

LCLS-II Undulator Segment Measurement Results

SXU-003

## SLAC Traveler for LCLS-II SXU Measurement Results

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:	29A804-003
Device name from magnet label:	SXU-003

### Measurement Procedure:

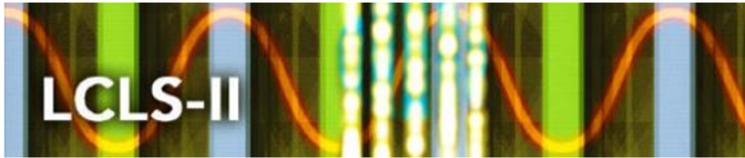
The measurements have been carried out after the undulator segment had been fully tuned according to the “LCLS-II Undulator Test Plan” (LCLS-TN-17-1).

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

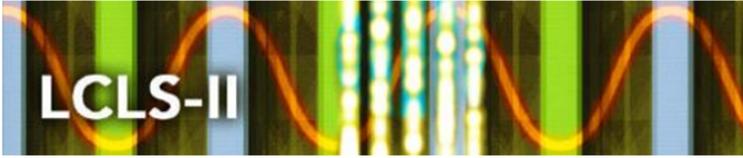
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MATLAB function "EvaluateUndulatorField" on	05/01/2019 16:54	
A. SCAN PARAMETERS		
z Scanning Date & Time Range	04/25/2019 15:35 - 04/26/2019 07:21	
Undulator Temperature	20.0453±0.0017	°C
x axis position	0.076275	mm
y axis position	0.000202	mm
Total number of poles per strongback	174	
Number of full field poles	168	
Number of core poles	160	
First core pole #	8	
Last core pole #	167	
Average $\lambda_u$	39.002	mm
RMS $\lambda_u$	25.1	$\mu\text{m}$
Scans averaged	3	
Tuning Gap	10.000	mm
Commissioning Gap	10.368	mm



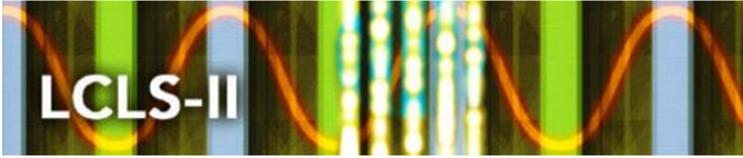
**Evaluation of Hall Probe Scans at Tuning Gap: Data Listing B**

MATLAB function "EvaluateUndulatorField" on	05/01/2019 16:54	
B. CORE EVALUATIONS FOR TUNING GAP		
Tuning Gap Scanning Date & Time Range	04/25/2019 20:20	
Tuning Gap Temperature	20.05±0.05	°C
Planar Hall Effect Correction Range	0.791600 - 4.101800	m
Planar Hall Effect x Corr Function	-0.53 G + (z - 0.791600 m)×0.14 G/m	
Planar Hall Effect y Corr Function	-0.33 G + (z - 0.791600 m)×0.23 G/m	
Coil Range	0.646773 - 4.246773	m
$\langle \lambda_u \rangle$	39.002±0.002	mm
$\langle k_u \rangle$	161.10±0.01	1/m
$\langle K_u \rangle$	4.2146±0.0006	
$\langle K_{\text{eff}} \rangle$ @ Tuning Temperature	4.21424±0.00004	
$\langle L_{\text{eff}} \rangle$	3.31417±0.00006	m
$\langle L_{2\pi} \rangle$	0.385338±0.000020	m
I1X (Cell Range Total)	+8.64	μTm
I2X (Cell Range Total)	-38.25	μTm <sup>2</sup>
I1Y (Cell Range Total)	-20.13	μTm
I2Y (Cell Range Total)	-38.26	μTm <sup>2</sup>
PI (Cell Range Total)	85,503.2	degXray
Phase Shake	1.40	degXray
Cell Phase Advance ( over 4.400000)	31,605.1 (88×360-74.9)	degXray
Undulator Entrance Phase	1403.5±0.1	degXray
Undulator Exit Phase	1401.6±0.1	degXray
Undulator Phase Imbalance: Entrance - Exit	1.9±0.2	degXray
Cell Entrance min. Phase Shifter Correction	36.5	degXray
Cell Exit min. Phase Shifter Correction	38.4	degXray



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

MATLAB function "EvaluateUndulatorField" on	05/01/2019 16:54	
C. CORE EVALUATIONS FOR COMMISSIONING GAP		
Commissioning Gap Scanning Date & Time Range	04/25/2019 20:20	
Commissining Gap Temperature	20.05±0.05	°C
Planar Hall Effect Correction Range	0.791600 - 4.102000	m
Planar Hall Effect x Corr Function	-0.54 G + (z - 0.791600 m)×0.15 G/m	
Planar Hall Effect y Corr Function	-0.33 G + (z - 0.791600 m)×0.22 G/m	
Coil Range	0.646773 - 4.246773	m
$\langle \lambda_u \rangle$	39.002±0.002	mm
$\langle k_u \rangle$	161.10±0.01	1/m
$\langle K_u \rangle$	4.0503±0.0006	
$\langle K_{\text{eff}} \rangle$ @ Tuning Temperature	4.05009±0.00004	
$\langle L_{\text{eff}} \rangle$	3.31464±0.00006	m
$\langle L_{2\pi} \rangle$	0.358883±0.000019	m
I1X (Cell Range Total)	+10.18	$\mu\text{Tm}$
I2X (Cell Range Total)	-30.10	$\mu\text{Tm}^2$
I1Y (Cell Range Total)	-17.74	$\mu\text{Tm}$
I2Y (Cell Range Total)	-20.90	$\mu\text{Tm}^2$
PI (Cell Range Total)	78,983.1	degXray
Phase Shake	1.50	degXray
Cell Phase Advance (over 4.400000 m)	31,683.7 (88×360+3.7)	degXray
Undulator Entrance Phase	1443.2 (8×180+3.2)±0.1	degXray
Undulator Exit Phase	1440.5 (8×180+0.5)±0.1	degXray
Undulator Phase Imbalance: Entrance - Exit	2.7±0.2	degXray
Cell Entrance min. Phase Shifter Correction	356.8	degXray
Cell Exit min. Phase Shifter Correction	359.5	degXray




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### Undulator Encoder Settings: Data Listing D

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MATLAB function "EvaluateUndulatorField" on	05/01/2019 17:02	
D. ENCODER SETTINGS		
Upstream Gap Encoder Gain	-19,999.8±2.6	
Upstream Scaled Gap Encoder Offset	228.682±0.0000	mm
Downstream Gap Encoder Gain	-20,000.2±4.0	
Downstream Scaled Gap Encoder Offset	228.461±0.0000	mm
Upstream Scaled Top Motor Encoder Offset	-1013.01900±0.00000	mm
Downstream Scaled Top Motor Encoder Offset	-1013.83300±0.00000	mm

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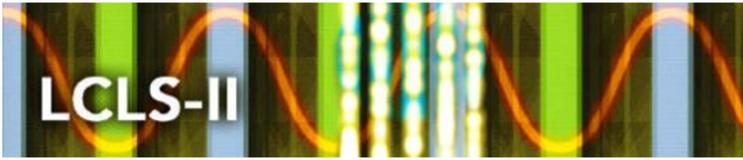
### Undulator Capacitive Sensor Values: Data Listing E

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#### E. CAPACITIVE SENSOR VALUES

Module	Pole	Capacitive Sensor Gap	Upstream Encoder	Downstream Encoder	
Ref	—	46.4798	50.0006	49.9990	mm
Ref	—	46.4798	50.0006	49.9990	mm
2	3/4	46.7157	46.7000	46.6999	mm
2	3/4	46.7157	46.7000	46.6999	mm
2	13/14	46.7234	46.7000	46.7000	mm
2	13/14	46.7234	46.7000	46.7000	mm
4	39/40	46.6649	46.6999	46.6999	mm
4	39/40	46.6649	46.6999	46.6999	mm
4	49/50	46.6739	46.6999	46.6999	mm
4	49/50	46.6739	46.6999	46.6999	mm
Ref	—	46.4798	50.0006	49.9990	mm
Ref	—	46.4798	50.0006	49.9990	mm

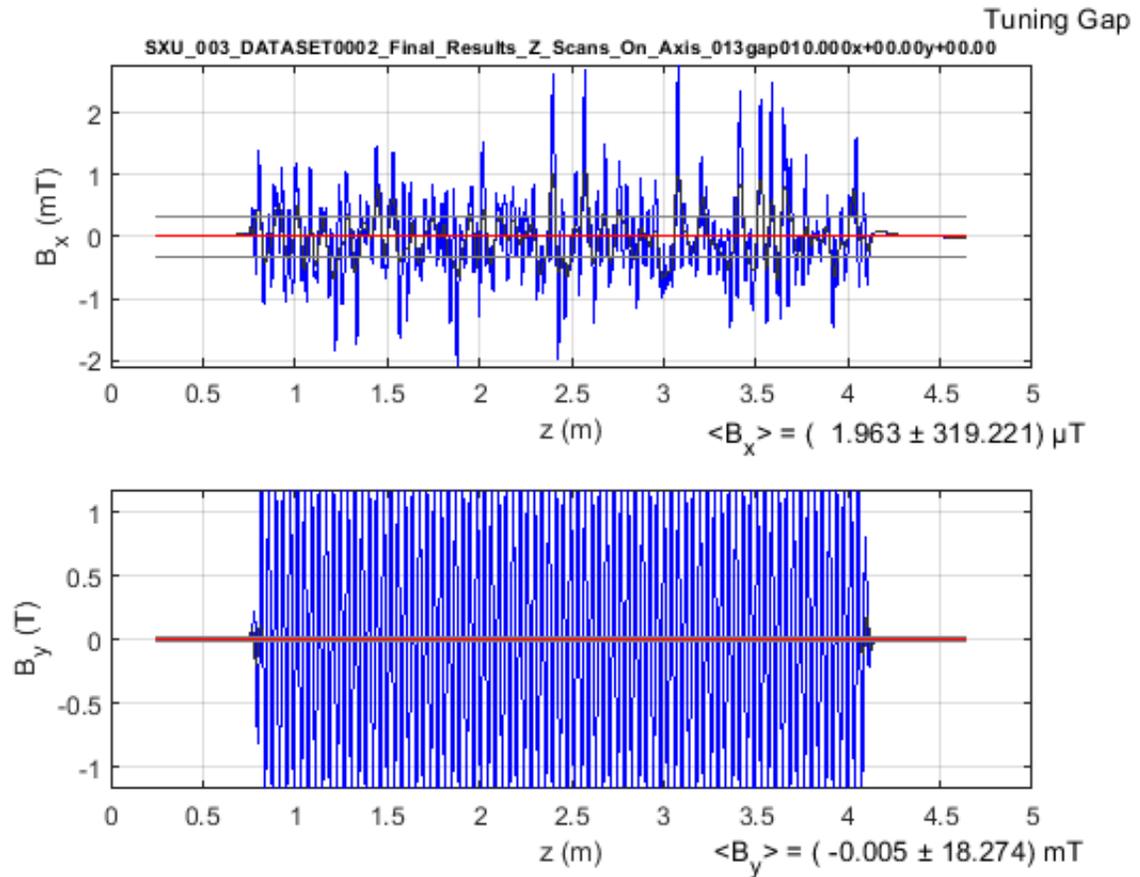
The following figures show result of the field analysis at the tuning gap.



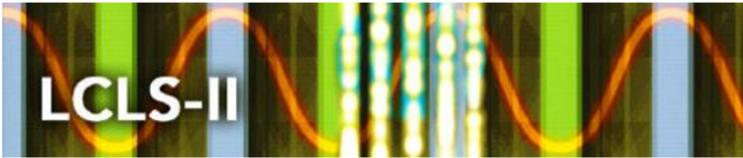
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### Evaluation of Hall Probe at Tuning Gap: $B_x$ & $B_y$ Plot

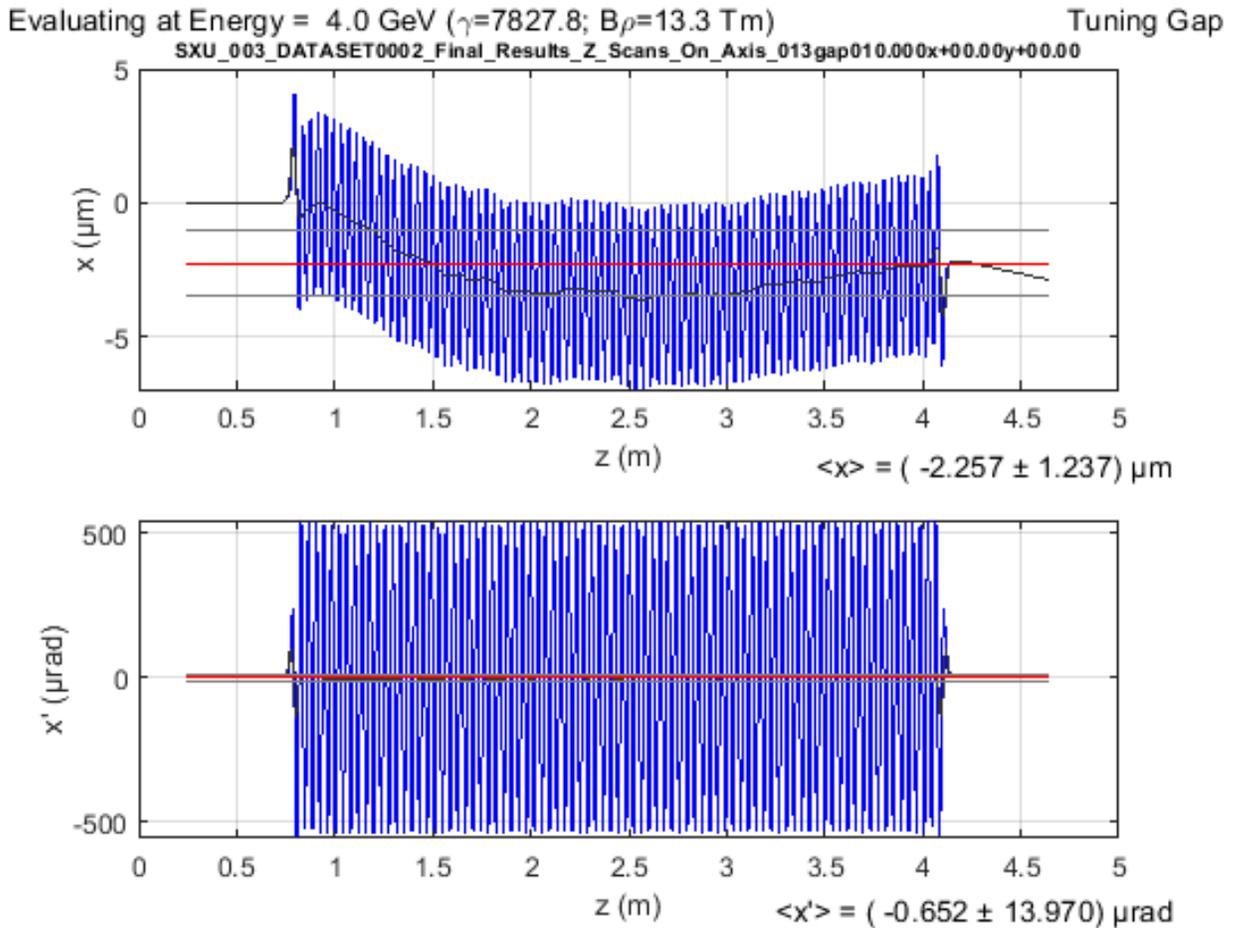
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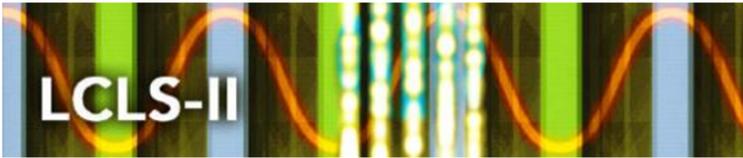
The figures show the x (upper) and y (lower) field components along the undulator tuning axis for the tuning gap. A running wiggler-period-average function is plotted in black (not very well visible in the lower figure). The horizontal lines indicate the mean (center red line) and the rms deviations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



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

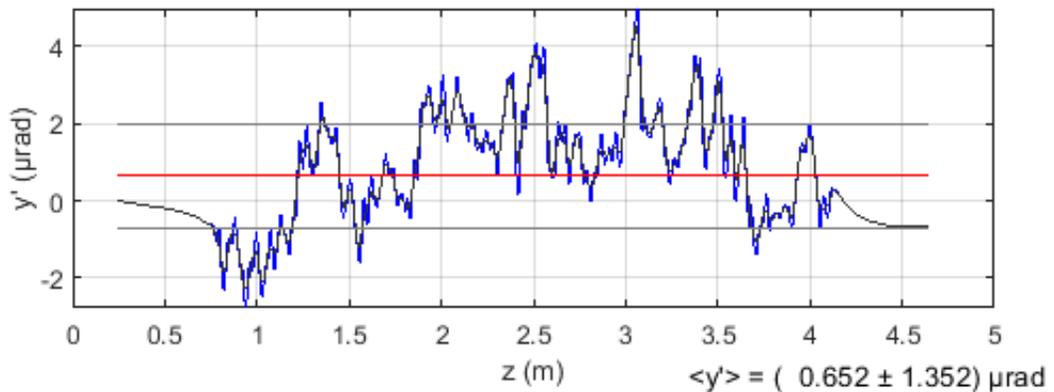
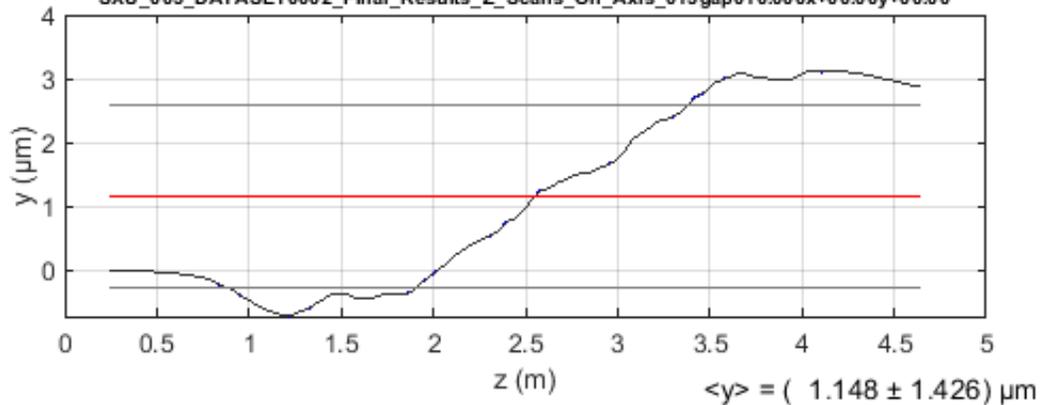


The figures show the  $x$  (upper) and  $x'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components and estimated for an electron beam energy of 4.0 GeV. A running wiggler-period-average function is plotted in black (difficult to see 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 wiggler-period-average function. The corresponding mean and rms values are also printed on the right hand side underneath each figure. [Documentary Information]

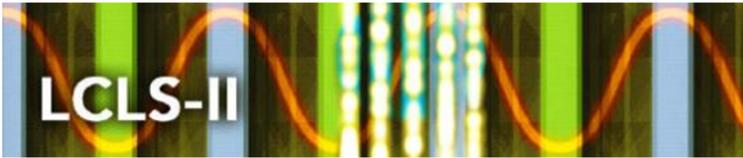


### Evaluation of Hall Probe Scans at Tuning Gap: $y$ & $y'$ Plot

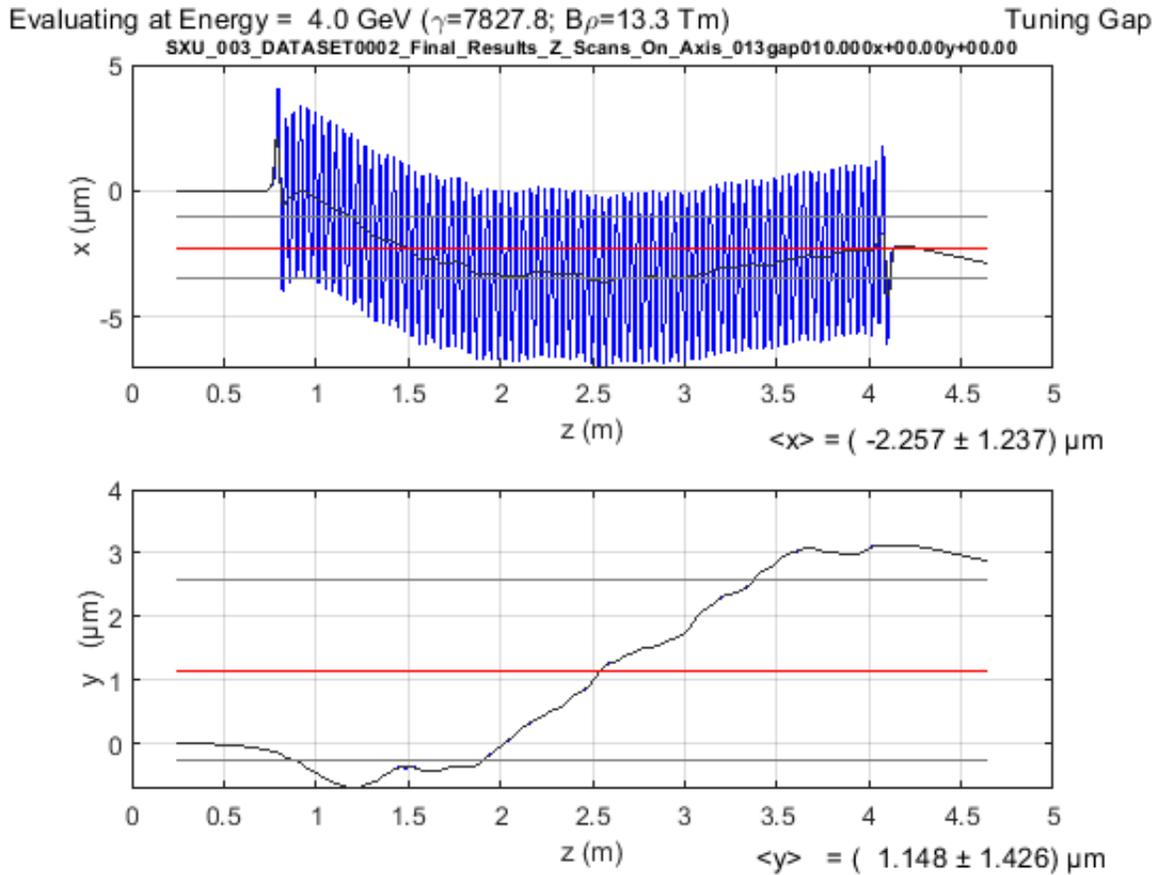
Evaluating at Energy = 4.0 GeV ( $\gamma=7827.8$ ;  $B\rho=13.3$  Tm) Tuning Gap  
SXU\_003\_DATASET0002\_Final\_Results\_Z\_Scans\_On\_Axis\_013gap010.000x+00.00y+00.00



