Delta Undulator Measurements At SLAC

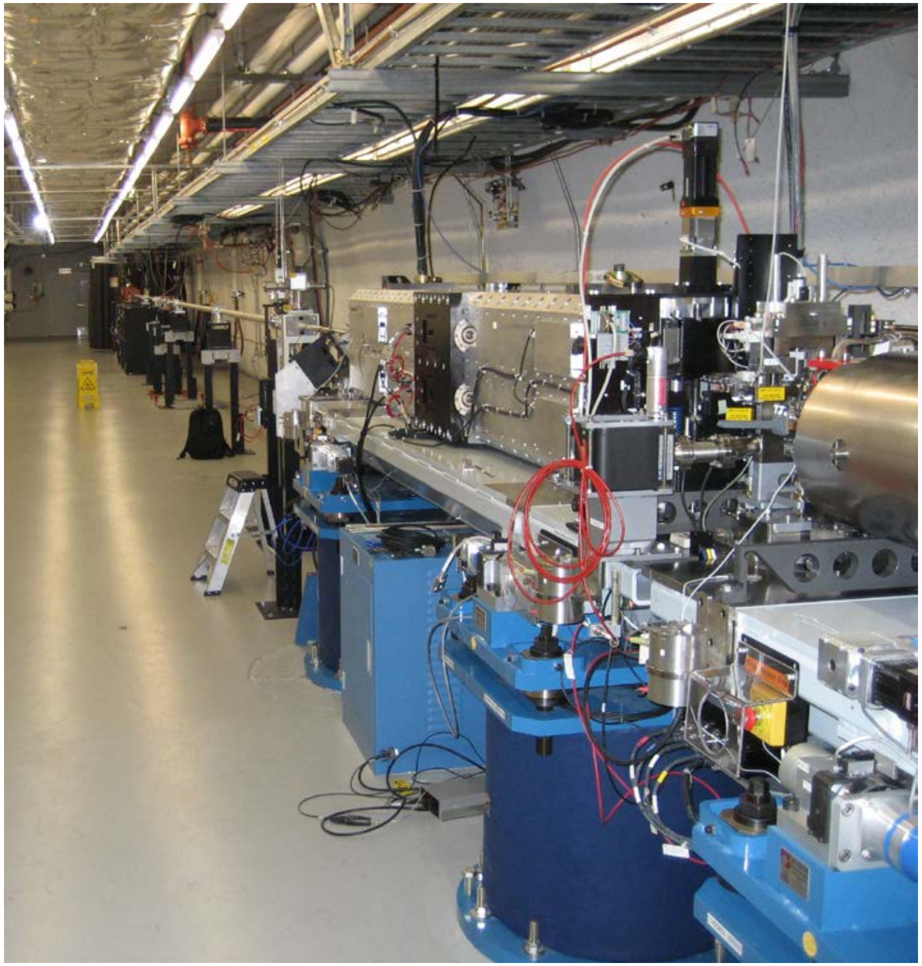
Zachary Wolf
SLAC

IMMW20
June 4-9, 2017

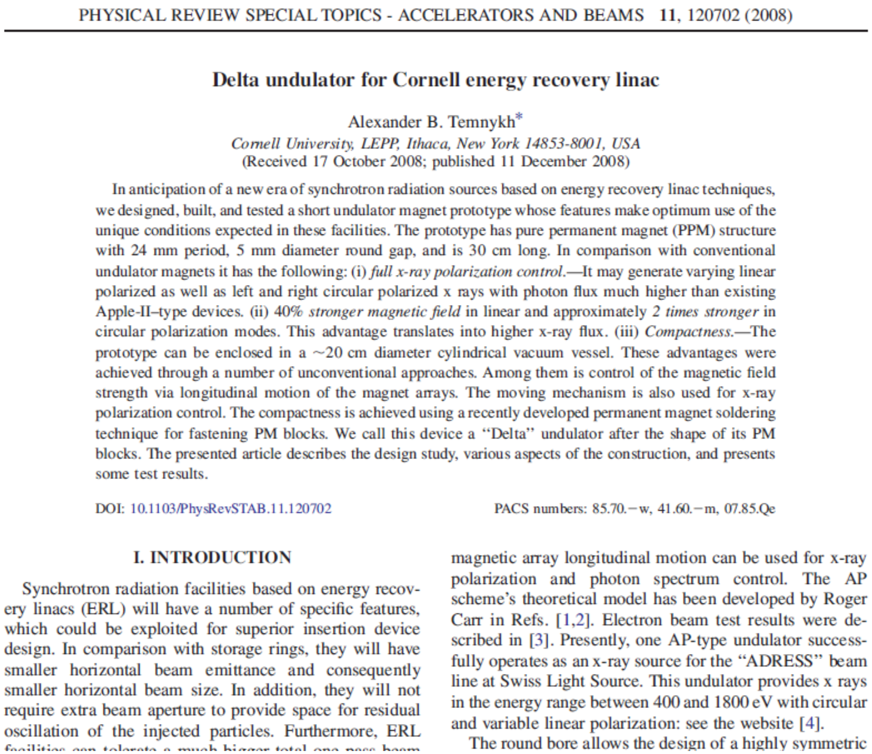
Delta Undulator

Produces elliptically polarized light.

Placed at end of LCLS. Uses the microbunched beam.



Delta Undulator



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 120702 (2008)

Delta undulator for Cornell energy recovery linac

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In anticipation of a new era of synchrotron radiation sources based on energy recovery linac techniques, we designed, built, and tested a short undulator magnet prototype whose features make optimum use of the unique conditions expected in these facilities. The prototype has pure permanent magnet (PPM) structure with 24 mm period, 5 mm diameter round gap, and is 30 cm long. In comparison with conventional undulator magnets it has the following: (i) *full x-ray polarization control.*—It may generate varying linear polarized as well as left and right circular polarized x rays with photon flux much higher than existing Apple-II–type devices. (ii) 40% *stronger magnetic field* in linear and approximately *2 times stronger* in circular polarization modes. This advantage translates into higher x-ray flux. (iii) *Compactness.*—The prototype can be enclosed in a ~20 cm diameter cylindrical vacuum vessel. These advantages were achieved through a number of unconventional approaches. Among them is control of the magnetic field strength via longitudinal motion of the magnet arrays. The moving mechanism is also used for x-ray polarization control. The compactness is achieved using a recently developed permanent magnet soldering technique for fastening PM blocks. We call this device a "Delta" undulator after the shape of its PM blocks. The presented article describes the design study, various aspects of the construction, and presents some test results.

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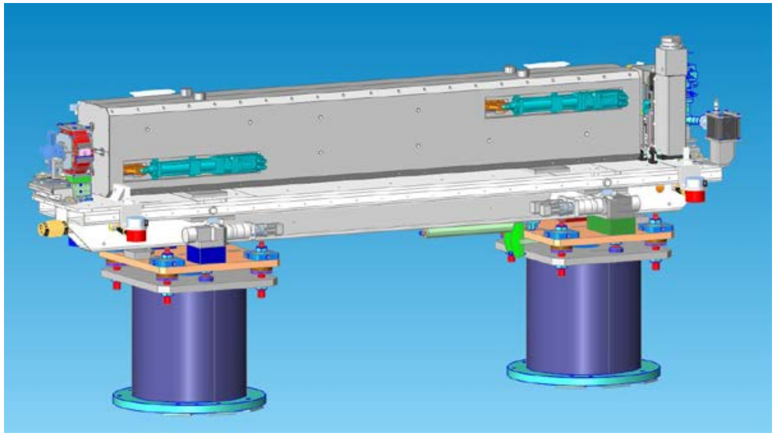
I. INTRODUCTION

Synchrotron radiation facilities based on energy recovery linacs (ERL) will have a number of specific features, which could be exploited for superior insertion device design. In comparison with storage rings, they will have smaller horizontal beam emittance and consequently smaller horizontal beam size. In addition, they will not require extra beam aperture to provide space for residual oscillation of the injected particles. Furthermore, ERL facilities can tolerate a much bigger total one pass beam

magnetic array longitudinal motion can be used for x-ray polarization and photon spectrum control. The AP scheme's theoretical model has been developed by Roger Carr in Refs. [1,2]. Electron beam test results were described in [3]. Presently, one AP-type undulator successfully operates as an x-ray source for the "ADRESS" beam line at Swiss Light Source. This undulator provides x rays in the energy range between 400 and 1800 eV with circular and variable linear polarization: see the website [4].

