# A Plan For Delta-II Magnetic Measurements And Assembly

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**Abstract**

An elliptically polarizing undulator is being built at SLAC for use in the LCLS-II SXR line. Magnetic measurements and precision assembly will play an important role in delivering a successful undulator. No adjustments to the undulator are possible after it is assembled, so precision measurements during assembly and precision assembly are required for the undulator to meet its tolerances. After assembly, extensive measurements are required to calibrate the Delta-II in its different polarization modes and various K values. In this note a plan is presented for the tuning, assembly, and calibration of the Delta-II undulator.

## 1 Introduction[1]

An elliptically polarizing undulator, Delta-II, is being built at SLAC for use in the LCLS-II SXR line. The Delta-II has no provision for tuning after it is assembled, so accurate magnetic measurements and high precision assembly will play a key role in the Delta-II's performance. In addition, characterizing the many modes and strengths of the undulator after assembly will require extensive magnetic measurements. These measurements must be accurate since it is envisioned to have several Delta-II's and they must be resonant with each other and with the existing SXR undulators. Since magnetic measurements and precision assembly will play a key role in the Delta-II's ultimate performance, a thorough plan for this effort must be made. This note presents a plan for doing the magnetic measurements and assembly of the Delta-II undulator so that all tolerances are met. Further detailed test plans for the various measurements required during assembly and calibration will follow.

A previous Delta undulator was built at SLAC for the original LCLS.[2] The Delta-II's main distinguishing feature is the ability to move the quadrants radially in order to change the K value without introducing a gradient in K.[3,4] Another feature of the Delta-II will be

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

[3]Z. Wolf, "Position Dependence Of The K Parameter In The Delta Undulator", LCLS-TN-16-1, January, 2016.

[4]M. Calvi et al., "Transverse Gradient In Apple-Type Undulators", J. Synchrotron Rad (2017) 24, 600-608.

the care put into the alignment of the magnet arrays in order to avoid phase errors.[5] Since phase errors are sensitive to taper of the magnet arrays at the sub-10 $\mu$m level, much of the Delta-II magnetic measurement and assembly work will take place on a CMM. Many lessons were learned from the original Delta undulator and the knowledge gained will be applied when building the Delta-II.

# 2 Overview

There are three main stages of magnetic measurements and assembly required for Delta-II:

1. Tune the quadrant magnet arrays at a Kugler bench. Many shims are required to tune each quadrant. The tuning will take many days for the four quadrants. The work must be done in a good ergonomic environment where a person can stand upright and work on the magnet array at chest level. We have previous experience with similar tuning at a Kugler bench with the original Delta undulator (see SLAC-PUB-16404 referenced above). For Delta-II, the same tuning effort at a Kugler bench will be applied, but with an additional final tuning on the CMM after the quadrants are placed on the strongbacks.

2. Assemble the undulator on a CMM. After the quadrants are tuned at a Kugler bench, they will be moved to a CMM and placed on the Delta-II strongbacks. Final tuning will be done using a Hall probe guided by the CMM. The beam axis will be fiducialized for each undulator half. The beam pipe will be installed in the bottom half. The two halves will be aligned with respect to each other and bolted together in order to complete the undulator.

3. Calibrate the Delta-II. A measurement system will be set up to perform many automated measurements of the Delta-II in its various modes and K values. This must be done with tight temperature control.

With this overview in mind, we now go through the steps in more detail to tune, build, and calibrate the Delta-II.

# 3 Tuning, Assembly, And Calibration Plan

## 3.1 Quadrant Tuning

1. The quadrant tuning will be done with virtual shimming, i.e. by adjusting magnet positions. A prerequisite is that all magnet holders have shims which allow the magnet blocks to be moved radially outward so that they don't protrude into the gap and interfere with the beam pipe. The blocks must also be moved transversely for tuning. A system must be developed for accurate transverse block motion measurements.

2. A second prerequisite for tuning is that all magnet blocks in a quadrant be initially mechanically aligned at the few micron level. The mechanical alignment will take place

[5] Z. Wolf, "Effect Of Quadrant Taper On Delta Undulator Phase Errors", LCLS-TN-15-2, February, 2015.

on a CMM. The magnet blocks will be aligned to a nominal mechanical centerline for each magnet keeper.