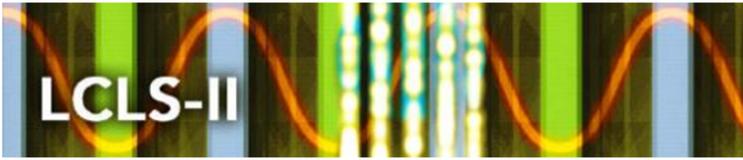
The figures show the  $y$  (upper) and  $y'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components and estimated for an electron beam energy of 4.0 GeV. A running wiggler-period-average function is plotted in black (difficult to see). 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 wiggler-period-average function. The corresponding mean and rms values are also printed on the right hand side underneath each figure. [Documentary Information]



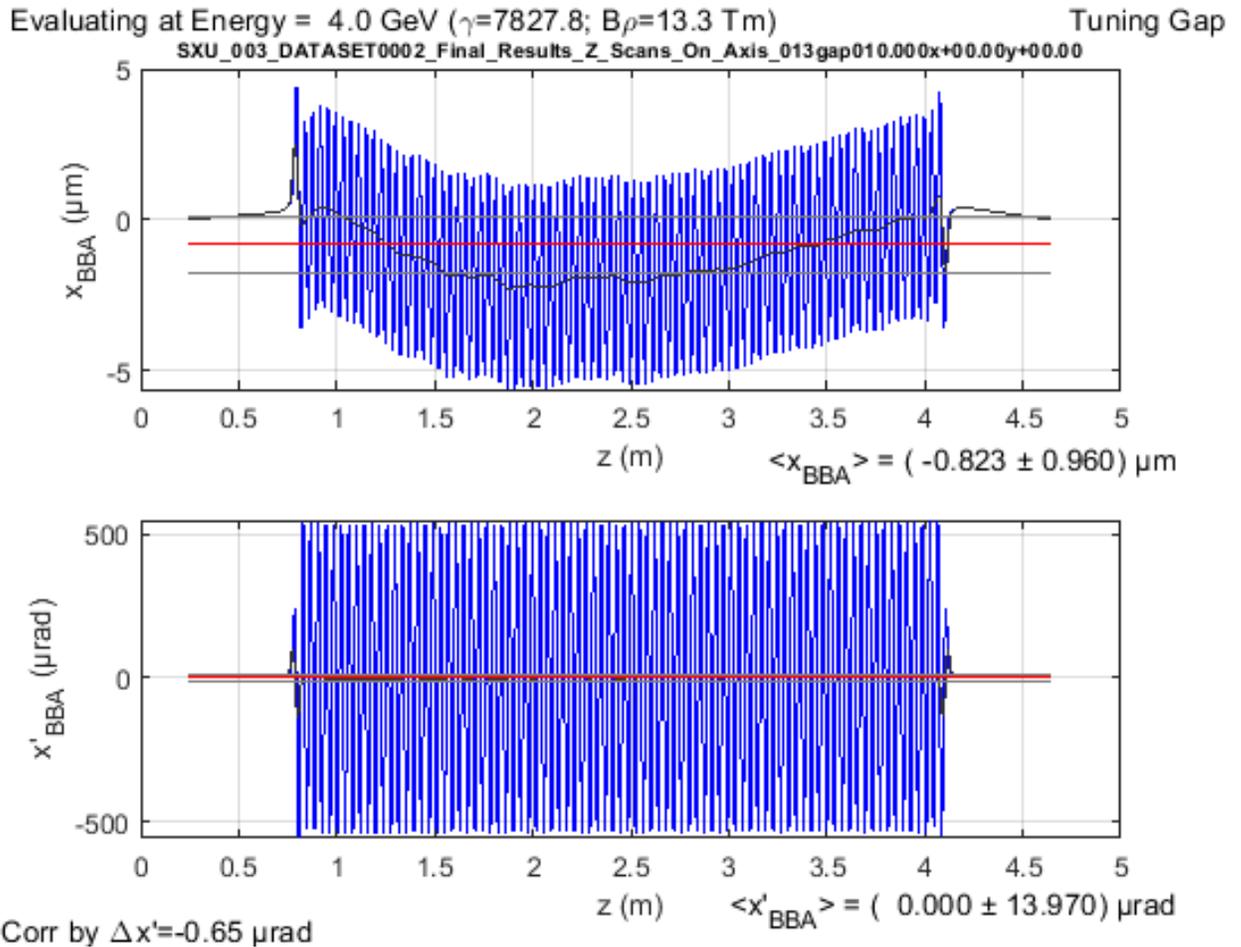
### Evaluation of Hall Probe Scans at Tuning Gap: $x$ & $y$ Plot



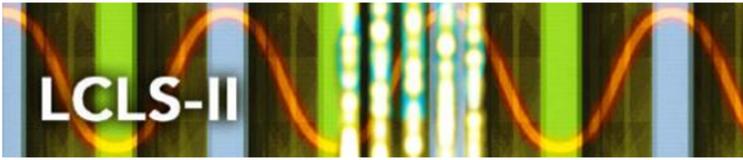
The figures show the  $x$  (upper) and  $y$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components and estimated for an electron beam energy of 4.0 GeV. A running wiggler-period-average function is plotted in black (identical with the trajectory 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 wiggler-period-average function. The corresponding mean and rms values are also printed on the right hand side underneath each figure. [Documentary Information]



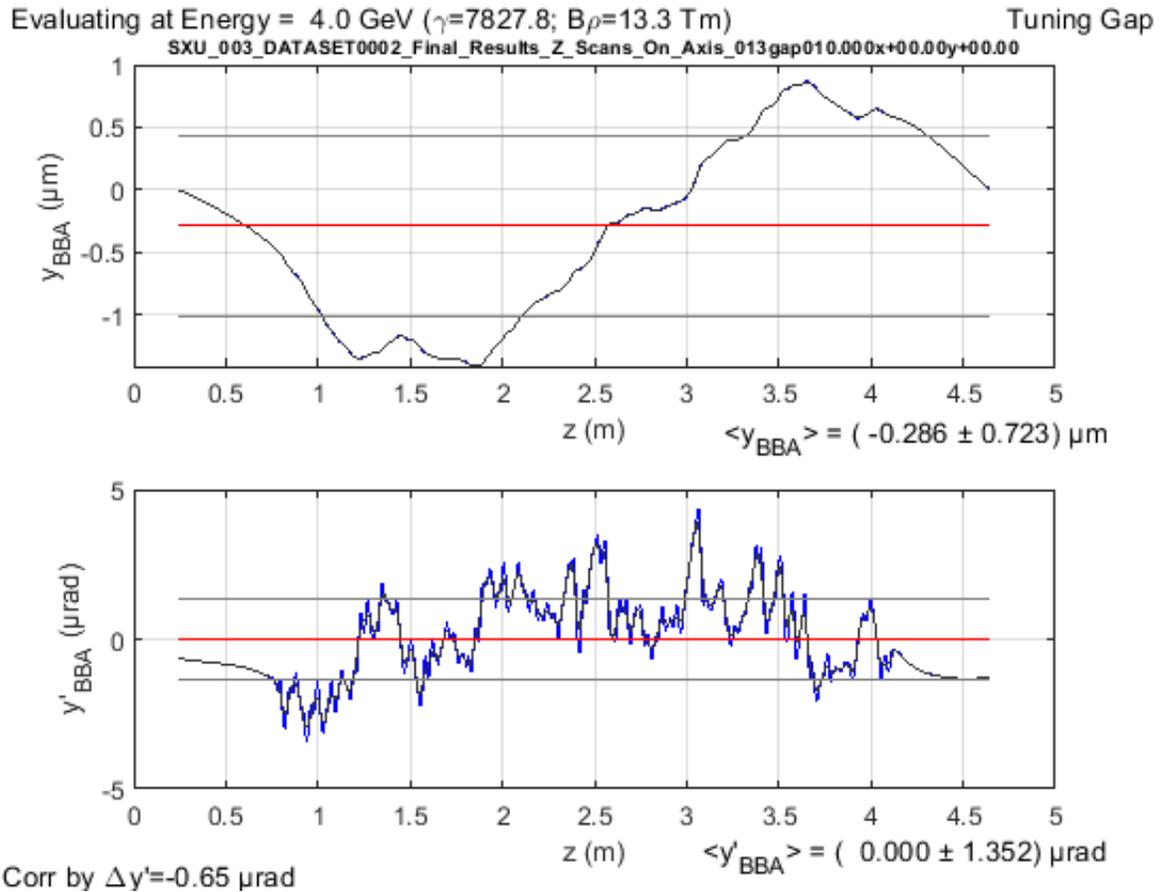
**Evaluation of Hall Probe plus BBA Correction at Tuning Gap:  $x$  &  $x'$  Plot**



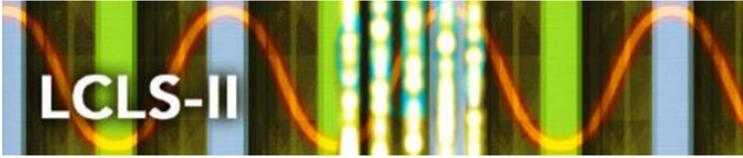
The figures show the  $x$  (upper) and  $x'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components after BBA correction (to zero the amplitudes at the cell boundaries) and estimated for an electron beam energy of 4.0 GeV. A running wiggler-period-average function is plotted in black (difficult to see 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 wiggler-period-average function. The corresponding mean and rms 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]



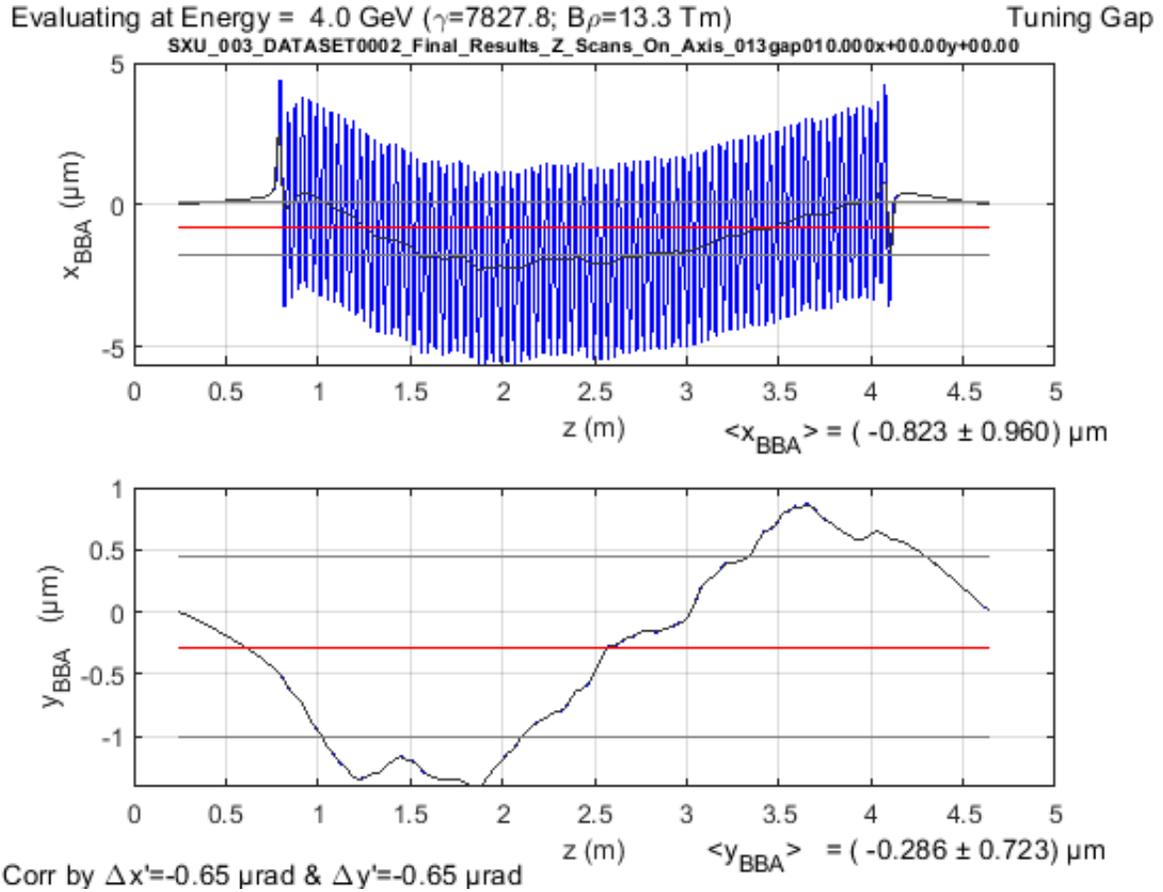
**Evaluation of Hall Probe plus BBA Correction at Tuning Gap:  $y$  &  $y'$  Plot**



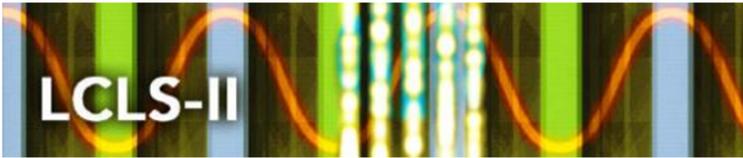
The figures show the  $y$  (upper) and  $y'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components after BBA correction (to zero the amplitudes at the cell boundaries) and estimated for an electron beam energy of 4.0 GeV. A running wiggler-period-average function is plotted in black (identical with the trajectories). 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 wiggler-period-average function. The corresponding mean and rms 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]



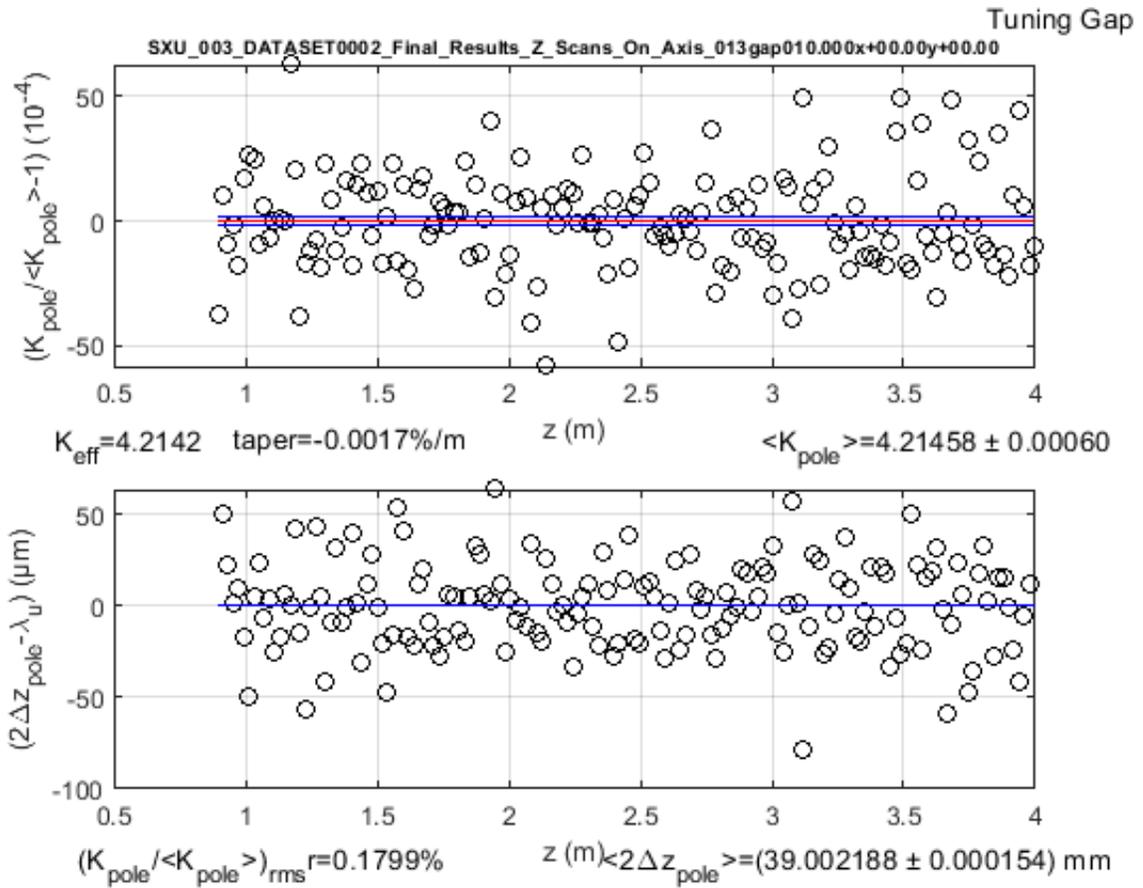
Evaluation of Hall Probe plus BBA Correction at Tuning Gap: *x* & *y* Plot



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 4.0 GeV. A running wiggler-period-average function is plotted in black (identical with the trajectory 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 wiggler-period-average function. The corresponding mean and rms 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]

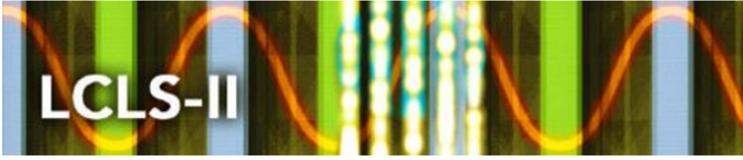


Evaluation of Hall Probe at Tuning Gap:  $K$  and  $\lambda_u$  Plot



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 160 core undulator poles for the tuning gap. The horizontal lines indicate the mean (center red line) and the rms deviations from the mean (two black lines above and below the average). The corresponding mean and rms values are also printed on the right hand side underneath each figure. [Documentary Information]

For description of  $K$  calculation see next page.



LCLS-II Undulator Segment Measurement Results

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$K$  calculation description for previous page:

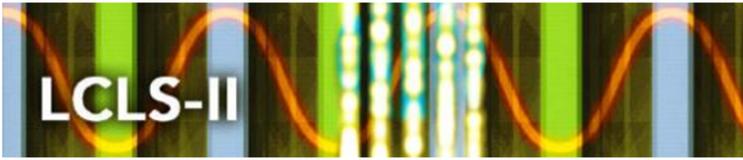
The undulator parameter,  $K_{pole}$ , in the upper figure, is calculated for each of the core poles based on the scanned vertical field values  $B_y(z)$  as well as an interpolation of the upstream,  $z_{(0-dn,pole)}$ , and downstream,  $z_{(0-up,pole)}$ , field zero crossing locations using the following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

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

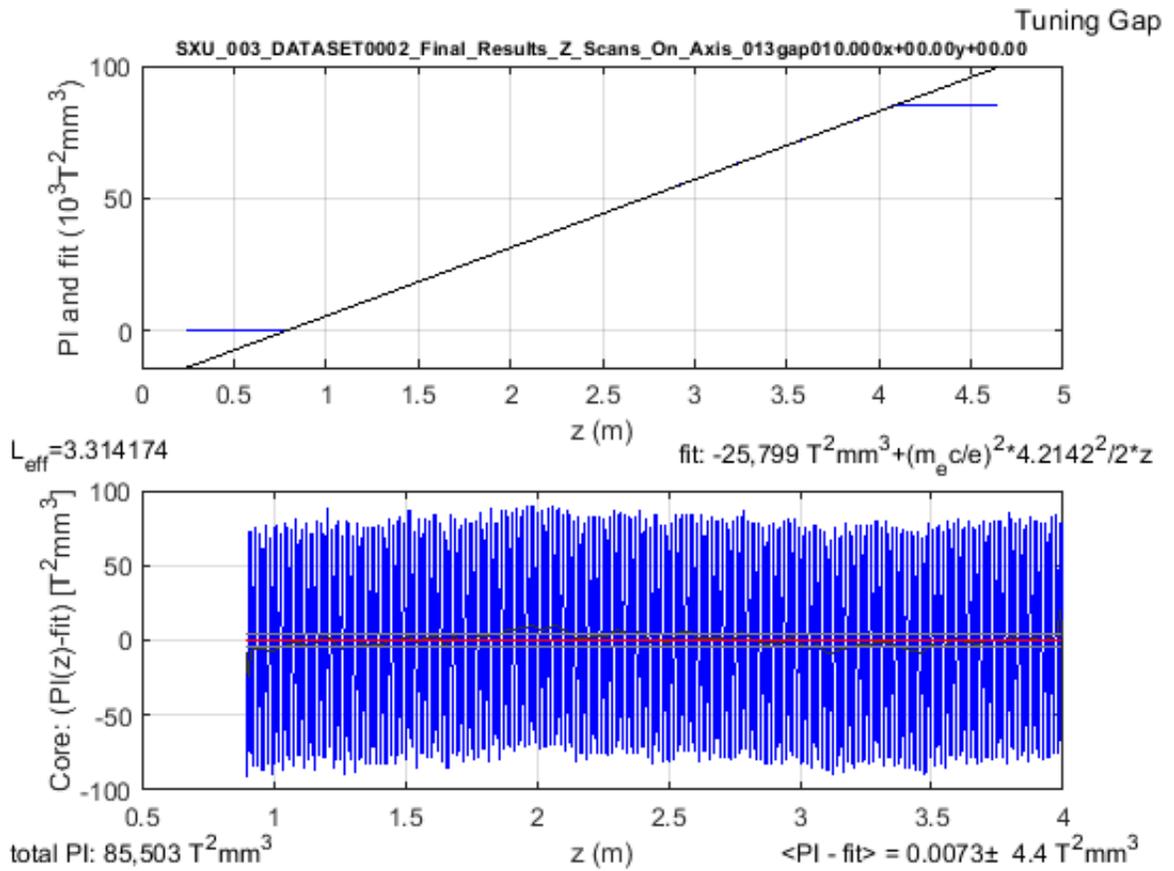
The term  $\frac{e}{m_e c}$  uses the electron mass,  $m_e$ , the speed of light,  $c$ , and the electron's electric charge,  $e$ . The variable  $\Delta z_{pole}$  stands for

$$\Delta z_{pole} = z_{0-dn,pole} - z_{0-up,pole}$$

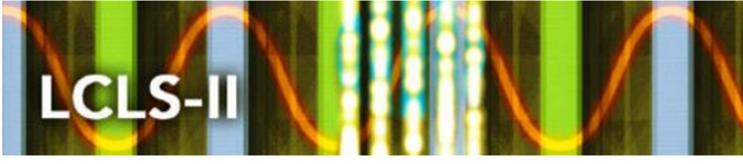
$$z_{pole} \approx \frac{1}{2} (z_{0-dn,pole} + z_{0-up,pole})$$



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



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



LCLS-II Undulator Segment Measurement Results

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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:  $L_{\text{eff}} = PI(z_{\text{max}}) / \left(\frac{d\overline{PI}(z)}{dz}\right)$ .

