Variable Gap Tapering for LCLS-II Undulators

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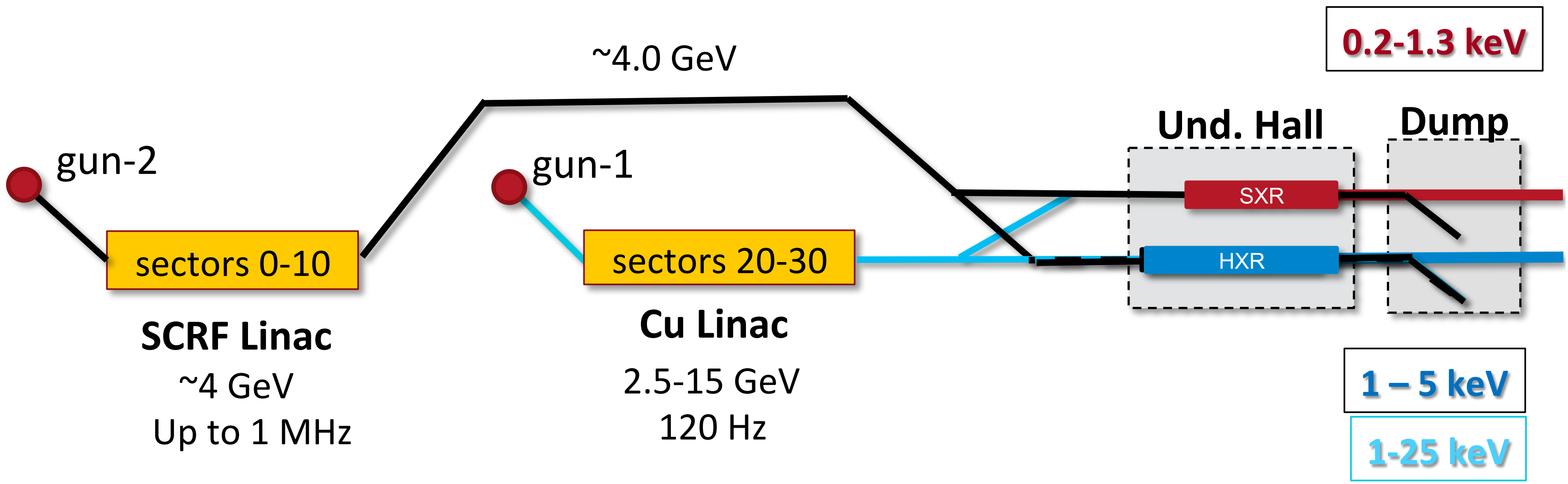
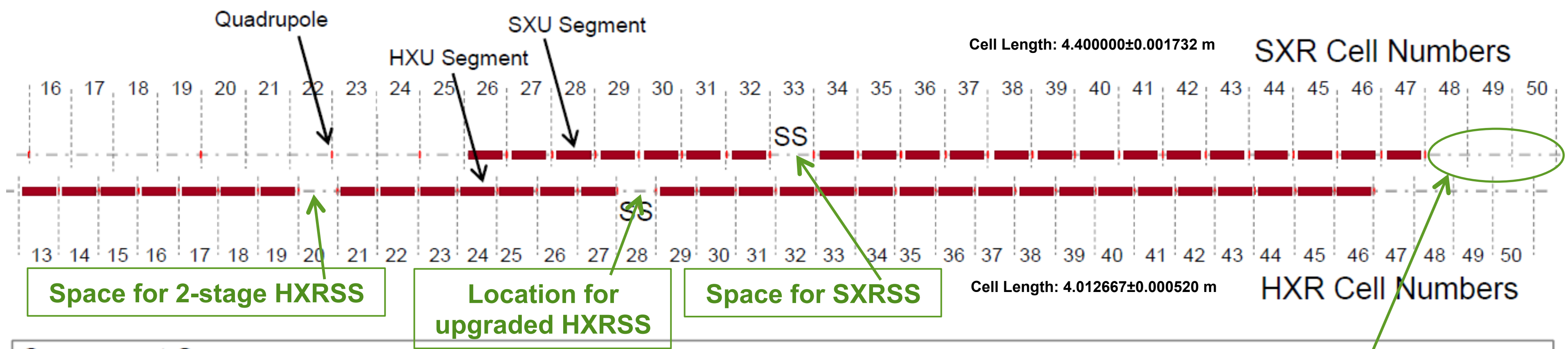
Schematic Layout of LCLS-II

- New Soft X-ray FEL with adjustable-gap undulator line (SXR)
- New Hard X-ray FEL with adjustable-gap undulator line (HXR)



LCLS-II SXR and HXR Component Layouts



Component Summary:

SXU (#21) : SXR26-SXR32; SXR34-SXR47

HXU (#32) : HXR13-HXR19; HXR21-HXR27; HXR29-SXR46

Quad⁺ (#60) : SXR15; SXR19; SXR22; SXR24, SXR26-SXR47; HXR13-HXR46;

RFBPM ⁺⁺ (#60+2) : SXR24; SXR25; SXR26-SXR47; (+1); HXR12; HXR13; HXR14-HXR46; (+1)

