DELTA-II Test Plan

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Abstract

An elliptically polarizing undulator is being built at SLAC for use in the LCLS-II SXR line. 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 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. 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. This note presents a plan for doing the magnetic measurements of the DELTA-II undulator in order to verify that all tolerances are met, and to calibrate it so that it can be made resonant with the other undulators.

A companion note to this test plan was written to describe the mechanics of the DELTA-II undulator, the expected fields in the undulator, and the magnetic measurement system setup.[2] The companion note should be consulted for setting the polarization modes and K value of the undulator.

The control system must provide PVs to set and read all required parameters of the undulator. A list of required undulator PVs for this test is given in the appendix.

2 Undulator Requirements

The DELTA-II undulator requirements are given in a Physics Requirements Document.[3] A list of the relevant requirements is given in the table below.

The DELTA-II undulator has no provision for adjustments after the undulator is assembled. Much care is going into the undulator tuning and assembly in order to meet these requirements. If the requirements are not met when the undulator is measured, the undulator must be disassembled and adjusted in order to meet the requirements.

[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, "Prerequisites For DELTA-II Magnetic Measurements", LCLS-TN-26-2, April, 2026.
[3] H.-D. Nuhn, "Delta-II Undulator Physics Requirements", unpublished.

Requirement	**Value**	**Units**
Minimum K	1.7212	
Maximum K	7.3547	
Tolerance $\Delta K/K$	3×10^{-4}	
First Field Integrals	< 40	μTm
Second Field Integrals	< 150	μTm^2
Phase Errors	< 4	deg
Cell Phase Error	< 4	deg
Alignment Accuracy	< 100	μm

Table 1: LCLS-HE undulator requirements.

3 Magnetic Measurement Test Plan

3.1 Initial Checkout

The control system will have EPICS PVs for all drive systems of the undulator. Before magnetic measurements, check using the PVs that all motions of the undulator are applied to the correct quadrant and the correct moving part. Check that component moves and encoder readings have the correct values. Check that limit switches are operational and will protect the undulator in case of any software errors requesting excessive moves.

Apply RTDs to the undulator for temperature measurements. Include undulator temperature in all measurement results.

Set up the stretched wire system before the undulator is installed. By moving the wire and using the magnetic field from reference magnets, confirm that the signal strength, polarity, and noise levels of the system are as expected. Use calibration magnets to verify the accuracy of the system for both first and second field integrals.

Move the Hall probe through the undulator beam pipe by hand. Check for any obstructions or sticking points.

Check the alignment of the optical system to verify its measurements through the entire length of the Hall probe scans.

Make several Hall probe scans and verify the measurement repeatability.

3.2 Cam Mover Tests

The cam mover system is different than the other cam mover systems in the undulator hall. New software must be written for the Delta-II cam movers. With an alignment crew, move the undulator in x, y, roll, pitch, and yaw, and verify that the actual motion is the same as the desired motion. Find and fix any software or hardware problems.

3.3 Field Integral Measurements

Set up the stretched wire system. Have an alignment crew move the wire onto the undulator axis to determine the transverse zero position. Fiducials on the undulator located during assembly on the CMM will allow the alignment crew to place the wire onto the undulator axis to better than 100 μm, which is sufficient.

In a sequence, perform the following steps looping over all modes and gap values:

1. Set the undulator to one of the baseline polarization modes LPVMF, LPHMF, CPRMF, CPLMF, EPRM1, EPRM2, EPLM1, or EPLM2.
2. Set the undulator gap to each value from the minimum gap of 6.60 mm to the maximum gap of 23.31 mm in steps of 0.5 mm.
3. Measure the first and second field integrals of B_x and B_y on the undulator axis using the moving wire.

