



LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU\_025

This traveler is intended to document the checking of the final magnetic measurements of an Undulator Segment performed on the Kugler bench in the Magnetic Measurement Facility (MMF) at SLAC after the completion of the tuning process. It contains basic performance indicators compared against tolerances as well as documentary information both in graphical and textual representation.

Serial number from magnet label:	29A804-025
Device name from magnet label:	HE_SXU_025

**Measurement Procedure:**

The measurements have been carried out after the undulator segment had been fully tuned according to the “LCLS-II-HE Undulator Test Plan” (LCLS-TN-22-9).

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**Evaluation of Hall Probe Scans: Data Listings A**

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MATLAB function "EvaluateUndulatorField" on	09/12/2024 20:07	
A. SCAN PARAMETERS		
z Scanning Date & Time Range	09/04/2024 22:28 - 09/12/2024 08:26	
Undulator Temperature	19.9034±0.0471	°C
x axis position	-0.075990	mm
y axis position	0.000204	mm
Total number of poles per strongback	122	
Number of full field poles	116	
Number of core poles	108	
First core pole #	8	
Last core pole #	115	
Average $\lambda_u$	55.996	mm
Standard deviation from average $\lambda_u$	30.3	$\mu\text{m}$
Average $k_u$	112.207	$\text{m}^{-1}$
Scans averaged	3	
Nominal Tuning Gap	10.0000	mm
Nominal Commissioning Gap	16.5790	mm



**Evaluation of Hall Probe Scans at Tuning Gap: Data Listing B**

MATLAB function "EvaluateUndulatorField" on	09/12/2024 20:07	
B. CORE EVALUATIONS FOR TUNING GAP		
Tuning Gap Scanning Date & Time Range	09/11/2024 12:49	
Actual Tuning Gap	10.0003	mm
Tuning Gap Temperature	+19.826±0.030	°C
Planar Hall Effect Correction Range	0.750200 - 4.150200	m
Planar Hall Effect x Corr Function	-0.19 G + (z - 0.750200 m)×0.24 G/m	
Planar Hall Effect y Corr Function	-0.03 G + (z - 0.750200 m)×0.08 G/m	
Coil Range	0.650134 - 4.250134	m
$\langle \lambda_u \rangle$	+55.997±0.017	mm
$\langle k_u \rangle$	+112.207±0.034	1/m
$\langle K_u \rangle$	+7.2910±0.0076	
$K_{\text{eff}}$ @ Tuning Temperature	+7.28803±0.00011	
$L_{\text{eff}}$	+3.300775±0.000098	m
$L_{2\pi}$	+1.54314±0.00047	m
I1X (Cell Range Total)	+7.31	$\mu\text{Tm}$
I2X (Cell Range Total)	+30.55	$\mu\text{Tm}^2$
I1Y (Cell Range Total)	+4.68	$\mu\text{Tm}$
I2Y (Cell Range Total)	+38.71	$\mu\text{Tm}^2$
PI (Cell Range Total)	254,686.2	$\text{T}^2\text{mm}^3$
Phase Shake	1.23	degXray
Cell Phase Advance ( over 4.400000 m)	21,477.0 (60×360-123.0)	degXray
Undulator Entrance Phase	+1019.0±1.2	degXray
Undulator Exit Phase	+1018.0±1.2	degXray
Undulator Phase Imbalance: Entrance - Exit	+0.9±1.7	degXray
Cell Entrance min. Phase Shifter Correction	61.0	degXray
Cell Exit min. Phase Shifter Correction	62.0	degXray



**Evaluation of Hall Probe Scans at Commissioning Gap: Data Listing C**

MATLAB function "EvaluateUndulatorField" on	09/12/2024 20:07	
C. CORE EVALUATIONS FOR COMMISSIONING GAP		
Commissioning Gap Scanning Date & Time Range	09/11/2024 12:49	
Actual Commissioning Gap	16.5799	mm
Commissining Gap Temperature	+19.826±0.030	°C
Planar Hall Effect Correction Range	0.750100 - 4.150100	m
Planar Hall Effect x Corr Function	-0.10 G + (z - 0.750100 m)×0.12 G/m	
Planar Hall Effect y Corr Function	-0.05 G + (z - 0.750100 m)×0.06 G/m	
Coil Range	0.650147 - 4.250147	m
$\langle \lambda_u \rangle$	+55.997±0.017	mm
$\langle k_u \rangle$	+112.206±0.033	1/m
$\langle K_u \rangle$	+4.2912±0.0043	
$K_{\text{eff}}$ @ Tuning Temperature	+4.290592±0.000064	
$L_{\text{eff}}$	+3.309424±0.000099	m
$L_{2\pi}$	+0.57143±0.00017	m
I1X (Cell Range Total)	+18.22	$\mu\text{Tm}$
I2X (Cell Range Total)	+54.63	$\mu\text{Tm}^2$
I1Y (Cell Range Total)	+11.65	$\mu\text{Tm}$
I2Y (Cell Range Total)	+30.75	$\mu\text{Tm}^2$
PI (Cell Range Total)	88,502.5	$\text{T}^2\text{mm}^3$
Phase Shake	1.52	degXray
Cell Phase Advance (over 4.400000 m)	21,963.1 (61×360+3.1)	degXray
Undulator Entrance Phase	1261.6 (7×180+1.6)±1.5	degXray
Undulator Exit Phase	1261.5 (7×180+1.5)±1.5	degXray
Undulator Phase Imbalance: Entrance - Exit	+0.0±2.1	degXray
Cell Entrance min. Phase Shifter Correction	+178.4±1.5	degXray
Cell Exit min. Phase Shifter Correction	+178.5±1.5	degXray




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**Undulator Encoder Settings: Data Listing D**

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MATLAB function "EvaluateUndulatorField" on 09/12/2024 20:10

D. ENCODER SETTINGS

Upstream Gap Encoder Line Spacing	-20000.00±0.25	EncoderCounts/mm
Upstream Scaled Gap Encoder Offset	227.8622	mm
Downstream Gap Encoder Line Spacing	-20000.00±0.25	EncoderCounts/mm
Downstream Scaled Gap Encoder Offset	227.9565	mm
Upstream Scaled Top Motor Encoder Offset	-990.4088	mm
Downstream Scaled Top Motor Encoder Offset	-995.7870	mm
Upstream Half Gap Encoder Line Spacing	20,000.0	EncoderCounts/mm
Upstream Half Gap Encoder Offset	-34.5168	mm
Downstream Half Gap Encoder Line Spacing	20,000.0	EncoderCounts/mm
Downstream Half Gap Encoder Offset	-33.8670	mm

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**Undulator Capacitive Sensor Values: Data Listing E**

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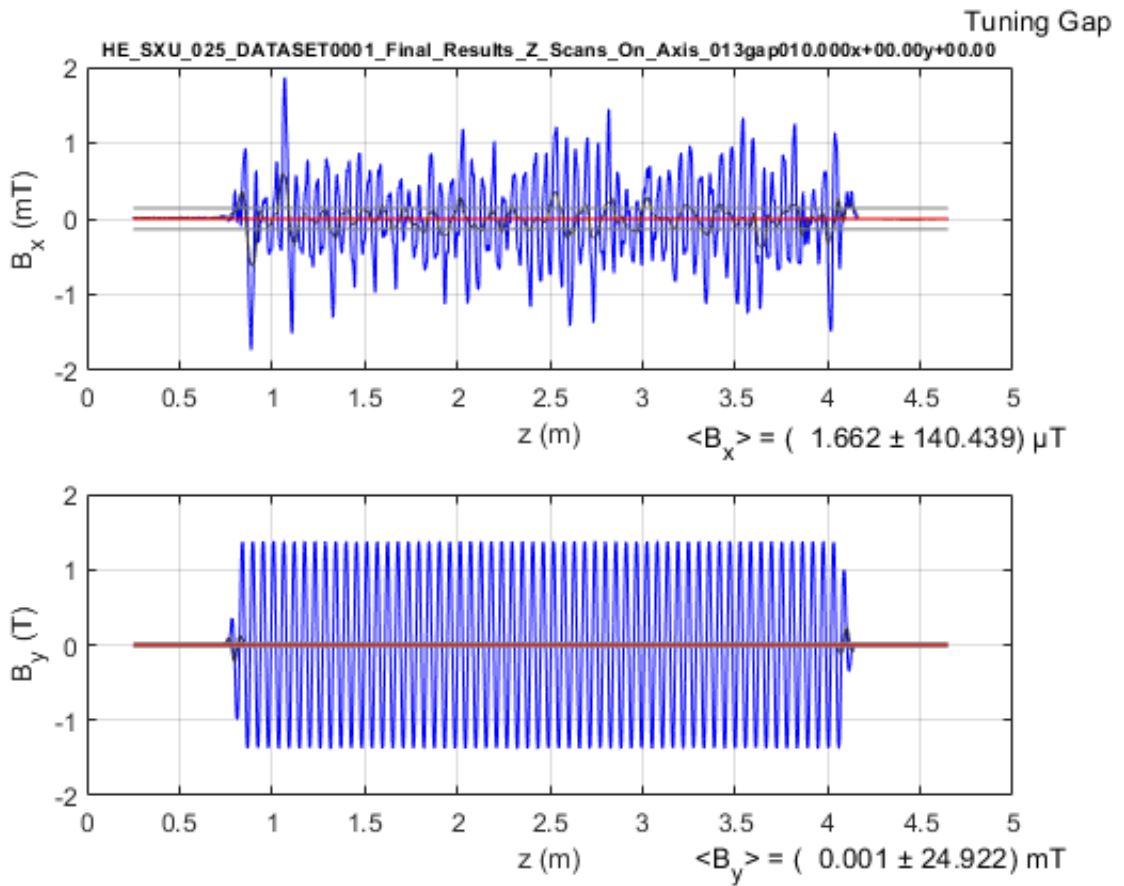
E. CAPACITIVE SENSOR VALUES

Module	Pole	Capacitive Sensor Gap	Upstream Encoder	Downstream Encoder	
Ref	—	46.2240	50.0000	50.0000	mm
Ref	—	46.2242	50.0000	50.0000	mm
1	10	46.4899	46.4999	46.4999	mm
1	10	46.4899	46.5000	46.4999	mm
1	15	46.4882	46.4999	46.4999	mm
1	15	46.4881	46.4999	46.4999	mm
3	25	46.4891	46.4999	46.4999	mm
3	25	46.4891	46.5000	46.4999	mm
3	30	46.4972	46.4999	46.4999	mm
3	30	46.4972	46.4999	46.4999	mm
Ref	—	46.2242	50.0001	50.0001	mm
Ref	—	46.2239	50.0001	50.0001	mm

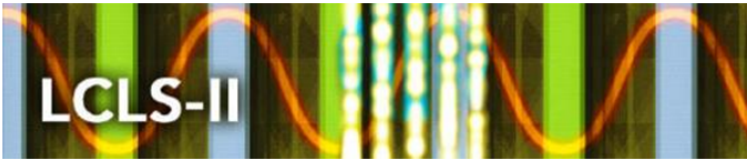
The following figures show results of the field analysis at the tuning gap.



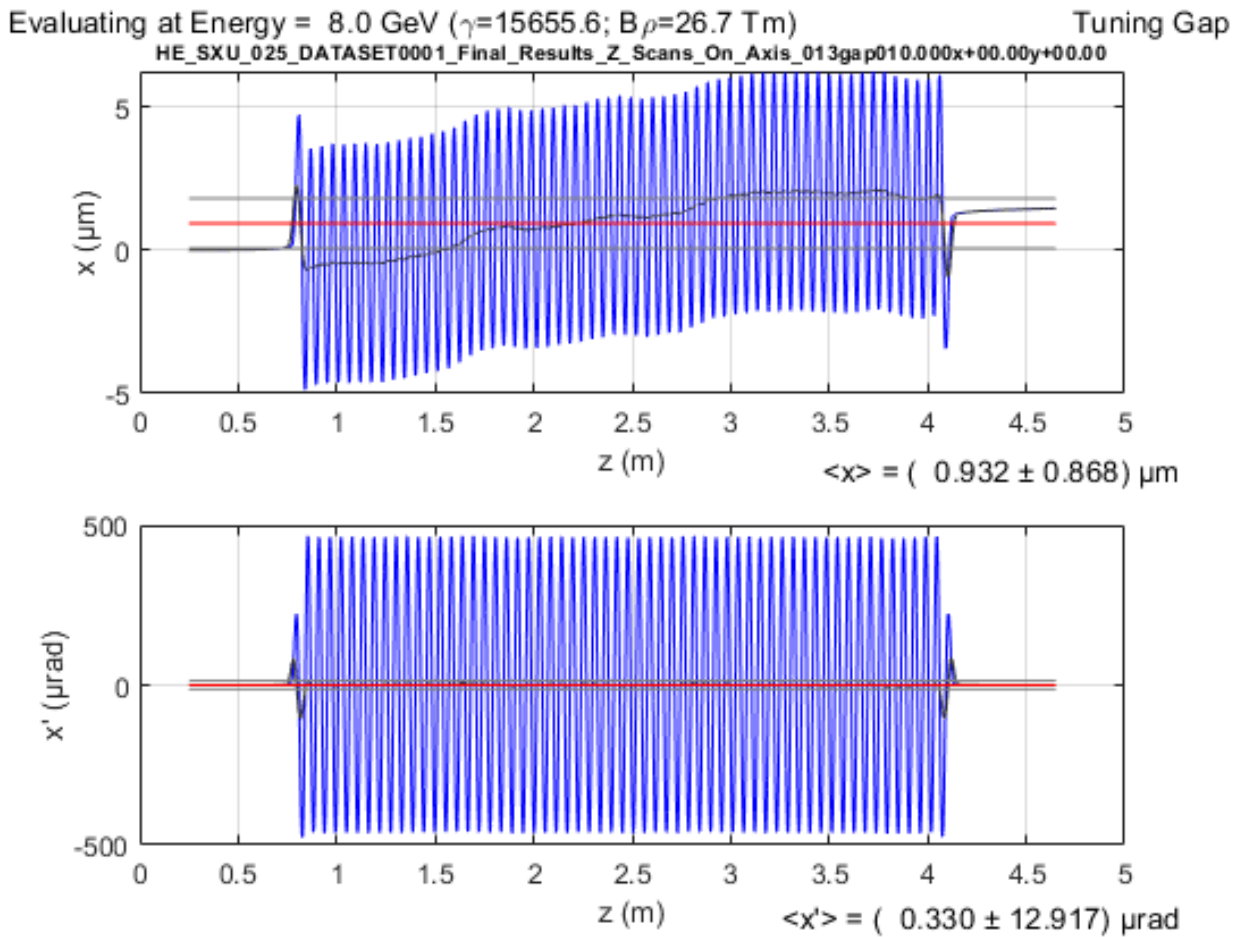
Evaluation of Hall Probe at Tuning Gap:  $B_x$  &  $B_y$  Plot



The figures show the x (upper) and y (lower) field components along the undulator tuning axis for the tuning gap. A running undulator-period-average function is plotted in black (not very well visible in the lower figure). The horizontal lines indicate the mean (center red line) and the rms deviations from the mean (two black lines above and below the average) of that undulator-period-average function. The corresponding mean values and standard deviations are also printed on the right hand side underneath each figure. [Documentary Information]



Evaluation of Hall Probe at Tuning Gap:  $x$  &  $x'$  Plot



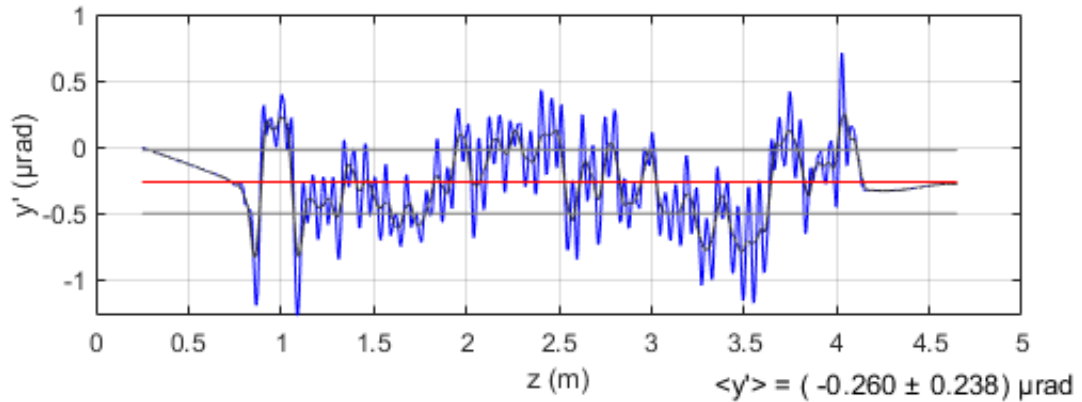
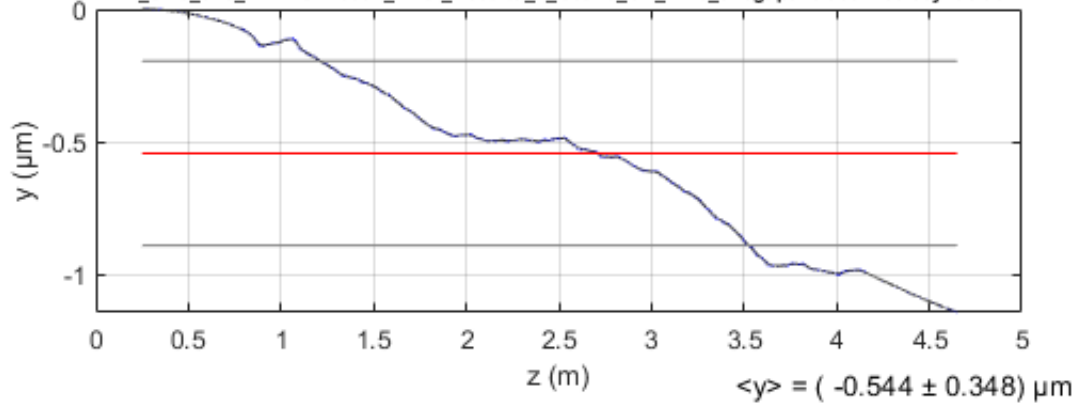
The figures show the  $x$  (upper) and  $x'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components and estimated for an electron beam energy of 8.0 GeV. A running undulator-period-average function is plotted in black (difficult to see in the lower figure). The horizontal lines indicate the mean values (center red line) and the standard deviations from the mean (two black lines above and below the average) of that undulator-period-average function. The corresponding mean values and standard deviations are also printed on the right hand side underneath each figure. [Documentary Information]



Evaluation of Hall Probe Scans at Tuning Gap:  $y$  &  $y'$  Plot

Evaluating at Energy = 8.0 GeV ( $\gamma=15655.6$ ;  $B\rho=26.7$  Tm) Tuning Gap

HE\_SXU\_025\_DATASET0001\_Final\_Results\_Z\_Scans\_On\_Axis\_013gap010.000x+00.00y+00.00

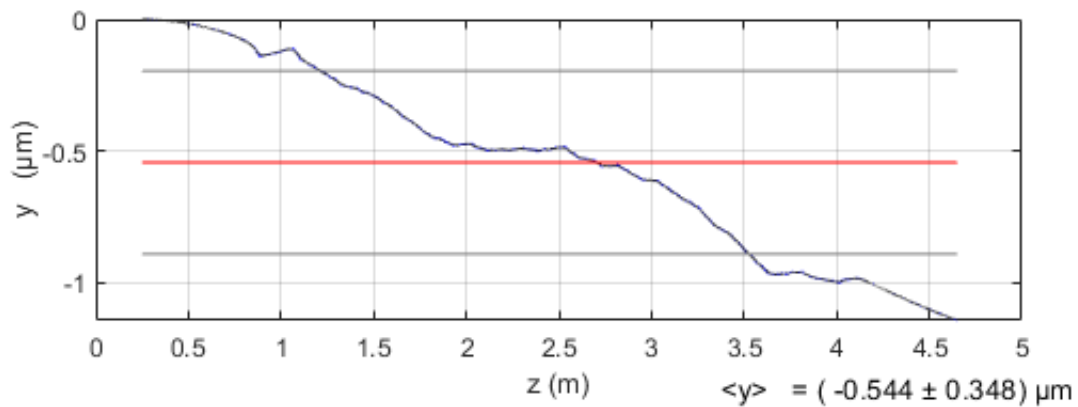
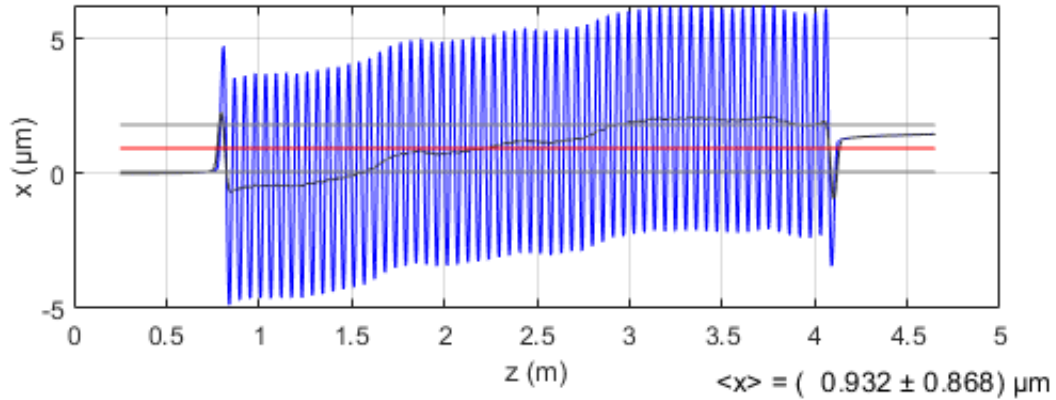


