

# HE-SXR Undulator Pre-Tuning Test Plan

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June 3, 2026

## Abstract

A magnetic measurement test stand was developed aiming to reduce the workload and time required for final tuning of the High-Energy Soft X-Rays (HE-SXR) undulators at the Magnetic Measurement Facility (MMF). This document outlines the measurement procedure, mechanical, and magnetic alignment steps that will be taken prior to performing the final tuning and measurements.

## 1. Introduction<sup>1</sup>

The LCLS-II high-energy upgrade (HE) includes new undulators for the soft X-ray (SXR) line, hereafter referred to as the HE-SXR undulator or simply HE-SXU. This upgrade requires tight control of the undulator field quality and therefore imposes strong demands on magnetic measurements and undulator tuning.

SLAC's Magnetic Measurements Group operates two precision Kugler benches in the Magnetic Measurement Facility (MMF), which are used for tuning and testing undulators in a temperature-controlled laboratory. The laboratory is maintained at approximately 20 °C, adjustable between 17 °C and 23 °C with 0.1 °C stability. One bench is dedicated to hard X-ray (HXR) undulators, while the other is used for SXR undulators. The undulators are oriented in the same direction as in the tunnel to minimize differences in the Earth's magnetic field. The benches are mounted on vibration-isolated foundations to preserve alignment. Hall probe calibrations are performed on-site, and nearby storage allows at least two undulators to thermally stabilize to room temperature prior to testing. Additional storage is available near the MMF. Undulators are stored and transported on-site under stable environmental conditions to prevent damage. The MMF also includes a coordinate measuring machine (CMM) for inspection and alignment of magnet arrays<sup>2</sup>.

Tuning a single HE-SXR undulator on a Kugler bench typically requires three to four weeks, with approximately one week spent on initial checks. A measurement setup,

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

<sup>2</sup>Z. Wolf, Y. Levashov, H.-D. Nuhn, "HE-SXR Undulator Test Plan", LCLS-TN-22-9, October 2022.

hereafter referred to as the *Dover bench*, was developed to pre-tune HE-SXR undulators, with the goal of reducing the time required for final tuning on the Kugler SXR bench (one of the two MMF benches used for tuning SXR undulators).

This note describes the Dover bench and outlines the HE-SXR undulator pre-tuning test plan, including procedures, requirements, hardware distribution, and the organization of measurement data.

## 2. Undulator Requirements

The HE-SXR undulator requirements are given in a Physics Requirements Document<sup>3</sup>. Table I shows the specifications that are relevant to the Dover bench pre-tuning phase. For coordinate system definition, refer to Fig. 1.

Table I: Undulator tolerances.

Parameter	Value
RMS phase error	5°
First field integral ( $x, y$ )	$\pm 50 \mu\text{Tm}$
Second field integral ( $x, y$ )	$\pm 200 \mu\text{Tm}^2$
Relative std of absolute peaks ( $y$ )	0.25 %

The integrated normal and skew quadrupole components are kept below 10 mT, being both tuned at the Dover and Kugler SXR bench.

## 3. Dover bench description

The Dover bench (Fig. 1) consists of a 5.35 m-long granite block equipped with a carriage that supports a Hall probe and a touch probe mounted on a horizontal rod. The total carriage travel range is 4.2 m, while the SXR undulator length is 3.4 m. The Dover bench is designed to follow principles similar to those of the Kugler SXR bench, including stretched wire, Hall probe, and touch probe measurements. Figure 2 shows the layout of the Dover bench hardware.

Linear stages are used for single stretched wire measurements. On the upstream (US) side, one of the XY stage towers supports the wire stretching mechanism, along with a kinematic base to set an alignment dipole to keep the Hall probe alignment when probes are exchanged. After the Hall probe is aligned, the magnet is removed to make space for the Zero Gauss Chamber. On the downstream (DS) side, the setup includes another XY

<sup>3</sup>D. Cesar et al., "LCLS-II-HE SXR Undulator System Physics Requirements", LCLSII-HE-1.3-PR-0049-R2, May, 2022.