SXR-PS ⁺⁺ (#20) : SXR26-SXR32; SXR34-SXR46

HXR-PS ⁺⁺ (#31) : HXR14-HXR19; HXR22-HXR27; HXR29-HXR46

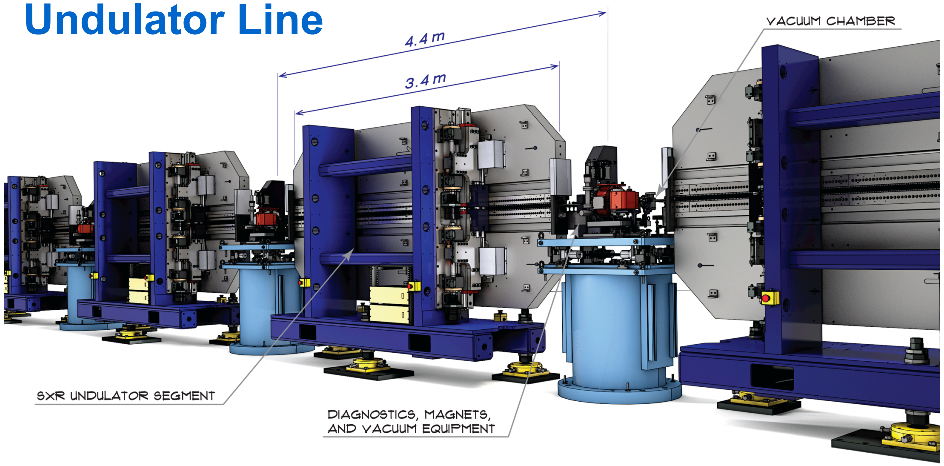
BLM ⁺ (#53) : SXR26-SXR32; SXR34-SXR47 ; HXR13-HXR19 ; HXR21-HXR27; HXR29-SXR46

⁺ Same Cell as following segment

⁺⁺ Same Cell as previous segment

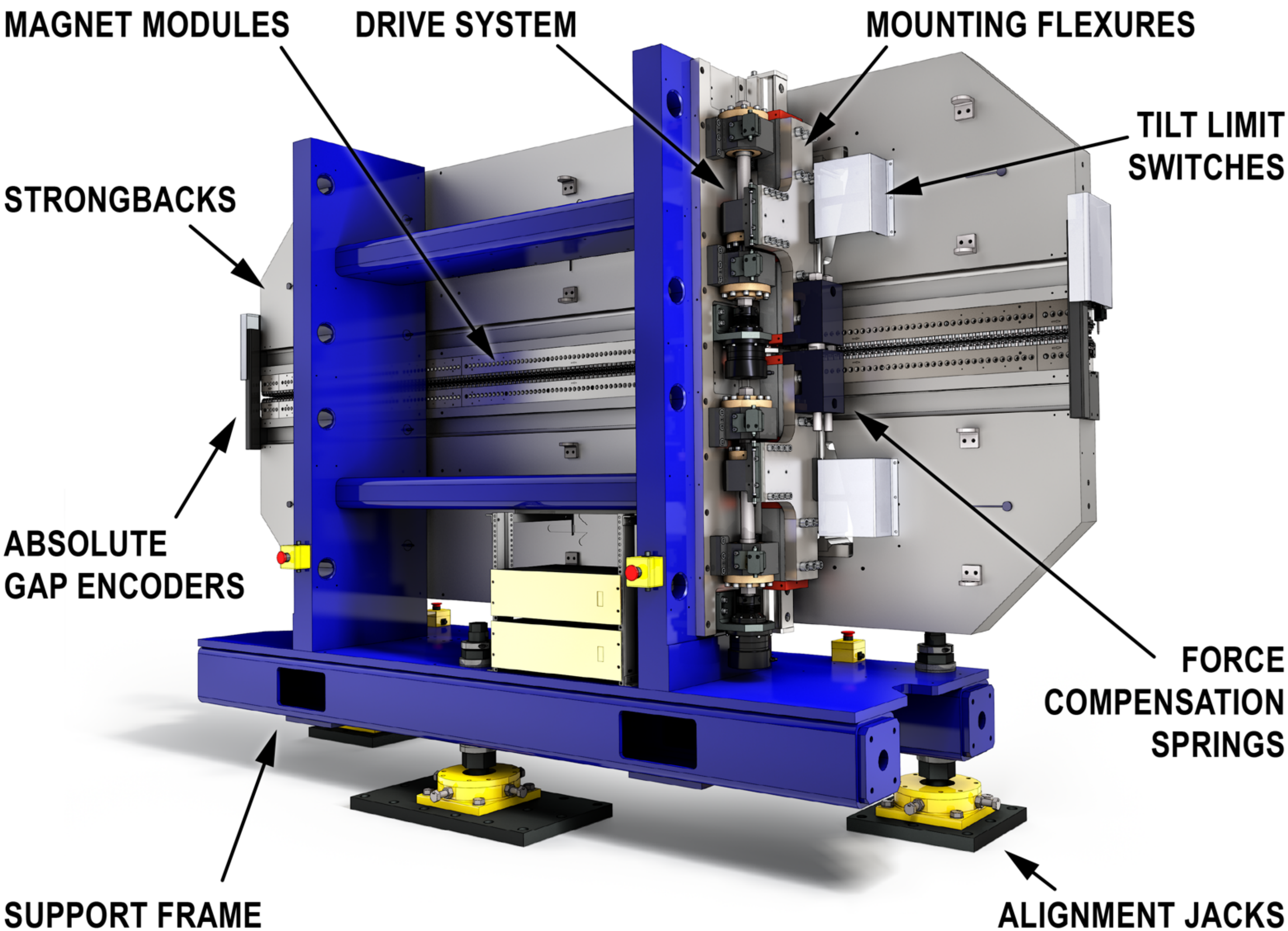
Undulator System Layout

SXR
Undulator Line

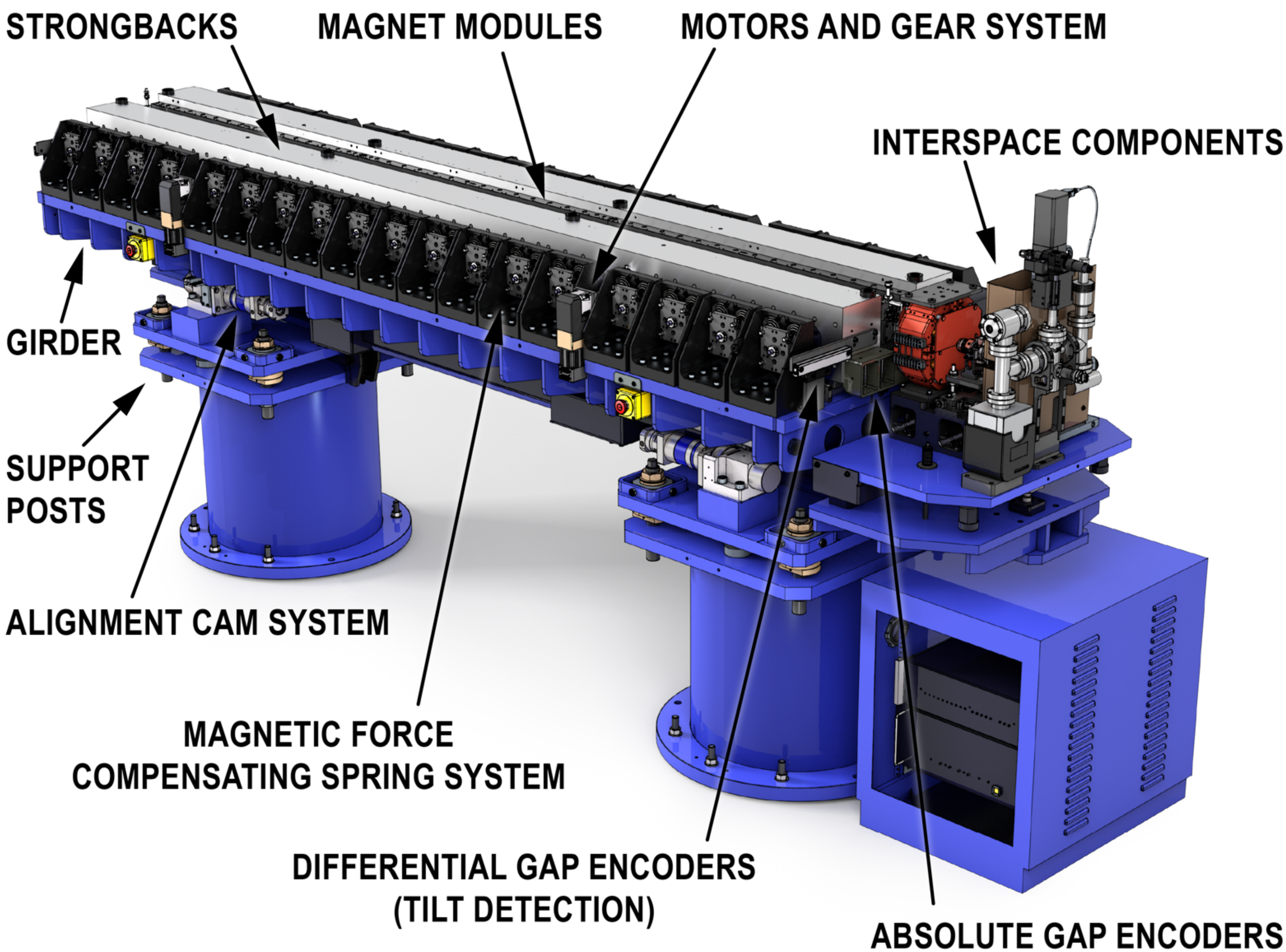


HXR
Undulator Line

LCLS-II SXR Undulator (HPU)



LCLS-II HXR Undulator (VPU)