3. Build a support stand for tuning at the HXR Kugler bench. The SXR Kugler bench is occupied with LCLS-II-HE undulators. The support stand must hold the quadrants so that the magnets are oriented vertically. This allows a horizontal Hall probe to do the measurements. The support stand must include provisions to move a quadrant in pitch, yaw, and roll in order to align it to the Kugler bench. The support stand should be built on an LCLS girder. The girder provides needed rigidity and it provides the necessary motions by using the cam movers under the girder.

4. Implement a touch probe measurement system at the HXR Kugler bench for accurate mechanical measurements. This is in addition to the Kugler bench's accurate magnetic measurements.

5. Place a quadrant at the HXR Kugler bench. Use conventional alignment to take out the roll so the magnets are oriented vertically.

6. Mechanically align the quadrant to the bench. The magnet blocks within each keeper have already been aligned in step 2, so only an alignment of the keepers is required. Use the touch probe measurements to find the horizontal position of the side of each magnet block near the Kugler bench. Use the position of the side of the block along with the CMM measurements from step 2 to find the center of each block. Fit the block center positions along the length of the quadrant to find the horizontal centerline of each keeper and the quadrant. Shim the magnet keepers so that the magnet blocks for the entire quadrant are on a straight line. Adjust the quadrant in yaw so its centerline is parallel to the bench.

7. Continue the work of the previous step to take the pitch out of the quadrant. Using the touch probe measurements, find the positions of the tops of all the magnets. Shim the magnet keepers so that the magnet blocks for the entire quadrant are on a straight line. The magnet blocks within each keeper have already been aligned in step 2. Fit the magnet top measurements with a line to determine the vertical position of the quadrant centerline. Adjust the quadrant in pitch so the centerline is vertically parallel to the bench. Iterate with the previous step, if necessary, to complete the mechanical alignment.

8. Find the horizontal position of the magnetic axis of the quadrant. Perform Hall probe scans of the quadrant along its length at different x-positions. The field at the vertical blocks is then reconstructed as a function of x and the center of the field pattern is found. This gives the magnetic center x-position of all the vertical blocks. An alternative method is to scan the Hall probe horizontally at each vertical magnet block. Fit the field measurements to find the center of the field profile at each block. When the center of the field pattern has been found at each vertical block, fit the center positions along the length of the quadrant with a line to determine the horizontal position of the magnetic centerline. Verify that the magnetic centerline is parallel to the bench. If it is not, make small adjustments to the quadrant yaw. Place the Hall probe so that its x-position is on the horizontal centerline.

9. Using the Hall probe, perform a longitudinal scan at a height of half the minimum gap above the magnet blocks and on the horizontal centerline. Find the peak fields. Verify that the peak fields do not have a taper. If there is a taper, adjust the pitch of the quadrant until the taper is removed. At this point, the vertical position of the magnetic axis of the quadrant is parallel to the bench. Perform scans at various heights above the quadrant. Set the Hall probe's vertical position so that the average peak field has a given predefined value. The Hall probe now moves down the magnetic axis of the quadrant. Small errors in the vertical Hall probe position can be tolerated since the quadrants can be moved radially in the Delta-II. By moving radially, each quadrant will be made to have the same strength on the magnetic axis. The final radial position of each quadrant, and thus the encoder offset for the radial position, will be determined later on the CMM. The quadrant is now ready for tuning.

10. Check the end magnet design. A new end design will be used in the Delta-II in an attempt to make the field integrals insensitive to the longitudinal quadrant positions due to permeability effects. Verify the end design by placing unmagnetized magnet blocks symmetrically above the end of the quadrant and observe any change to the calculated beam trajectory as the unmagnetized blocks are moved longitudinally. A fixture will need to be built to hold the unmagnetized blocks. Minimal change to the calculated beam trajectory should be observed as the unmagnetized blocks are moved, otherwise the end design must be revisited. Some small tuning of the end magnets is expected in order to correct for magnet strength and placement errors. Repeat using unmagnetized blocks to the side of the quadrant end magnets simulating the end of a neighboring quadrant.

11. Tune the four quadrants. Perform Hall probe scans longitudinally along the magnet array. Move the magnet blocks so that the calculated beam trajectories are straight, the field integrals are well within tolerance, and phase errors are minimized. Some final tuning will be required on the CMM to align the magnet keepers when the quadrant is moved, but the bulk of the tuning should be completed in this step.