After the on-axis measurements, perform in each polarization mode stretched wire measurements off the axis to measure the net integrated quadrupole and skew quadrupole of the undulator. Do the measurements at gaps of 6.60, 10.0, 15.0, 20.0 mm. Measure the first integral of B_x and B_y at $x = -1.2, -0.8, -0.4, 0.0, 0.4, 0.8, 1.2$ mm and $y = 0$ mm. Measure the first integral of B_x and B_y at $x = 0$ mm and $y = -1.2, -0.8, -0.4, 0.0, 0.4, 0.8, 1.2$ mm. Fit lines to the measurements and determine the integrated quadrupole and skew quadrupole strengths from the slopes of the lines.

3.4 Hall Probe Calibration

Before Hall probe measurements can begin, the Hall probe must have its B_x and B_y measurement elements calibrated in a calibration magnet using an NMR. The factory calibration of the B_z measurement element will be sufficient. A reference magnet must be available in the test setup to check the calibrations periodically during the measurements.

3.5 Hall Probe Measurements

1. Set up the Hall probe measurement system. Make sure the length of the scan range includes the fringe fields of the DELTA-II down to 0.4 Gauss. Make sure the zero Gauss chambers have zero field inside them.
2. Check the probe position relative to a straight line through the undulator using the optical measurement system.
3. Align the Hall probe roll in a vertical field standard such that the B_x sensor reads zero.
4. In the Hall probe analysis add offsets to the measurements to correct for the planar Hall effect so that the Hall probe field integrals agree with the stretched wire field integrals.
5. Put the undulator in linear polarization horizontal field mode. By changing the positioners on the Hall probe holder, measure at different x-positions. Make measurements at $x = -0.2, -0.1, 0.0, 0.1,$ and 0.2 mm. Determine the K value for each measurement. Find the x-position for minimum K, where the $\cosh\left(\frac{k_r}{\sqrt{2}}x\right)$ x-dependence is minimum. By changing the positioners on the Hall probe holder, measure at different y-positions. Make measurements at $y = -0.2, -0.1, 0.0, 0.1,$

and 0.2 mm. Determine the K value for each measurement. Find the y-position for minimum K, where the cosh $\left(\frac{k_r}{\sqrt{2}}y\right)$ y-dependence is minimum. The x and y positions for minimum K define the beam axis. As a check, repeat the procedure using linear polarization vertical field mode. Once the magnetic axis position is determined, have positioners for the Hall probe holder made which put the Hall probe on the magnetic axis.

6. Check for mechanical hysteresis in the undulator. Make measurements at given gaps after setting the gap from both larger and smaller gaps. Make measurements in different polarization modes after setting the mode along paths were the magnetic forces are different. Determine whether any prescriptions for setting the gap or polarization mode are necessary.

7. Perform an initial set of automated measurements in the polarization modes LPVMF, LPHMF, CPRMF, CPLMF, EPRM1, EPRM2, EPLM1, and EPLM2. These measurements should be done at each of the following gap values.

$$\text{gap} = \left[\begin{array}{c} 6.6, 6.7, 6.8, 7.0, 7.2, 7.4, 7.6, 7.8, 8.0, 8.25, 8.5, 8.75, \\ 9.0, 9.5, 10.0, 10.5, 11.0, 11.5, 12.0, 13.0, 14.0, 15.0, \\ 16.0, 17.0, 18.0, 19.0, 20.0, 21.0, 22.0, 23.0 \end{array} \right] \text{mm}$$

   Fit every other measurement and find the residuals to the fit of K vs gap. If the residuals of any of the points are above $\Delta K/K > 2 \times 10^{-4}$, update the list of gap values in order to reduce the residuals. Determine a final set of gap values for the measurements.

8. Using the final set of gap values, perform measurements and fit the K values in each mode. Verify that the residuals are below 2×10^{-4}.

9. Using fiducialization magnets and the map of the transverse probe position from the optical system, fiducialize the undulator.

3.6 Transportation Test

After the magnetic measurements, place the undulator on a truck and drive it to the undulator hall. Unload the undulator, then load it back on the truck and bring it back to the MMF. Repeat the magnetic measurements as necessary to determine if any changes to the undulator occurred. Determine if any changes to the undulator handling procedure are required.

