

LCLS-II Undulator Segment Measurement Results

SXU-005

## SLAC Traveler for LCLS-II SXU Segment Measurement Results

This traveler is intended to document the checking 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:	29A804-005
Device name from magnet label:	SXU-005

### Measurement Procedure:

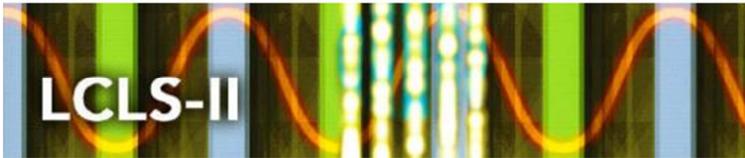
The measurements have been carried out after the undulator segment had been fully tuned according to “LCLS-II Undulator Test Plan” (LCLS-TN-17-1).

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

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MATLAB function "EvaluateUndulatorField" on	2/23/2018 10:04	
A. SCAN PARAMETERS		
Serial Number	29A804-005	
Device Name	SXU-005	
z Scanning Date & Time Range	02/16/2018 09:26 - 02/17/2018 01:06	
Undulator Temperature	20.1529± 0.0029	°C
Room Temperature	20.0846± 0.0050	°C
x axis position	0.075799	m
y axis position	0.000428	m
Total number of poles per strongback	174	
Number of full field poles	168	
Number of core poles	162	
First core pole #	8	
Last core pole #	167	
Average $\lambda_u$	39.003	mm
RMS $\lambda_u$	28.8	$\mu$ m
Scans averaged	3	
Tuning Gap	10	mm
Commissioning Gap	10.392	mm



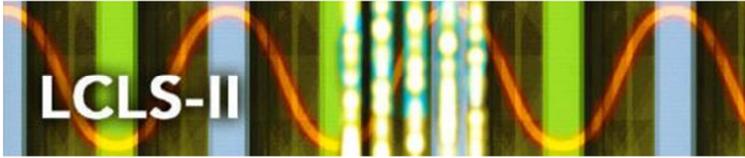
**Evaluation of Hall Probe Scans at Tuning Gap: Data Listings B**

MATLAB function "EvaluateUndulatorField" on	2/23/2018 10:04	
B. CORE EVALUATIONS FOR TUNING GAP		
Tuning Gap Scanning Date & Time	2/16/2018 14:03	
Tuning Gap Temperature	20.15± 0.05	°C
Planar Hall Effect Correction Range	0.789800 - 4.102800	m
Planar Hall Effect x Corr Function	-0.06 G + (z - 0.789800 m) * 0.20 G/m	
Planar Hall Effect y Corr Function	-0.44 G + (z - 0.789800 m) * 0.26 G/m	
Coil Range	0.646304 - 4.246304	m
<λ <sub>u</sub> >	39.003± 0.002	mm
<k <sub>u</sub> >	161.10± 0.01	1/m
<K <sub>u</sub> >	4.226±0.001	
<K <sub>eff</sub> > @ Tuning Temperature	4.22592±0.00004	
<L <sub>eff</sub> >	3.31381±0.00006	m
<L <sub>2π</sub> >	0.38727±0.00002	m
I1X (Cell Range Total)	9.08	μTm
I2X (Cell Range Total)	-0.97	μTm <sup>2</sup>
I1Y (Cell Range Total)	-16.01	μTm
I2Y (Cell Range Total)	-60.02	μTm <sup>2</sup>
PI (Cell Range Total)	85,968.50	T <sup>2</sup> mm <sup>3</sup>
Phase Shake	2.06	degXray
Cell Phase Advance (over 4.400000 m)	31,596.4 (88×360-83.6)	degXray
Undulator Entrance Phase	1219.0±0.2	degXray
Undulator Exit Phase	1217.4±0.2	degXray
Undulator Phase Imbalance: Entrance - Exit	1.5±0.2	degXray
Cell Entrance min. Phase Shifter Correction	221	degXray
Cell Exit min. Phase Shifter Correction	222.6	degXray



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

MATLAB function "EvaluateUndulatorField" on	2/23/2018 10:04	
C. CORE EVALUATIONS FOR COMMISSIONING GAP		
Commissioning Gap Scanning Date & Time	2/17/2018 1:14	
Commissioning Gap Temperature	20.15± 0.05	°C
Planar Hall Effect Correction Range	0.791200 - 4.101600	m
Planar Hall Effect x Corr Function	-0.09 G + (z - 0.791200 m) * 0.20 G/m	
Planar Hall Effect y Corr Function	-0.42 G + (z - 0.791200 m) * 0.27 G/m	
Coil Range	0.646307 - 4.246307	m
<λ <sub>u</sub> >	39.003± 0.002	mm
<k <sub>u</sub> >	161.10± 0.01	1/m
<K <sub>u</sub> >	4.050± 0.001	
<K <sub>eff</sub> > @ Tuning Temperature	4.05066± 0.00004	
<L <sub>eff</sub> >	3.31437± 0.00006	m
<L <sub>2π</sub> >	0.35898± 0.00002	m
I1X (Cell Range Total)	10.83	μTm
I2X (Cell Range Total)	5.39	μTm <sup>2</sup>
I1Y (Cell Range Total)	-20.1	μTm
I2Y (Cell Range Total)	-58.61	μTm <sup>2</sup>
PI (Cell Range Total)	78,999.00	T <sup>2</sup> mm <sup>3</sup>
Phase Shake	1.94	degXray
Cell Phase Advance (over 4.400000 m)	31,680.6 (88×360+0.6)	degXray
Undulator Entrance Phase	1260.9± 0.2	degXray
Undulator Exit Phase	1259.8± 0.2	degXray
Undulator Phase Imbalance: Entrance - Exit	1.1± 0.2	degXray
Cell Entrance min. Phase Shifter Correction	179.1	degXray
Cell Exit min. Phase Shifter Correction	180.2	degXray



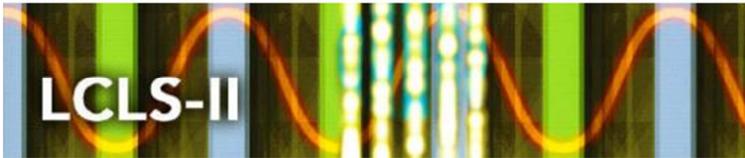
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## Undulator Encoder Values: Data Listings D

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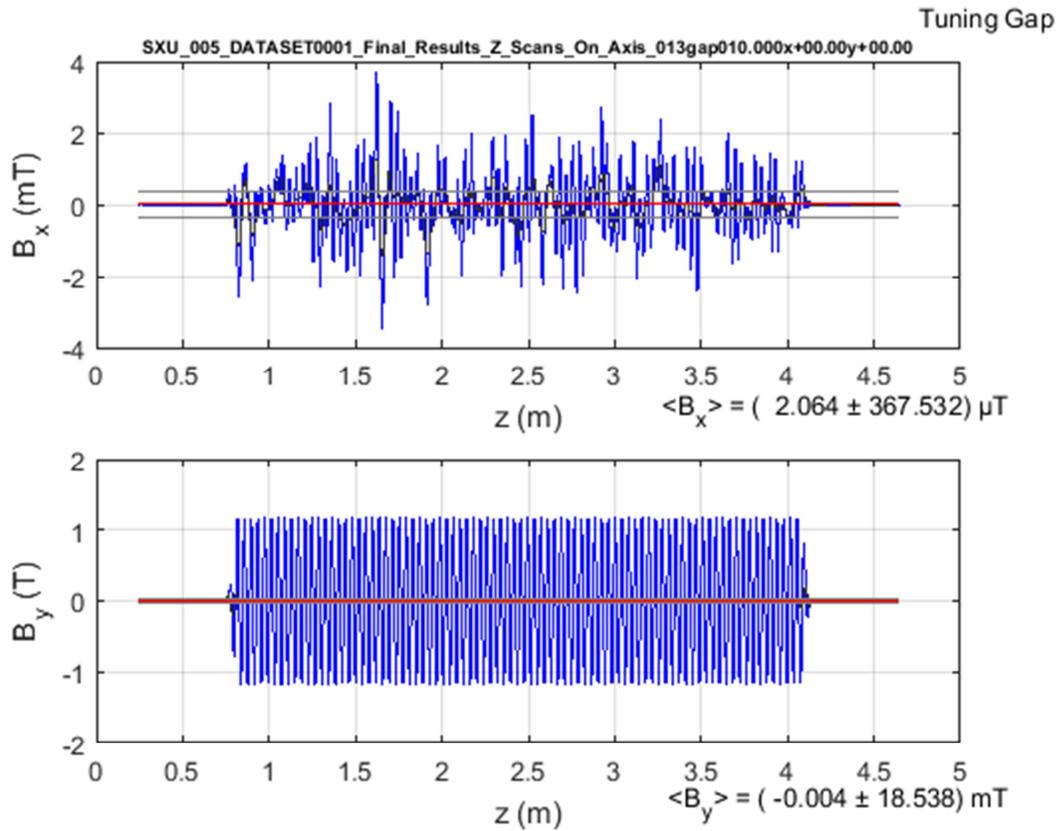
MATLAB function "EvaluateUndulatorField" on D. ENCODER SETTINGS	2/23/2018 10:04	
Upstream Gap Encoder Gain	-20,000.0±1.8	
Upstream Scaled Gap Encoder Offset	227.866±0.0000	mm
Downstream Gap Encoder Gain	-19,999.4±4.0	
Downstream Scaled Gap Encoder Offset	228.133±0.0000	mm
Upstream Scaled Top Motor Encoder Offset	-1015.240±0.000	mm
Downstream Scaled Top Motor Encoder Offset	-1014.850±0.000	mm

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

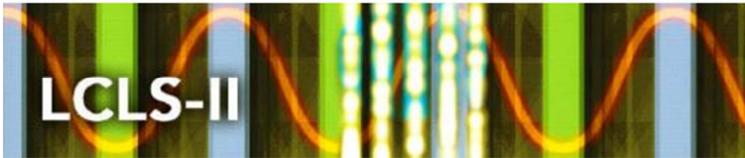


LCLS-II Undulator Segment Measurement Results

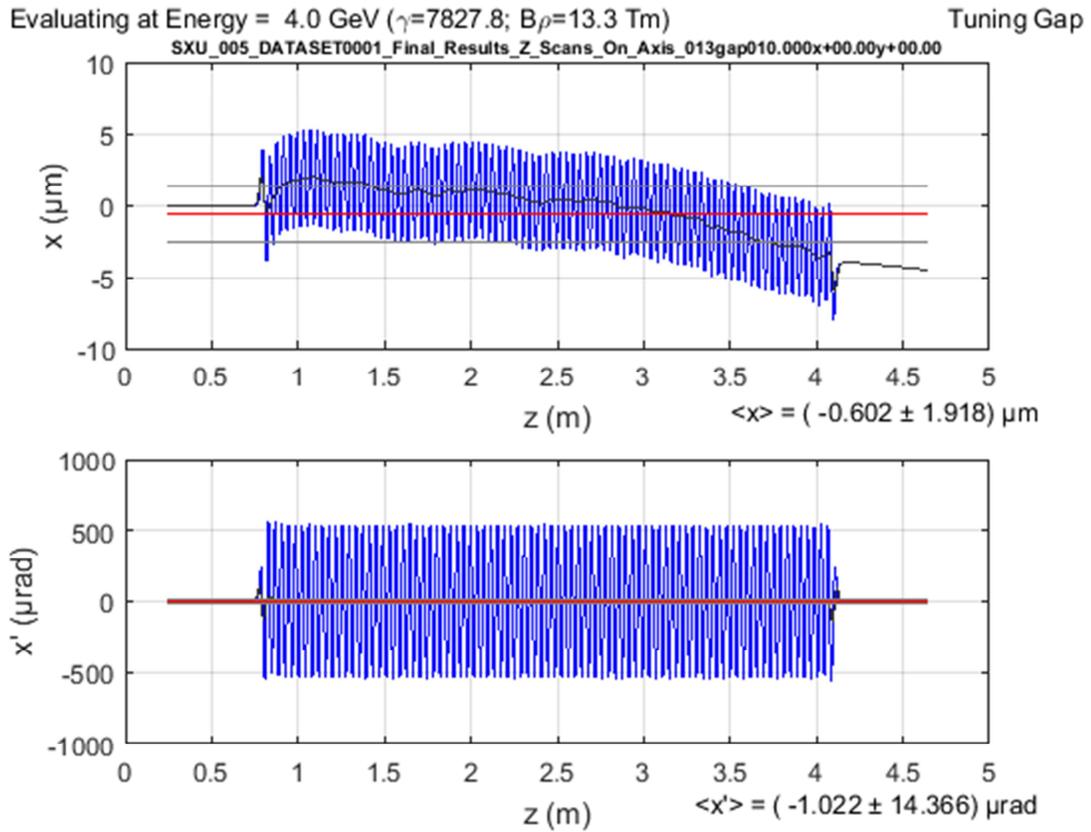
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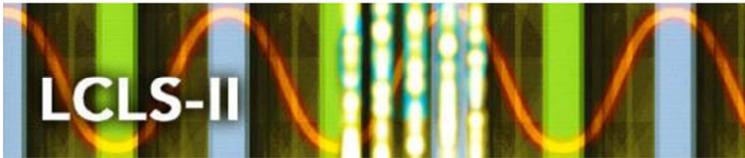
The figures show the x (upper) and y (lower) field components along the undulator tuning axis for the tuning gap. A running wiggler-period-average function is plotted in black (not very well visible in the lower figure). The horizontal lines indicate the mean (center red line) and the rms deviations 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]



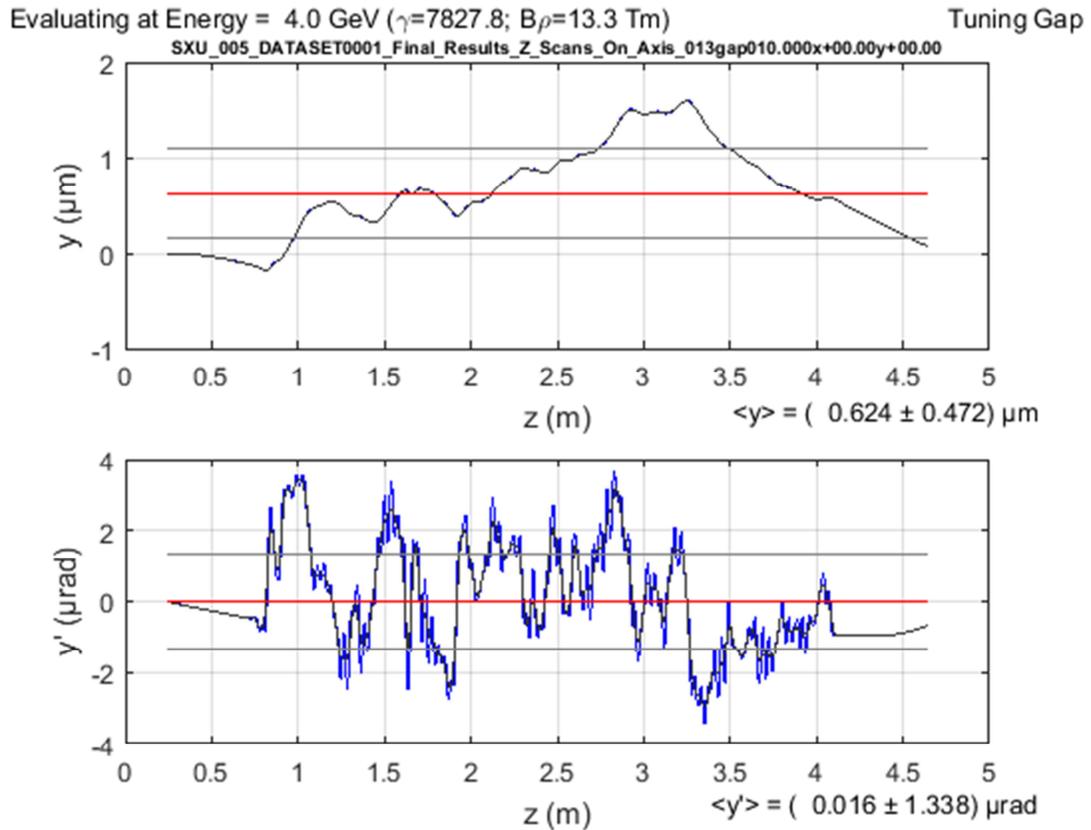
**Evaluation of Hall Probe at Tuning Gap:  $x$  &  $x'$  Plot**



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]



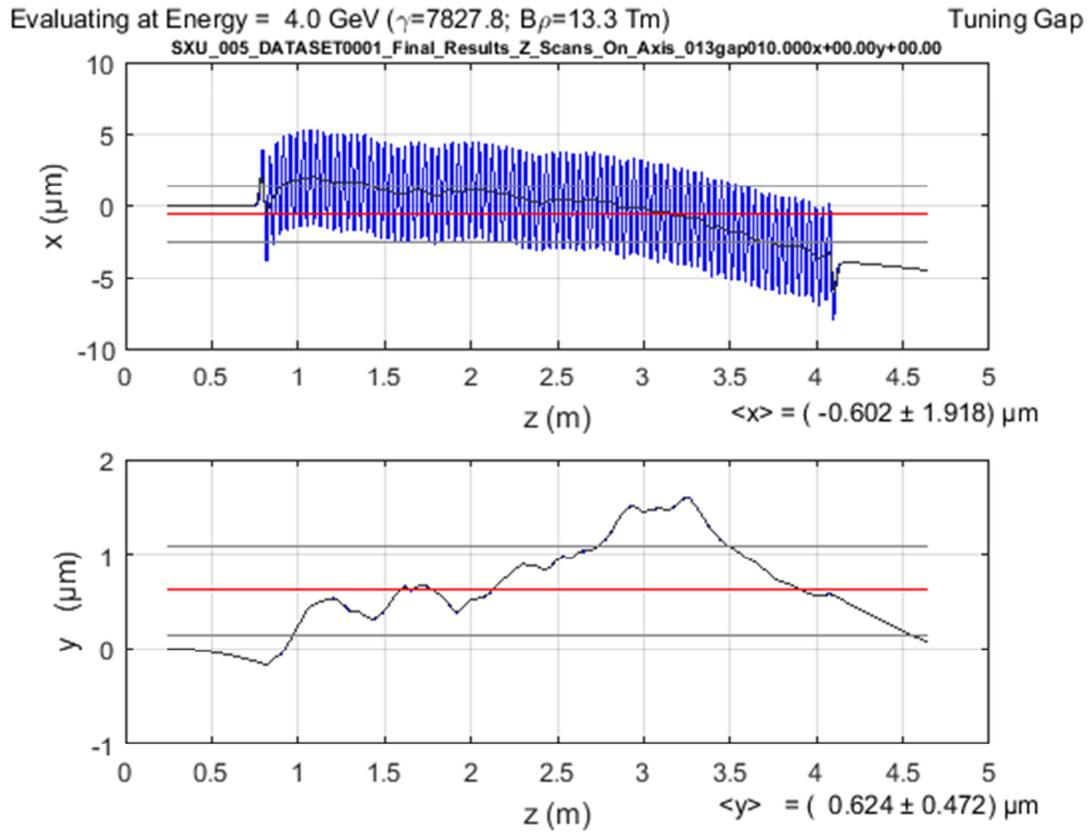
## Evaluation of Hall Probe Scans at Tuning Gap: $y$ & $y'$ Plot



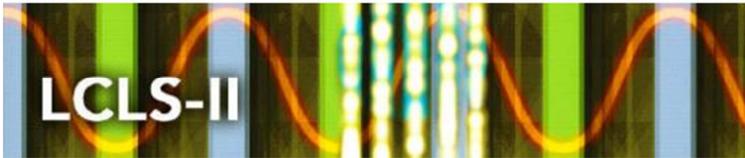
The figures show the  $y$  (upper) and  $y'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components and estimated for an electron beam energy of 4.0 GeV. A running wiggler-period-average function is plotted in black (difficult 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



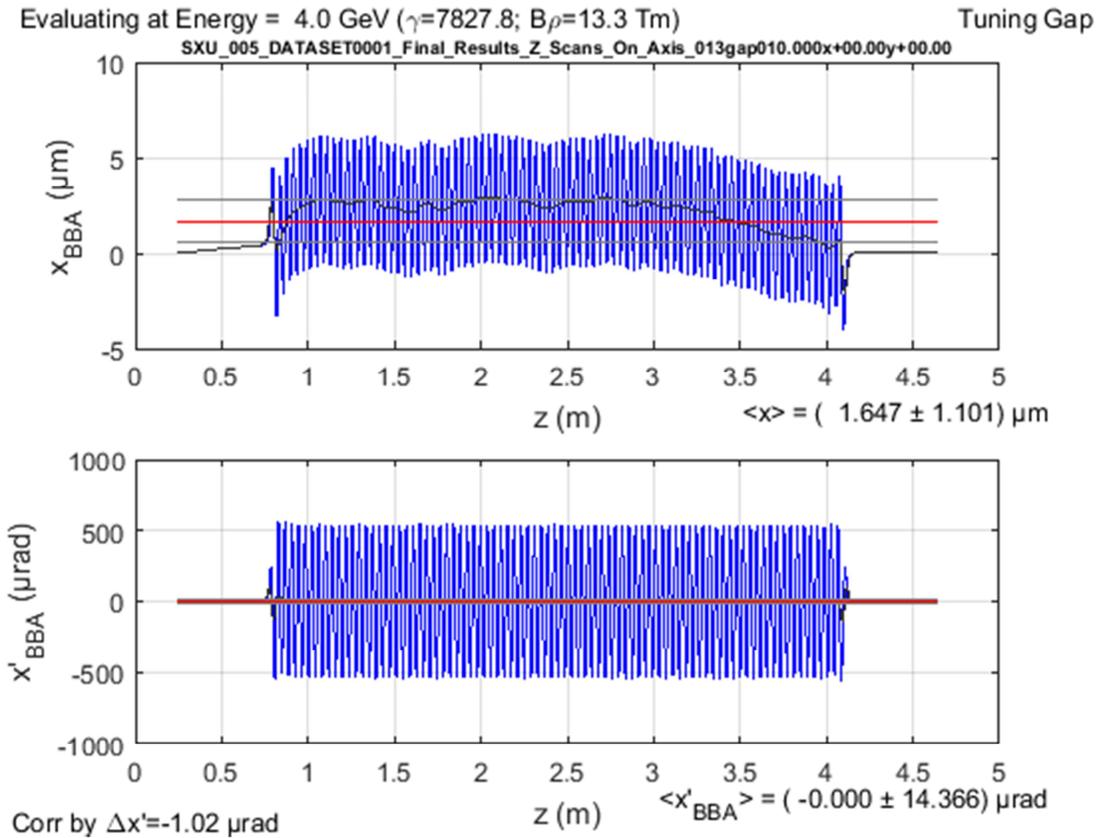
The figures show the x (upper) and y (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components and estimated for an electron beam energy of 4.0 GeV. A running wiggler-period-average function is plotted in black (identical with 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]