The figures show the  $y$  (upper) and  $y'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components and estimated for an electron beam energy of 8.0 GeV. A running undulator-period-average function is plotted in black (difficult to see). The horizontal lines indicate the mean values (center red line) and the standard deviations from the mean (two black lines above and below the average) of that undulator-period-average function. The corresponding mean values and standard deviations are also printed on the right hand side underneath each figure. [Documentary Information]



### Evaluation of Hall Probe Scans at Tuning Gap: $x$ & $y$ Plot

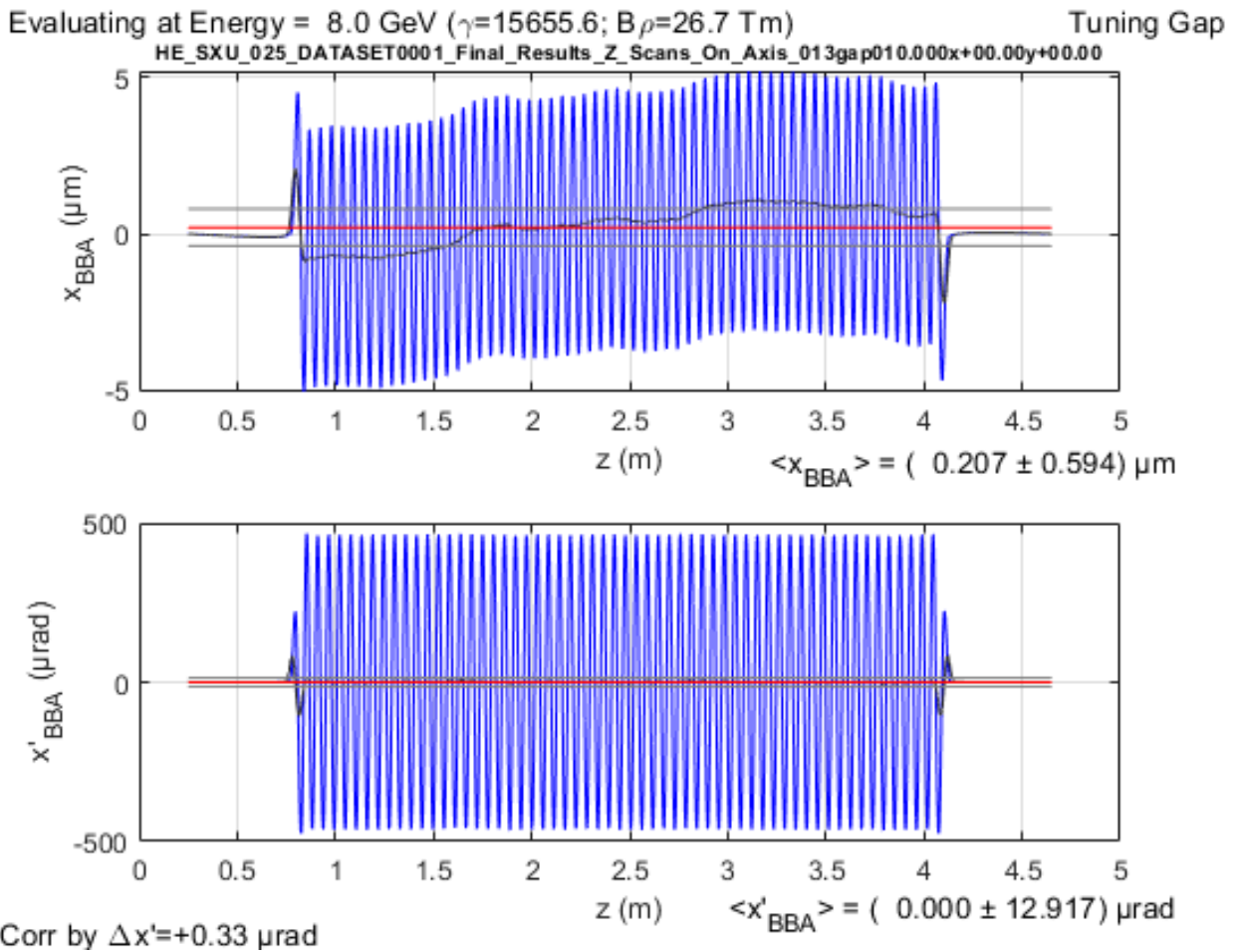
Evaluating at Energy = 8.0 GeV ( $\gamma=15655.6$ ;  $B\rho=26.7$  Tm) Tuning Gap  
HE\_SXU\_025\_DATASET0001\_Final\_Results\_Z\_Scans\_On\_Axis\_013gap010.000x+00.00y+00.00



The figures show the  $x$  (upper) and  $y$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components and estimated for an electron beam energy of 8.0 GeV. A running undulator-period-average function is plotted in black (identical with the trajectory in the lower figure). The horizontal lines indicate the mean values (center red line) and the standard deviations from the mean (two black lines above and below the average) of that undulator-period-average function. The corresponding mean values and standard values are also printed on the right hand side underneath each figure. [Documentary Information]



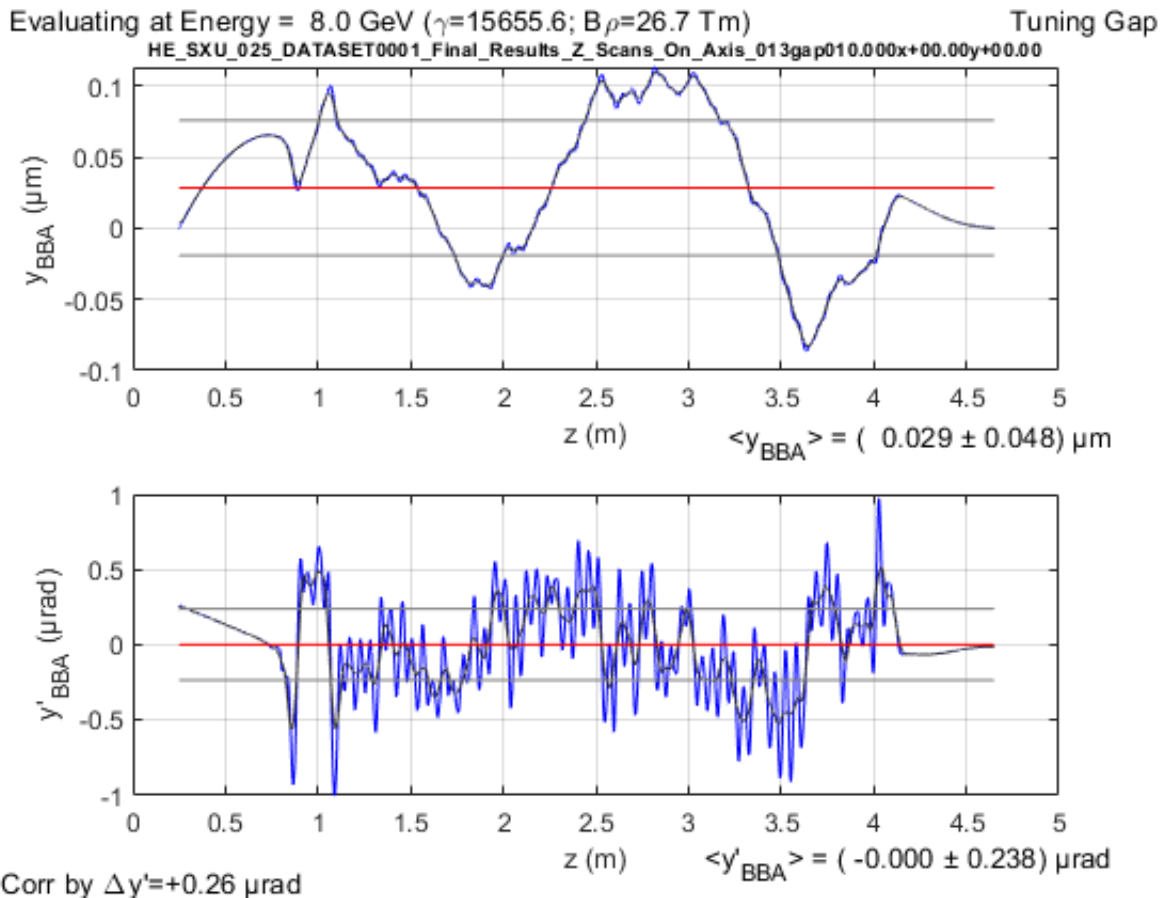
Evaluation of Hall Probe plus BBA Correction at Tuning Gap:  $x$  &  $x'$  Plot



The figures show the  $x$  (upper) and  $x'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components after BBA correction (to zero the amplitudes at the cell boundaries) and estimated for an electron beam energy of 8.0 GeV. A running undulator-period-average function is plotted in black (difficult to see in the lower figure). The horizontal lines indicate the mean values (center red line) and the standard deviations from the mean (two black lines above and below the average) of that undulator-period-average function. The corresponding mean values and standard values are also printed on the right hand side underneath each figure. The amount of BBA correction applied is printed underneath the lower left corner of the lower figure. [Documentary Information]



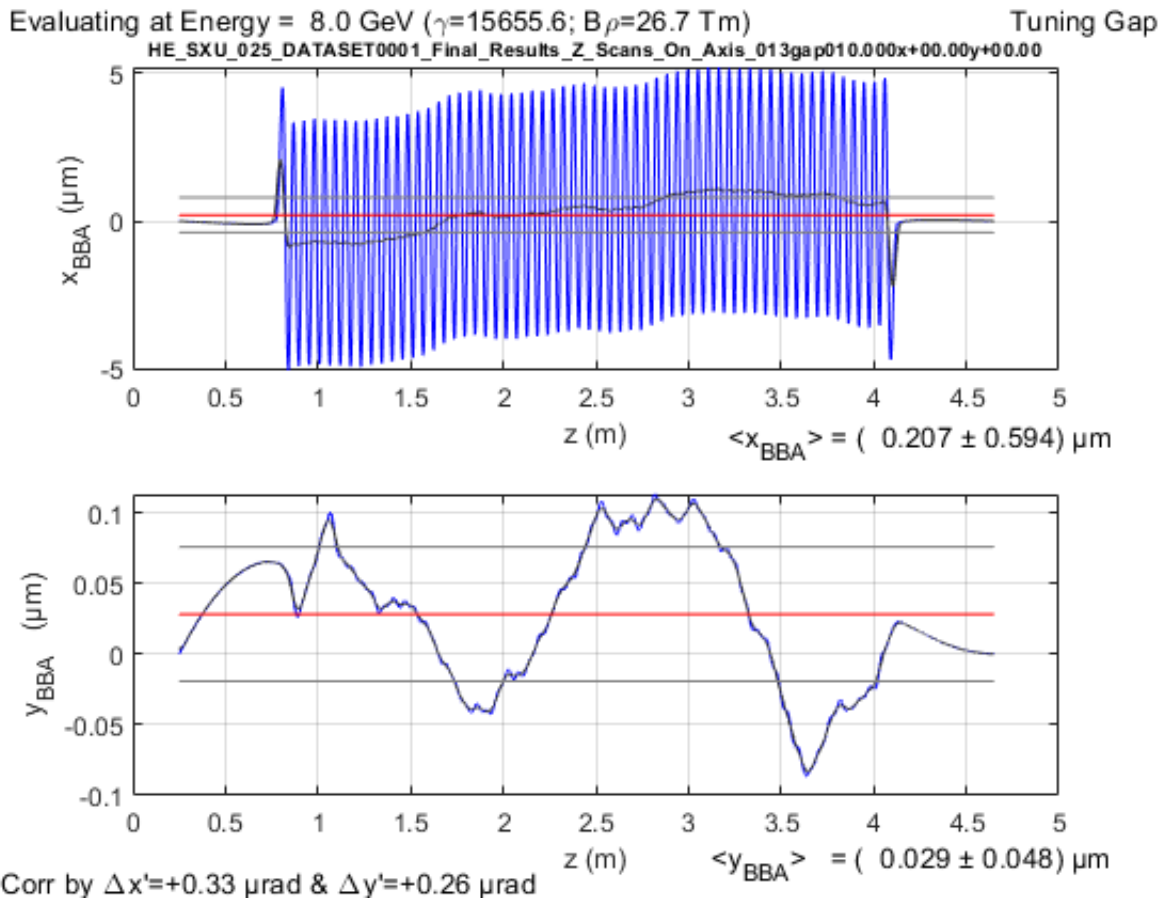
Evaluation of Hall Probe plus BBA Correction at Tuning Gap:  $y$  &  $y'$  Plot



The figures show the  $y$  (upper) and  $y'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components after BBA correction (to zero the amplitudes at the cell boundaries) and estimated for an electron beam energy of 8.0 GeV. A running undulator-period-average function is plotted in black (identical with the trajectories). The horizontal lines indicate the mean values (center red line) and the standard deviations from the mean (two black lines above and below the average) of that undulator-period-average function. The corresponding mean values and standard values are also printed on the right hand side underneath each figure. The amount of BBA correction applied is printed underneath the lower left corner of the lower figure. [Documentary Information]



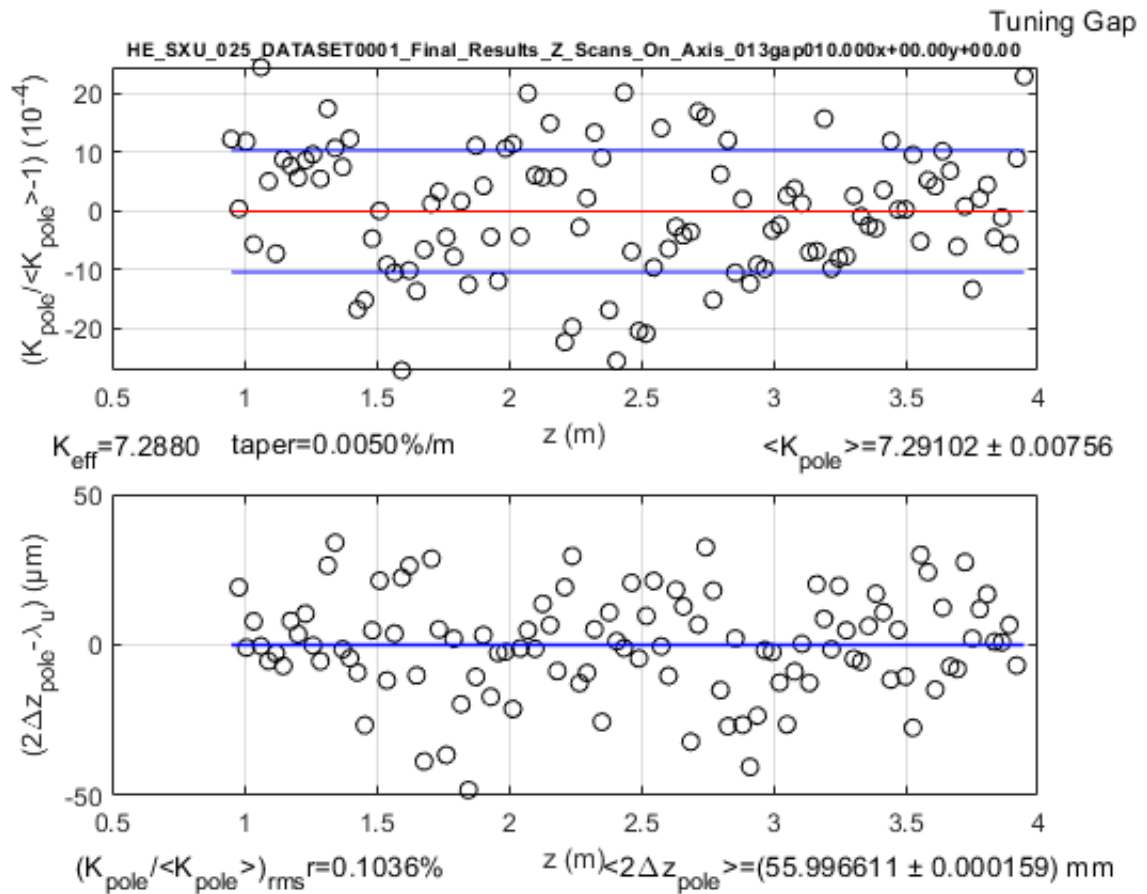
Evaluation of Hall Probe plus BBA Correction at Tuning Gap:  $x$  &  $y$  Plot



The figures show the  $x$  (upper) and  $y$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components after BBA correction (to zero the amplitudes at the cell boundaries) and estimated for an electron beam energy of 8.0 GeV. A running undulator-period-average function is plotted in black (identical with the trajectory in the lower figure). The horizontal lines indicate the mean values (center red line) and the standard deviations from the mean (two black lines above and below the average) of that undulator-period-average function. The corresponding mean values and standard values are also printed on the right hand side underneath each figure. The amount of BBA correction applied is printed underneath the lower left corner of the lower figure. [Documentary Information]



Evaluation of Hall Probe at Tuning Gap:  $K$  and  $\lambda_u$  Plot



The figures show the per-pole undulator strength  $K_{pole}$  (upper) and the deviation of the pole width from the expected value of  $\lambda_u/2$  (lower) for the 108 core undulator poles for the tuning gap. The horizontal lines indicate the mean values (center red line) and the standard deviations from the mean (two black lines above and below the average). The corresponding mean values and standard values are also printed on the right hand side underneath each figure. [Documentary Information]

For description of  $K$  calculation see next page.



LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU.025

$K$  calculation description for previous page:

The undulator parameter,  $K_{pole}$ , in the upper figure, is calculated for each of the core poles based on the scanned vertical field values  $B_y(z)$  as well as an interpolation of the upstream,  $z_{(0-dn,pole)}$ , and downstream,  $z_{(0-up,pole)}$ , field zero crossing locations using the following formula:

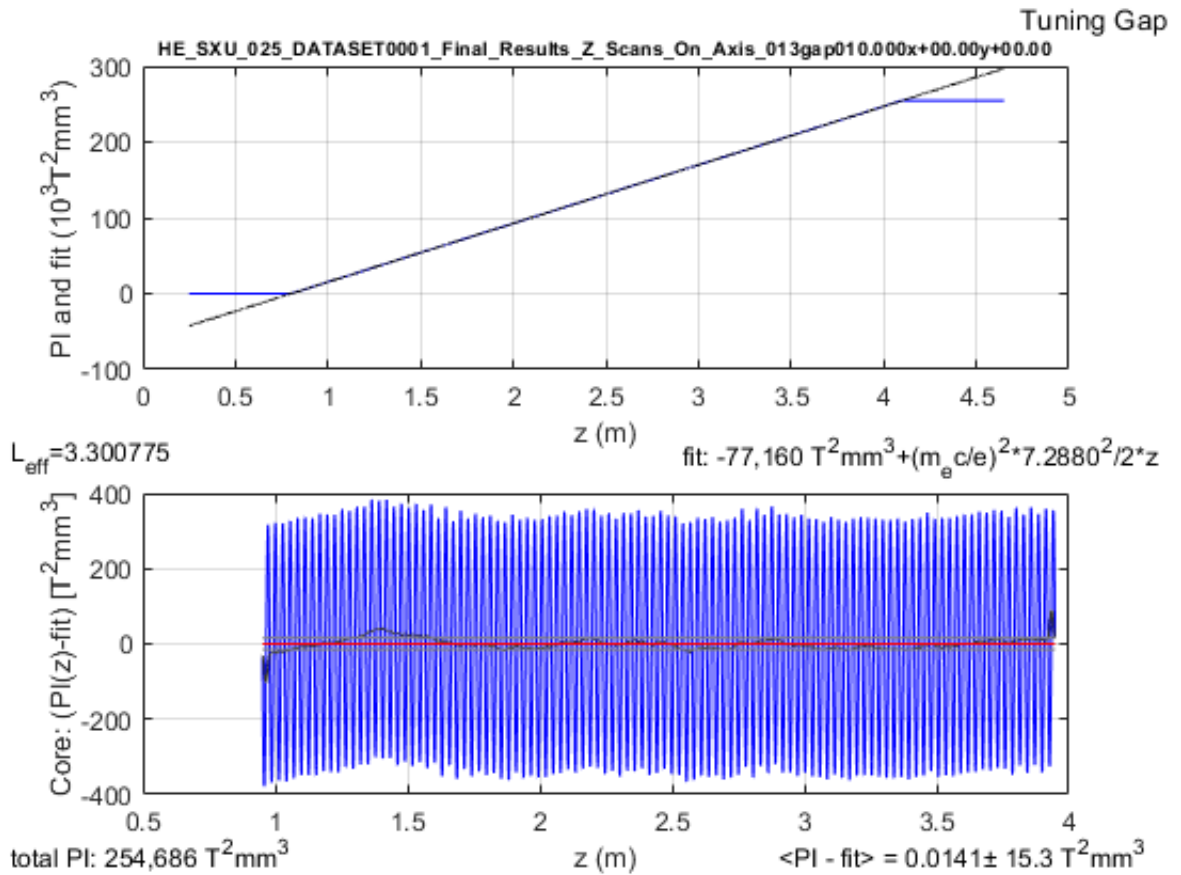
$$K_{pole}(z_{pole}) = \frac{\Delta z_{pole}}{2\pi} \frac{e}{m_e c} \sqrt{\frac{2}{\Delta z_{pole}} \int_{z_{0-up,pole}}^{z_{0-dn,pole}} B_y^2(\hat{z}) d\hat{z}}$$

The term  $\frac{e}{m_e c}$  uses the electron mass,  $m_e$ , the speed of light,  $c$ , and the electron's electric charge,  $e$ . The variable  $\Delta z_{pole}$  stands for

$$\begin{aligned} \Delta z_{pole} &= z_{0-dn,pole} - z_{0-up,pole} \\ z_{pole} &\approx \frac{1}{2} (z_{0-dn,pole} + z_{0-up,pole}) \end{aligned}$$



Evaluation of Hall Probe Scans for Tuning Gap: Phase Integral Plot



A description of the figure is given on the next page:



LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU.025

Figure description for previous page:

The upper figure shows the phase integral of an electron calculated from the measured on-axis magnetic field components for the tuning gap:

$$PI(z) = \int_0^z BL_{x1}^2(\hat{z}) d\hat{z} + \int_0^z BL_{y1}^2(\hat{z}) d\hat{z}$$

with

$$BL_{x1,y1}(z) = \int_0^z B_{x,y}(\hat{z}) d\hat{z} - \frac{1}{L} \int_0^L \left\{ \int_0^{\hat{z}} B_{x,y}(\hat{z}) d\hat{z} \right\} d\hat{z}.$$

The function

$$\overline{PI}(z) = \overline{PI}(0) + z \left( \frac{mc}{e} \right)^2 \frac{1}{2} K_{\text{eff}}^2,$$

fitted to the measured phase integral  $PI(z)$  (along the undulator core) with fit coefficients  $\left(\frac{mc}{e}\right)^2 \frac{1}{2} K_{\text{eff}}^2$  and can be seen as a straight black line in the upper plot. The values of the fit coefficients are printed at the right hand side underneath the upper figure. On the lower left of the upper figure the effective undulator length is printed, which is obtained as the distance over the undulator core, where the blue and black lines in the plot are on top of each other:  $L_{\text{eff}} = PI(z_{\text{max}}) / \left(\frac{dPI(z)}{dz}\right)$ .