4 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 shown in figure 1. The top level directory is *Magdata,* followed by *LCLS-II-HE*, followed by the magnet type *Undulator*. In the *Undulator* directory, there is a folder for each undulator named by the serial number, in this case DELTA-II. 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 *Mechanical Measurements, Tuning,* and *Final Results* folders are created.

After the undulator tuning is complete, a special set of final measurement runs is made. The measurement data and analysis results from these runs will go into the *Final Results* folder. The contents of the *Final Results* folder are shown in figure 2.

Within *Final Results*, there is a folder for the undulator *Fiducialization*, and there are folders containing the measurements and analysis results for each polarization mode. For each polarization mode, a set of stretched wire and Hall probe measurements will be made. The *Stretched Wire* data will go into folders containing both *On-Axis* and *Good Field Region* measurements. Files in the *On-Axis* and *Good Field Region* folders will contain measurement data with file names giving the measurement number, the undulator gap, and the (x, y) location of the wire measurement. Within each file, a header will give parameters of the wire motion and then tables will give the type of measurement, the integrated voltage, and the field integrals. Multiple measurements will be done and the average and rms deviation will be recorded.

The *Z Scans* folder under each polarization mode contains Hall probe magnetic measurement data. Both *On-Axis* and *Good Field Region* measurements will be made. Each *On-Axis* and *Good Field Region* folder will contain subfolders, one subfolder for each measurement. The subfolder names will give the measurement number, the undulator gap, and the (x, y) location of the measurement. In the fixed width format of the subfolder name in the figure, "s" represents a sign, "." represents a decimal point, and "n" is a decimal digit. The initial "nnn" is used to give the measurement number. The gap and probe positions are in millimeters. Within each subfolder will be a file named *zscan.dat* containing the measurement data. The *zscan.dat* file will consist of columns of the z positions, the V_x and V_y Hall probe voltages, and B_x and B_y values. Parameters, such as the Hall probe calibration file name and location, will be included in a header. The *zscan.dat* file will be analyzed and the analysis results will also go into the subfolder. The analysis results from all the subfolders will be further analyzed and the consolidated results will go into the *On-Axis* and *Good Field Region* folders.

The *Controls Data* folder for each polarization mode contains files needed to operate the undulator in that mode. Each file has the serial number and mode information both in the contents of the file and in the file name. The Controls group will put the contents of these files into their database. The files contain the undulator parameters used during testing plus a set of data for spline fits relating K, the phase matching corrections, and the field integrals, all to the undulator gap in the given mode.

The *Fiducialization* data comes from several sources: scale readings from the measurement bench, offsets between the center of the fiducialization magnets and tooling balls, laser tracker data, and alignment crew data. All files will be text files containing a header and the measured values. A program will read the data and write a fiducialization report containing the final results.

5 Conclusion

SLAC is building an elliptically polarizing undulator, DELTA-II. Extensive magnetic measurements on the completed undulator are necessary to characterize the undulator. This note gave the test plan for the final measurements.