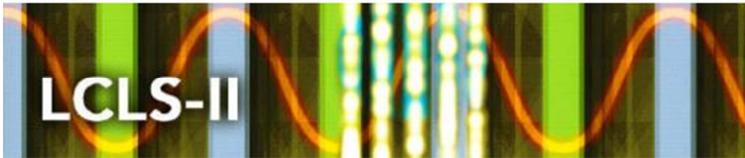
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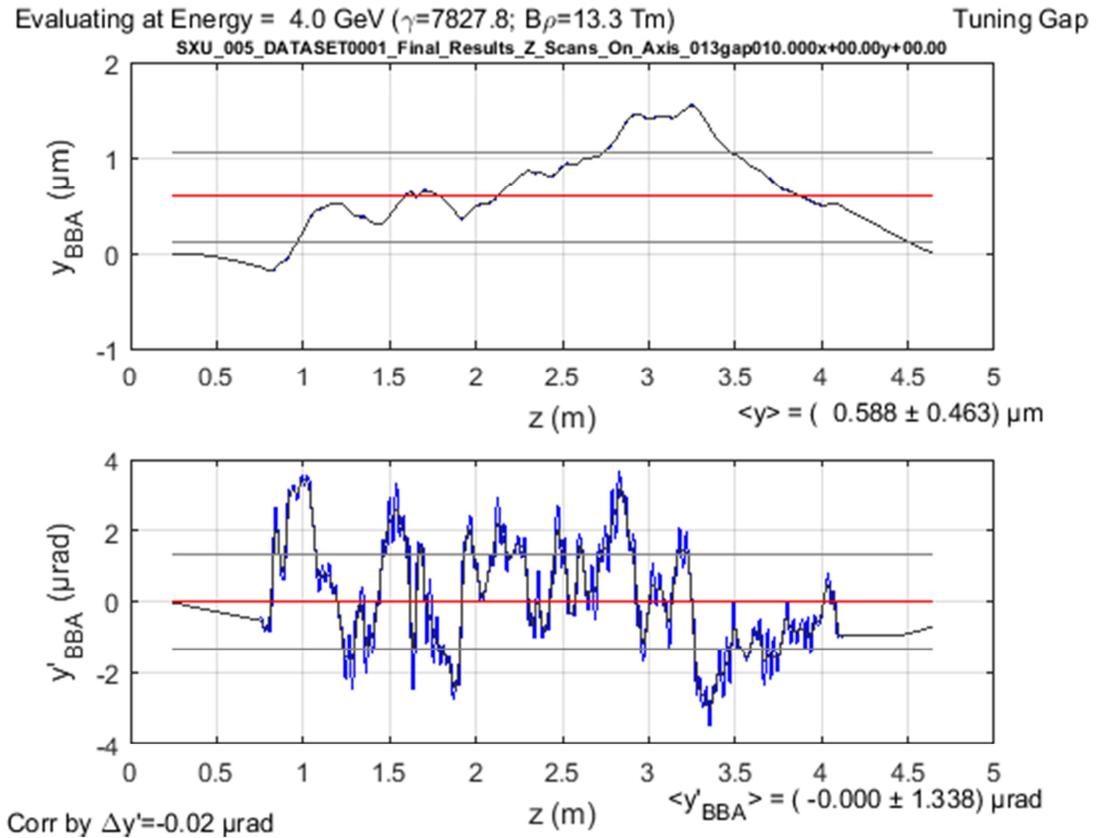
**Evaluation of Hall Probe plus BBA correction at Tuning Gap:  $x$  &  $x'$  Plot**



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**



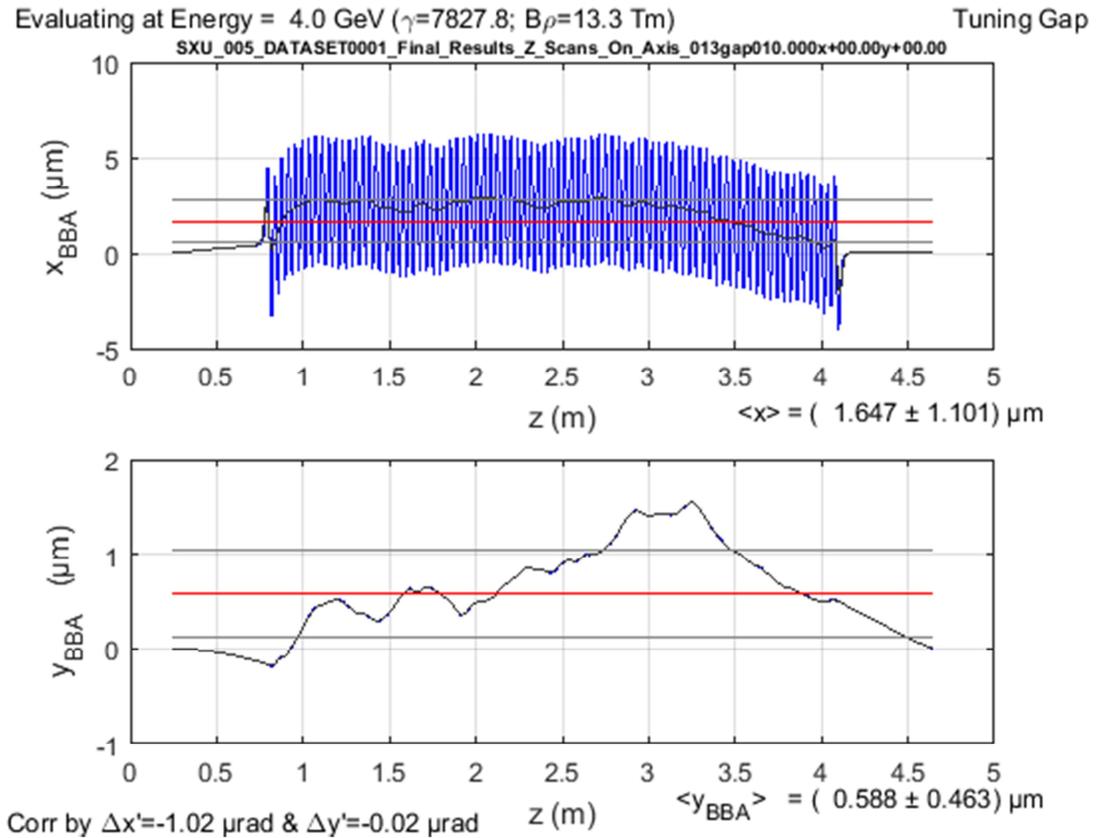
The figures show the  $y$  (upper) and  $y'$  (lower) electron beam trajectories along the undulator tuning axis for the tuning gap based on the measured magnetic field components after BBA correction (to zero the amplitudes at the cell boundaries) and estimated for an electron beam energy of 4.0 GeV. 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]



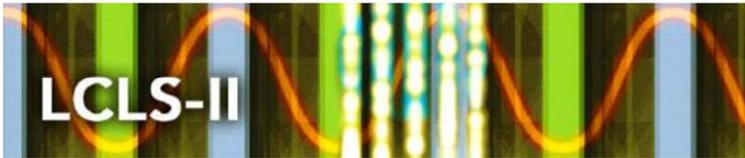
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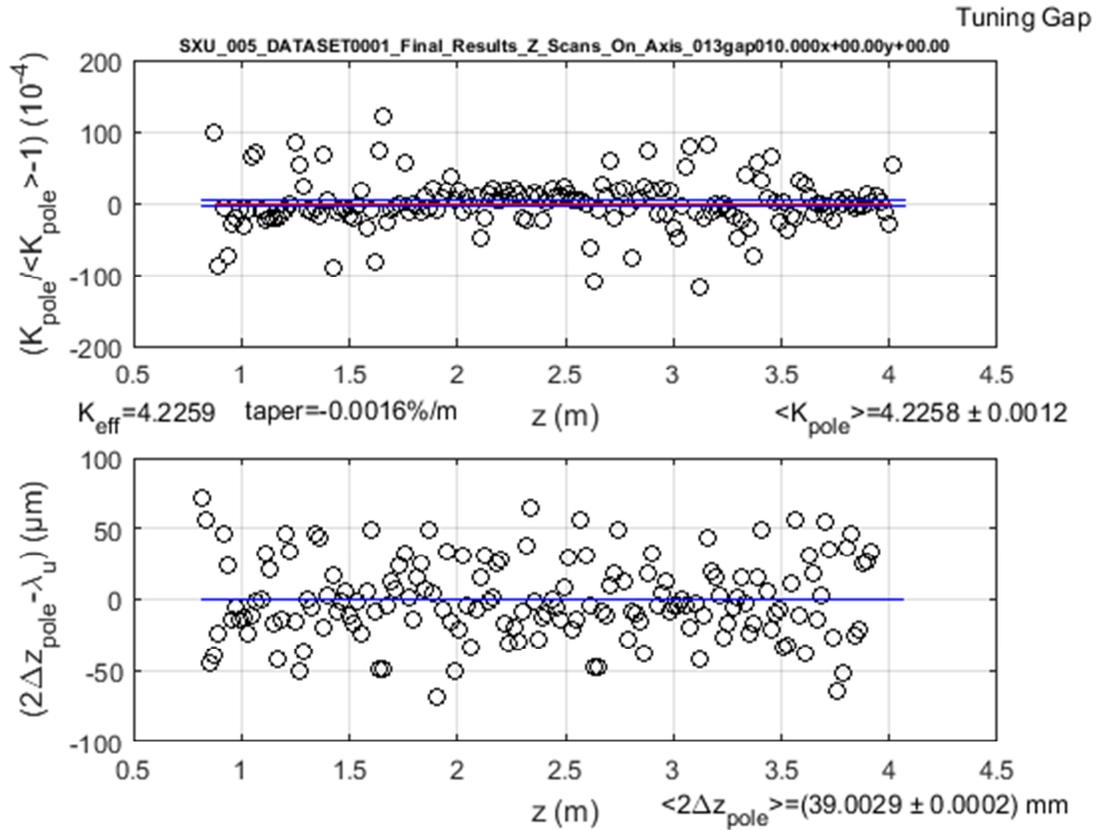
## Evaluation of Hall Probe plus BBA correction at Tuning Gap: $x$ & $y$ Plot



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]

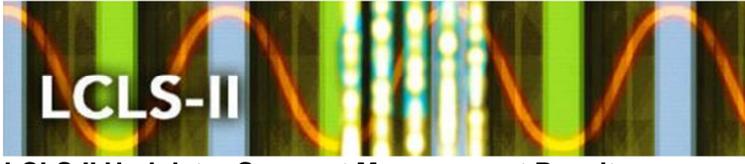


**Evaluation of Hall Probe at Tuning Gap:  $K$  and  $\lambda_u$  variations**



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 162 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.



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$K$  calculation description for previous page:

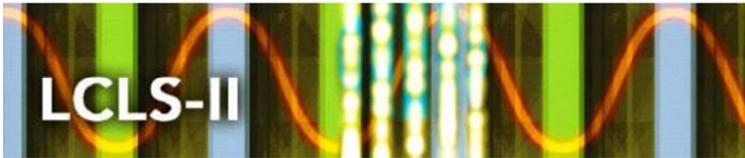
The undulator parameter,  $K_{pole}$ , in the upper figure, is calculated for each of the core poles based on the scanned vertical field values  $B_y(z)$  as well as an interpolation of the upstream,  $z_{0-dn,pole}$ , and downstream,  $z_{0-up,pole}$ , field zero crossing locations using the following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

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

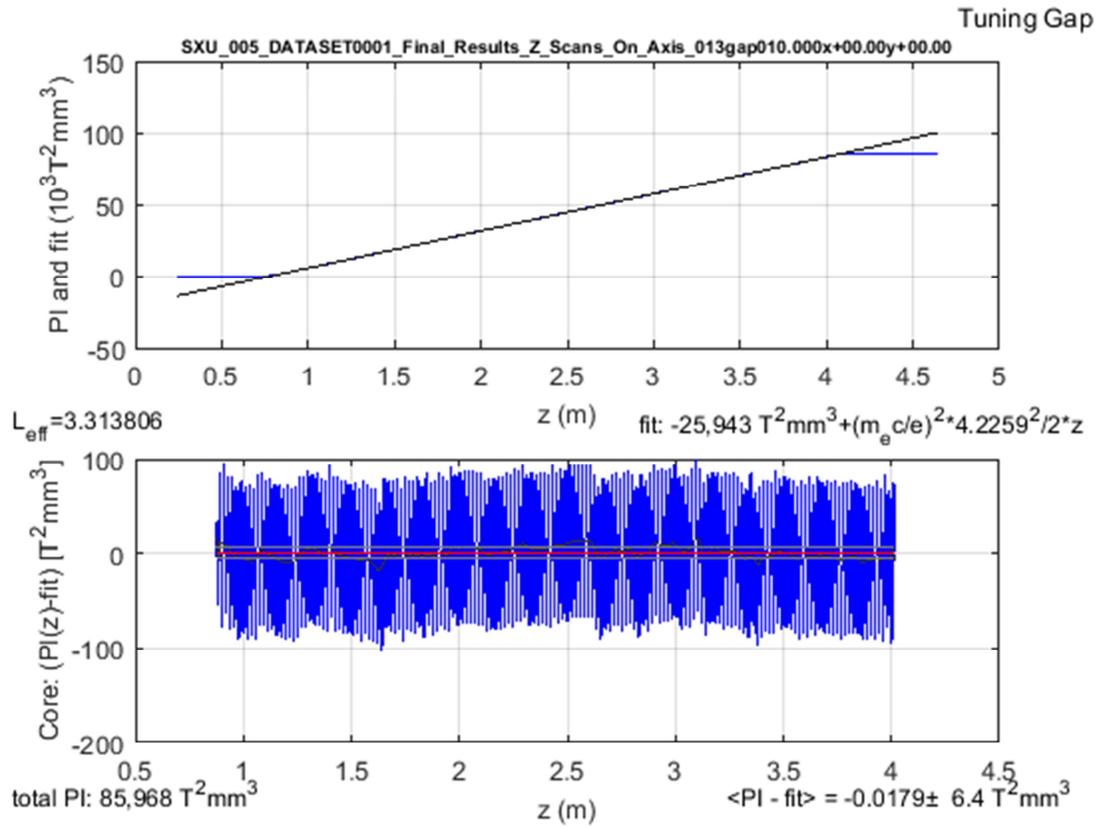
$$z_{pole} \approx \frac{1}{2} (z_{0-dn,pole} + z_{0-up,pole})$$



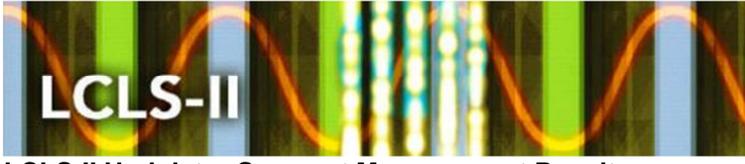
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## Evaluation of Hall Probe Scans for Tuning Gap: Phase Integral Plot



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



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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

$$\bar{PI}(z) = \bar{PI}(0) + z \left( \frac{m c}{e} \right)^2 \frac{1}{2} K_{eff}^2,$$

fitted to the measured phase integral  $PI(z)$  with fit coefficients  $\left( \frac{m c}{e} \right)^2 \frac{1}{2} K_{eff}^2$  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:  $L_{eff} = PI(z_{max}) / \left( \frac{d\bar{PI}(z)}{dz} \right)$ .

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.,  $PI(z_{max})$ , the right-hand side value of the blue line in the upper plot.

The wiggler period averaged phase deviation,  $\langle \Delta\phi \rangle_{\lambda_u}(z)$  can be calculated from  $PI(z)$  via

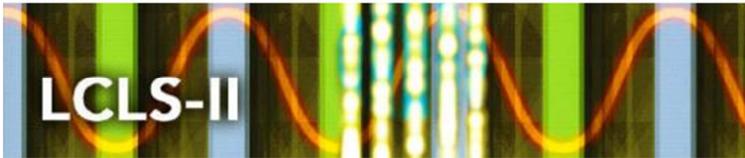
$$\langle \Delta\phi \rangle_{\lambda_u}(z) = \frac{2\pi}{L_{2\pi}} \left( \frac{e}{m c} \right)^2 \int_{z - \frac{\lambda_u}{2}}^{z + \frac{\lambda_u}{2}} (PI(\hat{z}) - \bar{PI}(\hat{z})) d\hat{z},$$

integrated over the undulator core.

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

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

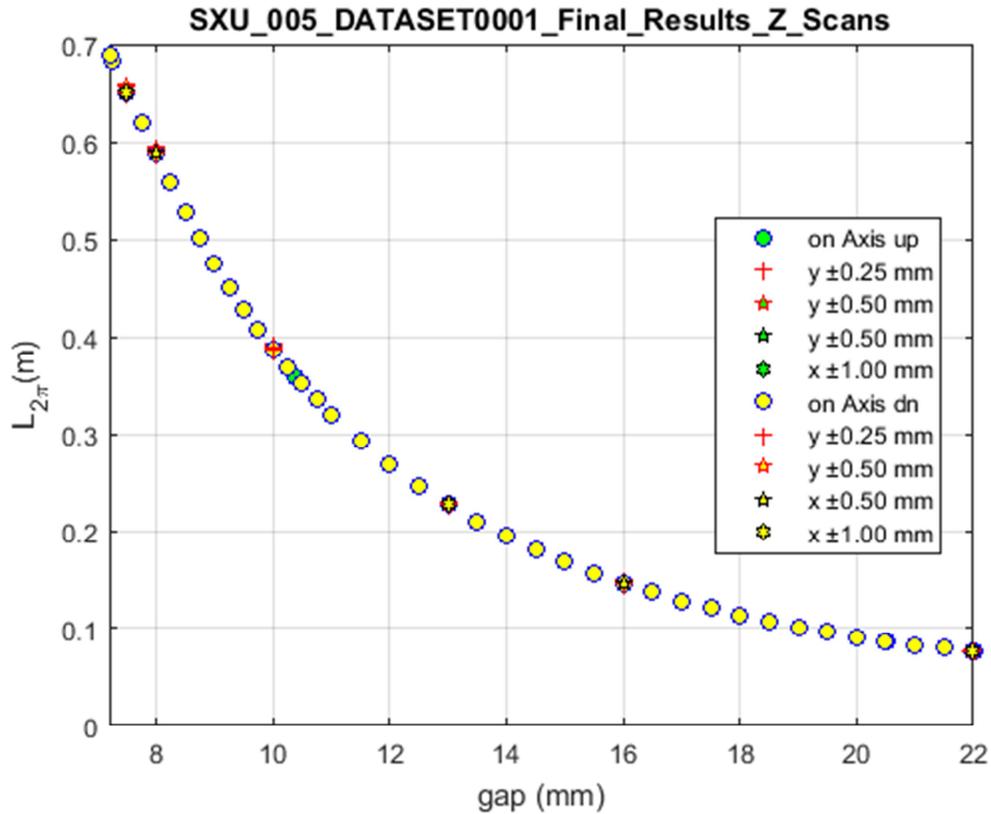
The following figures show the results of the gap dependent analysis.