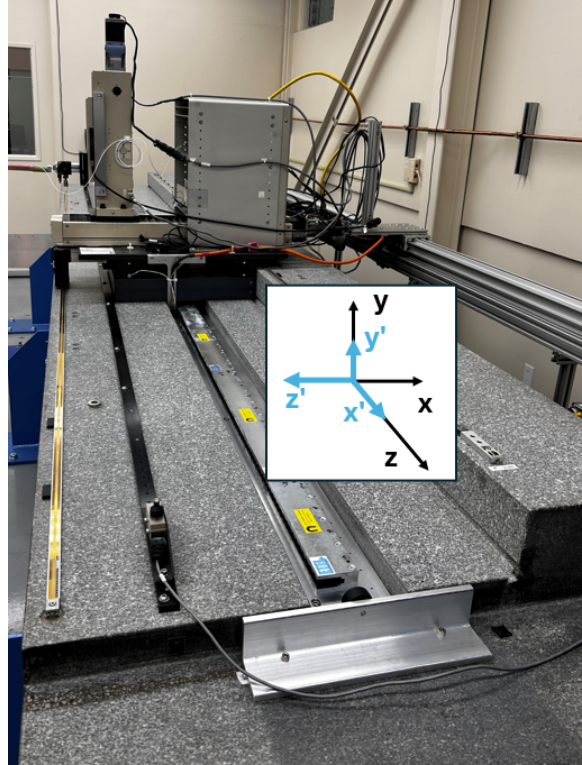


Fig. 1: Dover bench with coordinate systems. The inset shows the Dover coordinate system (black) and the Kugler SXR coordinate system (blue, primed).

stage tower, a fiducialization magnet used to transfer the Hall probe coordinate system to the stretched wire coordinate system<sup>4</sup>, and a reference touch probe piece.

The Dover bench system was designed to allow the wire to be positioned for measurements and parked to enable Hall and touch probe measurements. This avoids the need to remove and re-install the wire when a new undulator is set up at the Dover bench system. The wire can be aligned with the axis of the previous undulator to reduce the risk of damage during undulator movement and installation (see Step A.4 of Section 4).

Kugler benches are aligned parallel to the tunnel to minimize variations in the Earth's magnetic field between the measurement laboratory and the tunnel. Given the relative orientation of the Dover bench (90° rotation with respect to the Kugler bench), a gap-dependent correction is required. This correction was derived from a comparison of stretched wire measurements performed on the Kugler SXR and Dover benches for HE-SXU-003. To define the corrections, the difference between on-axis field integral measurements obtained from the Kugler SXR and Dover benches must be computed for

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<sup>4</sup>Y. Levashov, Z. Wolf, "Tests of coordinate transfer from magnetic to mechanical reference for LCLS undulator Fiducialization", LCLS-TN-05-10, April 2005.