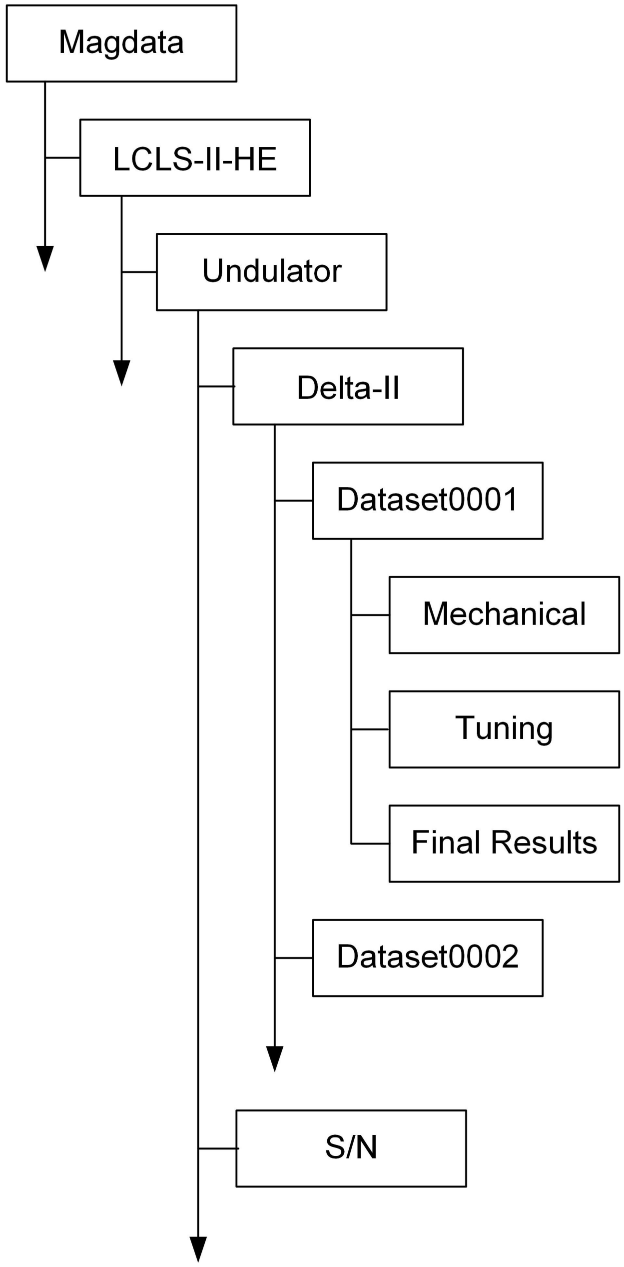

Figure 1: The undulator measurement data will be stored in a directory structure.