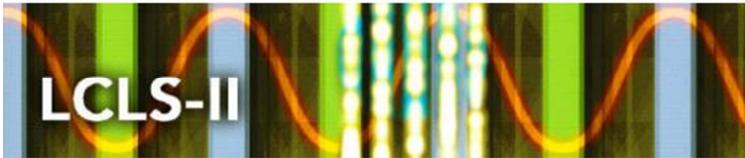
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**Evaluation of Hall Scans:  $L_{2\pi}$  vs gap**

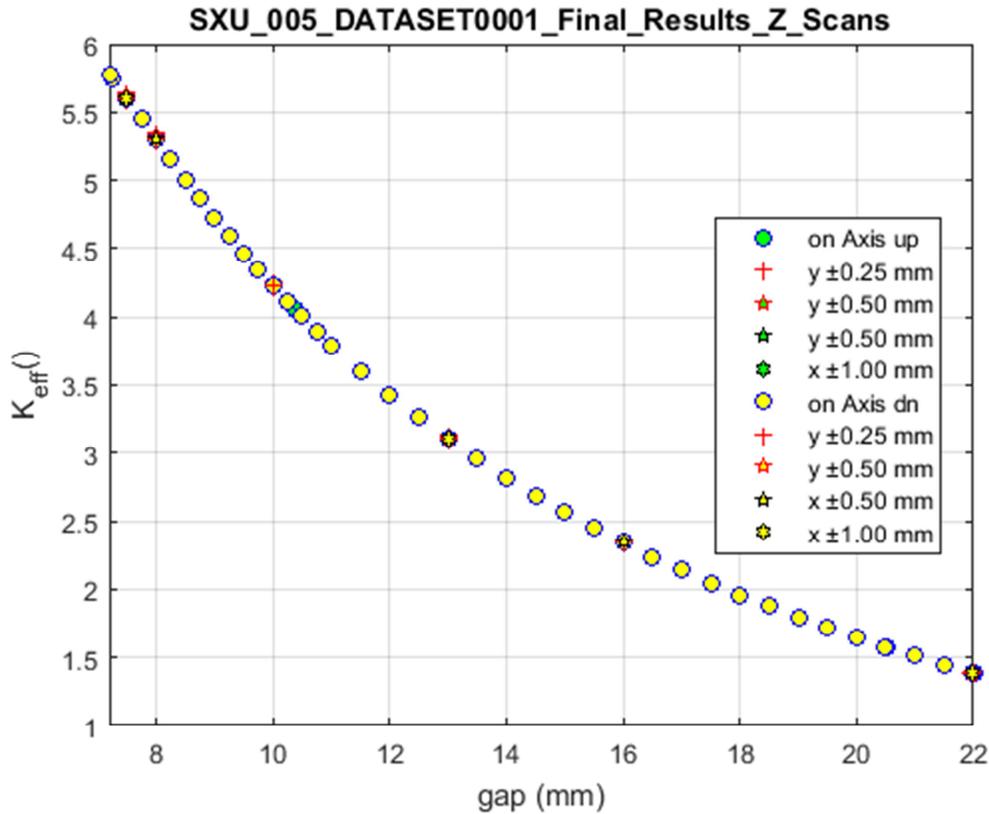
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The figure shows the free space distance over which a  $2\pi$  slippage occurs between the radiation field and the electron bunch (see explanation above) as a function of undulator gap over the operational gap range. Note: the free space travel distance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

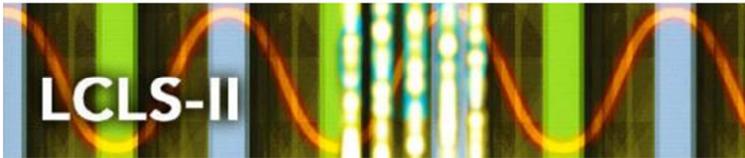


**Evaluation of Hall Scans:  $K_{eff}$  vs  $gap$**

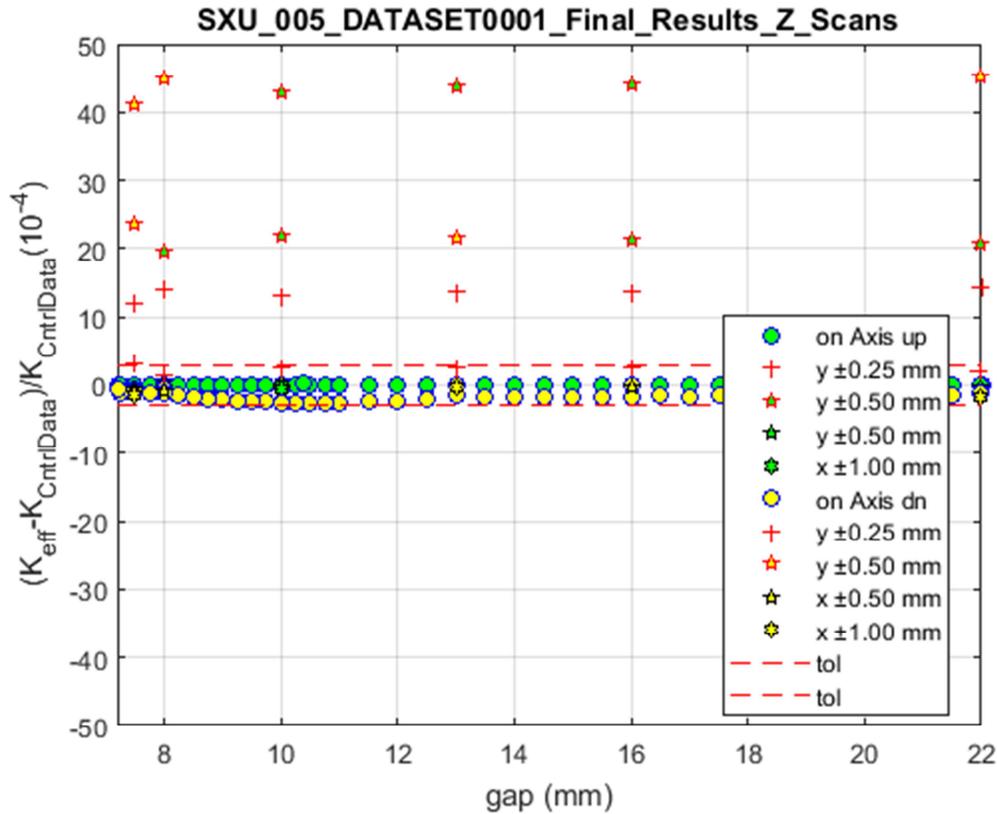


The figure shows undulator strength  $K_{eff}$  as a function of gap over the 7.2 mm – 22 mm operational range. The legend shows a number of different cases that will be explained later in this document because their effect cannot be observed in this full scale plot. Note: The gap values are derived 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.  $K_{eff}(gap)$  and  $gap(K_{eff})$ ) will be done during operations based on the list of reference data points stored in file `sxu_005_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  $K_{eff}(gap)$  and  $gap(K_{eff})$  can be calculated via cubic spline fits or equivalent. [Documentary Information]

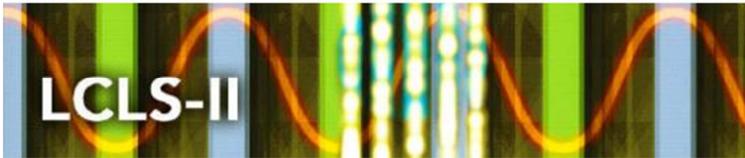


Evaluation of Hall Scans:  $K_{eff} - K_{control}$  vs  $gap$

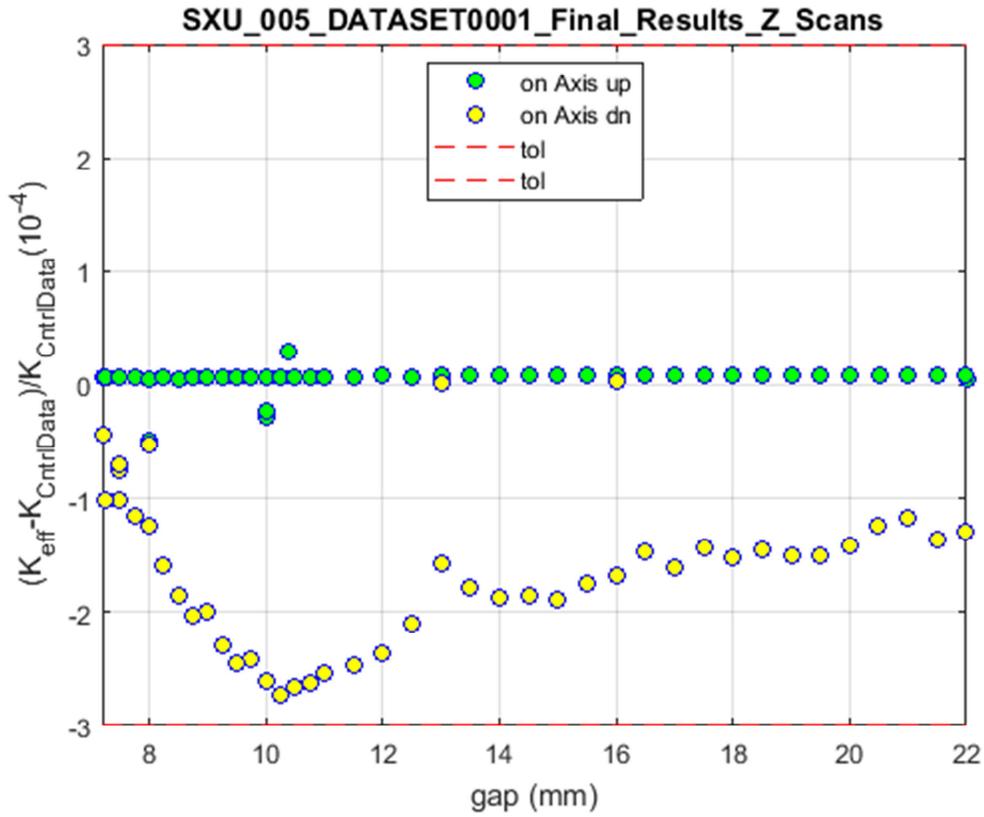


The figure shows the relative difference between the measured undulator strength  $K_{eff}$  and a cubic spline fit to the list of reference data points stored in file `sxu_005_k_vs_gap_spline.dat` in the Controls Data folder on the V: drive as a function of gap over the 7.2 mm – 22 mm operational range.

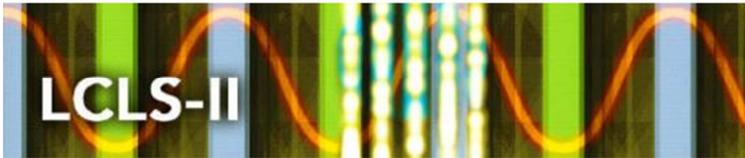
The legend explains the different cases that are shown in the plot: The green filled circles are data acquired on axis as the gap was changed from close to open. The yellow filled circles are data acquired on axis as the gap was changed from open to close. The horizontal red dashed lines show the tolerance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



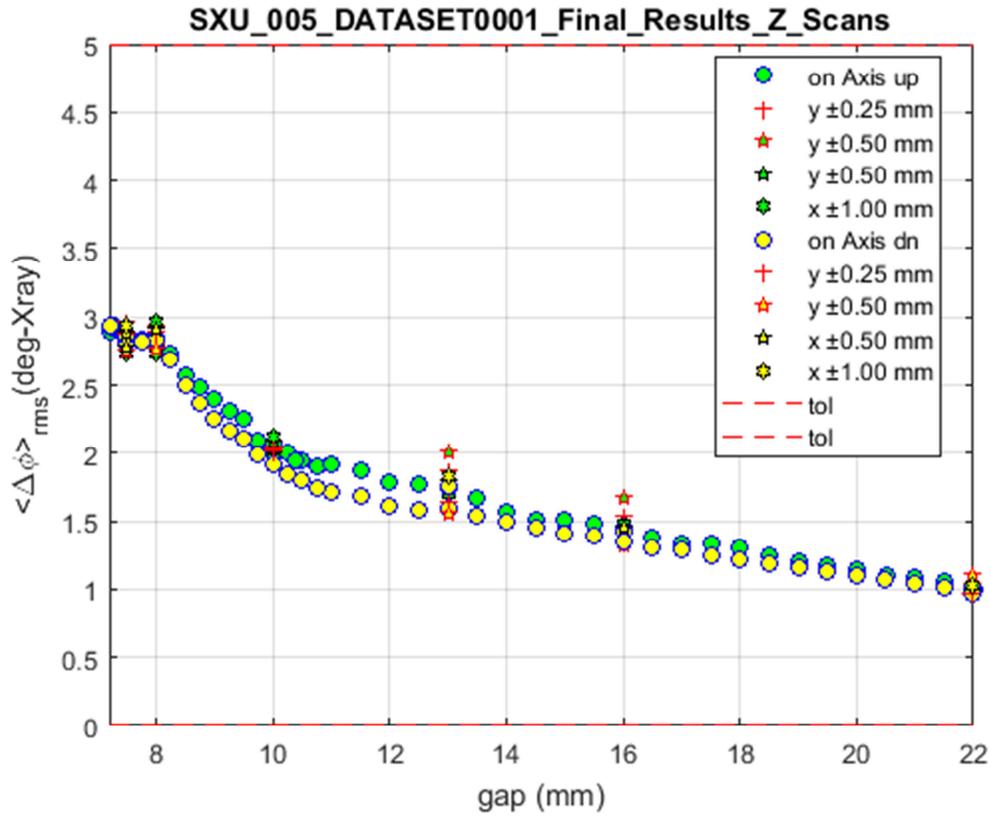
**Evaluation of Hall Scans:  $(K_{eff} - K_{CntrlData})/K_{CntrlData}$  vs *gap***



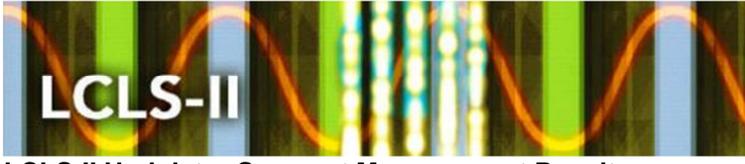
The figure shows some of the data shown in the previous figure but with a larger vertical scale that just captures the tolerance range. The hysteresis effect is more clearly visible. The off-axis measurements are not shown.



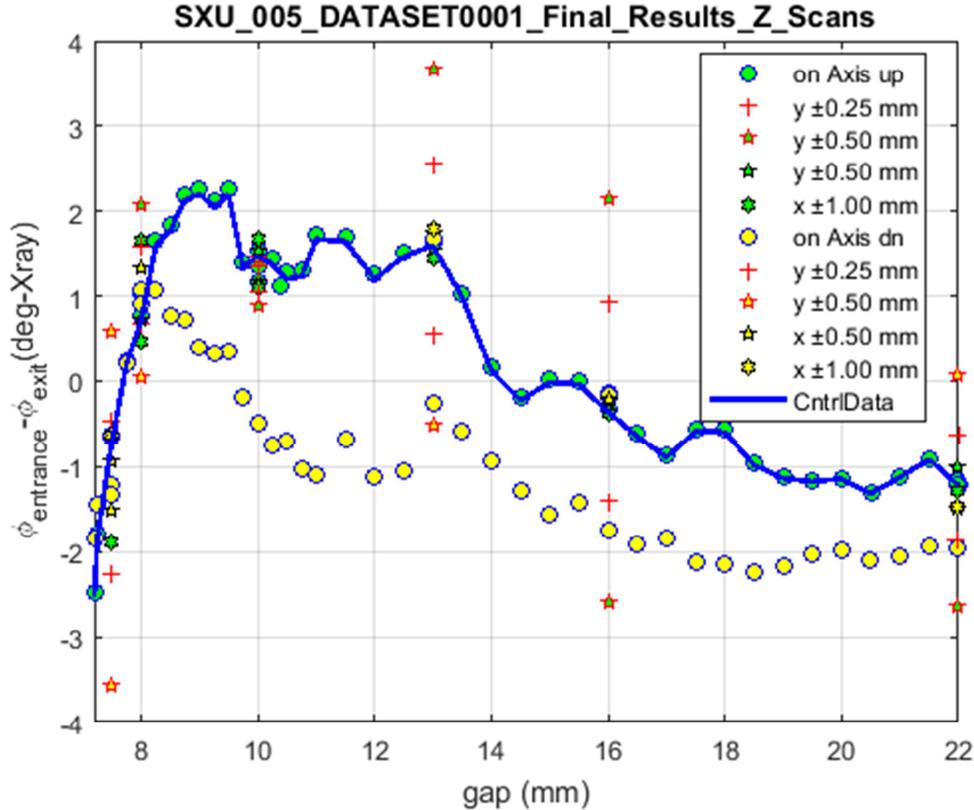
Evaluation of Hall Probe: Phase Shake vs. gap



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

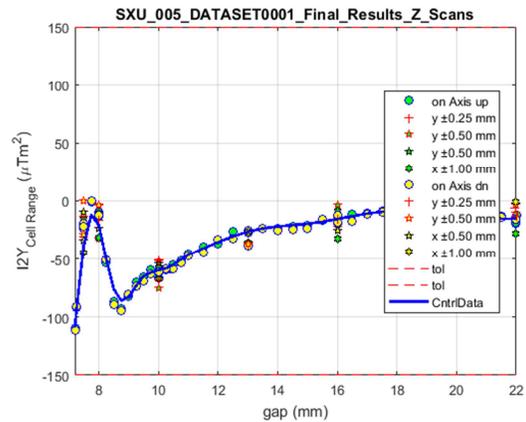
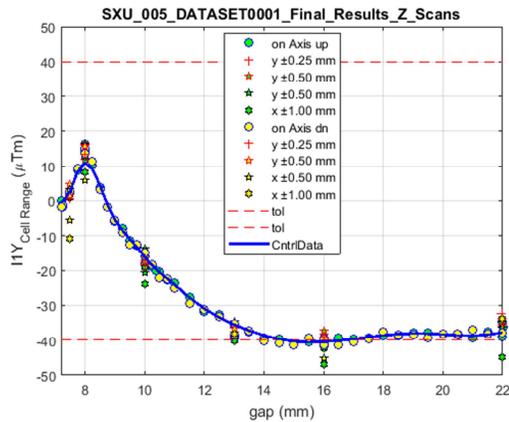
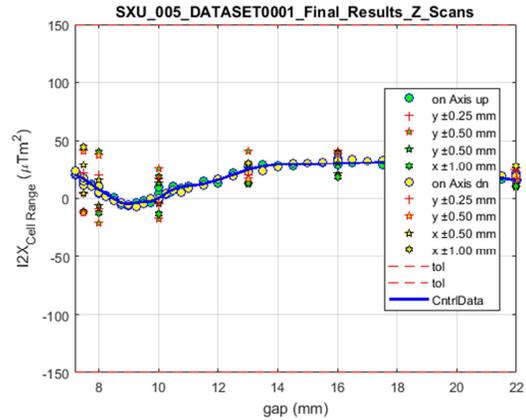
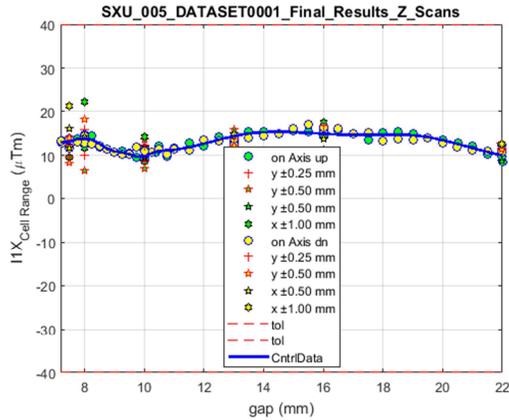
$$\phi_{entrance} = -\phi(z_{Cell-start}) + \frac{1}{n+1} \sum_{j=1}^{n+1} (\phi(z_{B0,j}) - \pi(j-1)),$$

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

Here,  $z_{B0,j}$  is the z location of the zero crossing of  $B_y(z)$  in front of the  $j^{th}$  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

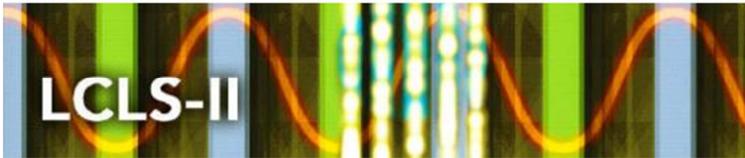
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“...i2xvsgap\_spline.dat”,

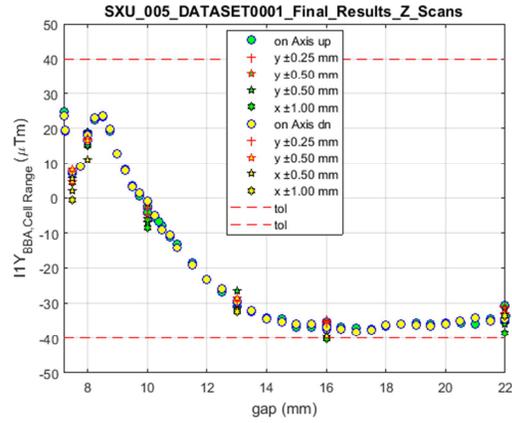
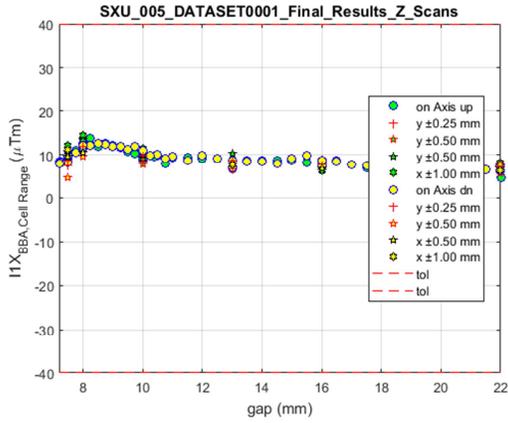
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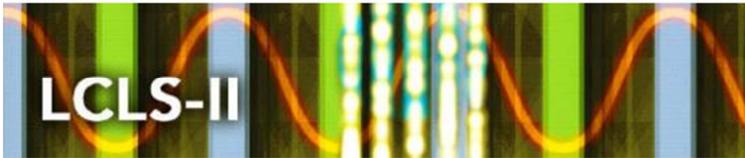
and demonstrate how the controls representations of the field integrals relates to the actual measurements (see final section of this document for file information).



## Evaluation of Hall Probe: BBA Corrected Field Integrals

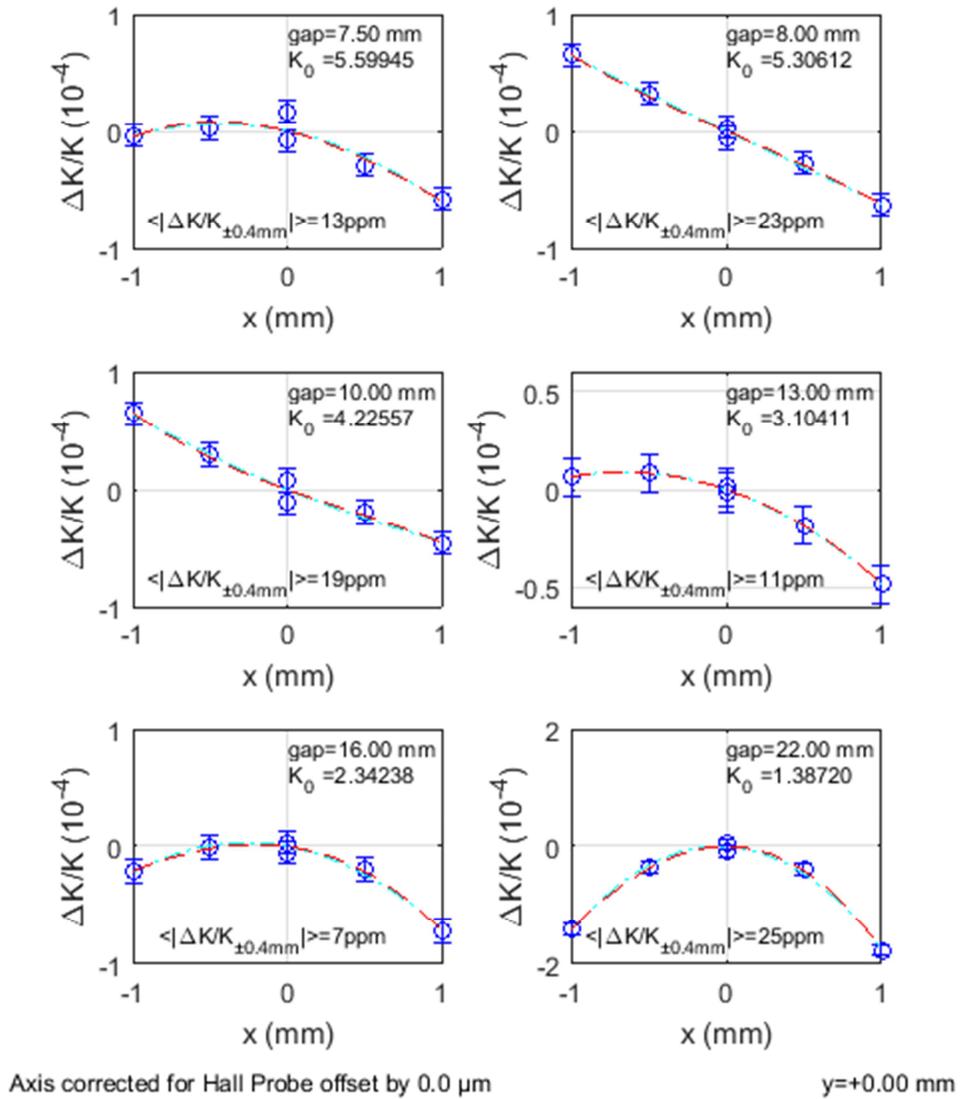


The figure shows the first integrals after a BBA equivalent correction was applied. The values stay within tolerance over the operational range.