The round bore allows the design of a highly symmetric

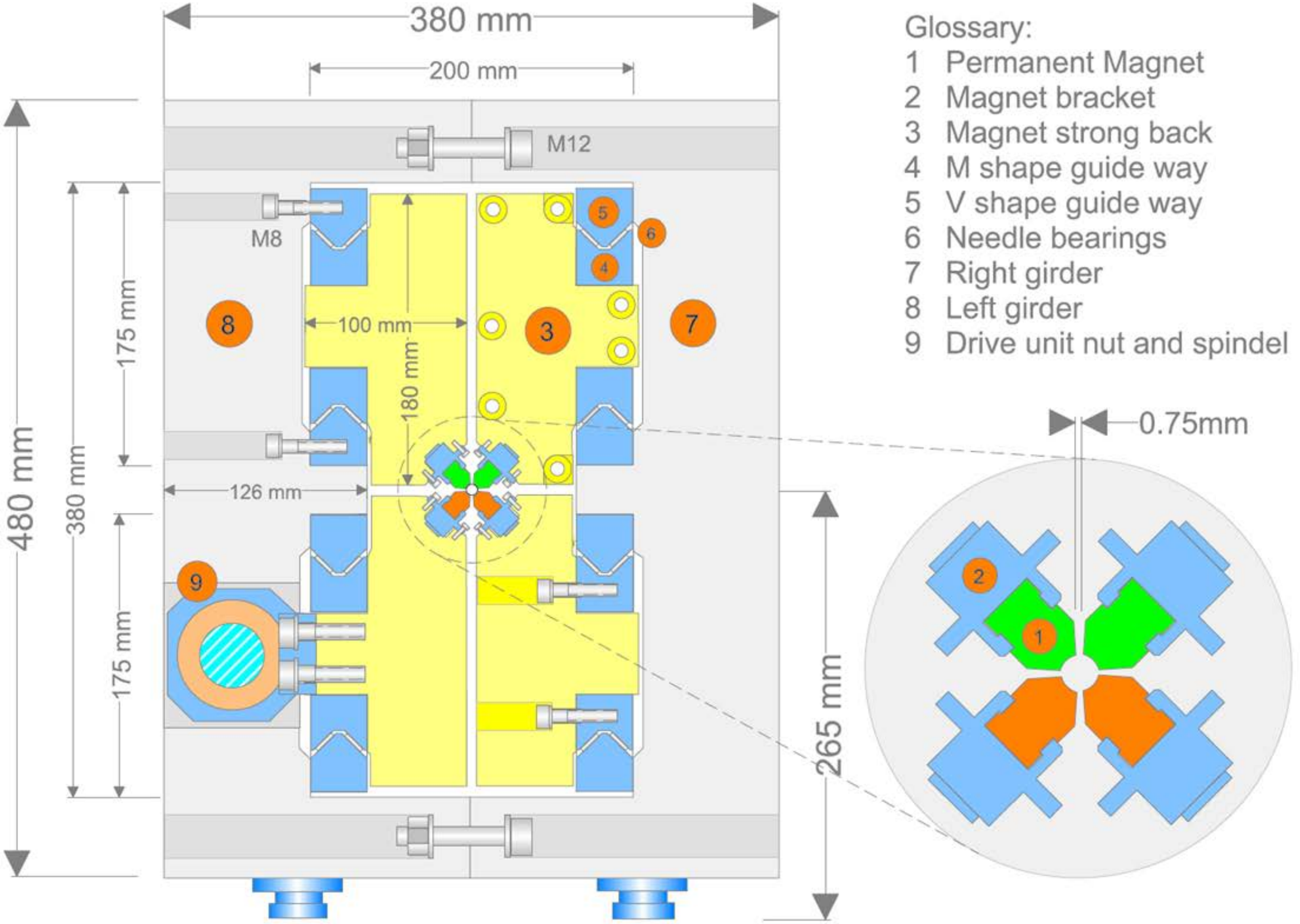


EPU in a package compatible with LCLS

Use same alignment strategy. Undulator and quadrupole on the same girder.

Delta Cross Section

Franz Peters



Glossary:

1 Permanent Magnet
2 Magnet bracket
3 Magnet strong back
4 M shape guide way
5 V shape guide way
6 Needle bearings
7 Right girder
8 Left girder
9 Drive unit nut and spindel

2.2 t magnetic forces due to very small gaps

Delta Undulator

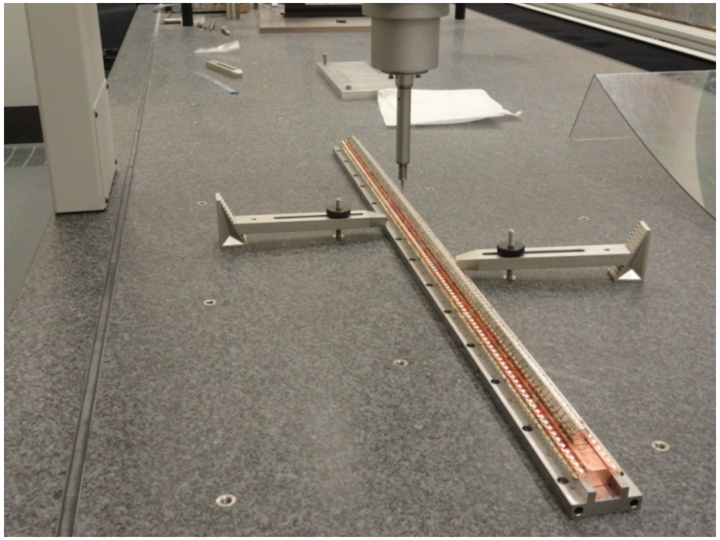
Benefits:

- Very compact source of elliptically polarized light

Costs:

- Can’t tune after assembly
    - Tune quadrants, use superposition
- Very tight assembly tolerances
- Measurements can only be done from the ends in a 6 mm diameter tube
- Difficult to achieve the tolerances to required to make an FEL out of Delta undulators.

Delta Quadrant Assembly And Tuning

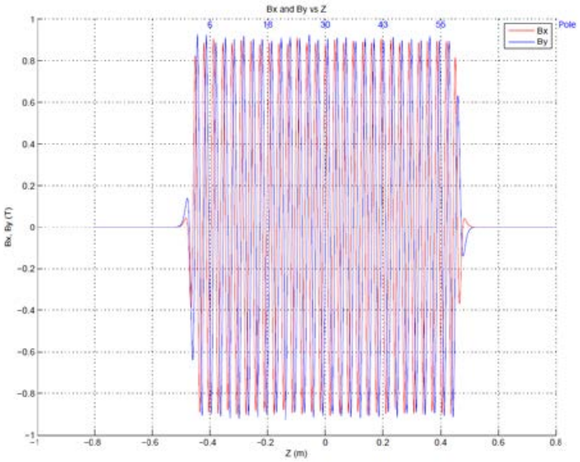


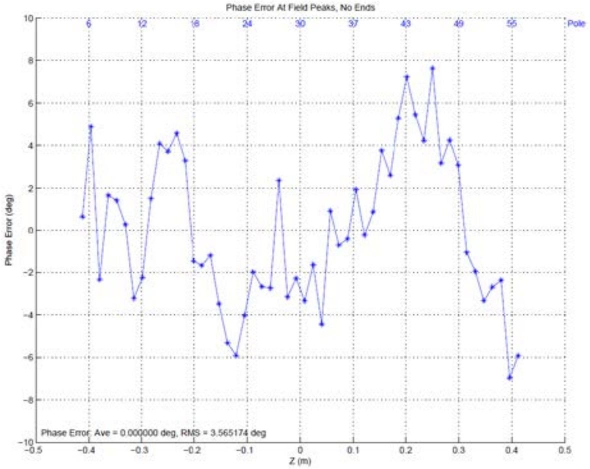
Mechanically align blocks using CMM.

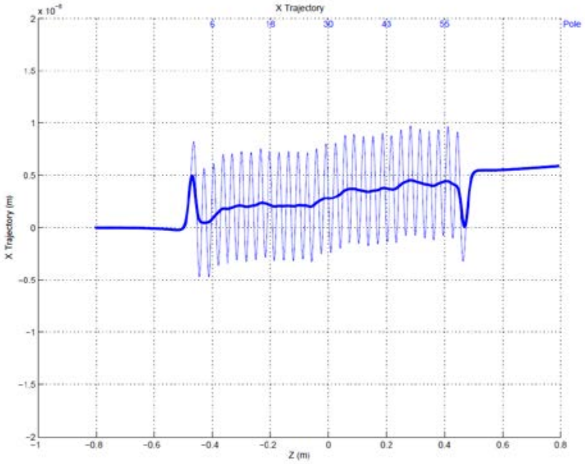
Move blocks using magnetic measurements to straighten trajectories and minimize phase errors.

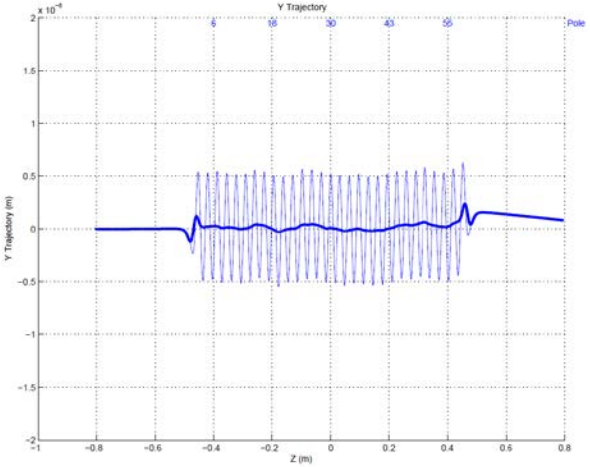
In Software Superpose Quadrant Fields To Simulate Assembled Undulator, Correct If Necessary

Example CP+. Expect undulator within tolerance, but no permeability effects in superposition.



