LCLS-II HXR Undulator Fiducialization And Girder Alignment Plan

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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 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 vertical, must be less than 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 1.00 mm horizontally and 0.14 mm vertically.

6. 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
   (b) using the fiducialization magnet location, calibration, and offsets to the magnetic axis, determine the beam axis
   (c) locate a set of fiducials relative to the beam axis for future alignment of the undulator
   (d) 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
   (e) make all vacuum connections

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

(c) check that the RFBPM dipole cavity is properly installed on the beam axis

(d) make any adjustments to the alignment, if necessary

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

The CMM measures positions in its machine coordinate system, but it can display results in user specified coordinate systems. We will present data 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 to define a coordinate system for all final measurements and alignment.

4.1 Girder Coordinate System

In order to initially locate components on the undulator, we wish to use a coordinate system related to undulator mechanical 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 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 the intersection of a line along the axis of the hole 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. A line is established between the two points defined by the holes to determine the w-axis of the undulator. This line determines the pitch and yaw of the girder. We will first make the (u, v, w) coordinate system located in the girder, then we will translate up to the beam

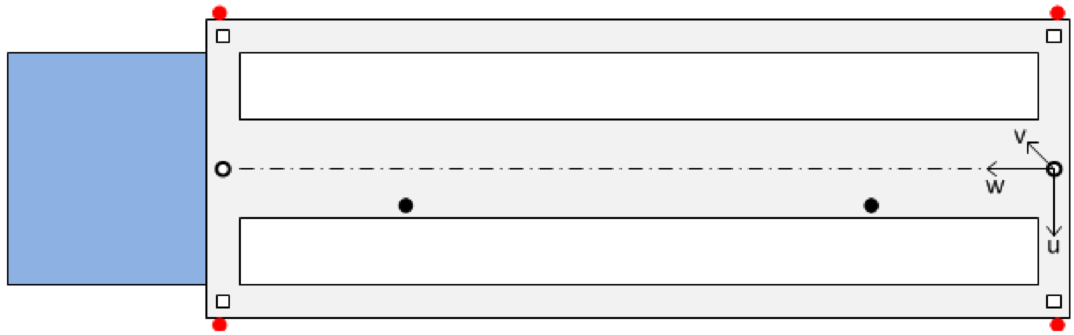

Figure 1: Girder features are used to establish the girder coordinate system.

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 defines a direction and is used to determine the roll of the girder.

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 can now be defined. The w-axis is along the line between the centers of the precision holes. A plane perpendicular to the w-axis containing the center of the upstream hole contains the u-axis and the v-axis. The v-axis is along the projection of the normal onto the plane perpendicular to the w-axis. 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.

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 girder coordinate system. The z-axis is parallel to the w-axis and it determines the pitch and yaw of the undulator. The y-axis is parallel to the v-axis and determines roll. The x-axis is perpendicular to both the z and y axes. The (x, y, z) system is orthogonal. The origin is along the v-axis, 143.76 mm above the point defining the center of the upstream precision hole. 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 of 9 mm. The tooling balls are a redundant set shown in red in the figure. They allow us to easily reestablish the girder (x, y, z) system.

4.2 Fiducialized Beam Axis Coordinate System

Once the undulator is fiducialized, we will use the fiducialized beam axis to define the (x, y, z) coordinate system for all future work. This system is illustrated in figure 2. The procedure to define the coordinates is very similar to the procedure used to define the girder coordinate system, except that two points on the magnetic axis are used instead of two mechanical points on the girder.