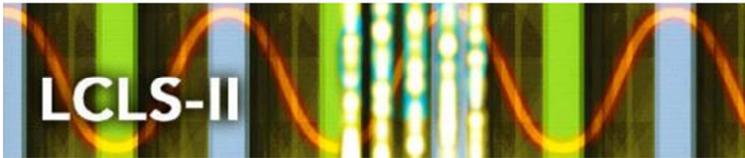
### Evaluation of Hall Probe: K vs. x dependence

SXU\_005\_DATASET0001\_Final\_Results\_Z\_Scans

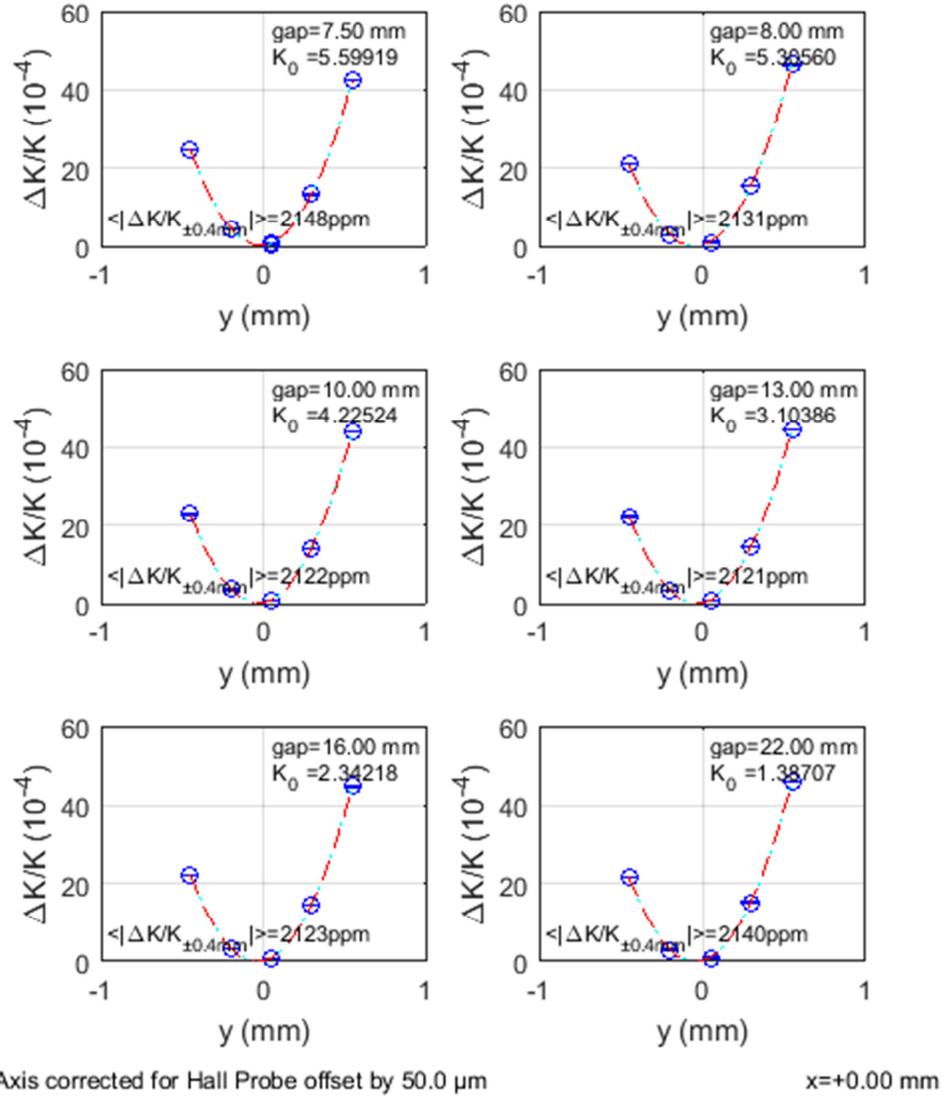


The figure shows the deviation of the relative undulator strength,  $K$ , from the off-axis value,  $K_0$ , as function of  $x$  at a number of operational gaps. The average deviation at  $z=0.4$  mm is well below the tolerance of 160 ppm in all cases.

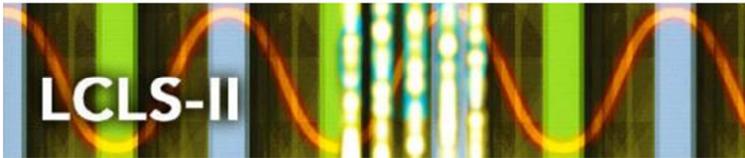
### Evaluation of Hall Probe: K vs. y dependence



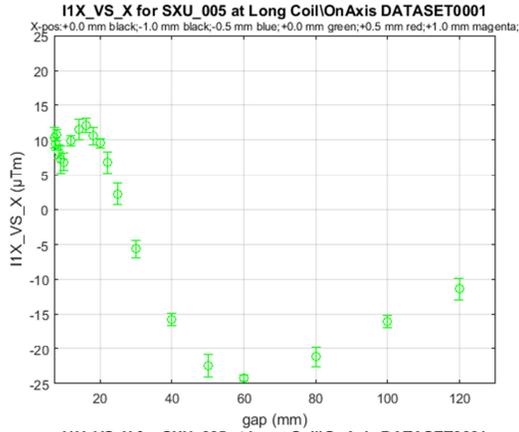
SXU\_005\_DATASET0001\_Final\_Results\_Z\_Scans

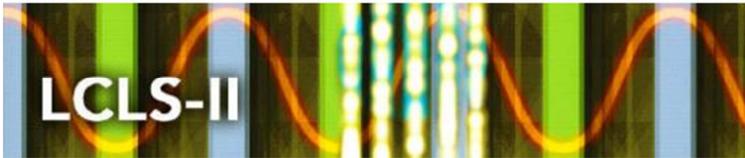


The figure shows the deviation of the relative undulator strength,  $K$ , value from the on-axis value,  $K_0$ , as function of  $y$  at a number of operational gaps. The deviations follow closely the expected functional form  $(\cosh(k_u y) - 1)$ . [Documentary Information]

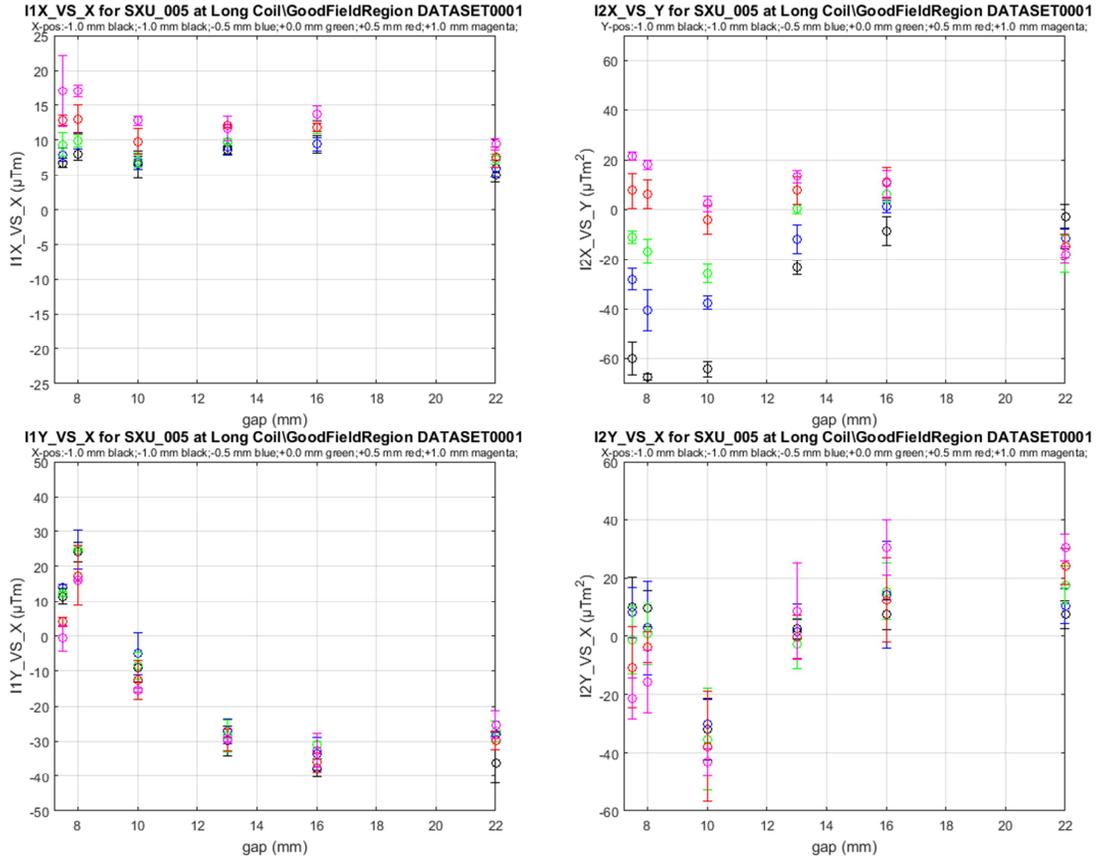


### Long Coil Measurement of the On-Axis Field Integrals

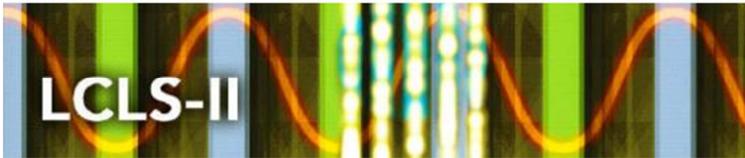




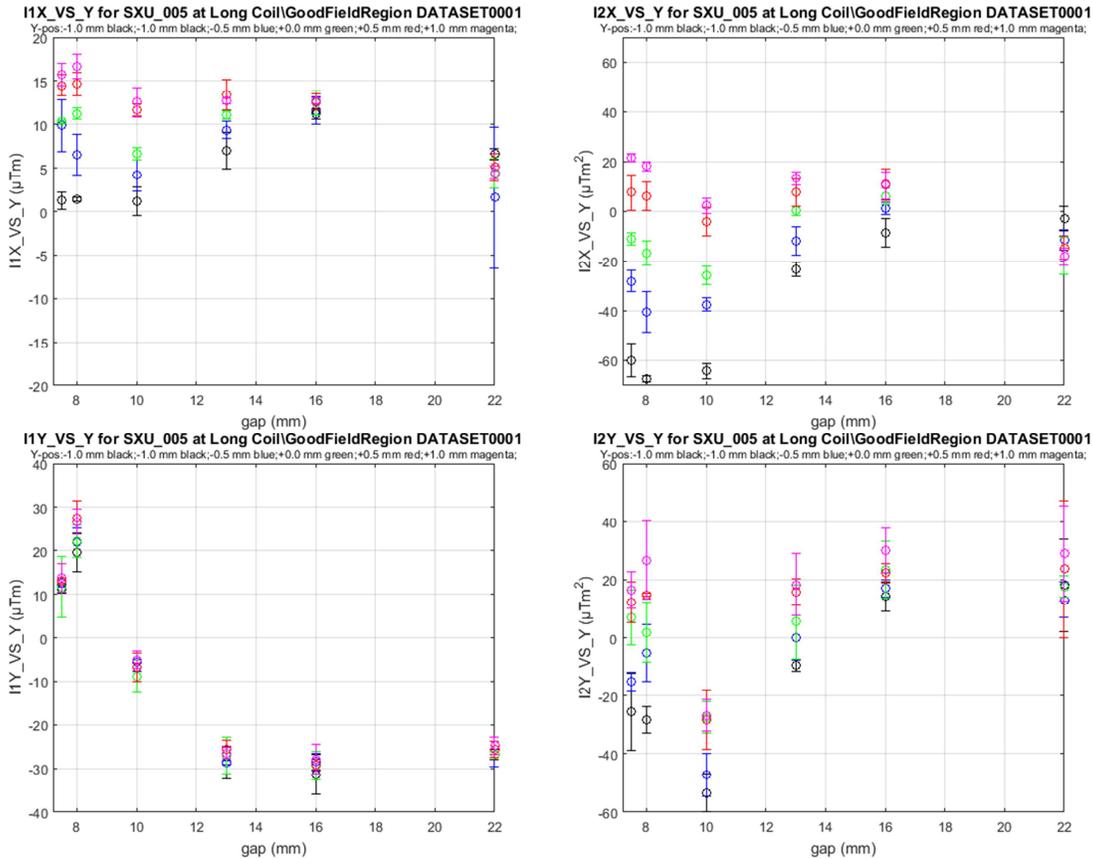
### Long Coil Measurement of the Horizontally Off-Axis Field Integrals



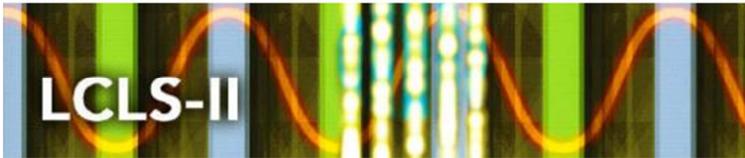
The figure shows the field integrals obtained from long coil measurements off axis in the horizontal plane using colors to indicate offset distance (black: -1.0 mm, blue: -0.5 mm, green: on-axis; red: +0.5 mm, magenta: +1.0 mm). The vertical axes extend over the tolerance range. All integrals are in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



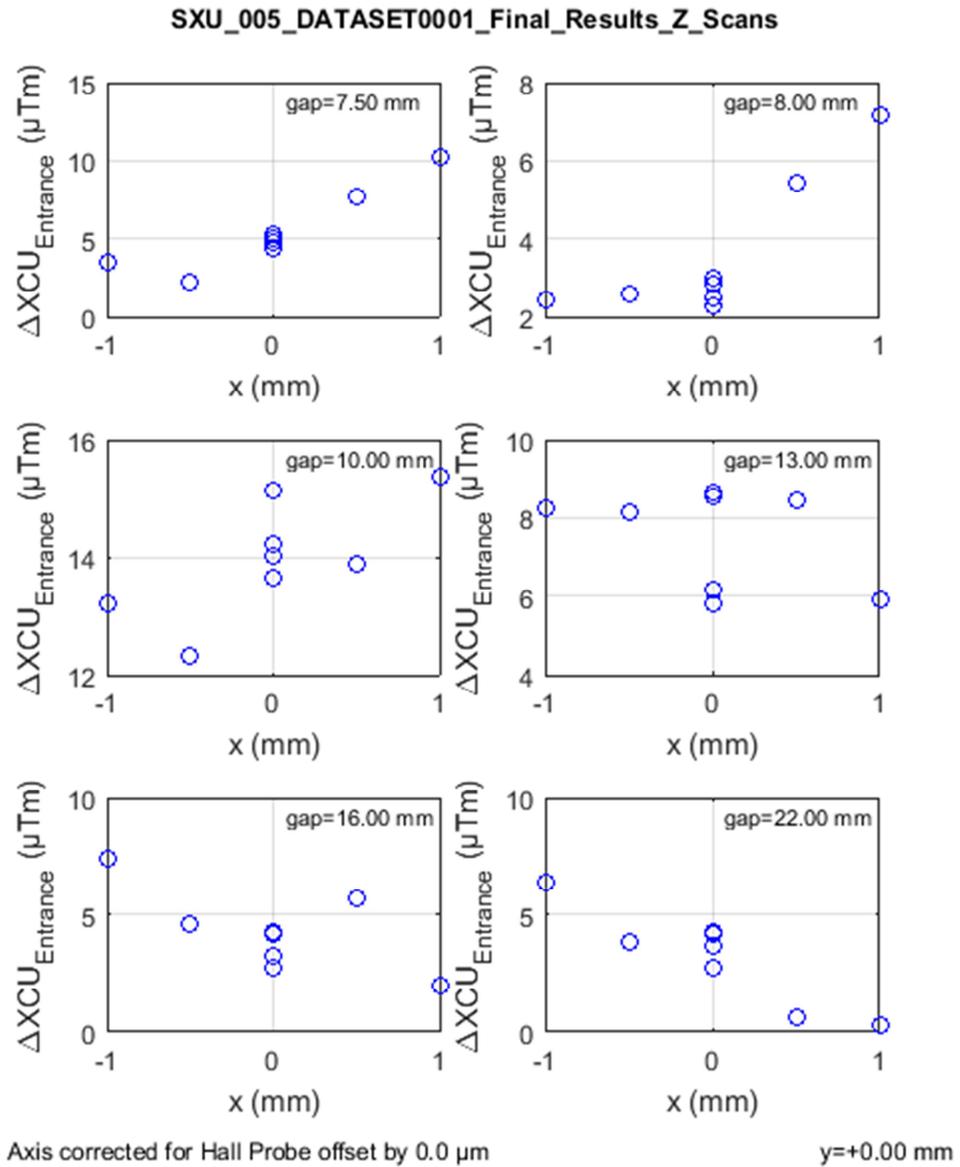
## Long Coil Measurement of the Vertically Off-Axis Field Integrals



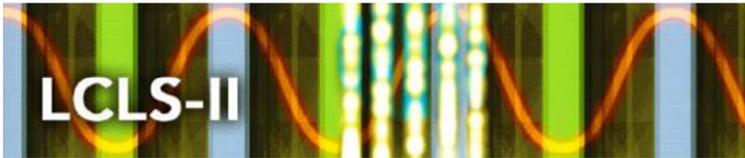
The figure shows the integrals obtained from long coil measurements off axis in the vertical plane using colors to indicate offset distance (black: -1.0 mm, blue: -0.5 mm, green: on-axis; red: +0.5 mm, magenta: +1.0 mm). The vertical axes extend of the tolerance range. All integrals are in tolerance.



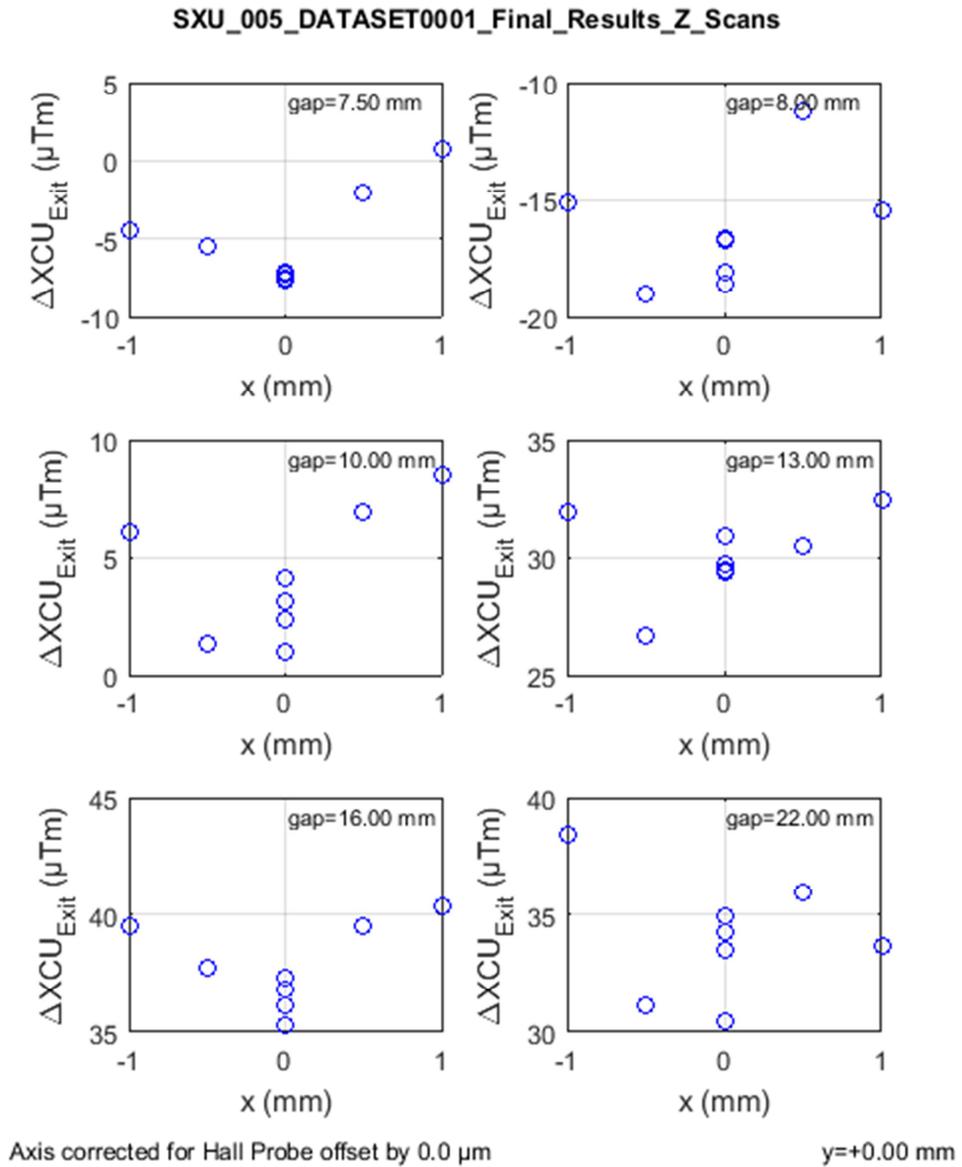
**Estimated Upstream Horizontal Corrector Strength Requirement vs. x**



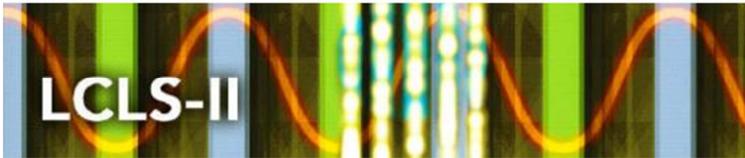
The figure shows the required strength of the upstream horizontal corrector to remove the second vertical undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z plane. All values are small and well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