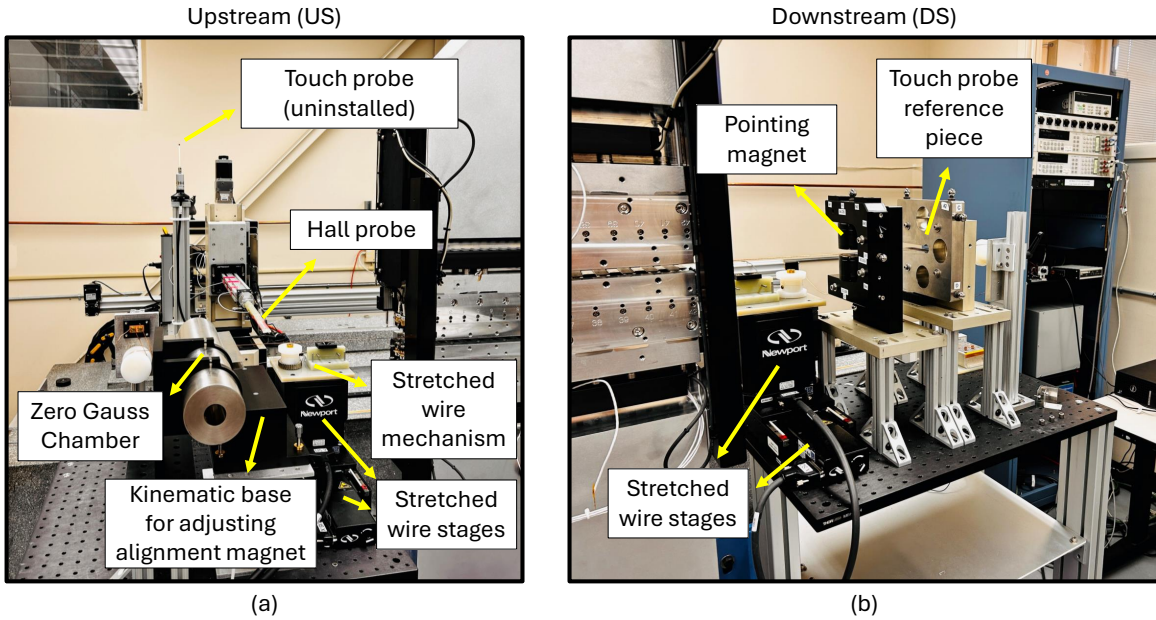


Fig. 2: Dover bench room hardware layout at the undulator upstream (a) and downstream (b) ends.

all relevant conditions in terms of  $x$  and  $y$  positions and gap values (see Steps 2, 3, and 4 of Section 4-E). This difference is then added to the Dover bench stretched wire measurements to ensure consistency with the Kugler SXR bench results. Figure 3 shows the field integrals measured with the stretched wire on the Dover and Kugler benches for the untuned HE-SXU-003.

The first field integral of the vertical component ( $I_{1y}$ ) is consistent between the two

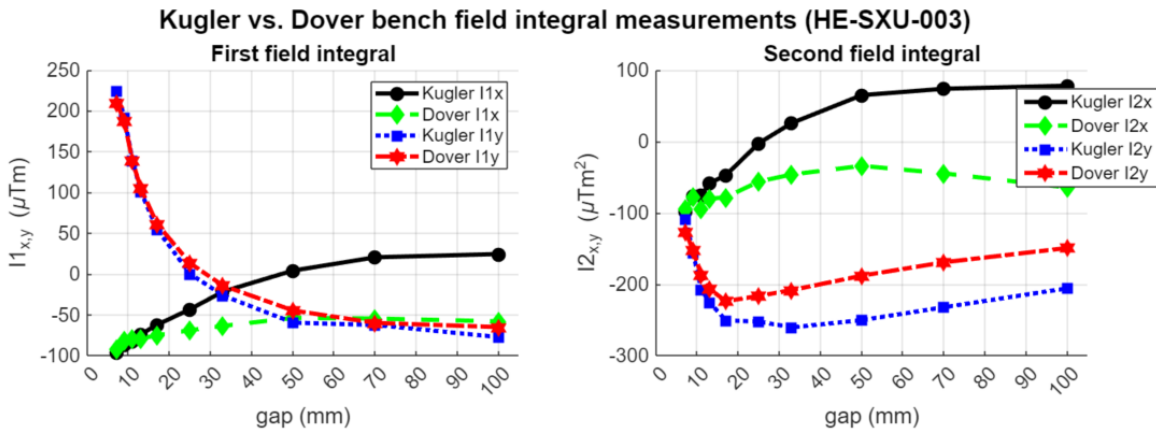


Fig. 3: Field integral measurements from the Kugler and Dover benches for HE-SXU-003.

benches, since it does not depend on their relative orientation. For small gaps, the undulator jaws provide magnetic shielding, and both benches produce similar results in this range. Differences begin to appear around a gap of 15 mm, where background fields start to affect the measurements.