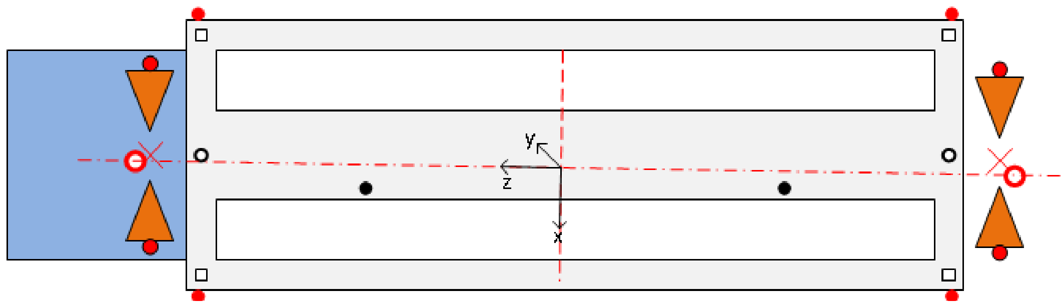

Figure 2: The fiducialized beam axis is used to define the primary coordinate system for the undulator.

The magnetic measurements are done by first fitting a line down the center of the magnetic field distribution, and then performing all measurements on this magnetic axis of the undulator. All undulator parameter calculations (K value, phase errors, etc.) are done from these measurements, so in order to understand the behavior of the undulator, we wish the beam to go down the line that the probes measure on. Since this line is determined magnetically and is intangible, we must find a method to determine this line mechanically. We do this by using "fiducialization magnets" which have a very high gradient and let us determine a zero field point with micron repeatability. The position of the zero field point relative to tooling balls is determined in a calibration procedure. Each zero field point is marked by an X in the figure, and its position is known relative to the tooling balls represented by solid red circles on the fiducialization magnets. The probe used for magnetic measurements moves on a line and points on the line at the longitudinal position of the fiducialization magnets are shown as the red open circles. The relative position of each open circle on the line to the zero field point X is measured at the Kugler bench by moving the probe transversely from the measurement axis to the zero field point using scales to determine the distance moved. Thus we know the position of the red open circles relative to the X positions in the figure. When the undulator with the fiducialization magnets attached is moved to the CMM, the CMM is used to measure the position of the tooling balls on the fiducialization magnets. The offsets to the zero field point and from the zero field point to the magnetic axis are know, so we know the position of a point on the beam axis at each end of the undulator.

The line between the two points on the beam axis is used to define the z-axis of our coordinate system. The z-axis determines the pitch and yaw of the undulator. The four flats on the undulator described above for the girder coordinate system are fit to define a plane and the normal to the plane. The projection of the normal onto a plane perpendicular to the z-axis defines the y-axis. The y-axis determines the roll of the undulator. The x-axis is perpendicular to both the z-axis and the y-axis.

The origin of the coordinate system must now be determined. The undulator has an even number of poles and an odd number of magnets in each jaw. The average of all the magnet positions along the z axis is used to define the z-position of the center of the undulator. We take the origin of our coordinate system on the line defining the z-axis at the mechanical average z-position of all the magnets.

Once the coordinate system is defined, the CMM can give all measurement results in this system. The positions of fiducials on the outside of the undulator are measured in this coordinate system. The fiducials then allow the coordinate system to be reestablished for further work in the MMF or in the tunnel.

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
   (a) Perform controls setup and checks.
   (b) Set up the nominal beam axis coordinate system.
   (c) 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 of all the z-positions and use this as the z-position of the center of the undulator. Relate this z-position to fiducials on the undulator for positioning the undulator in the tunnel.

(j) Open the undulator gap and locate the pins used to position the beam pipe. Verify that within the adjustment range, the beam pipe can be positioned on the nominal beam axis.

5. Move the undulator to the Kugler bench.

    (a) Perform controls setup and checks.

    (b) 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. (Depending on how reproducibly the cam surfaces are attached relative to the beam axis, this step may be unnecessary after several undulators.)

    (c) Use capacitive sensors to measure the undulator position.

    (d) 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

    (a) Tune the x trajectory, y trajectory, and the phase.

(b) Tune the field integrals.
(c) Using capacitive sensors, make sure no poles extend too far into the gap.
(d) Make the final data set characterizing the undulator.