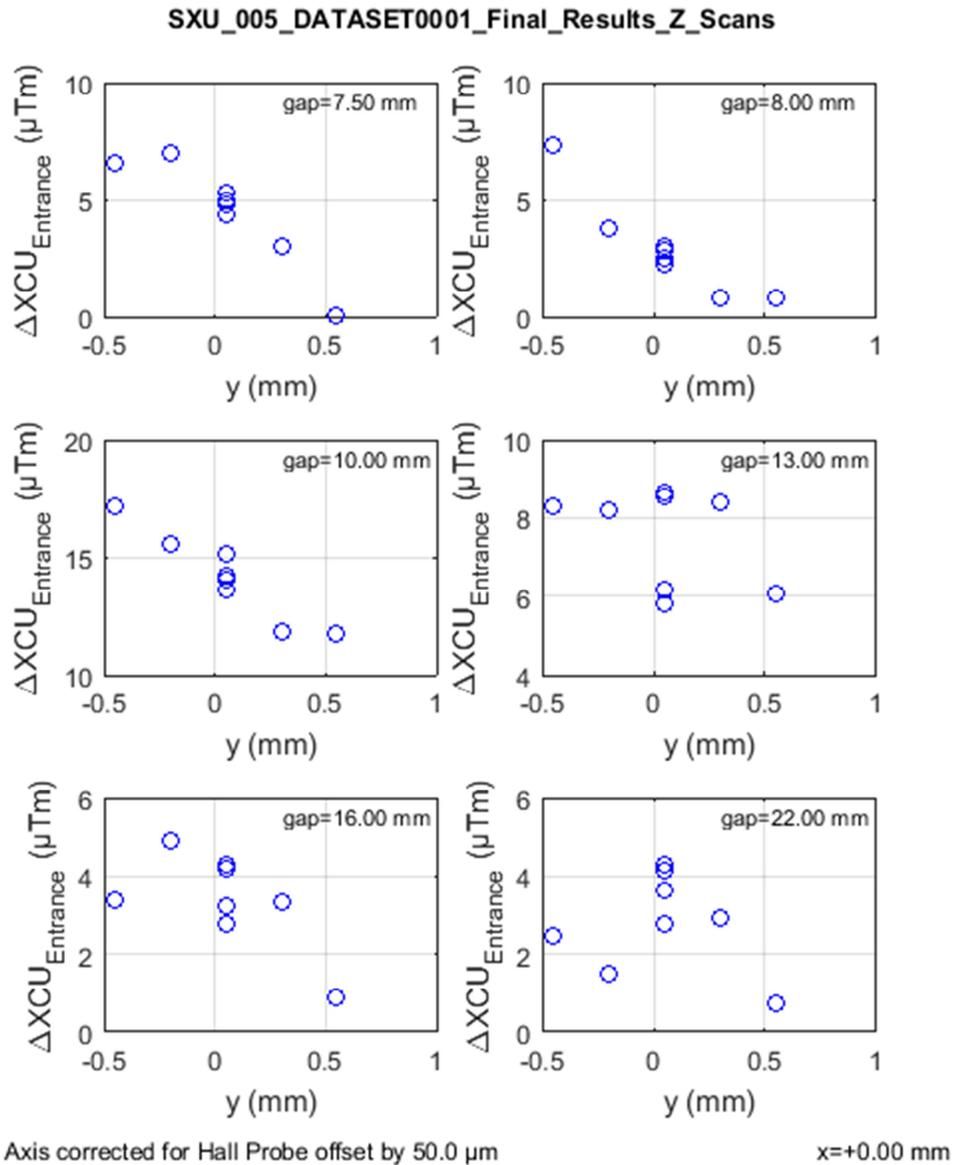
**Estimated Downstream Horizontal Corrector Strength Requirement vs. x**



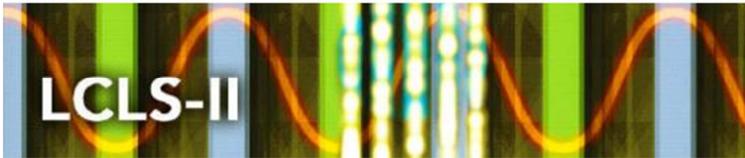
The figure shows the required strength of the downstream horizontal corrector to remove the first vertical undulator field integral and upstream corrector field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z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



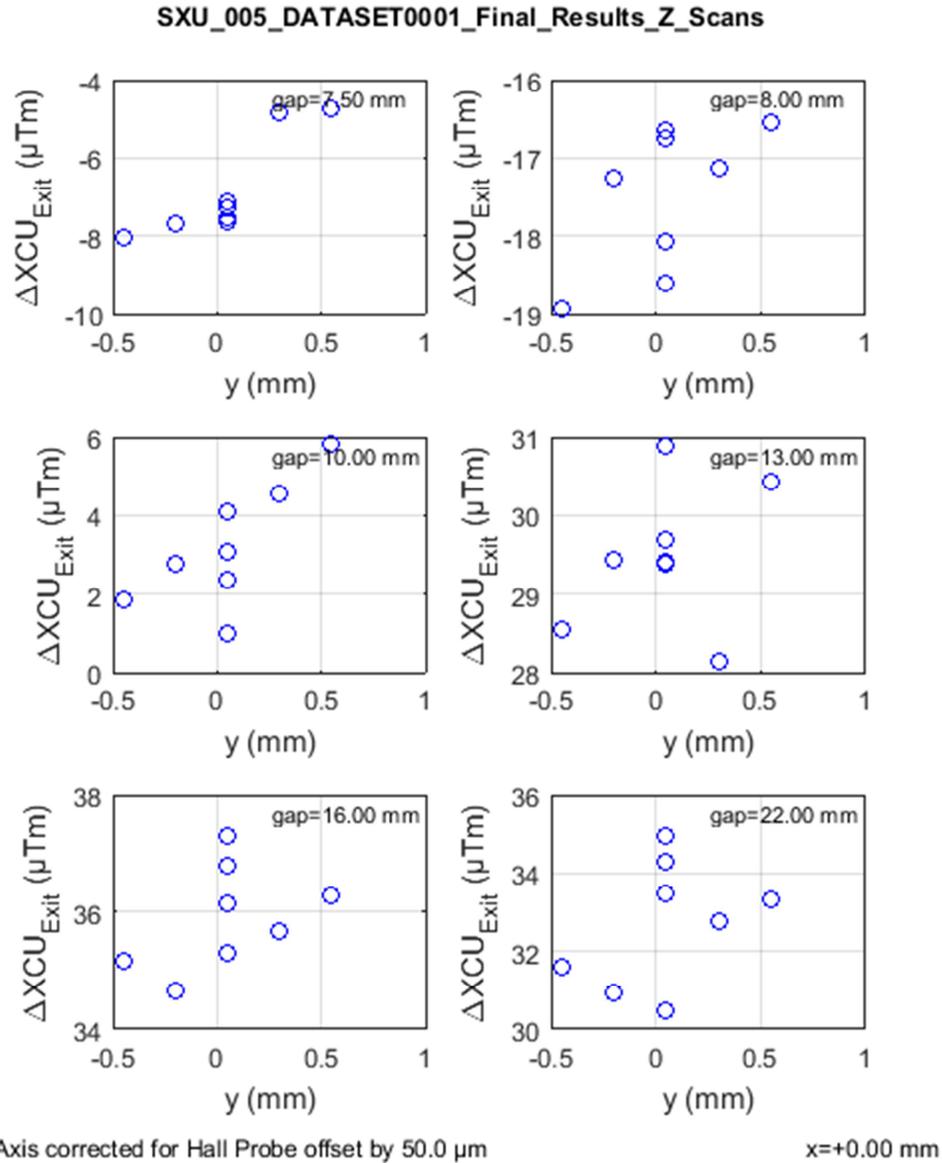
**Estimated Upstream Horizontal Corrector Strength Requirement vs. y**



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.



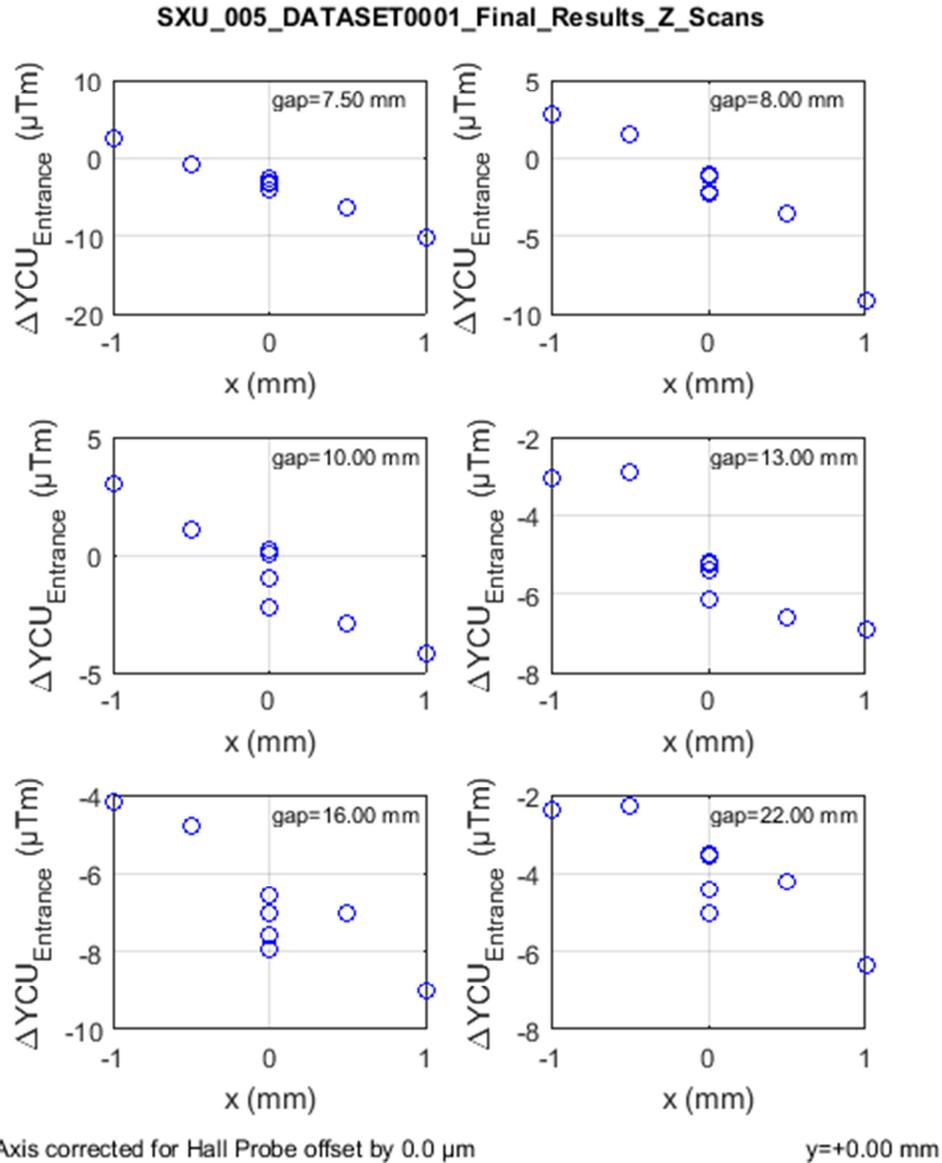
**Estimated Downstream Horizontal Corrector Strength Requirement vs. y**



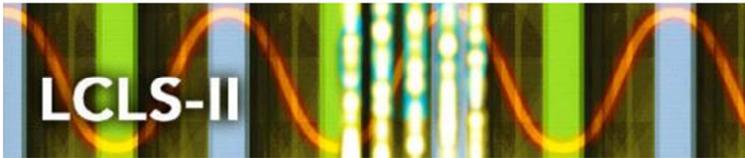
The figure shows the required strength of the upstream horizontal corrector to remove the first vertical undulator and upstream corrector field integrals at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the y-z plane. All values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



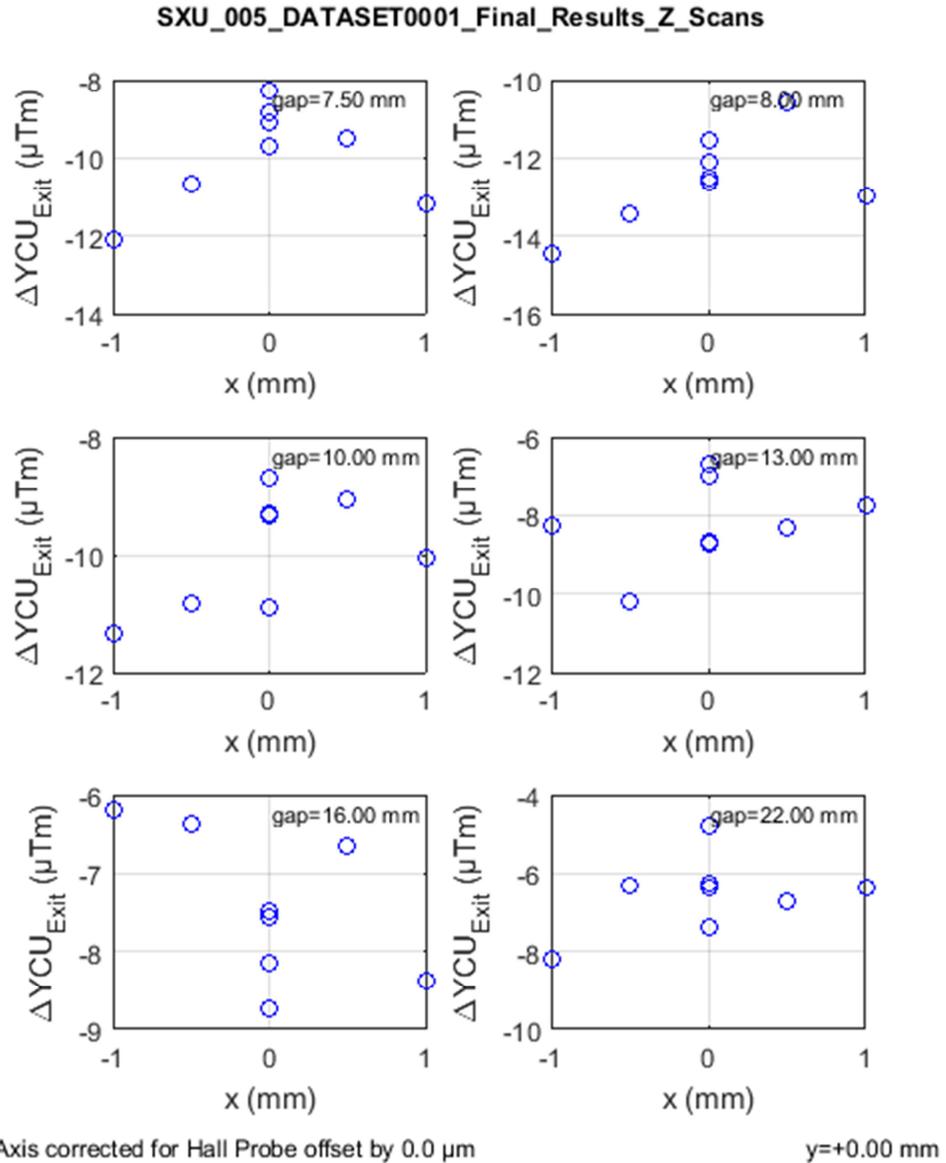
### Estimated Upstream Vertical Corrector Strength Requirement vs. x



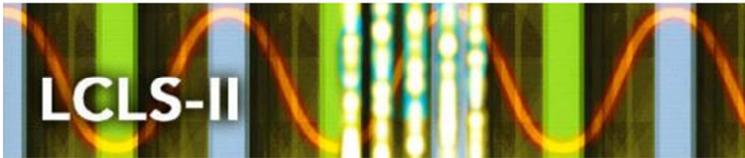
The figure shows the required strength of the upstream horizontal corrector to remove the second horizontal undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z plane. All values are small and well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



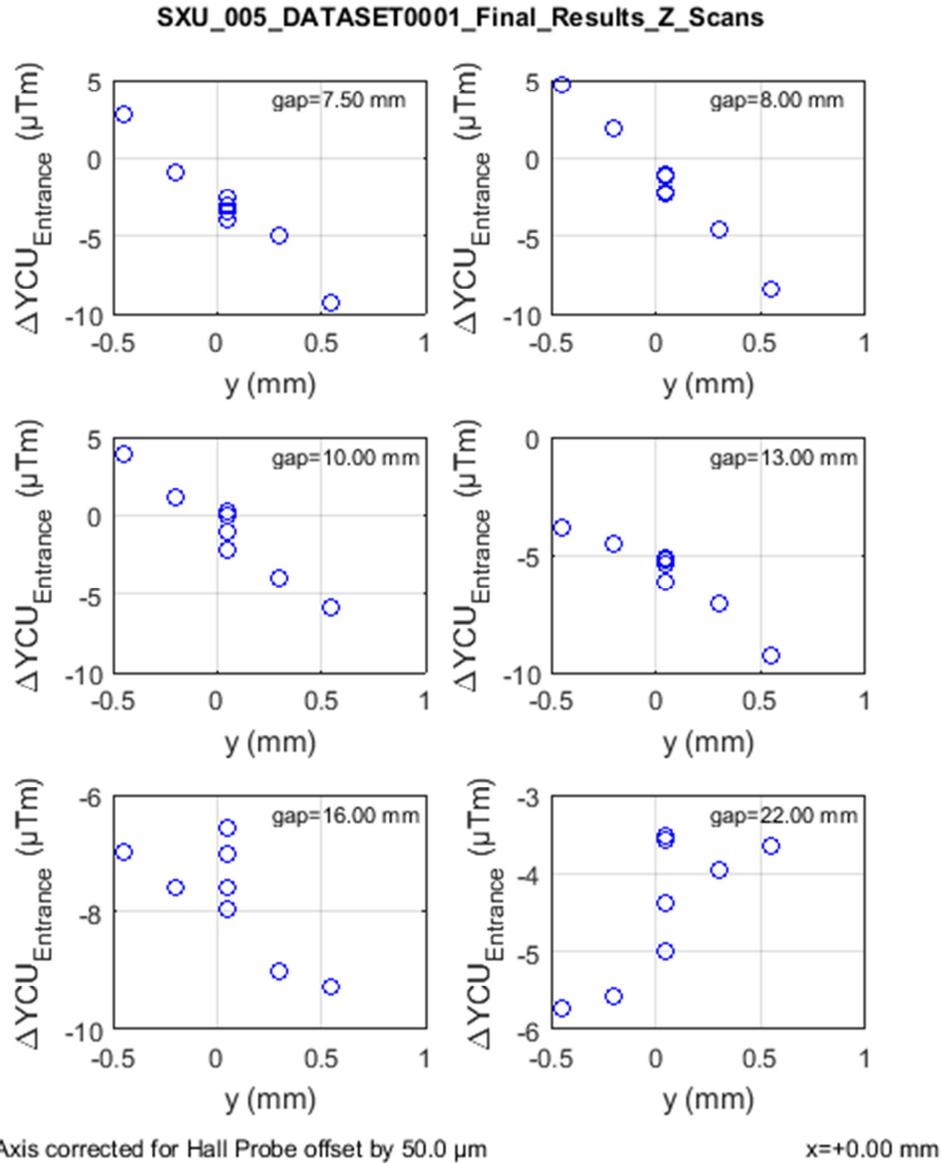
**Estimated Downstream Vertical Corrector Strength Requirement vs. x**



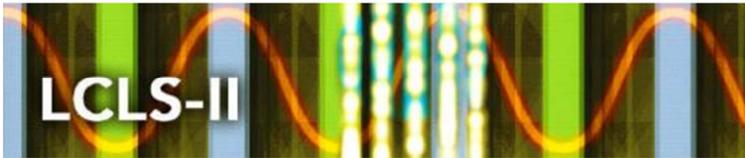
The figure shows the required strength of the downstream vertical corrector to remove the first horizontal undulator field integral and upstream corrector field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the x-z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



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



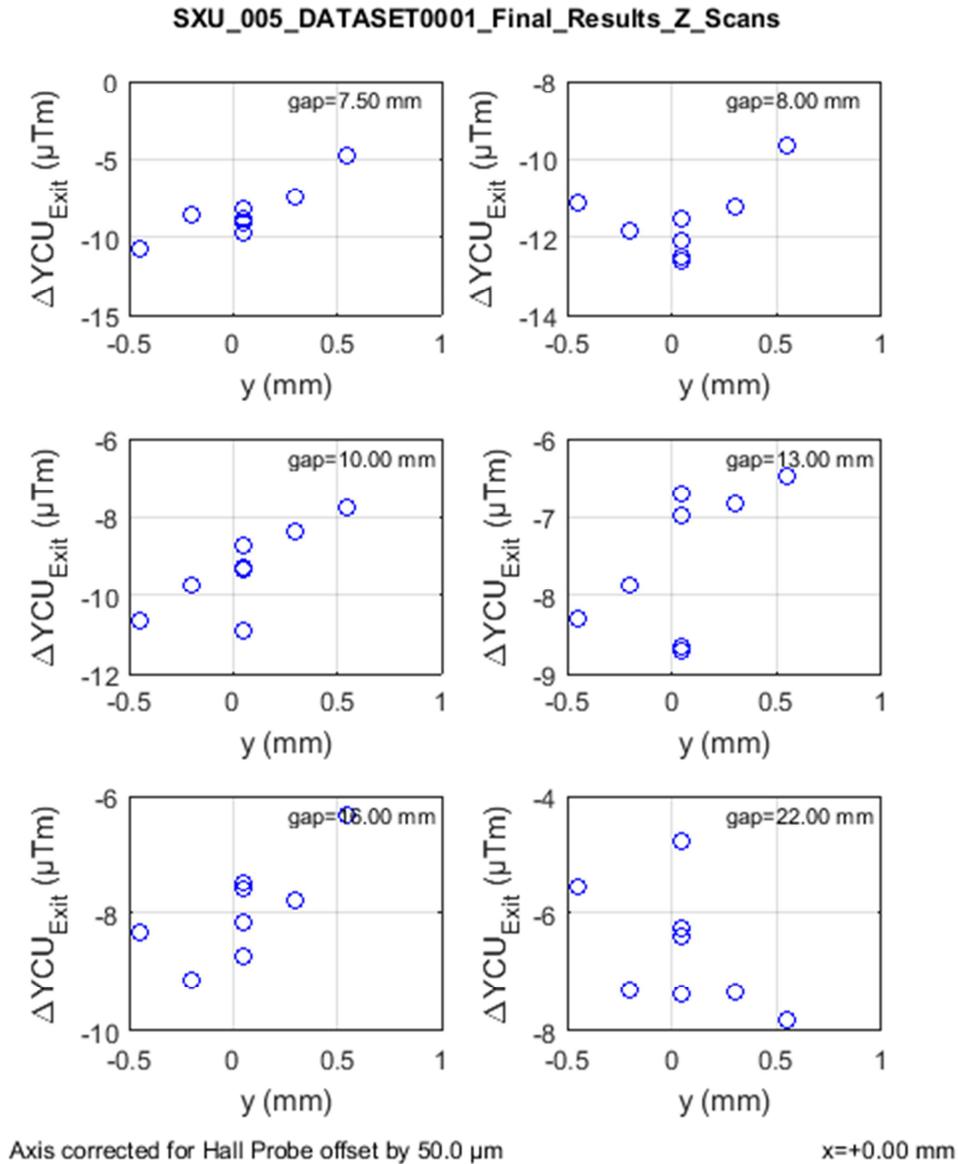
The figure shows the required strength of the upstream vertical corrector to remove the second horizontal undulator field integral at the downstream BPM for a number of operational undulator gaps. The analysis was done at a number of off-axis locations in the y-z plane. All values are small and well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



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### Estimated Downstream Vertical Corrector Strength Requirement vs. y

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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.