### 3.2 Undulator Assembly On The CMM

1. Write software to make the CMM move the Hall probe on a straight line between two given arbitrary points, and to generate uniformly spaced triggers as the probe moves. Verify the performance by recording the CMM coordinates at the triggered positions. Analyze the data to confirm that the trigger positions are on a straight line and are uniformly spaced.

2. Implement a system to determine the Hall probe position in the CMM coordinate system. Such a system is routinely used to locate the Hall probe at the Kugler benches. A special fiducialization magnet is used which has a well defined zero field point, and which is calibrated so the zero field point position is known relative to tooling balls on the outside of the magnet.[6] Locate the tooling balls on the

[6] Y. Levashov et al., "Tests Of Coordinate Transfer From Magnetic To Mechanical Reference For LCLS Undulator Fiducialization", LCLS-TN-05-10, April, 2005.

fiducialization magnet with a conventional CMM probe. Using the fiducialization magnet calibration, determine the zero field point location in the CMM coordinate system. Exchange the CMM stylus probe with the Hall probe. Scan the magnetic field in the fiducialization magnet using the Hall probe. The resulting field map gives magnetic field readings as a function of CMM location readings. Analyze the field map to determine the zero field point location. The zero field point location is now known both from the tooling ball locations on the fiducialization magnet and from the Hall probe map. There will be an offset between the two methods to account for the difference in position of the Hall element relative to the stylus used for mechanical measurements. Determine the offset and correct the Hall probe position so it agrees with the mechanical positions given by the CMM. After the offset correction, use the CMM to scan the field of the fiducialization magnet. Use the resulting field map to find the zero field point. Verify that the zero field point is at the position as determined by using the touch probe and the tooling balls.

3. Implement a reference magnet, an alignment magnet, and a zero Gauss chamber for the CMM magnetic measurements. The Hall probe will make measurements when it is oriented horizontal and when it is rotated perpendicular to the undulator quadrants at +45 degrees and −45 degrees. All angles are measured relative to the flat granite surface of the CMM. Hall probe alignment magnets are routinely used at the Kugler benches. These magnets can be borrowed, or new ones made. Special supports for the alignment magnets will be required to hold them at ±45 degrees. Similarly, reference magnets are routinely used at the Kugler benches to check Hall probe calibrations. A reference magnet can be borrowed from a Kugler bench, but supports for the reference magnet must be made. The supports must hold the reference magnet horizontal and at +45 degrees and −45 degrees. A zero Gauss chamber will need to be purchased if a spare is not available. Mounts for the zero Gauss chamber need to be made to hold it at 0, +45, and −45 degrees. In the steps below, whenever the Hall probe is used on the CMM, it must be first aligned using the alignment magnets, the calibration must be checked using the reference magnet, and then, before every measurement, the offset must be corrected using the zero Gauss chamber.

4. Commission the CMM for magnetic measurements. In order to do this, an LCLS-II reference undulator will be used. Place the reference undulator on the CMM. Using the CMM coordinates of the undulator fiducials along with the undulator fiducialization and calibration, determine the magnetic axis of the undulator in the CMM coordinate system. Place the Hall probe in the CMM and perform the alignment, calibration check, and offset correction mentioned in the previous step. Determine its position in CMM coordinates using the fiducialization magnet. Move the Hall probe to the undulator midplane and to each magnet pole along the undulator. Scan the magnetic field at each pole both horizontally and vertically to determine the magnetic center of the field at that longitudinal location. Fit the magnetic centers to find the magnetic axis of the undulator. Verify that the measured magnetic axis is at the location given by the undulator fiducialization and calibration. Perform a Hall probe scan of the reference undulator along the magnetic axis. Analyze the data and calculate the K value. The K value must agree with the calibrated value of the reference

undulator in order for the CMM to be commissioned for magnetic measurements.