The lower figure shows the residuals between the phase integral and the fit function over the core part of the undulator magnet. A running wiggler-period-averaged function is plotted in black. The horizontal lines indicate the mean (center red line) and the rms deviations from the mean (two blue lines above and below the mean) of that wiggler-period-averaged function. The corresponding mean and rms 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 wiggler period averaged phase,  $\langle \Phi \rangle_{\lambda_u}(z)$  can be calculated from  $PI(z)$  via

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

integrated over the undulator core.

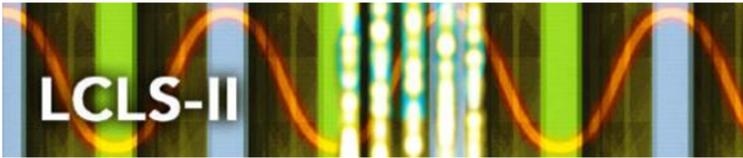
Here  $L_{2\pi} = \lambda_u \left(1 + \frac{1}{2} K_{\text{eff}}^2\right)$  (see next figure) is the free space distance over which a phase slippage of  $2\pi$  occurs. The phase shake,  $\langle \Delta \phi \rangle_{\text{rms}}$ , which will be discussed later in this document, is calculated as

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

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

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

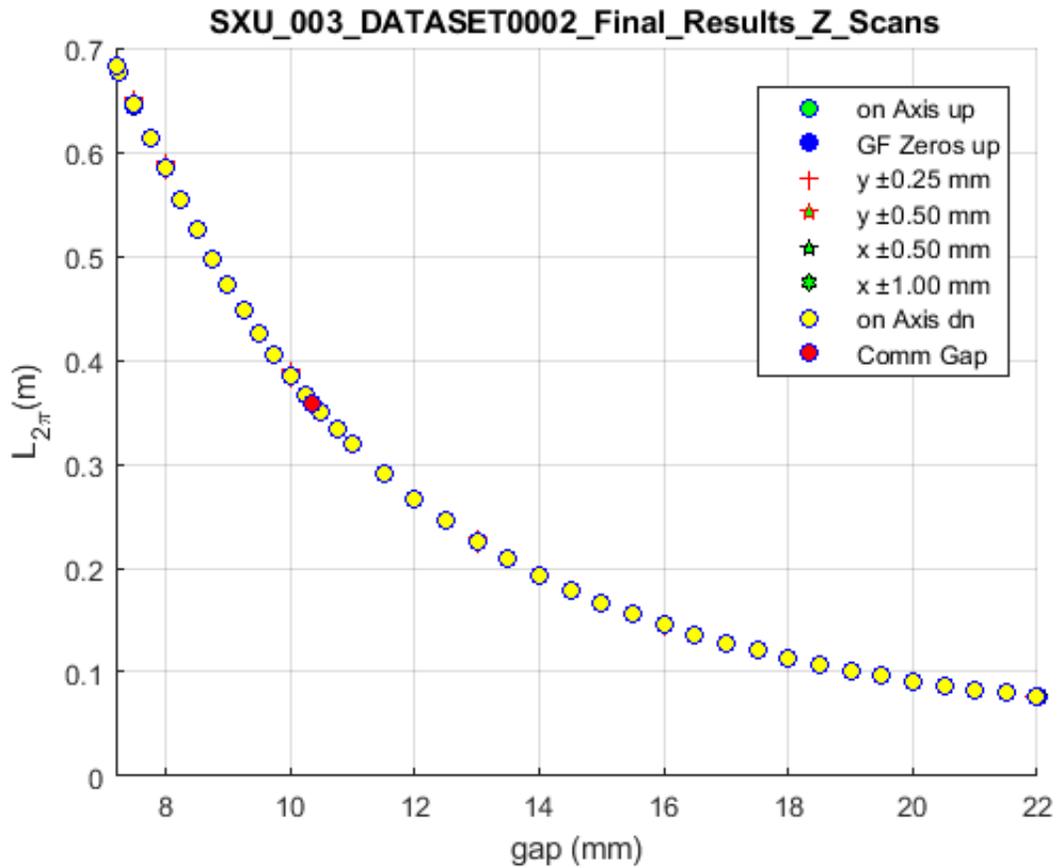
The following figures show the results of the gap dependent analysis.



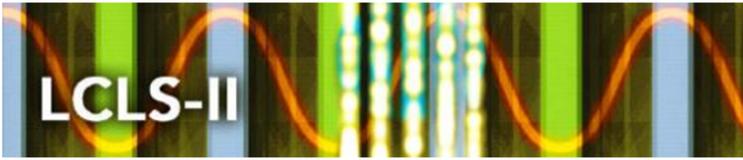
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Evaluation of Hall Scans:  $L_{2\pi}$  vs gap

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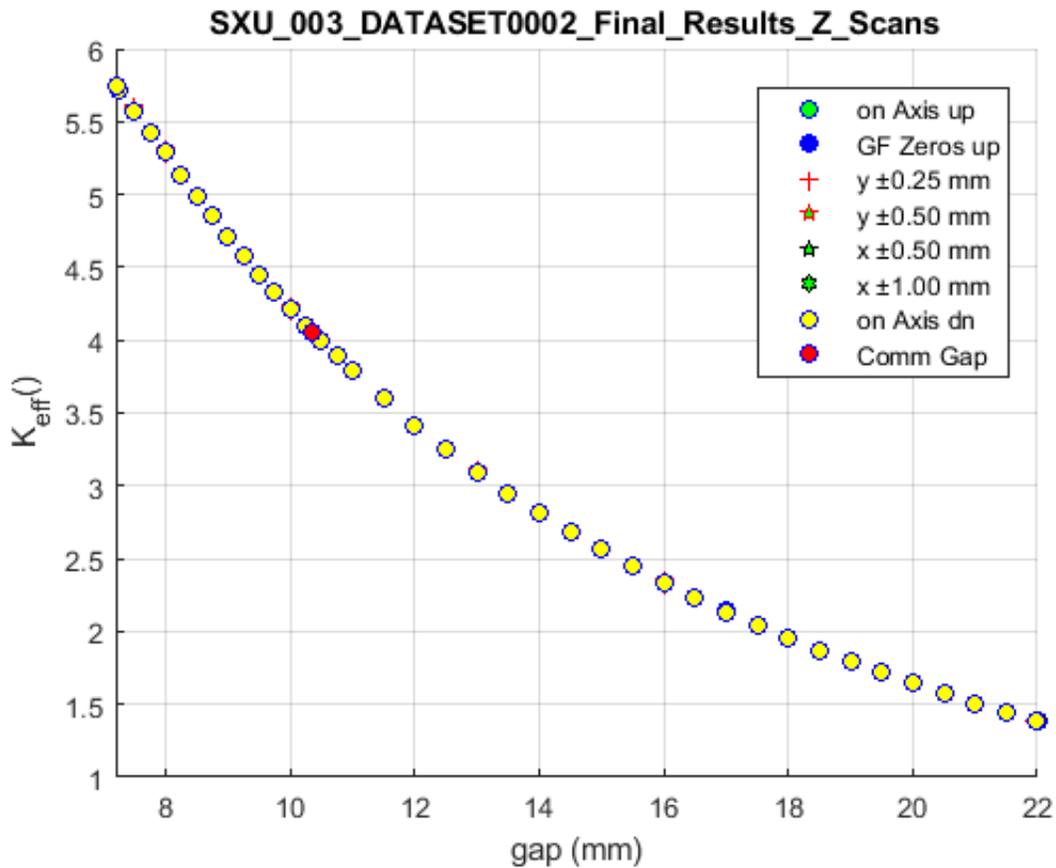
The figure shows the free space distance over which a  $2\pi$  slippage occurs between the radiation field and the electron bunch (see explanation above) as a function of undulator gap over the operational gap range. Note: the free space travel distance required to accumulate  $2\pi$  slippage gets shorter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



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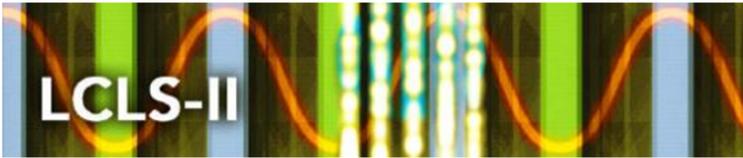
### Evaluation of Hall Scans: $K_{\text{eff}}$ vs gap

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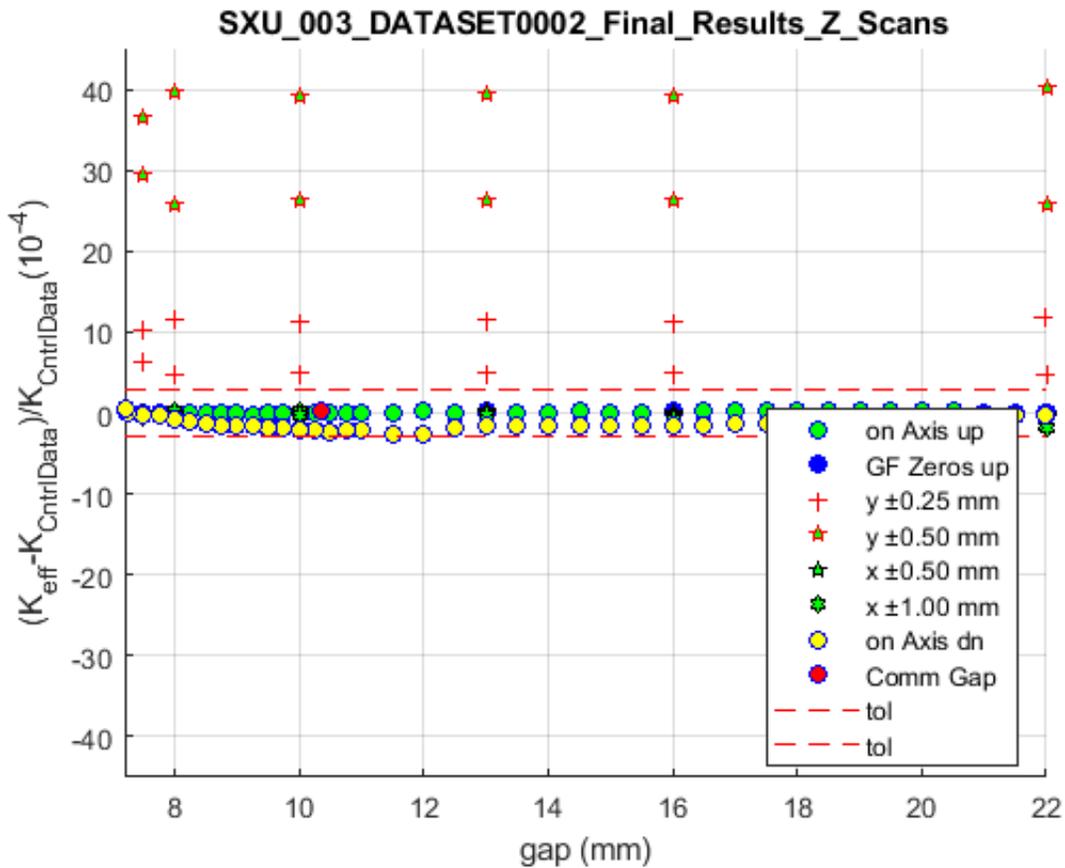


The figure shows undulator strength  $K_{\text{eff}}$  as a function of gap over the 7.2 mm—22 mm operational range. The legend shows a number of different cases that will be explained later in this document because their effect cannot be observed in this full scale plot. Note: The gap values are derived 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_003_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]

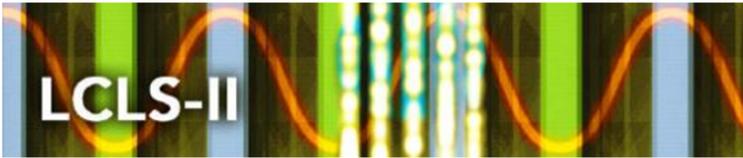


Evaluation of Hall Scans:  $K_{\text{eff}} - K_{\text{control}}$  vs gap

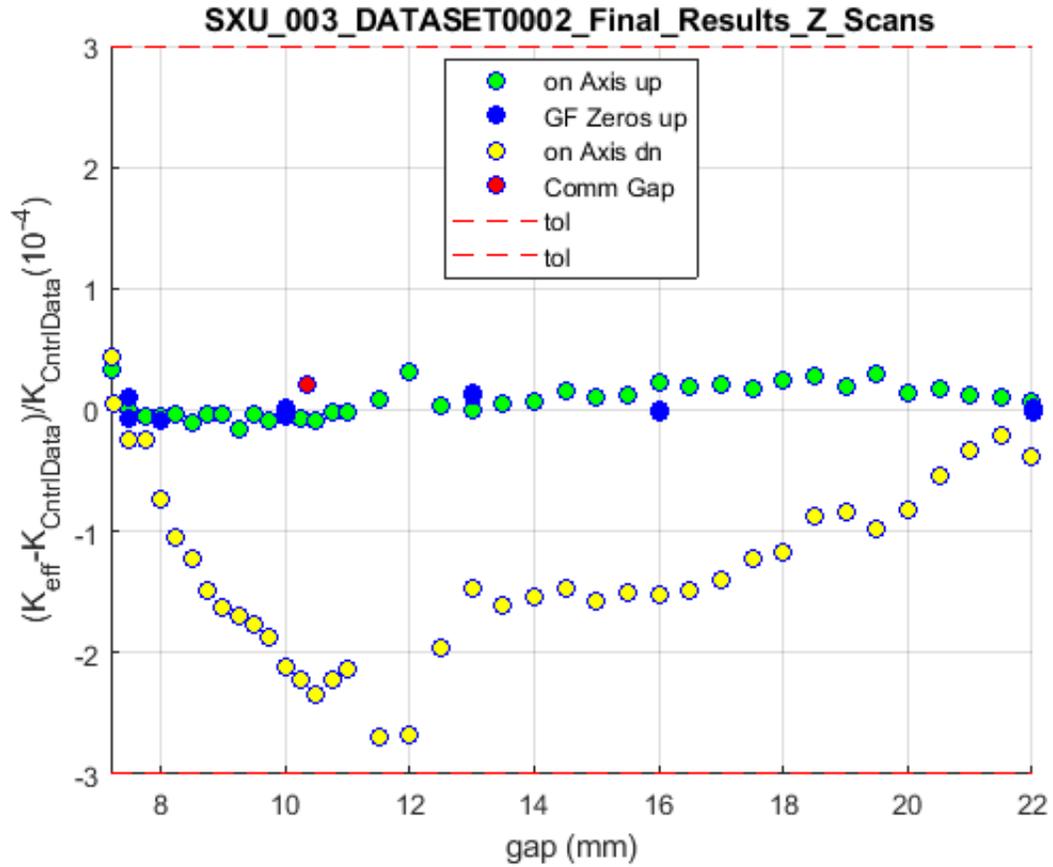


The figure shows the relative difference between the measured undulator strength  $K_{\text{eff}}$  and a cubic spline fit to the list of reference data points stored in file `sxu_003_k_vs_gap_spline.dat` in the Controls Data folder on the V: drive as a function of gap over the 7.2 mm—22 mm operational range.

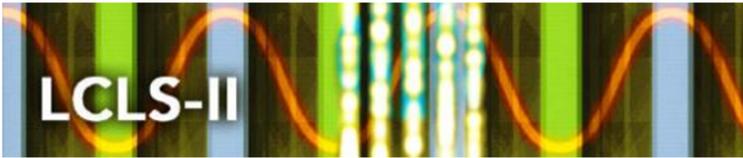
The legend explains the different cases that are shown in the plot: The green filled circles are data acquired on axis as the gap was changed from close to open. The yellow filled circles are data acquired on axis as the gap was changed from open to close. The horizontal red dashed lines show the tolerance 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.



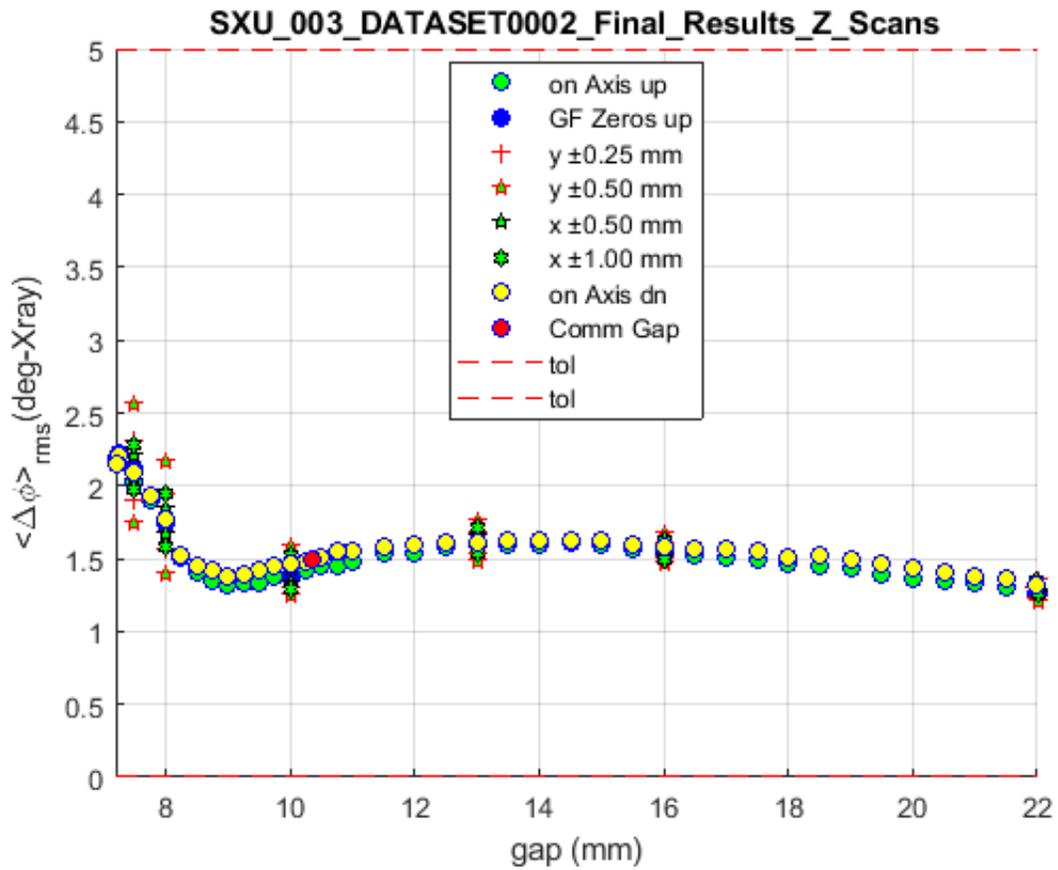
**Evaluation of Hall Scans:  $(K_{\text{eff}} - K_{\text{CntrlData}}) / K_{\text{CntrlData}}$  vs gap**



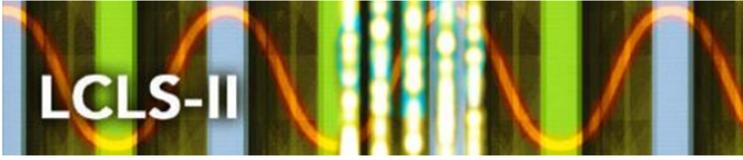
The figure shows some of the data shown in the previous figure but with a larger vertical scale that just captures the tolerance range. The off-axis measurements are not shown.