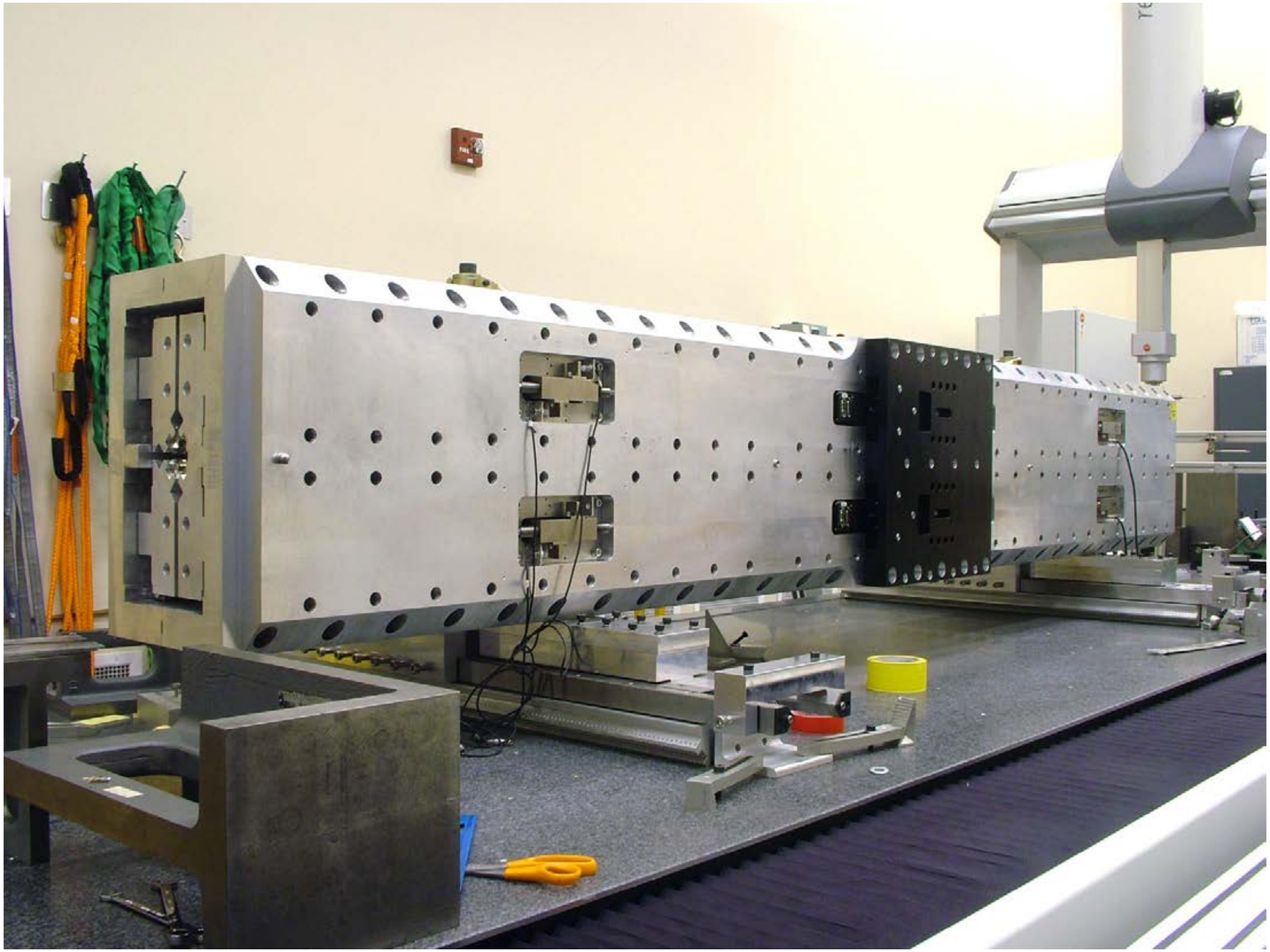




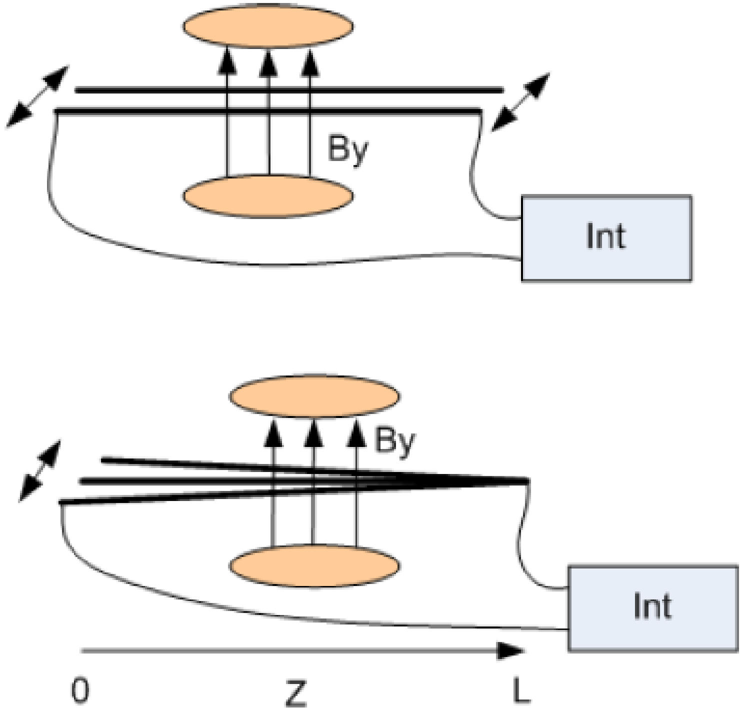


(Prototype)