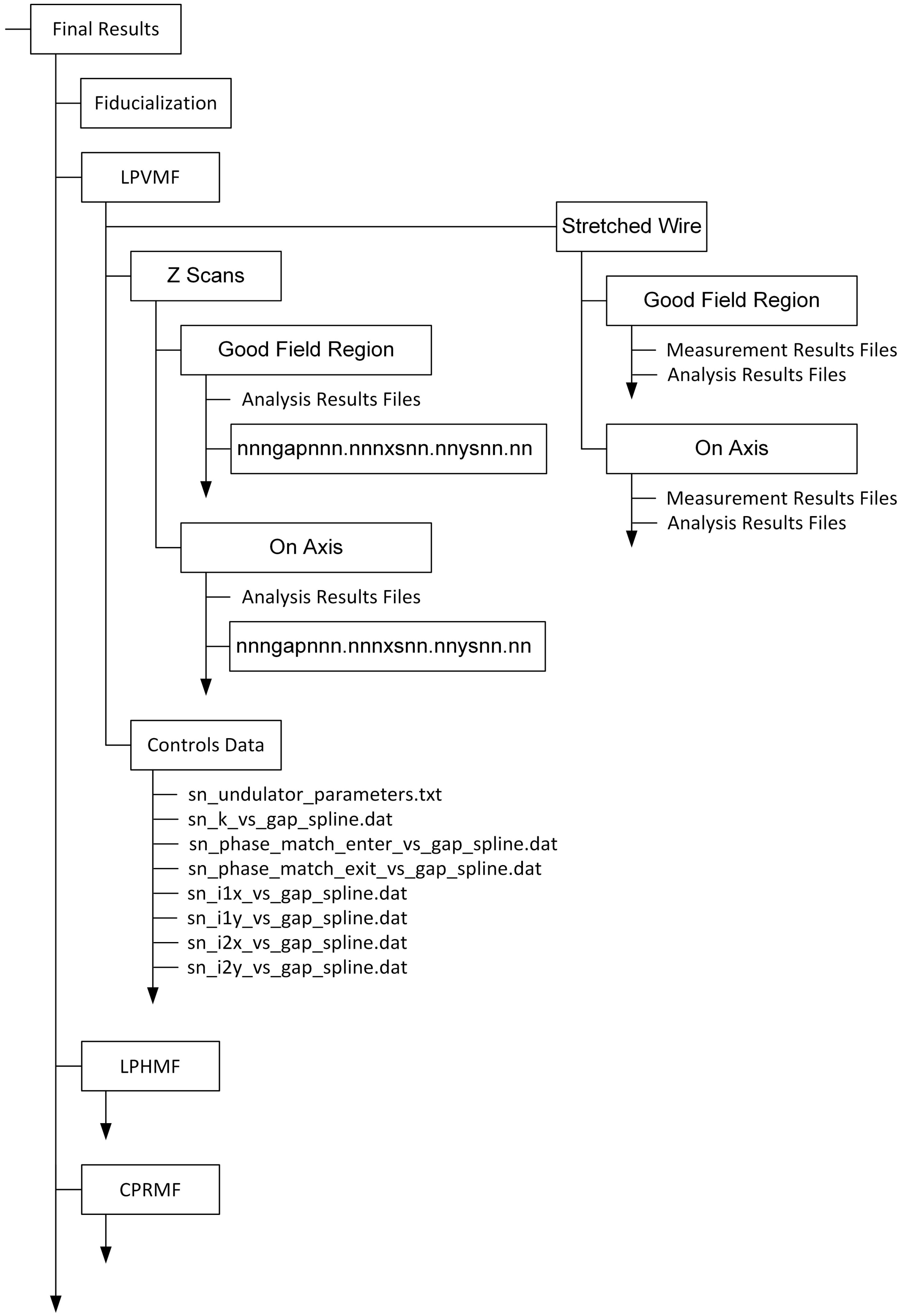

Figure 2: Contents of the Final Results folder.

Appendix

MMF PVs		
Prefix USEG:MMF:DELTA-II:		
Sample PV Name	Description	Read/Write
AbsEncMainCarrierQ1Ref	Main carrier absolute encoder value when in the reference position of quadrant 1	R/W
AbsEncMainCarrierQ2Ref	Main carrier absolute encoder value when in the reference position of quadrant 2	R/W
AbsEncMainCarrierQ3Ref	Main carrier absolute encoder value when in the reference position of quadrant 3	R/W
AbsEncMainCarrierQ4Ref	Main carrier absolute encoder value when in the reference position of quadrant 4	R/W
IncEncMainCarrierQ1Ref	Main carrier incremental encoder value relative to index when in the reference position of quadrant 1	R/W
IncEncMainCarrierQ2Ref	Main carrier incremental encoder value relative to index when in the reference position of quadrant 2	R/W
IncEncMainCarrierQ3Ref	Main carrier incremental encoder value relative to index when in the reference position of quadrant 3	R/W
IncEncMainCarrierQ4Ref	Main carrier incremental encoder value relative to index when in the reference position of quadrant 4	R/W
AbsEncMagnetCarrierQ1Ref	Magnet carrier absolute encoder value when in the reference position of quadrant 1	R/W
AbsEncMagnetCarrierQ2Ref	Magnet carrier absolute encoder value when in the reference position of quadrant 2	R/W
AbsEncMagnetCarrierQ3Ref	Magnet carrier absolute encoder value when in the reference position of quadrant 3	R/W
AbsEncMagnetCarrierQ4Ref	Magnet carrier absolute encoder value when in the reference position of quadrant 4	R/W
IncEncMagnetCarrierQ1Ref	Magnet carrier incremental encoder value relative to index when in the reference position of quadrant 1	R/W
IncEncMagnetCarrierQ2Ref	Magnet carrier incremental encoder value relative to index when in the reference position of quadrant 2	R/W
IncEncMagnetCarrierQ3Ref	Magnet carrier incremental encoder value relative to index when in the reference position of quadrant 3	R/W