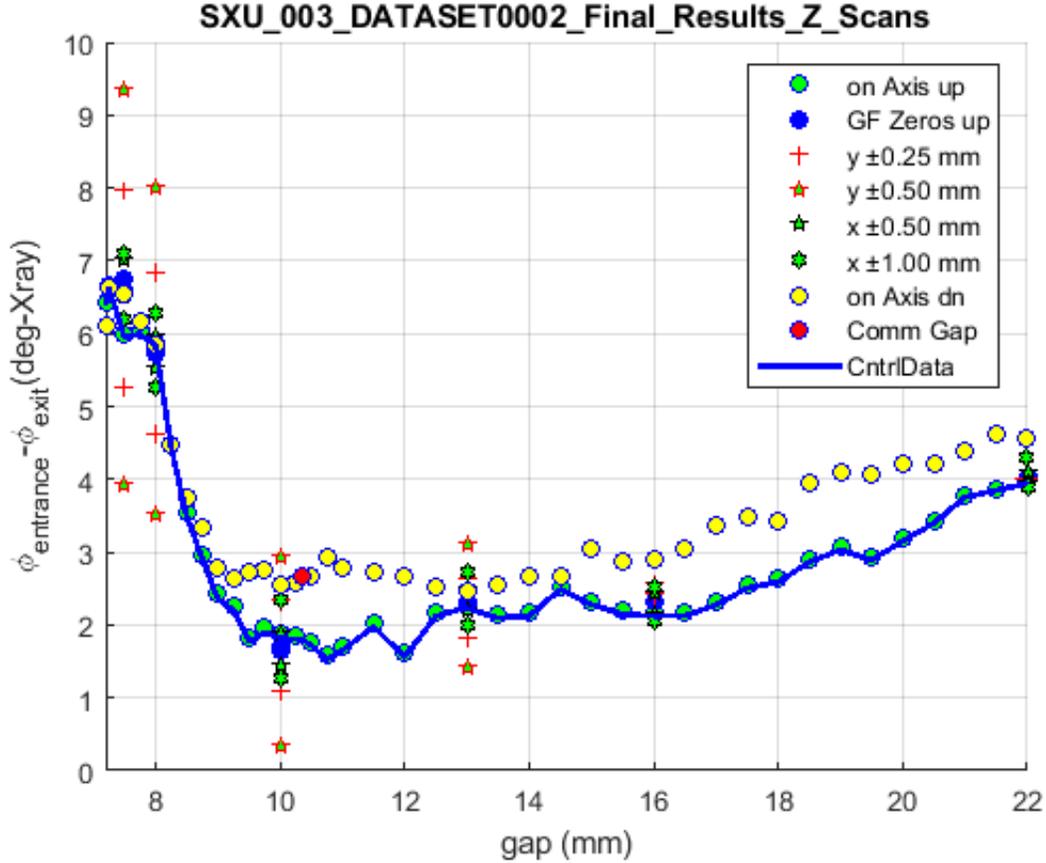
### Evaluation of Hall Scans: Phase Shake vs gap



The figure shows the phase shake,  $\langle \Delta\phi \rangle_{rms}$ , (see above) 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".

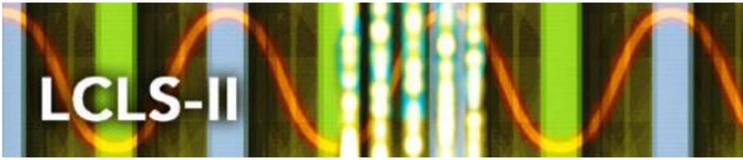
```

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

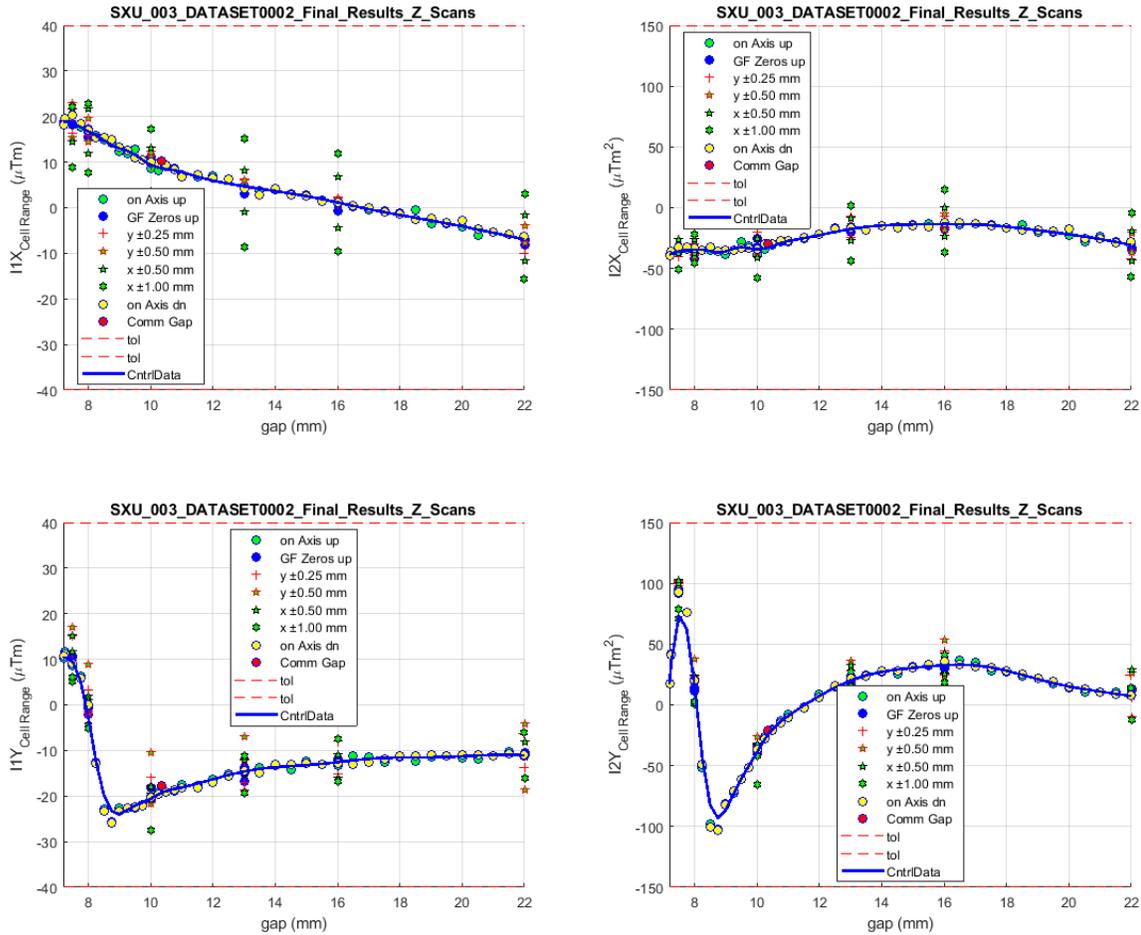
$$\phi_{\text{entrance}} = -\phi(z_{\text{Cell-Start}}) + \frac{1}{n+1} \sum_{j=1}^{n+1} (\phi(z_{B0,j}) - \pi(j-1)).$$

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

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



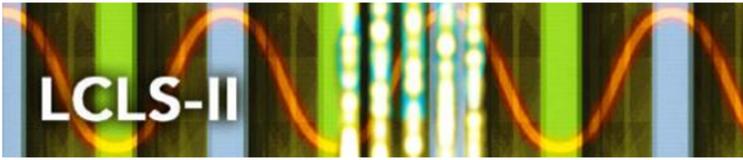
The figures show the field integrals ( $I1X$ ,  $I2X$ ,  $I1Y$ ,  $I2Y$ ) as function of the operational gap. The proximity of the green and yellow circles shows that the field integrals are not sensitive to the hysteresis in  $K$  as seen on a previous page. The blue curves are spline fits to the data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