5. Place a Delta-II strongback on the CMM and fiducialize the strongback. First set up the CMM coordinate system using the conventional probe so that the surfaces holding the magnet carriers are at ±45 degrees. These surfaces are illustrated in figure 1. Fit planes to the ±45 degree surfaces. In software, shift the fitted planes

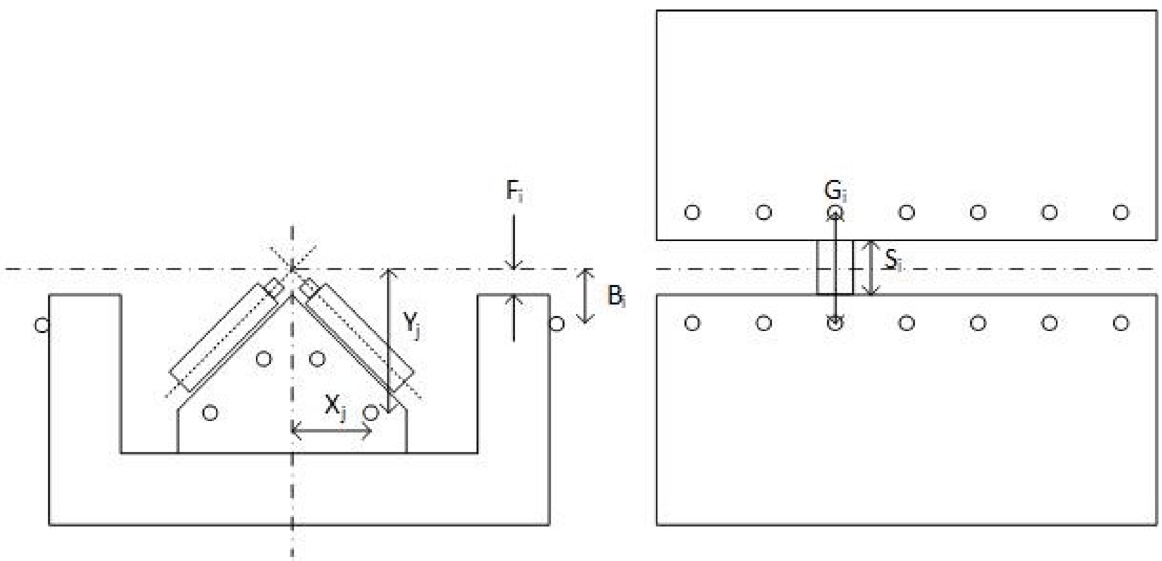


Figure 1: Delta-II strongback end view (left) and side view (right). The figure shows the ±45 degree surfaces where the magnet keepers are mounted. There are tooling balls on the ends which are used in the fiducialization. The tooling balls on the sides are to check the gap after shims are inserted and the halves are bolted together.

away from the strongback by the nominal height of the magnet centers relative to the ±45 degree surfaces. The magnets were adjusted to the nominal height in step 2 of the quadrant tuning above. The intersection of the two shifted fitted planes defines the geometric axis of the strongback. Establish a coordinate system where the geometric axis is along the z-direction, the y-direction bisects the ±45 degree surfaces, and the x-direction is perpendicular to the y and z axes. In this coordinate system, reference magnets must be set up which set the Hall probe angle at ±45 degrees. At each end of the strongback mount a constellation of tooling balls which can be used to locate the geometric axis at future times. Measure the positions of the tooling balls relative to the geometric axis at both ends of the strongback. On the sides of the strongback there are flats for shims and tooling balls on the outside of each flat. The flats will be used to vertically position the two halves of the Delta-II so that the geometric axis of each half coincides with the other. Measure the distance of each flat from the x-z plane. Measure the distance of each tooling ball from the x-z plane. The flats and tooling balls will be used at a later step during undulator assembly.

6. Place a magnet array for a quadrant on the strongback. The magnets are at 45

degrees relative to the coordinate system. Mount a fiducialization magnet at 45 degrees. An intermediate coordinate system at 45 degrees can be set up in the CMM software in order to simplify the CMM measurements, however, in the following steps only the main coordinate system relative to the CMM granite will be used.

7. Using the conventional probe of the CMM, locate the position of each magnet in the quadrant. Establish a geometric axis for the quadrant. The transverse position of the geometric axis is given by a fit to the transverse positions of the magnets. The radial position of the geometric axis is given by a fit to the tops of the magnets corrected by the nominal position of the undulator axis away from the magnet array. Shim the quadrant until the geometric axis of the quadrant coincides with the geometric axis of the strongback.