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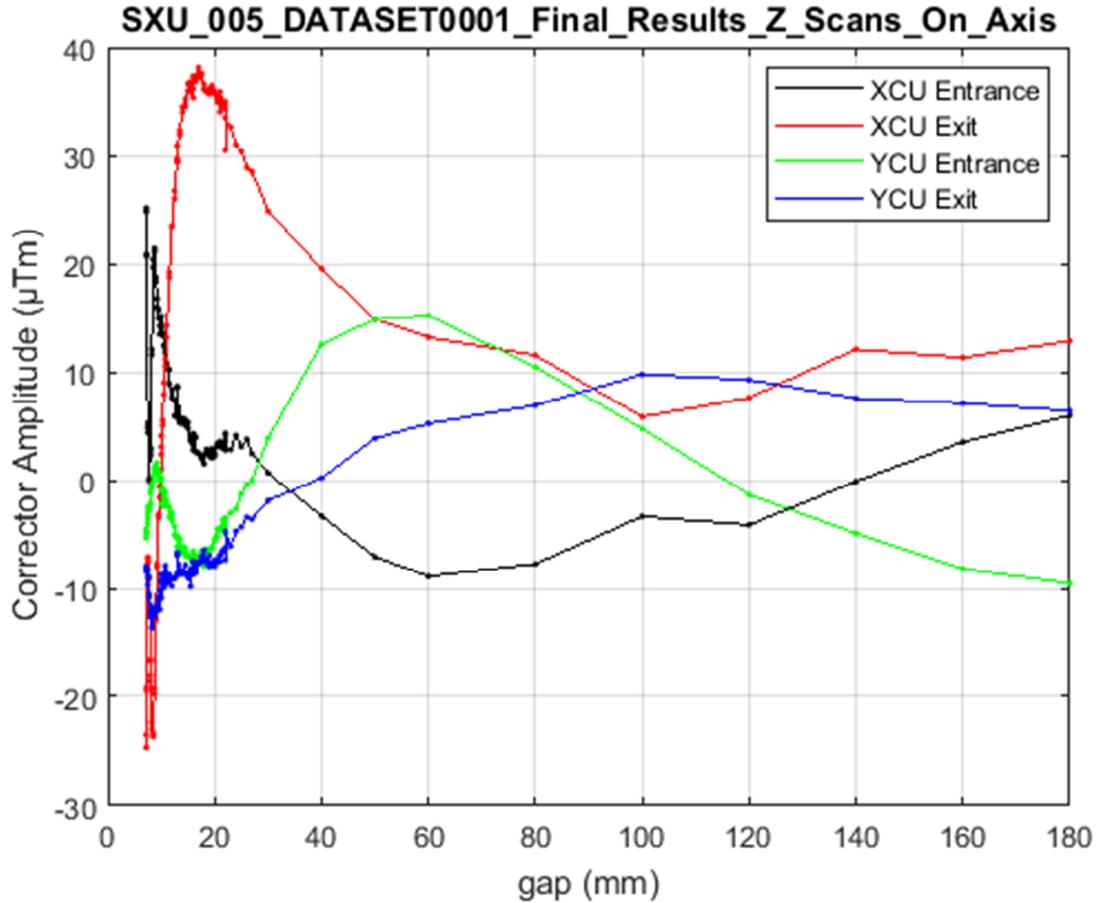
### Estimated Corrector Strengths Requirement vs. gap

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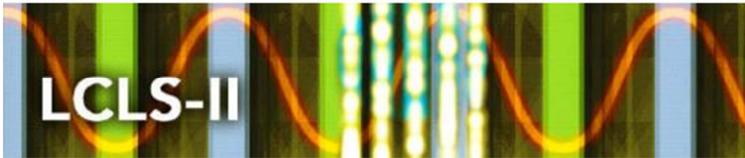


LCLS-II Undulator Segment Measurement Results

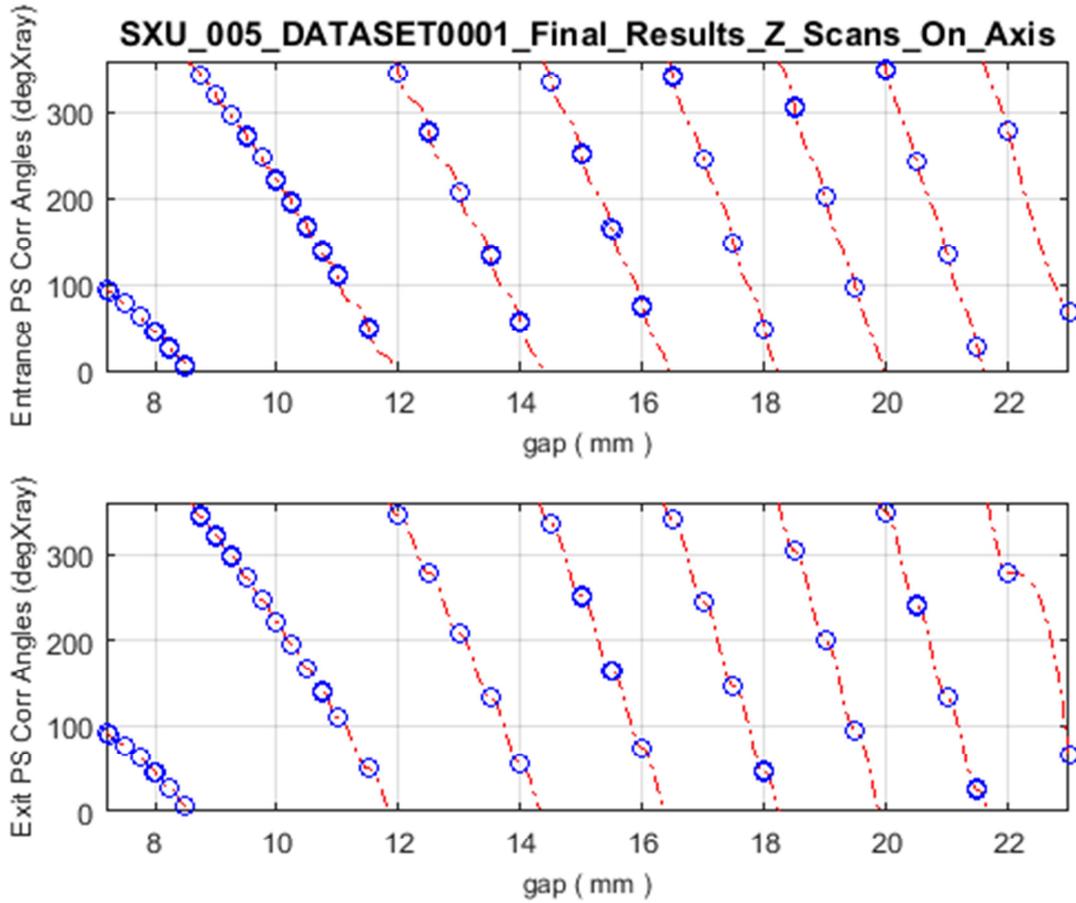
SXU-005



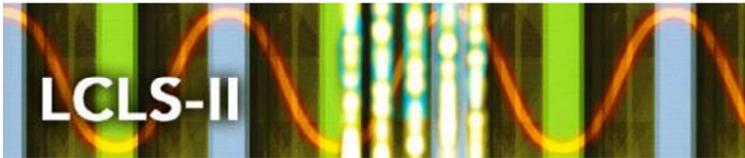
The figure shows as a function of undulator gap the required strengths of the upstream and downstream horizontal and vertical correctors to remove the effect of undulator field integrals at the downstream BPM over the entire available gap range. All values are small and well below the maximum correction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



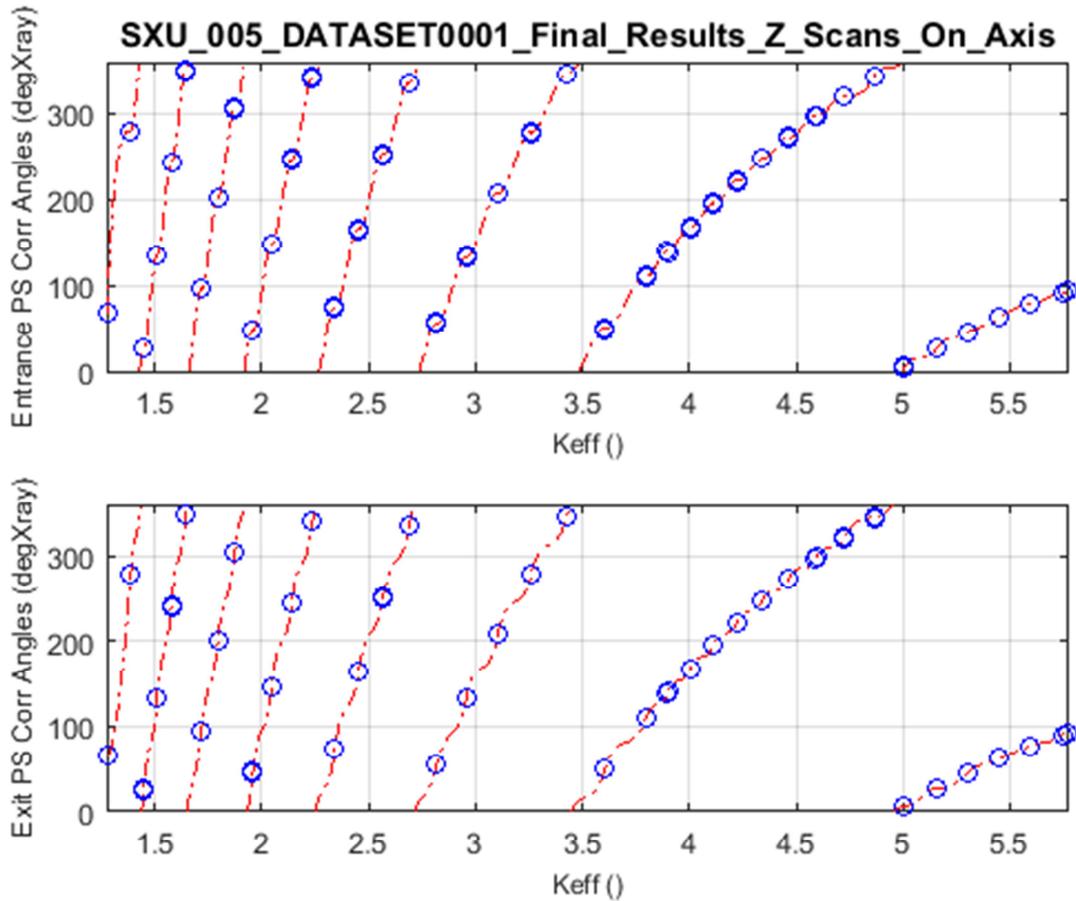
### Estimated Phase Shifter (Angle) Change Requirement vs. gap



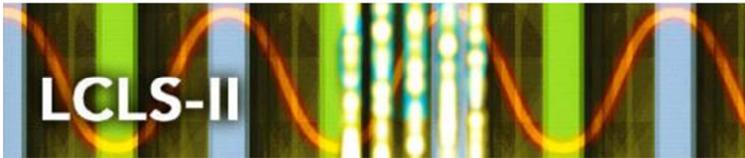
The top and bottom figures show as a function of undulator gap the required correction angles to be added to the upstream and downstream phase shifters, respectively. The red lines indicate the minimum required phase shifter phase angle increases, which are in the 0 to 360 degXray phase shift range.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



### Estimated Phase Shifter (Angle) Change Requirement vs. $K_{eff}$



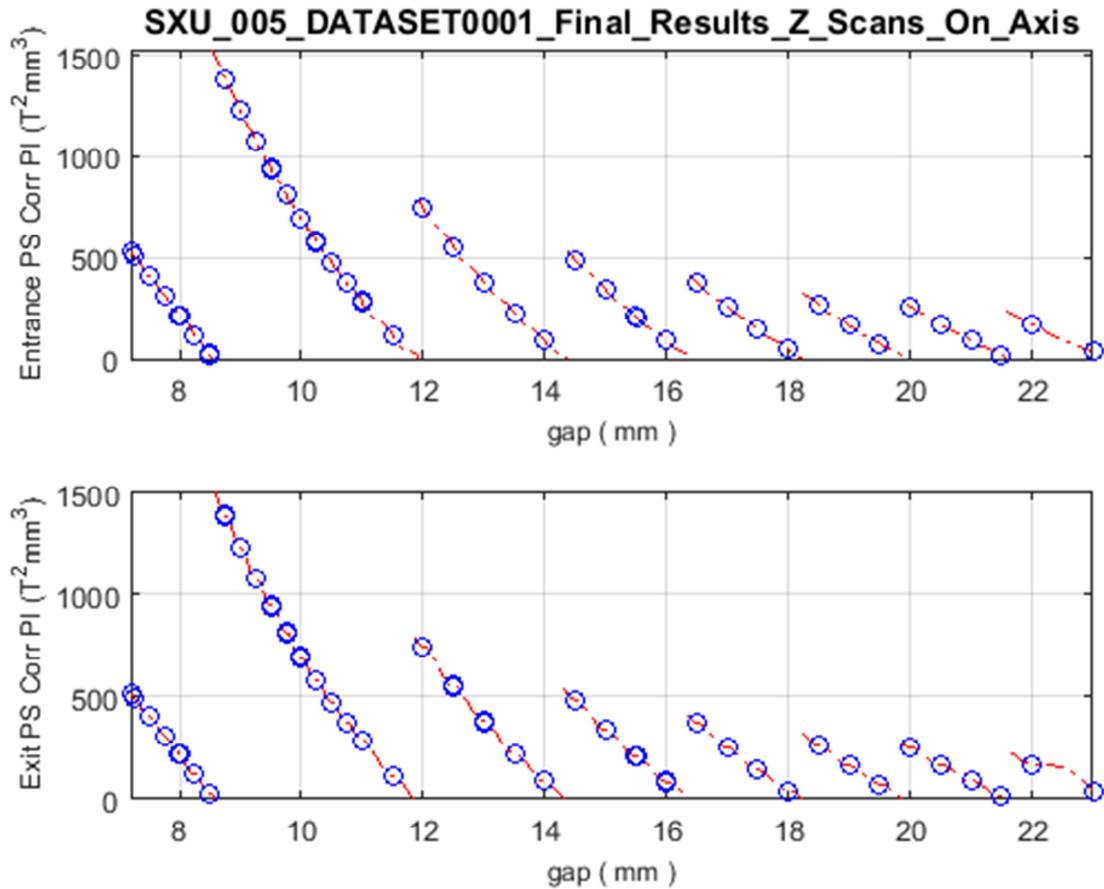
The top and bottom figures as a function of undulator parameter  $K_{eff}$  the required correction angles to be added to the upstream and downstream phase shifters, respectively. The red lines indicate the minimum required phase shifter phase angle increases, which are in the 0 to 360 degXray phase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



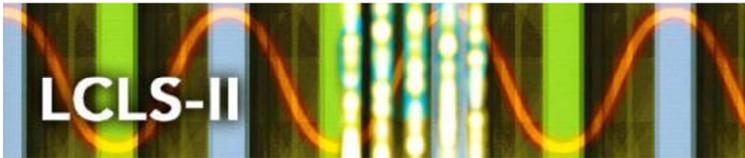
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**Estimated Phase Shifter (Phase Integral Change) Requirement vs. gap**

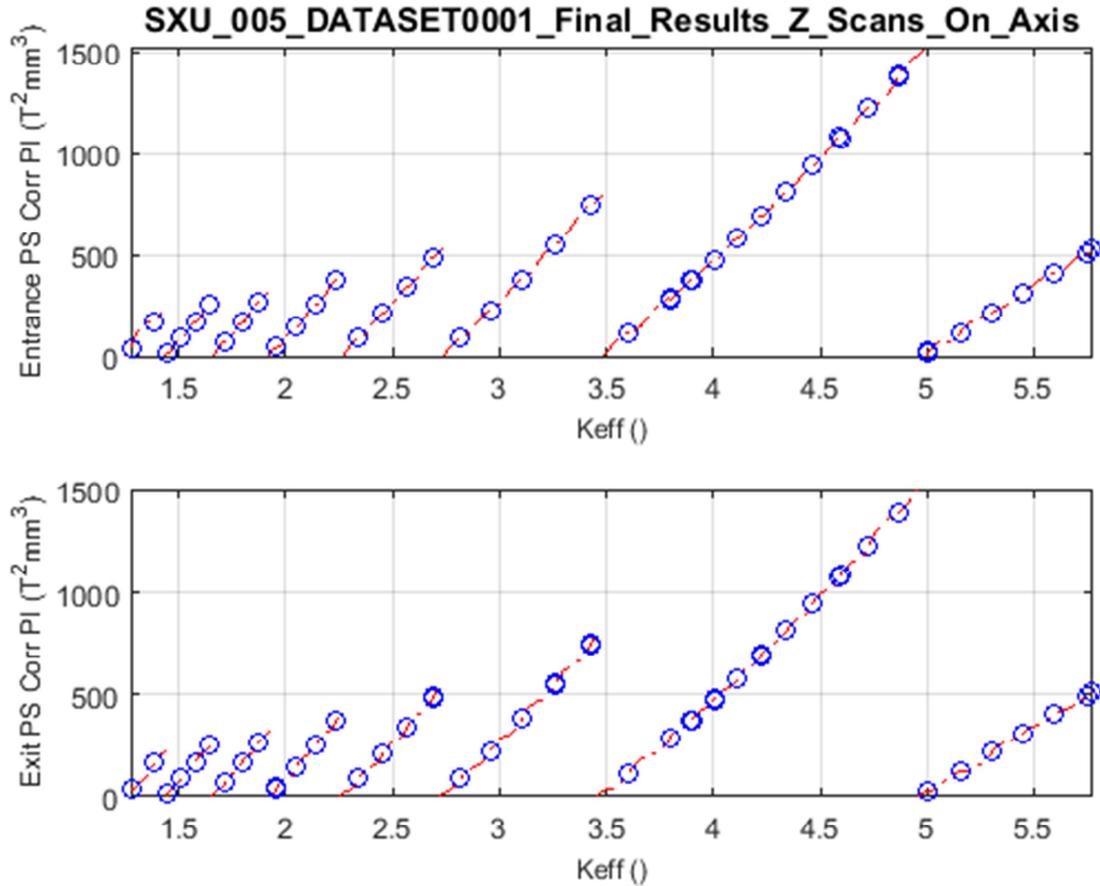
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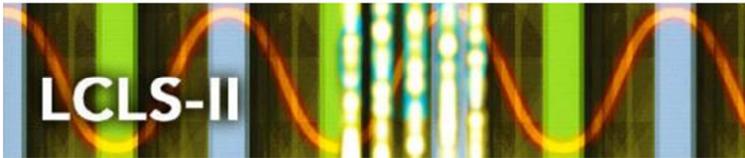
The top and bottom figures show as a function of undulator gap the required correction phase integral (PI) values to be added to the upstream and downstream phase shifters, respectively. The red lines indicate the minimum required phase shifter phase angle increases, which are in the 0 to 360 degXray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



### Estimated Phase Shifter (Angle) Requirement vs. gap



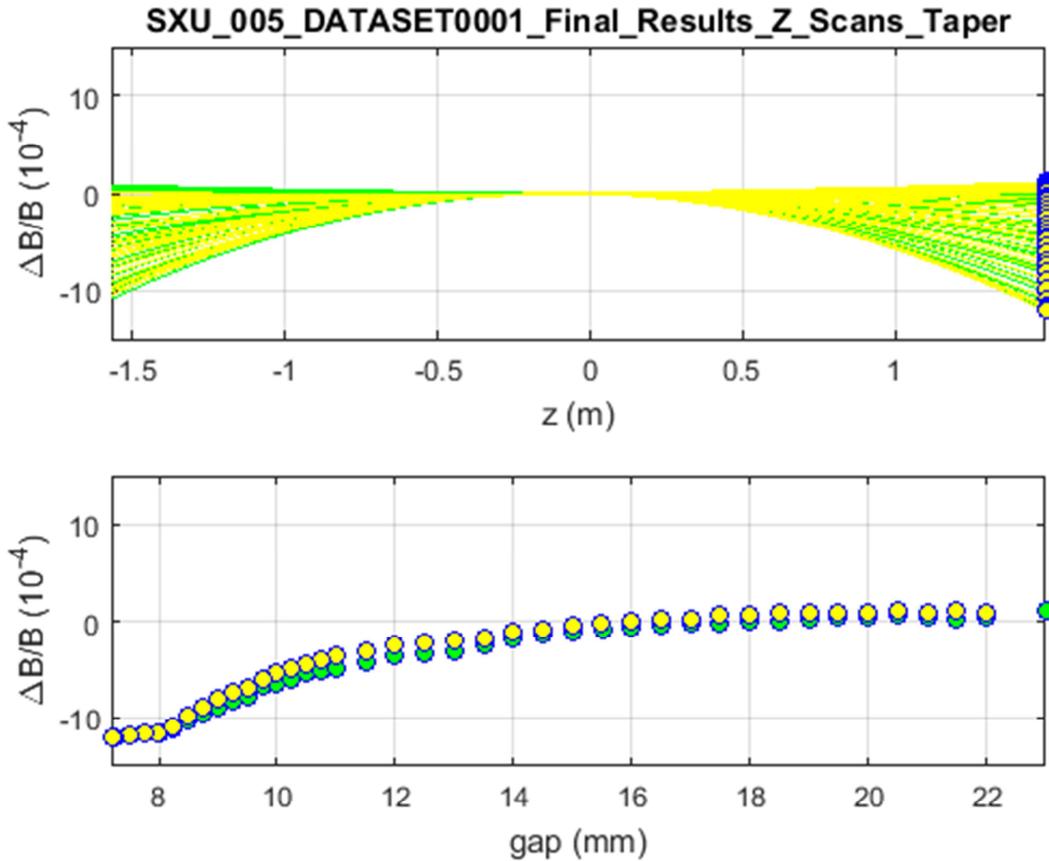
The top and bottom figures show as a function of undulator parameter  $K_{eff}$  the required correction phase integral (PI) values to be added to the upstream and downstream phase shifters, respectively. The red lines indicate the minimum required phase shifter phase angle increases, which are in the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



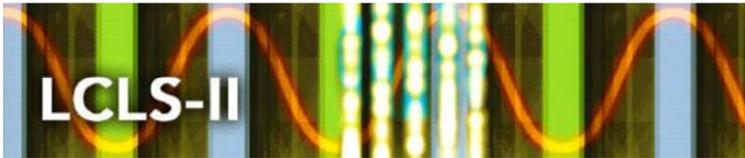
LCLS-II Undulator Segment Measurement Results

SXU-005

## Zero Taper Fits vs. gap

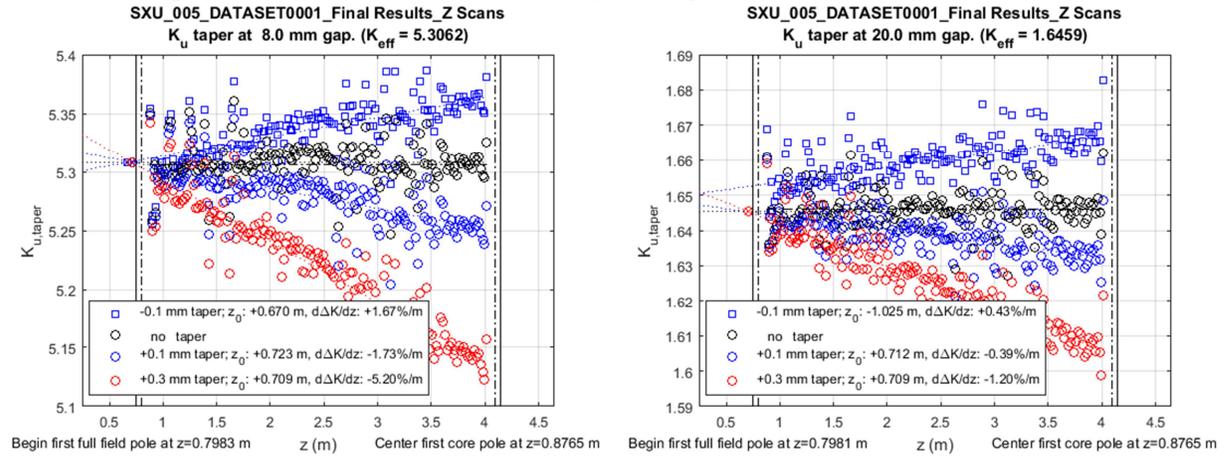


The top figure shows quadratic fits to the absolute values  $K_u$  for each core pole for different gaps when the device is set to zero taper. Green curves indicate that the gap was approached from smaller gaps, while yellow curves indicate approach from larger gaps. The fitted  $K_u$  value of the last 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 micrometer. The taper can be varied over the  $\pm 300 \mu\text{m}$ -range.