```

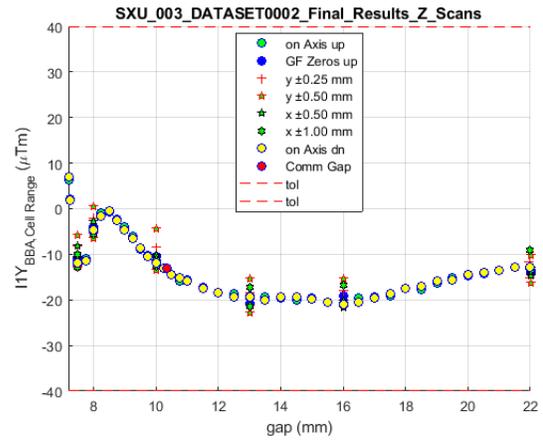
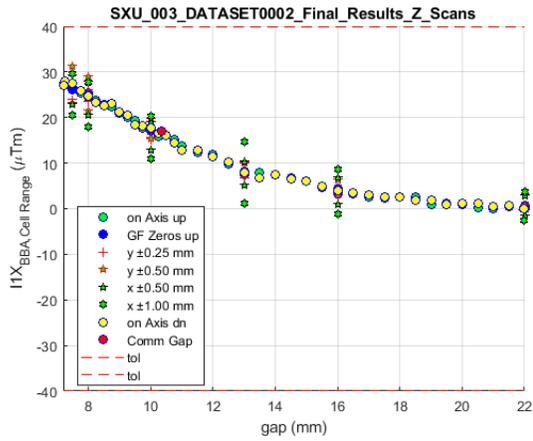
"...i1xvsgap_spline.dat",
"...i2xvsgap_spline.dat",
"...i1yvsgap_spline.dat",
"...i2yvsgap_spline.dat",

```

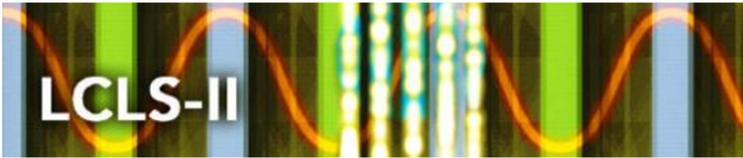
and demonstrate how the controls representations of the field integrals relates to the actual measurements (see final section of this document for file information).



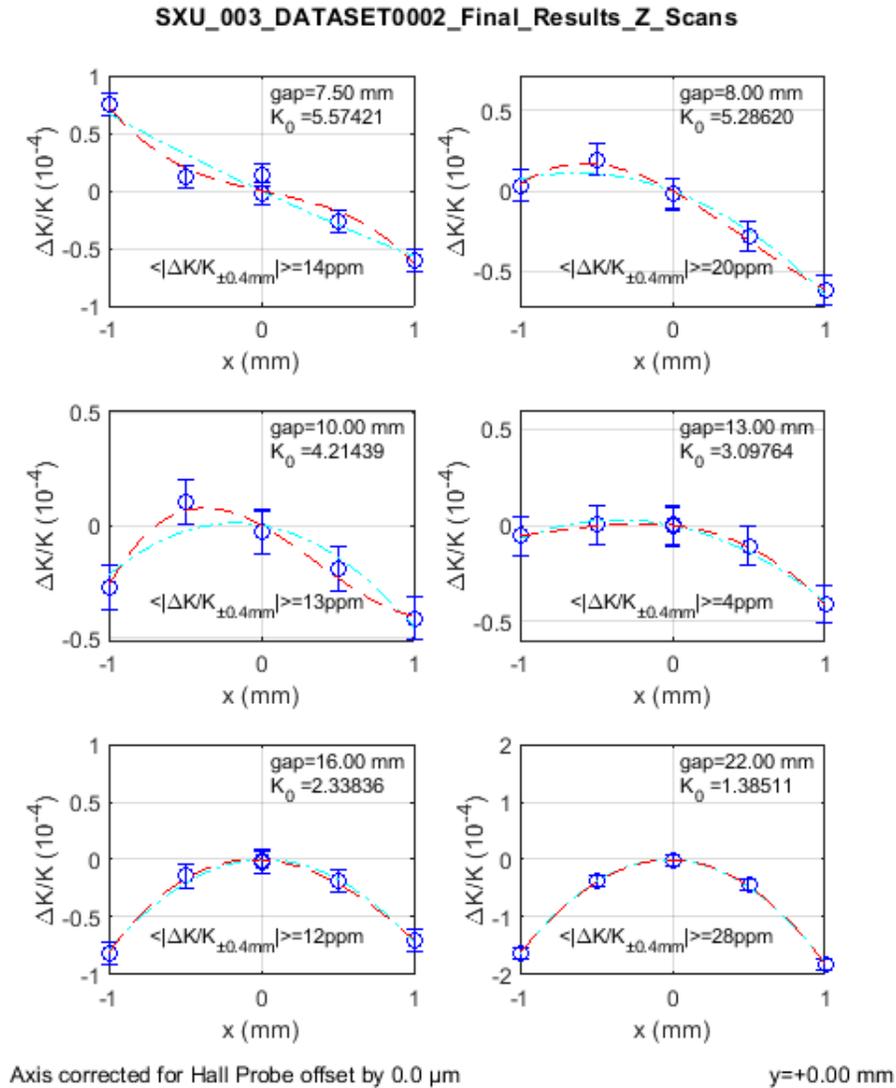
## Evaluation of Hall Probe: BBA Field Integrals



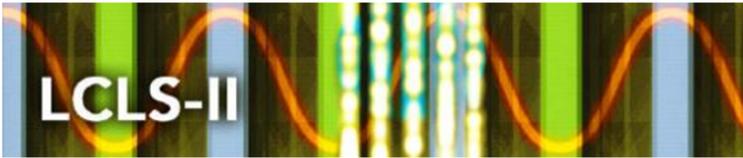
The figure shows the first integrals after a BBA equivalent correction was applied. The values stay within tolerance over the operational range.



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

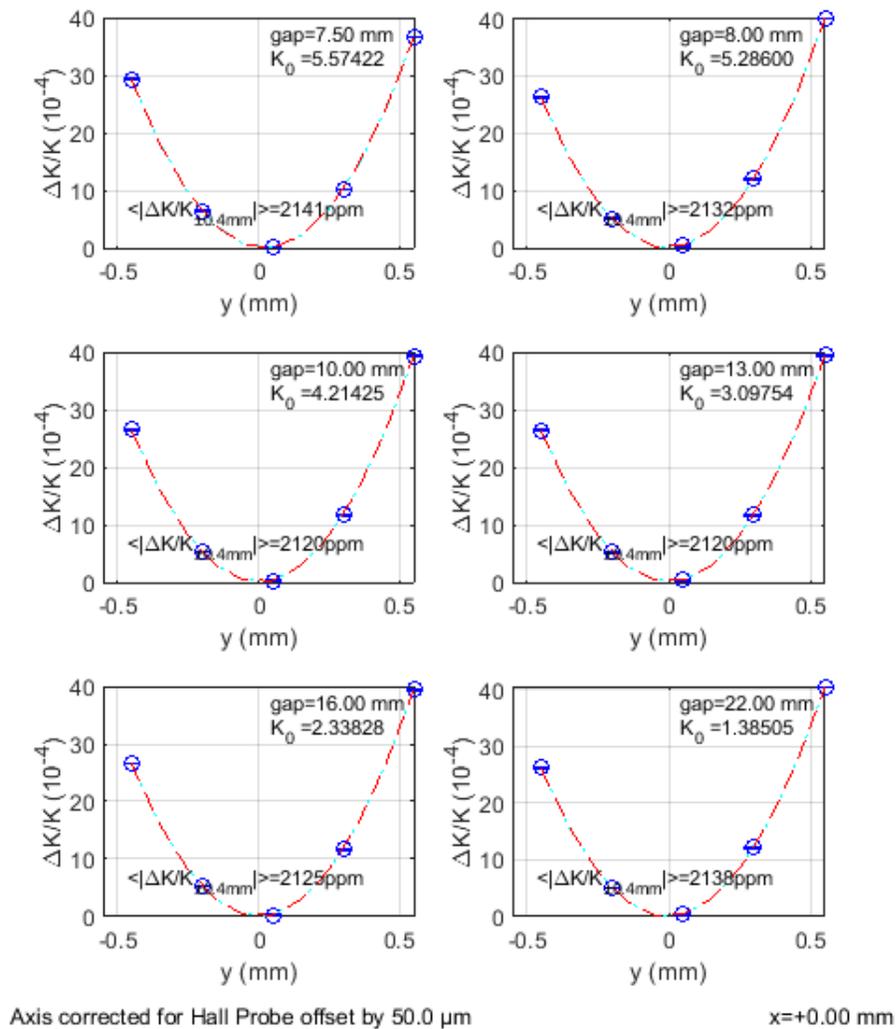


The figure shows the deviation of the relative undulator strength,  $K$ , from the off-axis value,  $K_0$ , as function of  $x$  at a number of operational gaps. The average deviation at  $z = 0.4$  mm is well below the tolerance of 160 ppm in all cases.

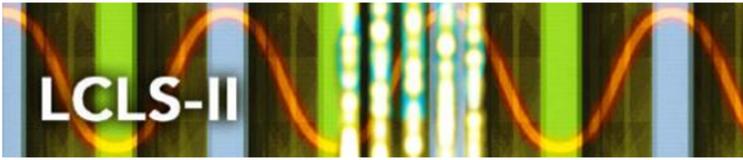


Evaluation of Hall Scans:  $K$  vs.  $y$  dependence

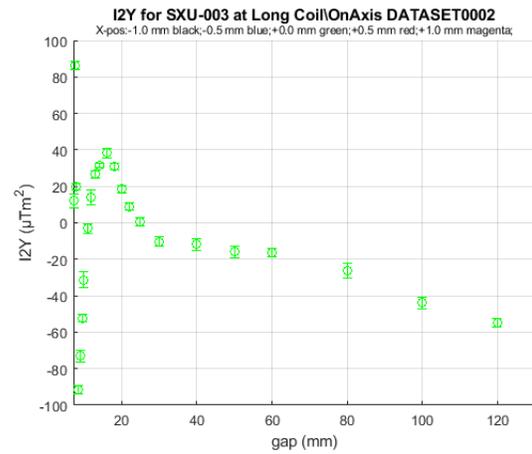
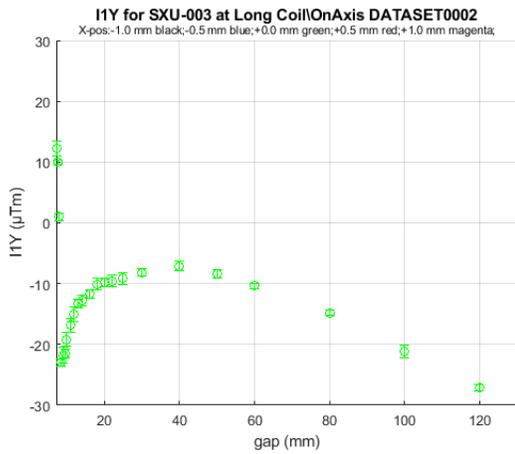
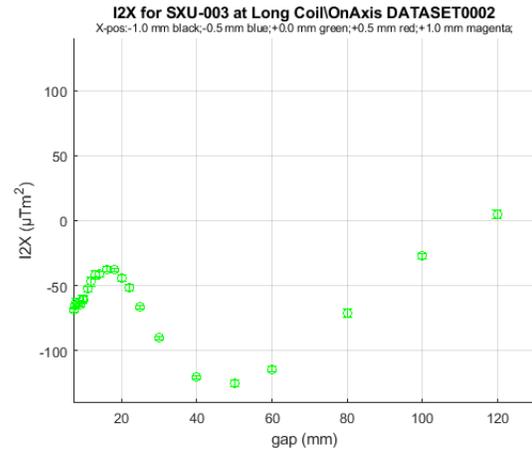
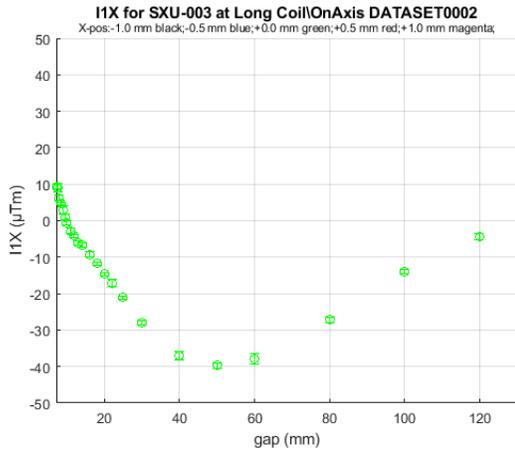
SXU\_003\_DATASET0002\_Final\_Results\_Z\_Scans



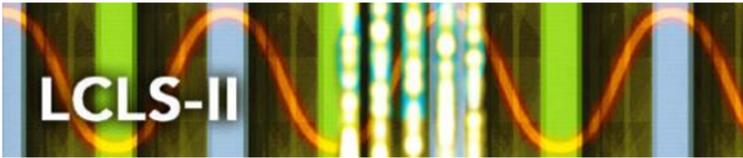
The figure shows the deviation of the relative undulator strength,  $K$ , value from the on-axis value,  $K_0$ , as function of  $y$  at a number of operational gaps. The deviations follow closely the expected functional form  $(\cosh(k_u y) - 1)$ . [Documentary Information]



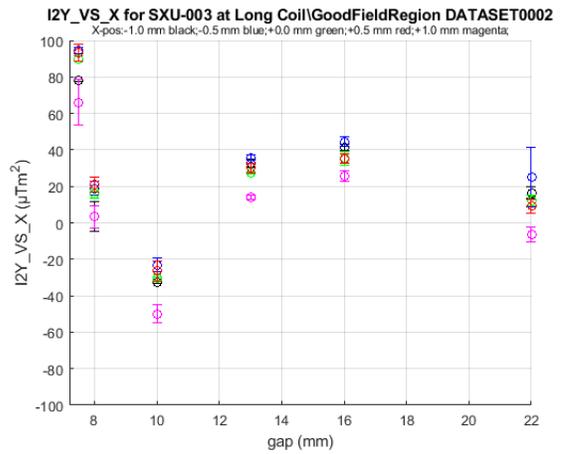
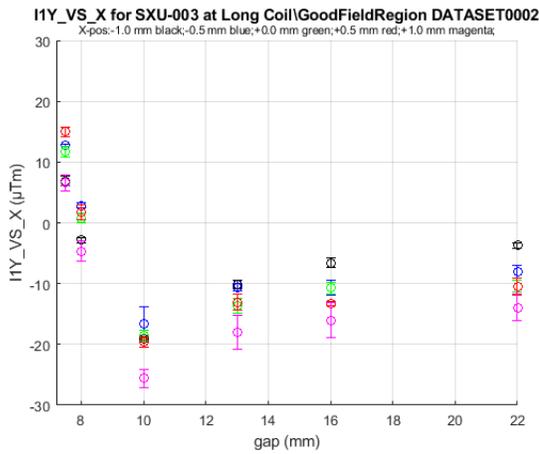
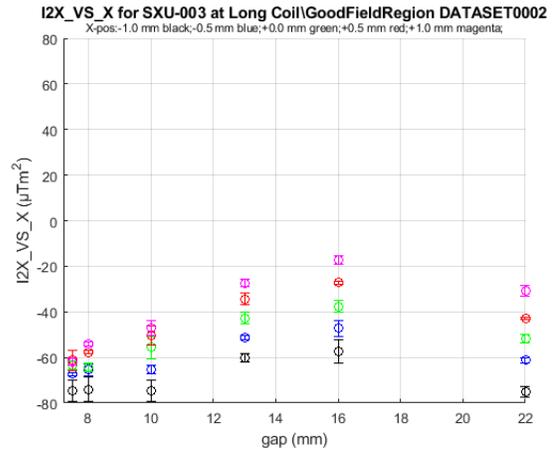
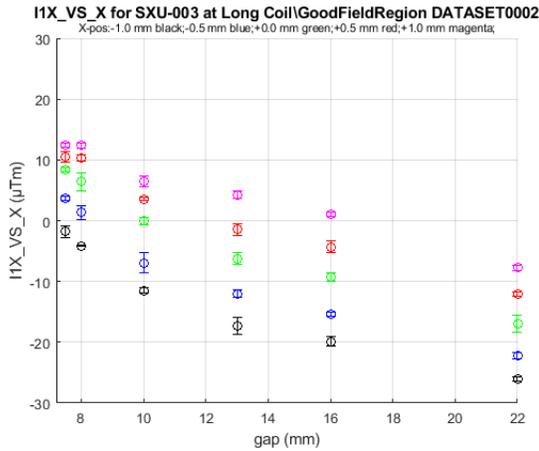
### Long Coil Measurement of the On-Axis Field Integrals



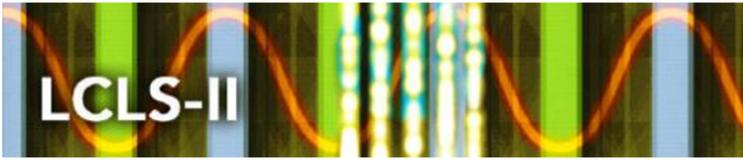
The figure shows the field integrals obtained from long coil measurements on-axis. The vertical axes extend over the tolerance range. All integrals are in tolerance.



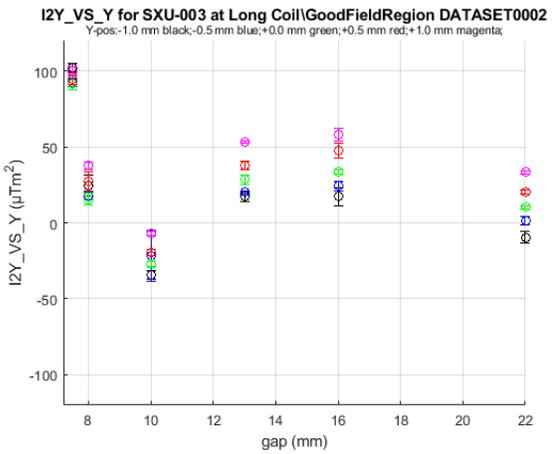
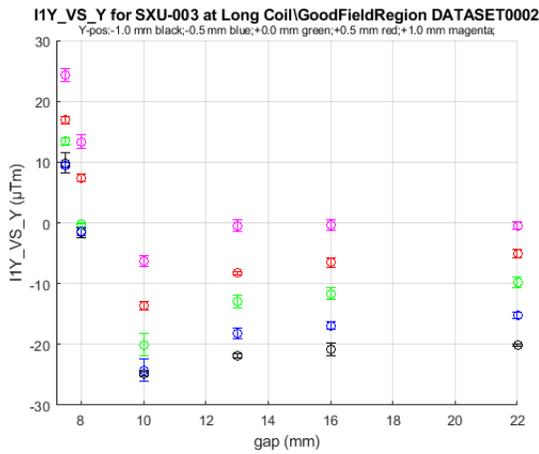
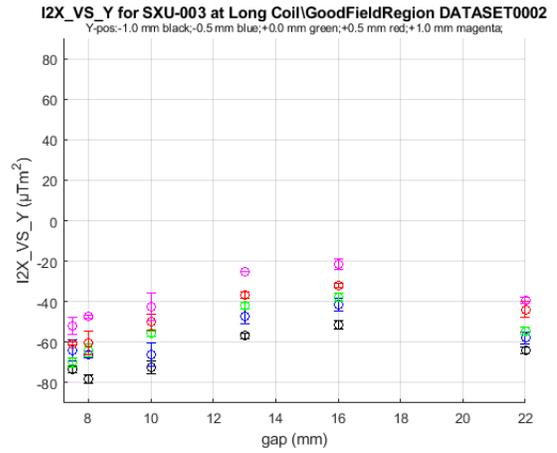
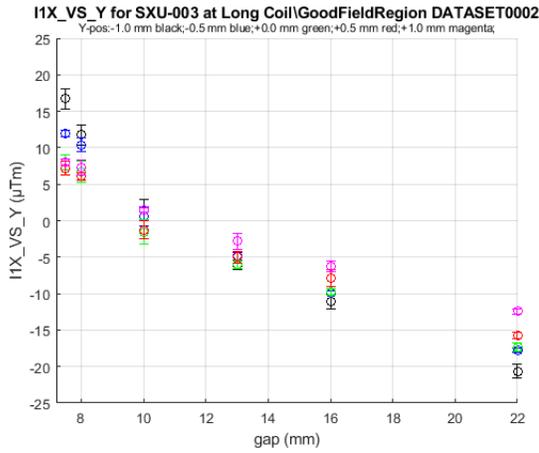
## Long Coil Measurement of the Horizontally Off-Axis Field Integrals



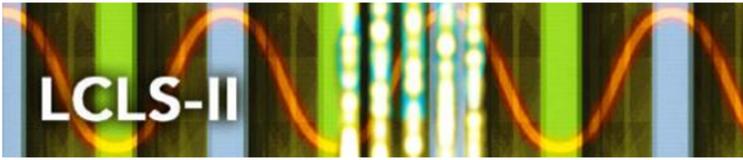
The figure shows the integrals obtained from long coil measurements off axis in the vertical plane using colors to indicate offset distance (black: -1.0 mm, blue: -0.5 mm, green: on-axis; red: +0.5 mm, magenta: +1.0 mm). The vertical axes extend of the tolerance range. All integrals are in tolerance.



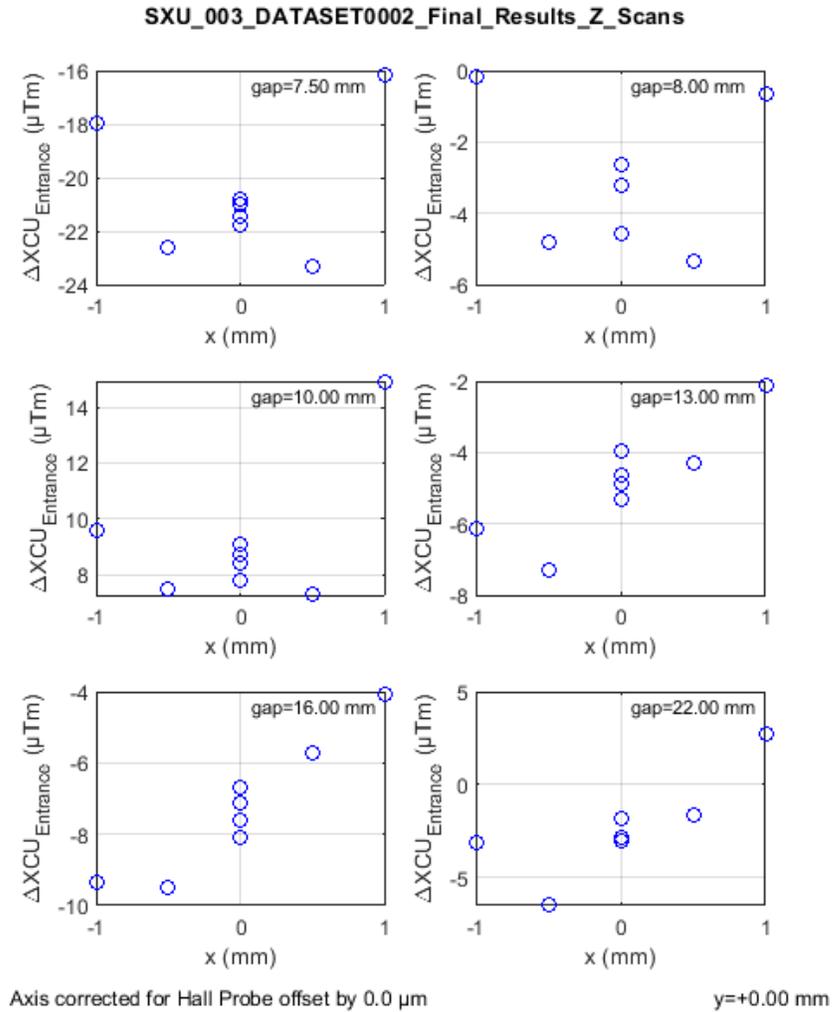
## Long Coil Measurement of the Vertically Off-Axis Field Integrals



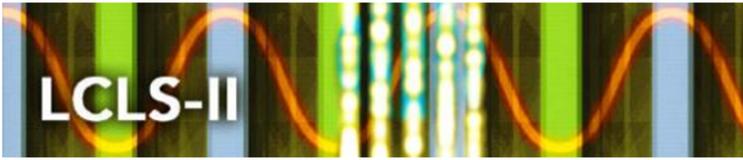
The figure shows the field integrals obtained from long coil measurements off axis in the horizontal plane using colors to indicate offset distance (black: -1.0 mm, blue: -0.5 mm, green: on-axis; red: +0.5 mm, magenta: +1.0 mm). The vertical axes extend over the tolerance range. All integrals are in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



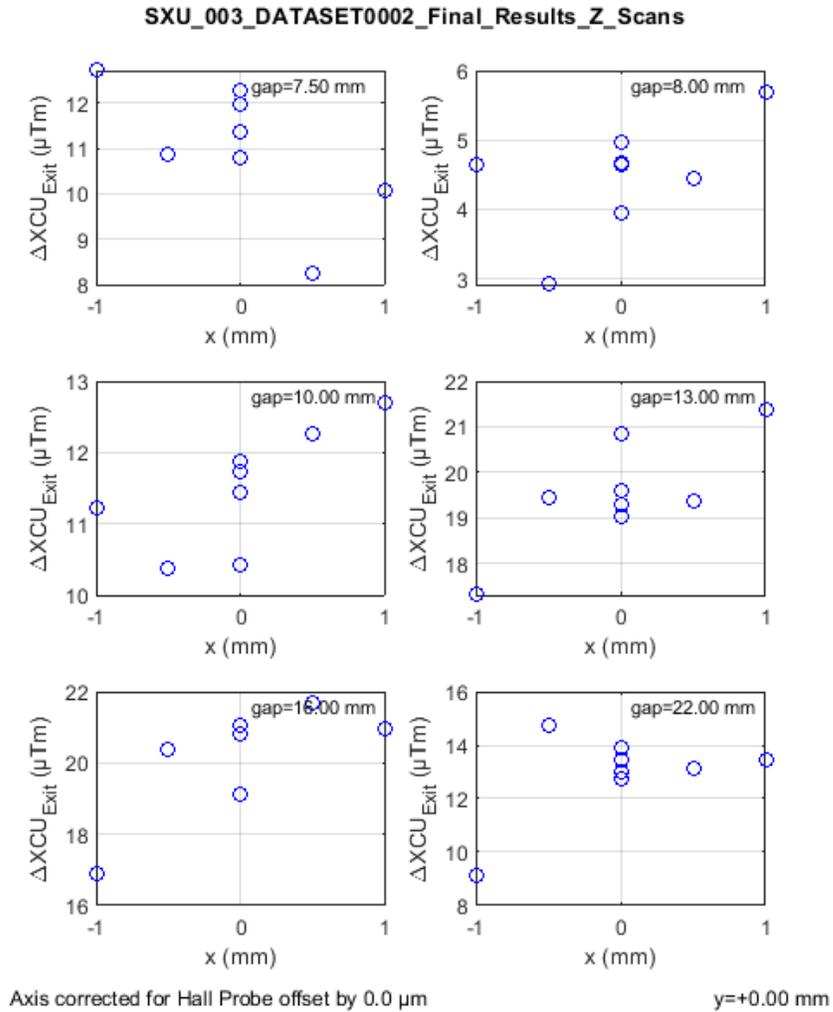
**Estimated Upstream Horizontal Corrector Strength Requirement vs.  $x$**



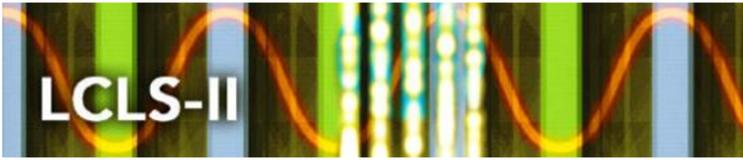
The figure shows the required strength of the upstream horizontal corrector to remove the second vertical undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z plane. All values are small and well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



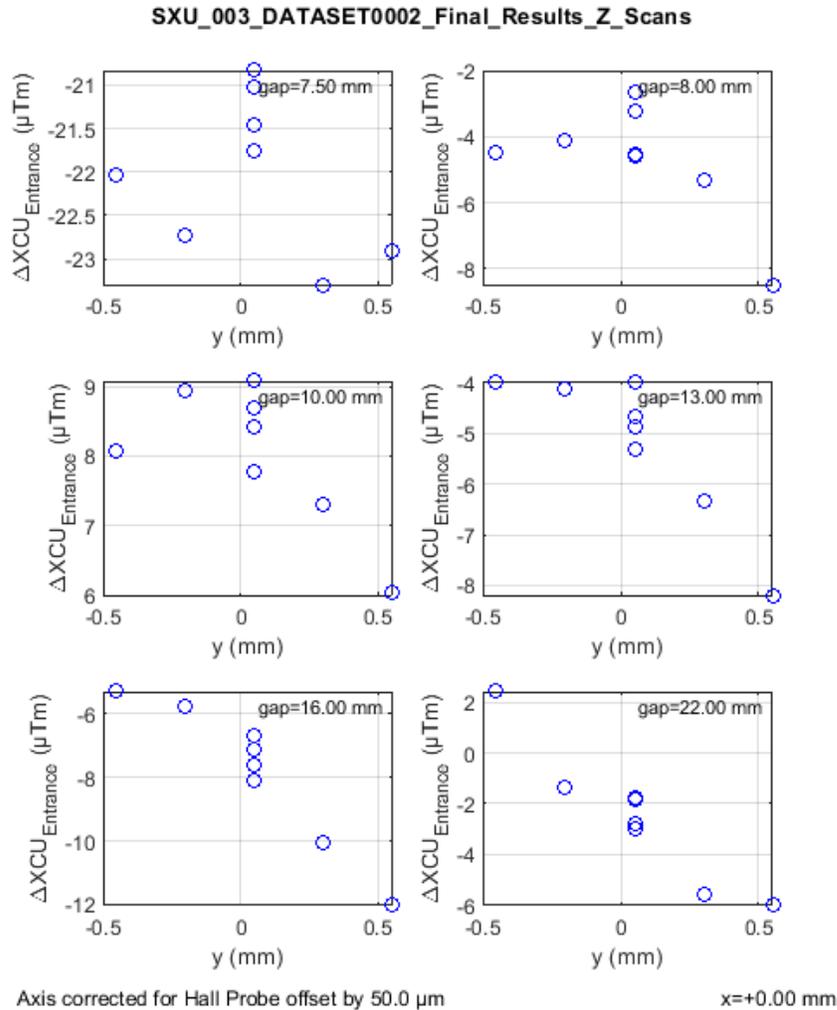
**Estimated Downstream Horizontal Corrector Strength Requirement vs.  $x$**



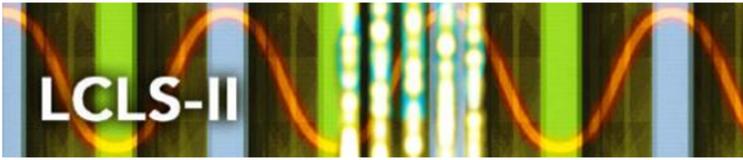