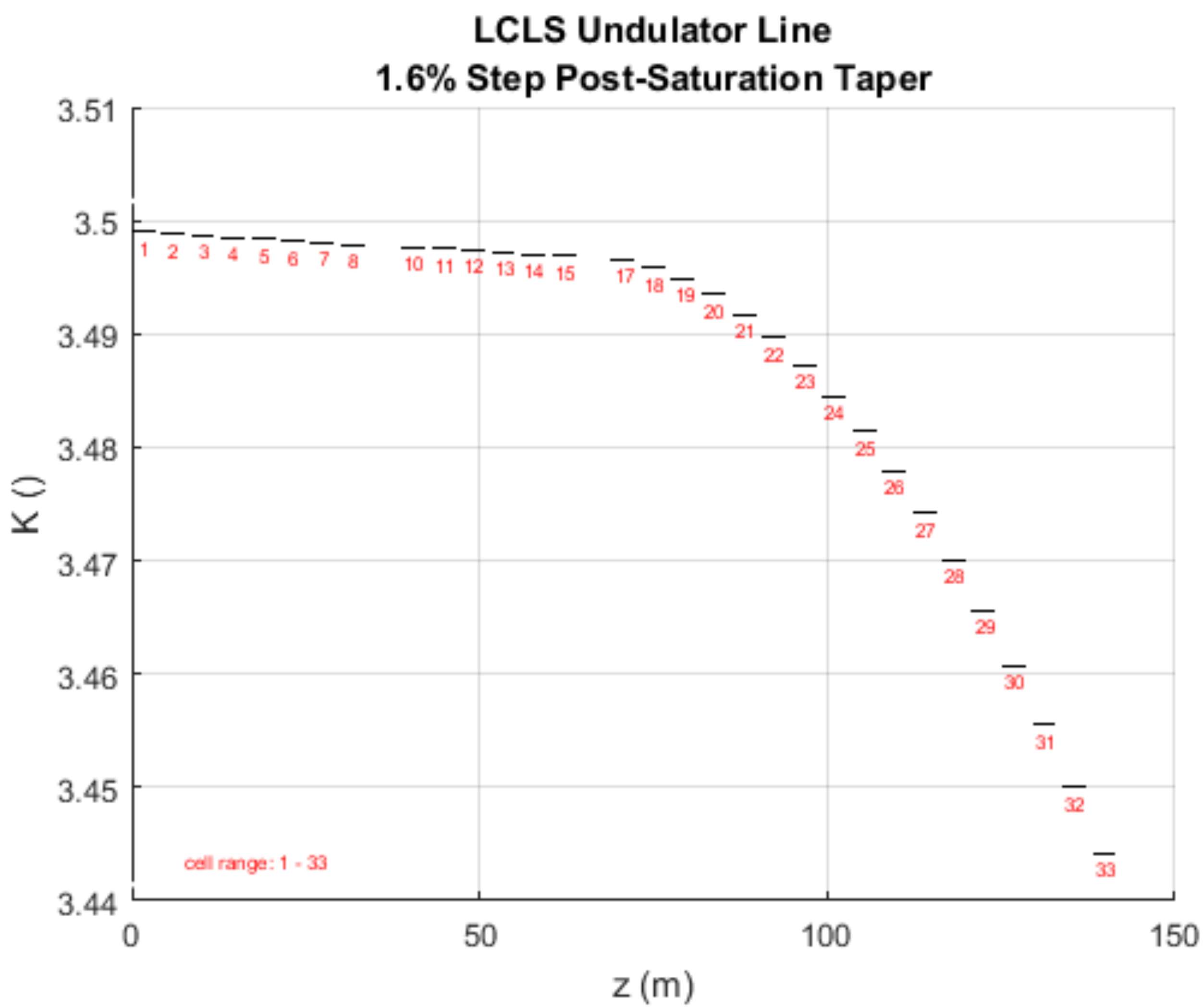


LCLS-II Undulator Dimensions and Ranges

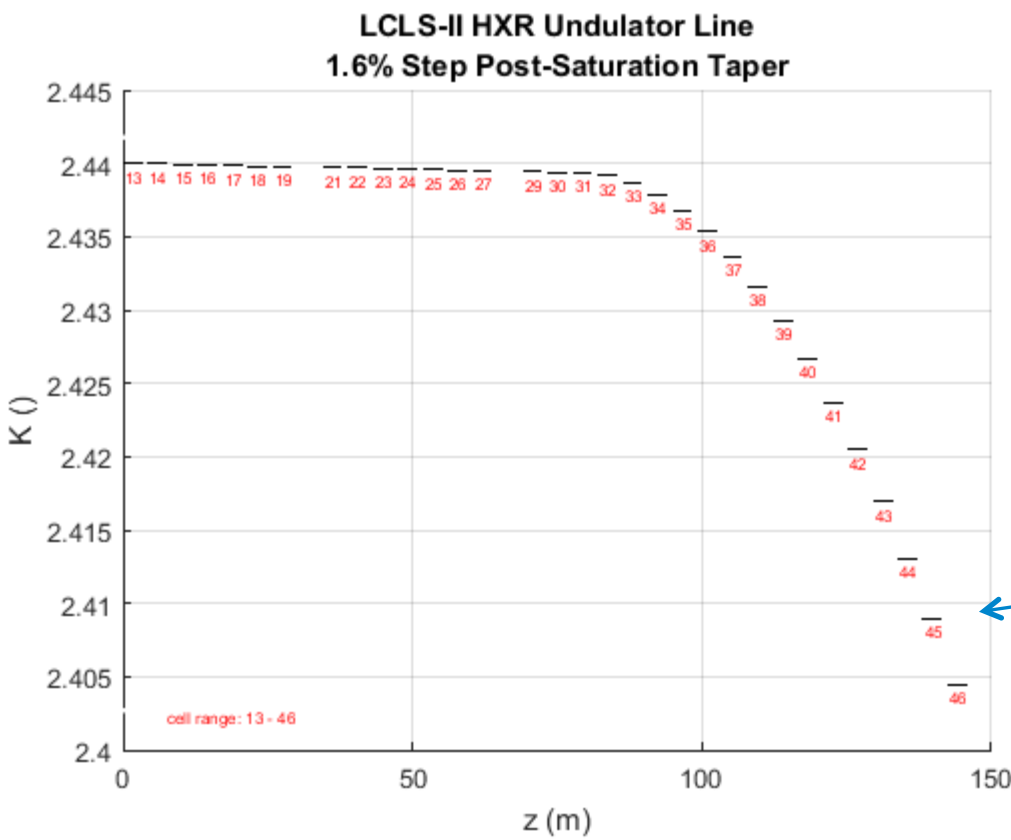
Parameter	SXU / SCRF	SXU / Cu	HXU / SCRF	HXU / Cu	Unit
Undulator period length	39		26		mm
Total segment length	3.4		3.4		m
Number of periods per strong back	87		130		
X-ray energy range, required*	0.2 – 1.3	0.2 – 10	1.0 – 5.0	1 – 25	keV
Undulator operational gap range	7.2 – 20	7.2 – 20	7.2 – 18	7.2 – 19	mm
