_{4r} are made. The reference pole does not provide a check in this case because the x position of the ideal beam axis also depends on the undulator gap, as discussed above. However, the following quantities must all be equal at the $100 \mu\text{m}$ level and do provide a useful check.

$$\begin{aligned}
 & x_{1u} + x_{2u} + x_{4u} \\
 = & x_{1u} + x_{2u} + x_{3u} + x_{4uu} \\
 = & x_{1d} + x_{2d} + x_{3d} + x_{4ud} \\
 = & x_{1d} + x_{2d} + x_{4d} \\
 = & x_{1r} + x_{2r} + x_{4r}
 \end{aligned} \tag{3}$$

These equations can be combined to yield 4 simple direct checks between the bench and CMM setups.

$$\begin{aligned}
y_{4u} - y_{4uu} &= y_{3u} \\
y_{4d} - y_{4ud} &= y_{3d} \\
x_{4u} - x_{4uu} &= x_{3u} \\
x_{4d} - x_{4ud} &= x_{3d}
\end{aligned} \tag{4}$$

5.3 Optical Alignment Fiducialization Check

The undulator will be fiducialized with the optical alignment equipment. The Hall probe package will be located. The manufacturer provides the location of the Hall probe active element relative to the package and an uncertainty on the location. The Hall probe active element position, which is the same as the ideal beam axis, is determined relative to the undulator tooling balls as a direct check of the fiducialization.

The Hall probe is clamped in a holder, making direct observation of the y position of the package impractical using the sight level. To find the y position of the package, a Keyence laser distance sensor is used. It measures the distance between the top of the Hall probe package and a gauge block under the Hall probe. The sight level is then used to measure the distance from the gauge block to the line of sight. The combination of the distance from the Hall probe active element to the top of the package, the distance from the top of the package to the gauge block, and the distance from the gauge block to the telescope line of sight is indicated by y_{4k} in figure 4.

This is a direct check of the fiducialization, but, unfortunately, has somewhat large uncertainties. The manufacturer's error specification on the distance from the Hall probe active element to the top of the package is $100 \mu\text{m}$. The Keyence sensor measures the distance from the top of the package to the gauge block at the few μm level. The error on the distance from the gauge block to the telescope line of sight is approximately $100 \mu\text{m}$. The total error on locating the position where the Hall probe is measuring is then approximately $140 \mu\text{m}$. This is larger than the required measurement accuracy, but provides a useful indication of global math errors or of a fiducialization magnet being bumped during transport.

The direct check of the fiducialization is given by

$$\begin{aligned}
&y_{4k} \\
&= y_{1u} + y_{2u} + y_{3u} + y_{4uu} \\
&= y_{1d} + y_{2d} + y_{3d} + y_{4ud}
\end{aligned} \tag{5}$$

A similar check is performed for x giving

$$\begin{aligned}
&x_{4k} \\
&= x_{1u} + x_{2u} + x_{3u} + x_{4uu} \\
&= x_{1d} + x_{2d} + x_{3d} + x_{4ud}
\end{aligned} \tag{6}$$

5.4 Mechanical Measurements Check

The undulator is tuned so that the ideal beam axis is at the average vertical minima of the magnetic field. The minima of the field is expected to be on the midplane of the undulator.

Because of this, it is reasonable to expect that the fiducialization gives the ideal beam axis on the mechanical midplane of the undulator. The mechanical midplane of the undulator is measured with the CMM as shown in figure 5. The midpoint between upper and lower poles is located for all pole pairs. A linear fit is made to the midpoints and the distance from the fitted line to the tooling balls, y_{mu} and y_{md} is determined. The values of y_{mu} and y_{md} are compared to the fiducialization values y_u and y_d , and should be equal.

$$\begin{aligned} y_{mu} &= y_u \\ y_{md} &= y_d \end{aligned} \tag{7}$$

Any inequality indicates an error and must be investigated.

Measurements relative to the undulator center line also provide a useful check. The CMM will locate the mechanical center line of the undulator by touching the upper and lower pole faces in the gap and finding the midpoint in y , and touching the front face of the poles and knowing the pole width determine the midpoint in x . The fiducialized beam axis is then related to the mechanical center line. Call its offset $(\Delta x_{mech}, \Delta y_{mech})$.