The figure shows the required strength of the downstream horizontal corrector to remove the first vertical undulator field integral and upstream corrector field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z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



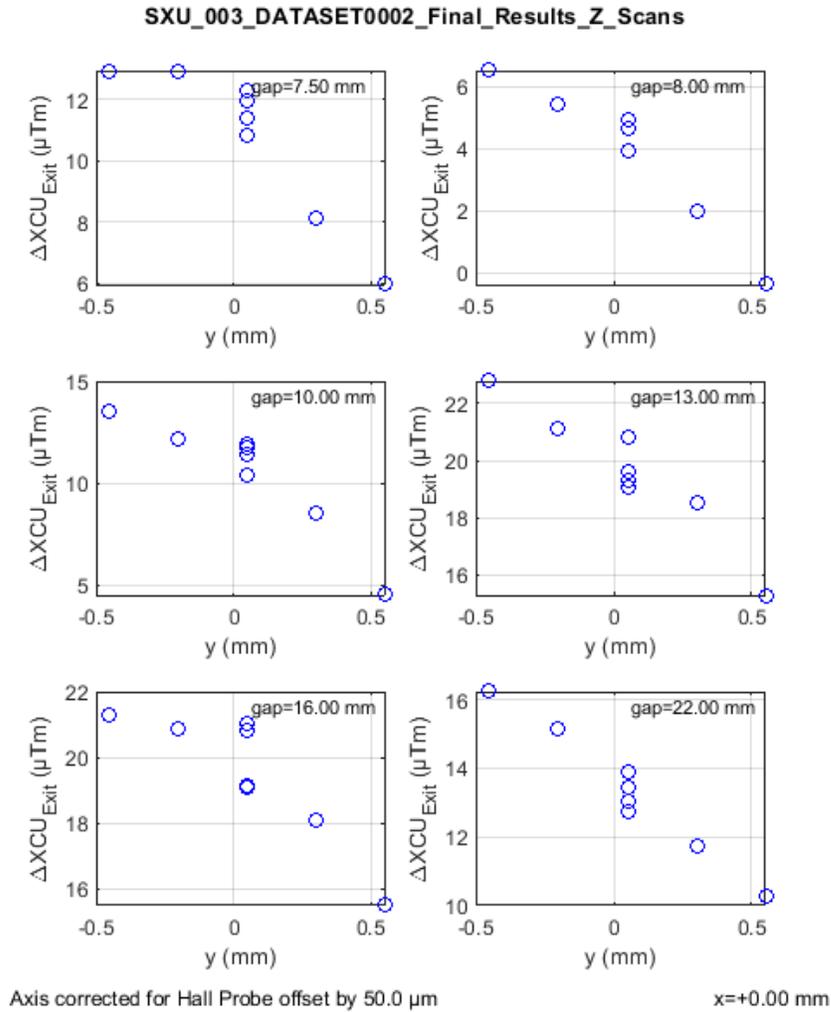
**Estimated Upstream Horizontal Corrector Strength Requirement vs.  $y$**



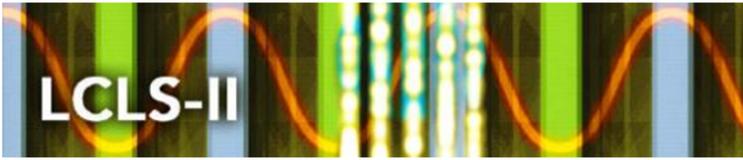
The figure shows the required strength of the upstream horizontal corrector to remove the second vertical undulator field integrals at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the  $y$ - $z$  plane. All values are small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



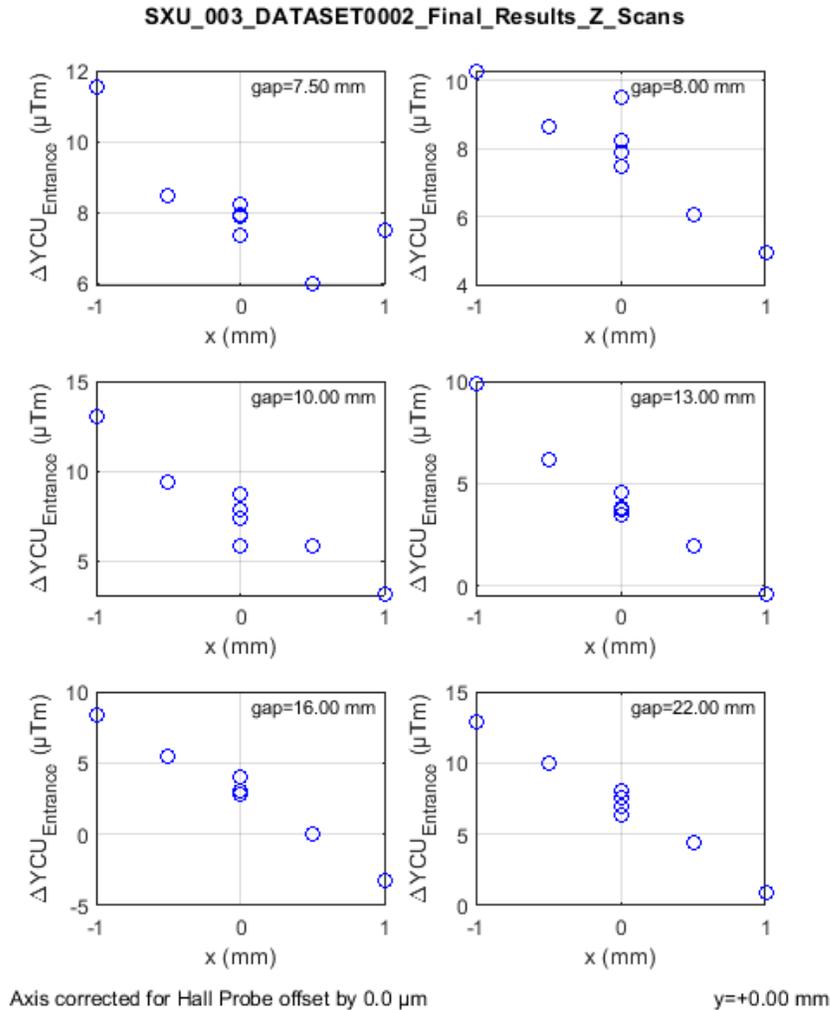
**Estimated Downstream Horizontal Corrector Strength Requirement vs.  $y$**



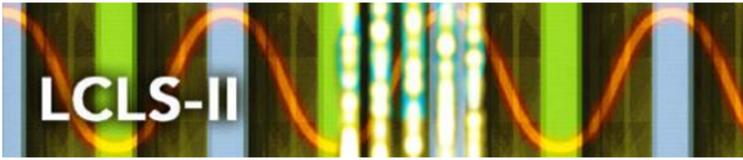
The figure shows the required strength of the upstream horizontal corrector to remove the first vertical undulator and upstream corrector field integrals at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the  $y$ - $z$  plane.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



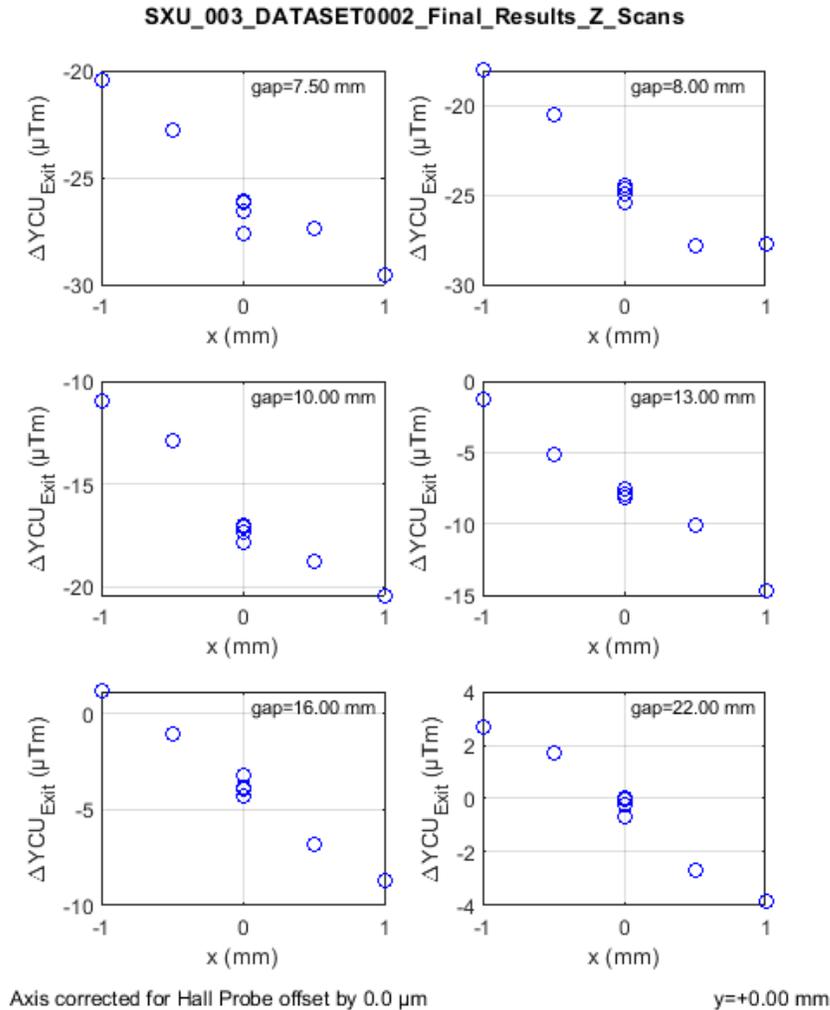
### Estimated Upstream Vertical Corrector Strength Requirement vs. $x$



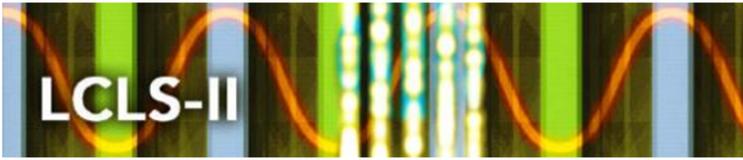
The figure shows the required strength of the upstream horizontal corrector to remove the second horizontal undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z plane. All values are small and well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



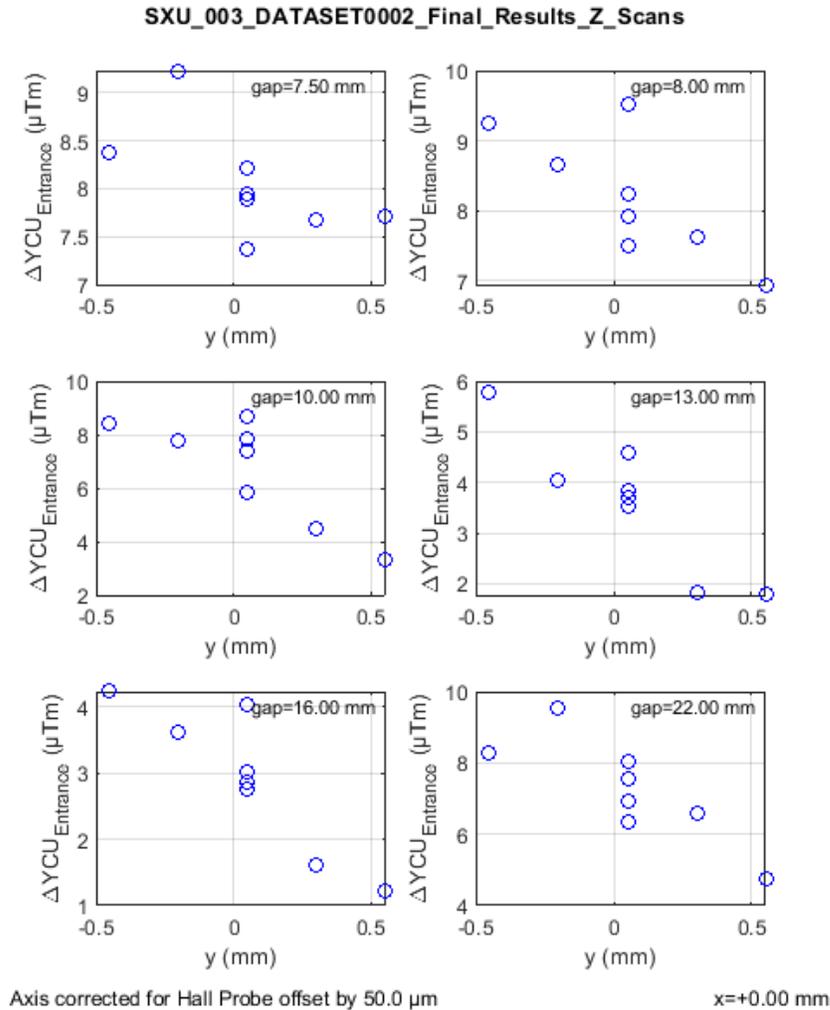
**Estimated Downstream Vertical Corrector Strength Requirement vs.  $x$**



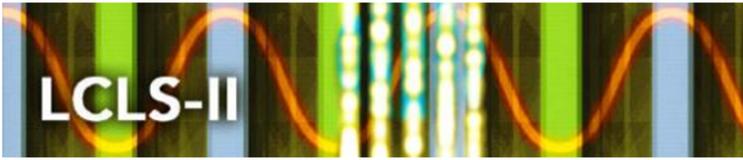
The figure shows the required strength of the downstream vertical corrector to remove the first horizontal undulator field integral and upstream corrector field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z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



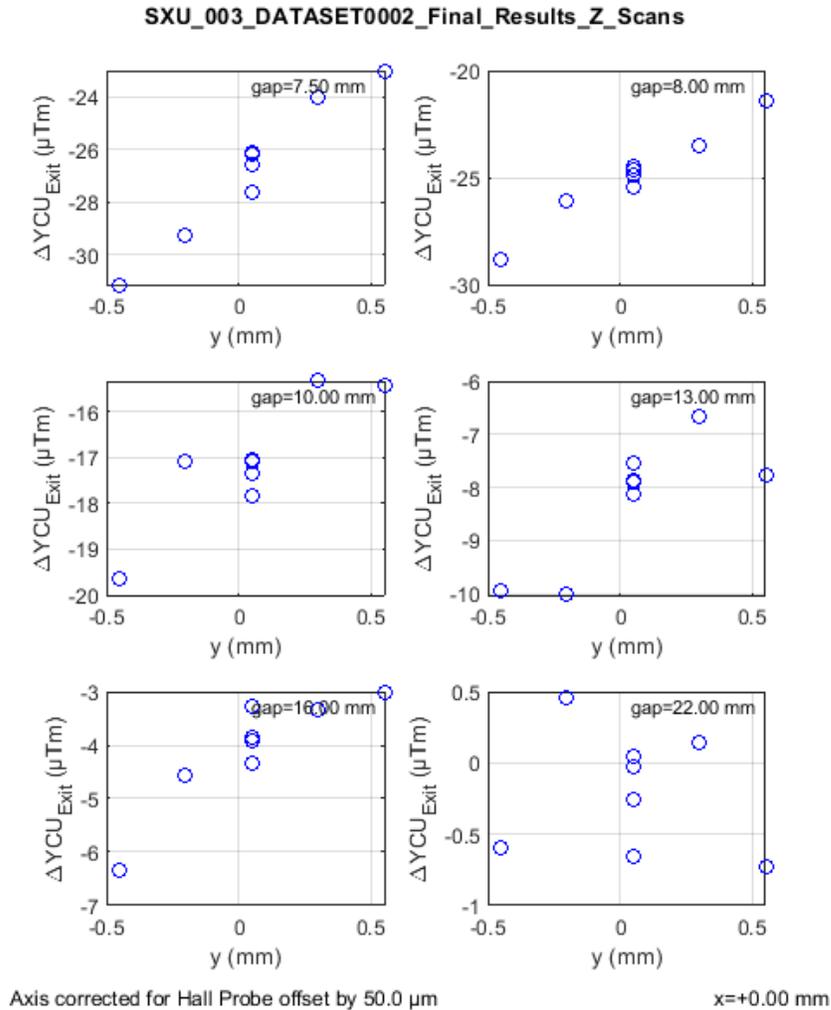
### Estimated Upstream Vertical Corrector Strength Requirement vs. $y$



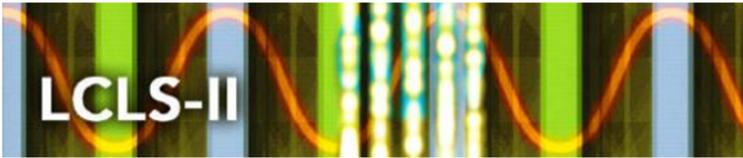
The figure shows the required strength of the upstream vertical corrector to remove the second horizontal undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the  $y$ - $z$  plane. All values are small and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



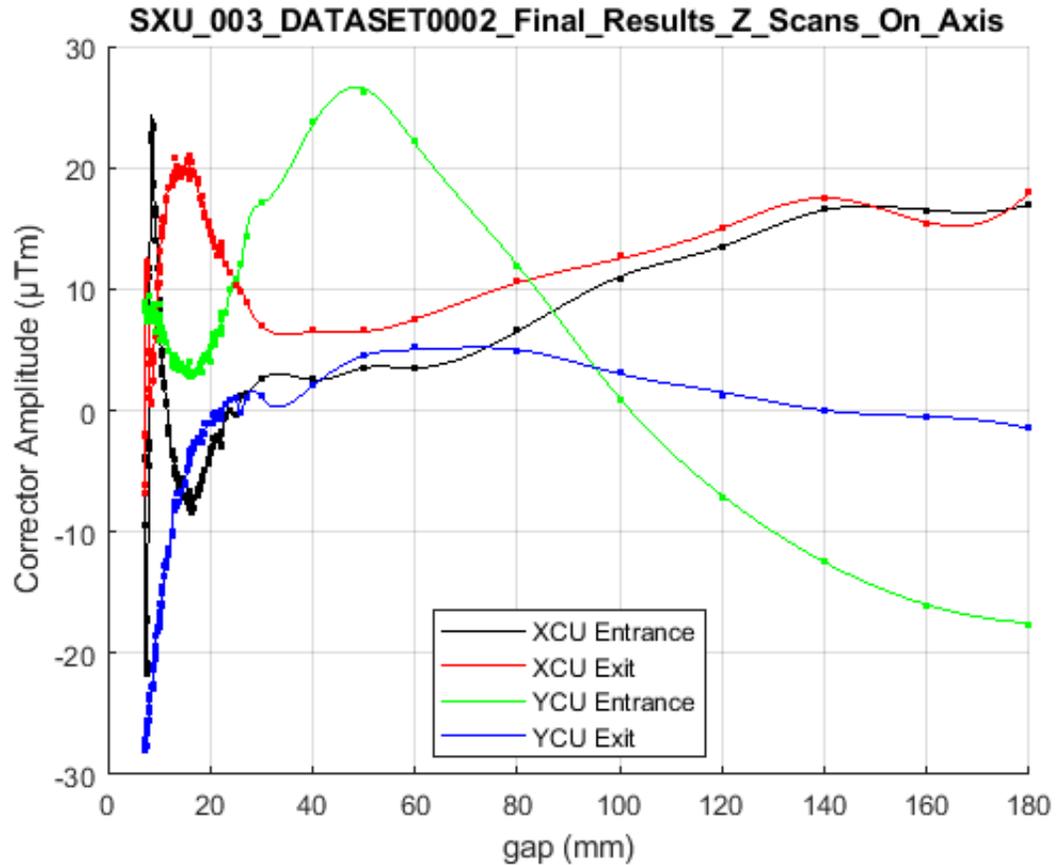
**Estimated Downstream Vertical Corrector Strength Requirement vs.  $y$**



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  $\mu\text{Tm}$  of the actual correctors.



### Estimated Corrector Strengths Requirement vs. gap



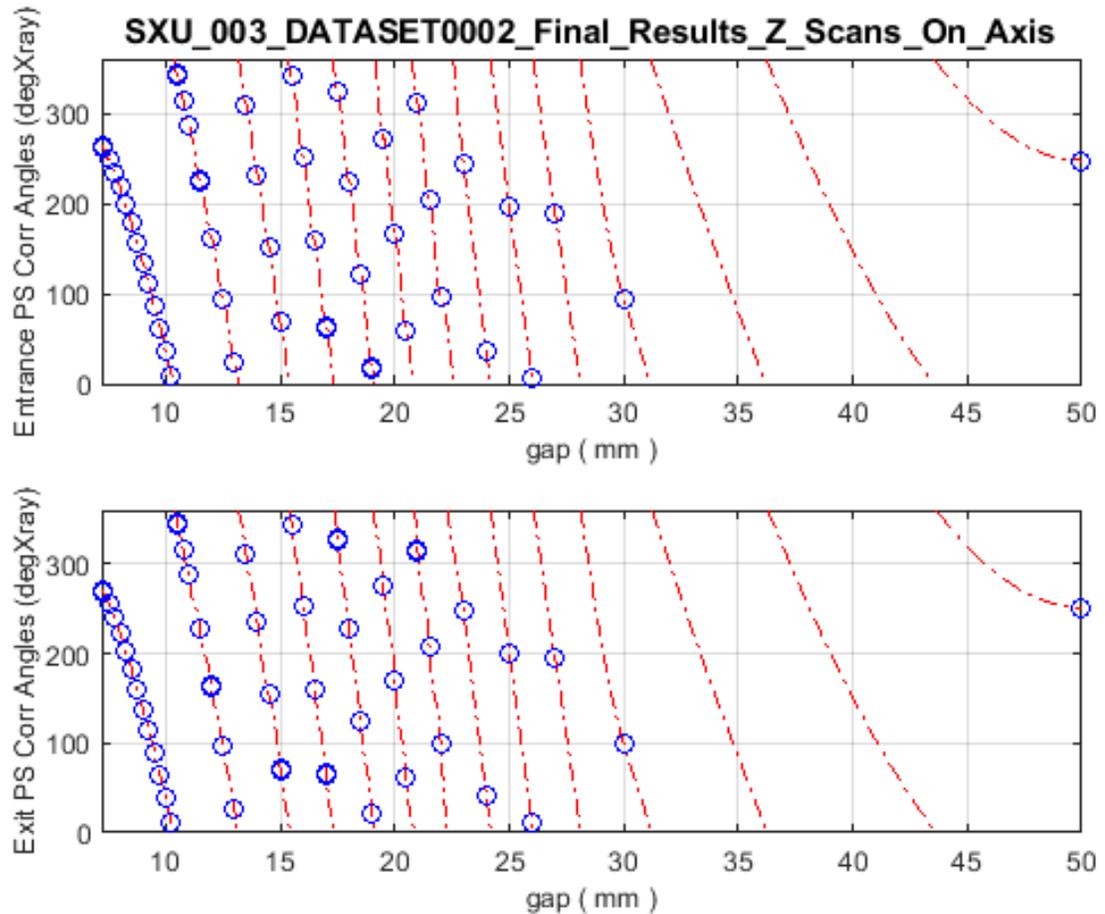
The figure shows as a function of undulator gap the required strengths of the upstream and downstream horizontal and vertical correctors to remove the effect of undulator field integrals at the downstream BPM over the entire available gap range. All values are small and well below the maximum correction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



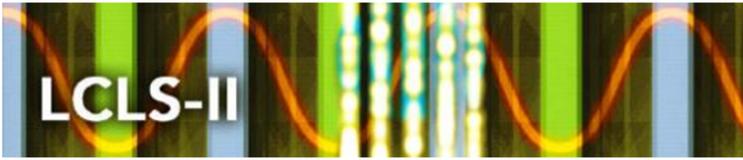
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**Estimated Phase Shifter Angle Change Requirement vs. gap**

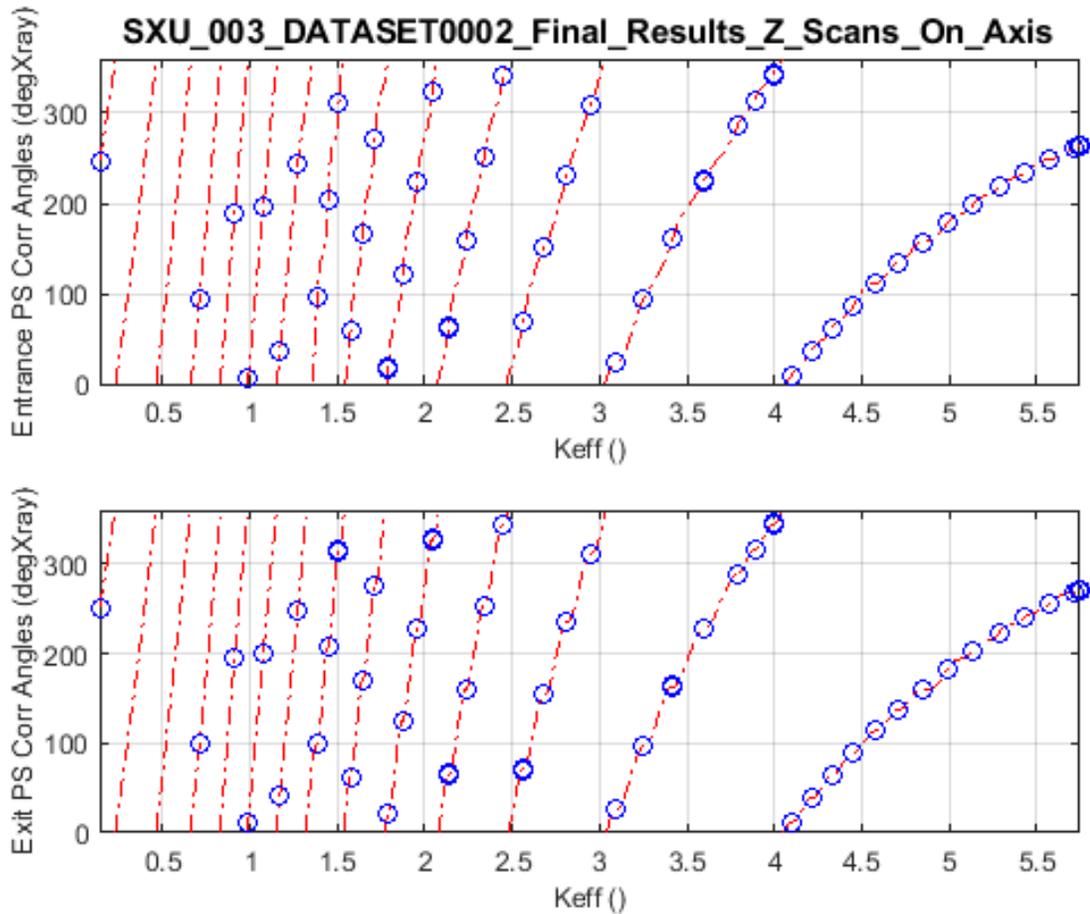
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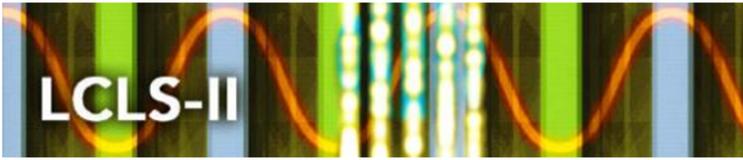
The top and bottom figures show as a function of undulator gap the required correction angles to be added to the upstream and downstream phase shifters, respectively. The red lines indicate the minimum required phase shifter phase angle increases, which are in the 0 to 360 degXray phase shift range. The blue circles indicate MMF measurements.



**Estimated Phase Shifter Angle Change Requirement vs.  $K_{eff}$**



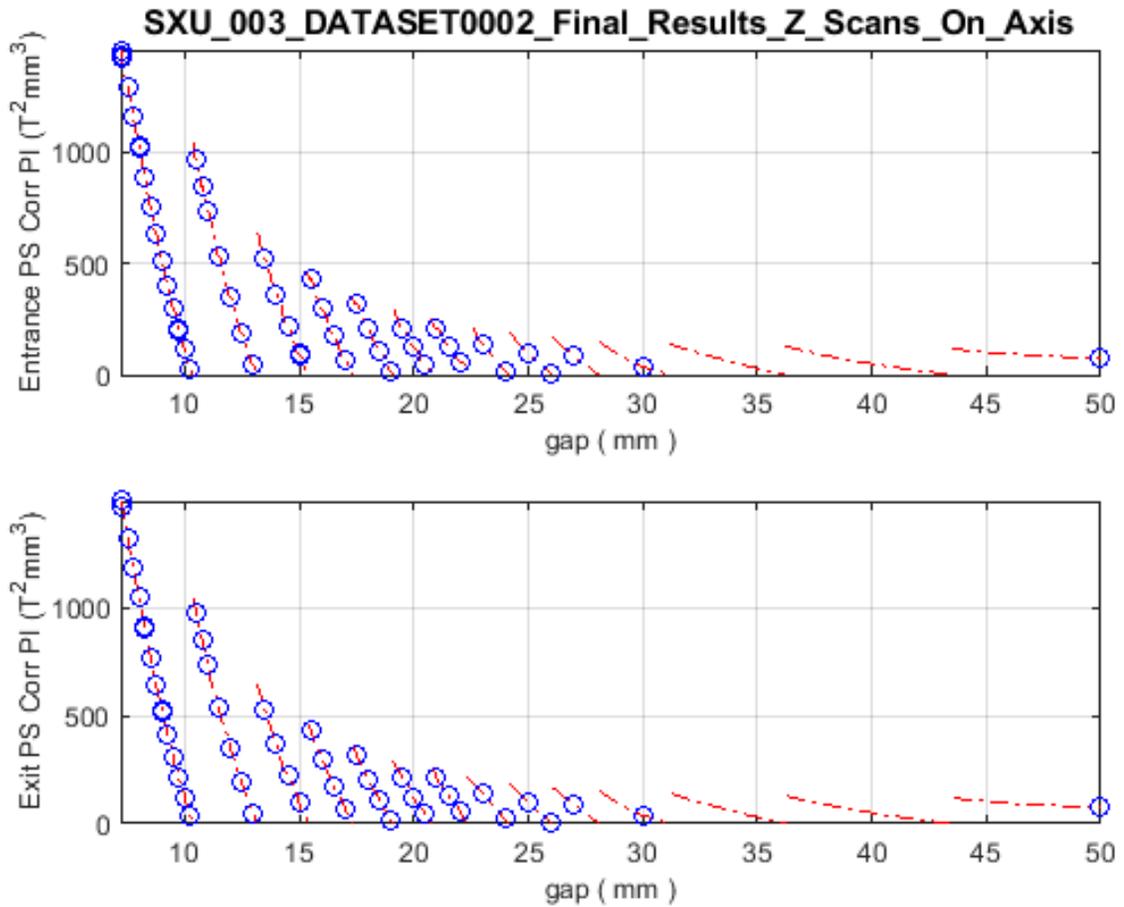