The lower figure shows the residuals between the phase integral and the fit function over the core part of the undulator magnet. A running undulator-period-averaged function is plotted in black. The horizontal lines indicate the mean values (center red line) and the standard deviations from the mean (two blue lines above and below the mean) of that undulator-period-averaged function. The corresponding mean values and standard values are also printed on the right hand side underneath the figure. On the lower left of the plot, the total phase integral accumulated along the undulator magnet, is shown, i.e.,  $PI(z_{\text{max}})$ , the right-hand side value of the blue line in the upper plot.

The undulator-period averaged phase,  $\langle \Phi \rangle_{\lambda_u}(z)$  can be calculated from  $PI(z)$  via

$$\langle \Phi \rangle_{\lambda_u}(z) = \frac{2\pi}{L_{2\pi}} \left( \frac{e}{mc} \right)^2 \frac{1}{\lambda_u} \int_{z - \frac{\lambda_u}{2}}^{z + \frac{\lambda_u}{2}} (PI(\hat{z}) - \overline{PI}(\hat{z})) d\hat{z}, \quad (1)$$

integrated over the undulator core.

Here  $L_{2\pi} = \lambda_u \left(1 + \frac{1}{2} K_{\text{eff}}^2\right)$  (see next figure) is the free space distance over which a phase slippage of  $2\pi$  occurs. The phase shake,  $\langle \Delta \phi \rangle_{\text{rms}}$ , which will be discussed later in this document, is calculated as

$$\langle \Delta \phi \rangle_{\text{rms}} = (\Delta \langle \Phi \rangle_{\lambda_u})_{\text{rms}} = (\langle \Phi \rangle_{\lambda_u}(z) - \langle \langle \Phi \rangle_{\lambda_u}(z) \rangle)_{\text{rms}}$$

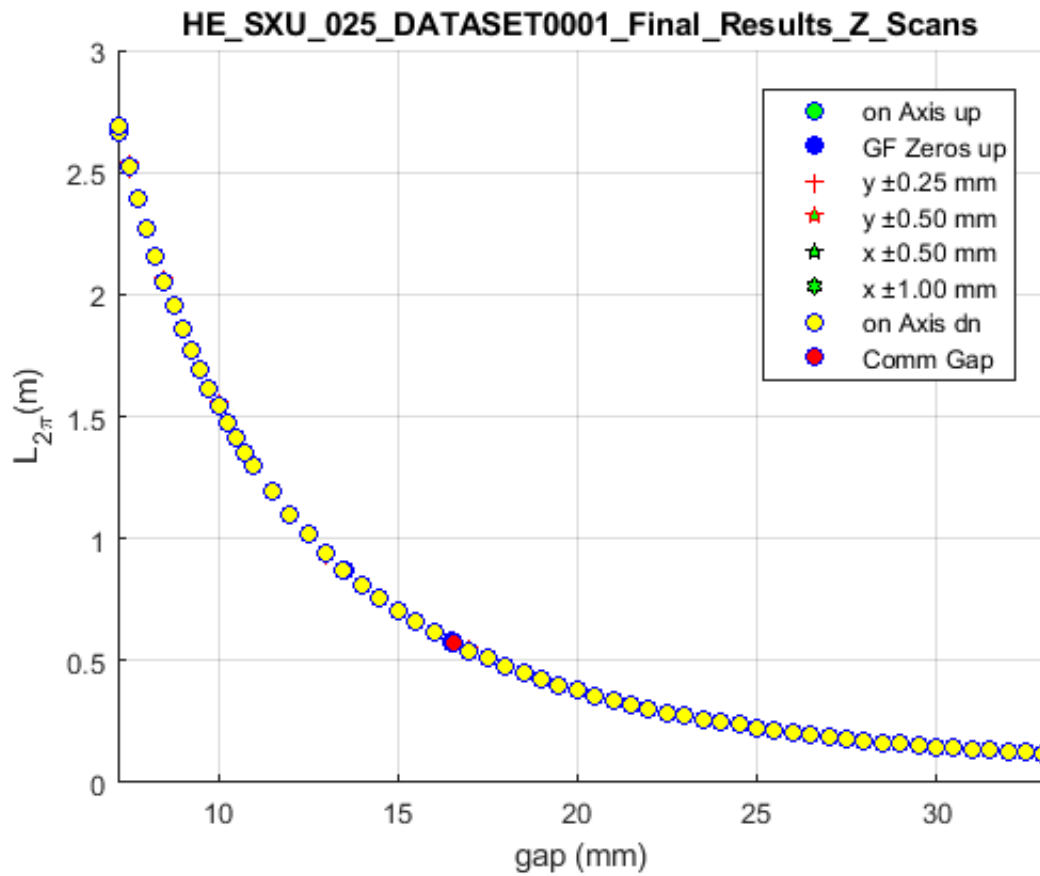
The cell phase  $\phi(z)$  is calculated over the entire cell length (not just the undulator core)

$$\phi(z) = \frac{360 \text{ degXray}}{L_{2\pi}} \left( z - z_{\text{center}} + \left( \frac{e}{mc} \right)^2 PI(z) \right).$$

The following figures show the results of the gap dependent analysis.



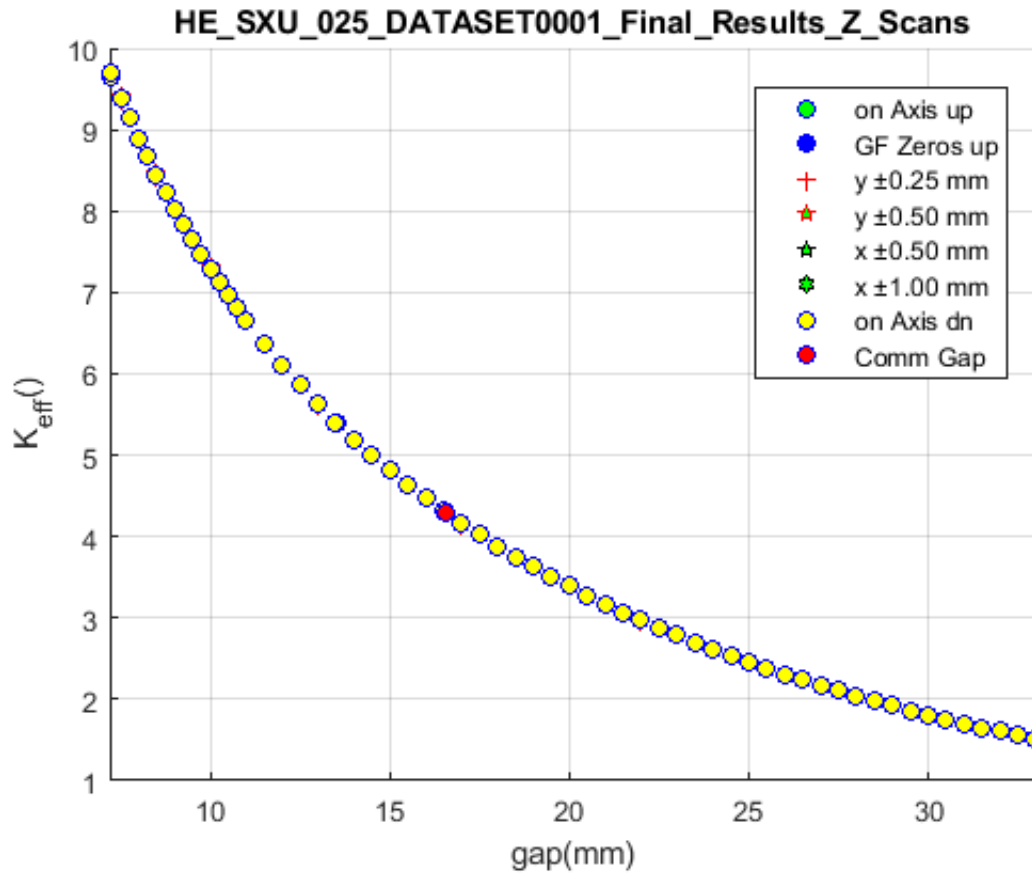
Evaluation of Hall Scans:  $L_{2\pi}$  vs gap



The figure shows the free space distance over which a  $2\pi$  slippage occurs between the radiation field and the electron bunch (see explanation above) as a function of undulator gap over the operational gap range. Note: the free space travel distance required to accumulate  $2\pi$  slippage gets shorter towards larger gap values, which correspond to shorter undulator wavelengths. [Documentary Information]



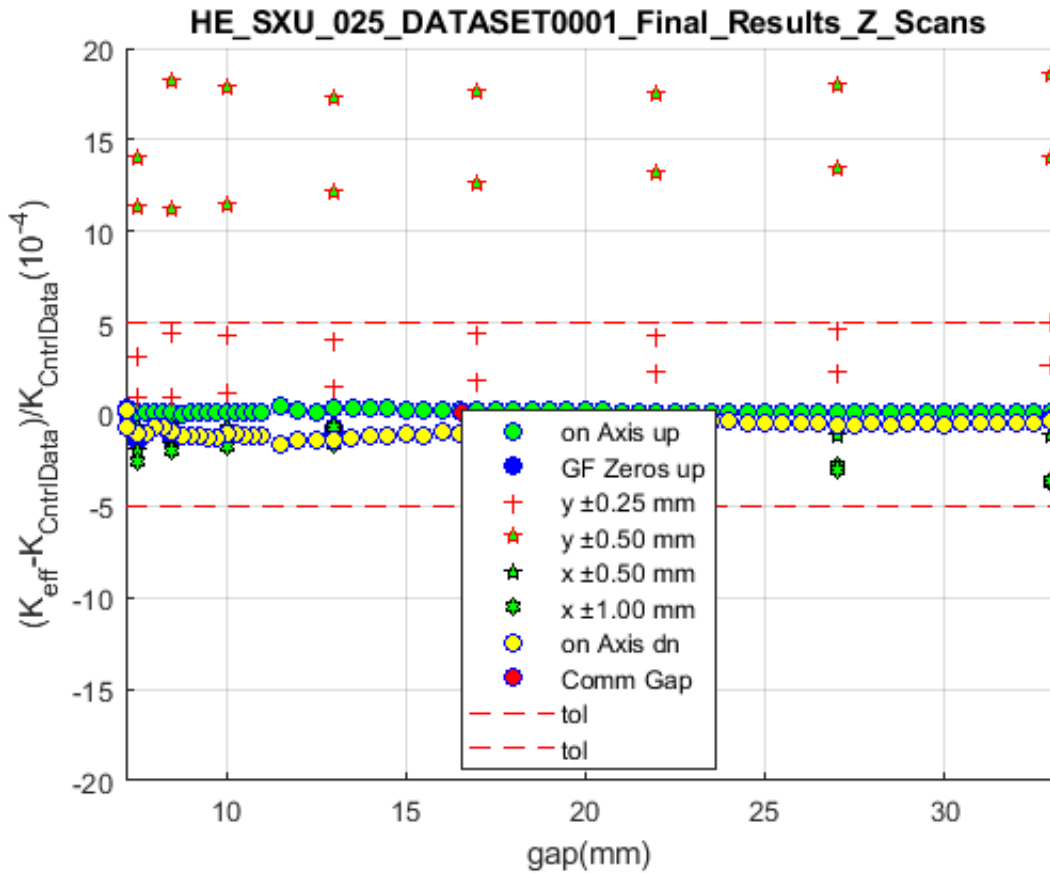
Evaluation of Hall Scans:  $K_{\text{eff}}$  vs gap



The figure shows undulator strength  $K_{\text{eff}}$  as a function of gap over the 7.2 mm—33 mm operational range. The legend shows a number of different cases that will be explained later in this document, because their effect cannot be observed in this full scale plot. Note: The gap values are derived from the readings of the two gap encoders installed on the SXU. In that sense these are nominal gap numbers that will be close but not identical to each of the individual pole separations measured across the undulator gap. The continuous conversion between the two axes (i.e.  $K_{\text{eff}}(\text{gap})$  and  $\text{gap}(K_{\text{eff}})$ ) will be done during operations based on the list of reference data points stored in file `sxu_025_k_vs_gap_spline.dat` in the Controls Data folder on the V: drive (see final section of this document for file information). From that list  $K_{\text{eff}}(\text{gap})$  and  $\text{gap}(K_{\text{eff}})$  can be calculated via cubic spline fits or equivalent. [Documentary Information]



Evaluation of Hall Scans:  $K_{\text{eff}} - K_{\text{control}}$  vs gap

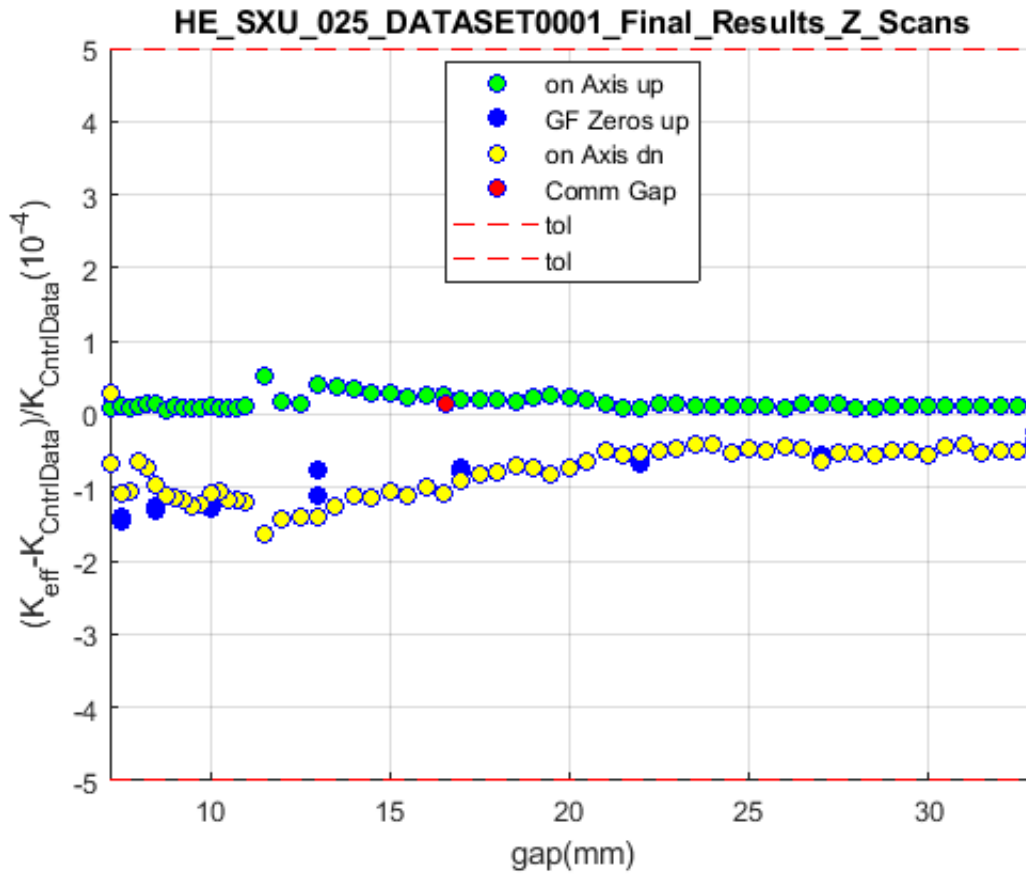


The figure shows the relative difference between the measured undulator strength  $K_{\text{eff}}$  and a cubic spline fit to the list of reference data points stored in file `sxu_025_k_vs_gap_spline.dat` in the Controls Data folder on the V: drive as a function of gap over the 7.2 mm—33 mm operational range.

The legend explains the different cases that are shown in the plot: The green filled circles are data acquired on axis as the gap was changed from close to open. The yellow filled circles are data acquired on axis as the gap was changed from open to close. The horizontal red dashed lines show the tolerance limits. Note: The undulator  $K_{\text{eff}}$  value shows a hysteresis, i.e., for a given gap, the value depends on the direction of gap motion to reach that gap. While this is not a desirable feature, its effect stays within the given tolerance and will be acceptable. The other symbols shown indicate off-axis measurements that are added for interest only. The tolerance limits apply for on-axis readings, only.



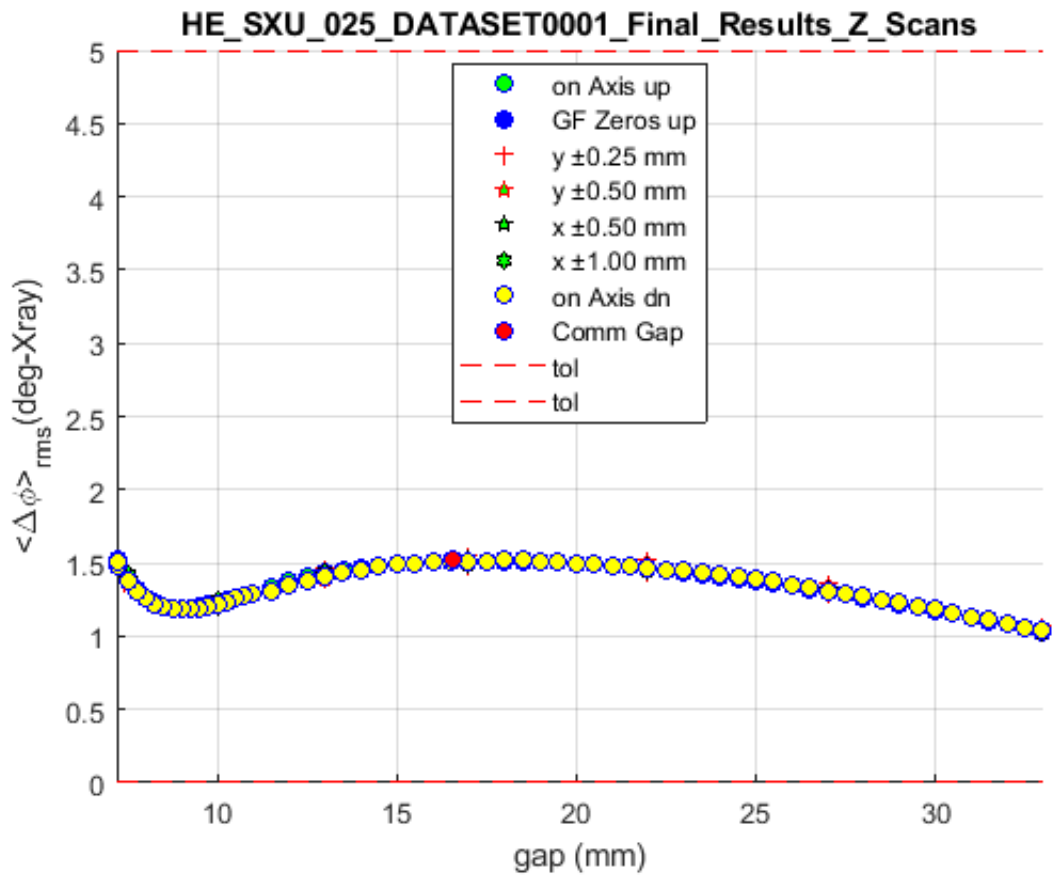
Evaluation of Hall Scans:  $(K_{\text{eff}} - K_{\text{CntrlData}}) / K_{\text{CntrlData}}$  vs gap



The figure shows some of the data shown in the previous figure but with a larger vertical scale that just captures the tolerance range. The off-axis measurements are not shown.