8. Add fiducialization magnets

(a) Add the fiducialization magnets to the undulator ends.
(b) Find the center of each fiducialization magnet with the Hall probe.
(c) 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) Perform controls setup and checks.
(c) Establish the nominal beam axis coordinate system to begin.
(d) At the 9 mm tuning gap, 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.
(e) At 9 mm gap, fiducialize tooling balls on the exterior of the undulator in the fiducialized beam axis coordinate system.

10. Perform the following measurements at the 9 mm tuning gap in the fiducialized beam axis coordinate system. Record the load cell readings and encoder readings.

(a) 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. The x-position of each pole on both jaws showing the calculated stay clear region for the beam pipe at 7.2 mm gap.
(b) Measure the y-position of the top of each pole.
(c) Measure the y-position of the top of the magnet keepers.
(d) Measure the z-position of each magnet by touching it on both ends and finding the center point.
(e) Measure the x-position of each magnet and determine the recess from the poles.

(f) 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.

(g) From the measurements, verify that the roll angle of the symmetry line between poles is within tolerance.

(h) From the x and y-positions 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.

(i) From the measured z-position of all the magnets, calculate the average of all the z-positions and use this as the z-position of the center of the undulator. Relate this z-position to fiducials on the undulator for positioning the undulator in the tunnel.

11. On the first undulator, repeat the magnetic measurements and fiducialization on all three cam surface mounting positions. Determine whether the measurements and fiducialization depend on the mounting position. If so, all undulators must be assigned a mounting position before measurements begin.

12. Move the undulator to the assembly area

    (a) Perform controls setup and checks.

    (b) Install the beam pipe.

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

    (d) Install the interspace components. Include a phase shifter, even though it will be removed for storage, in order to check for any mounting issues.

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

    (f) Align the RFBPM dipole cavity to the fiducialized beam axis.

    (g) Make all vacuum connections, pump down and check for leaks.

13. Move the undulator with the beam pipe and interspace components to the CMM

    (a) Perform controls setup and checks.

    (b) Record the alignment of critical components at undulator gaps of 7.2, 10, 15, 20, and 40 mm:

        i. Record the x,y-position of the center of the quadrupole relative to the fiducialized beam axis.

        ii. Record the x,y-position of the center of the RFBPM dipole cavity relative to the fiducialized beam axis.

    (c) Record the beam pipe position at 20 mm gap so that there is access to the sides of the beam pipe:

        i. Measure the x-position of the midpoint of the beam pipe relative to the fiducialized beam axis.

        ii. Measure the top y-position of the beam pipe and calculate the y-position of the center of the chamber relative to the fiducialized beam axis.
        iii. Measure the x-position of each magnet pole at the vertical center and check that the fiducialized beam axis has been properly reestablished.
    (d) If any components are positioned out of tolerance, make any necessary adjustments to the alignment and repeat the measurements of this step.

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.

6 Logistical Plan

The list of steps to fiducialize and do the girder assembly and alignment of an HXR undulator must be completed in an efficient and timely manner. In this section we make a logistical plan for doing the work. Many steps by several specialized groups of people are involved. In order to have a functional plan, we must compartmentalize the efforts and make each effort as independent as possible from other efforts. We divide the work into two largely independent efforts: 1) fiducialize the undulators, and 2) do the girder assembly and alignment. We now go through the logistics of each effort.

6.1 Undulator Fiducialization Logistical Plan

Consider the list of steps shown in figure 3. We start with an initial configuration. The CMM is free. An undulator marked 'a' is in the temperature conditioning area. An undulator marked 'b' is at the Kugler bench and the magnetic fiducialization is just finishing. An undulator marked 'c' is in a queue of received undulators. The procedure to receive the undulators is not discussed in this plan.

When the work on the undulator at the Kugler bench is one day away from being complete, we proceed to day 1 of the logistical plan. In the morning we move the undulator from the temperature conditioning area to the CMM. During the day, the undulator controls are set up and checked. At night, an automated program performs the CMM measurements outlined in step 4 of the fiducialization and girder alignment plan given above.