Undulator parameter range, K	5.5 – 1.5	5.5 – 1.5	2.4 – 0.57	2.4 – 0.54	
Electron energy range, operational	3.6 – 4.0	2.5 – 9	3.3 – 4.0	2.5 – 15	GeV
Maximum gap taper	300		300		µm

*at 4.0 GeV, the lower limit is 0.25 and 1.5 keV, respectively

LCLS Step Taper Only



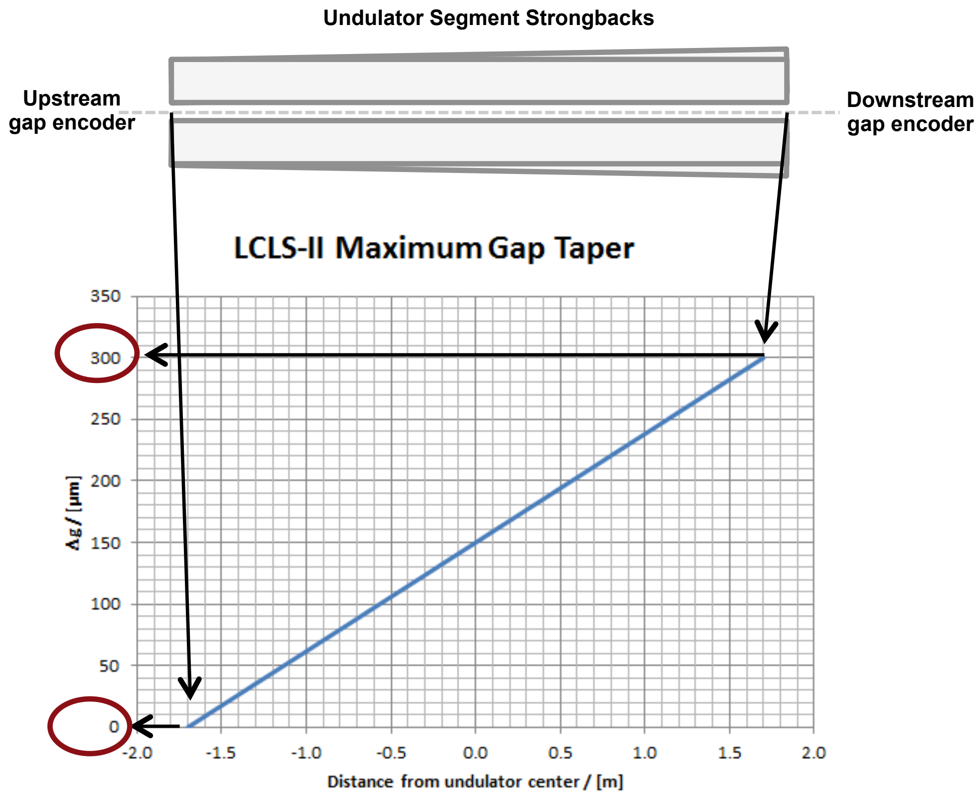
LCLS-II Allows Continuous Taper



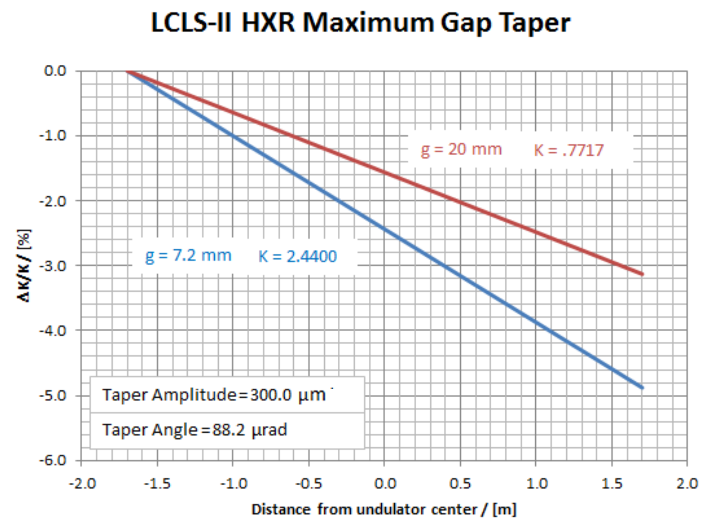
Gap Encoder Difference [um]
(Downstream – Upstream)

