Commissioning of the Delta Polarizing Undulator at LCLS

Heinz-Dieter Nuhn for the Delta Project Team

Wednesday, August 26, 2015

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

WED01

Authors

H.-D. Nuhn#, **S.D. Anderson**, **R.N. Coffee**, **Y. Ding**, **Z. Huang**, **M. Ilchen**, **Y. Levashov**, **A.A. Lutman**, **J. MacArthur**, **A. Marinelli**, **S.P. Moeller**, **F. Peters**, **Z. Wolf**, SLAC National Accelerator Laboratory (SLAC)

A.B. Temnykh, Cornell University (CLASSE)

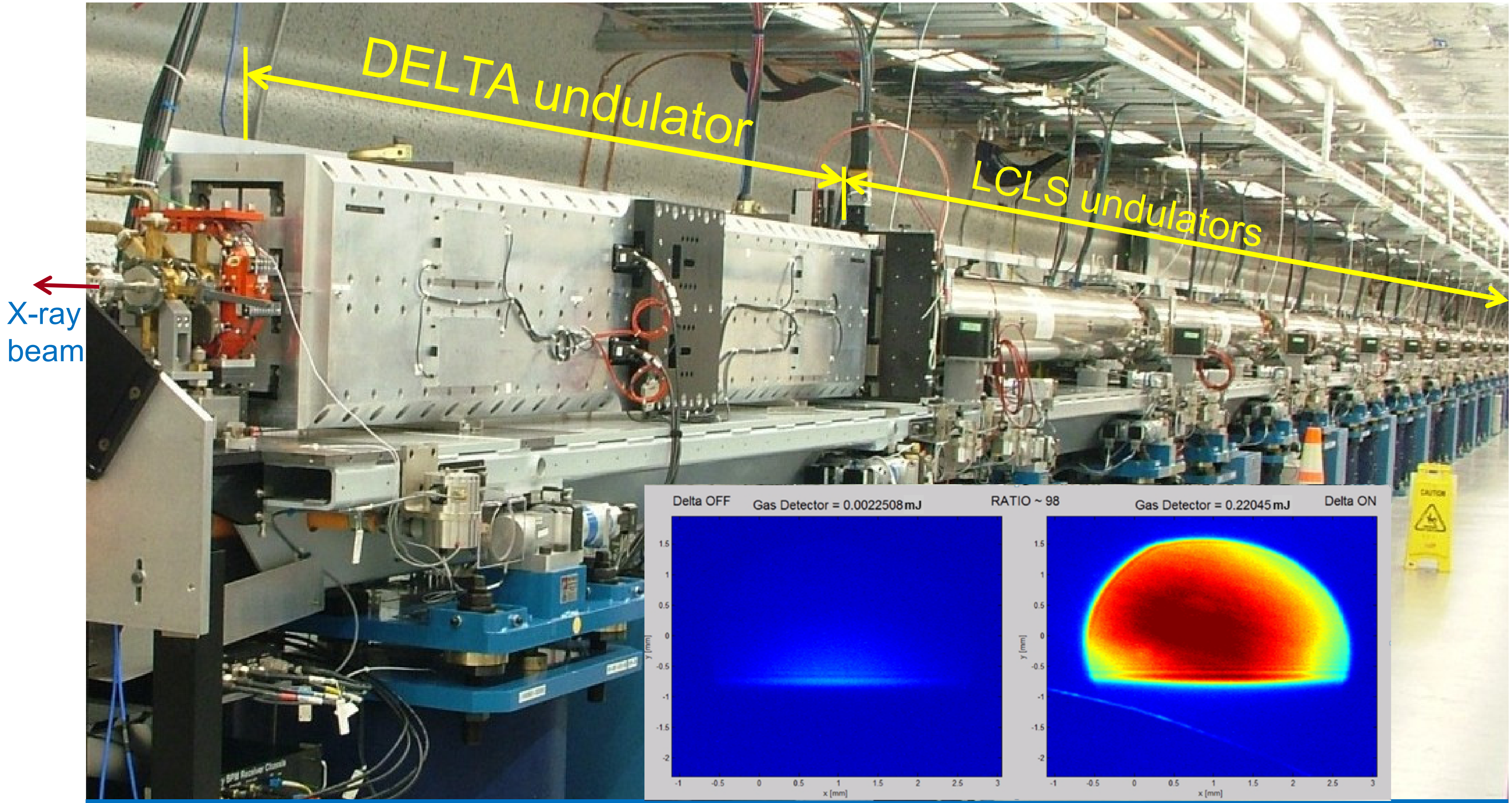
G. Hartmann, **J. Viefhaus**, Deutsches Elektronen-Synchrotron (DESY)

J. Buck, European XFEL GmbH (XFEL.EU)

A.O. Lindahl, University of Gothenburg Department of Physics

We appreciate the opportunity to present our results at this conference!

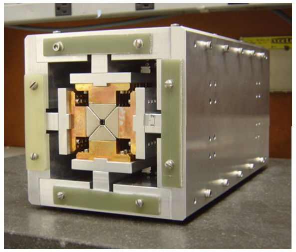
Circular Polarized FEL X-Rays at LCLS



X-ray beam polarization controllable from circulator through elliptical to linear

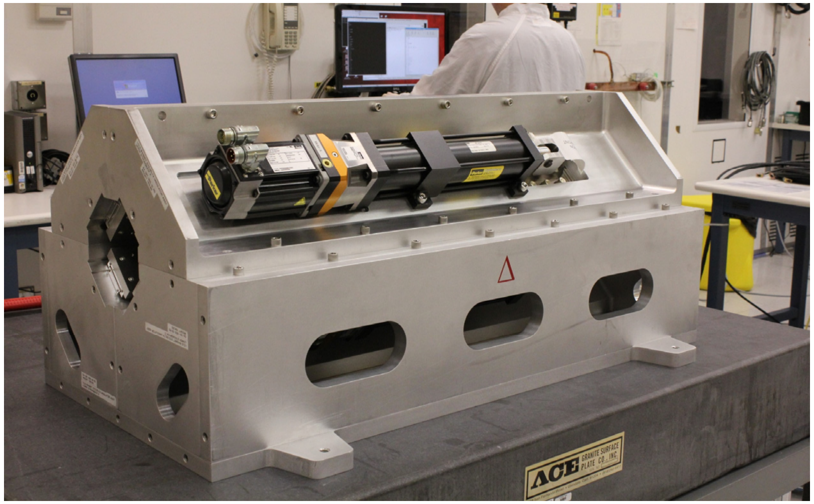
Delta Development

Cornell University
Proof-of-Principle
0.3 m



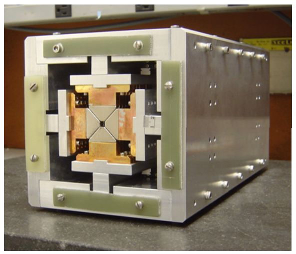
A. Temnykh,
Phys. Rev. ST Accel. Beams
11, 120702 (2008).