8. Place the Hall probe in the CMM. Align the Hall probe using the alignment magnet mounted at 45 degrees. Using the fiducialization magnet, establish the coordinates of the Hall probe in the CMM system. The procedure for finding the Hall probe location will essentially be the same as given above, but will need to be modified to account for the 45 degree mounting angle.

9. Transversely scan at 45 degrees all the magnets of the quadrant using the Hall probe. Verify that the transverse position of the magnetic axis of the quadrant is along the strongback geometric axis. Correct as necessary by shimming the magnet keepers.

10. Measure the peak fields on the strongback geometric axis. Verify that there is no taper in the peak fields. Correct as necessary by shimming the magnet keepers.

11. Perform a longitudinal scan of the quadrant on the strongback geometric axis. Perform fine tuning of the quadrant until the calculated beam trajectory is straight, the field integrals are within tolerance, and the phase errors are minimized. Repeat as necessary.

12. Perform scans of the quadrant at different radial positions with the Hall probe at 45 degrees. Find the peak fields. Verify that there is no taper in the peak fields at the different radial positions. This verifies that the drive system moves the quadrant radially without introducing pitch.

13. Move the quadrant radially until the average peak field has a specified value. This determines the encoder offset for the radial motion of the quadrant. Set the radial encoder offset so the encoder reads half the minimum gap.

14. Move the quadrant axially until it is located symmetrically on the strongback. This determined the encoder offset for the axial motion of the quadrant. Set the axial encoder offset so the encoder reads 0 mm. Perform a scan of the quadrant and measure the position of the peak fields. Find the axial position of the center of the peak fields in the CMM coordinate system. This position will be used later to axially align the two quadrants on the strongback.

15. In preparation for mounting the second quadrant on the strongback, move the first quadrant radially as far from the strongback geometric axis as possible. Measure the

magnetic fields on the strongback geometric axis. These values will be subtracted from the measurements of the second quadrant placed on the strongback. The first quadrant cannot be moved far enough away that its fields are insignificant. The residual field will add to the field from the second quadrant by superposition. The residual field from the first quadrant has no taper and produces straight trajectories without phase errors. Because of this, errors in the subtraction process should not significantly affect the tuning or taper of the second quadrant. There may be small effects, however, due to the permeability of the magnet blocks. These effects are mostly expected at the quadrant ends and should be known from the studies at the Kugler bench mentioned above. The effect of the field from the first quadrant is expected to be largest when setting the encoder offsets of the second quadrant. This is discussed in steps below and checks have been put in place to know if there is an error.

16. Mount a fiducialization magnet at -45 degrees. Prepare a mount for the Hall probe at -45 degrees in preparation for magnetic measurements of the second quadrant in the strongback. Set up an intermediate coordinate system at -45 degrees in the CMM software if this simplifies the measurements, however, the steps below will be given in the main coordinate system relative to the CMM granite.

17. Place the second quadrant on the strongback. Repeat the alignment steps as done for the first quadrant. Repeat all magnetic measurements done on the first quadrant, but this time subtracting the measurements from the first quadrant in the retracted position. Tune the second quadrant removing any taper in the peak fields.

18. Determine the radial encoder offset for the second quadrant. Perform scans at different radial positions and subtract the field from the first quadrant from each scan. The axial position of the second quadrant should be fairly well aligned to the first quadrant in the previous step. Find the radial position which gives the specified field on-axis and set the encoder offset so it reads half the minimum gap. This radial position will be checked in a later step.

19. Determine the axial encoder offset for the second quadrant. Perform a scan of the second quadrant at half the minimum gap radial position and subtract the field from the first quadrant. Find the peak fields and find the z-position of the center of the peak fields in the CMM coordinate system. Move the second quadrant so the z-position of the center of the peak fields is the same as the z-position of the center of the peak fields from the first quadrant measured previously. Set the axial encoder offset so the encoder reads zero.

20. Check the radial position of the second quadrant. Move both the first and second quadrants so that their radial positions are at half the minimum gap and their axial positions are 0 mm. Mount the Hall probe at zero degrees. Scan the field on the geometric axis. The peak vertical field should have no taper and the average value should be $\sqrt{2}$ times the specified value for the quadrants. The horizontal field should be zero. If this is not the case, study the measurements and make small adjustments to the encoder offsets until these conditions are met.