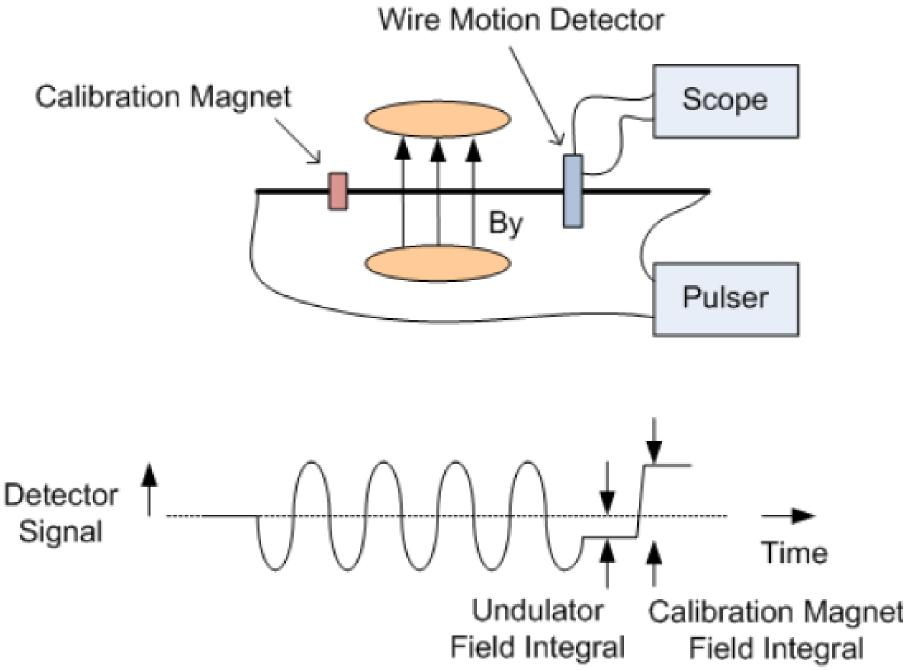
Delta Assembly



Delta Field Integrals

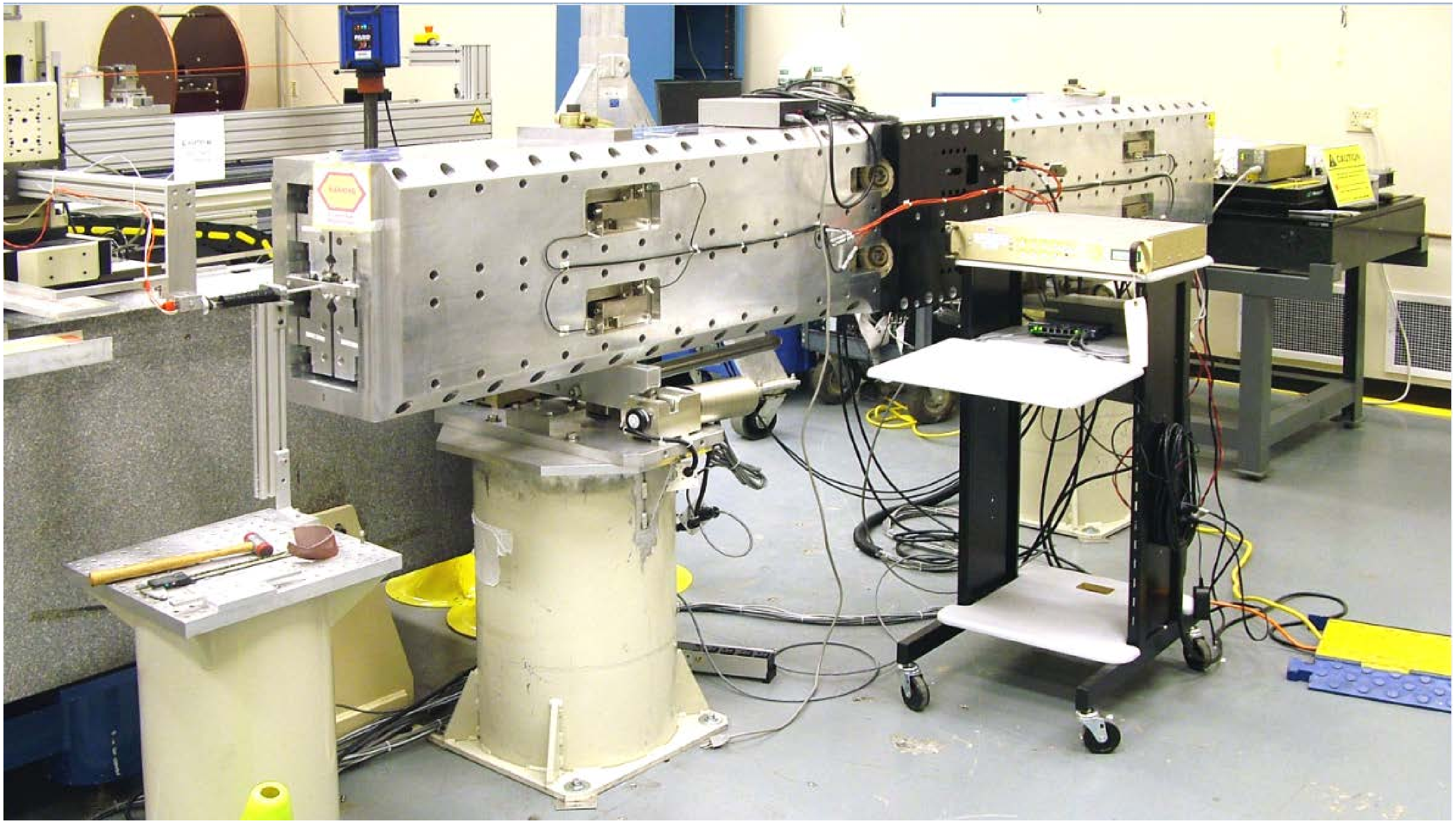


Moving Wire



Pulsed Wire

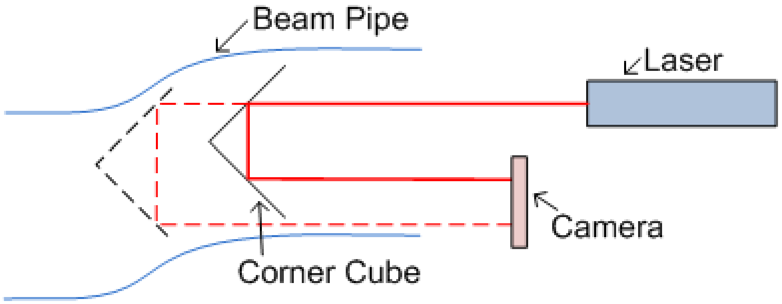
Hall Probe Measurements

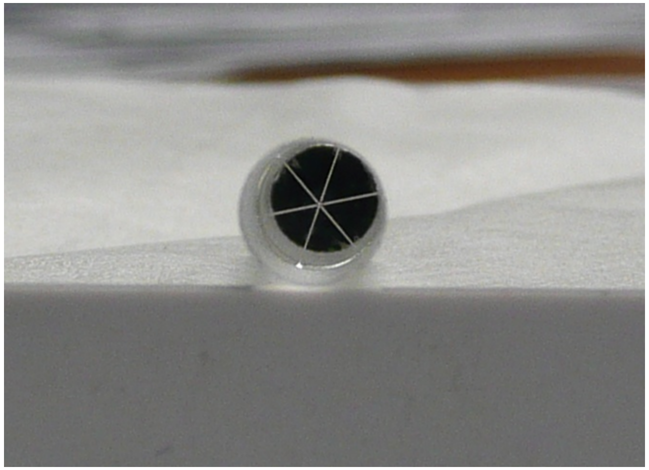


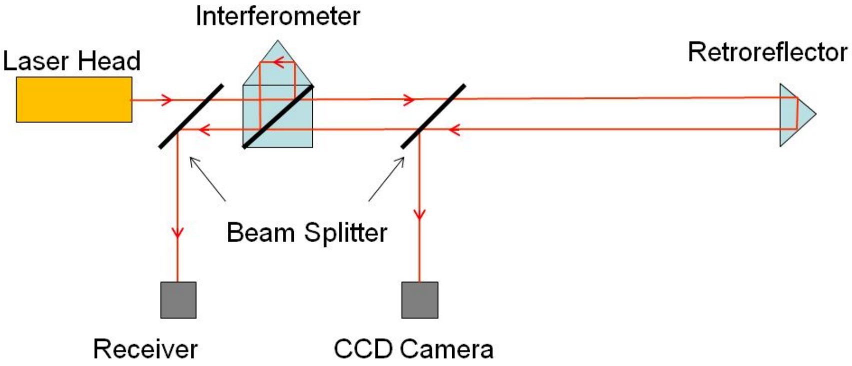
The only access for measurements is through the end of the beam pipe.

Measure Probe Position

Transverse location from corner cube. Longitudinal location from interferometer.



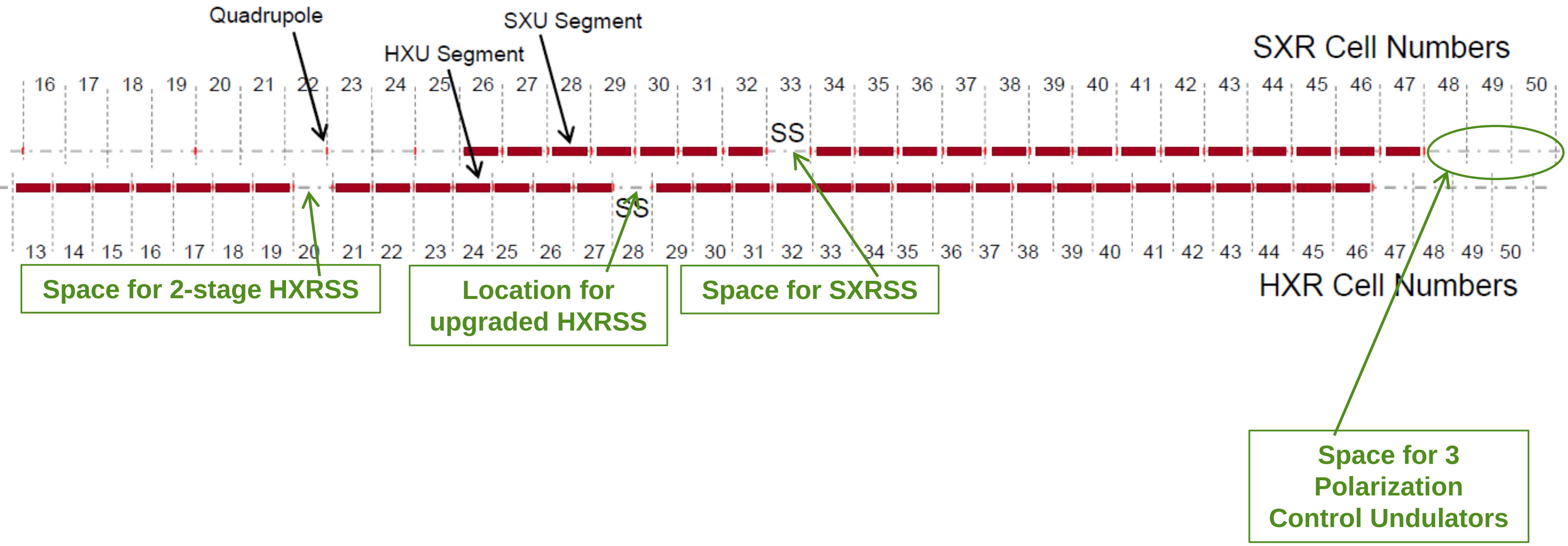




Georg Gassner

New Project

LCLS-II, Delta-II



Space for 2-stage HXRSS

Location for upgraded HXRSS

Space for SXRSS

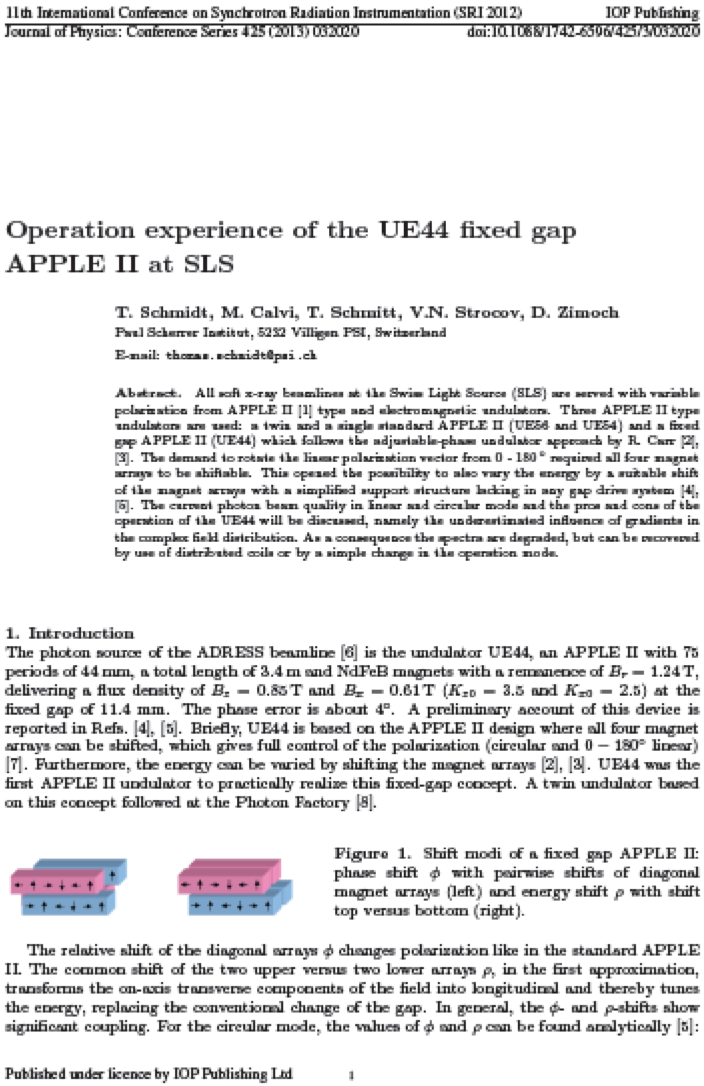
Space for 3 Polarization Control Undulators

Delta-II

- Challenges/Improvements
  - Position dependence of the K value
  - Assembly tolerance to minimize phase errors
  - Measurement/assembly plan on CMM
  - Measurements of assembled undulator

Delta-II K Value Position Dependence

Swiss Light Source



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Operation experience of the UE44 fixed gap APPLE II at SLS

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Abstract. All soft x-ray beamlines at the Swiss Light Source (SLS) are served with variable polarization from APPLE II [1] type and electromagnetic undulators. Three APPLE II type undulators are used: a twin and a single standard APPLE II (UE56 and UE54) and a fixed gap APPLE II (UE44) which follows the adjustable-phase undulator approach by R. Carr [2], [3]. The demand to rotate the linear polarization vector from 0 - 180 ° required all four magnet arrays to be shiftable. This opened the possibility to also vary the energy by a suitable shift of the magnet arrays with a simplified support structure lacking in any gap drive system [4], [5]. The current photon beam quality in linear and circular mode and the pros and cons of the operation of the UE44 will be discussed, namely the underestimated influence of gradients in the complex field distribution. As a consequence the spectra are degraded, but can be recovered by use of distributed coils or by a simple change in the operation mode.

1. Introduction

The photon source of the ADRESS beamline [6] is the undulator UE44, an APPLE II with 75 periods of 44 mm, a total length of 3.4 m and NdFeB magnets with a remanence of $B_r = 1.24$ T, delivering a flux density of $B_z = 0.85$ T and $B_x = 0.61$ T ($K_{z0} = 3.5$ and $K_{x0} = 2.5$) at the fixed gap of 11.4 mm. The phase error is about 4°. A preliminary account of this device is reported in Refs. [4], [5]. Briefly, UE44 is based on the APPLE II design where all four magnet arrays can be shifted, which gives full control of the polarization (circular and $0 - 180°$ linear) [7]. Furthermore, the energy can be varied by shifting the magnet arrays [2], [3]. UE44 was the first APPLE II undulator to practically realize this fixed-gap concept. A twin undulator based on this concept followed at the Photon Factory [8].

Figure 1. Shift modi of a fixed gap APPLE II: phase shift ϕ with pairwise shifts of diagonal magnet arrays (left) and energy shift ρ with shift top versus bottom (right).