Given the agreement in  $I_{1y}$ , the second field integral is expected to follow the same trend. However, Fig. 3 indicates an offset between the benches. The source of this difference is still being studied. One possible explanation is a small offset of the wire position from the magnetic center.

## **4. Procedure at the Dover Bench setup**

### **A. Preliminaries**

Before an undulator gets installed at the Dover bench setup:

- 1) The undulator magnets must be protected with plastic covers.
- 2) The undulator gap must be set to 150 mm.
- 3) The vacuum chamber linear potentiometers must be secured with brackets.
- 4) The stretched wire must be aligned with the undulator axis. Given the large gap during transportation and installation, previous undulator data can be used to position the wire.
- 5) The granite bench must be covered with plastic during undulator swaps to prevent dust deposition on its surfaces.

### **B. Set the undulator**

After transporting the undulator to the Dover bench area:

- 1) Bolt the undulator to the floor.
- 2) Add undulator identification labels and module number labels.
- 3) Have the controls team make all necessary wiring connections to operate the undulator.
- 4) Have the controls team set and/or verify all limit switches, encoder offsets, and hard stops.
- 5) Cycle the undulator about 400 times by sequentially varying the gap. One cycle is defined as the following sequence (in mm): 7.2, 8, 10, 12, 15, 20, 25, 33, 25, 20, 15, 10, 8, and 7.2<sup>5</sup>.

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<sup>5</sup>The criteria for defining these gaps are not strict. The selected values ensure that all three compensation springs are compressed during the cycle and that operation spans the full undulator range, i.e., between 7.2 mm and 33 mm.

### C. Align the undulator to the bench mechanically

- 1) Set the undulator gap to the tuning gap value (10 mm). The encoder offsets pre-set by controls team (Step B.4) can be used at this stage, as later touch probe measurements will be used to refine the offsets to set the gap more accurately ( $\pm 25 \mu\text{m}$ ).
- 2) Have the alignment team align the undulator to the bench. Wait one day before loosening and re-tightening the undulator flexure bolts (a procedure called “relaxation”).
- 3) Remove the plastic covering from the granite bench and clean its surfaces with isopropyl alcohol.
- 4) Set the gap to the tuning gap and measure the gap straightness with the touch probe every 10 poles.
- 5) Adjust encoder offsets to make the jaws parallel and level within a pitch of  $\pm 20 \mu\text{rad}$ . Adjust the average gap to  $(10.025 \pm 0.025) \text{ mm}$ , and correct individual poles to maintain their positions within  $\pm 20 \mu\text{m}$ . Repeat Steps C.4 and C.5 if necessary.
- 6) Check the compensation spring stack gaps.
- 7) Repeat the gap straightness measurement every 10 poles.
- 8) Refine encoder offsets to achieve jaw parallelism and levelness within  $\pm 10 \mu\text{rad}$ , and maintain individual pole positions within  $\pm 20 \mu\text{m}$ . Repeat Steps C.7 and C.8 if necessary.
- 9) Measure the gap straightness at every pole.
- 10) Perform final encoder offset corrections to meet the same tolerances:  $\pm 10 \mu\text{rad}$  for pitch and  $\pm 20 \mu\text{m}$  for pole positions.