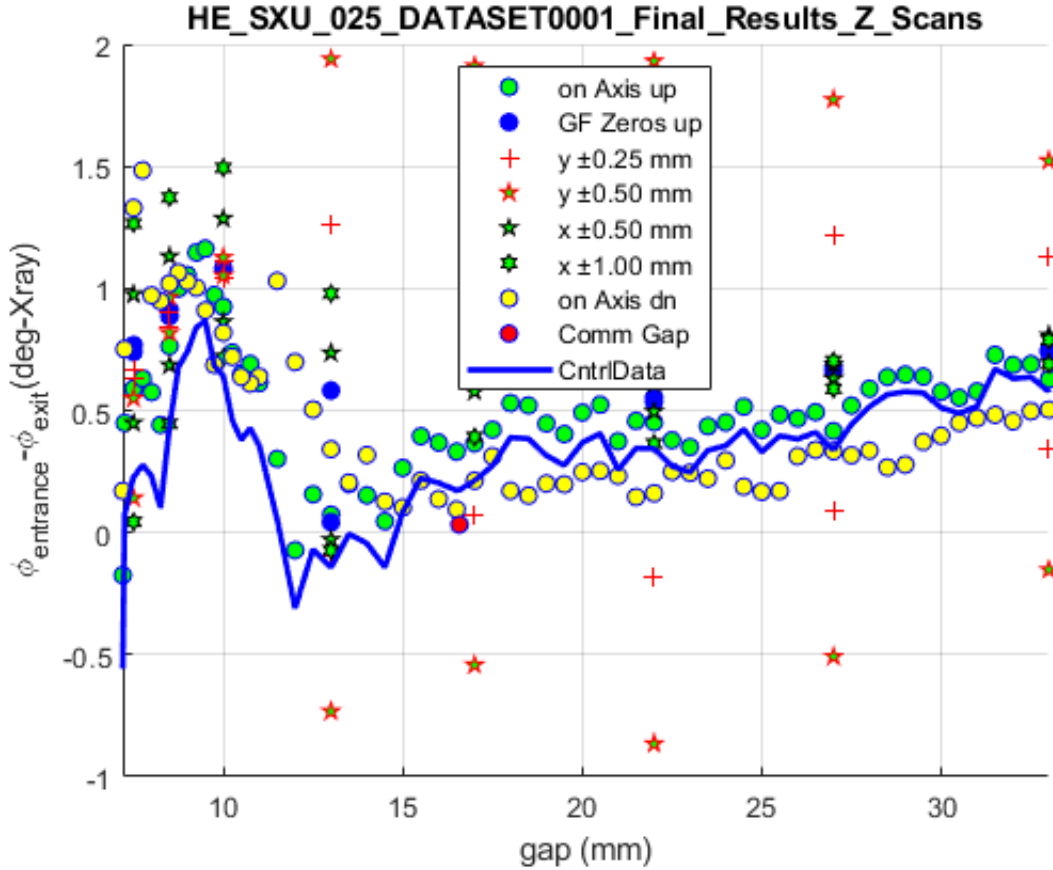
### Evaluation of Hall Scans: Phase Shake vs gap



The figure shows the phase shake,  $\langle \Delta\phi \rangle_{rms}$ , (see Eq. 1 above on page 15) as a function of operational gap. The vertical axis extends over the entire tolerance range. The values show a slight hysteresis (show explanation above) but are well within tolerance.



Evaluation of Hall Probe: Entrance to Exit Phase Error Balance vs. gap



The figure shows a (negligible) imbalance of the entrance (cell boundary start to undulator core) to the exit (undulator core to cell boundary end) phase slippage for the undulator. In addition to the signals described above, the blue curve is a spline fit to the difference of the data in files

```
“..._phase_match_enter_vs_gap_spline.dat”
“..._phase_match_exit_vs_gap_spline.dat”.
```

The small change in phase difference between opening and closing measurements shows the effect of gap hysteresis. The explanation for the legend items can be found on previous pages above. The entrance and exit phase slippage is calculated as

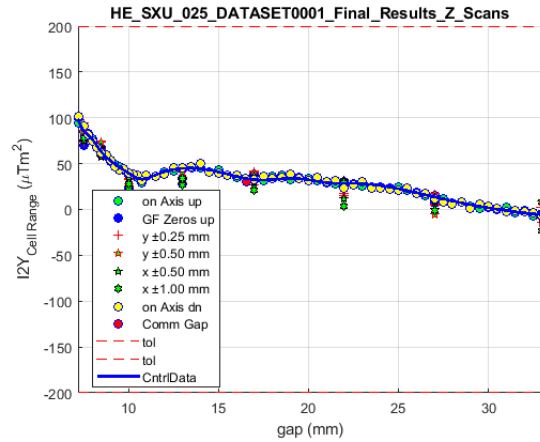
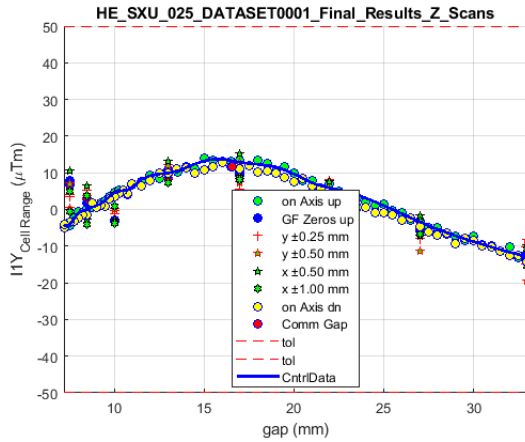
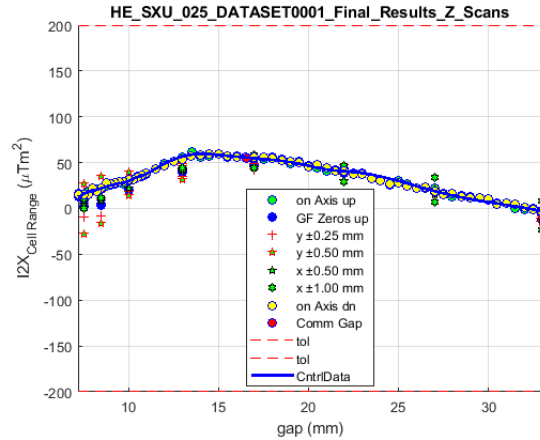
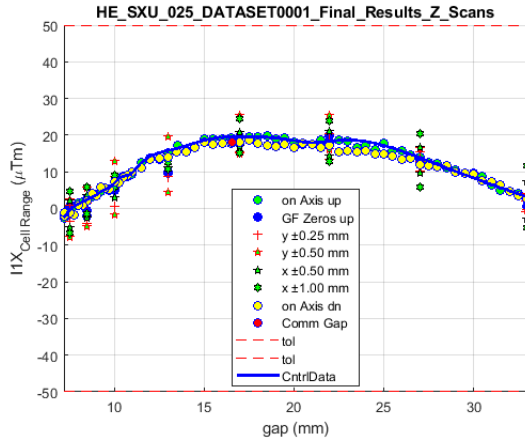
$$\phi_{\text{entrance}} = -\phi(z_{\text{Cell-Start}}) + \frac{1}{n+1} \sum_{j=1}^{n+1} (\phi(z_{(B0,j)}) - \pi(j-1)). \quad (2)$$

$$\phi_{\text{exit}} = -\phi(z_{\text{Cell-End}}) - \frac{1}{n+1} \sum_{j=1}^{n+1} (\phi(z_{(B0,j)}) + \pi(n+1-j)). \quad (3)$$

Here,  $z_{(B0,j)}$  is the  $z$  location of the zero crossing of  $B_y(z)$  in front of the  $j^{\text{th}}$  core  $B_y$  peak.  $z_{(B0,(n+1))}$  is the  $z$  location of the field zero of  $B_y(z)$  after the last core  $B_y$  peak.



Evaluation of Hall Probe: Field Integrals vs. gap



The figures show the field integrals (I1X, I2X, I1Y, I2Y) as functions of the operational gap. The proximity of the green and yellow circles shows that the field integrals are not sensitive to the hysteresis in  $K$  as seen on a previous page. The blue curves are spline fits to the data in files

```

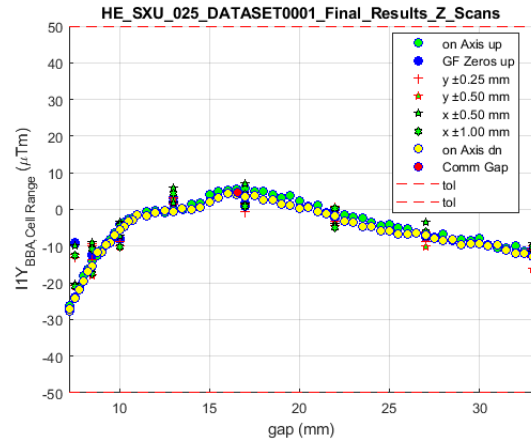
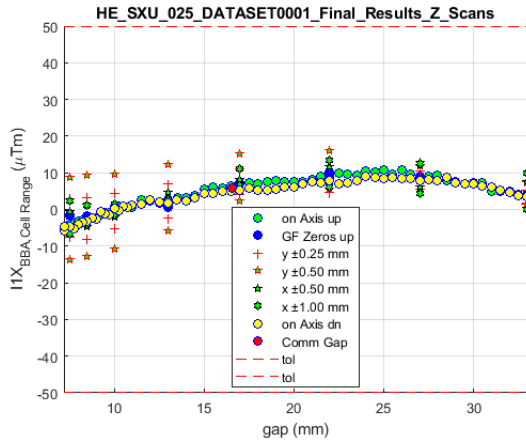
"...i1xvsgap_spline.dat",
"...i2xvsgap_spline.dat",
"...i1yvsgap_spline.dat",
"...i2yvsgap_spline.dat",

```

and demonstrate how the controls representations of the field integrals relates to the actual measurements (see final section of this document for file information).



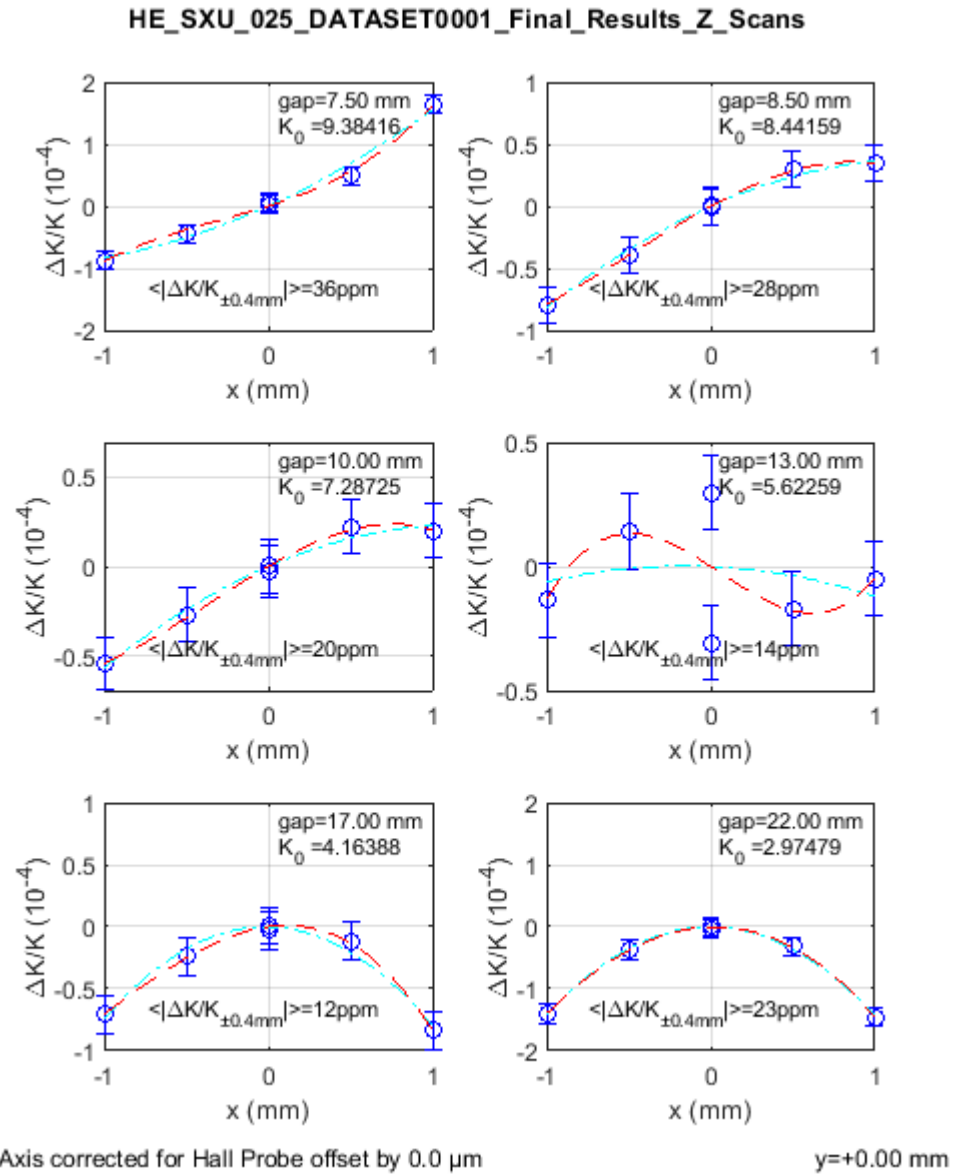
### Evaluation of Hall Probe: BBA Field Integrals



The figure shows the first integrals after a BBA equivalent correction was applied. The values stay within tolerance over the operational range.



Evaluation of Hall Scans:  $K$  vs.  $x$  dependence

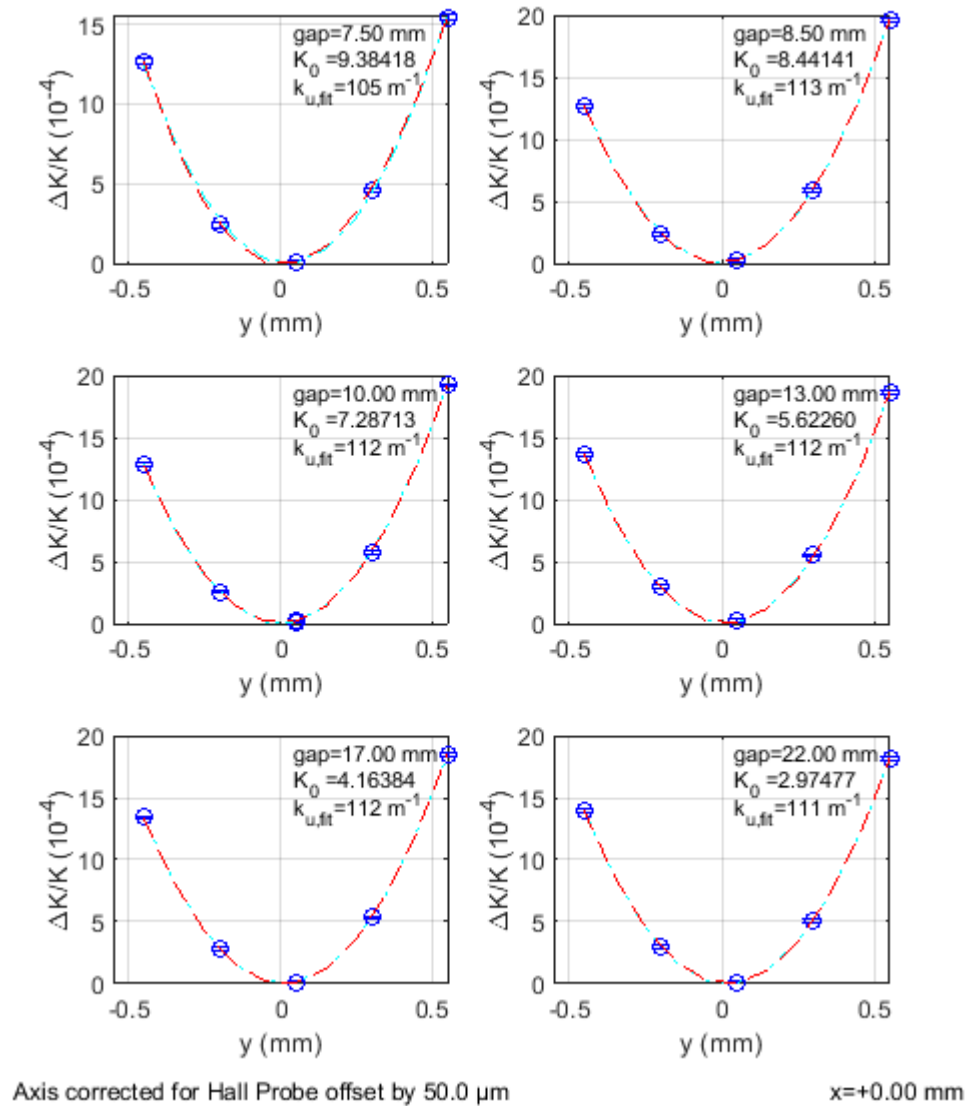


The figure shows the deviation of the relative undulator strength,  $K$ , from the off-axis value,  $K_0$ , as function of  $x$  at a number of operational gaps. The dash-dot lines are polynomial fits to the data (cyan: 2<sup>nd</sup> order, red: 3<sup>rd</sup> order). The average deviation at  $z = 0.4$  mm is well below the tolerance of 160 ppm in all cases.



Evaluation of Hall Scans:  $K$  vs.  $y$  dependence

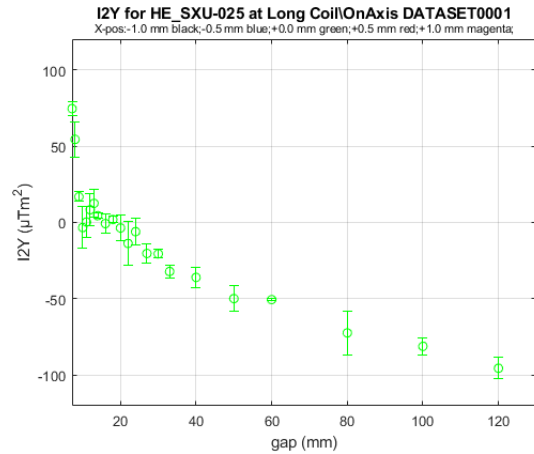
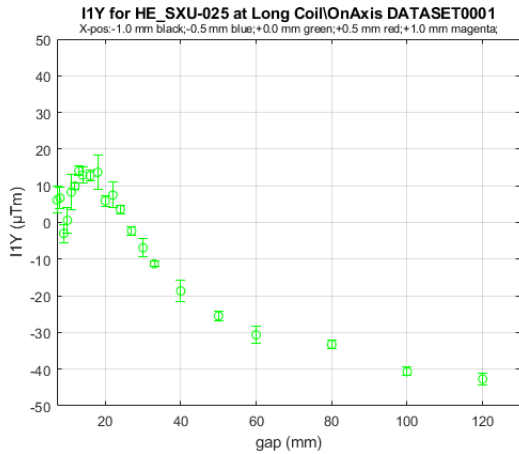
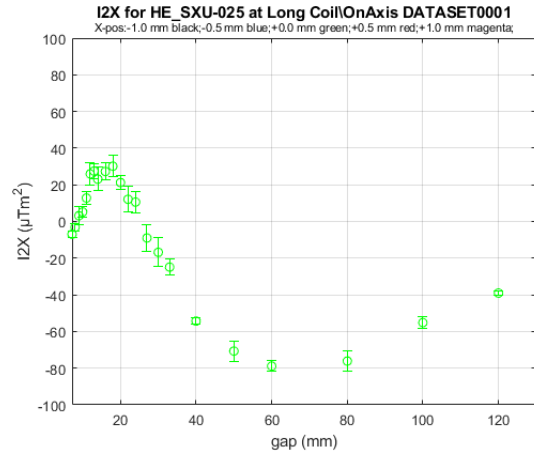
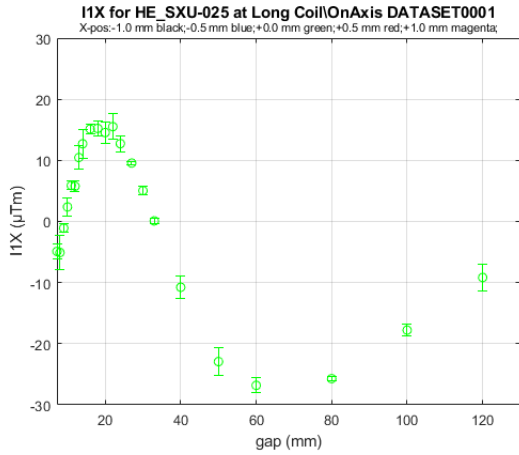
HE\_SXU\_025\_DATASET0001\_Final\_Results\_Z\_Scans



The figure shows the deviation of the relative undulator strength,  $K$ , from the off-axis value,  $K_0$ , as function of  $y$  at a number of operational gaps. The dash—dot lines are polynomial fits to the data (cyan: 2<sup>nd</sup> order, red: 3<sup>rd</sup> order). The deviations follow closely the expected functional form ( $\cosh(k_u y) - 1$ ). The value of  $k_{u,fit}$ , calculated from the fit parameters, is recorded in the upper right hand corner of each figure. These values are quite close to the expected value of  $112.207 m^{-1}$ .