The figure shows  $K_{u,taper}$  for the 162 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, 20 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) to 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  $K_{eff}$  of the untapered undulator. For the 20 gap, the pivot point for the negative taper deviates from those for the other tapers.

The taper operation for this segment is functional.

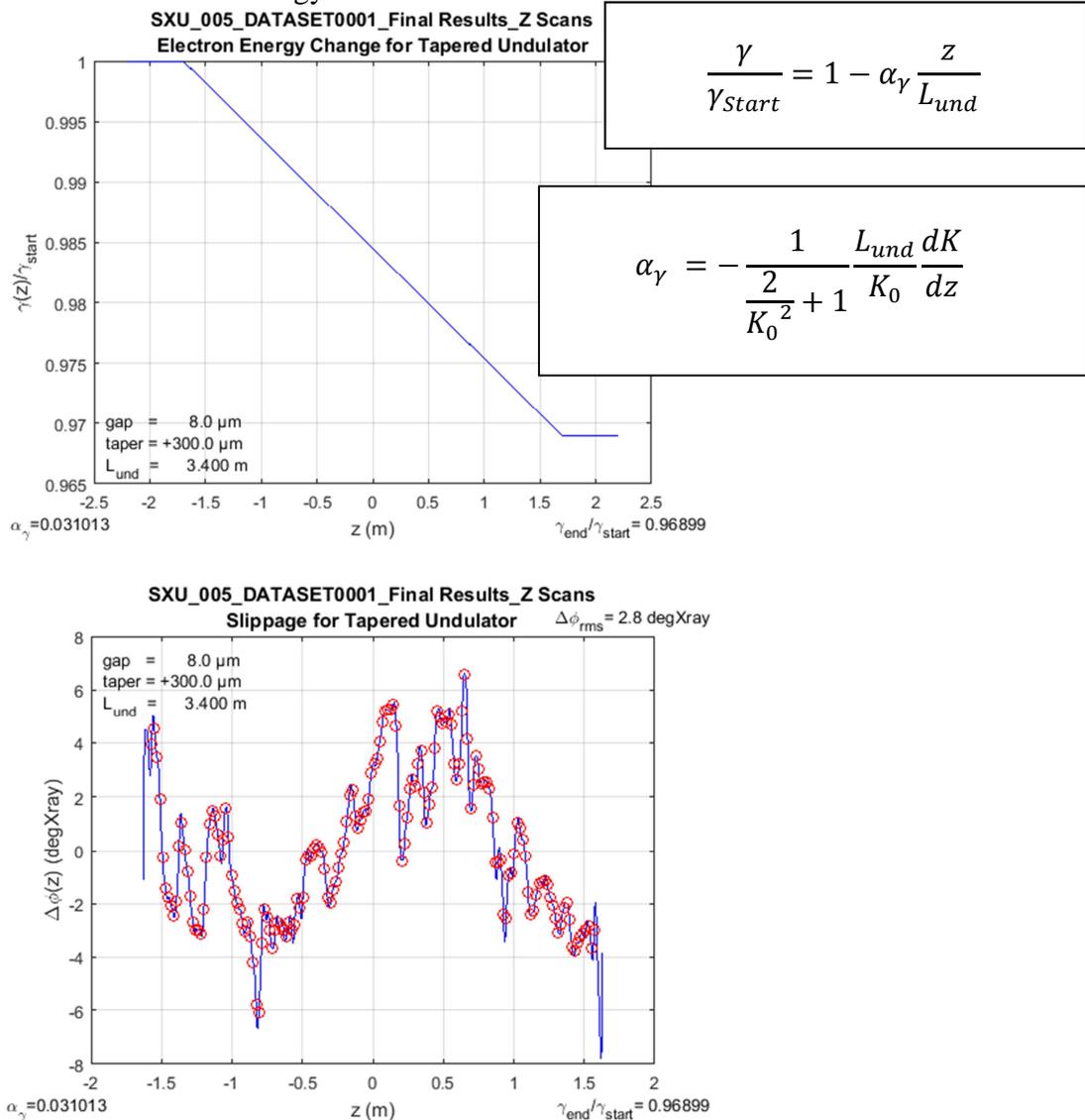


LCLS-II Undulator Segment Measurement Results

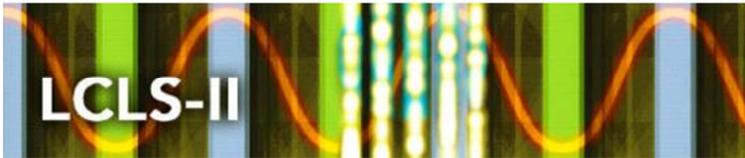
SXU-005

## Gap Tapering– Matching Energy Loss

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.



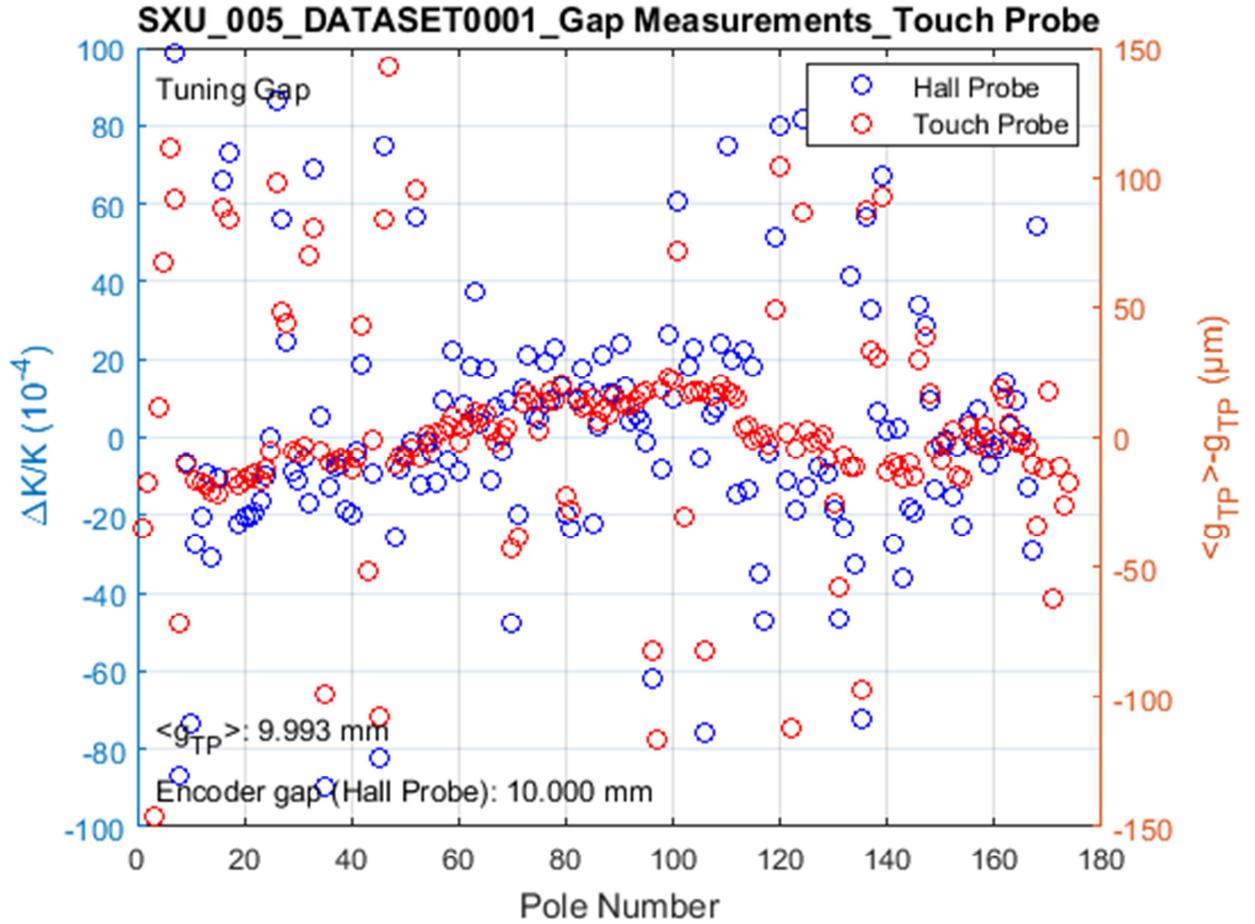
The upper figure shows a simplified linear energy loss function (Lorentz factor  $\gamma/\gamma_{start}$ ) optimized for the 0.3 mm gap taper at an 8 mm nominal gap. The lower figure shows the phase error along the undulator segment for the same parameters. The phase shake is only 2.8 degXray.



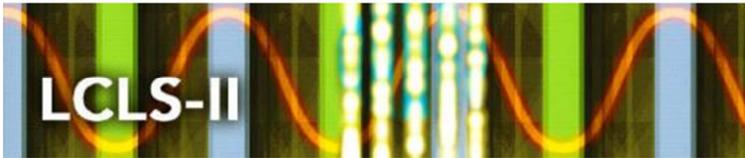
LCLS-II Undulator Segment Measurement Results

SXU-005

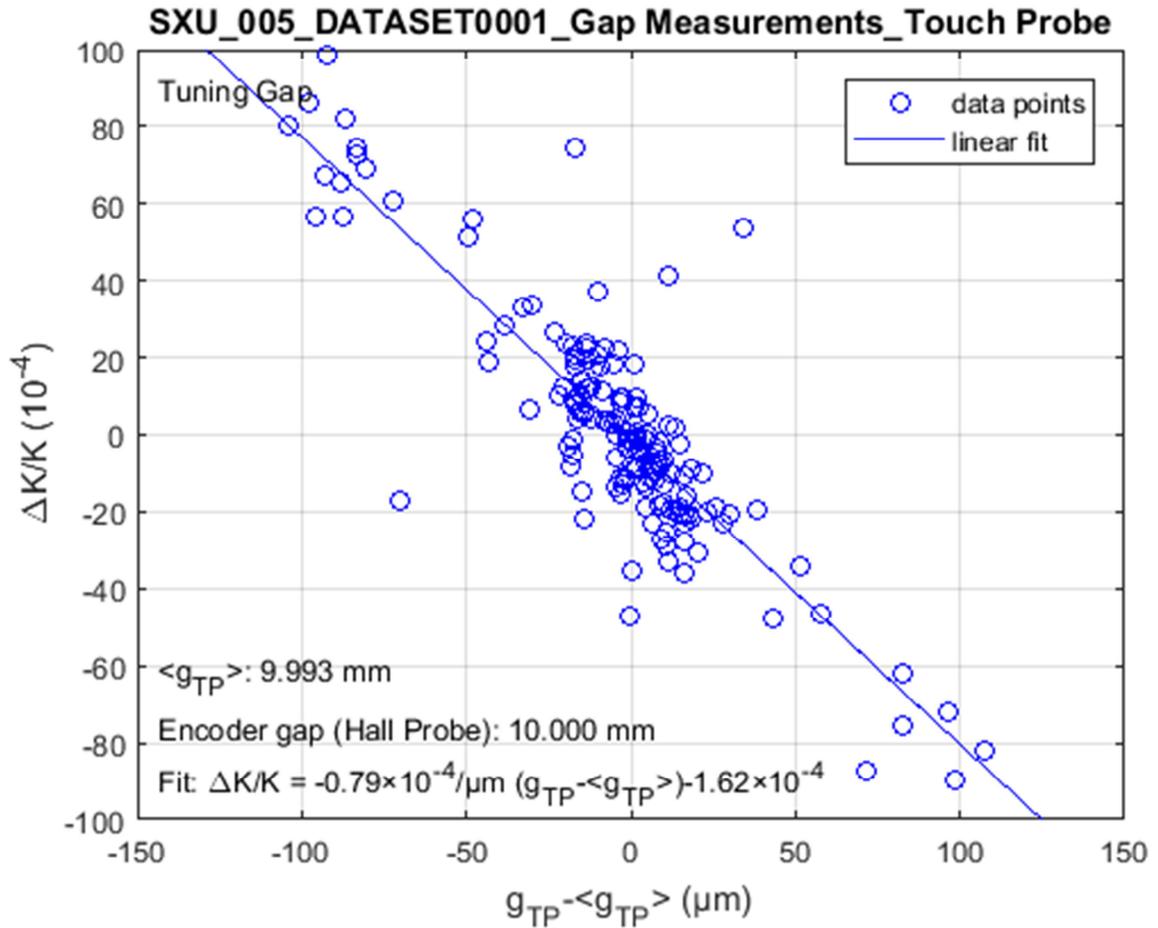
### Touch Probe (TP) Analysis – Per pole gap vs per pole K (untapered)



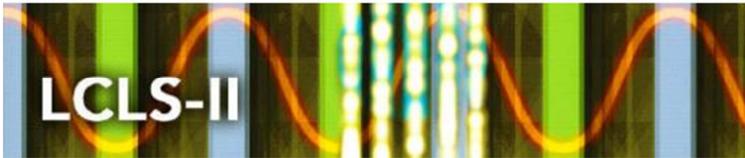
The figure shows  $\Delta K/K$  (blue, left axis) (for the 162 core poles) as well as mechanical gap heights  $\langle g_{TP} \rangle - g_{TP}$  (red, right axis) (for all 174 poles) based on touch probe measurements versus pole number. The large amplitude outliers are the result of tuning.



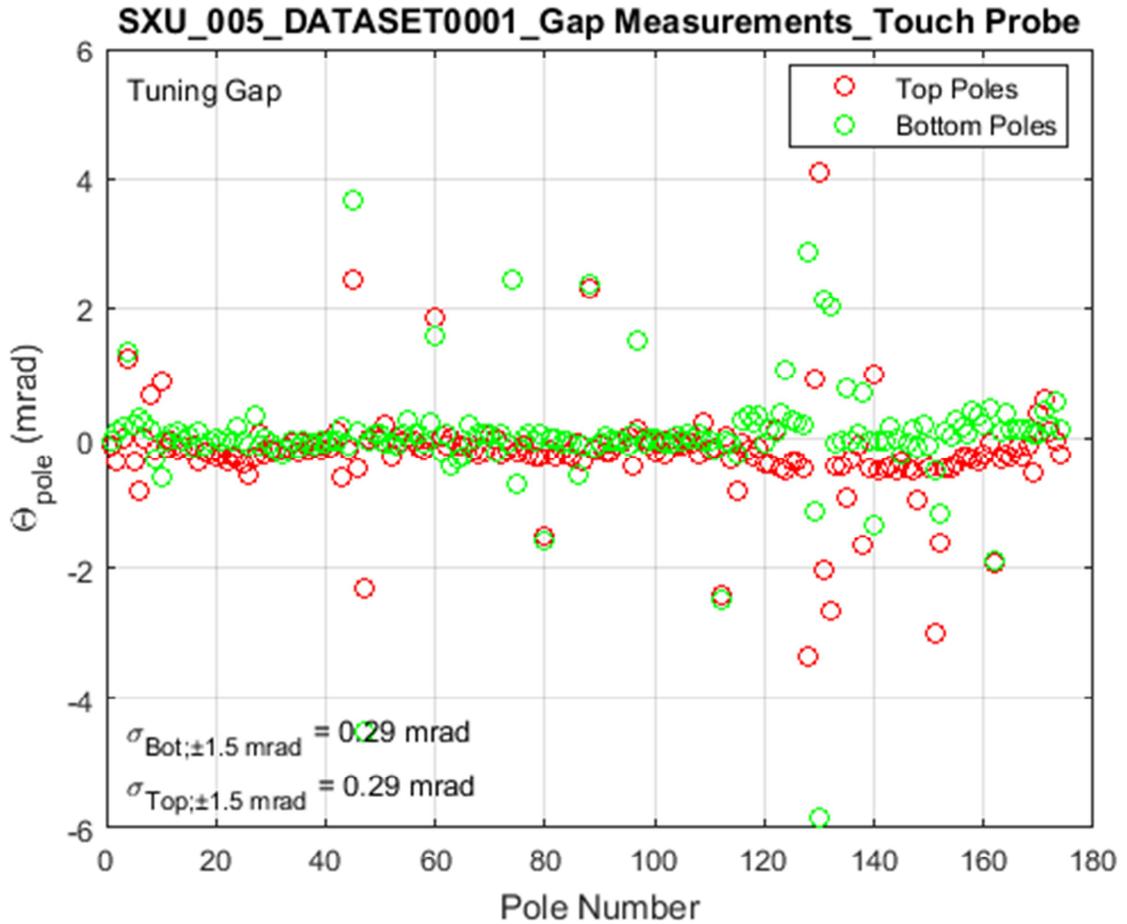
**Touch Probe (TP) Analysis – K vs per pole gap (untapered)**



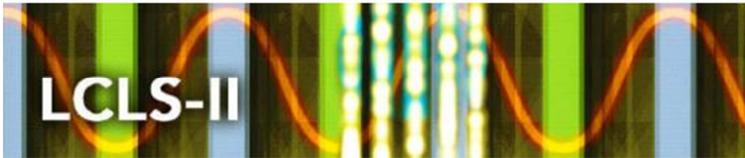
The figure shows the correlation between the  $\Delta K_u/K_u$  for each pole from Hall probe measurements for the tuning gap and the deviation of the pole gap measured by the touch probe relative to its average (for the 164 core poles). The average gap measured with the touch probe and the one measured 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)



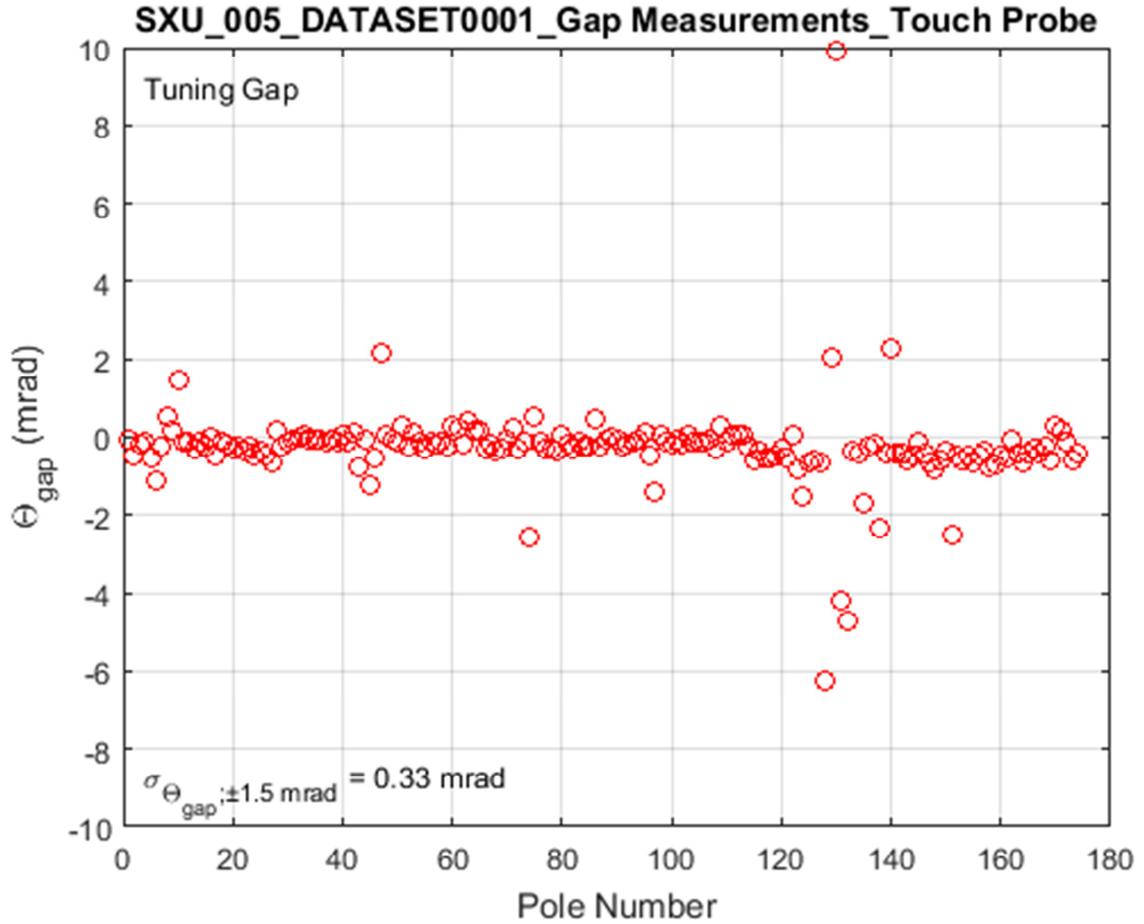
The figure shows the cant angles of each pole (top red, bottom green) relative to the horizontal plane defined by the Kugler bench at the Tuning Gap for all 174 poles, measured by the touch probe. The rms width of each distribution within a  $\pm 1.5$  mrad band is shown in the lower left corner of the figure. Note: that the distribution of the top pole angles is almost 3 times wider than that of the bottom pole angles. Not clear what the reason for this is.