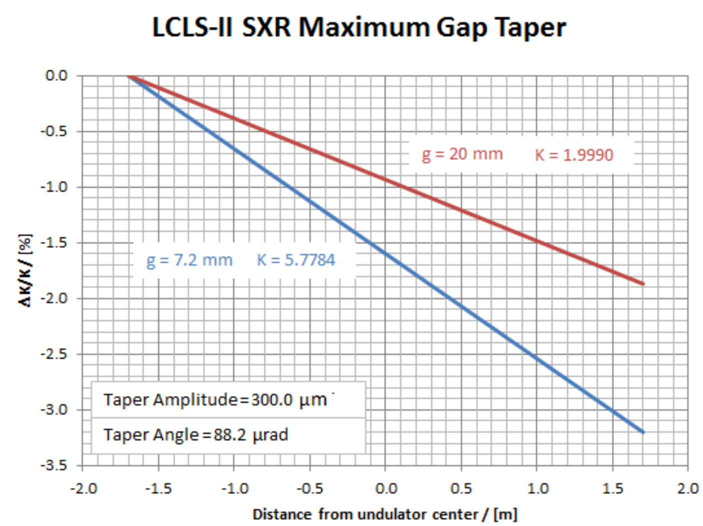
LCLS-II Undulator Segment

300 µm taper over 3.4-m segment length (~88 µrad)

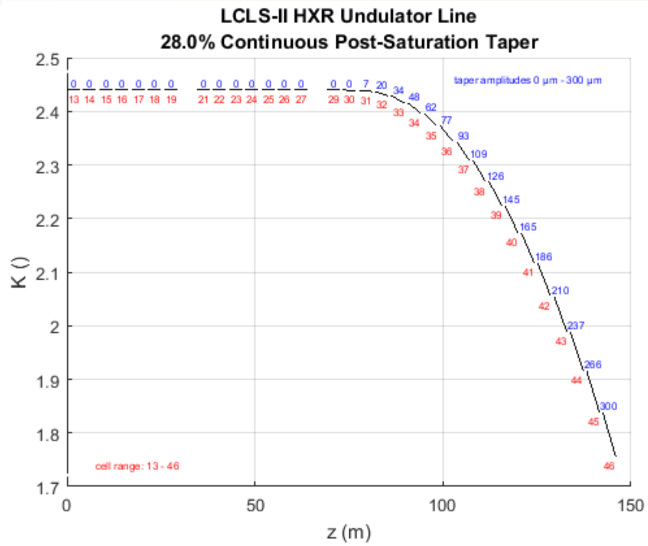


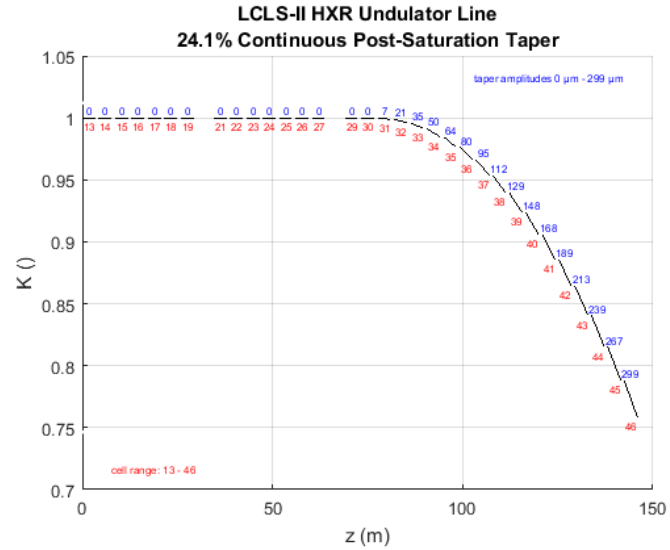
$$\Delta K/K \approx -(5.08 - 3.08\, g/\lambda_u)\, \Delta g/\lambda_u$$