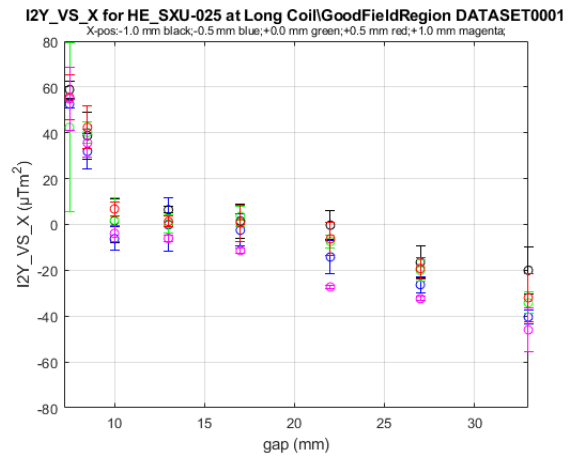
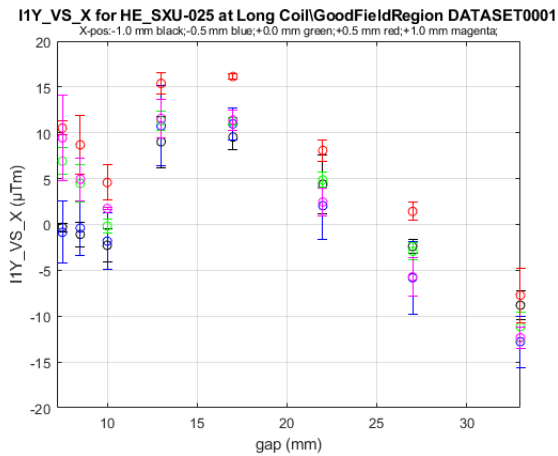
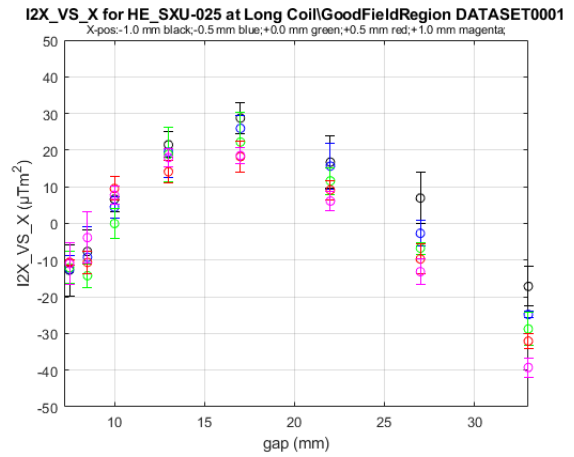
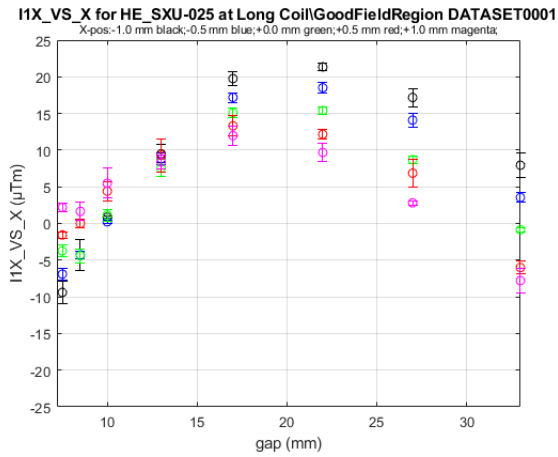
### Long Coil Measurement of the On-Axis Field Integrals



The figure shows the field integrals obtained from long coil measurements on-axis. The vertical axes extend over the tolerance range. All integrals are in tolerance.



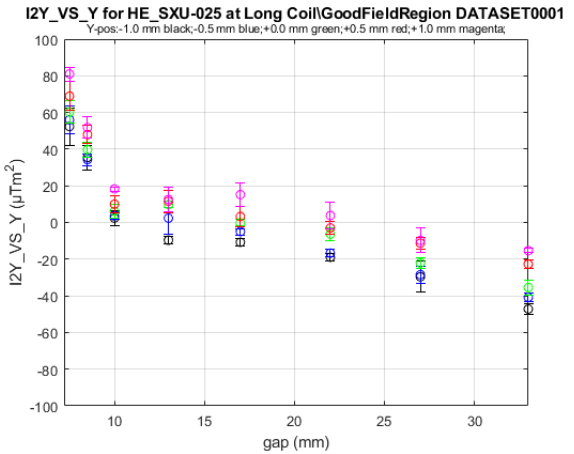
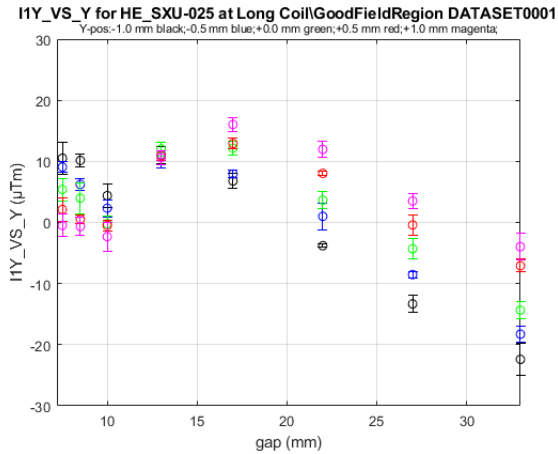
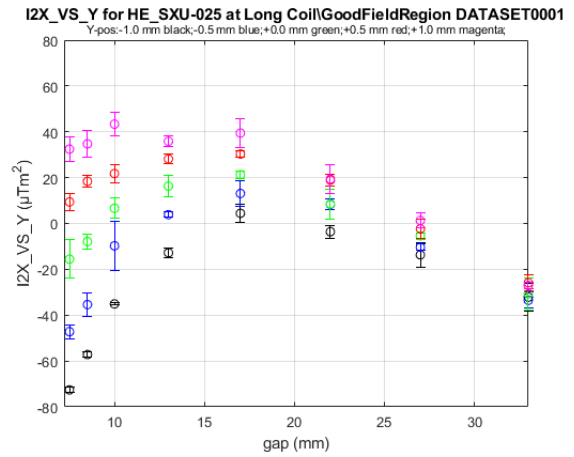
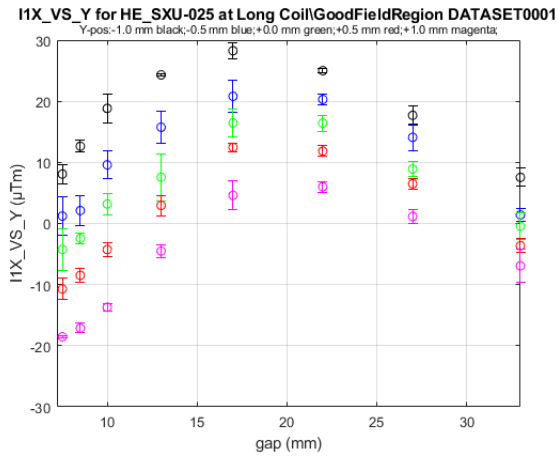
### Long Coil Measurement of the Horizontally Off-Axis Field Integrals



The figure shows the integrals obtained from long coil measurements off axis in the vertical plane using colors to indicate offset distance (black: -1.0 mm, blue: -0.5 mm, green: on-axis; red: +0.5 mm, magenta: +1.0 mm). The vertical axes extend of the tolerance range. All integrals are in tolerance.



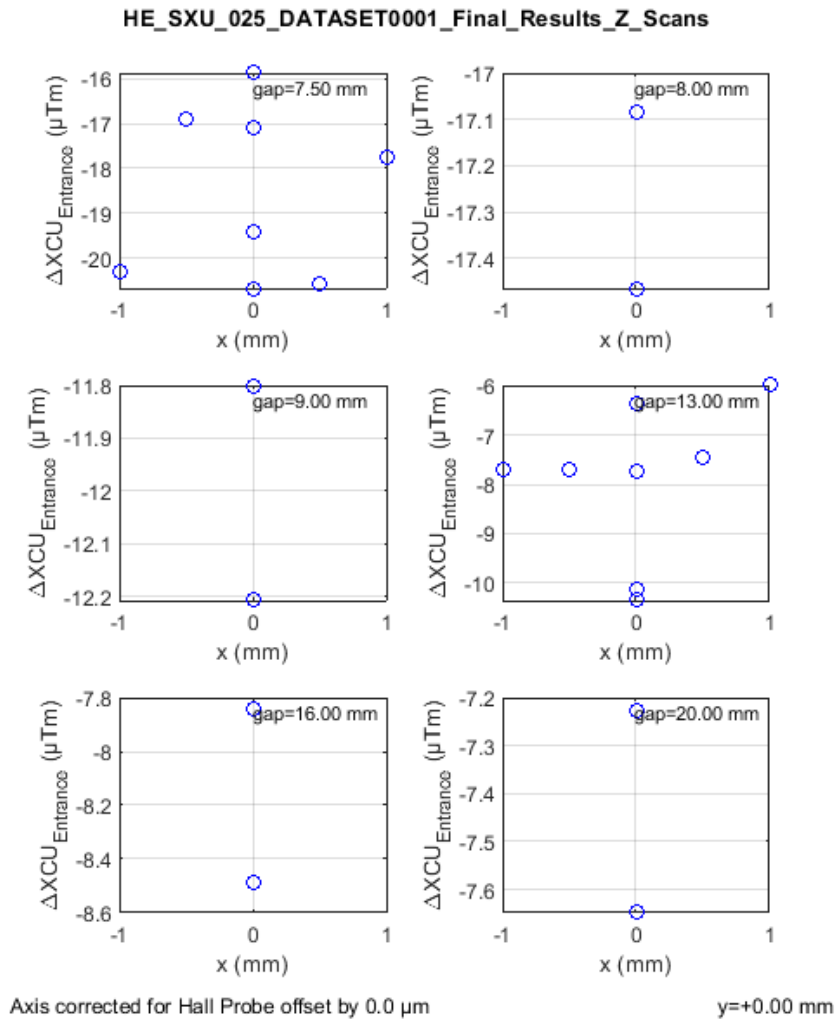
Long Coil Measurement of the Vertically Off-Axis Field Integrals



The figure shows the field integrals obtained from long coil measurements off axis in the horizontal plane using colors to indicate offset distance (black: -1.0 mm, blue: -0.5 mm, green: on-axis; red: +0.5 mm, magenta: +1.0 mm). The vertical axes extend over the tolerance range. All integrals are in tolerance.



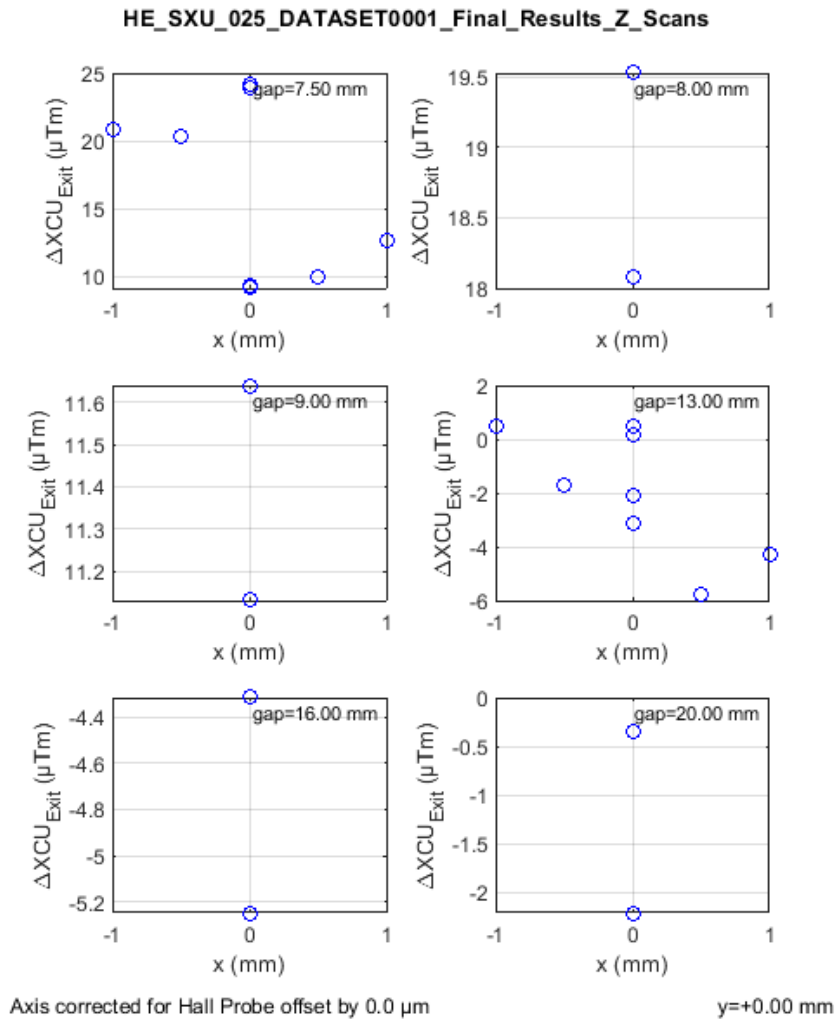
Estimated Upstream Horizontal Corrector Strength Requirement vs.  $x$



The figure shows the required strength of the upstream horizontal corrector to remove the second vertical undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z plane. All values are small and well below the maximum correction capabilities of greater than 550  $\mu Tm$  of the actual correctors.



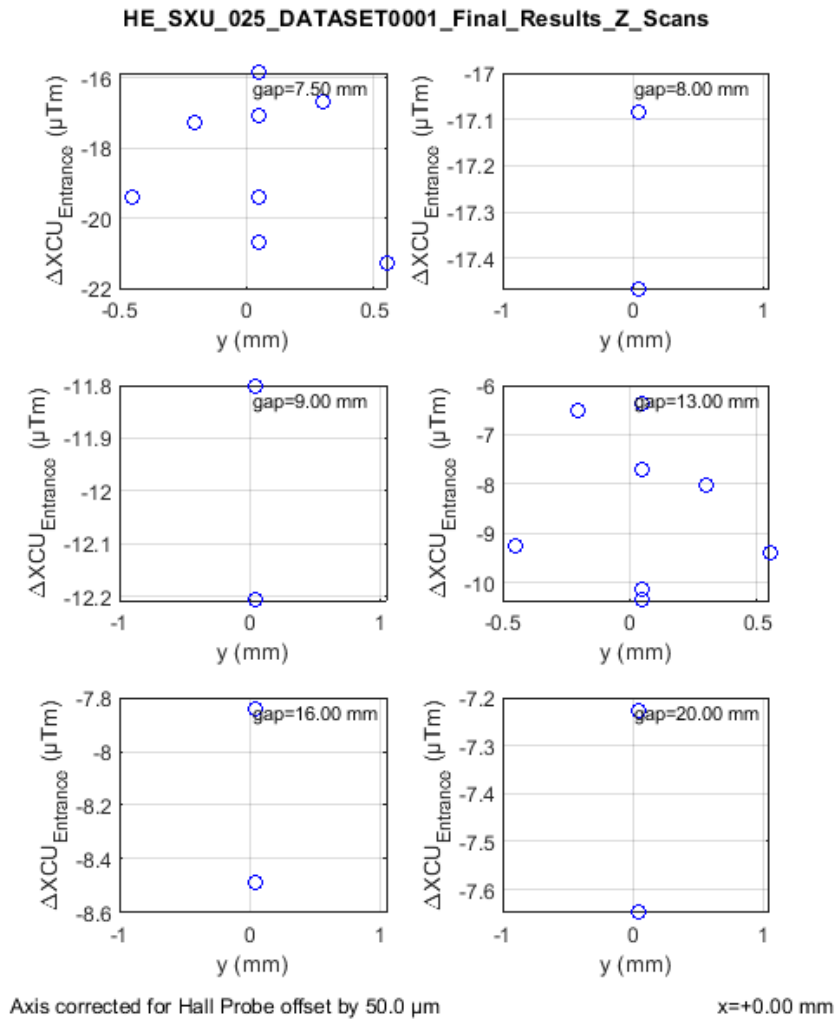
**Estimated Downstream Horizontal Corrector Strength Requirement vs.  $x$**



The figure shows the required strength of the downstream horizontal corrector to remove the first vertical undulator field integral and upstream corrector field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z plane. All values are small and well below the maximum correction capabilities of greater than 550  $\mu Tm$  of the actual correctors.



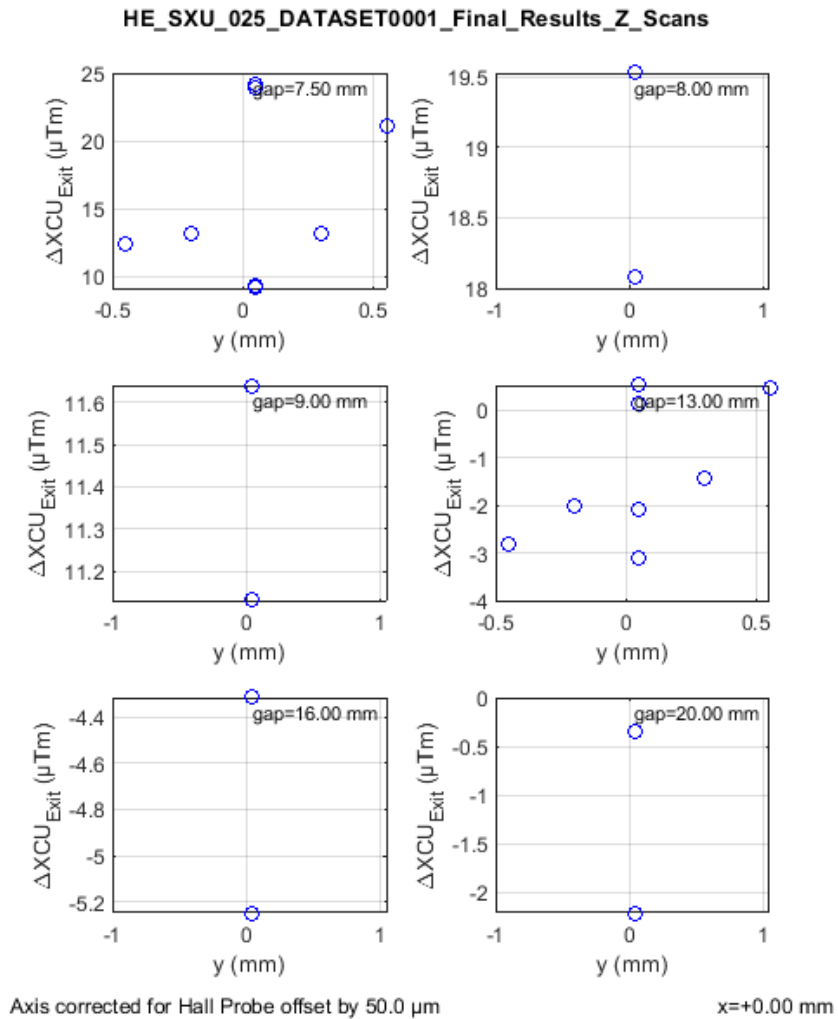
Estimated Upstream Horizontal Corrector Strength Requirement vs.  $y$



The figure shows the required strength of the upstream horizontal corrector to remove the second vertical undulator field integrals at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the y-z plane. All values are small and well below the maximum correction capabilities of greater than 550  $\mu Tm$  of the actual correctors.



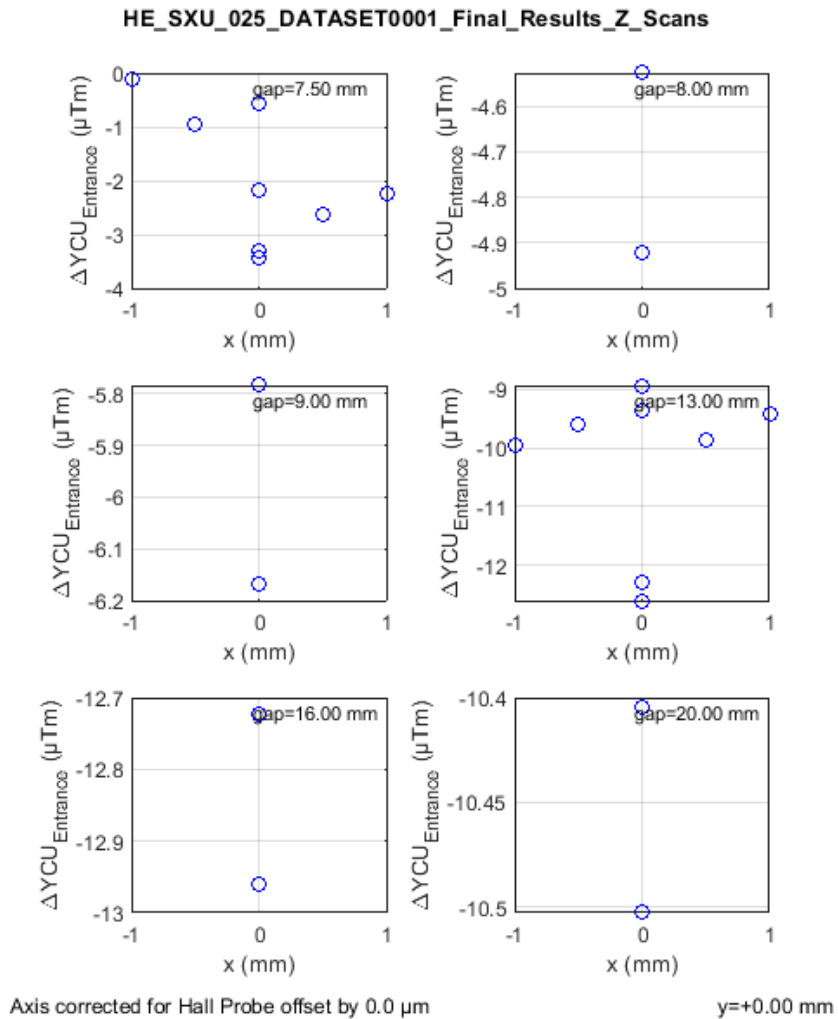
Estimated Downstream Horizontal Corrector Strength Requirement vs.  $y$



The figure shows the required strength of the upstream horizontal corrector to remove the first vertical undulator and upstream corrector field integrals at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the  $y$ - $z$  plane. All values are small and well below the maximum correction amplitude of greater than 550  $\mu Tm$  capabilities of the actual correctors.