The relative shift of the diagonal arrays ϕ changes polarization like in the standard APPLE II. The common shift of the two upper versus two lower arrays ρ, in the first approximation, transforms the on-axis transverse components of the field into longitudinal and thereby tunes the energy, replacing the conventional change of the gap. In general, the ϕ- and ρ-shifts show significant coupling. For the circular mode, the values of ϕ and ρ can be found analytically [5]:

1

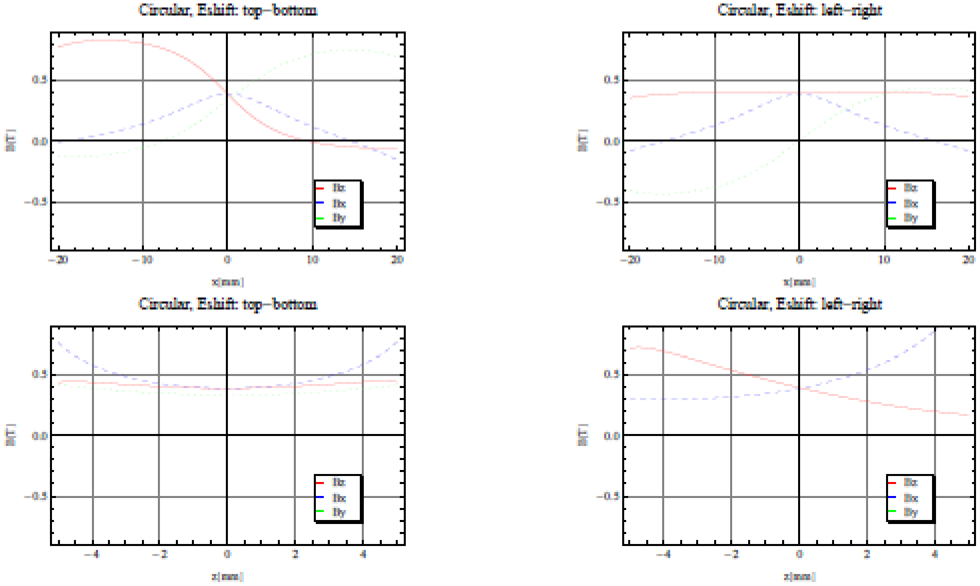


Figure 5. Field distribution for the circular mode in top-bottom (left) and left-right (right) energy shift setup. The gradient of the vertical field inl x-direction (horizontal) broadens the spectrum. The gradient in z-direction (vertical) is harmless because of the small vertical beam size.

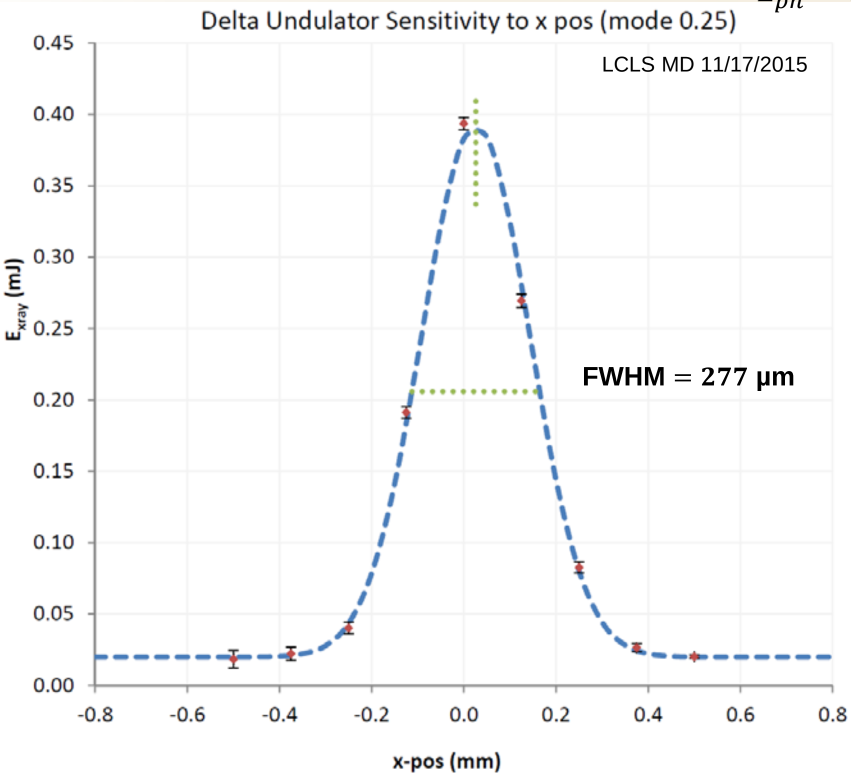
Delta: Horizontal and Vertical Position Sensitivity

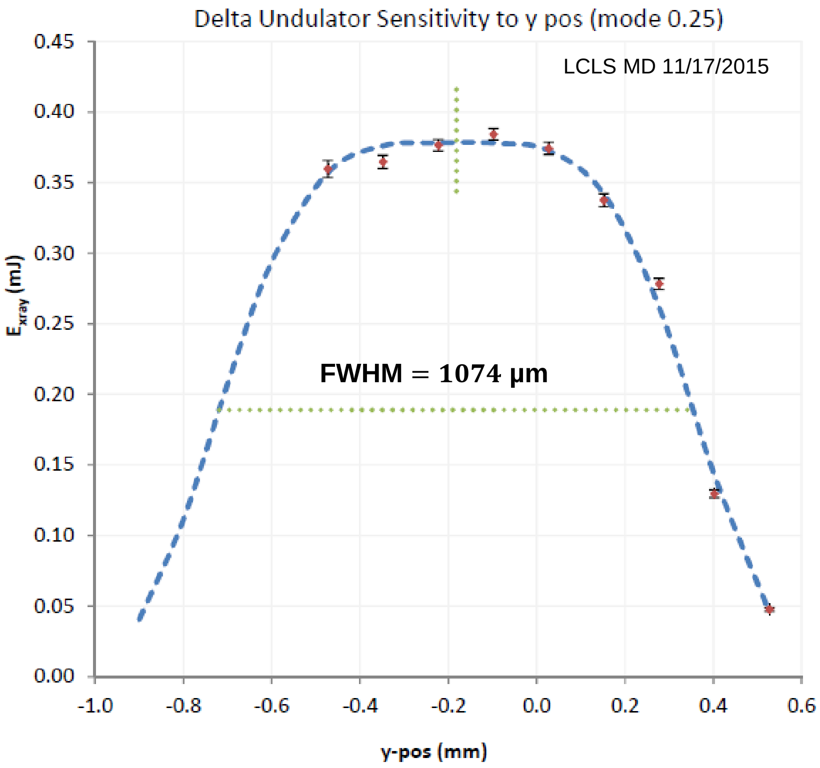
LCLS MD 11/17/2015

Heinz-Dieter Nuhn

$K_{\mathrm{Delta},res} / K_{\mathrm{Delta},max} = 0.942$

$E_{ph} = 530$ eV





$$E_{xray} = E_{xray,0}\, e^{-\frac{\left(\left.\frac{\partial K_{\mathrm{Delta}}}{\partial x}\right|_{x=y=0}(x-x_{res})\right)^2}{2\,\sigma_K^{\,2}}} + E_{xray,bg}$$

$\left.\frac{\partial K_{\mathrm{Delta}}}{\partial x}\right|_{x=y=0} = 8.05 \times 10^{-5}$ /µm

$x_{res} = 26$ µm

$E_{xray,0} = 0.372$ mJ

$E_{xray,bg} = 0.020$ mJ

$K_{res} = 3.372$

$\sigma_K = 0.00946$

$$E_{xray} = E_{xray,0}\, e^{-\frac{\left(K_{res}\ \cosh\left(k_y\,(y-y_{res})\right)-K_{res}\right)^2}{2\,\sigma_K^{\,2}}} + E_{xray,bg}$$

$k_y = 152$ m^{-1} [compare to 129.0 m^{-1} from model]*

$y_{res} = -181.8$ µm

$E_{xray,0} = 0.378$ mJ

$K_{res} = 3.372$

$\sigma_K = 0.00946$

*Alexander Temnikh, private communication

K Gradients In Delta

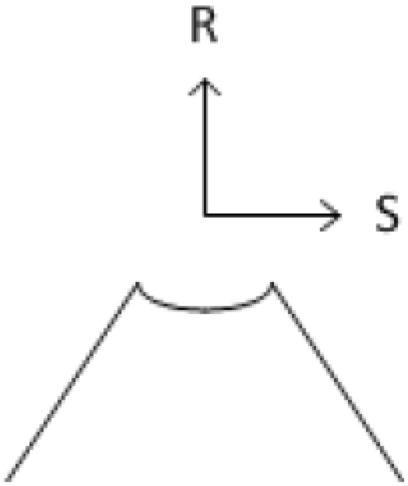
- What causes the asymmetric position dependence of K?
- There is only hyperbolic cosine position dependence in the model of two crossed adjustable phase planar undulators.
- What are the alignment tolerance effects on Delta-II?
- Is there a model to help explain this behavior so that we can make predictions for Delta-II?
- Are there design changes that can minimize this effect?

A Model To Explain The Delta-II K Value Position Dependence

Add field rolloff to the model of two crossed, planar, adjustable phase undulators.

Model to explain the position dependence of K

LCLS-TN-16-1



For one quadrant

$$\phi = \phi_0 \cos(k_s s) \exp\left(-k_r r\right) \cos\left(k_u \left(z - z_0\right)\right)$$

$$-k_s^2 + k_r^2 - k_u^2 = 0$$

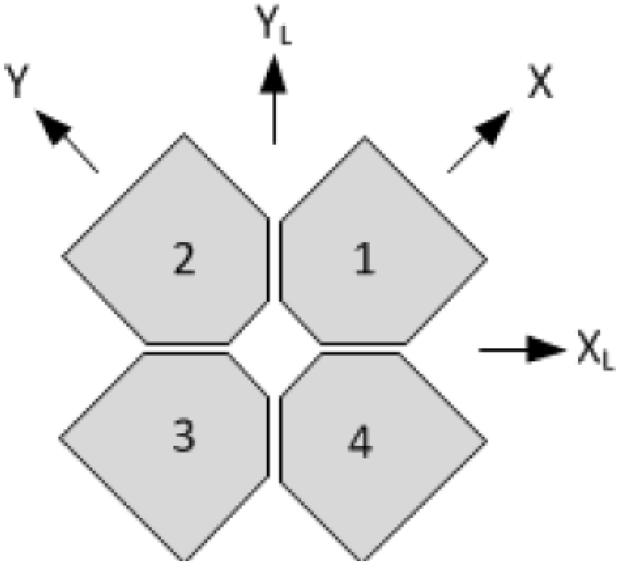
Delta Measurements:
k_u = 196 1/m
k_r = 270 1/m
k_s = 186 1/m

Potential decreases exponentially away from the quadrant, decreases away from the center line, varies sinusoidally in z, obeys Laplace’s equation.