LCLS-II Undulator Segment Measurement Results

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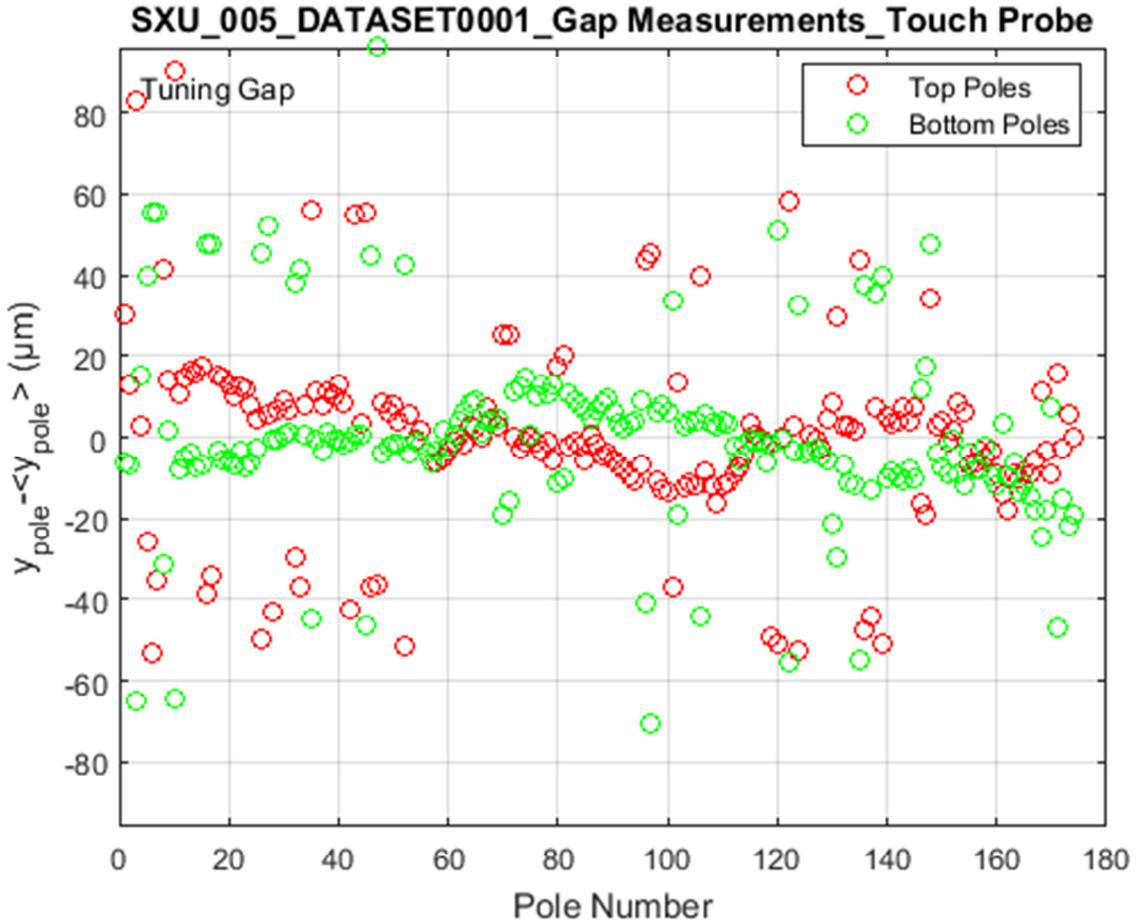
## Touch Probe (TP) Analysis – Gap Cant Angles (untapered)



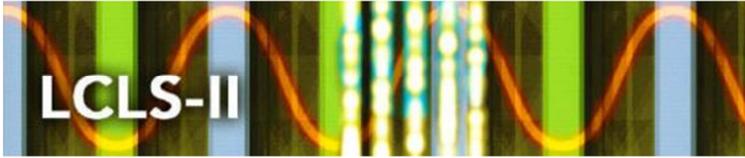
The figure shows the cant angles between the top and bottom part of each pole at the Tuning Gap for all 174 poles, measured by the touch probe. The rms width of the distribution within a  $\pm 1.5$  mrad band is shown in the lower left corner of the figure.



**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 174 poles, measured by the touch probe. Note: The right most upper magnet module appears to be mounted too high by almost 10 μm relative to the others.



LCLS-II Undulator Segment Measurement Results

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**Measurement Results are stored:**

**At V-Drive:**

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

\_\_\_\_\_

**In Folder:**

SXU\_005\DATASET0001\Final Results\

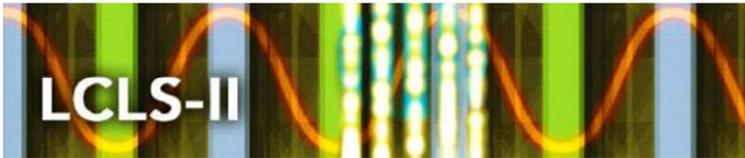
\_\_\_\_\_

**Confirmation of File Locations:**

The following lists 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

001gap007.500x-01.00y+00.00\zscan.dat	exists
002gap007.500x-00.50y+00.00\zscan.dat	exists
003gap007.500x+00.00y+00.00\zscan.dat	exists
004gap007.500x+00.50y+00.00\zscan.dat	exists
005gap007.500x+01.00y+00.00\zscan.dat	exists
006gap007.500x+00.00y-00.50\zscan.dat	exists
003gap007.500x+00.00y+00.00\zscan.dat	exists
010gap007.500x+00.00y+00.50\zscan.dat	exists
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023gap010.000x+00.00y+00.00\zscan.dat	exists



LCLS-II Undulator Segment Measurement Results

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024gap010.000x+00.50y+00.00\zscan.dat	exists
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026gap010.000x+00.00y-00.50\zscan.dat	exists
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043gap016.000x+00.00y+00.00\zscan.dat	exists
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Sub Folder: Z Scans\On Axis exists

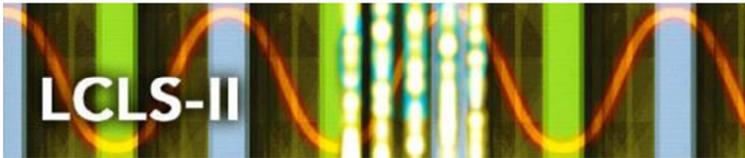
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007gap008.500x+00.00y+00.00\zscan.dat	exists
008gap008.750x+00.00y+00.00\zscan.dat	exists



LCLS-II Undulator Segment Measurement Results

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**LCLS-II Undulator Segment Measurement Results**

**SXU-005**

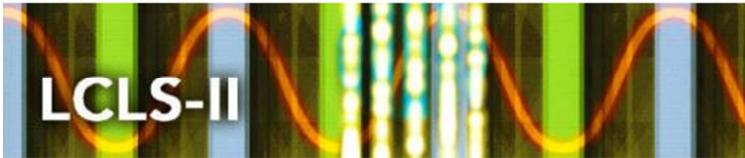
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**Sub Folder: Z Scans\Commissioning Gap exists**

001gap010.391x+00.00y+00.00\zscan.dat	exists
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**Sub Folder: Long Coil\Good Field Region exists**

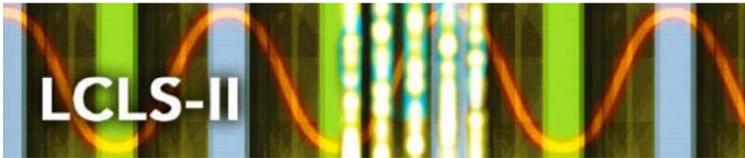
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## LCLS-II Undulator Segment Measurement Results

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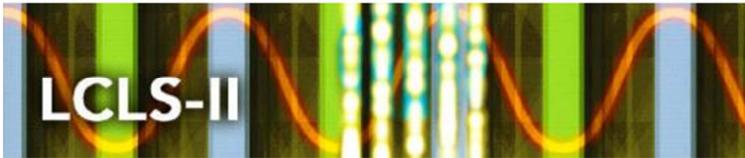
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## LCLS-II Undulator Segment Measurement Results

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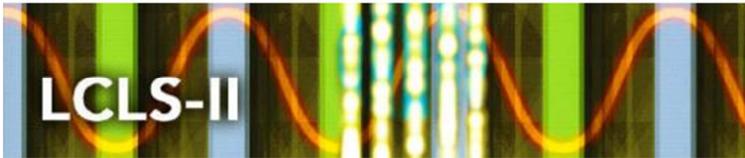
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245gap100.000x+01.00y+00.00_i1Y_integrals.txt	exists
261gap100.000x+00.00y-01.00_i1Y_integrals.txt	exists
265gap100.000x+00.00y+01.00_i1Y_integrals.txt	exists
006gap007.500x-01.00y+00.00_i2Y_integrals.txt	exists
007gap007.500x-00.50y+00.00_i2Y_integrals.txt	exists
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009gap007.500x+00.50y+00.00_i2Y_integrals.txt	exists
010gap007.500x+01.00y+00.00_i2Y_integrals.txt	exists
026gap007.500x+00.00y-01.00_i2Y_integrals.txt	exists
030gap007.500x+00.00y+01.00_i2Y_integrals.txt	exists
046gap008.000x-01.00y+00.00_i2Y_integrals.txt	exists
047gap008.000x-00.50y+00.00_i2Y_integrals.txt	exists
048gap008.000x+00.00y+00.00_i2Y_integrals.txt	exists
049gap008.000x+00.50y+00.00_i2Y_integrals.txt	exists
050gap008.000x+01.00y+00.00_i2Y_integrals.txt	exists
066gap008.000x+00.00y-01.00_i2Y_integrals.txt	exists
070gap008.000x+00.00y+01.00_i2Y_integrals.txt	exists
086gap010.000x-01.00y+00.00_i2Y_integrals.txt	exists
087gap010.000x-00.50y+00.00_i2Y_integrals.txt	exists
088gap010.000x+00.00y+00.00_i2Y_integrals.txt	exists
089gap010.000x+00.50y+00.00_i2Y_integrals.txt	exists
090gap010.000x+01.00y+00.00_i2Y_integrals.txt	exists
106gap010.000x+00.00y-01.00_i2Y_integrals.txt	exists
110gap010.000x+00.00y+01.00_i2Y_integrals.txt	exists
126gap013.000x-01.00y+00.00_i2Y_integrals.txt	exists
127gap013.000x-00.50y+00.00_i2Y_integrals.txt	exists
128gap013.000x+00.00y+00.00_i2Y_integrals.txt	exists
129gap013.000x+00.50y+00.00_i2Y_integrals.txt	exists
130gap013.000x+01.00y+00.00_i2Y_integrals.txt	exists
146gap013.000x+00.00y-01.00_i2Y_integrals.txt	exists
150gap013.000x+00.00y+01.00_i2Y_integrals.txt	exists



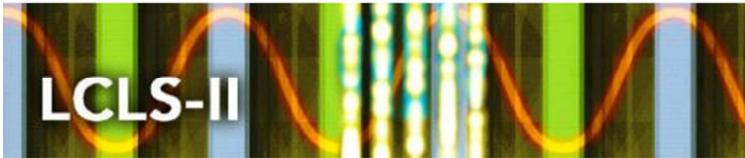
**LCLS-II Undulator Segment Measurement Results**

**SXU-005**

166gap016.000x-01.00y+00.00_i2Y_integrals.txt	exists
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168gap016.000x+00.00y+00.00_i2Y_integrals.txt	exists
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170gap016.000x+01.00y+00.00_i2Y_integrals.txt	exists
186gap016.000x+00.00y-01.00_i2Y_integrals.txt	exists
190gap016.000x+00.00y+01.00_i2Y_integrals.txt	exists
206gap022.000x-01.00y+00.00_i2Y_integrals.txt	exists
207gap022.000x-00.50y+00.00_i2Y_integrals.txt	exists
208gap022.000x+00.00y+00.00_i2Y_integrals.txt	exists
209gap022.000x+00.50y+00.00_i2Y_integrals.txt	exists
210gap022.000x+01.00y+00.00_i2Y_integrals.txt	exists
226gap022.000x+00.00y-01.00_i2Y_integrals.txt	exists
230gap022.000x+00.00y+01.00_i2Y_integrals.txt	exists
246gap100.000x-01.00y+00.00_i2Y_integrals.txt	exists
247gap100.000x-00.50y+00.00_i2Y_integrals.txt	exists
248gap100.000x+00.00y+00.00_i2Y_integrals.txt	exists
249gap100.000x+00.50y+00.00_i2Y_integrals.txt	exists
250gap100.000x+01.00y+00.00_i2Y_integrals.txt	exists
266gap100.000x+00.00y-01.00_i2Y_integrals.txt	exists
270gap100.000x+00.00y+01.00_i2Y_integrals.txt	exists

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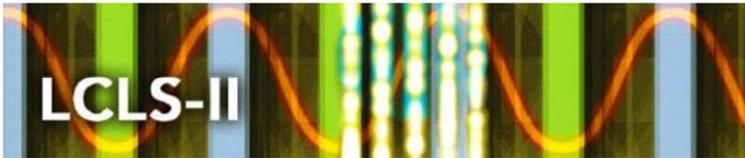
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001gap007.200x+00.00y+00.00_i1Y_integrals.txt	exists
002gap007.200x+00.00y+00.00_i2Y_integrals.txt	exists
007gap007.500x+00.00y+00.00_i1X_integrals.txt	exists
008gap007.500x+00.00y+00.00_i2X_integrals.txt	exists
005gap007.500x+00.00y+00.00_i1Y_integrals.txt	exists
006gap007.500x+00.00y+00.00_i2Y_integrals.txt	exists
011gap008.000x+00.00y+00.00_i1X_integrals.txt	exists
012gap008.000x+00.00y+00.00_i2X_integrals.txt	exists
009gap008.000x+00.00y+00.00_i1Y_integrals.txt	exists
010gap008.000x+00.00y+00.00_i2Y_integrals.txt	exists



## LCLS-II Undulator Segment Measurement Results

SXU-005

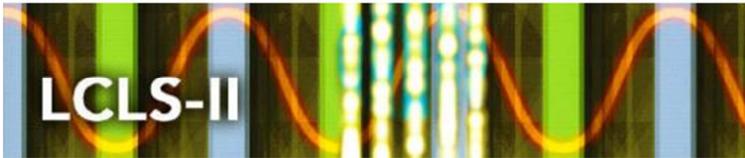
015gap008.500x+00.00y+00.00_i1X_integrals.txt	exists
016gap008.500x+00.00y+00.00_i2X_integrals.txt	exists
013gap008.500x+00.00y+00.00_i1Y_integrals.txt	exists
014gap008.500x+00.00y+00.00_i2Y_integrals.txt	exists
019gap009.000x+00.00y+00.00_i1X_integrals.txt	exists
020gap009.000x+00.00y+00.00_i2X_integrals.txt	exists
017gap009.000x+00.00y+00.00_i1Y_integrals.txt	exists
018gap009.000x+00.00y+00.00_i2Y_integrals.txt	exists
023gap010.000x+00.00y+00.00_i1X_integrals.txt	exists
024gap010.000x+00.00y+00.00_i2X_integrals.txt	exists
021gap010.000x+00.00y+00.00_i1Y_integrals.txt	exists
022gap010.000x+00.00y+00.00_i2Y_integrals.txt	exists
027gap012.000x+00.00y+00.00_i1X_integrals.txt	exists
028gap012.000x+00.00y+00.00_i2X_integrals.txt	exists
025gap012.000x+00.00y+00.00_i1Y_integrals.txt	exists
026gap012.000x+00.00y+00.00_i2Y_integrals.txt	exists
031gap014.000x+00.00y+00.00_i1X_integrals.txt	exists
032gap014.000x+00.00y+00.00_i2X_integrals.txt	exists
029gap014.000x+00.00y+00.00_i1Y_integrals.txt	exists
030gap014.000x+00.00y+00.00_i2Y_integrals.txt	exists
035gap016.000x+00.00y+00.00_i1X_integrals.txt	exists
036gap016.000x+00.00y+00.00_i2X_integrals.txt	exists
033gap016.000x+00.00y+00.00_i1Y_integrals.txt	exists
034gap016.000x+00.00y+00.00_i2Y_integrals.txt	exists
039gap018.000x+00.00y+00.00_i1X_integrals.txt	exists
040gap018.000x+00.00y+00.00_i2X_integrals.txt	exists
037gap018.000x+00.00y+00.00_i1Y_integrals.txt	exists
038gap018.000x+00.00y+00.00_i2Y_integrals.txt	exists
043gap020.000x+00.00y+00.00_i1X_integrals.txt	exists
044gap020.000x+00.00y+00.00_i2X_integrals.txt	exists
041gap020.000x+00.00y+00.00_i1Y_integrals.txt	exists
042gap020.000x+00.00y+00.00_i2Y_integrals.txt	exists
047gap022.000x+00.00y+00.00_i1X_integrals.txt	exists
048gap022.000x+00.00y+00.00_i2X_integrals.txt	exists
045gap022.000x+00.00y+00.00_i1Y_integrals.txt	exists
046gap022.000x+00.00y+00.00_i2Y_integrals.txt	exists
051gap025.000x+00.00y+00.00_i1X_integrals.txt	exists
052gap025.000x+00.00y+00.00_i2X_integrals.txt	exists



LCLS-II Undulator Segment Measurement Results

SXU-005

049gap025.000x+00.00y+00.00_i1Y_integrals.txt	exists
050gap025.000x+00.00y+00.00_i2Y_integrals.txt	exists
055gap030.000x+00.00y+00.00_i1X_integrals.txt	exists
056gap030.000x+00.00y+00.00_i2X_integrals.txt	exists
053gap030.000x+00.00y+00.00_i1Y_integrals.txt	exists
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059gap040.000x+00.00y+00.00_i1X_integrals.txt	exists
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063gap050.000x+00.00y+00.00_i1X_integrals.txt	exists
064gap050.000x+00.00y+00.00_i2X_integrals.txt	exists
061gap050.000x+00.00y+00.00_i1Y_integrals.txt	exists
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067gap060.000x+00.00y+00.00_i1X_integrals.txt	exists
068gap060.000x+00.00y+00.00_i2X_integrals.txt	exists
065gap060.000x+00.00y+00.00_i1Y_integrals.txt	exists
066gap060.000x+00.00y+00.00_i2Y_integrals.txt	exists
071gap080.000x+00.00y+00.00_i1X_integrals.txt	exists
072gap080.000x+00.00y+00.00_i2X_integrals.txt	exists
069gap080.000x+00.00y+00.00_i1Y_integrals.txt	exists
070gap080.000x+00.00y+00.00_i2Y_integrals.txt	exists
075gap100.000x+00.00y+00.00_i1X_integrals.txt	exists
076gap100.000x+00.00y+00.00_i2X_integrals.txt	exists
073gap100.000x+00.00y+00.00_i1Y_integrals.txt	exists
074gap100.000x+00.00y+00.00_i2Y_integrals.txt	exists
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078gap120.000x+00.00y+00.00_i2Y_integrals.txt	exists
083gap140.000x+00.00y+00.00_i1X_integrals.txt	exists
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081gap140.000x+00.00y+00.00_i1Y_integrals.txt	exists
082gap140.000x+00.00y+00.00_i2Y_integrals.txt	exists
087gap160.000x+00.00y+00.00_i1X_integrals.txt	exists
088gap160.000x+00.00y+00.00_i2X_integrals.txt	exists
085gap160.000x+00.00y+00.00_i1Y_integrals.txt	exists
086gap160.000x+00.00y+00.00_i2Y_integrals.txt	exists



**LCLS-II Undulator Segment Measurement Results**

**SXU-005**

091gap180.000x+00.00y+00.00_i1X_integrals.txt	exists
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090gap180.000x+00.00y+00.00_i2Y_integrals.txt	exists

**Sub Folder: Fiducialization exists**

LCLS2 SXU 005 Fiducial Report.docx	exists
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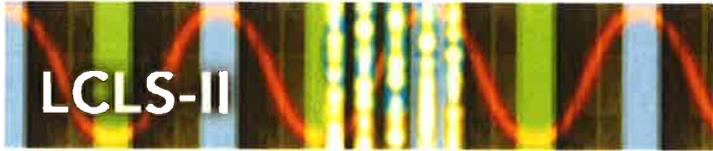
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**Sub Folder: Gap Measurements\Touch Probe exists**

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GAP10mmRun09_Pts.txt	exists

**Sub Folder: Controls Data exists**

sxu_005_parameters.txt	exists
sxu_005_k_vs_gap_spline.dat	exists
sxu_005_phase_match_enter_vs_gap_spline.dat	exists
sxu_005_phase_match_exit_vs_gap_spline.dat	exists
sxu_005_yctr_vs_gap_spline.dat	exists
sxu_005_i1xvsgap_spline.dat	exists
sxu_005_i1yvsgap_spline.dat	exists
sxu_005_i2xvsgap_spline.dat	exists
sxu_005_i2yvsgap_spline.dat	exists



**LCLS-II Undulator Segment Measurement Results**

**SXU-005**

Summary of findings

Finding	Solution

Approval and Assignment by Heinz-Dieter Nuhn:

Data Storage Checked:	Y	Y/N
Magnet accepted:	Y	Y/N
Assigned Location	SXU-005	Undulator Name

	Heinz-Dieter Nuhn	3/16/2018
(Signature)	(Name)	(Date)