SLAC
Prototype
1.0 m



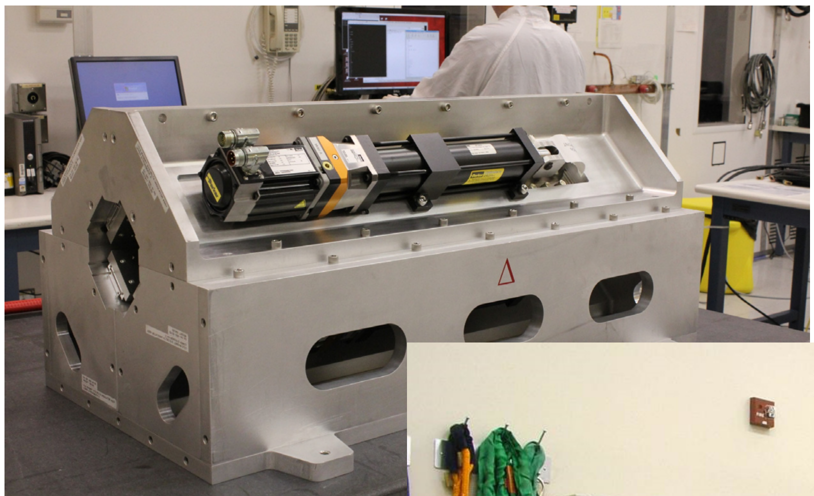
Delta Development

Cornell University
Proof-of-Principle
0.3 m

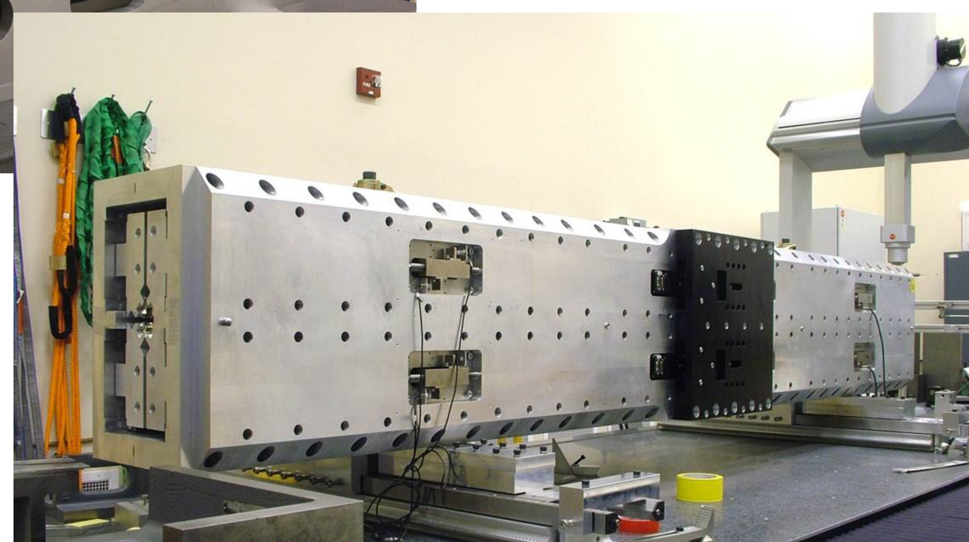


A. Temnykh,
Phys. Rev. ST Accel. Beams
11, 120702 (2008).

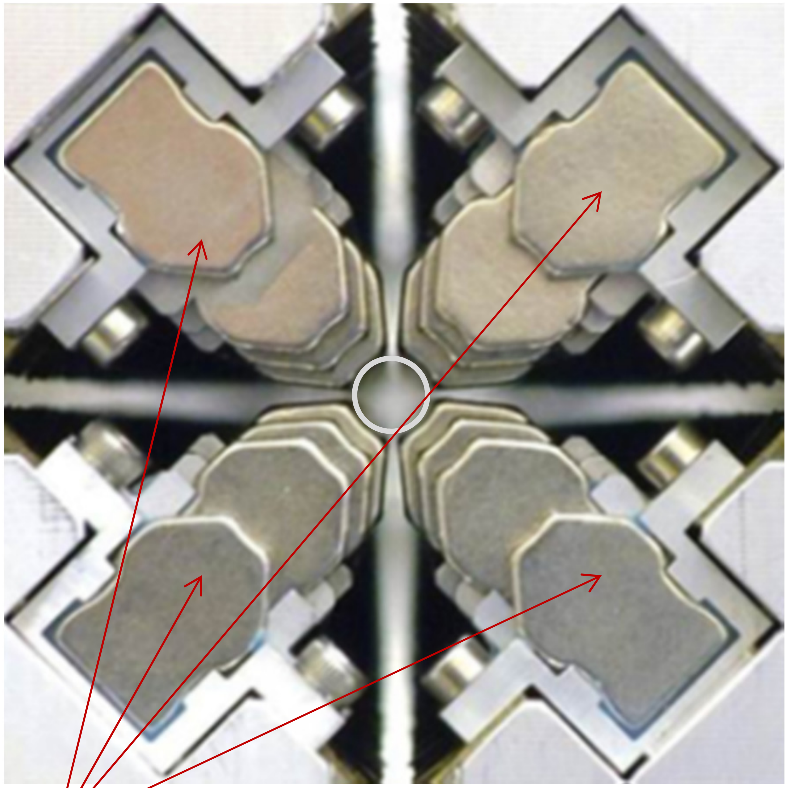
SLAC
Prototype
1.0 m

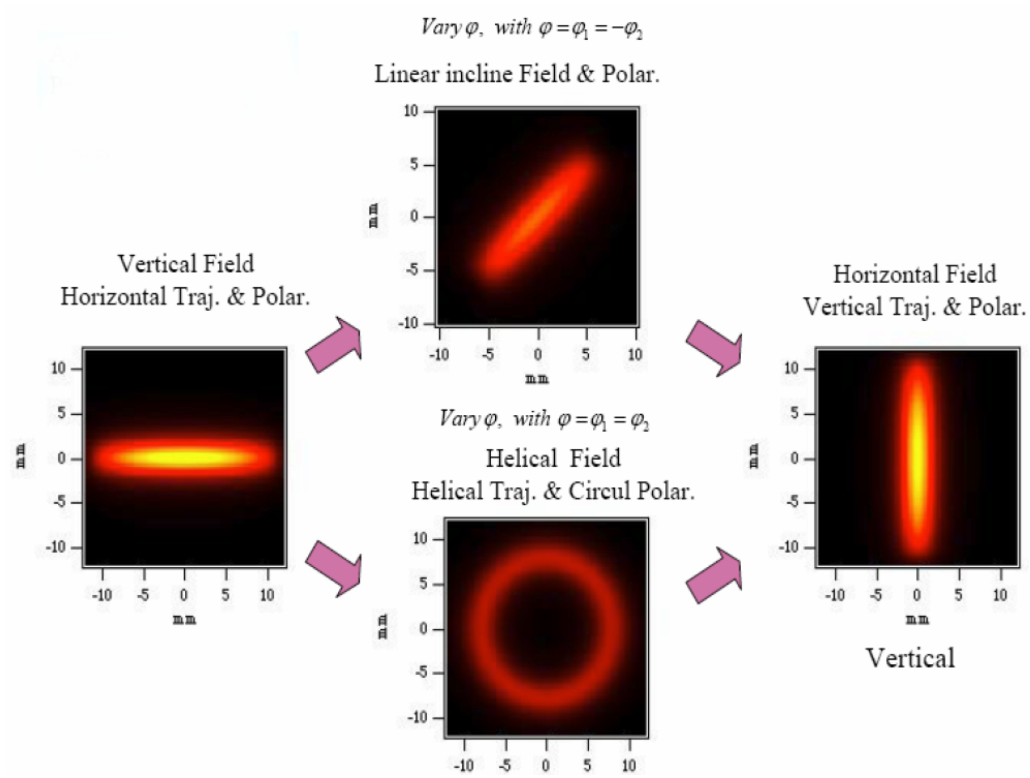


SLAC
LCLS Delta
3.2 m



Variable Phase Undulator for Polarization Control





Four independent quadrants of permanent magnets move longitudinally at fixed gap.

By sliding the quadrants it is possible to control the K from full to zero

and to have full control the polarization

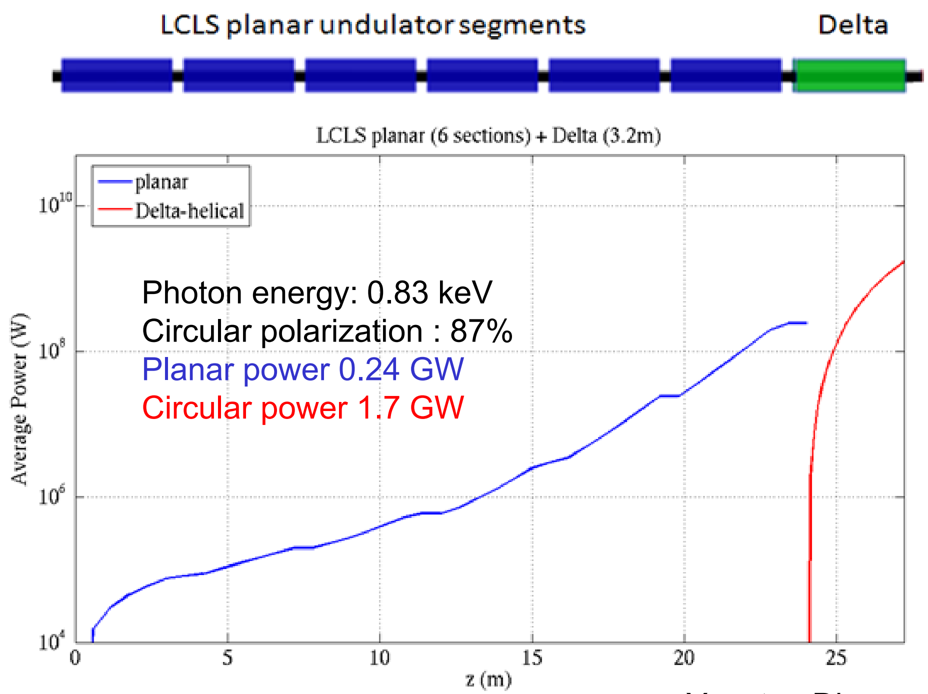
Delta Benefit Expectations (2012)

SLAC

Short Term:

- Add circular polarization capability to the current LCLS (in afterburner configuration).