IncEncMagnetCarrierQ4Ref	Magnet carrier incremental encoder value relative to index when in the reference position of quadrant 4	R/W
PosMainCarrierQ1Des	Desired position of main carrier of quadrant 1 along its rails	R/W
PosMainCarrierQ2Des	Desired position of main carrier of quadrant 2 along its rails	R/W
PosMainCarrierQ3Des	Desired position of main carrier of quadrant 3 along its rails	R/W
PosMainCarrierQ4Des	Desired position of main carrier of quadrant 4 along its rails	R/W
PosMagnetCarrierQ1Des	Desired position of magnet carrier of quadrant 1 along its rails	R/W
PosMagnetCarrierQ2Des	Desired position of magnet carrier of quadrant 2 along its rails	R/W
PosMagnetCarrierQ3Des	Desired position of magnet carrier of quadrant 3 along its rails	R/W
PosMagnetCarrierQ4Des	Desired position of magnet carrier of quadrant 4 along its rails	R/W
GoCarrier	Moves the 8 motors of the main and magnet carriers to the desired positions along the rails	W
AbsEncMainCarrierQ1Rbck	Absolute encoder reading from the main carrier of quadrant 1	R
AbsEncMainCarrierQ2Rbck	Absolute encoder reading from the main carrier of quadrant 2	R
AbsEncMainCarrierQ3Rbck	Absolute encoder reading from the main carrier of quadrant 3	R
AbsEncMainCarrierQ4Rbck	Absolute encoder reading from the main carrier of quadrant 4	R
IncEncMainCarrierQ1Rbck	Incremental encoder reading from the main carrier of quadrant 1	R
IncEncMainCarrierQ2Rbck	Incremental encoder reading from the main carrier of quadrant 2	R
IncEncMainCarrierQ3Rbck	Incremental encoder reading from the main carrier of quadrant 3	R
IncEncMainCarrierQ4Rbck	Incremental encoder reading from the main carrier of quadrant 4	R
AbsEncMagnetCarrierQ1Rbck	Absolute encoder reading from the magnet carrier of quadrant 1	R
AbsEncMagnetCarrierQ2Rbck	Absolute encoder reading from the magnet carrier of quadrant 2	R
AbsEncMagnetCarrierQ3Rbck	Absolute encoder reading from the magnet carrier of quadrant 3	R

AbsEncMagnetCarrierQ4Rbck	Absolute encoder reading from the magnet carrier of quadrant 4	R
IncEncMagnetCarrierQ1Rbck	Incremental encoder reading from the magnet carrier of quadrant 1	R
IncEncMagnetCarrierQ2Rbck	Incremental encoder reading from the magnet carrier of quadrant 2	R
IncEncMagnetCarrierQ3Rbck	Incremental encoder reading from the magnet carrier of quadrant 3	R
IncEncMagnetCarrierQ4Rbck	Incremental encoder reading from the magnet carrier of quadrant 4	R
TempUSQ1	Upstream temperature measurement of quadrant 1 magnet array	R
TempDSQ1	Downstream temperature measurement of quadrant 1 magnet array	R
TempUSQ3	Upstream temperature measurement of quadrant 3 magnet array	R
TempDSQ3	Downstream temperature measurement of quadrant 3 magnet array	R
MeanTemp	Average the 4 temperature measurements to get the mean magnet array temperature	R
TempUSBP	Upstream temperature measurement of the beam pipe	R
TempDSBP	Downstream temperature measurement of the beam pipe	R
PolModeDes	Desired polarization mode, takes argument LPVMF, EPRM1, EPLM1, CPRMF, CPLMF, EPRM2, EPLM2, or LPHMF	R/W
PolModeAct	Actual polarization mode, read the 4 magnet carrier absolute encoders and determine the current polarization mode ignoring global moves for centering, return an error if the magnet arrays don't form a polarization mode within tolerance	R
PolModeTol	Tolerance for the magnet carrier positions for being in a polarization mode	R/W
GoPolMode	Move the magnet carriers relative to their reference position in order to set the desired polarization mode. At the extremes of the main carrier motion, globally move all four magnet carriers so they are within their range.	W
GapDes	Desired gap, the main carriers are the same distance from the reference position within tolerance,	R/W