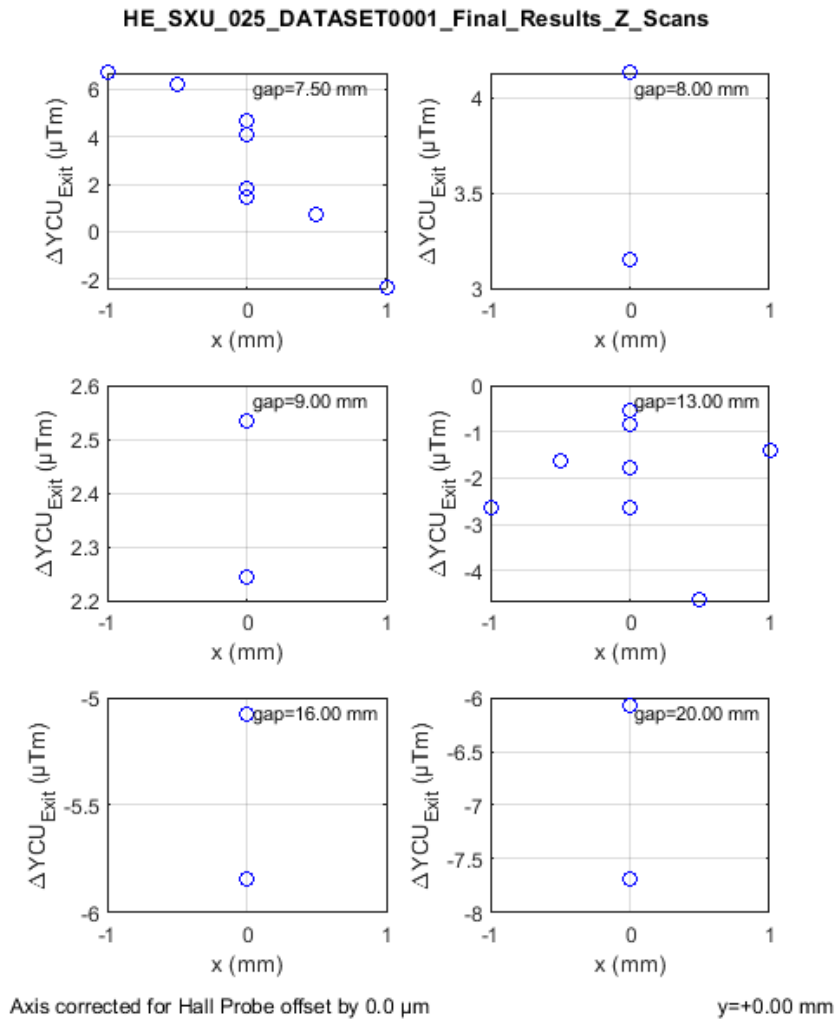
**Estimated Upstream Vertical Corrector Strength Requirement vs.  $x$**



The figure shows the required strength of the upstream horizontal corrector to remove the second horizontal undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z plane. All values are small and well below the maximum correction capabilities of greater than 550  $\mu Tm$  of the actual correctors.



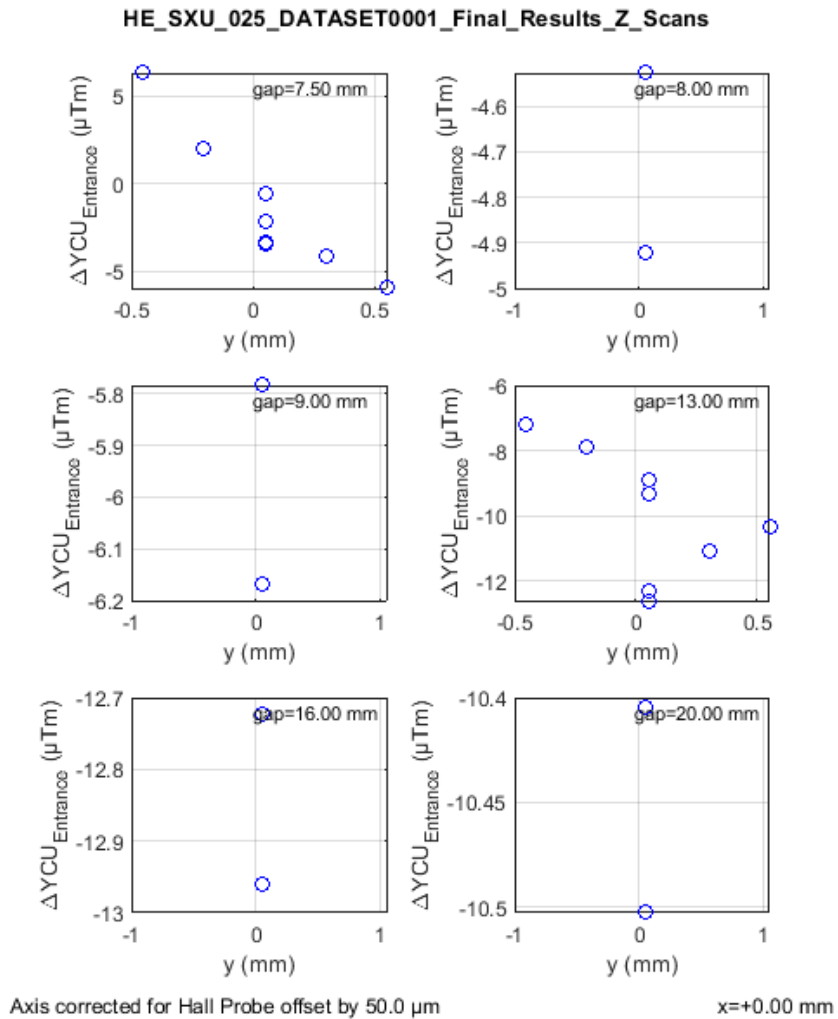
**Estimated Downstream Vertical Corrector Strength Requirement vs.  $x$**



The figure shows the required strength of the downstream vertical corrector to remove the first horizontal undulator field integral and upstream corrector field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z plane. All values are small and well below the maximum correction capabilities of greater than 550  $\mu Tm$  of the actual correctors.



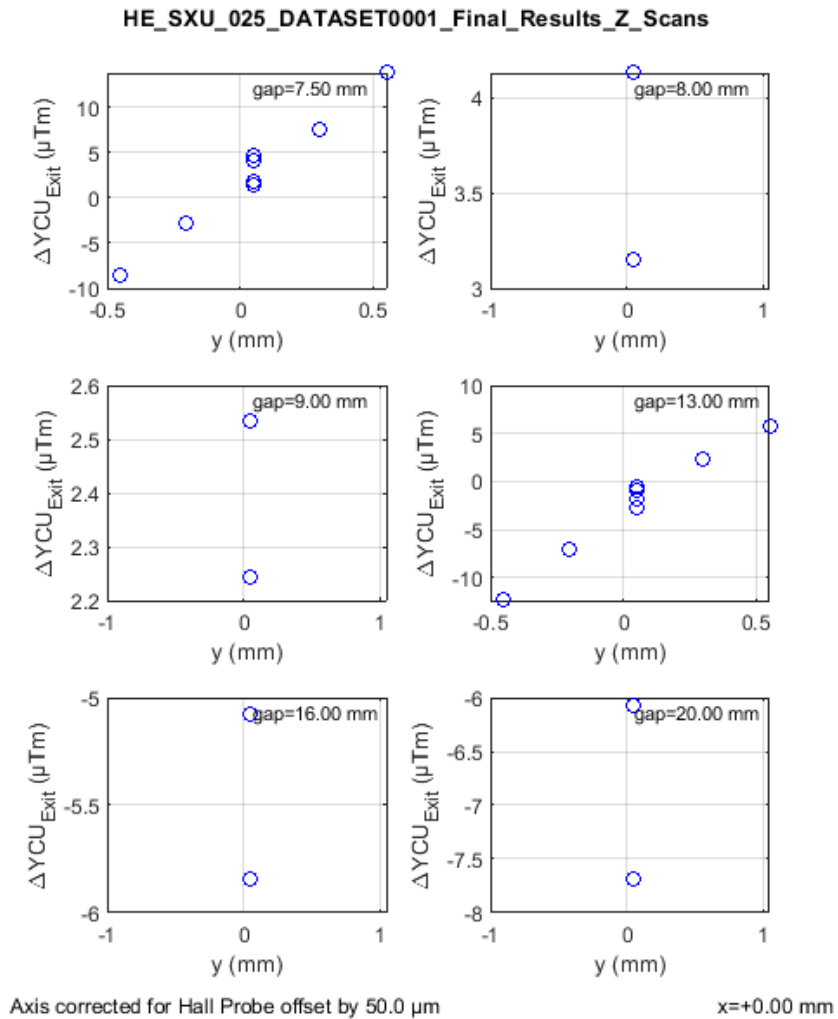
**Estimated Upstream Vertical Corrector Strength Requirement vs.  $y$**



The figure shows the required strength of the upstream vertical corrector to remove the second horizontal undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the  $y$ - $z$  plane. All values are small and well below the maximum correction capabilities of greater than 550  $\mu Tm$  of the actual correctors.



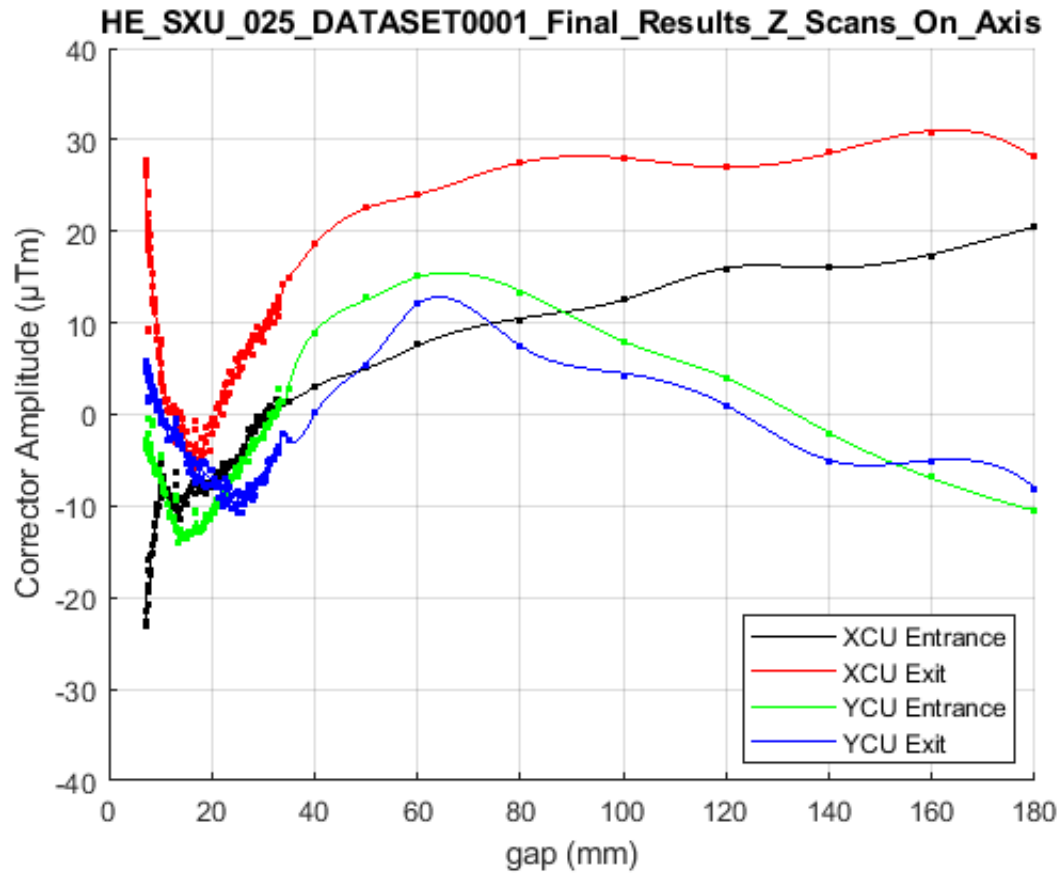
**Estimated Downstream Vertical Corrector Strength Requirement vs.  $y$**



The figure shows the required strength of the downstream vertical corrector to remove the first horizontal undulator field integral and the upstream corrector field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the  $y$ - $z$  plane. All values are small and well below the maximum correction capabilities of greater than 550  $\mu Tm$  of the actual correctors.



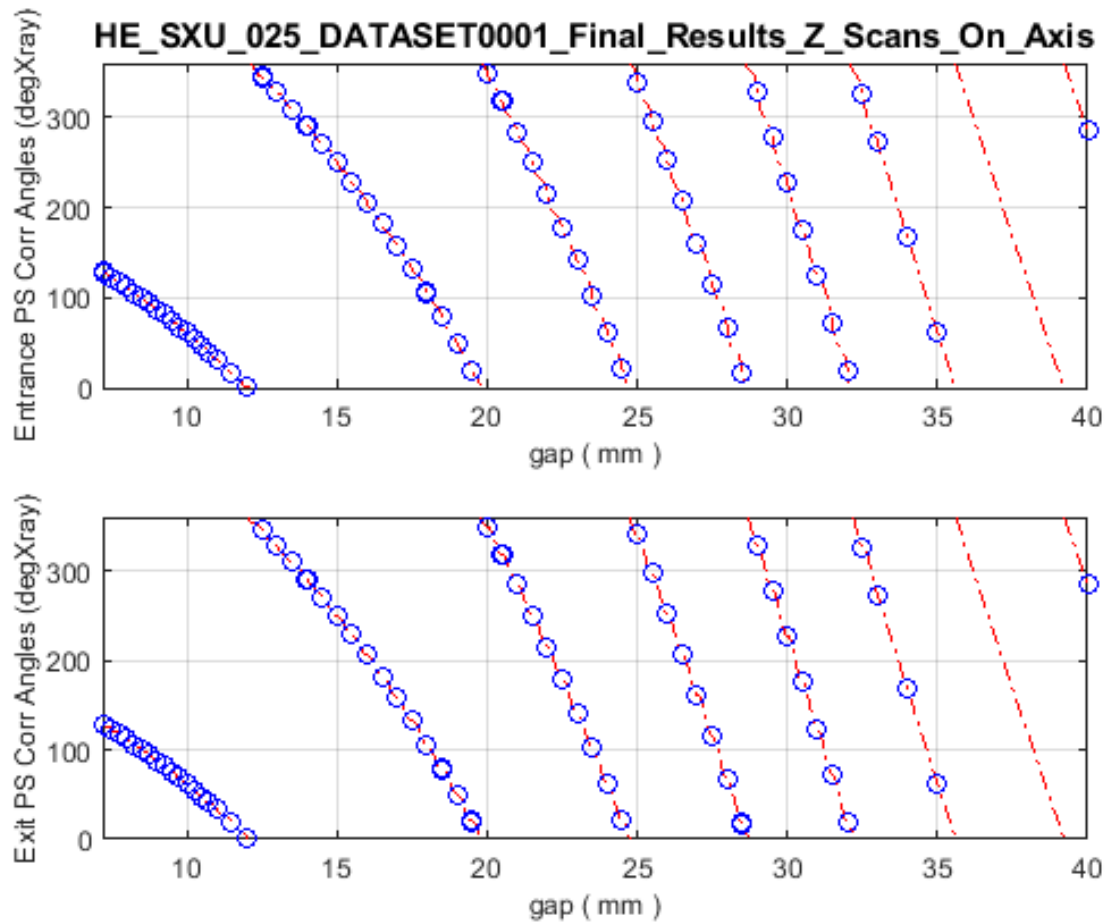
### Estimated Corrector Strengths Requirement vs. gap



The figure shows as a function of undulator gap the required strengths of the upstream and downstream horizontal and vertical correctors to remove the effect of undulator field integrals at the downstream BPM over the entire available gap range. All values are small and well below the maximum correction capabilities of greater than 550  $\mu\text{Tm}$  of the actual correctors.



### Measured Undulator Entrance and Exit Phase Delays vs. gap

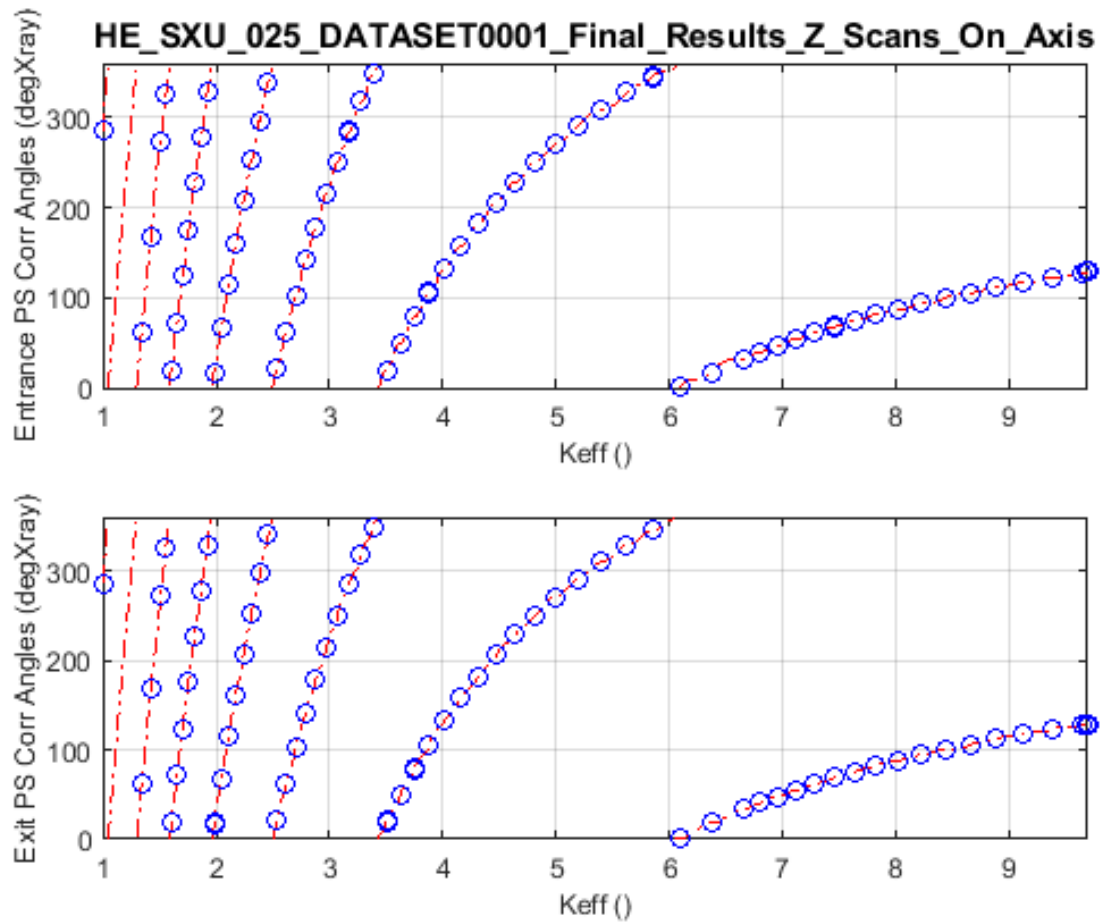


The two figures show, as a function of undulator gap, the phase delays generated by the undulator entrance and exit sections (as calculated by Eqs. 2 and 3 show on page 21), respectively, as red dash—dotted lines. The blue circles indicate MMF measurements.

Note: The break-ups of the function are just for fitting it into the 0 - 360 degXray range, they are not related to the phaseshifter resets needed during operations.