Day 2 is a busy day. The undulator on the CMM, marked 'a', is first placed temporarily on the floor out of the way. The undulator at the Kugler bench, marked 'b', is moved to the CMM. Undulator 'a' is now moved to the Kugler bench. Since many riggers are present for the moves, we also move the undulator marked 'c' from the receiving queue to the temperature conditioning area. The Controls group must now connect and perform checks on the undulator marked 'b' on the CMM. Afterward, the Controls group must connect and perform checks on the undulator marked 'a' at the Kugler bench. The fiducialization on the CMM must be completed this day. At night, the CMM measurements of step 10 of the itemized plan given above must be performed.

Day 3 is more relaxed. The undulator marked 'b' is moved from the CMM to a queue for girder assembly and alignment work. If the assembly area is free, the undulator can be moved directly into the assembly area reducing the number of moves. An alignment crew positions the undulator marked 'a' at the Kugler bench. Magnetic alignment of the probes begins. The Controls group begins checkouts of the undulator marked 'c' in the temperature conditioning area.

Days 4 to 10: At the Kugler bench, many measurements must now take place. We estimate that it will take 3 days to tune the undulator. Shims will be required to compensate the difference in the Earth's field between LBNL and SLAC, and between ANL and SLAC. We are uncertain about the state of tuning that the undulators will arrive in. The 3 days gives us a buffer to make the adjustments we feel are required. After tuning, the final dataset begins. This takes 4 days: one day and night of coil measurements, one day and night of Hall probe measurements, one day of measurements with the gap tapered, measurements at the commissioning gap, etc., and one day of logging controls data, performing capacitive sensor gap measurements, placing the fiducialization magnets, and finding the offsets from the magnetic axis used for the measurements to the fiducialization magnet's zero field point. This last day is day 10 in the sequence. The fiducialization magnets are on the undulator and the next day the undulator must be moved to the CMM to finish the fiducialization. But this is the same as what we called day 1 of the sequence. On day 10, the undulator in the temperature conditioning area must be moved to the CMM and measured. The cycle has started to repeat. The whole process takes 9 days per undulator. We consider this an optimistic, but possible plan. When making the schedule, one must also include time to measure the reference undulator (approximately 1 week every 5 weeks), and a contingency must be added for equipment failure and other unforeseen events.

6.2 Girder Assembly And Alignment Logistical Plan

Note that in the undulator fiducialization logistical plan, the CMM is free for most of the time. This lets us uncouple the undulator fiducialization from the girder assembly and alignment.

The steps for the girder assembly and alignment logistical plan are shown in figure 4. The initial configuration shows the girder assembly and alignment area free. An undulator marked 'a' is in the queue. Note that if the assembly area is free after undulator fiducialization, undulator 'a' can be moved directly from the CMM to the assembly area instead of to the queue, reducing the number of moves.

On day 1, the undulator marked 'a' is moved to the assembly and alignment area. The controls are connected and a controls checkout is performed. Assembly and alignment work can begin on this day.

For days 2 to 4, girder assembly and alignment work is performed. The work corresponds to steps 12 and 13 in the test plan. Mechanical technicians do the assembly work, vacuum technicians make all beam pipe connections, and an alignment crew uses a laser tracker to align the beam pipe, RFBPM, and quadrupole to the fiducialized beam axis.

On day 5, the undulator is moved to the CMM. Controls are connected and checked.

An automated program makes final measurements for the rest of the day and night.

On day 6, the undulator is moved to the storage area. It is wrapped in plastic and crated for storage.

The CMM is used for only one day for girder assembly and alignment. This should easily fit into the undulator fiducialization schedule.

7 Conclusion

A plan was presented which fulfills the scientific need of meeting the undulator physics requirements. A logistics plan was presented which shows the throughput of the MMF. The undulator fiducialization and girder assembly and alignment should take roughly 9 days per undulator. This is considered an optimistic but achievable schedule. One must add time to the schedule for measuring the reference undulator (approximately 1 week every 5 weeks) and a contingency must be added for equipment failure and other unforeseen events. The girder assembly and alignment work fits into the 9 day per undulator schedule. Final alignment checks on the CMM also fit into this schedule.