GapAct	Actual gap, read the 4 main carrier absolute encoders to determine the radial position of each quadrant and then to determine the gap, return an error if the main carriers are not at the same position within tolerance relative to the reference	R
GapTol	Tolerance for the main carriers to be the same distance from the reference position	R/W
GoGap	Move the main carriers to set the undulator gap to the desired value.	W
Center	Move the 4 magnet carriers to center them in the undulator, this compensates for the main carrier longitudinal motion	W
SetModeGapCenter	This PV is given PolModeDes and GapDes. It then uses the Go PVs to set the polarization mode and the gap. It also uses the Center PV to center the magnet carriers.	W
Status	Value 0 if the magnet arrays are set to a value in Table 1, the magnet arrays are centered in the undulator, and the main carriers are all the same distance from the reference, return a positive integer giving an error code indicating which positions are out of tolerance	R
Kdes	Desired K value, calculate and return the desired gap including temperature corrections	R/W
Kact	Actual K value, calculate K from the gap including temperature corrections	R
MainCarrierRailAngle	Angle of main carrier rails relative to the undulator axis	R
ZPosMainCarrierQ1Des	Desired z-position of main carrier of quadrant 1	R/W
ZPosMainCarrierQ2Des	Desired z-position of main carrier of quadrant 2	R/W
ZPosMainCarrierQ3Des	Desired z-position of main carrier of quadrant 3	R/W
ZPosMainCarrierQ4Des	Desired z-position of main carrier of quadrant 4	R/W
GoZPos	Move the motors of the main carriers to move each axis to the desired z-position	W
ZRelPosMagnetCarrierQ1Des	Desired position of magnet carrier of quadrant 1 relative to the main carrier	R/W
ZRelPosMagnetCarrierQ2Des	Desired position of magnet carrier of quadrant 2 relative to the main carrier	R/W
ZRelPosMagnetCarrierQ3Des	Desired position of magnet carrier of quadrant 3 relative to the main carrier	R/W
ZRelPosMagnetCarrierQ4Des	Desired position of magnet carrier of quadrant 4 relative to the main carrier	R/W

GoZRelPos	Move the motors of the magnet carriers to move each axis to the desired z-position relative to the main carriers	W
RPosMainCarrierQ1Des	Desired radial position of main carrier of quadrant 1	R/W
RPosMainCarrierQ2Des	Desired radial position of main carrier of quadrant 2	R/W
RPosMainCarrierQ3Des	Desired radial position of main carrier of quadrant 3	R/W
RPosMainCarrierQ4Des	Desired radial position of main carrier of quadrant 4	R/W
GoRPos	Move the motors to move each axis to the desired radial position	W
ZPosMainCarrierQ1Act	Get the main carrier z-position of quadrant 1	R
ZPosMainCarrierQ2Act	Get the main carrier z-position of quadrant 2	R
ZPosMainCarrierQ3Act	Get the main carrier z-position of quadrant 3	R
ZPosMainCarrierQ4Act	Get the main carrier z-position of quadrant 4	R
RPosMainCarrierQ1Act	Get the main carrier radial position of quadrant 1	R
RPosMainCarrierQ2Act	Get the main carrier radial position of quadrant 2	R
RPosMainCarrierQ3Act	Get the main carrier radial position of quadrant 3	R
RPosMainCarrierQ4Act	Get the main carrier radial position of quadrant 4	R
ZPosMagnetCarrierQ1Act	Get the magnet carrier z-position of quadrant 1 including both main carrier and magnet carrier motion	R
ZPosMagnetCarrierQ2Act	Get the magnet carrier z-position of quadrant 2 including both main carrier and magnet carrier motion	R
ZPosMagnetCarrierQ3Act	Get the magnet carrier z-position of quadrant 3 including both main carrier and magnet carrier motion	R
ZPosMagnetCarrierQ4Act	Get the magnet carrier z-position of quadrant 4 including both main carrier and magnet carrier motion	R