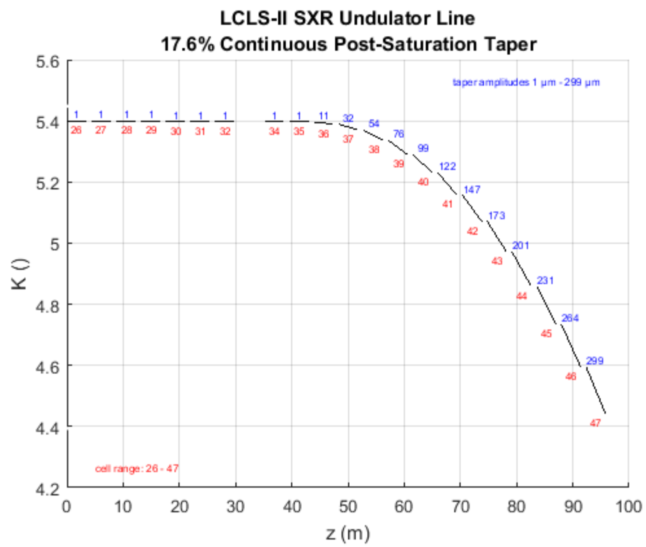


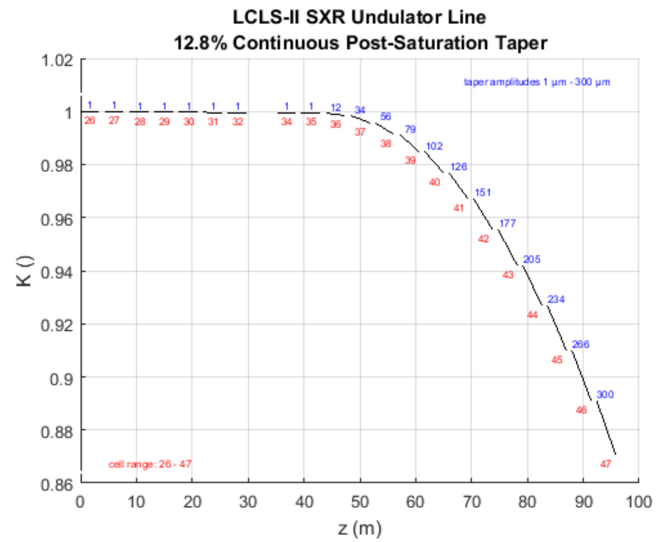


Large Taper Ranges at LCLS-II





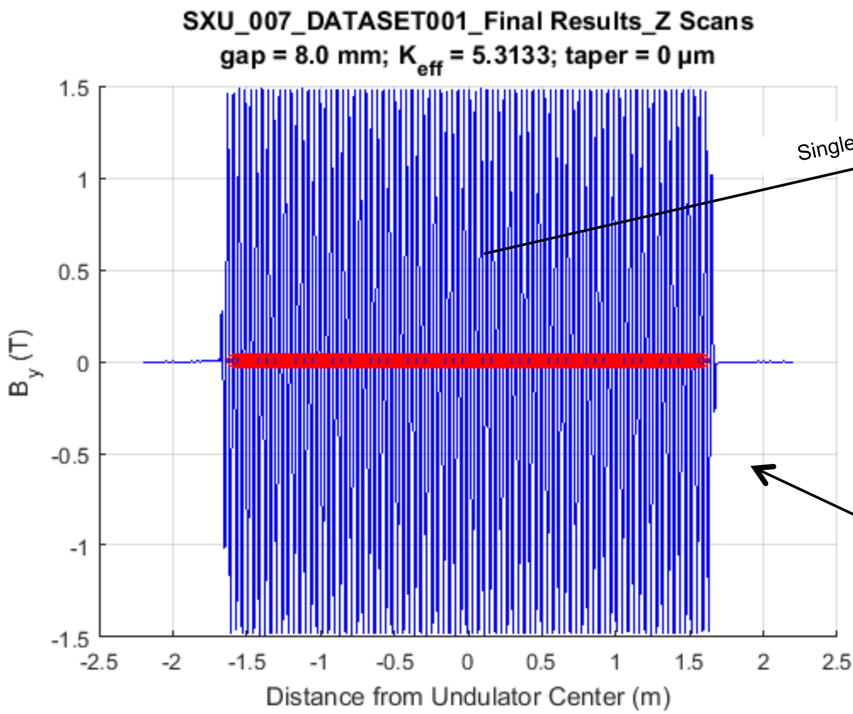


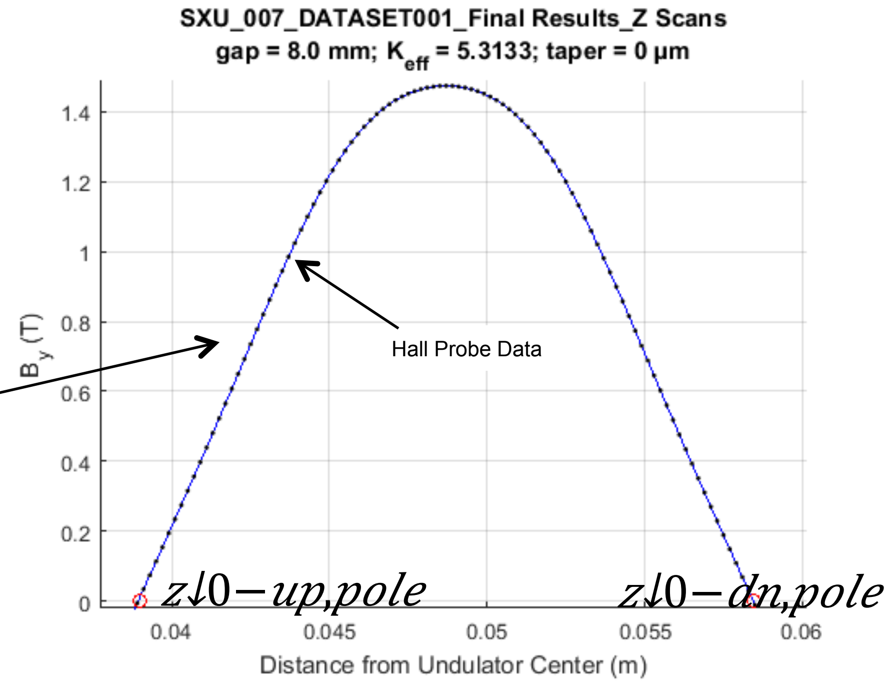


SXU-007 Field Measurements: (1) Untapered

$\langle K_{pole} \rangle$ = 5.3153±0.0006

K_{eff} = 5.3133±0.0001





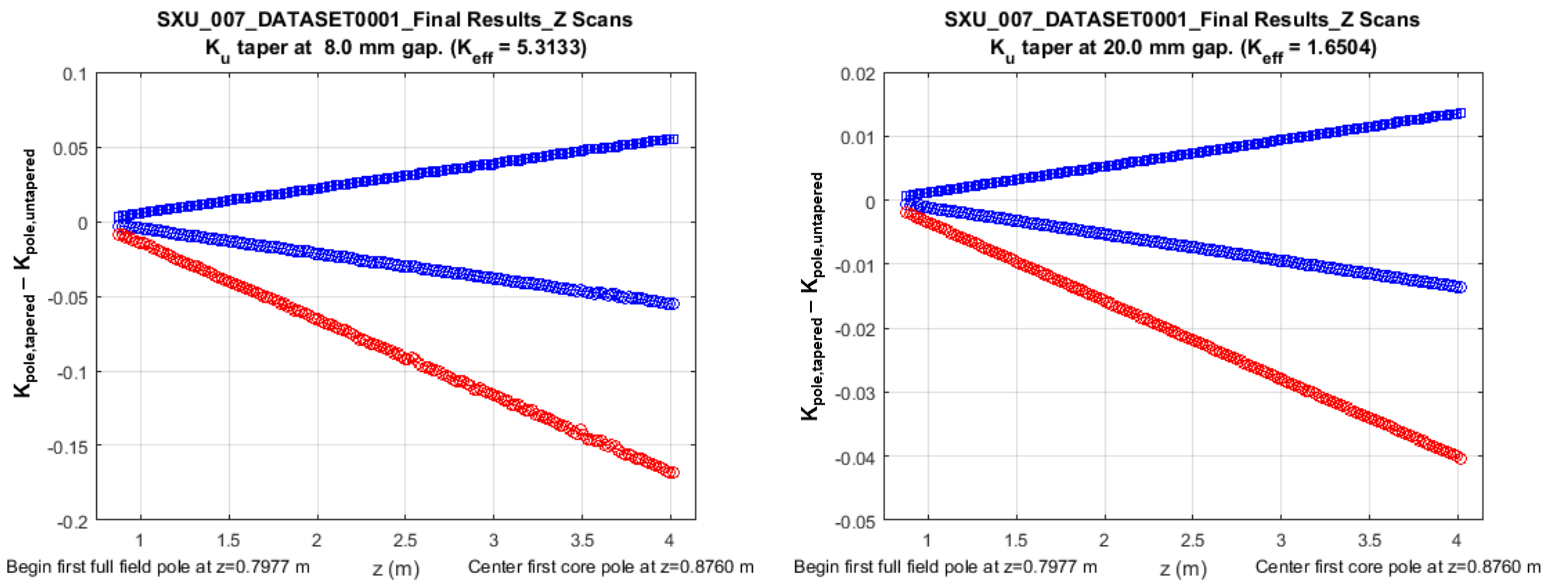
$z_{0-up,pole}$ $z_{0-dn,pole}$

$K_{pole}(z_{pole}) = \Delta z_{pole} / 2\pi \; e/m_e c \, \mathrm{v}$

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

$z_{pole} \approx 1/2 \; (z_{0-dn,pole} + z_{0-}$

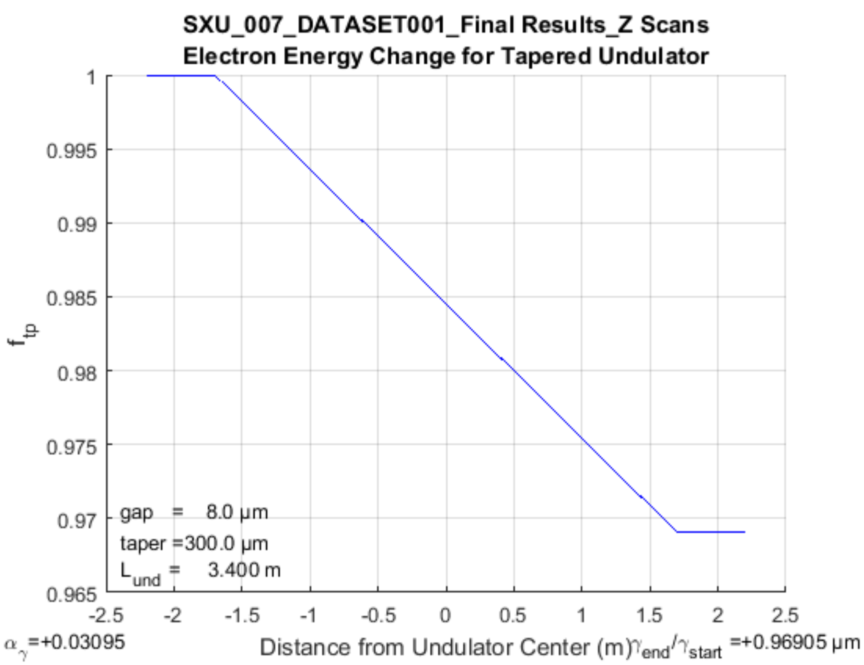
SXU-007 Field Measurements: (2) Tapered



- Measured K_{pole} values for SXU tapers of +100 µm and +300 µm and reversed taper of -100 µm at 8 mm and 20 mm gap.
- Difference between tapered and untapered K_{pole} values is only according to gap change.
  (No distortion at large tapers observed)

Field Evaluations for Tapered Undulators