Primary Photon Energy Range 0.28 – 2.0 keV

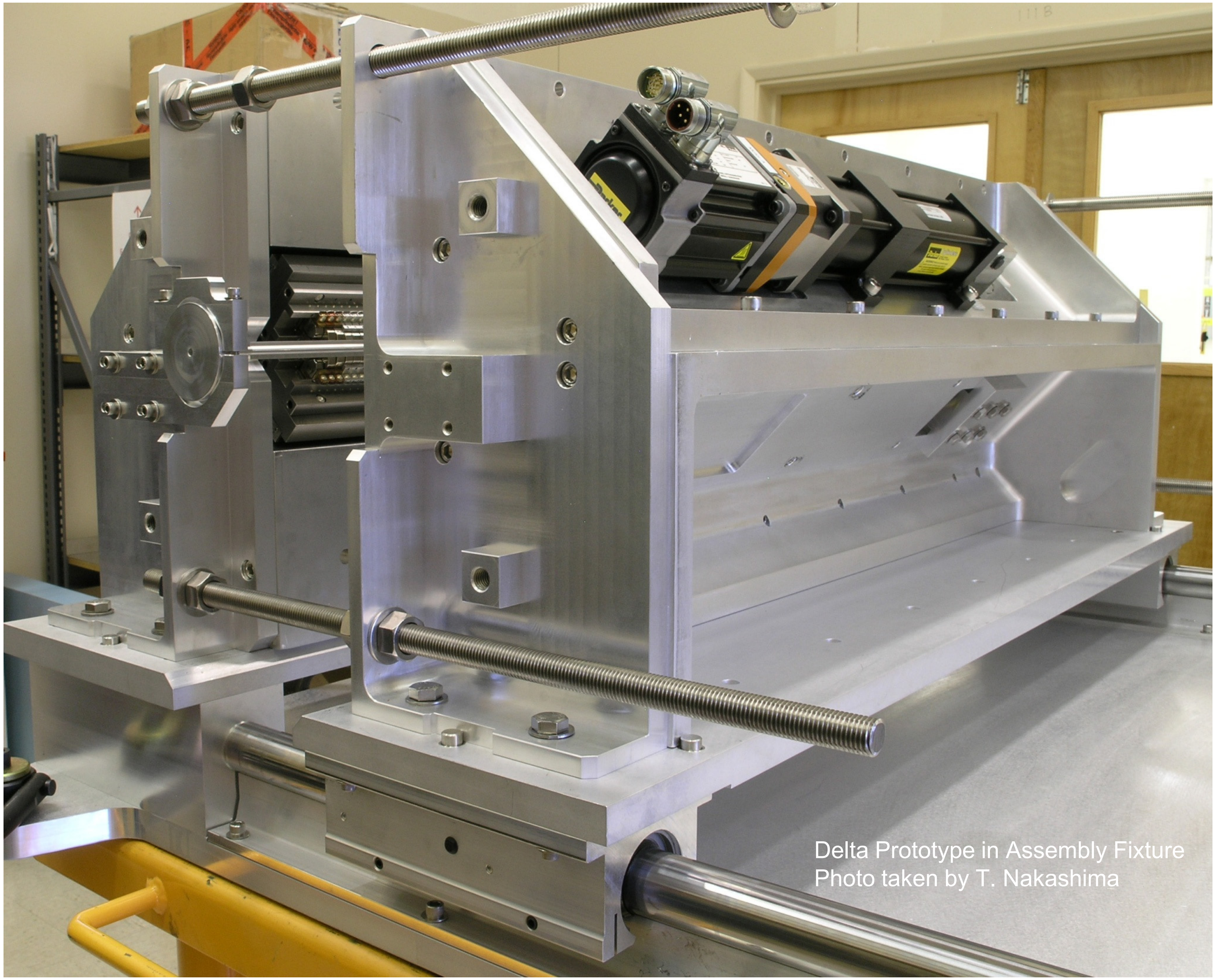


Yuantao Ding

Long Term:

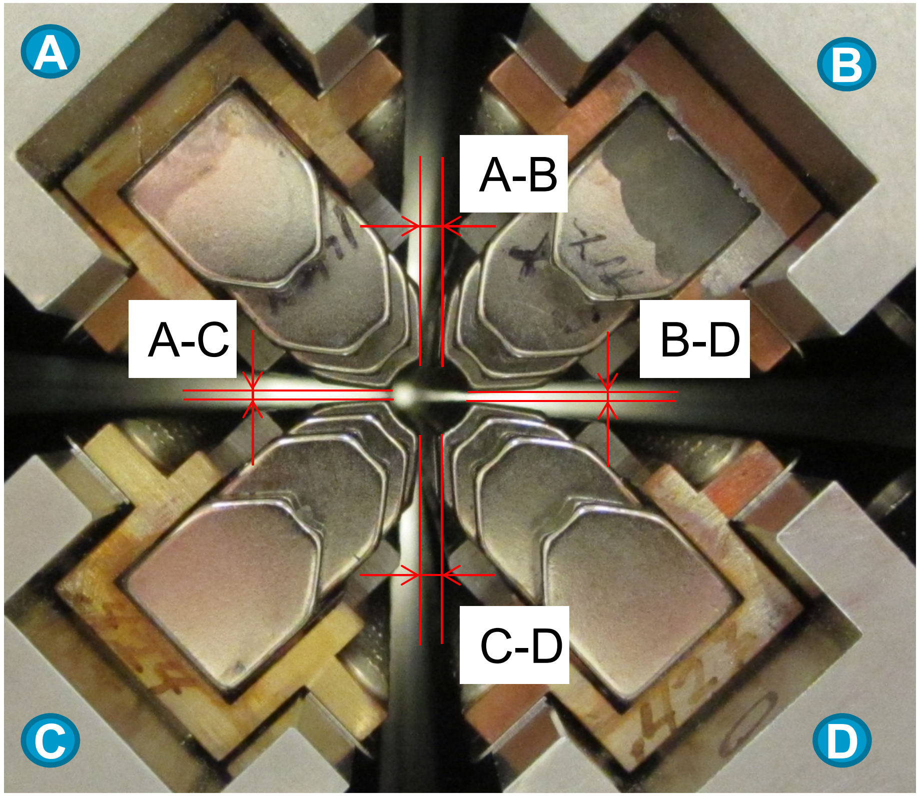
- Provide polarization control for the LCLS-II SXR line.
- Build future Delta x-ray FELs with full polarization control and full tunability under LCLS type alignment control.

Delta 1.0-m Prototype (during assembly)