### D. Align the Hall probe and undulator magnetically

- 1) Set the undulator gap to the tuning gap.
- 2) Align the Hall probe pitch and roll using its manual goniometers. This is done by aligning an alignment dipole magnet with the bench and adjusting the goniometers such that the horizontal field component remains unchanged when flipping the magnet, while the vertical component is maximized.
- 3) Perform a Hall probe scan along the undulator to locate the third pole position.
- 4) At every third pole, scan the Hall probe in  $x$  and  $y$  to determine the magnetic center.
- 5) Determine the magnetic center at each pole from the scans, and fit the resulting positions as a function of  $z$  with a straight line. The fitted line defines the magnetic axis.
- 6) Adjust the undulator position to align its magnetic axis using only mechanical adjustments at the support feet and encoder settings. Repeat Step D.4 and Step D.5 if necessary. The pitch and yaw must be less than  $10 \mu\text{rad}$ . If the horizontal field component exceeds  $2 \text{ mT}$ , either the Hall probe alignment must be repeated or the undulator roll must be adjusted. The magnetic axis defines  $x = 0$  and  $y = 0$  for the Hall probe coordinate system and represents the beam axis.

- 7) Perform a Hall probe scan along the magnetic axis at the tuning gap and check for taper in the magnetic field peaks. If necessary, correct the taper using the gap encoder offsets. The slope of the linear fit of absolute peaks vs.  $z$  should be within  $\pm 5 \times 10^{-5}$  T/m.
- 8) Measure the fiducialization magnet with the Hall probe. This procedure enables the transfer of the Hall probe coordinate system to the stretched wire system.

### **E. Undulator tuning: trajectory, quadrupole components, phase error, and field integrals**

The following procedure is intended to adjust the trajectory, quadrupole components, phase error, and field integrals to meet the requirements presented in Section 2. LBNL software is used to determine appropriate shim combinations and placements based on measurements taken at multiple gaps and various  $x$ -positions. The specific measurement gaps and  $x$ -positions are defined by LBNL staff according to the undulator parameters. The software determines both the shim types and their exact locations. When pole motion adjustments are required, capacitive sensors should be used to monitor and document the pole movements. The relative standard deviation of absolute  $B_y$  peaks (positive and negative) must be kept below 0.25% to minimize phase errors.

The steps to tune trajectory, quadrupole components, phase error, and field integrals are presented below.

- 1) Set the Hall probe at  $y = 0$  and perform measurements along the  $z$ -axis at  $x = -2$  mm,  $x = 0$  mm, and  $x = 2$  mm for gaps of 7.5 mm, 10 mm, and 33 mm.
- 2) Set the stretched wire along the undulator axis. Measure the first and second field integrals for both  $x$  and  $y$  components at gaps of 7.2 mm, 9 mm, 11 mm, 13 mm, 17 mm, 25 mm, 33 mm, 50 mm, 70 mm, and 100 mm. Apply the compensation constants (see Section 3) to ensure agreement between Dover bench and Kugler SXR bench measurements.
- 3) Correct the Hall probe data at  $x = y = 0$  and a gap of 10 mm by applying offsets as a function of  $z$  such that the field integrals derived from the Hall probe agree with the stretched wire data from Step E.2.
- 4) Set the stretched wire along the undulator axis. Measure the first field integrals at  $y = 0$  and  $x = -2$  mm,  $x = 0$  mm, and  $x = 2$  mm for gaps of 7.5 mm, 10 mm, and 33 mm. Apply the compensation constants (see Section 3) to ensure agreement between Dover bench and Kugler SXR bench measurements.
- 5) Input the data from Steps E.1 and E.4 into the LBNL software to determine the shim combinations required to correct the trajectory and quadrupole components.
- 6) Repeat Steps E.1 to E.5 to refine the trajectory and quadrupole components (if needed), and to correct the phase error.
- 7) Repeat Steps E.1 to E.6 to further refine the trajectory, quadrupole components and phase error (if needed), and to correct the field integrals.

- 8) Confirm that the trajectory, quadrupole components, phase error, and field integrals are within the requirements presented in Section 2.
- 9) Repeat Steps E.1 to E.7 if necessary.

## F. Undulator preparation for transport after pre-tuning

- 1) Open the gap to 150 mm, disconnect the undulator, and save the undulator controller configuration (encoder offsets, half-gap encoders, etc.).
- 2) Confirm that the vacuum chamber linear potentiometers are secured with brackets.
- 3) Install protective plastic covers on the top and bottom jaws.
- 4) Cover the granite bench with plastic.
- 5) Set the stretched wire along the undulator axis.