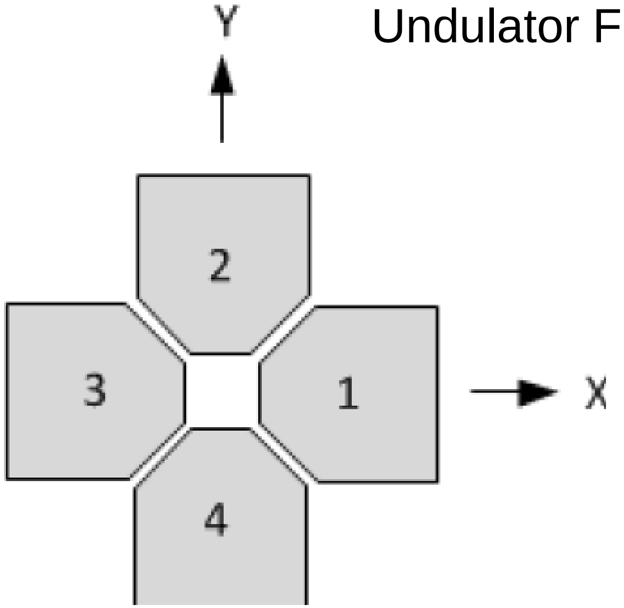
This potential can be considered the dominant term in a Fourier expansion.

Delta-II K Value Position Dependence

Lab Frame



Undulator Frame



Potential for each quadrant:

$$\begin{aligned}
\phi_1(x,y,z) &= \phi_{0Q}\cos(k_s y)\exp\left(k_r x\right)\cos\left(k_u\left(z-z_{01}\right)\right)\\
\phi_2(x,y,z) &= \phi_{0Q}\cos(k_s x)\exp\left(k_r y\right)\cos\left(k_u\left(z-z_{02}\right)\right)\\
\phi_3(x,y,z) &= -\phi_{0Q}\cos(k_s y)\exp\left(-k_r x\right)\cos\left(k_u\left(z-z_{03}\right)\right)\\
\phi_4(x,y,z) &= -\phi_{0Q}\cos(k_s x)\exp\left(-k_r y\right)\cos\left(k_u\left(z-z_{04}\right)\right)
\end{aligned}$$

Do calculations in the undulator frame.

Delta-II K Value Position Dependence

Combine quadrants 1 and 3, also 2 and 4. Two crossed adjustable phase undulators.

$$\begin{aligned} z_{01} &= Z_{13} + \frac{\Delta_{13}}{2} \\ z_{03} &= Z_{13} - \frac{\Delta_{13}}{2} \end{aligned} \qquad \begin{aligned} z_{02} &= Z_{24} + \frac{\Delta_{24}}{2} \\ z_{04} &= Z_{24} - \frac{\Delta_{24}}{2} \end{aligned}$$

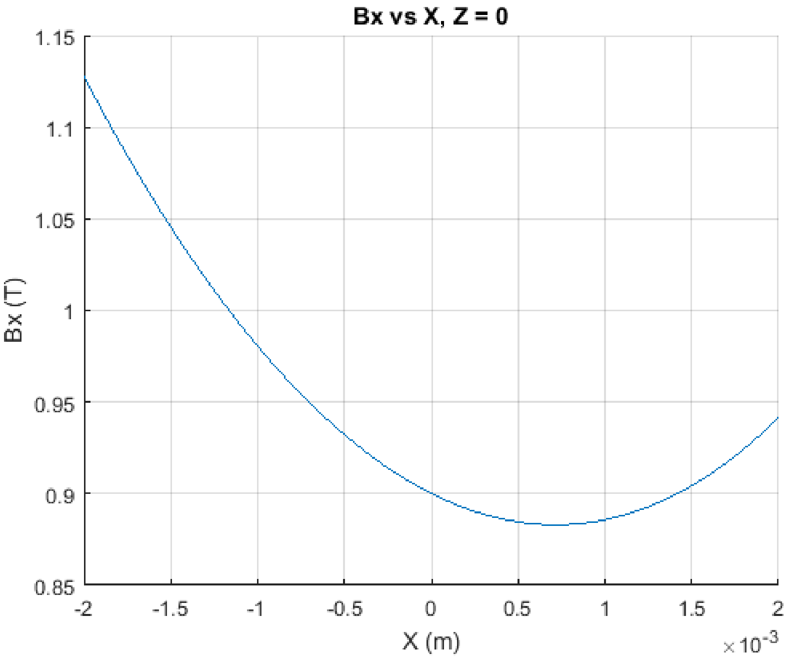
$$Z_{13} = \frac{z_{01} + z_{03}}{2} \qquad Z_{24} = \frac{z_{02} + z_{04}}{2}$$

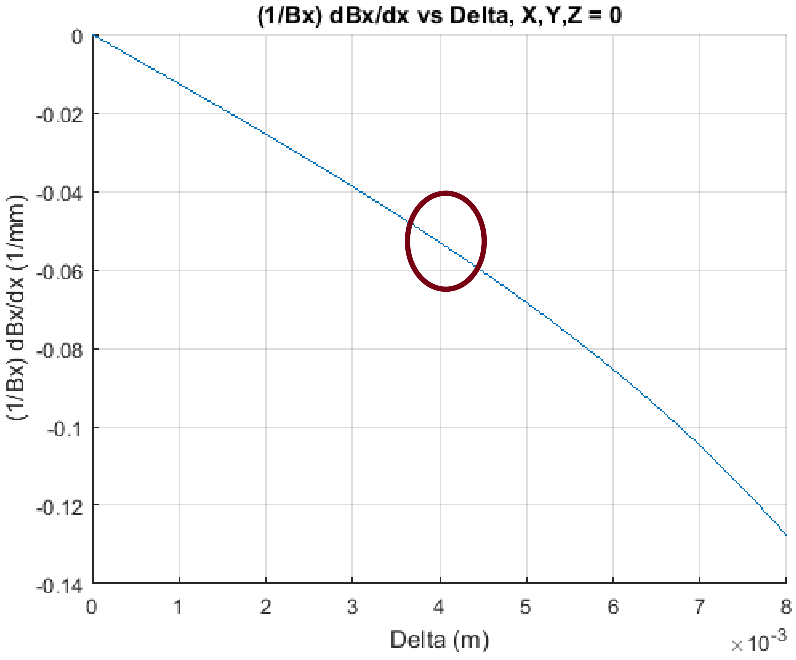
$$\Delta_{13} = z_{01} - z_{03} \qquad \Delta_{24} = z_{02} - z_{04}$$

$$\begin{aligned} \phi_{13} &= 2\phi_{0Q} \cos(k_s y) \sinh(k_r x) \cos\left(k_u \frac{\Delta_{13}}{2}\right) \cos\left(k_u \left(z - Z_{13}\right)\right) \\ &\quad + 2\phi_{0Q} \cos(k_s y) \cosh(k_r x) \sin\left(k_u \frac{\Delta_{13}}{2}\right) \sin\left(k_u \left(z - Z_{13}\right)\right) \end{aligned}$$

$$\begin{aligned} \phi_{24} &= 2\phi_{0Q} \cos(k_s x) \sinh(k_r y) \cos\left(k_u \frac{\Delta_{24}}{2}\right) \cos\left(k_u \left(z - Z_{24}\right)\right) \\ &\quad + 2\phi_{0Q} \cos(k_s x) \cosh(k_r y) \sin\left(k_u \frac{\Delta_{24}}{2}\right) \sin\left(k_u \left(z - Z_{24}\right)\right) \end{aligned}$$

Example Position Dependence Of Fields





Circular mode
Krel = 0.9

Bx changes 5% per mm.

Delta-II K Value Position Dependence

LCLS-TN-16-1

Undulator frame.

Linear mode

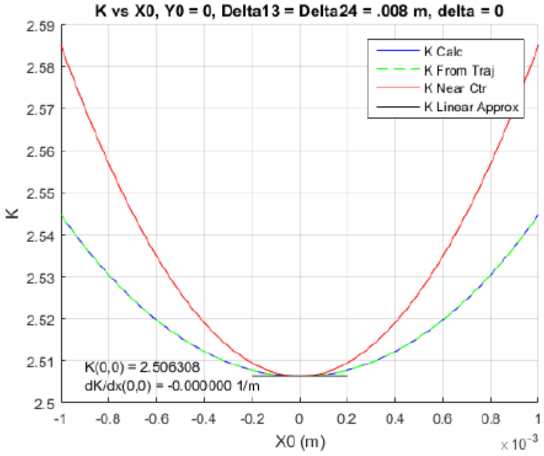

K vs X0, Y0 = 0, Delta13 = Delta24 = .008 m, delta = 0

Figure 3: This figure shows how K varies with x_0 when $y_0 = 0$ in linear polarization vertical magnetic field mode.

Approximate K near center

Full formula for K

Circular mode

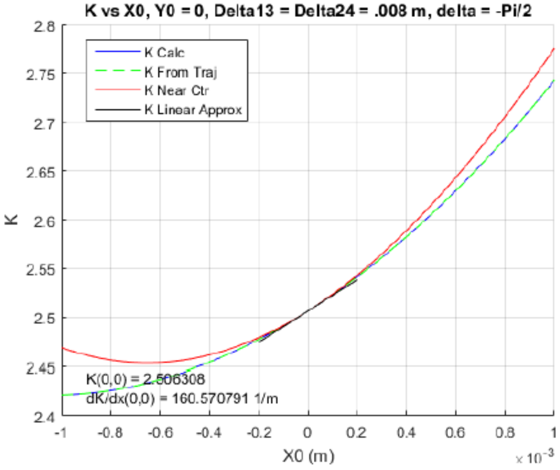

K vs X0, Y0 = 0, Delta13 = Delta24 = .008 m, delta = -Pi/2

Figure 7: This figure shows how K varies with x_0 when $y_0 = 0$ in circular polarization right hand magnetic field mode.