Measured Undulator Entrance and Exit Phase Delays vs.  $K_{\text{eff}}$

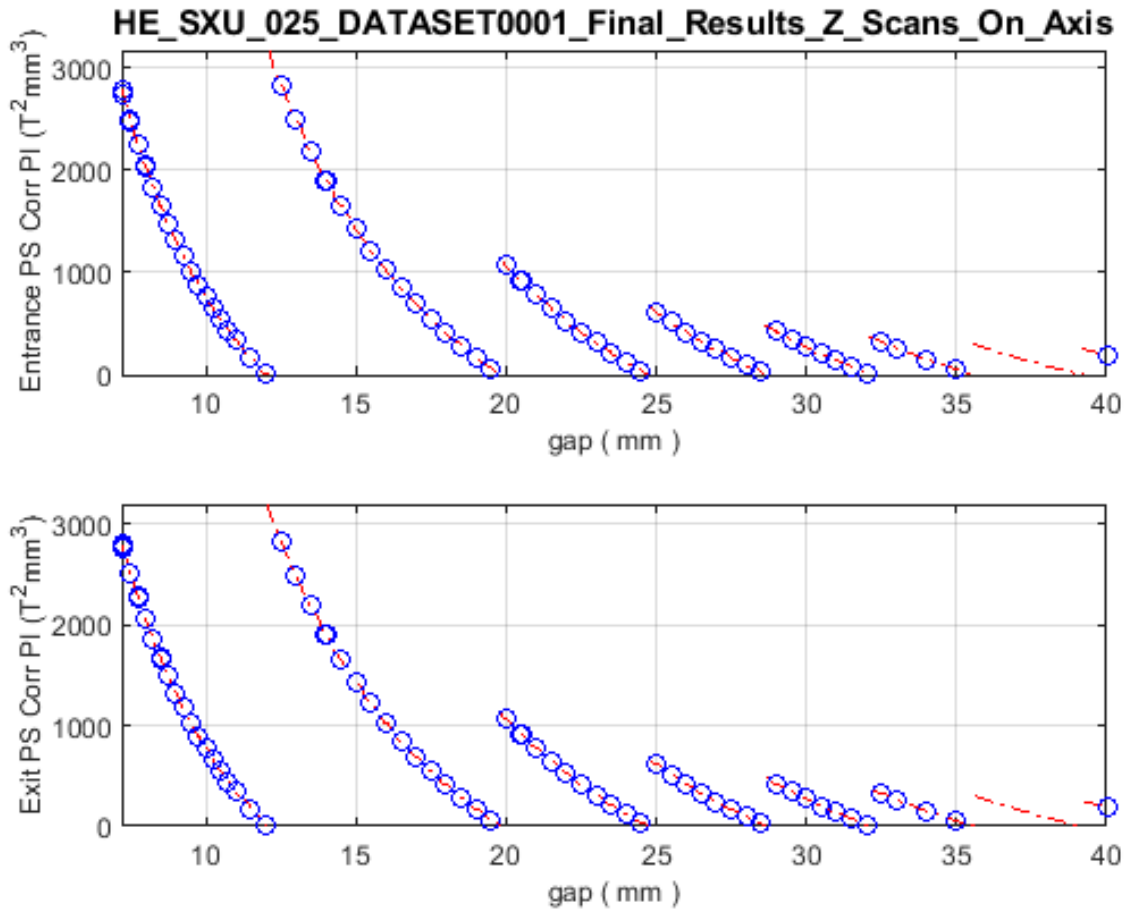


The two figures show, as a function of undulator parameter,  $K_{\text{eff}}$ , the phase delays generated by the undulator entrance and exit sections (as calculated by Eqs. 2 and 3 shown on page 21), respectively, as red dash—dotted lines. The blue circles indicate MMF measurements.

Note: The break-ups of the function are just for fitting it into the 0 - 360 degXray range, they are not related to the phaseshifter resets needed during operations.



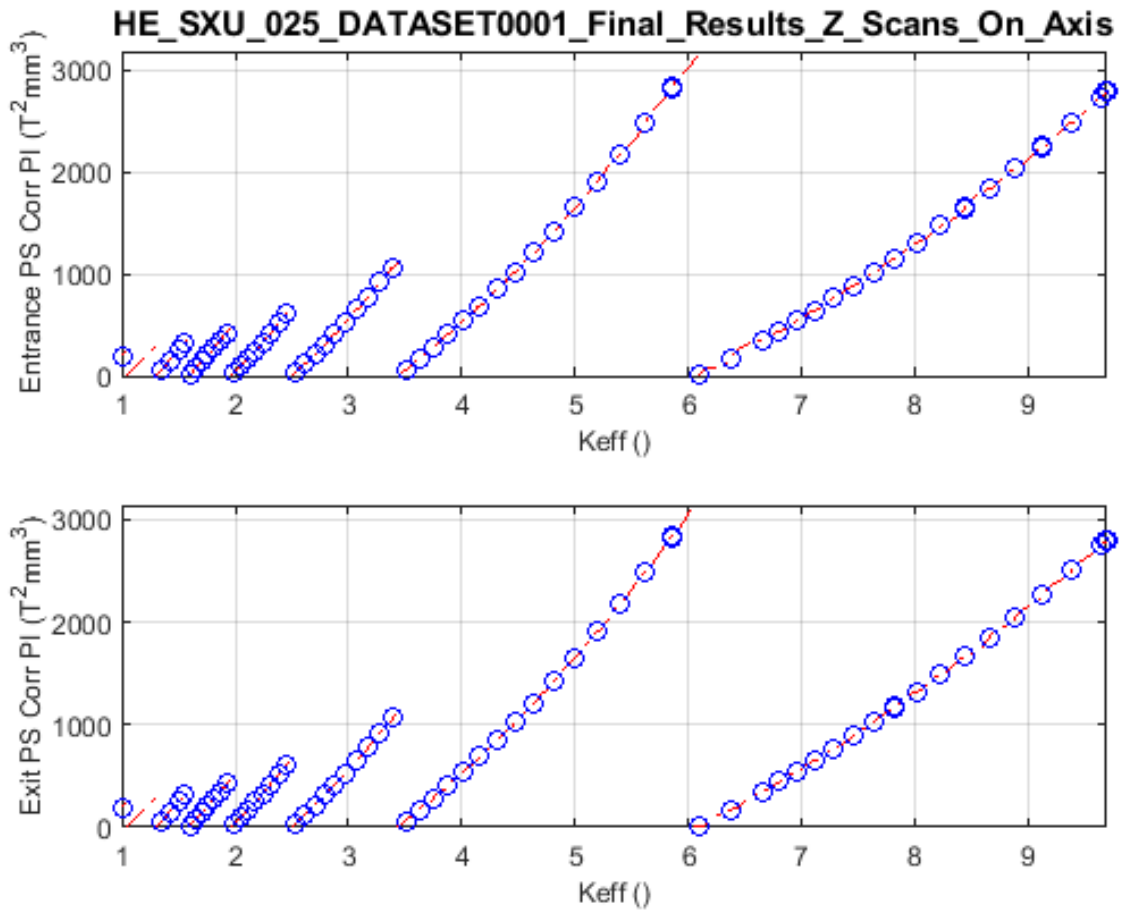
Phase Integrals from Undulator Entrance and Exit Phase Delays vs. gap



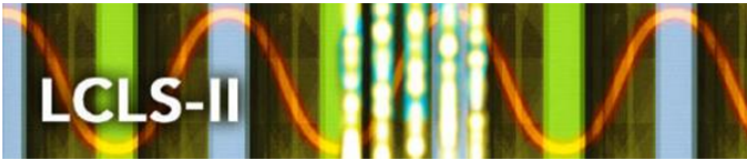
The two figures show, as a function of undulator gap, the phase integral (*PI*) values corresponding to the phase delay angles shown in the figures on page 38. The red dash—dotted lines and the blue circles indicate MMF measurements corresponds to the same symbols in the figures on page 38.



Phase Integrals from Undulator Entrance and Exit Phase Delays vs.  $K_{eff}$

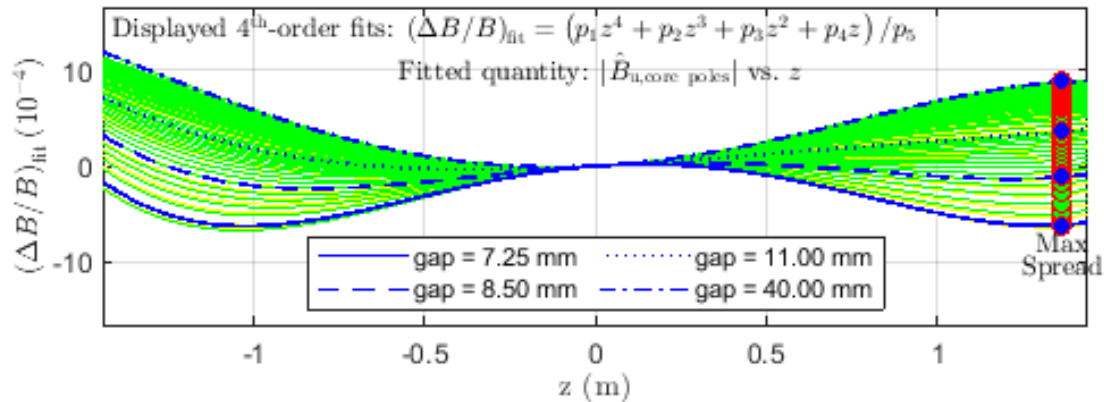


The two figures show, as a function of undulator  $K_{eff}$ , the phase integral ( $PI$ ) values corresponding to the phase delay angles shown in the figures on page 39. The red dash—dotted lines and the blue circles indicate MMF measurements corresponds to the same symbols in the figures on page 39.

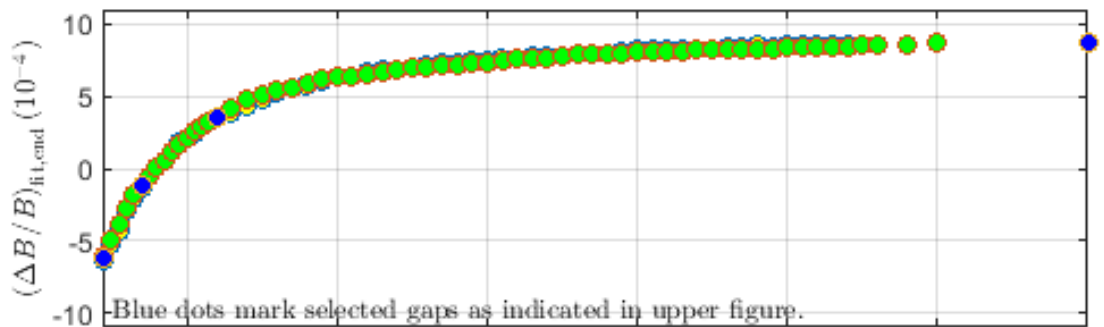


Zero Taper Fit vs. gap

HE\_SXU.025\_DATASET0001\_Final\_Results\_Z\_Scans\_ZeroTaper  
 Fitted Undulator Field Peaks for Various Undulator Gaps



Right Hand Side Values from Upper Figure



Green colors indicate:  
 gap changes in opening direction

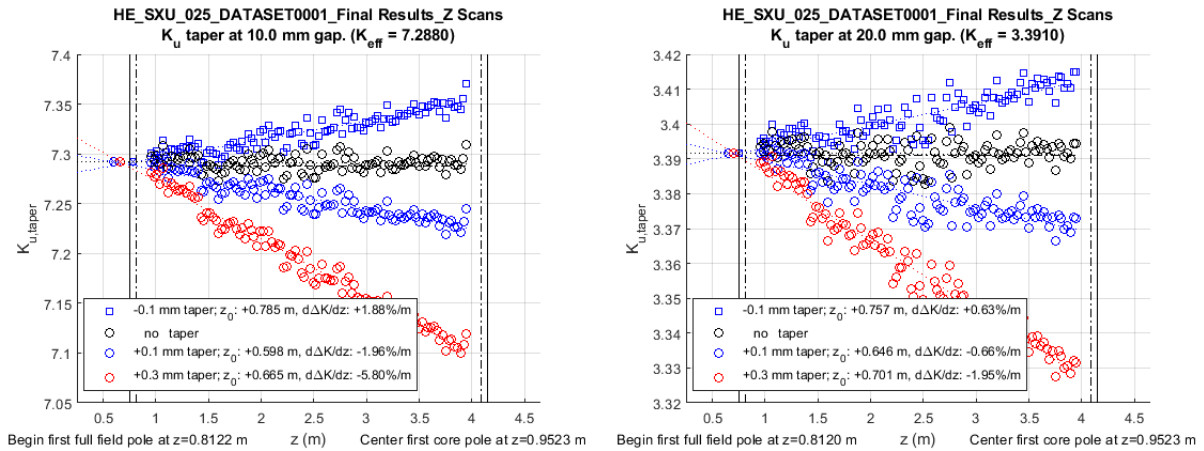
Yellow colors indicate:  
 gap changes in closing direction

The top figure shows 4<sup>th</sup> order fits ( $B_{fit}(z) = p_1 \times z^4 + p_2 \times z^3 + p_3 \times z^2 + p_4 \times z + p_5$ ) to the absolute peak values,  $\hat{B}_u$ , for each core pole for different gaps when the device is set to zero taper. Plotted are  $B_{fit}(z)/p_5 - 1$ . Green curves indicate that the gap was approached from smaller gaps, while yellow curves indicate approach from larger gaps. The  $B_{fit}(z)/p_5 - 1$  value at the  $z$ -position, where the spread is largest is marked with a solid circle with the same color coding. The bottom figure shows the same solid circles as in the upper plot but this time plotted against the corresponding undulator gap values. As expected, the figures show that the undulator has a small 4<sup>th</sup> order taper that varies with gap. This could explain the phase shake dependence on gap as shown in an earlier figure (see page 20).



### Gap Tapering—Tapered $K_u$ Values

The SXU devices support a gap taper, which is controlled by the taper PV, which holds the difference between the upstream and downstream gap encoder readings measured in micro-meter. The taper can be varied over the  $\pm 300 \mu\text{m}$ -range.

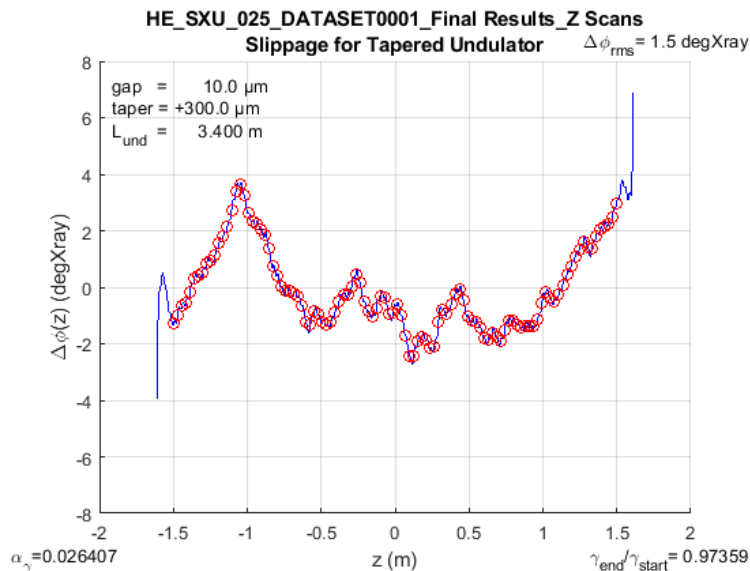
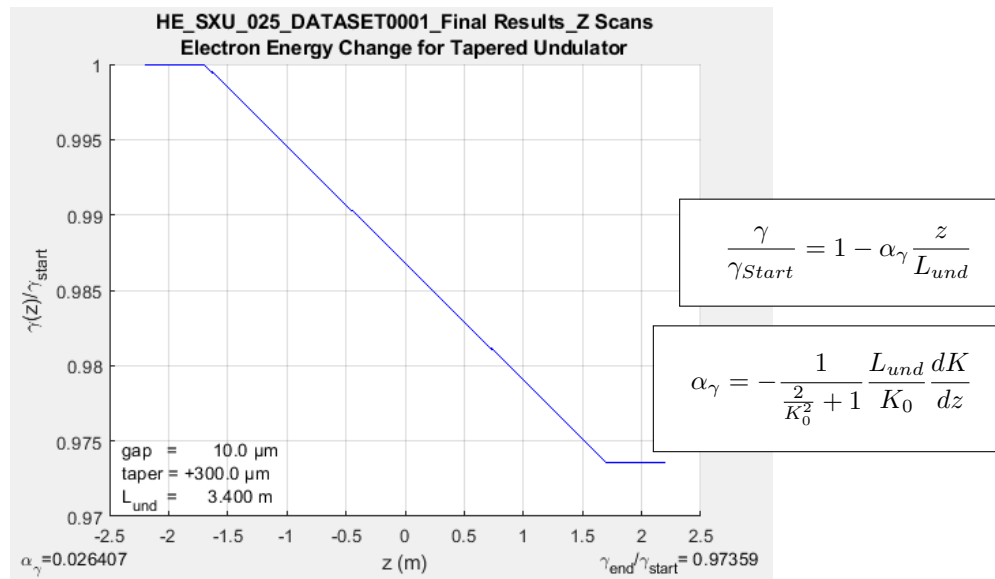


The figure shows  $K_u$ , taper for the 108 core poles based on Hall probe measurements versus  $z$  location for 4 different taper amplitudes ( $-100 \mu\text{m}$ ,  $0 \mu\text{m}$ ,  $+100 \mu\text{m}$ ,  $+300 \mu\text{m}$ ) and 2 different gaps (8 mm, 22 mm). The vertical dashed lines indicate the beginning of the first and the end of the last full field pole. The solid vertical lines indicate the longitudinal limits of strongback. The crosses on the left hand side of the undulator segment border surrounded by the  $K_u$ , taper symbol for the representative taper amplitude indicate the intersections between linear fits (indicated by dotted lines in the representative color) and the  $K_u$  values untapered case with each of the tapered cases. The horizontal dash—dotted line next to the figure center (hard to see) indicated the level of  $K_{\text{eff}}$  of the untapered undulator. The taper operation for this segment is functional.



### Gap Tapering—Tapered $K_u$ Values

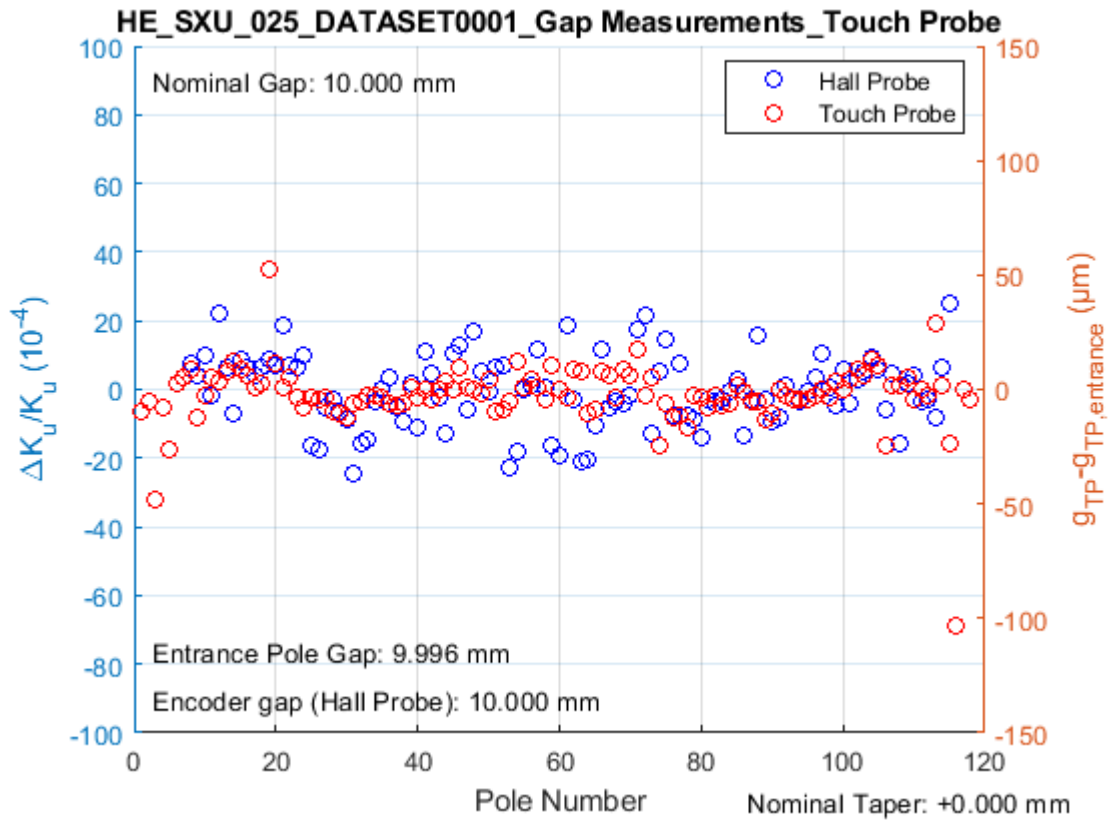
Generally, gap tapering will cause significant increases in the phase shake within the undulator segment. If however during high gain FEL operation the electrons loose significant amounts of energy, a matching gap taper can reduce the total phase shake to stay within the original parallel gap phase shake tolerance for constant energy.



The upper figure shows a simplified linear energy loss function (Lorentz factor  $\gamma/\gamma_{Start}$ ) optimized for the 0.3 mm gap taper at an 10 mm nominal gap. The lower figure shows the phase error along the undulator segment for the same parameters.