## 5. Measurement Results<sup>6</sup>

All raw data and analysis results are available from the SLAC web site. The data is stored in a directory structure as shown in Fig. 4. The top level directory is *magdata*, followed by *DOVER BENCH*, 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. For the HE-SXR undulators, the serial number has the format HE\_SXU\_nnn. For refurbished SXR undulators, the SXU\_nnn part of the name is unchanged from its LCLS-II value. 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*, *Tuning*, *Lifetime Test*, and *Fiducialization* folders are created. Each contains all the relevant measurements. For instance, the contents of the *Tuning* folder are shown in Fig. 4. Multiple runs are required and the data and analysis results from each run go into a run folder. An index file gives a description of each run. Within a run, multiple measurements may be made. For Hall probe scans, each measurement and its analysis results go into a folder whose name is determined by the measurement number, the gap, and the  $x$  and  $y$  probe positions for the measurement. The fixed width format is “nnngapnnn.nnnxnn.nnnysnn.nnn”, where “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. All data files are text files. All Hall probe measurement data files are called “zscan.dat”. In this way the analysis programs can be more easily automated so the contents of a folder are known in advance. Analysis results are in both text files and either postscript plot files or PDF plot files.

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<sup>6</sup>The Dover bench measurement results are organized in a similar way compared to Kugler SXR results. Kugler SXR measurement results are placed as describe in (Z. Wolf, Y. Levashov, H.-D. Nuhn, “HE-SXR Undulator Test Plan”, LCLS-TN-22-9, October, 2022). Some folders and types of measurements that are performed with the Kugler SXR bench are not performed at the Dover bench, including Final Results, Gap Measurements, and Capacitive Sensor data.