In the linear modes K vs x does not have a slope at the beam axis. In the circular modes, however, K vs x does have a slope at the beam axis.

This can make setting several undulators to the same K value almost impossible using calibration and alignment techniques.

Delta-II K Value Position Dependence

Going to the laboratory frame and setting the relative shifts of the two variable phase undulators to be the same, the formula simplifies. There is a gradient in x, but not in y.

In the primary modes, $\Delta_{13} = \Delta_{24} = \Delta$. In this case

$$\frac{\partial K}{\partial x_{0L}} = -\frac{K_0}{k_u} k_s^2 \sin\left(k_u \frac{\Delta}{2}\right) \sin(\delta)$$

$$\frac{\partial K}{\partial y_{0L}} = 0$$

$$\Delta_{13} = z_{01} - z_{03} \qquad \Delta_{24} = z_{02} - z_{04}$$

$$Z_{13} = \frac{z_{01} + z_{03}}{2} \qquad Z_{24} = \frac{z_{02} + z_{04}}{2}$$

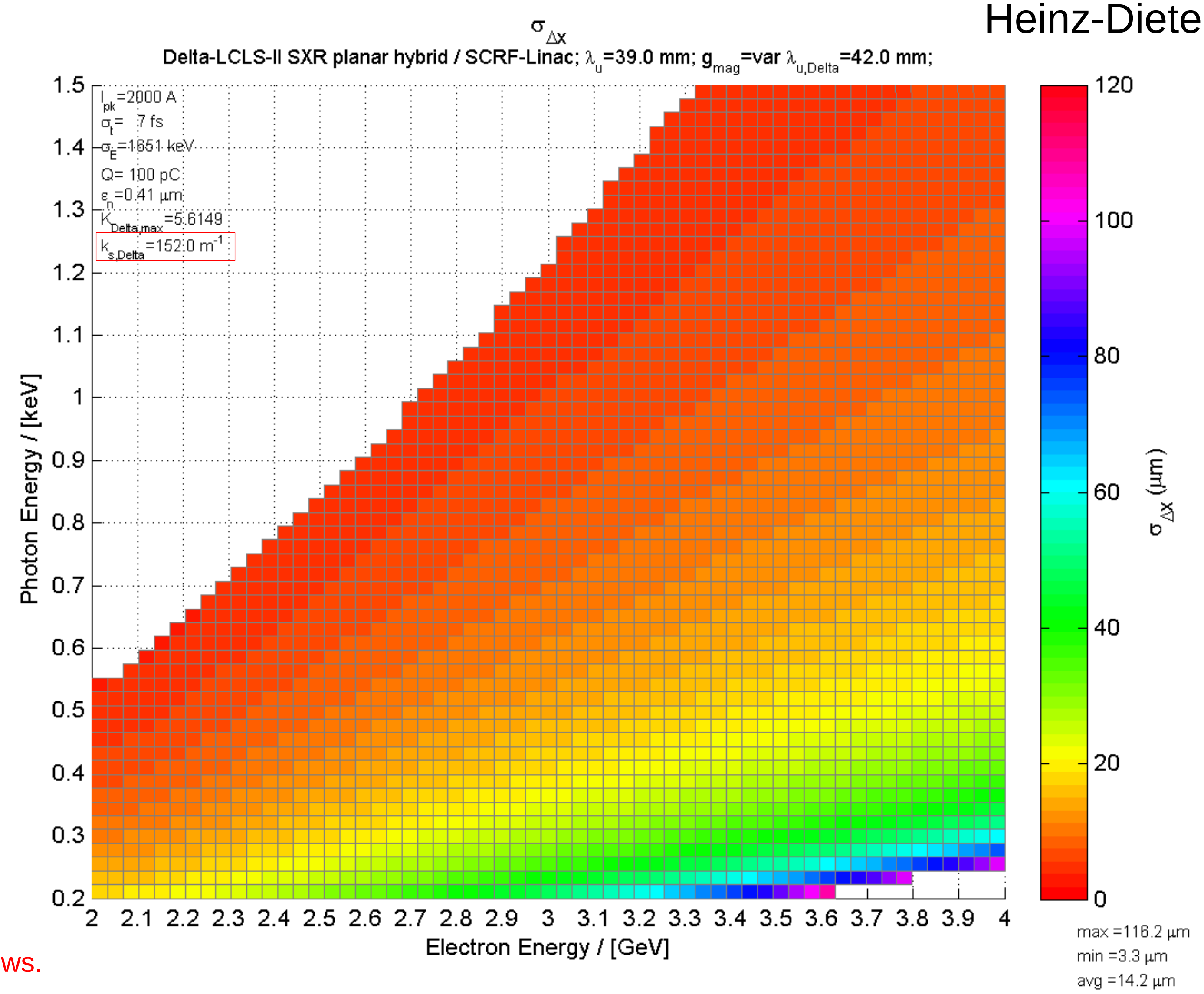
$$\delta = k_u \left(Z_{13} - Z_{24}\right)$$

Note that the gradient comes from the field rolloff k_s. It grows as the row shift Δ increases. It is largest in the circular modes where δ = π/2.

With A Delta-like Undulator
Predicted DELTA-II RMS X-Resonance Width

Heinz-Dieter Nuhn

$$\sigma_{\Delta x} = \frac{1.25\,\rho_{1D}}{\left.\frac{1}{K}\frac{\partial K}{\partial x}\right|_{x=y=0}}$$



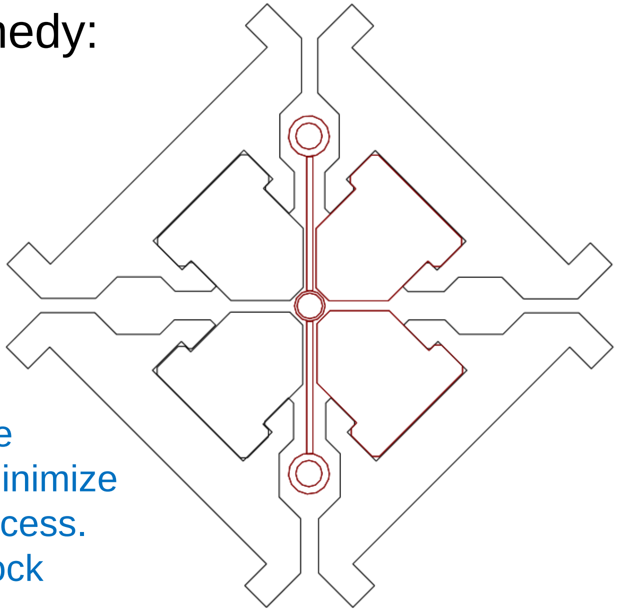
No gap change.
Change K by shifting rows.

Delta-II K Value Position Dependence

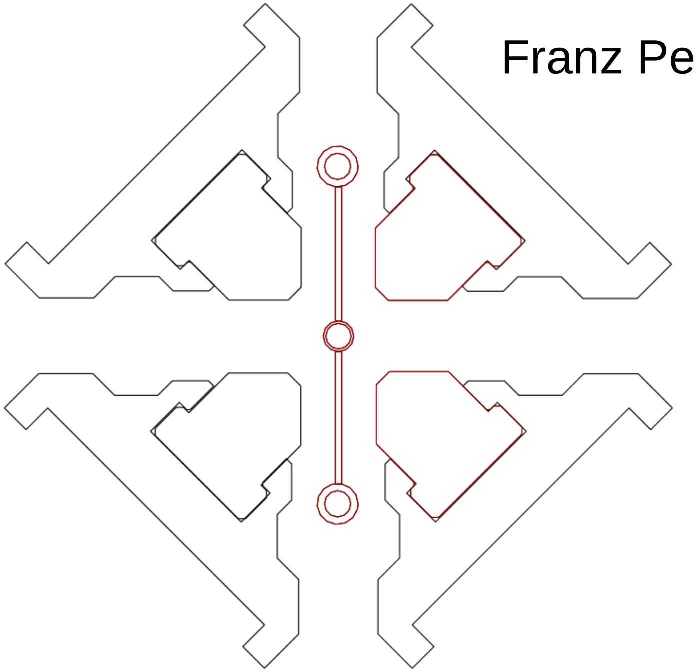
The gradient depends on k_s. It is zero for crossed planar undulators.
The gradient gets bigger as the row shift gets bigger, or as the K value gets smaller.
The gradient is zero in the linear modes, and is largest in the circular modes.

The gradient will cause alignment problems with the three Delta-II undulators.

Remedy:



Franz Peters' design



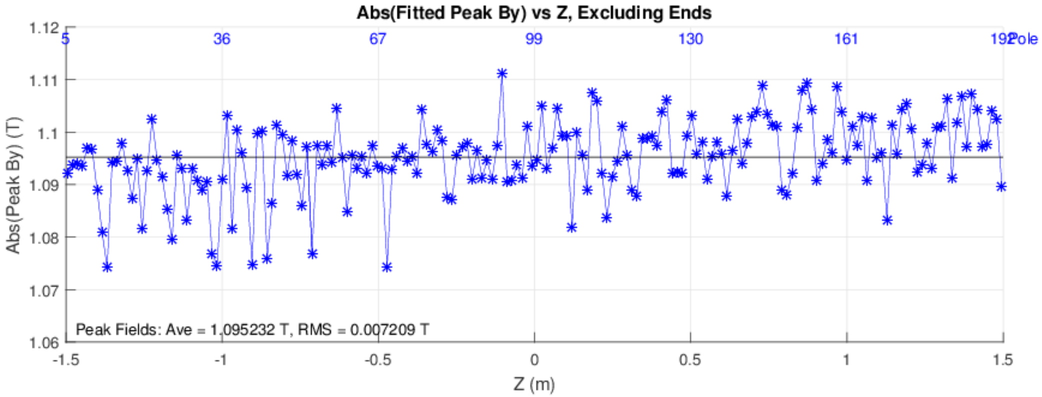
Tried to shape magnets to minimize k_s, but no success. Limited by block size.

Operate at small relative row shift and increase the gap to adjust K.