Delta Prototype in Assembly Fixture
Photo taken by T. Nakashima

1.0-m Prototype – Row Movement

SLAC

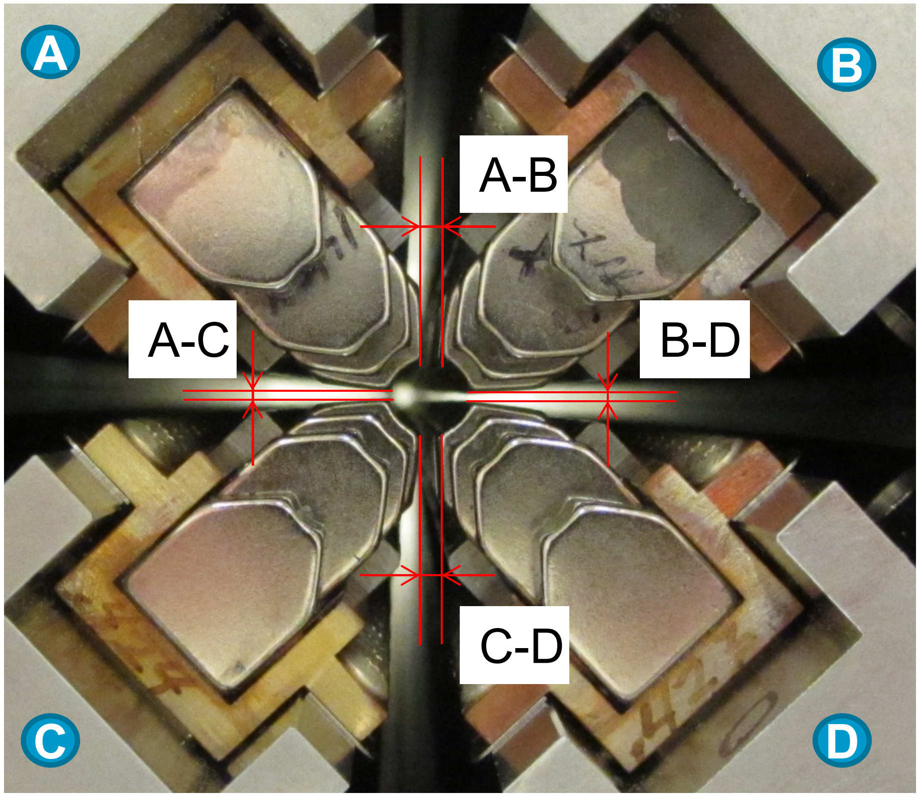


For measurements plastic filler gauge was used. Measurement accuracy ~ 25 µm. Nominal A-B dimension ~ 635 µm.

Mode: Planer / vertical field		Dimensions are µm			
A,B,C,D = 0					
		A-B	B-D	C-D	A-C
Reference		1,397	597	1,334	635
Mode: Helical right					
A,D = 0	B,C = +8mm				
		A-B	B-D	C-D	A-C
		1,359	699	1,270	762
Change from reference		38	-102	64	-127
Mode: Helical left					
A,D = 0	B,C = -8mm				
		A-B	B-D	C-D	A-C
		1,334	762	1,207	762
Change from reference		-64	165	-127	127
Mode: Planer / horizontal field					
A,B =0	B,C = -16mm				
		A-B	B-D	C-D	A-C
		1,143	940	1,080	914
Change from reference		-254	343	-254	279
A	B				
C	D				

1.0-m Prototype – Row Movement

SLAC

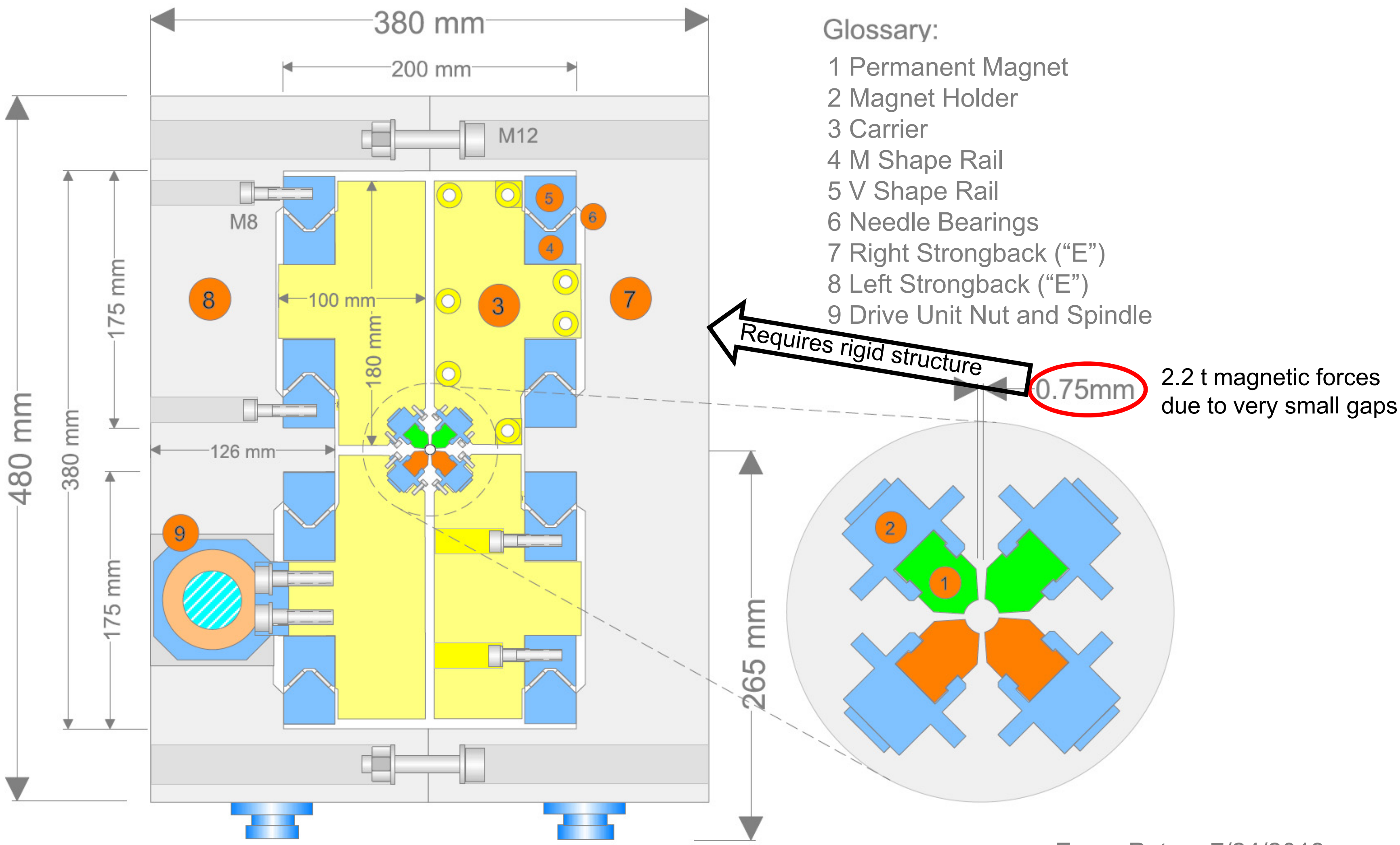


For measurements plastic filler gauge was used. Measurement accuracy ~ 25 µm.
Nominal A-B dimension ~ 635 µm

Mode: Planer / vertical field			Dimensions are µm		
A,B,C,D = 0					
		A-B	B-D	C-D	A-C
Reference		1,397	597	1,334	635
Mode: Helical right					
A,D = 0	B,C = +8mm				
		A-B	B-D	C-D	A-C
		1,359	699	1,270	762
Change from reference		38	-102	64	-127
Mode: Helical left					
A,D = 0	B,C = -8mm				
		A-B	B-D	C-D	A-C
		1,334	762	1,207	762
Change from reference		-64	165	-127	127
Mode: Planer / horizontal field					
A,B =0	B,C = -16mm				
		A-B	B-D	C-D	A-C
		1,143	940	1,080	914
Change from reference		-254	343	-254	279
A	B				

Much more rigid design required for 3.2-m Delta

3.20- Delta Undulator Components (new design)



Glossary:

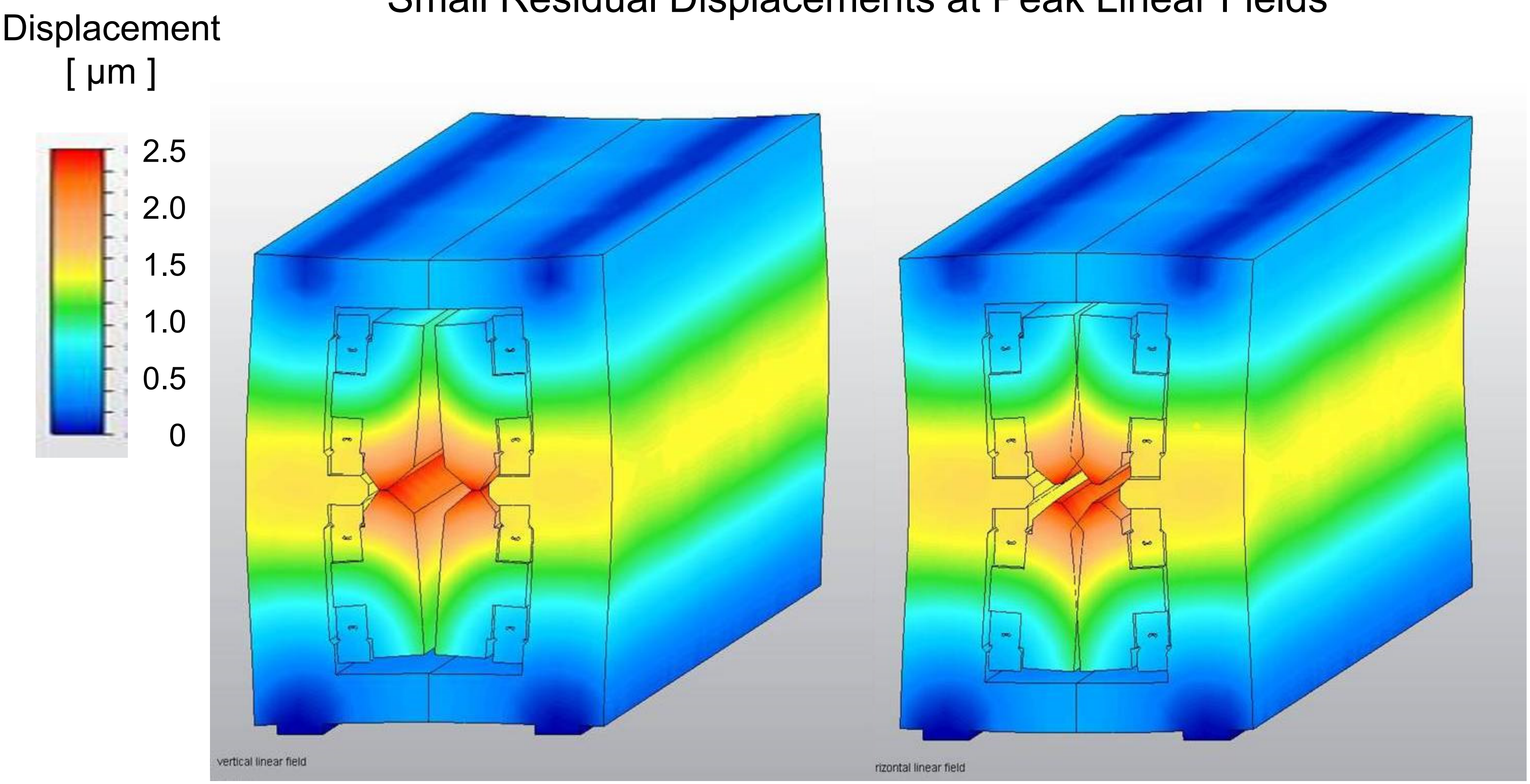
1 Permanent Magnet
2 Magnet Holder
3 Carrier
4 M Shape Rail
5 V Shape Rail
6 Needle Bearings
7 Right Strongback ("E")
8 Left Strongback ("E")
9 Drive Unit Nut and Spindle