Magnetically, the Hall probe is moved vertically and horizontally at a large number of poles to determine the magnetic center line. The location of the beam axis is known. The distance the Hall probe is moved from the beam axis to the magnetic center line is measured with electronic scales on the carriage of the measurement bench. Call the distance $(\Delta x_{mag}, \Delta y_{mag})$.

We assume the magnetic and mechanical center lines agree. In this case, we have the check

$$\begin{aligned} \Delta x_{mag} &= \Delta x_{mech} \\ \Delta y_{mag} &= \Delta y_{mech} \end{aligned} \tag{8}$$

The roll measurements done with a level on the flats of the undulator can also be checked. The CMM will scan the upper and lower pole faces of each set of poles. A line halfway between the poles will be established. The average direction of all the lines halfway between the poles will be used to establish the midplane of the undulator. The mechanical roll measurement on the upstream and downstream ends, $roll_{mu}$ and $roll_{md}$ respectively, are given by the angle between the midplane and the undulator flats.

On the fine tuning bench, the capacitive sensors and cam movers are used to make the midplane horizontal. The roll measurements referenced to gravity using the level should then agree with the mechanical roll measurements.

$$\begin{aligned} roll_{mu} &= roll_u \\ roll_{md} &= roll_d \end{aligned} \tag{9}$$

Any inequality indicates an error in the measurements and must be investigated.

6 Fiducialization Plan

1. Preliminaries

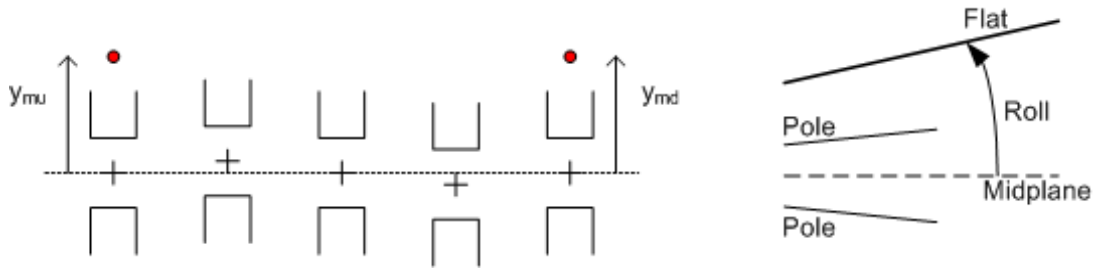


Figure 5: A check is made with the CMM to determine whether the fiducialization gives the ideal beam axis on the mechanical midplane of the undulator. Another check is made of the roll measurements on the undulator flats.

Calibrate the fiducialization magnets which go on each end of the undulator. Calibrate the fixed fiducialization magnet mounted on a pedestal at the end of the undulator. Calibrate the reference poles used by the capacitive sensor system.

2. Mechanically align the undulator to the test stand
 - (a) Have an alignment crew roughly place the undulator so the probes go through it without touching.
 - (b) Use capacitive sensors to measure the undulator position.
 - (c) Use the cam movers to move the undulator into position.
3. 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 ($N \simeq 15$), 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.
4. Determine the tuning axis
 - (a) Measure K at $y = 0$, $x = -2.5, -2.0, \dots, 2.5$ mm.
 - (b) Fit the measurements to find the x location where K has the specified value.
 - (c) Translate the coordinate system. Redefine the $x = 0$ position as the position found in step (b) where K has the desired value.
 - (d) Measure K at the new $x = 0$ position as a check.
 - (e) Leave the Hall probe at $x = 0$, $y = 0$ and perform all tuning along the line at this position.

5. 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 ideal beam axis.

6. Add fiducialization magnets

- (a) Add the fiducialization magnets to the undulator ends.
- (b) Record positions required to calculate the offset from the ideal beam axis to the center of the fiducialization magnets.
- (c) Perform step *b* at both ends of the undulator and at the reference fiducialization magnet.
- (d) Write results to a data file.

7. Optical fiducialization

- (a) Set up a sight level to measure all *y* tooling balls.
- (b) Record 2 *y*-readings on the 2 undulator flats for the undulator roll measurement. A tiltmeter may also be used.
- (c) Set up a jig transit to measure all *x* tooling balls.
- (d) Record all measurements in a data file.
- (e) Perform an analysis of the data at this point to look for problems before the undulator is moved to the CMM.