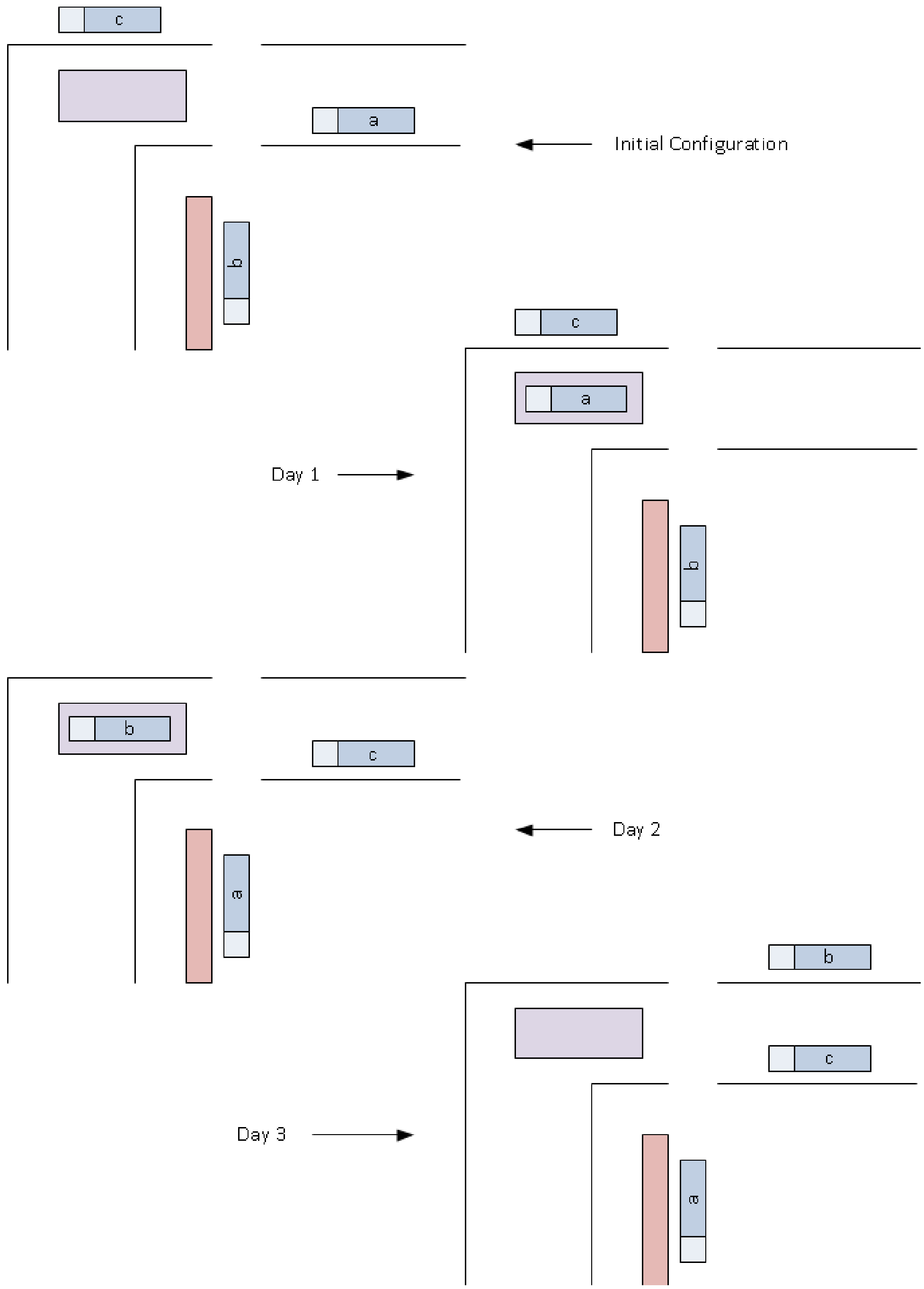

Figure 3: Key logistical steps for undulator fiducialization.