Franz Peters 7/24/2013

Structural Stiffness Controls Strong Magnetic Forces

SLAC

Small Residual Displacements at Peak Linear Fields



Vertical Linear Field

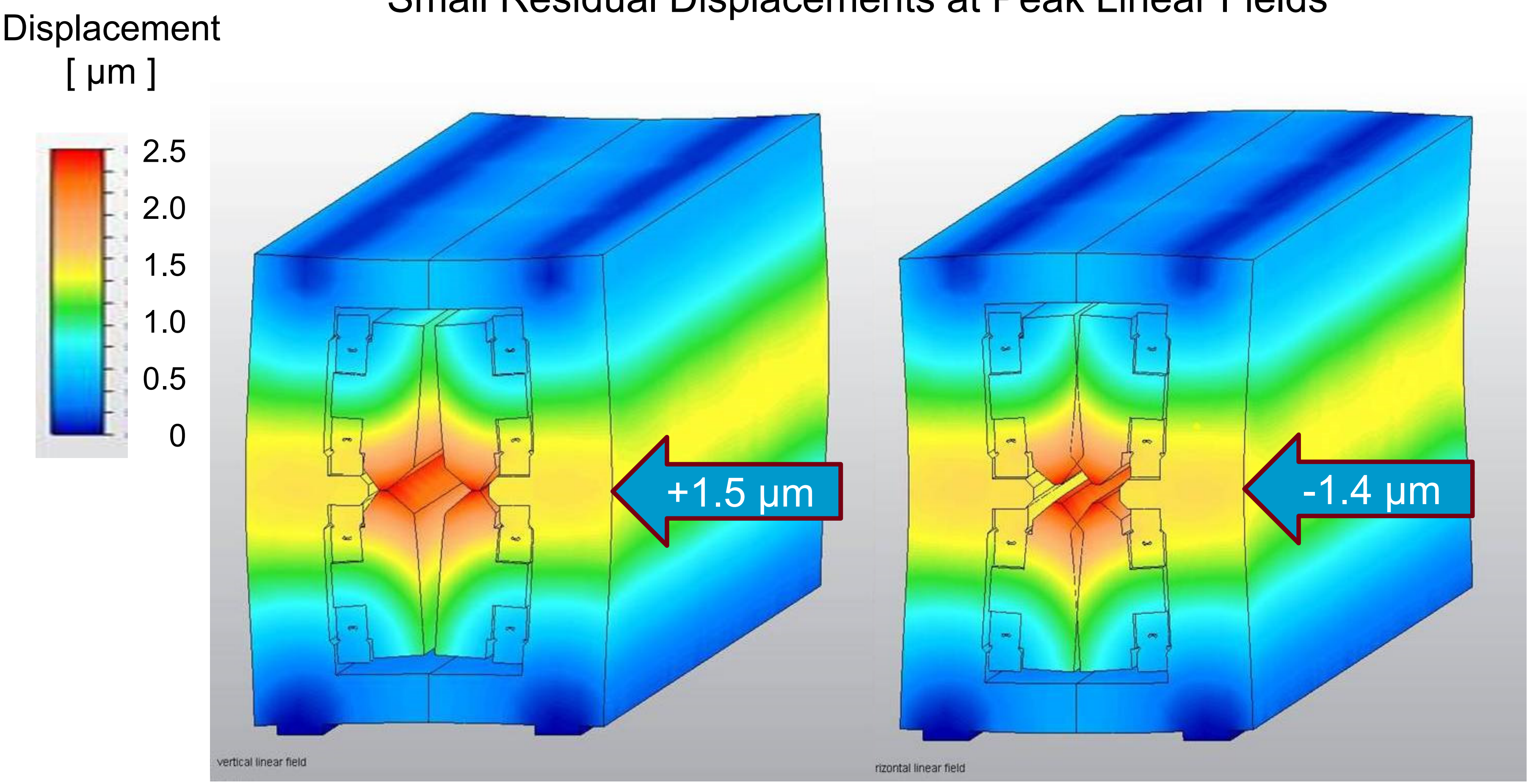
Horizontal Linear Field

Franz Peters 7/24/2013

Will provide required micron-level reproducibility

Structural Stiffness Controls Strong Magnetic Forces

Small Residual Displacements at Peak Linear Fields



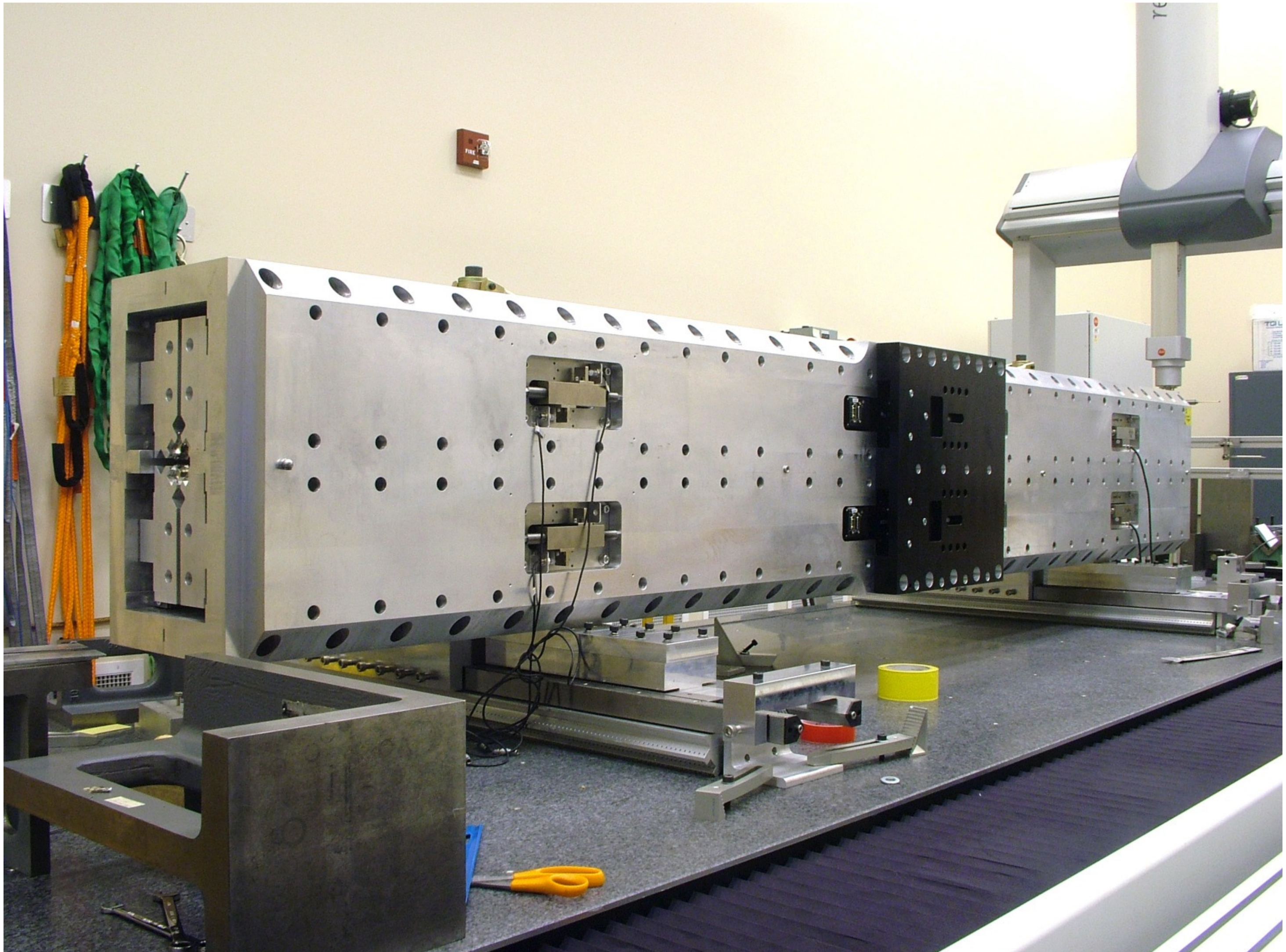
Vertical Linear Field Horizontal Linear Field