21. At this point, the undulator half is complete and can be removed from the CMM.

22. Repeat all the above steps for the second undulator half.

23. Install the beam pipe in the second undulator half. Place the beam pipe on the CMM, align it so that it is straight. Move the quadrants of the second strongback to their maximum radial position. Insert the beam pipe in the second strongback. Precisely align the beam pipe center to the strongback geometric axis. The beam pipe mount must be built so that it can be attached to the second strongback, and it must have provisions to determine the location of the beam pipe centerline and to move the centerline onto the strongback geometric axis.

24. Turn the first undulator half up-side-down in preparation to mount it on the second half. Add the measured distances from the flats to the x-z plane for each half. Build shims whose heights are equal to the added distances. Insert the shims between the halves and loosely bolt the halves together. Use the tooling balls at the ends to establish the geometric axis for each strongback. Move the top half in x and yaw until the geometric axes of the two halves coincide. Move the top half in z until the z=0 longitudinal positions of the quadrants are aligned. Tightly bolt the two halves together. Check that the distance between the tooling balls on the sides is equal to the sum of the distances from the x-z plane to each tooling ball. This verifies that the gap is correct along the length of the undulator. Check that the tooling balls on the sides of the lower strongback have kept their relation to the x-z plane of the lower strongback. This verifies that the undulator doesn't have a vertical bow after the weight of the upper strongback has been added. Check that the geometric axes coincide after tightening the bolts by using the tooling balls at the end of each half. The fiducialization of the undulator is now given by the tooling balls at the ends. The undulator is complete.

### 3.3 Undulator Calibration

1. Build a system with tight temperature control for the calibration measurements. The measurement system will be used to pull a Hall probe through the beam pipe of the undulator. The beam pipe is assumed to be precisely positioned so its center is on the undulator axis. The Hall probe is guided by the beam pipe and it will move longitudinally parallel to the beam pipe center. The Hall probe will be moved transversely onto the undulator magnetic axis in a step below. The longitudinal position of the Hall probe is given by an interferometer triggered when a magnetic measurement sample is taken. The triggers are generated by a linear scale on the bench pulling the Hall probe.

2. The measurement system must have alignment magnets to take pitch, roll, and yaw out of the Hall probe. The system must also have reference magnets to check the Hall probe $B_x$ and $B_y$ calibrations. A zero Gauss chamber is required to take out probe offsets. A fiducialization magnet is required to measure changes in the Hall probe transverse position which happen in the next step.

3. Perform longitudinal scans at different x and y positions by shimming the Hall probe. Shimming the Hall probe in y has already been tested. More development work is needed to shim the Hall probe in x. Find the shim values that position the Hall probe on the magnetic axis of the undulator. The magnetic axis can be found by placing the undulator in planar vertical and horizontal modes and mapping the hyperbolic cosine dependence of the fields. Use the shims which position the Hall probe on the magnetic axis for all on-axis measurements. Put in known differences in the shims for off-axis measurements.

4. Automate the measurements. We expect several hundred measurements are necessary to characterize the undulator at all settings. The system must be protected so that it stops if any abnormality occurs.

5. Calibrate the Hall probe when necessary by removing it and placing it in the MMF's Hall probe calibration magnet.

6. A separate test plan will be written detailing the calibration measurements to be performed.

7. Provision has been made to slide the beam pipe out the end of the undulator and replace it in case the Hall probe measurements scratch the inner surface of the beam pipe beyond tolerance. The straightness of the beam pipe used for magnetic measurements has a tighter tolerance than the straightness required for operation. If the beam pipe is to be replaced, the beam pipe replacement procedure must be tested in advance to verify that the new beam pipe meets the straightness required for operation.

## 4 Conclusion

The Delta-II has no provision for tuning after it is assembled, so the steps leading up to the completed undulator require precise magnetic measurements for tuning and high precision assembly so that all tolerances on the undulator are met. After assembly, many magnetic measurements are required to fully characterize the Delta-II in its various modes and K values. These measurements must be accurate so that the Delta-II is resonant with the existing SXR undulators and future Delta-II undulators. This note presented a plan for the magnetic measurements used for tuning and during assembly, the precision assembly, and the final calibration.