8. Fiducialization on the CMM and mechanical checks

- (a) Move the undulator to the CMM. Mount the undulator on a kinematic mount, identical to the mount used at the fine tuning test bench.
- (b) Establish a preliminary coordinate system roughly aligned to the undulator. In the CMM's natural coordinate system, 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 approximately along the undulator ideal beam axis. Roll of the undulator introduces cosine errors in the offsets which will be corrected once the roll angle of the undulator is established.
- (c) Measure lines along all 226 undulator upper poles and lower poles.
- (d) Calculate the symmetry line between each upper and lower pole. Average the angles of the symmetry lines to establish the mechanical roll angle of the undulator in the CMM's coordinate system.
- (e) Establish a coordinate system tied to the undulator. Repeat step *b*, but this time use the offsets from the fiducialization magnet tooling balls along lines parallel and perpendicular to the line along the mechanical roll angle of the undulator.

Set the x axis along the mechanical roll direction, set the z axis along the line between the positions of the ideal beam axis determined using the fiducialization magnets at each end of the undulator, and set the y axis perpendicular to x and z . The origins of the x and y axes are on the ideal beam axis. The origin of the z axis at the midpoint of measurements taken on the outside faces of pole #1 and pole #226. This coordinate system is used for all dimensional and fiducialization calculations.

- (f) For each pair of poles, record and plot the gap height at the location of the y - z plane. Record and plot the y position of each pole at $x = 0$. This gives the pole locations relative to the ideal beam axis.
- (g) Measure and record the angle between the x axis and the flats on the undulator.
- (h) Measure and record all tooling ball positions on the undulator.
- (i) Determine offsets from the tooling balls on the fiducialization magnets to the tooling balls on the undulator.
- (j) Record the transformation between the coordinate system and a new coordinate system based on the x and y undulator tooling balls on the upstream end and the y tooling ball on the downstream end. This transformation can be used to re-establish the ideal beam axis coordinate system once the fiducialization magnets have been removed.

9. Analyze data

Run the computer program which reads all data files, writes the output results, and performs all checks.

7 Measurement Results

All raw data and analysis results will be available from the SLAC web site. The data will be stored in a directory structure as show in figure 6. The top level directory is *Magdata*, followed by *LCLS*, followed by the magnet type *Undulator*. In the *Undulator* directory, there is a folder for each undulator named by the serial number. For each undulator, *Dataset* directories are made. When the undulator comes back for multiple measurements over time, each set of measurements goes into a new dataset. Within each dataset, the *Rough Tuning*, *Fine Tuning*, *Tuning Results*, *Fiducialization*, *Temperature*, and *Mechanical Measurements* folders are created. Each contains all the relevant measurements. All data files will be text files. There will be several types of data files with different formats depending on the measurement.

All fiducialization data will be put in the *Fiducialization* folder. The data comes from several sources. For each of the three fiducialization magnets used, a file will be included containing the calibration. A file will contain the calibration data of the reference poles. The scale readings from the measurement bench giving the offset from the ideal beam axis to the center of the three fiducialization magnets will be included. All optical alignment measurements will be entered into a computerized form with the measurements written to a data file. CMM data will be written to a data file. CMM check data will be written to