Franz Peters 7/24/2013

Will provide required micron-level reproducibility

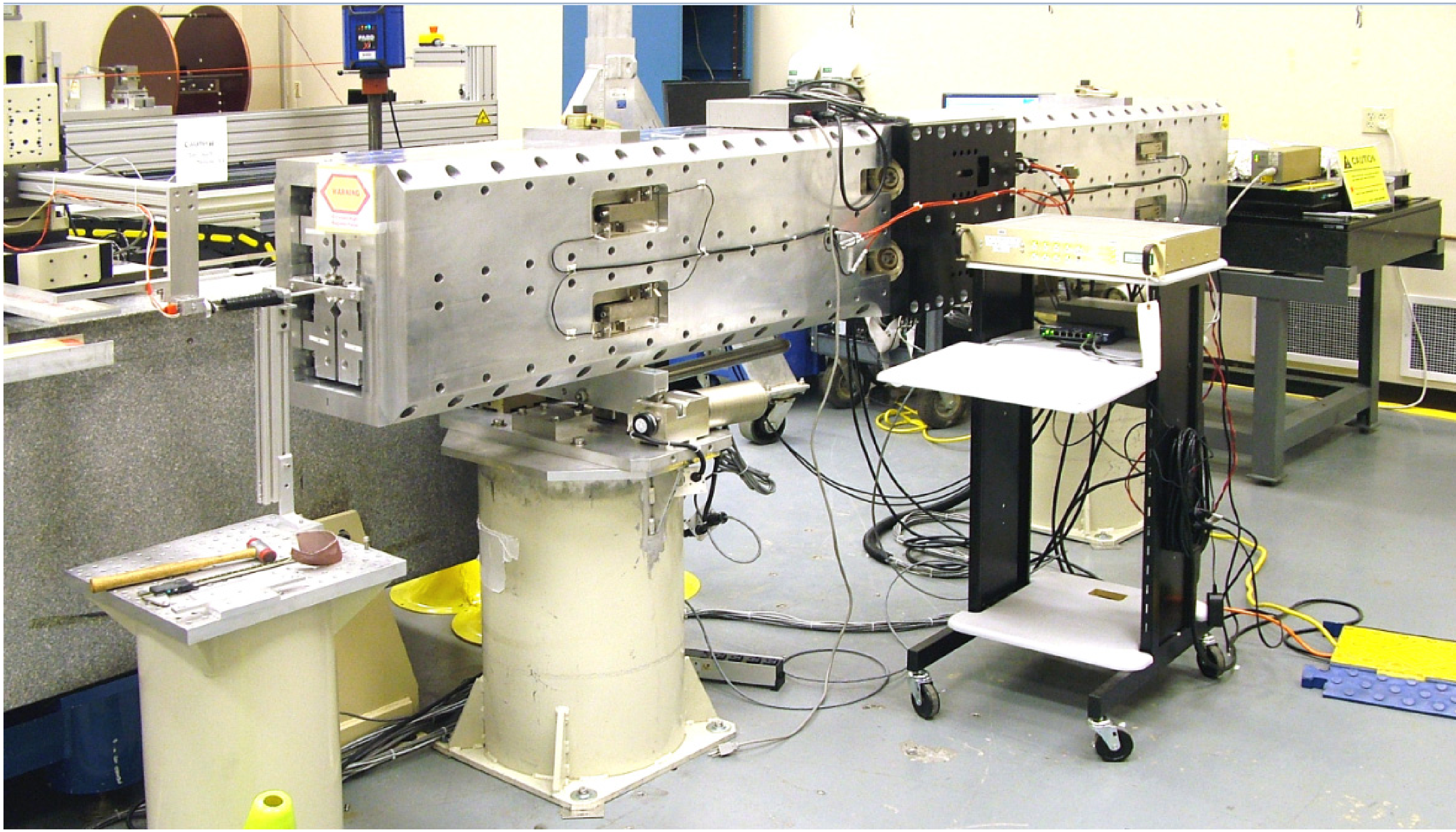
Quadrant Tuning

Delta Assembly Complete



Delta Field Mapping

SLAC

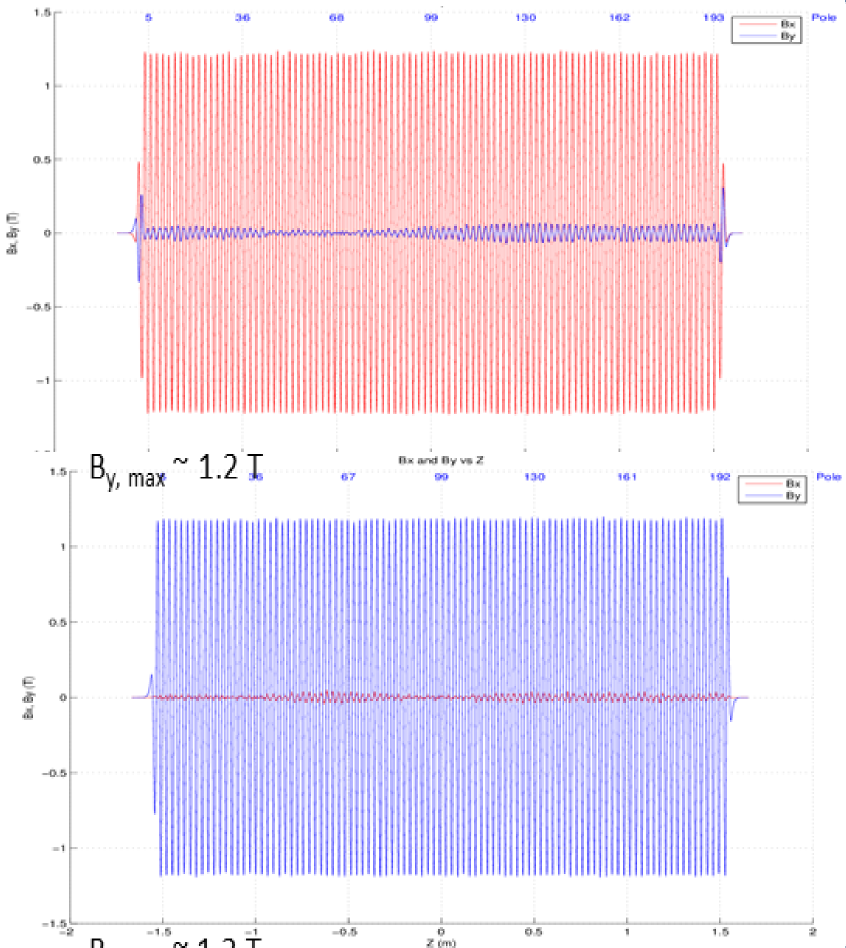


Yurii Levashov, Zack Wolf, Scott Anderson, Bob Pushor

Delta Field Mapping Result: Examples

SLAC

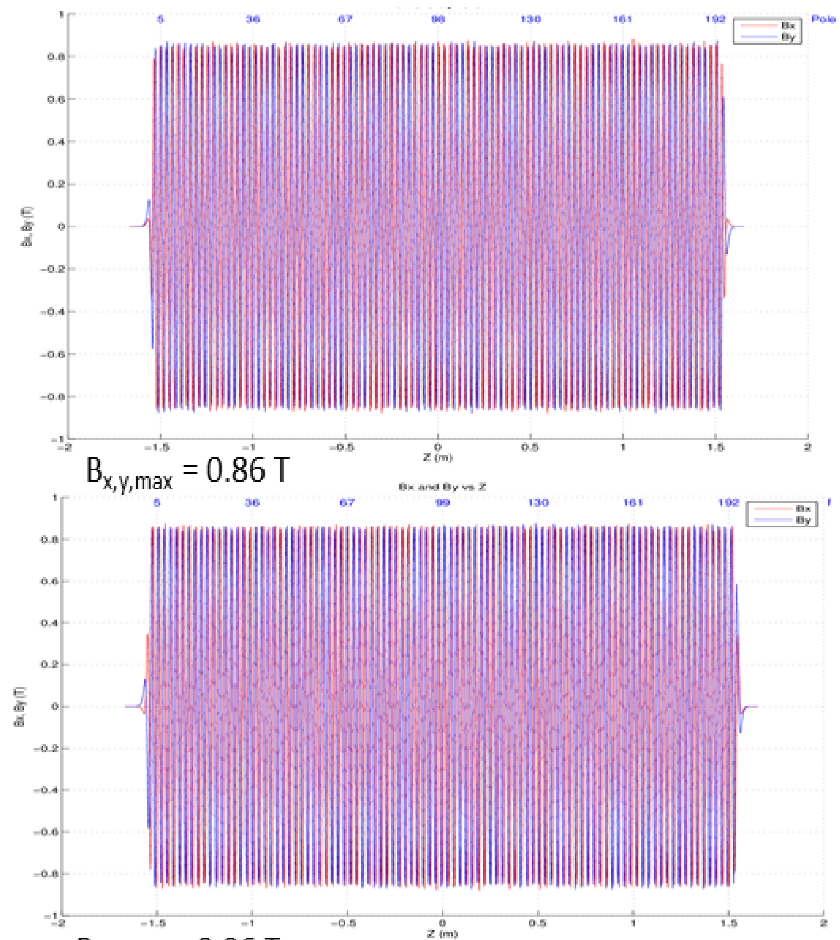
LH and LV polarization modes



$B_{y,\ max}$ ~ 1.2 T

$B_{x,\ max}$ ~ 1.2 T