The top and bottom figures as a function of undulator parameter  $K_{eff}$  the required correction angles to be added to the upstream and downstream phase shifters, respectively. The red lines indicate the minimum required phase shifter phase angle increases, which are in the 0 to 360 degXray phase shift range. The blue circles indicate MMF measurements.



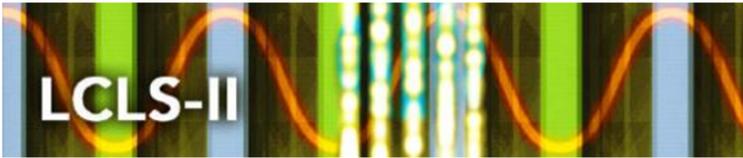
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### Estimated Phase Shifter Phase Integral Change Requirement vs. gap

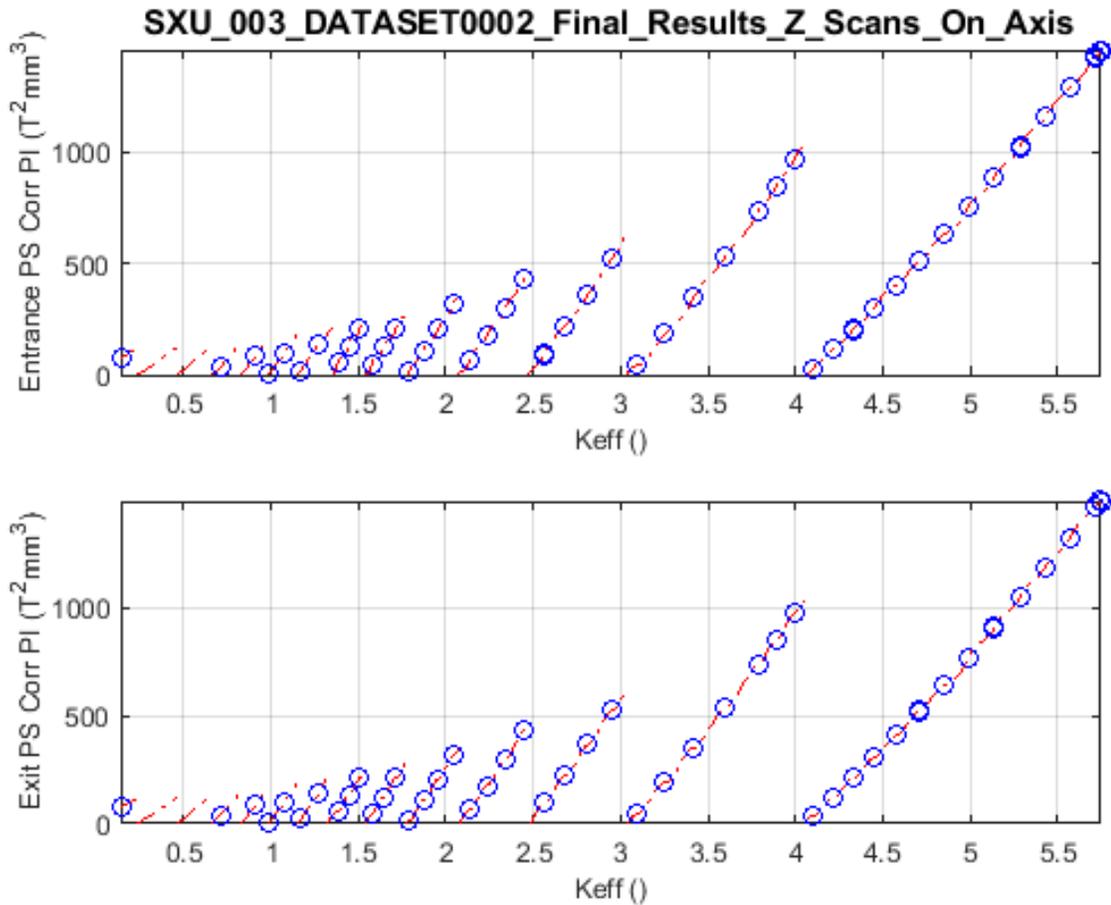
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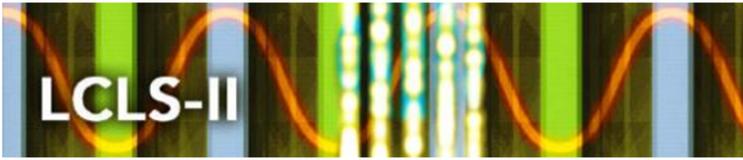
The top and bottom figures show as a function of undulator gap the required correction phase integral (PI) values to be added to the upstream and downstream phase shifters, respectively. The red lines indicate the minimum required phase shifter phase angle increases, which are in the 0 to 360 degXray phase shift range. The blue circles indicate MMF measurements.



Estimated Phase Shifter Phase Integral Change Requirement vs.  $K_{eff}$



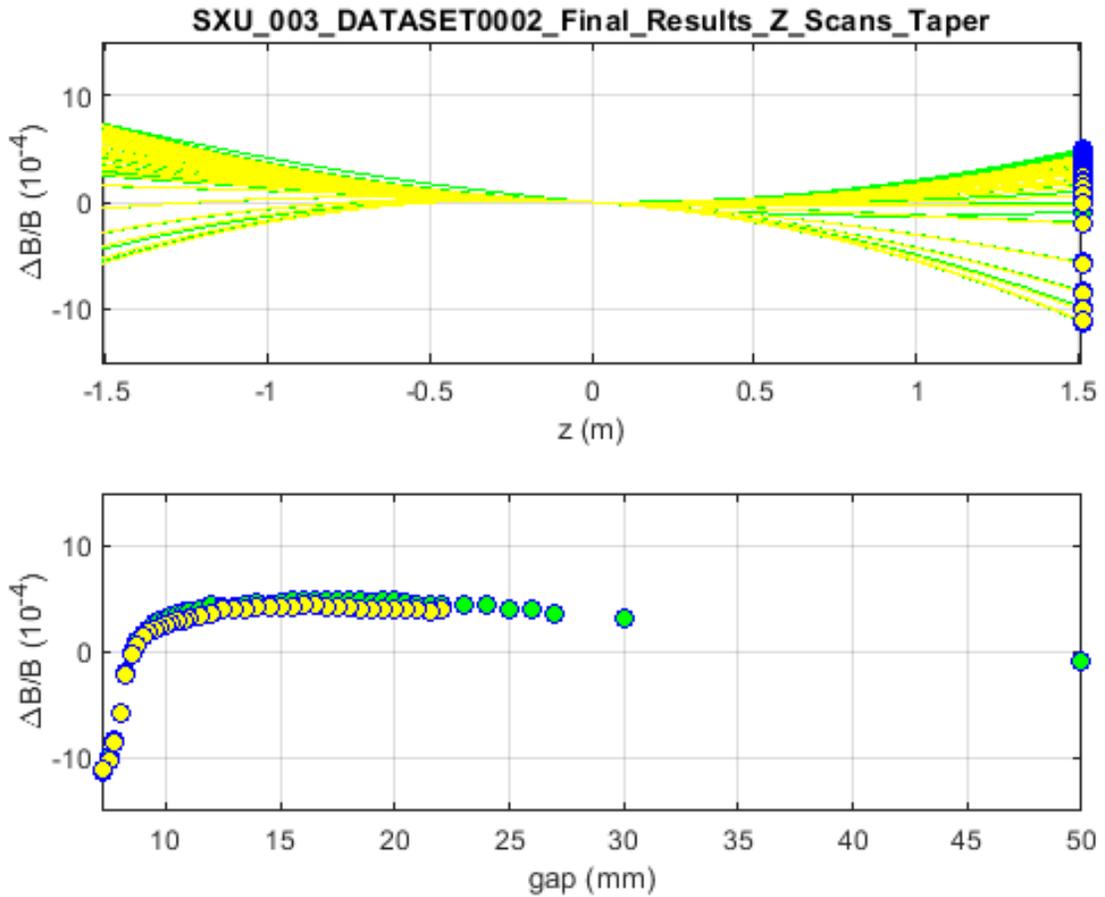
The top and bottom figures show as a function of undulator parameter  $K_{eff}$  the required correction phase integral (PI) values to be added to the upstream and downstream phase shifters, respectively. The red lines indicate the minimum required phase shifter phase angle increases, which are in the 0 to 360 degXray phase shift range. The blue circles indicate MMF measurements.



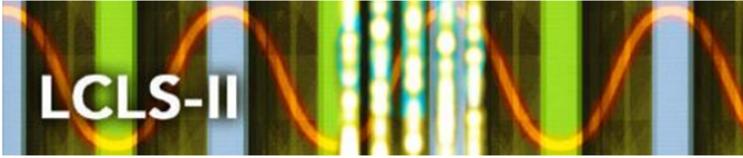
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### Zero Taper Fit vs. gap

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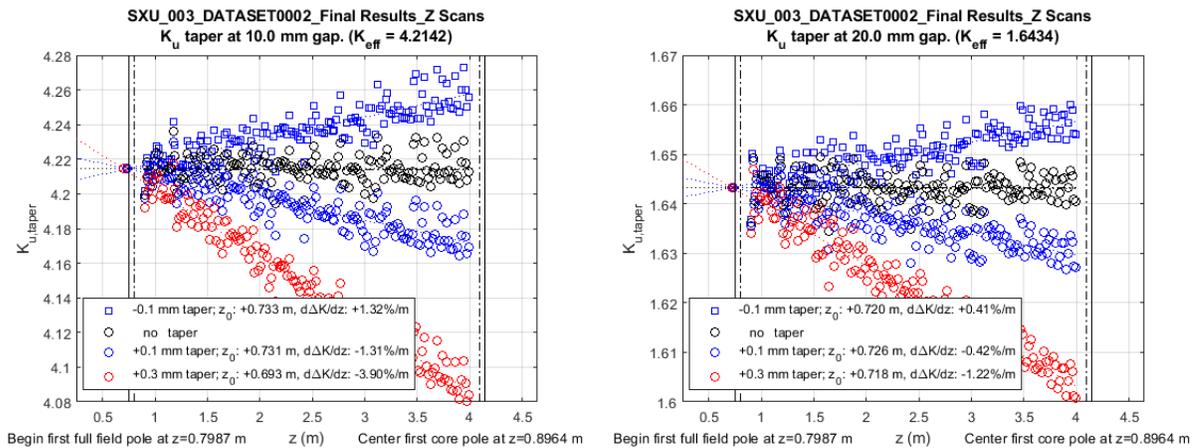


The top figure shows quadratic fits to the absolute values  $K_u$  for each core pole for different gaps when the device is set to zero taper. Green curves indicate that the gap was approached from smaller gaps, while yellow curves indicate approach from larger gaps. The fitted  $K_u$  value of the last pole is marked with a solid circle with the same color coding. The bottom shows the same solid circles as in the upper plot but this time plotted against the corresponding undulator gap encoder values. The figures show that the undulator has a small quadratic taper that varies with gap. This could explain the phase shake dependence on gap as shown in an earlier figure.

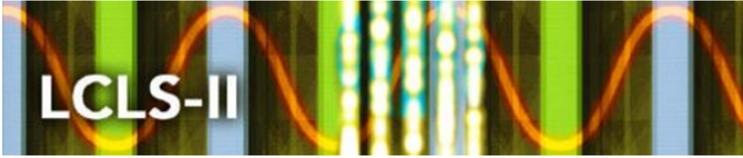


## Gap Tapering—Tapered $K_u$ Values

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.

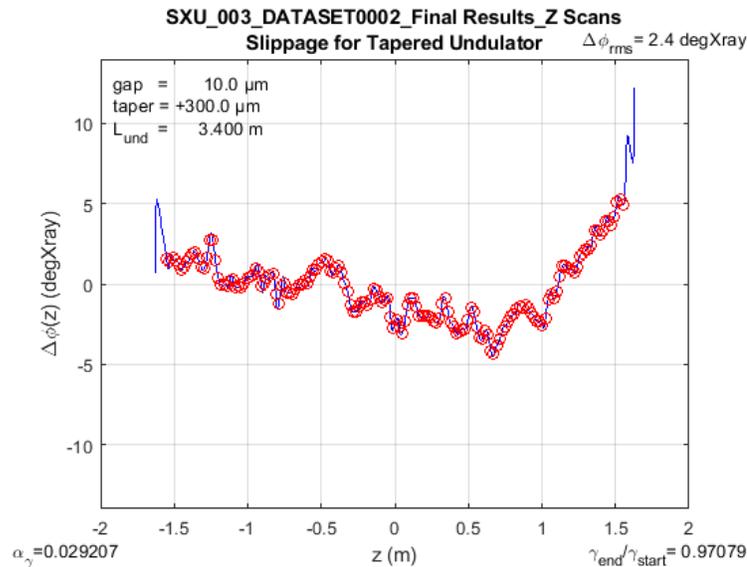
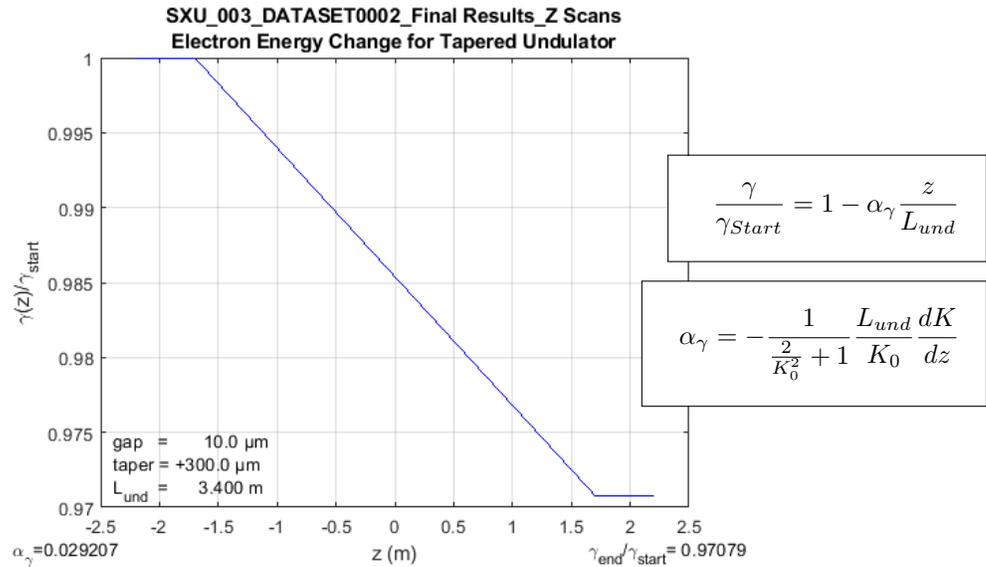


The figure shows  $K_u$ , taper for the 160 core poles based on Hall probe measurements versus  $z$  location for 4 different taper amplitudes ( $-100 \mu\text{m}$ ,  $0 \mu\text{m}$ ,  $+100 \mu\text{m}$ ,  $+300 \mu\text{m}$ ) and 2 different gaps (8 mm, 22 mm). The vertical dashed lines indicate the 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.

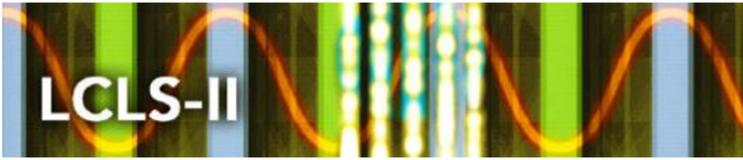


### Gap Tapering—Tapered $K_u$ Values

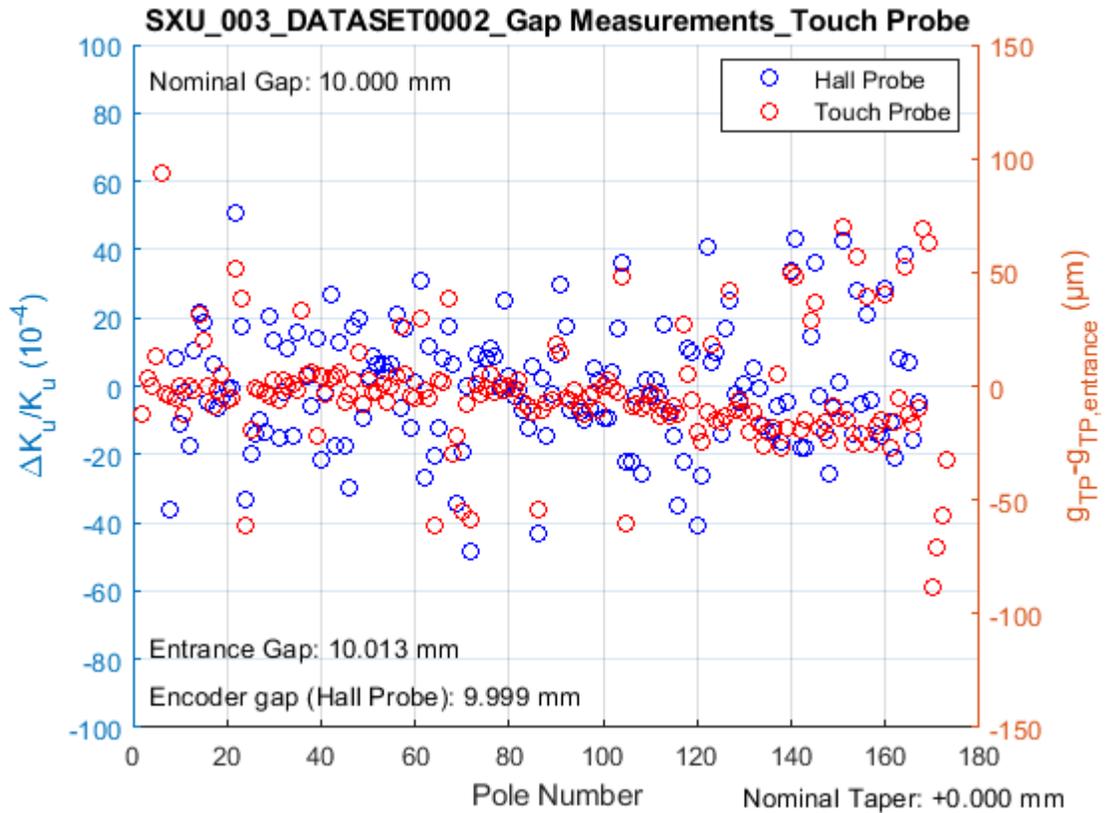
Generally, gap tapering will cause significant increases in the phase shake within the undulator segment. If however during high gain FEL operation the electrons loose significant amounts of energy, a matching gap taper can reduce the total phase shake to stay within the original parallel gap phase shake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



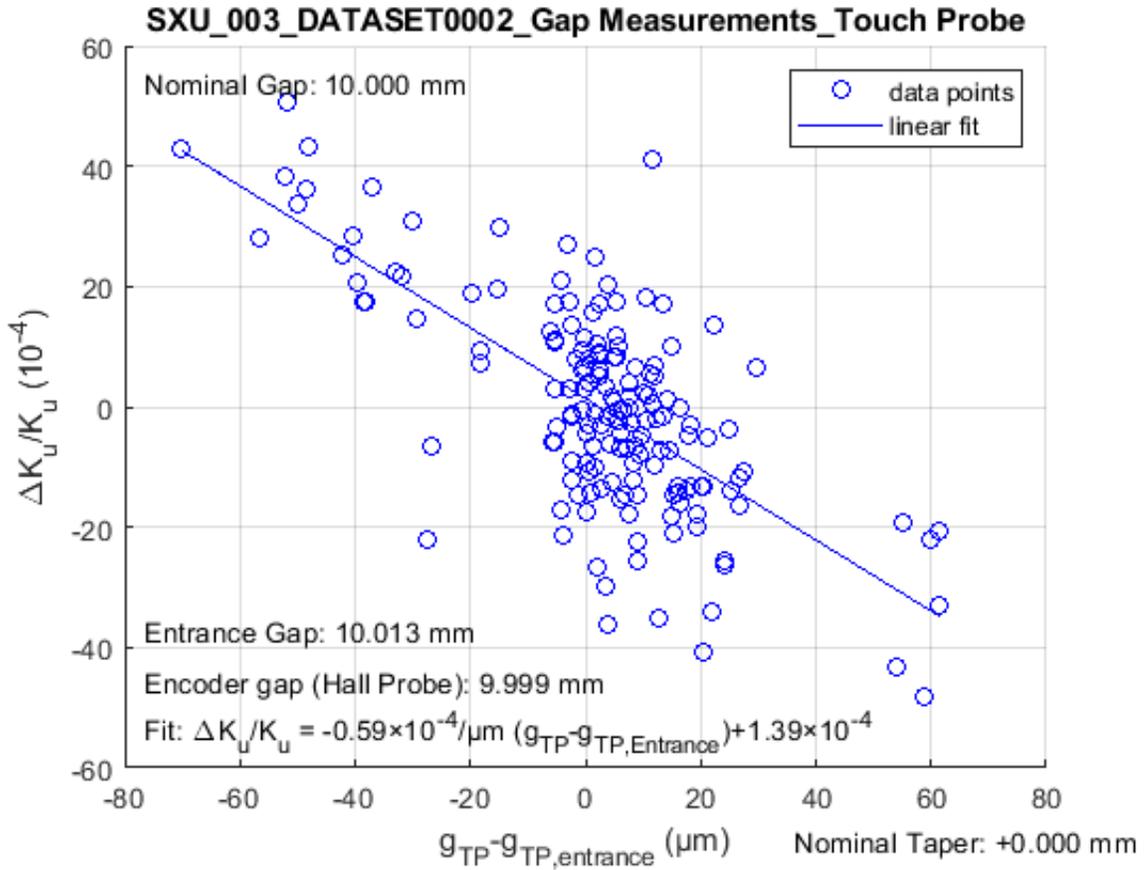
Touch Probe (TP) Analysis — Per pole gap vs. per pole  $K$  (untapered)



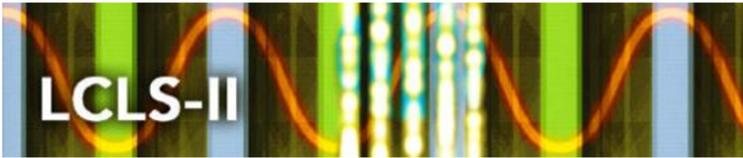
The figure shows  $\Delta K/K$  (blue, left axis) (for the 160 core poles) as well as mechanical gap heights ( $\langle g_{TP} \rangle - g_{TP}$ ) (red, right axis) (for all 174 poles) based on touch probe measurements versus pole number. The large amplitude outliers are the result of tuning.