- Standard calculations of phase shake and total phase assume constant beam energy and can not be applied to tapered undulators.
- Instead assume that taper is necessary because of energy loss along undulator segment, i.e., $\gamma=\gamma(z)=\gamma_{start}\,(1-\alpha$
- A value for α_{γ} can be found that minimizes the change of phase advance per period.



$$\gamma(z)=\gamma_{start}\; f_{tp}(z)$$

$$f_{tp}(z)=\{\, 1 \;\text{for } z<z_{u,start} \;\; 1-\alpha_{\gamma}\,($$

Phase Calculations

- The phase slippage for changing energy along undulator segment is

$$\Delta\varphi_{taper}(z)=\frac{2\pi}{\lambda_u}\left(1+\frac{1}{2}K(g_{start})^2\right)\int_0^z \frac{1}{f_{tp}(z)^2}\,(1+\ldots$$

- The field integrals are calculated as usual

$$I1x(z)=\int_0^z B_x(z)\,dz \qquad I1y(z)=\int_0^z B_y(z)\,dz$$

- The slopes and trajectories are

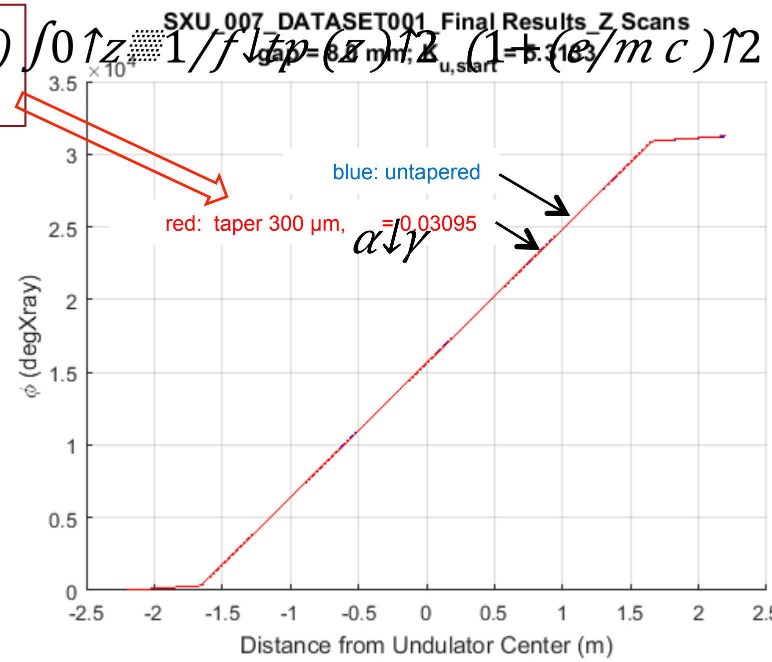
$$\frac{d}{dz}y(z)=-\frac{1}{(B\rho)_{start}}\,I1x(z) \qquad \frac{d}{dz}x(z)=\frac{1}{(B\rho)_{start}}\ldots$$