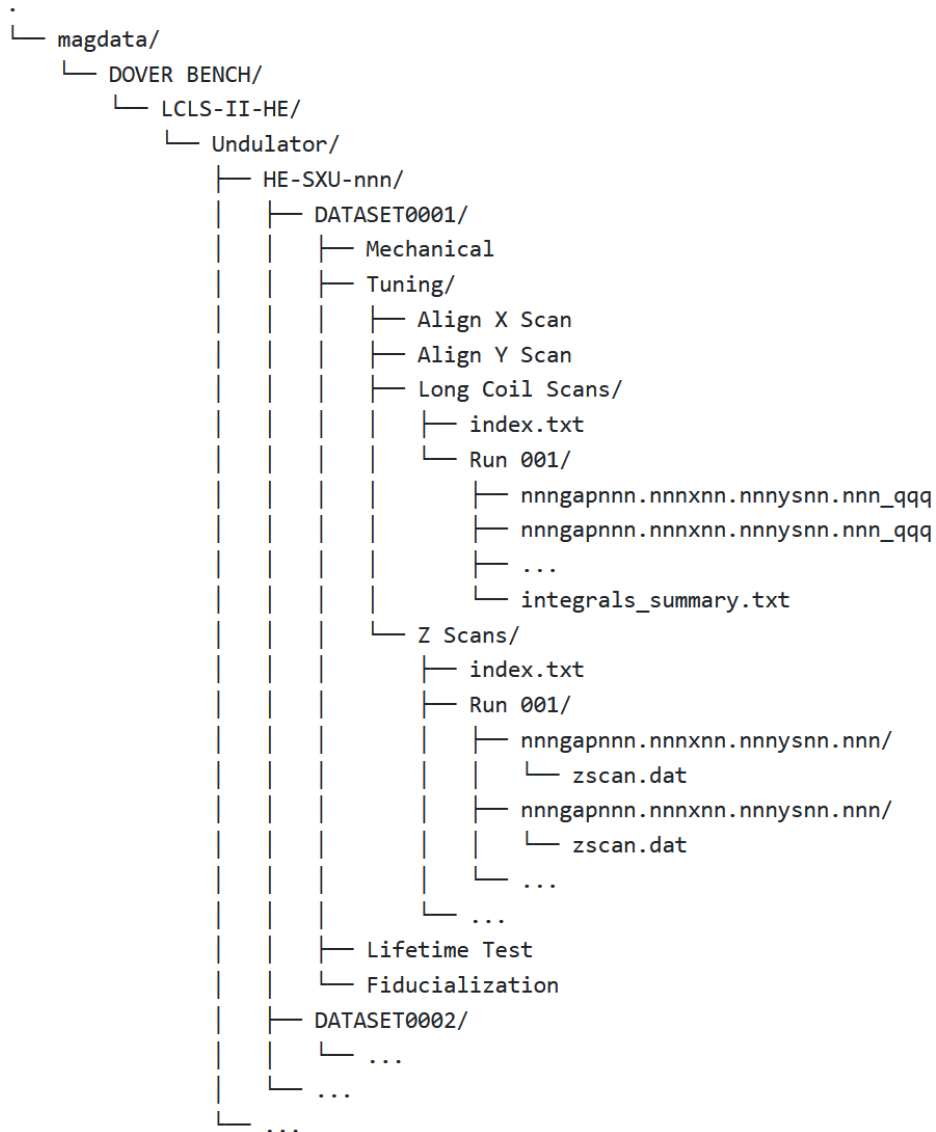


Fig. 4: Directory structure of the Dover bench measurements data.

For stretched wire measurements, a similar scheme is used. A run folder contains multiple measurements. Each measurement produces data files with format “*nnngapnnn.nnnxnn.nnnysnn.nnn\_qqq\_t*”. The first part of the data file name, up to the first underscore, contains the measurement number, the gap, and the  $x$  and  $y$  coil position, using the same format as the Hall probe scans. After the first underscore, “*qqq*” describes the quantity being measured and are “*i1x*”, “*i2x*”, “*i1y*”, or “*i2y*” for the first or second field integrals in  $x$  or  $y$ . The “*t*” refers to a file type descriptor. Summaries of the field integral measurements are provided in a file called “*integrals\_summary.txt*”.

The mechanical measurements folder contains measurements from a touch probe or

other device characterizing the mechanical properties of the undulator.

*Align X Scan* and *Align Y Scan* folders include files from scanning the Hall probe in  $x$  and  $y$  and finding the magnetic center. This is done at a number of poles down the undulator. Both folders are inside *Tuning*.

The  $z$ -scan magnetic measurement data consists 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, are included in a header. Two separate analysis programs are run on the data. The first computes the trajectories, phase, etc. The second computes the shims required to tune the undulator. These programs output text files containing the results and also plots in postscript or PDF files or Matlab figure files.

The long coil data consists of the  $(x, y)$  location of the coil, parameters of the coil motion, the integrated voltage, and the first and second field integrals. Multiple measurements are done. Each measurement is recorded and the average and rms deviation is provided. Output files are text files containing a header and the first and second integrals in  $x$  and  $y$ .

When stretched wire measurements are associated with a particular Hall probe scan in order to correct Hall probe offsets, the coil data may be placed in the folder with the associated Hall probe measurement.

The *Lifetime Test* folder has the gap cycling data. The fiducialization data is put in its own folder. The folder contains the fiducialization magnet location measurement and the spreadsheet to calculate the stretched wire stages position to place the wire at the magnetic center.

## 6. Summary

A magnetic measurement and pre-tuning system, referred to as the Dover bench, was developed to accelerate the tuning of the HE-SXR undulators at SLAC. This report outlines the test plan for pre-tuning HE-SXR undulators on the Dover bench, including the measurement procedures, alignment methods, and data processing required to ensure consistency with Kugler SXR bench results.

### *Acknowledgements*

Many thanks to Robert Pushor and Scott Jansson for their significant technical support during the Dover bench development.