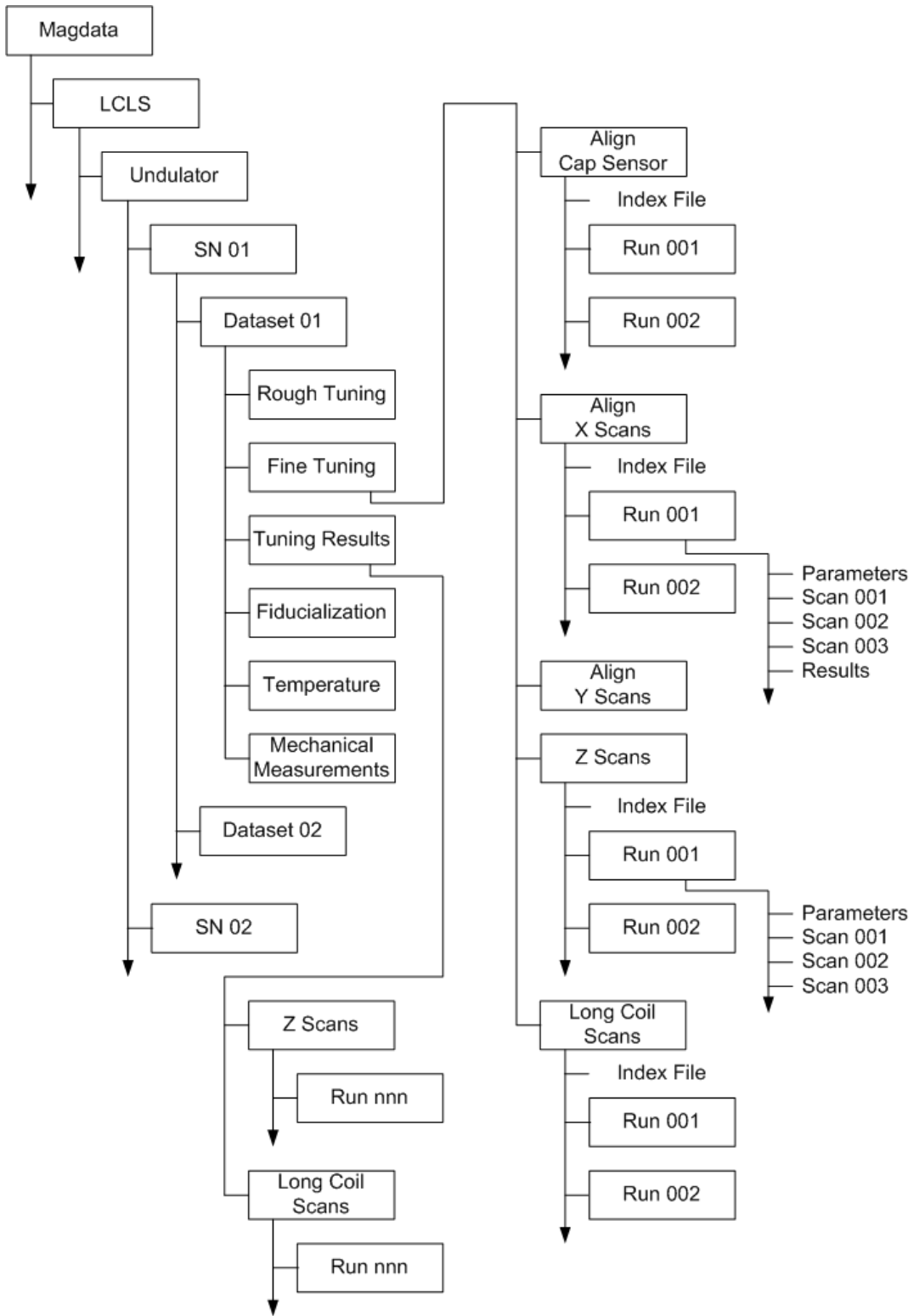


Figure 6: The undulator measurement data will be stored in a directory structure.

a file. Finally, the analysis program will summarize all of the data contained in the input files and give the offsets from the ideal beam axis to the undulator tooling balls.

An illustration of the various files required and their contents is given below. The file names are only suggestive. The names of the contents follow the conventions used in this note. In practice, redundant measurements are made which will be included in the files in addition to the minimal information given below. Also, calculated offsets (y_{1u} , y_{3u} , etc.) will be replaced by the actual measurements of positions in the data files. The results file will contain a summary of all the input data and check results, in addition to the final results.

fiducial_mag.cal

$x_{2u}, y_{2u}, x_{2d}, y_{2d}, x_{2r}, y_{2r}$

reference_pole.cal

x_{2p}, y_{2p}

bench_scale_meas.dat

$x_{1u}, y_{1u}, x_{1d}, y_{1d}, x_{1r}, y_{1r}, \Delta x_{mag}, \Delta y_{mag}$

undulator_roll.dat

$roll_u, roll_d$

optical_check.dat

$x_{4u}, y_{4u}, x_{4d}, y_{4d}, x_{4r}, y_{4r}, x_{4uu}, y_{4uu}, x_{4ud}, y_{4ud}, x_{4p}, y_{4p}, x_{4k}, y_{4k}$

cmm_meas.dat

$x_{3u}, y_{3u}, x_{3d}, y_{3d}, z_{pole1}, z_{pole226}$

cmm_check.dat

$y_{mu}, y_{md}, roll_{mu}, roll_{md}, \Delta x_{mech}, \Delta y_{mech}$

fiducialization_results.dat

$x_u, y_u, x_d, y_d, z_{ctr}, roll_u, roll_d$