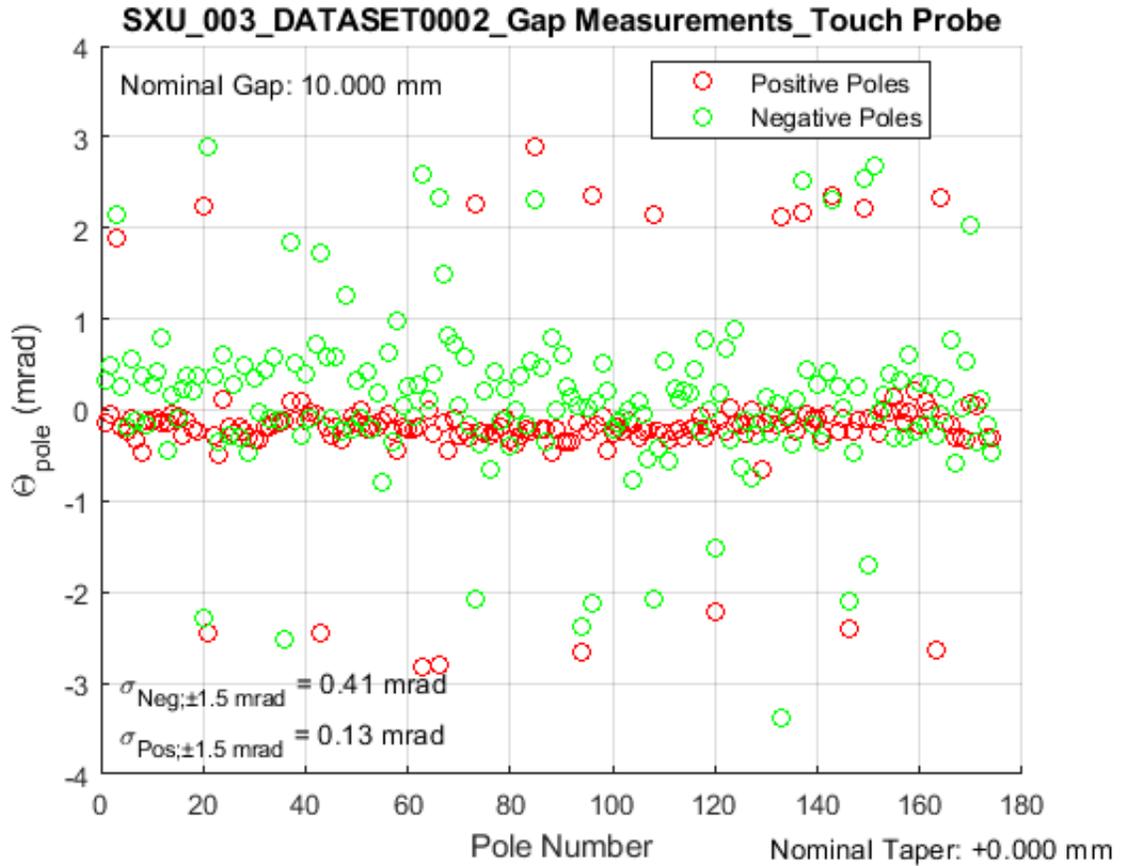
Touch Probe (TP) Analysis —  $K$  vs. per pole gap (untapered)



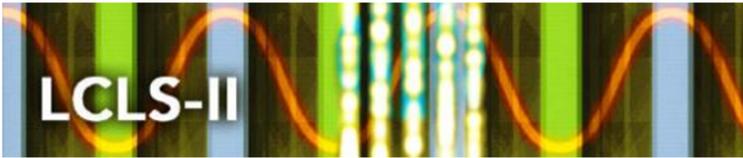
The figure shows the correlation between the  $\Delta K_u/K_u$  for each pole from Hall probe measurements for the tuning gap and the deviation of the pole gap measured by the touch probe relative to its average (for the 160 core poles). The average gap measured with the touch probe and the one measured with the gap encoder are shown in the lower left corner of the figure. Also shown is the fit function.



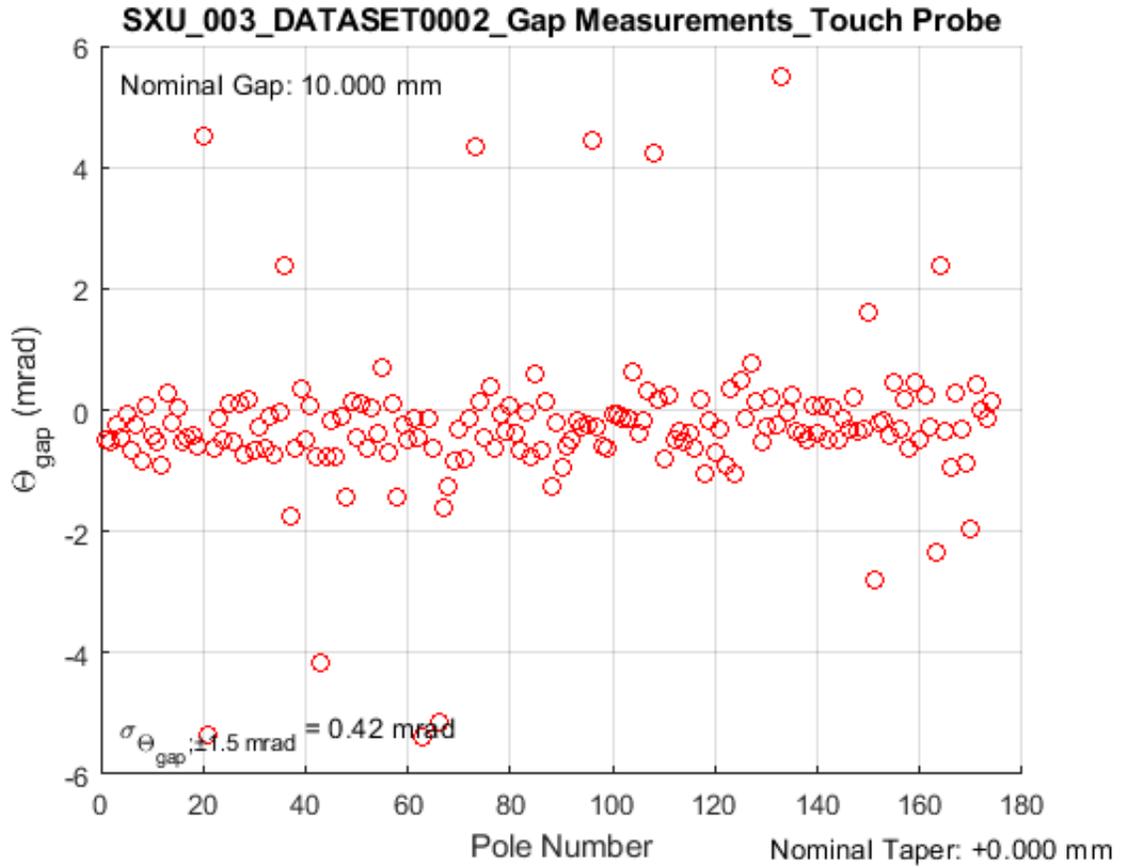
Touch Probe (TP) Analysis — Pole Cant Angles (untapered)



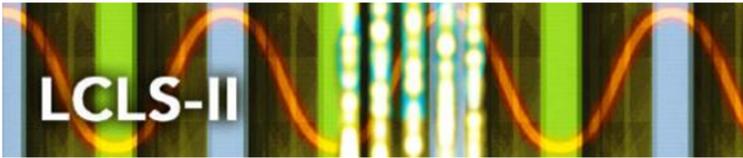
The figure shows the cant angles of each pole (top red, bottom green) relative to the horizontal plane defined by the Kugler bench at the Tuning Gap for all 174 poles, measured by the touch probe. The rms width of each distribution within a  $\pm 1.5$  mrad band is shown in the lower left corner of the figure.



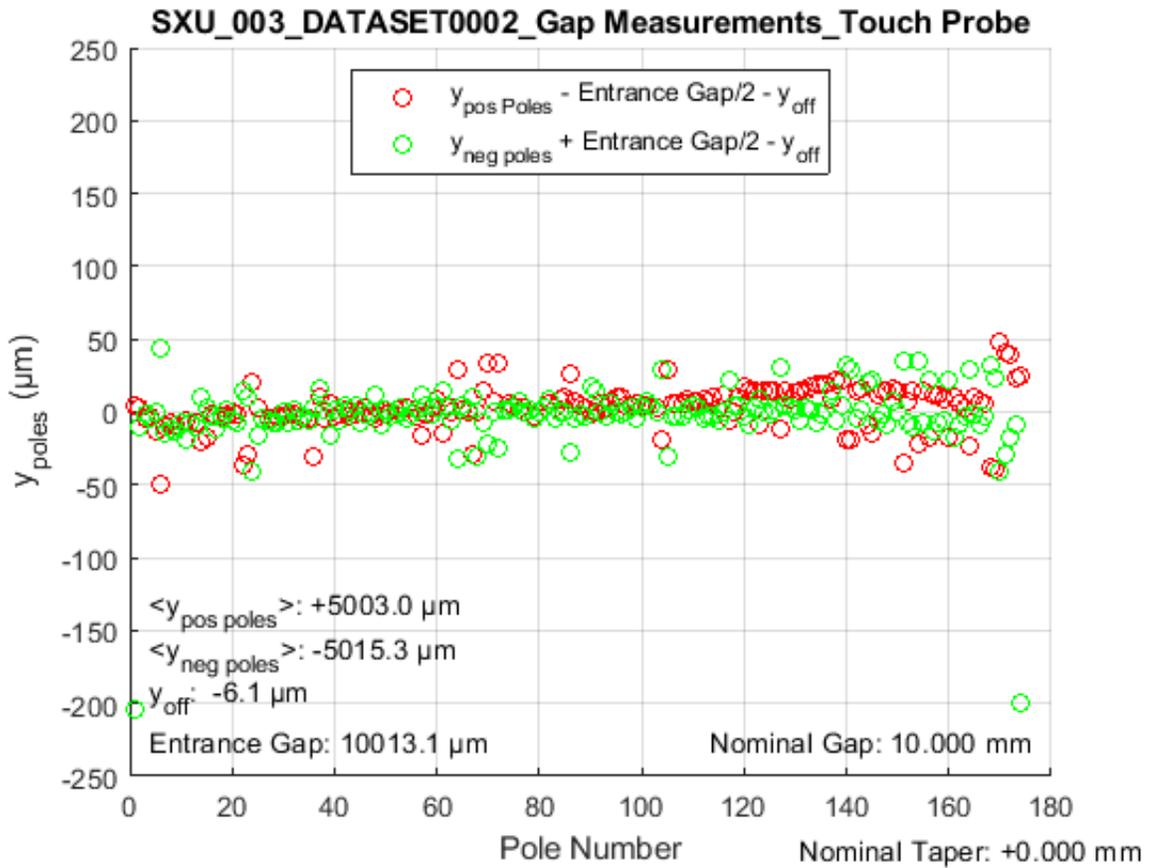
Touch Probe (TP) Analysis — Gap Cant Angles (untapered)



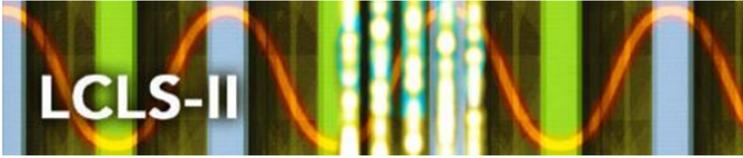
The figure shows the cant angles between the top and bottom part of each pole at the Tuning Gap for all 174 poles, measured by the touch probe. The rms width of each distribution within a  $\pm 1.5$  mrad band is shown in the lower left corner of the figure.



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 define by the Kugler bench at the Tuning Gap for all 174 poles, measured by the touch probe.



LCLS-II Undulator Segment Measurement Results

SXU-003

## Measurement Results are stored:

### At V-Drive:

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

### In Folder

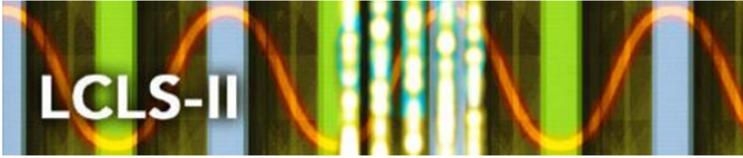
SXU-003\DATASET0002\MagServe\Final Results\  
 \_\_\_\_\_

## Confirmation of File Locations:

The following tables list all required data files documenting the tuning 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

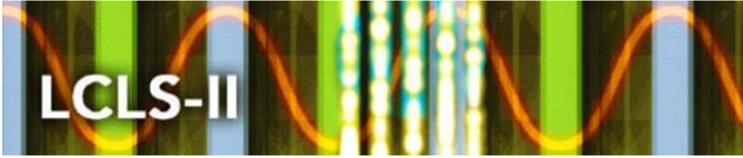
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Sub folder: Z Scans\On Axis exists

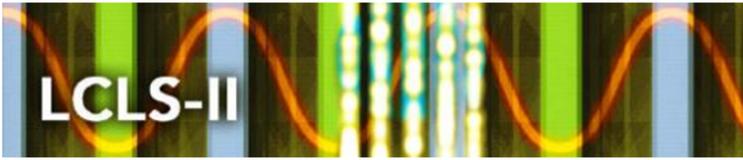
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LCLS-II Undulator Segment Measurement Results

SXU-003

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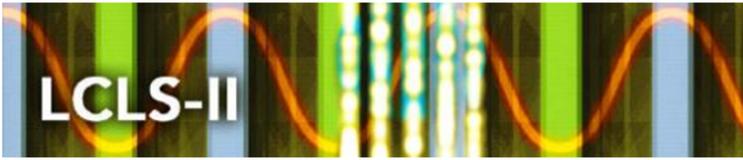
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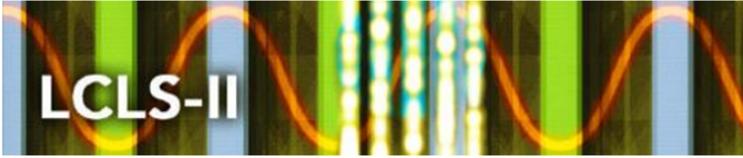
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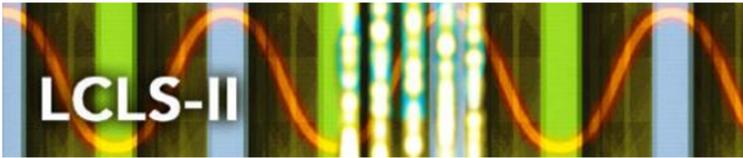
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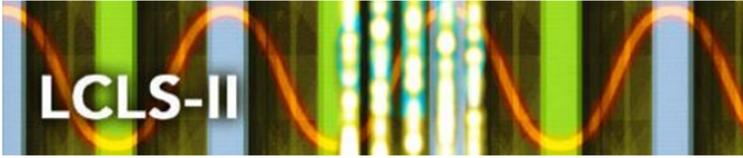
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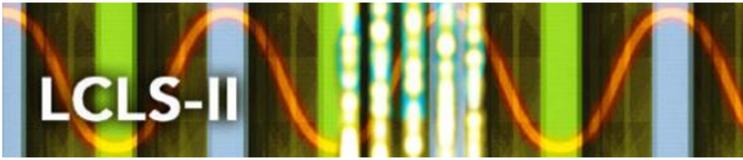
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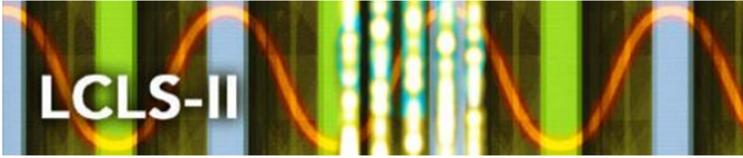
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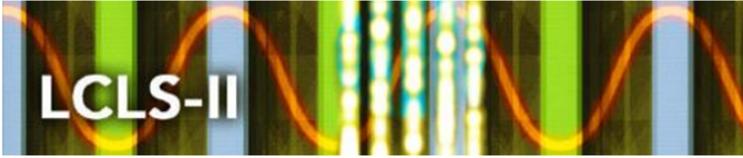
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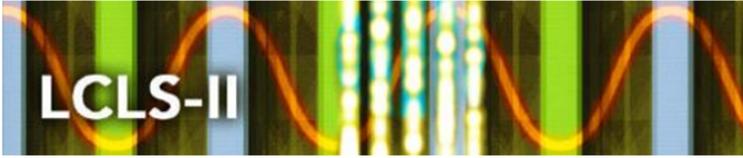
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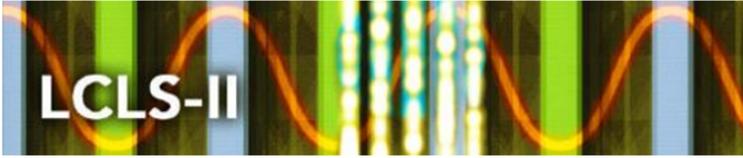
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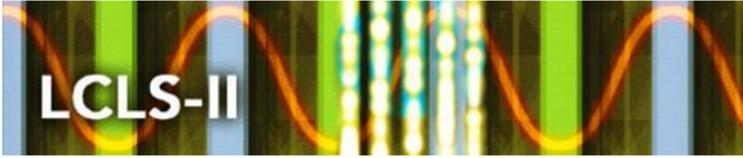


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Sub folder: **Fiducialization** exists

LCLS2 SXU 003 Fiducial Report.docx	exists
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Sub folder: **Gap Measurements** exists



LCLS-II Undulator Segment Measurement Results

SXU-003

Sub folder: Gap Measurements\Touch Probe exists

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Sub folder: Capacitive Sensors exists

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Sub folder: Controls Data 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:	SXU-003	

	Heinz-Dieter Nuhn	May 1, 2019
(Signature)	(Name)	(Date)