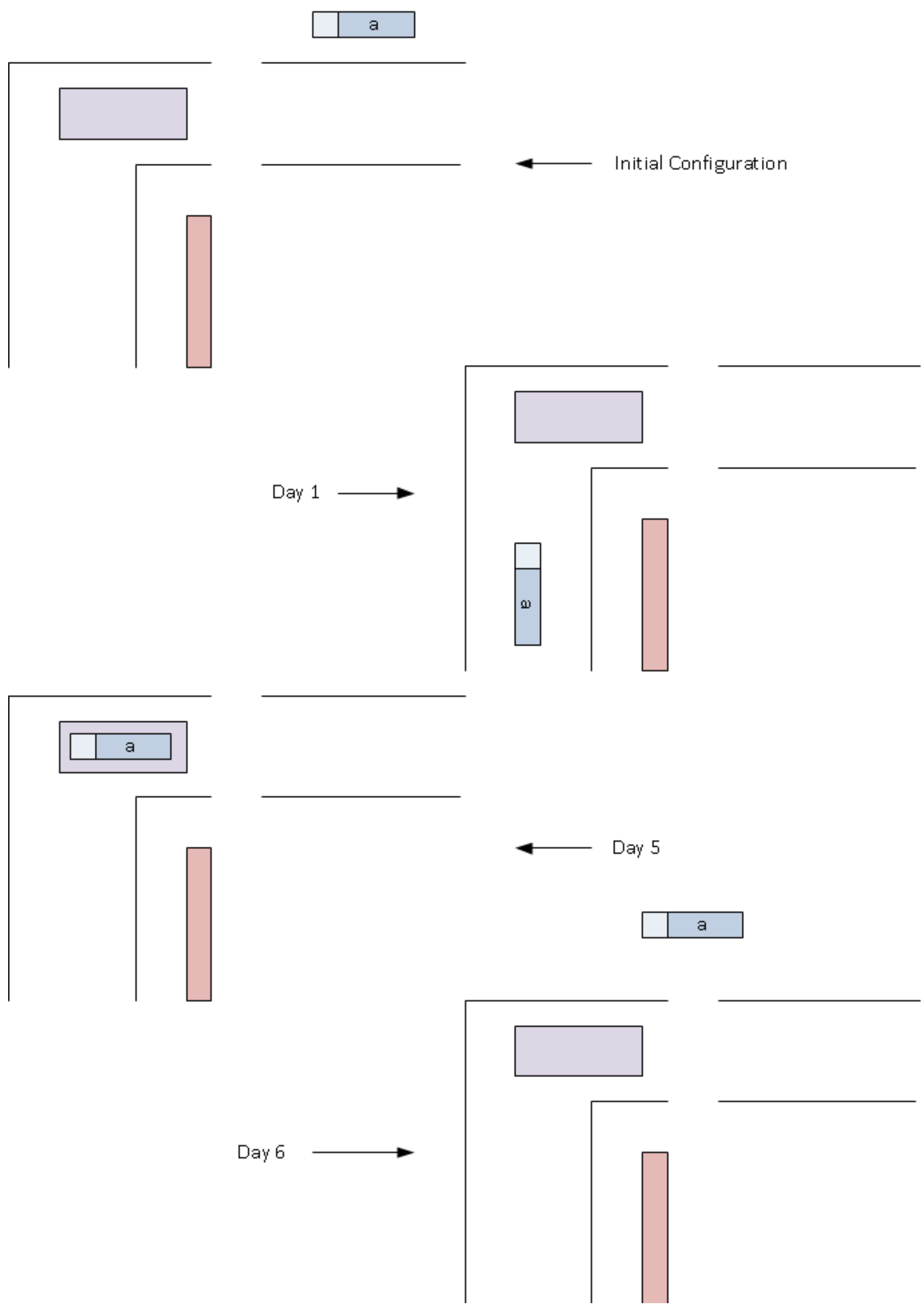

Figure 4: Key logistical steps for girder assembly and alignment.