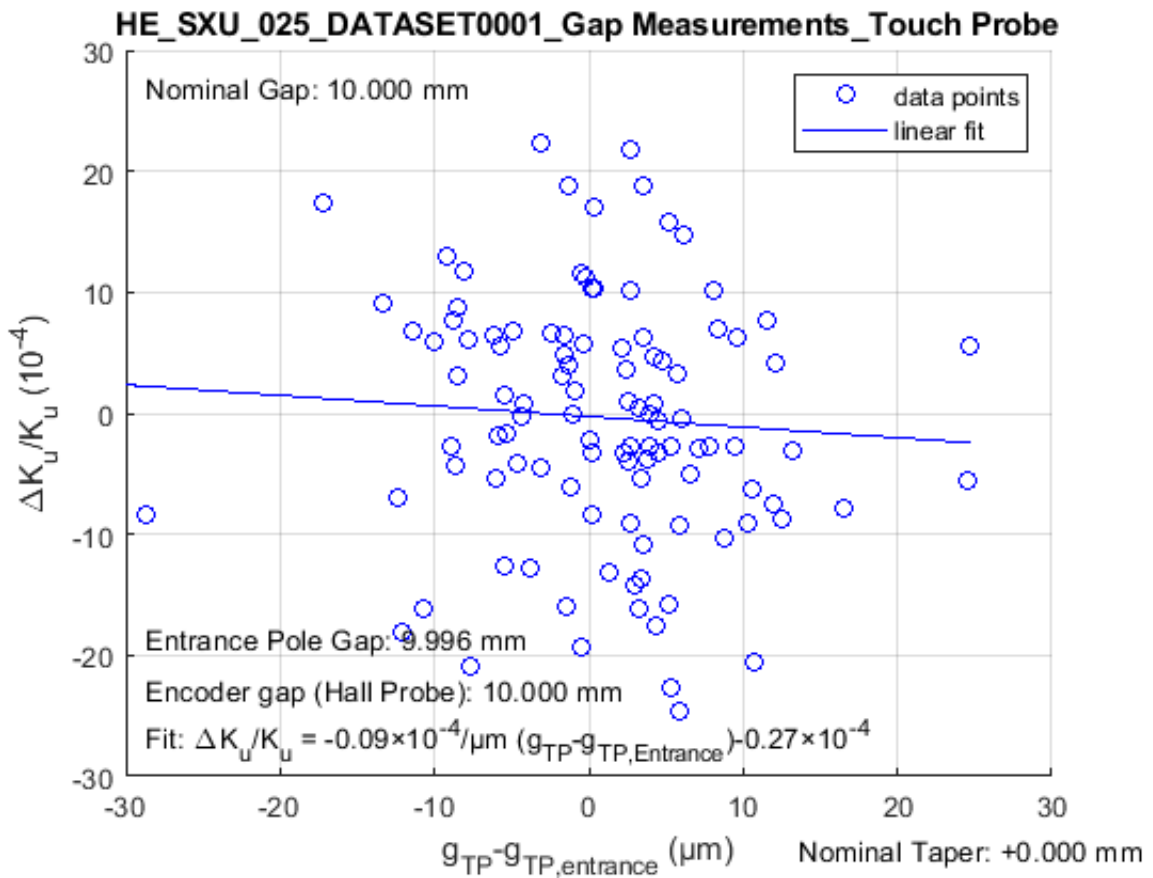
Touch Probe (TP) Analysis — Per pole gap vs. per pole  $K$  (untapered)



The figure shows  $\Delta K/K$  (blue, left axis) (for the 108 core poles) as well as mechanical gap heights ( $\langle g_{TP} \rangle - g_{TP}$ ) (red, right axis) (for all 122 poles) based on touch probe measurements versus pole number. The large amplitude outliers are the result of tuning.



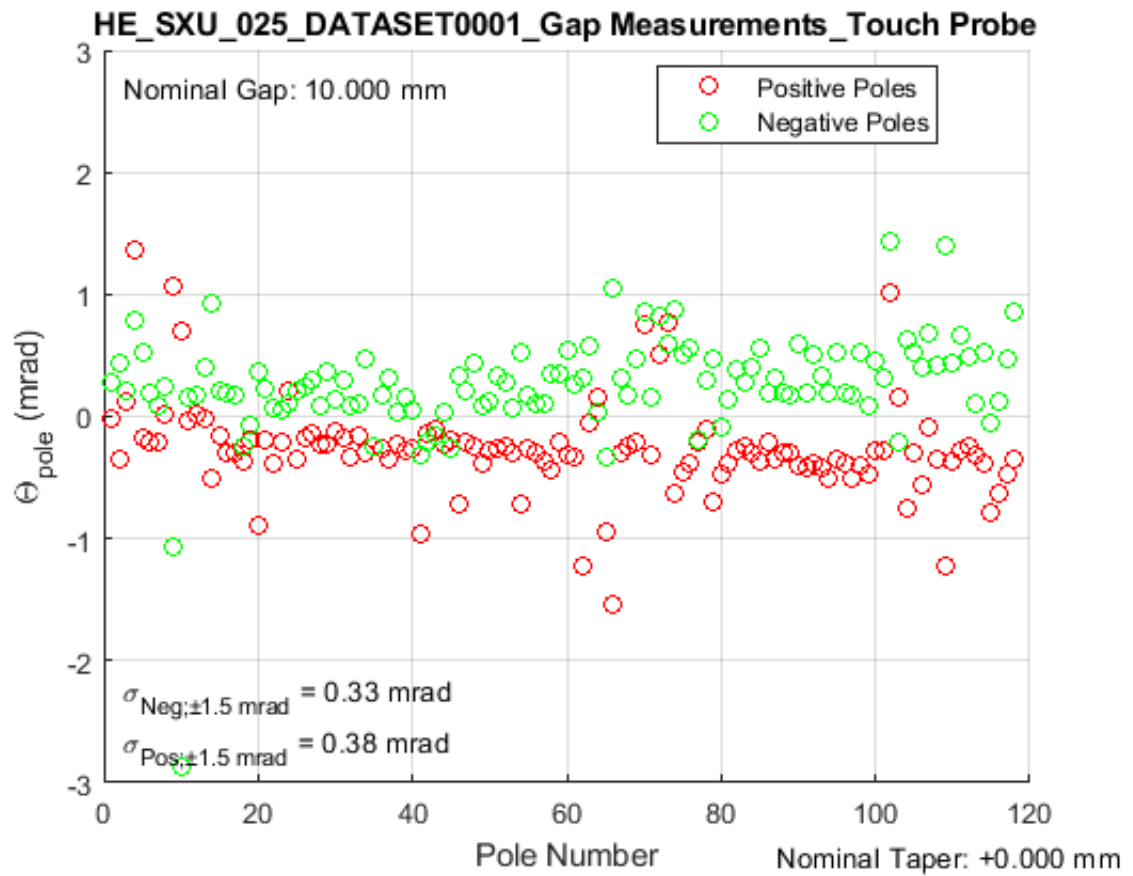
Touch Probe (TP) Analysis —  $K$  vs. per pole gap (untapered)



The figure shows the correlation between the  $\Delta K_u/K_u$  for each pole from Hall probe measurements for the tuning gap and the deviation of the pole gap measured by the touch probe relative to its average (for the 108 core poles). The average gap measured with the touch probe and the one measured with the gap encoder are shown in the lower left corner of the figure. Also shown is the fit function.



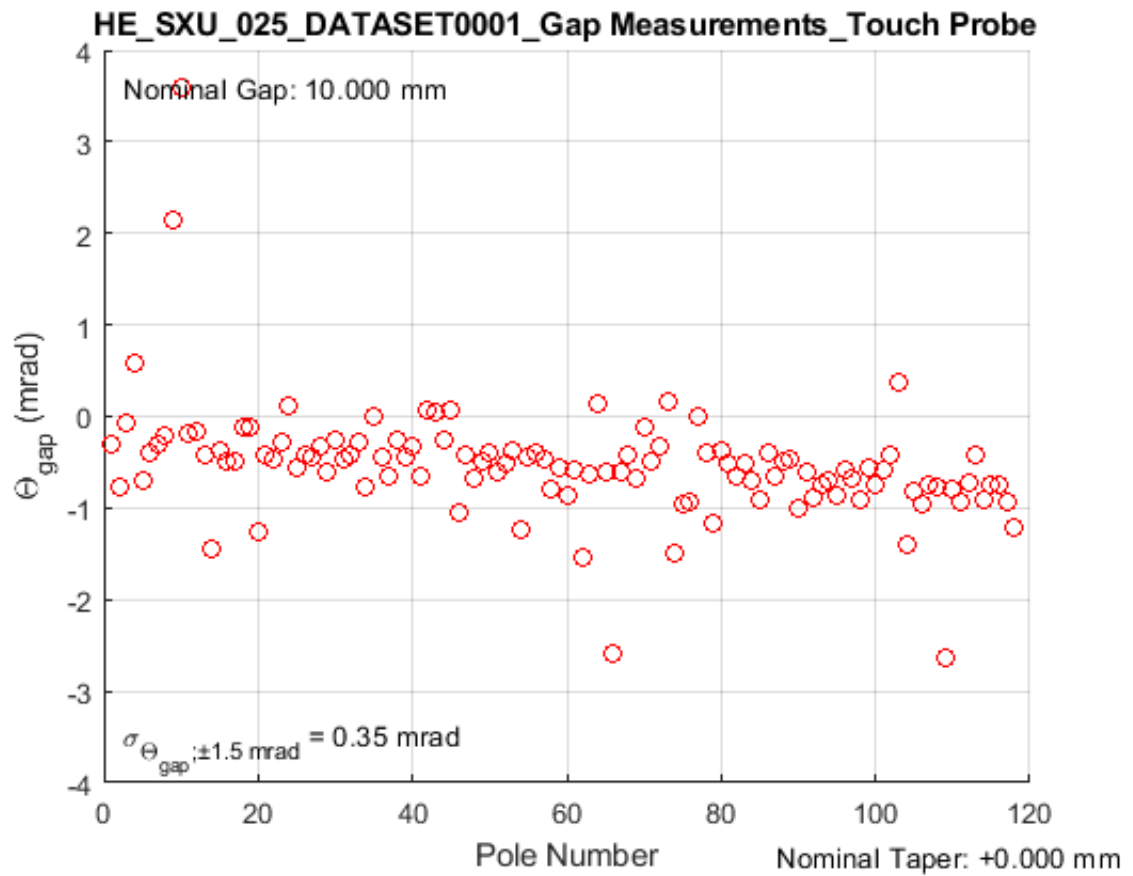
Touch Probe (TP) Analysis — Pole Cant Angles (untapered)



The figure shows the cant angles of each pole (top red, bottom green) relative to the horizontal plane defined by the Kugler bench at the Tuning Gap for all 122 poles, measured by the touch probe. The rms width of each distribution within a  $\pm 1.5$  mrad band is shown in the lower left corner of the figure.



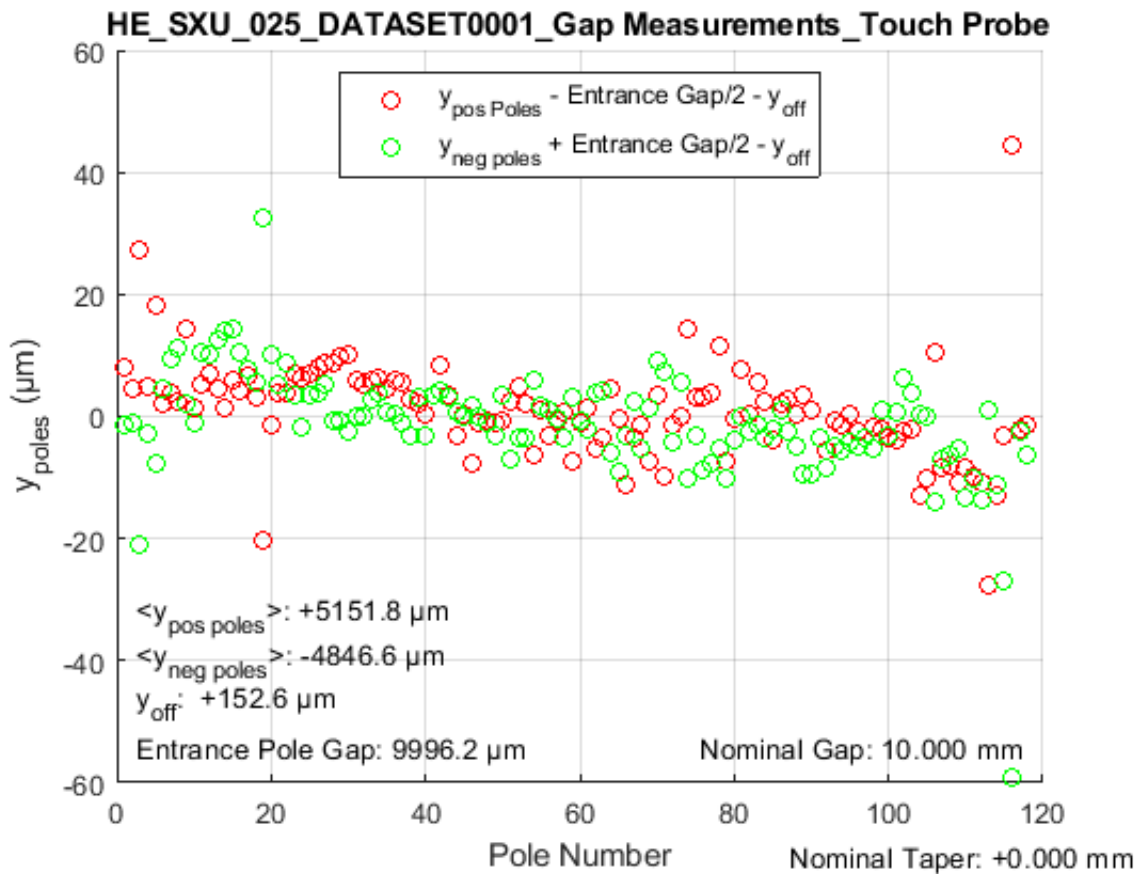
Touch Probe (TP) Analysis — Gap Cant Angles (untapered)



The figure shows the cant angles between the top and bottom part of each pole at the Tuning Gap for all 122 poles, measured by the touch probe. The rms width of each distribution within a  $\pm 1.5$  mrad band is shown in the lower left corner of the figure.



Touch Probe (TP) Analysis — Pole Heights (untapered)



The figure shows the relative vertical positions of the center of each pole (top red, bottom green) relative to the horizontal plane defined by the Kugler bench at the Tuning Gap for all 122 poles, measured by the touch probe.



LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU.025

## Measurement Results are stored:

### At V-Drive:

V:\MET\MagServe\MagData\LCLS-II-HE\Undulator\  
 \_\_\_\_\_

### In Folder

HE\_SXU.025\DATASET0001\Final Results\  
 \_\_\_\_\_

## Confirmation of File Locations:

The following tables list all required data files documenting the calibration results. An existence check was done and the result is indicated next to each filename as “exists” or “missing”.

Sub folder: **Z Scans\Good Field Region**      **exists**

005gap007.500x-01.00y+00.00\zscan.dat	exists
004gap007.500x-00.50y+00.00\zscan.dat	exists
003gap007.500x+00.00y+00.00\zscan.dat	exists
002gap007.500x+00.50y+00.00\zscan.dat	exists
001gap007.500x+01.00y+00.00\zscan.dat	exists
006gap007.500x+00.00y-00.50\zscan.dat	exists
007gap007.500x+00.00y-00.25\zscan.dat	exists
009gap007.500x+00.00y+00.25\zscan.dat	exists
010gap007.500x+00.00y+00.50\zscan.dat	exists
015gap008.500x-01.00y+00.00\zscan.dat	exists
014gap008.500x-00.50y+00.00\zscan.dat	exists
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012gap008.500x+00.50y+00.00\zscan.dat	exists
011gap008.500x+01.00y+00.00\zscan.dat	exists
016gap008.500x+00.00y-00.50\zscan.dat	exists
017gap008.500x+00.00y-00.25\zscan.dat	exists
019gap008.500x+00.00y+00.25\zscan.dat	exists
020gap008.500x+00.00y+00.50\zscan.dat	exists
025gap010.000x-01.00y+00.00\zscan.dat	exists



LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU.025

024gap010.000x-00.50y+00.00\zscan.dat	exists
023gap010.000x+00.00y+00.00\zscan.dat	exists
022gap010.000x+00.50y+00.00\zscan.dat	exists
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027gap010.000x+00.00y-00.25\zscan.dat	exists
029gap010.000x+00.00y+00.25\zscan.dat	exists
030gap010.000x+00.00y+00.50\zscan.dat	exists
035gap013.000x-01.00y+00.00\zscan.dat	exists
034gap013.000x-00.50y+00.00\zscan.dat	exists
033gap013.000x+00.00y+00.00\zscan.dat	exists
032gap013.000x+00.50y+00.00\zscan.dat	exists
031gap013.000x+01.00y+00.00\zscan.dat	exists
036gap013.000x+00.00y-00.50\zscan.dat	exists
037gap013.000x+00.00y-00.25\zscan.dat	exists
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049gap017.000x+00.00y+00.25\zscan.dat	exists
050gap017.000x+00.00y+00.50\zscan.dat	exists
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054gap022.000x-00.50y+00.00\zscan.dat	exists
053gap022.000x+00.00y+00.00\zscan.dat	exists
052gap022.000x+00.50y+00.00\zscan.dat	exists
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056gap022.000x+00.00y-00.50\zscan.dat	exists
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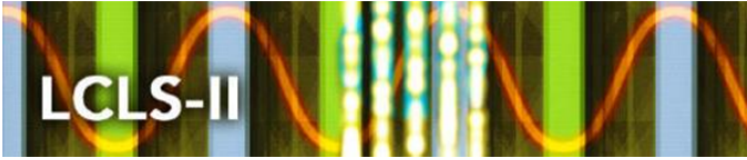
LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU.025

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Sub folder: Z Scans\On Axis exists

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003gap007.500x+00.00y+00.00\zscan.dat	exists
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014gap010.250x+00.00y+00.00\zscan.dat	exists
015gap010.500x+00.00y+00.00\zscan.dat	exists



016gap010.750x+00.00y+00.00\zscan.dat	exists
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018gap011.500x+00.00y+00.00\zscan.dat	exists
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070gap140.000x+00.00y+00.00\zscan.dat	exists
071gap160.000x+00.00y+00.00\zscan.dat	exists
072gap180.000x+00.00y+00.00\zscan.dat	exists

Sub folder: Z Scans\Commissioning Gap exists

001gap016.579x+00.00y+00.00\zscan.dat	exists
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Sub folder: Z Scans\Gap with taper exists

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001gap010.000taper+0.100x+00.00y+00.00\zscan.dat	exists
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006gap020.000taper-0.100x+00.00y+00.00\zscan.dat	exists
008gap020.000taper+0.000x+00.00y+00.00\zscan.dat	exists
002gap020.000taper+0.100x+00.00y+00.00\zscan.dat	exists
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LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU.025

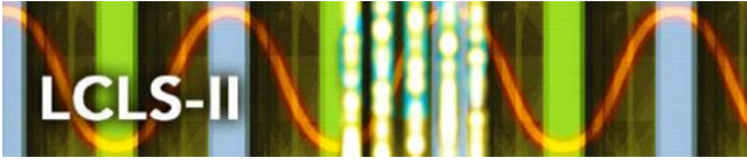
Sub folder: Long Coil exists

Sub folder: Long Coil\Good Field Region exists

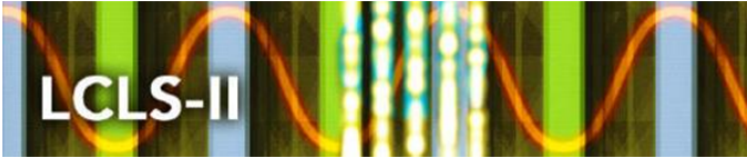
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244gap027.000x-00.50y+00.00.i1Y_integrals.txt	exists
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285gap033.000x-01.00y+00.00.i1Y_integrals.txt	exists



284gap033.000x-00.50y+00.00.i1Y_integrals.txt	exists
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066gap008.500x+00.00y-01.00.i2Y_integrals.txt	exists
070gap008.500x+00.00y+01.00.i2Y_integrals.txt	exists
090gap010.000x-01.00y+00.00.i2Y_integrals.txt	exists
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106gap010.000x+00.00y-01.00.i2Y_integrals.txt	exists
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130gap013.000x-01.00y+00.00.i2Y_integrals.txt	exists
129gap013.000x-00.50y+00.00.i2Y_integrals.txt	exists



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328gap100.000x+00.00y+00.00.i2Y_integrals.txt	exists



LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU.025

327gap100.000x+00.50y+00.00.i2Y_integrals.txt	exists
326gap100.000x+01.00y+00.00.i2Y_integrals.txt	exists
346gap100.000x+00.00y-01.00.i2Y_integrals.txt	exists
350gap100.000x+00.00y+01.00.i2Y_integrals.txt	exists

Sub folder: Long Coil\On Axis exists

integrals_summary.txt	exists
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097gap180.000x+00.00y+00.00.i1Y_integrals.txt	exists



LCLS-II-HE Undulator Segment Measurement Results

HE\_SXU.025

098gap180.000x+00.00y+00.00.i2Y.integrals.txt	exists
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Sub folder: Fiducialization exists

LCLS2HE SXU 025 Fiducial Report.docx	exists
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Sub folder: Gap Measurements exists

Sub folder: Gap Measurements\Touch Probe exists

003gap010.000taper-0.100.pdf	exists
003gap010.000taper-0.100.txt	exists
004gap010.000taper+0.000.pdf	exists
004gap010.000taper+0.000.txt	exists
001gap010.000taper+0.100.pdf	exists
001gap010.000taper+0.100.txt	exists
002gap010.000taper+0.300.pdf	exists
002gap010.000taper+0.300.txt	exists

Sub folder: Capacitive Sensors exists

gap_dat_ru1.dat	exists
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Sub folder: Controls Data exists

he_sxu_025_parameters.txt	exists
he_sxu_025_k_vs_gap_spline.dat	exists
he_sxu_025_phase_match_enter_vs_gap_spline.dat	exists
he_sxu_025_phase_match_exit_vs_gap_spline.dat	exists
he_sxu_025_i1xvsgap_spline.dat	exists
he_sxu_025_i1yvsgap_spline.dat	exists
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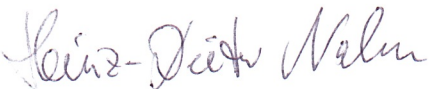


Summary of findings

Finding	Solution

Approval and Assignment by Heinz-Dieter Nuhn

Data Storage Checked:	Y	
Magnet Accepted:	Y	
Assigned Location:	HE.SXU_025	

	Heinz-Dieter Nuhn	September 12, 2024
(Signature)	(Name)	(Date)