Delta-II Construction Tolerances

LCLS-TN-15-2

Delta Measured Peak Fields, LPVMF mode, Krel = 0.9



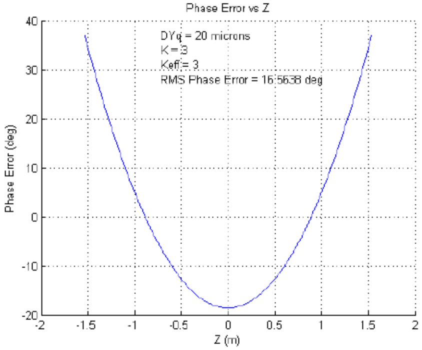
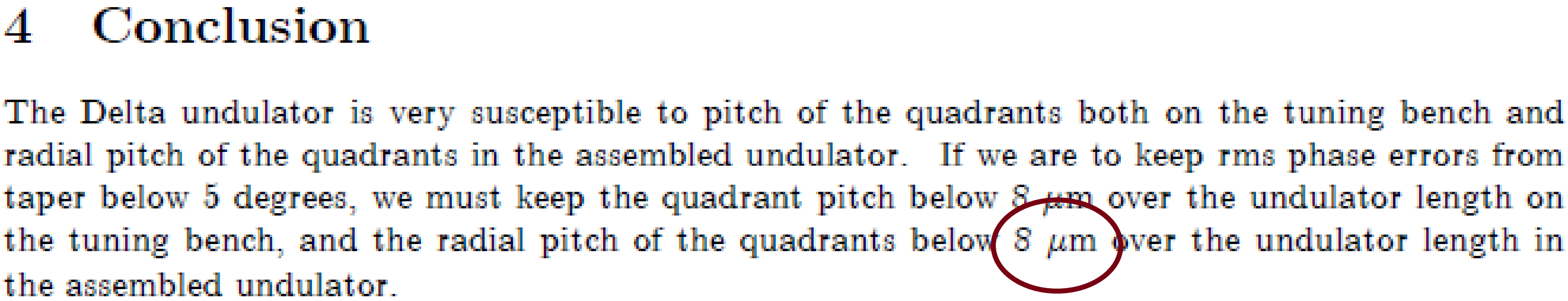


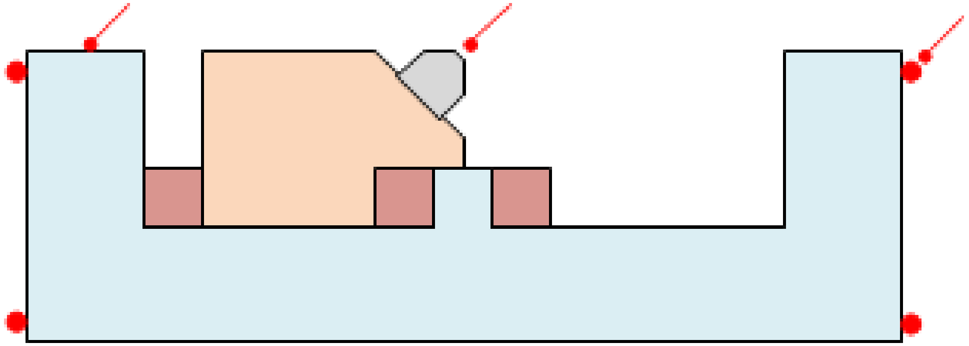
Figure 6: Phase error and K shift when the undulator is assembled with magnet array tapers of 40 μm over the 3.1 m undulator length.



4 Conclusion

The Delta undulator is very susceptible to pitch of the quadrants both on the tuning bench and radial pitch of the quadrants in the assembled undulator. If we are to keep rms phase errors from taper below 5 degrees, we must keep the quadrant pitch below 8 μm over the undulator length on the tuning bench, and the radial pitch of the quadrants below 8 μm over the undulator length in the assembled undulator.

Delta-II Assembly Plan
Build Delta-II On A CMM

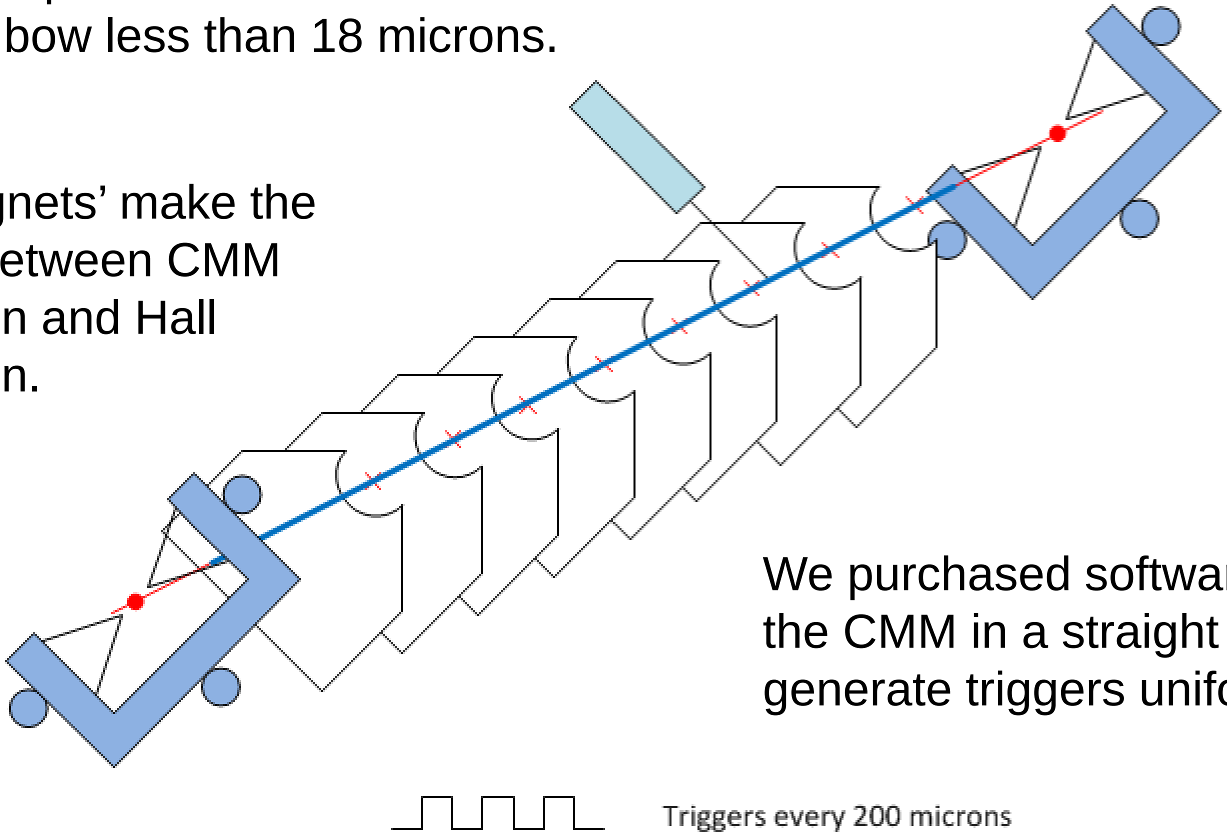


Move the blocks in order to move the magnet mechanical axis to the fiducialized geometric axis of the strongback.

Measure On Line Between Pointed Magnet Centers

Line radial taper less than 8 microns.
Line radial bow less than 18 microns.

‘Pointed magnets’ make the connection between CMM probe position and Hall probe position.



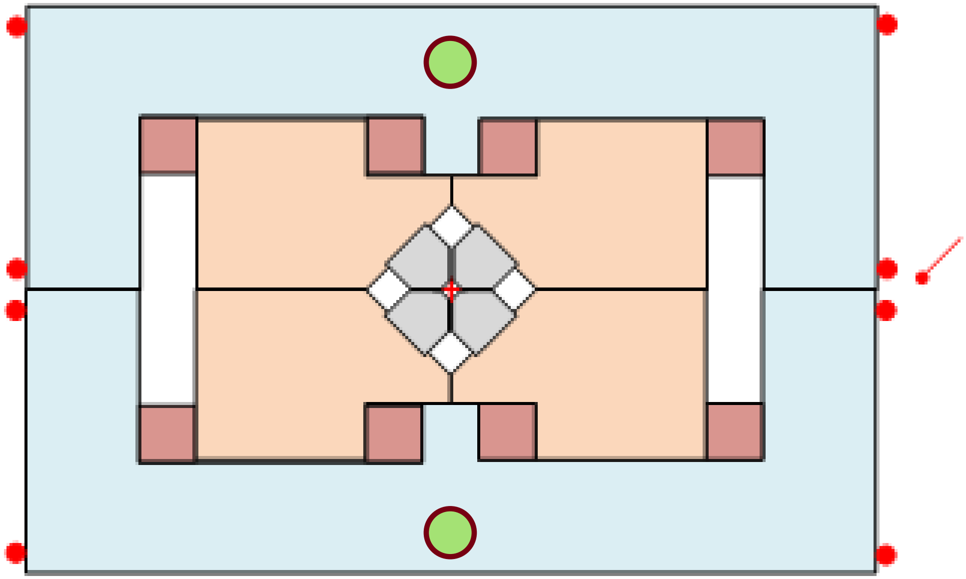
We purchased software to move the CMM in a straight line and generate triggers uniformly spaced.

Triggers every 200 microns

Move on straight line between endpoints.

Move blocks to tune quadrant.

Assembled Undulator



Flats on E set Y and pitch.
Use tooling balls on E to set X and yaw.

Need tooling balls at ends to determine Y after assembly. (Green)

Measurements Of The Assembled Undulator

Requirements:

- Measure at many gaps
- Measure at many row shifts
- Measure in many modes
- Measure the fields on-axis and off-axis

Possible Solutions:

- Safali --- We are trying to fit a Safali rail system into the mechanical design.
- Probe Array --- An array of probes is very difficult to calibrate and it is hard to get all the cables out. Plus, corrections have to be made when the probe array goes off a straight line. Enough measurements need to be made to characterize the field and do the corrections.
- Delta-I --- We can measure in a beam pipe centered on the beam axis, but this is not an ideal solution.
- Safali --- We can possibly move a beam pipe to keep the probe moving on a straight line.

Conclusion

- A Delta undulator was successfully built and used in LCLS-I
- Modifications must be made for LCLS-II
    - The K gradient must be reduced (by moving the magnet arrays radially)
    - Tighter construction tolerances must be met
    - We are looking for a better way to measure the assembled undulator.