$$(B\rho)_{start}=\gamma_{start}\,mc/e$$

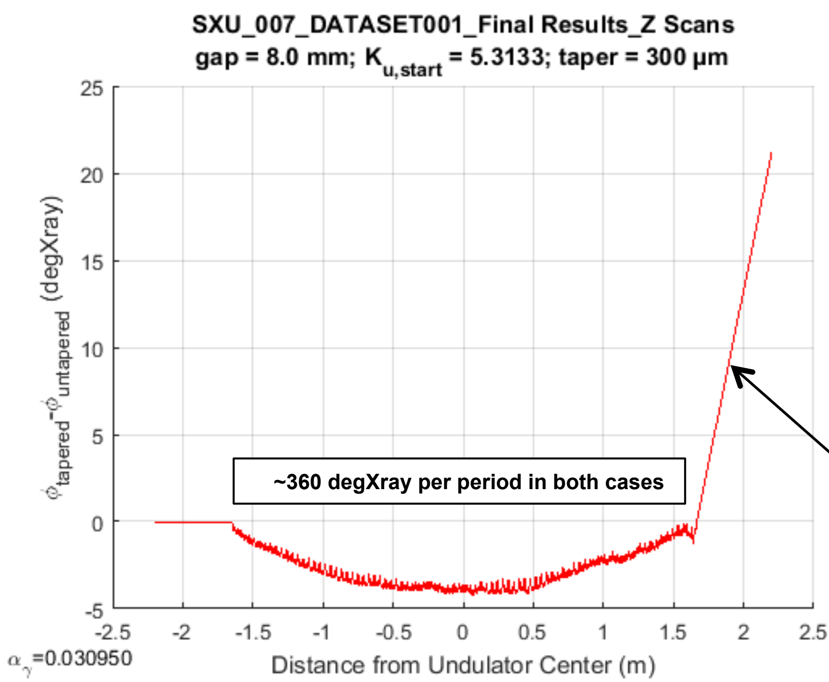
$$y(z)=-\frac{1}{(B\rho)_{start}}\int_0^z I1x(z)\,dz \qquad x(z)=\frac{1}{(B\rho)_{start}}\int_0^z\ldots$$

Phase Measurements

$$\Delta\varphi_{taper}(z) = \frac{2\pi}{\lambda_u\left(1+\frac{1}{2}K(g_{start})^2\right)}\int_0^z \frac{1}{f_{tp}(z)^2}\left(1+\left(\frac{e}{mc}\right)^2 (I1x(z\ldots$$



Difference



During free space travel after undulator, phase advance per unit length is longer for larger regular tapers due to lower electron energies.

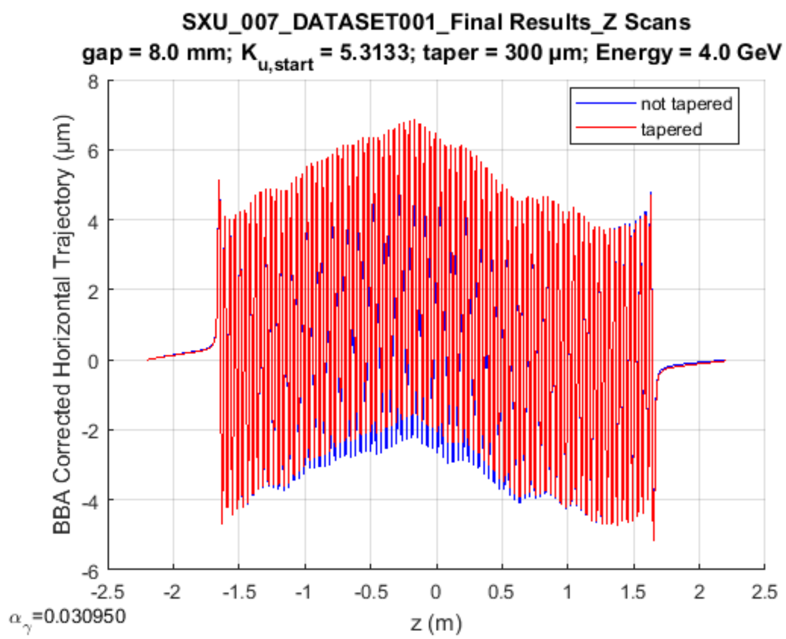
$$\frac{d}{dz}\left(\varphi_{tapered} - \varphi_{untapered}\right) = \frac{360}{\lambda_u\left(1+\frac{1}{2}K(g_{start})^2\right)}\left(1/\ldots\right)$$

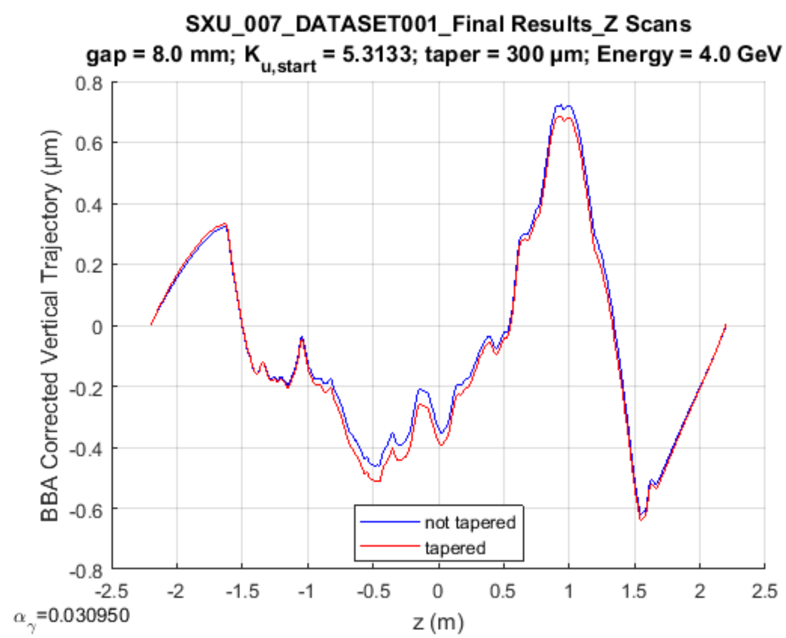
For SXU-007, at 300 μm taper and 8 mm gap

$$\frac{d}{dz}\left(\varphi_{tapered} - \varphi_{untapered}\right) = 38.6 \text{ degXray / m}$$

This will be corrected with a phase shifter.

SXU-007 Trajectories





- BBA corrected horizontal and vertical trajectories for +300 µm SXU taper based on field measurements.
- Only insignificant deviation from untapered trajectories observed.

Summary

- The LCLS-II undulators allow continuous gap tapering
- Limits are ±300 μm over segment length (~±88 μrad)
- SXU taper measurements look promising:
- If adjusted to compensate for energy loss, tapering
  - will mostly change the downstream phase advance
  - will only slightly increase overall phase shake
  - will not significantly steer the electron beam
- HXU (vertically polarizing undulator) taper measurements will follow soon

Thank you for your attention!