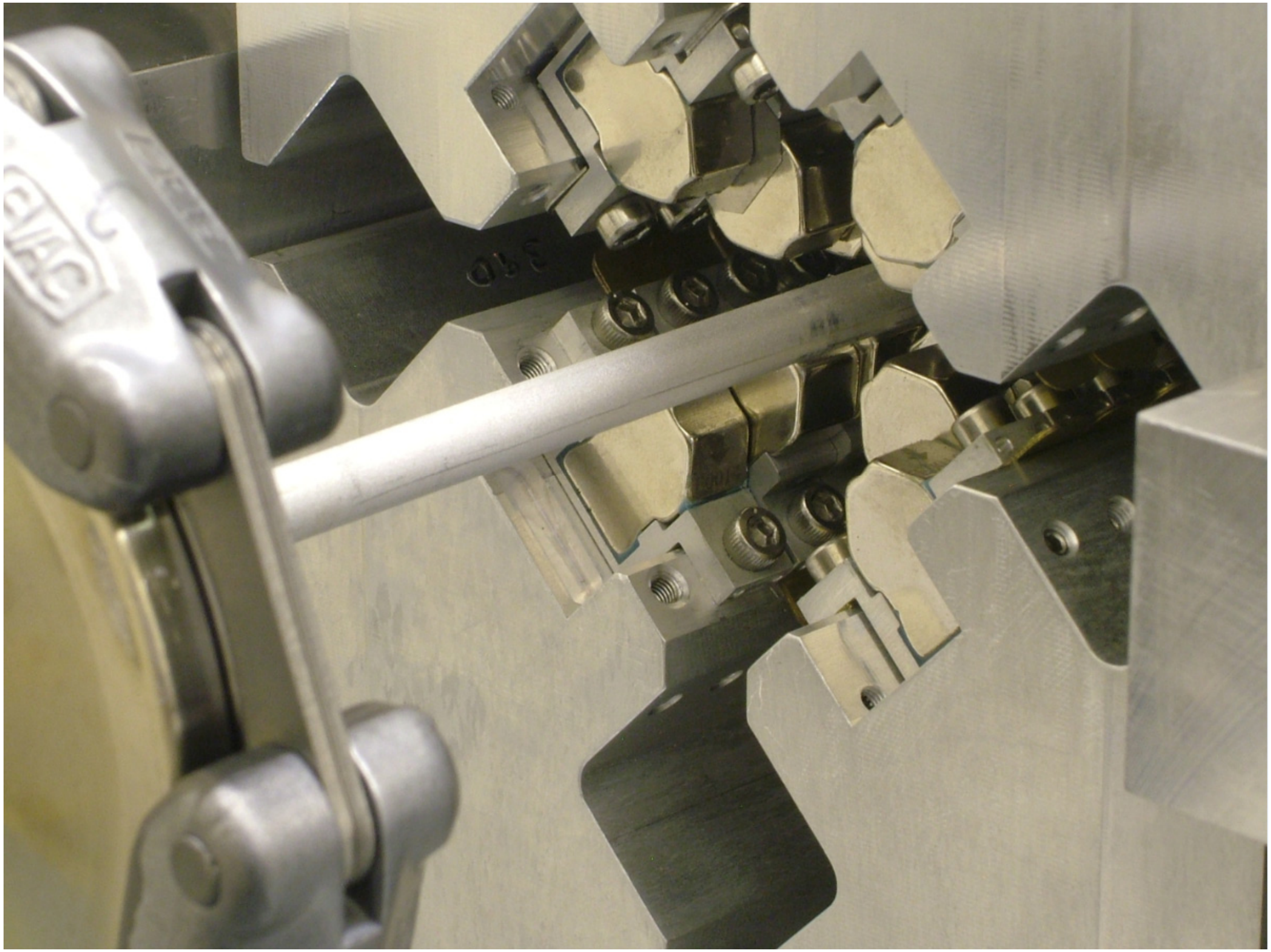
CL and CR polarization modes



$B_{x,y,max}$ = 0.86 T

$B_{x,y,max}$ = 0.86 T

Delta with Vacuum Chamber



Phase Shifter

Motor

Spindle

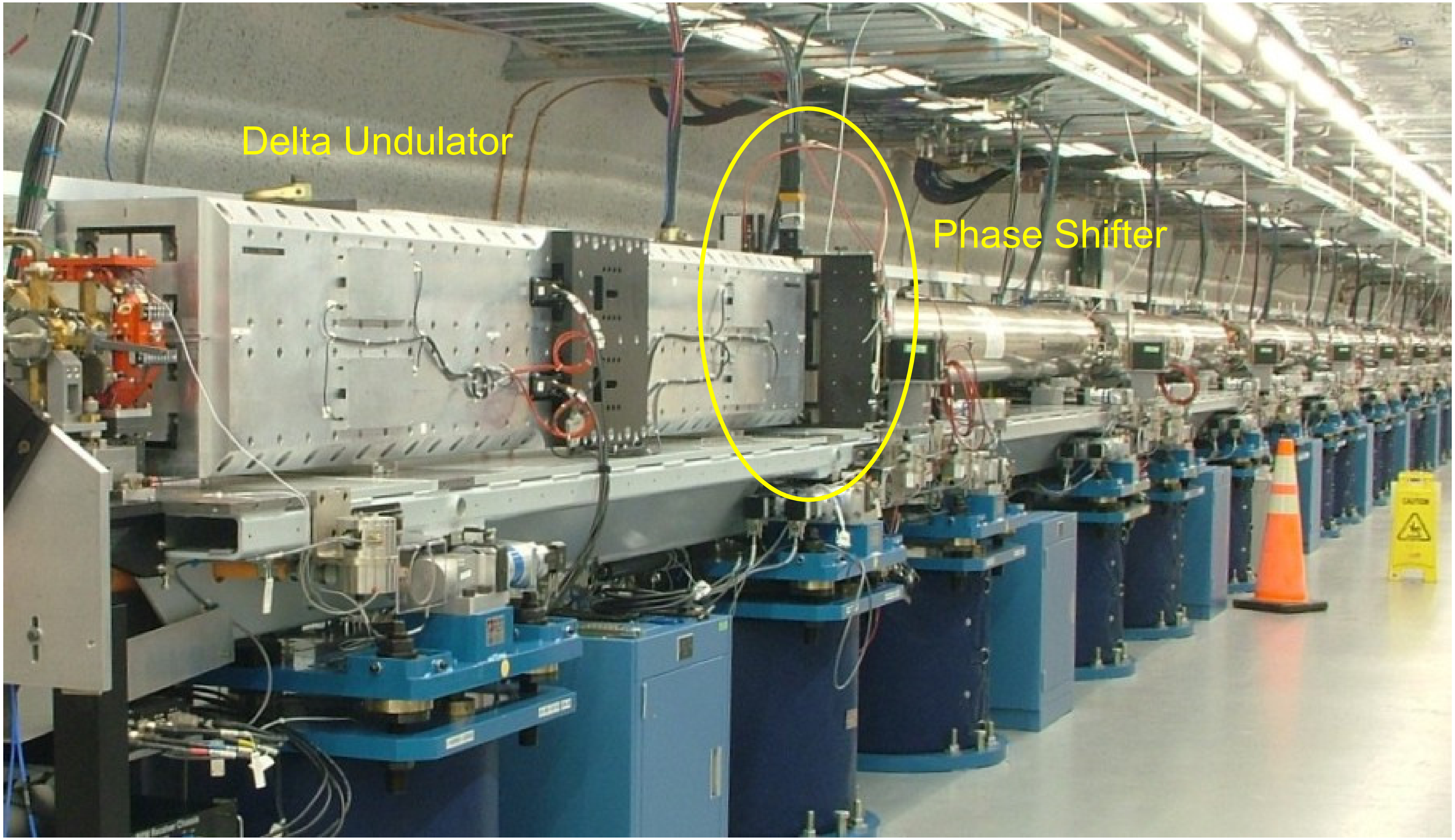
Magnet Array

Force Compensation

Zack Wolf

Delta Undulator and Phase Shifter installed on U33

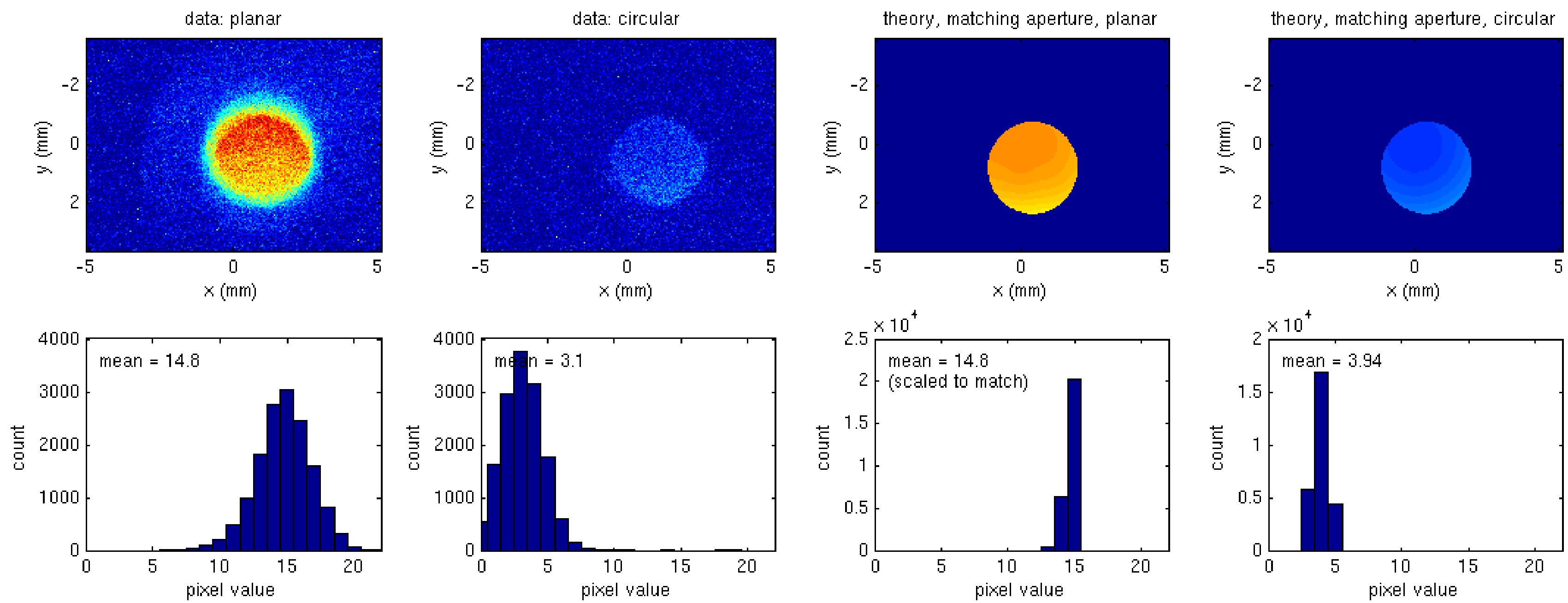
SLAC



October 2014

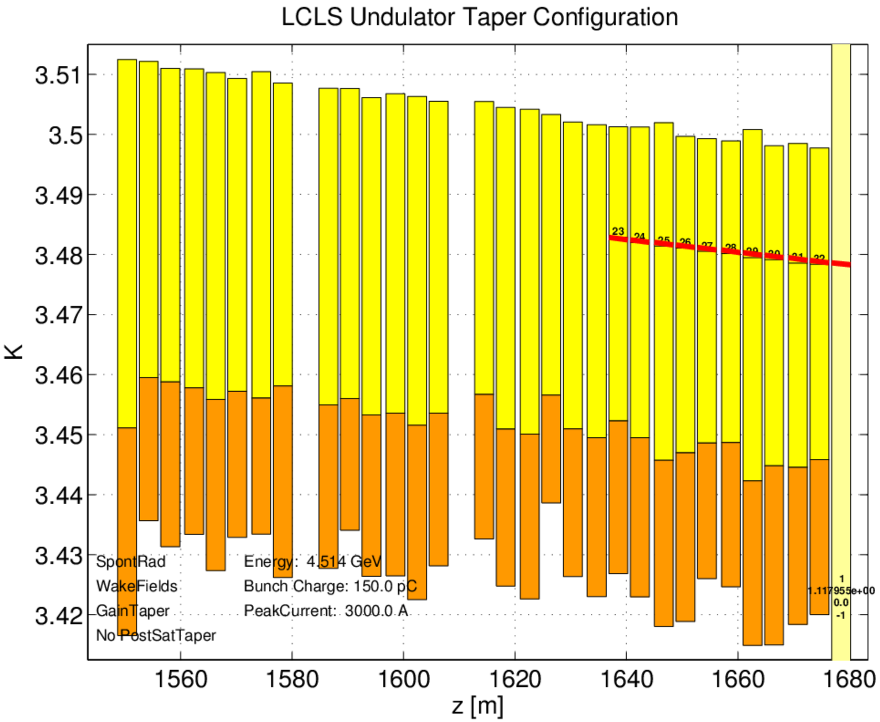
First Light Through Delta Undulator

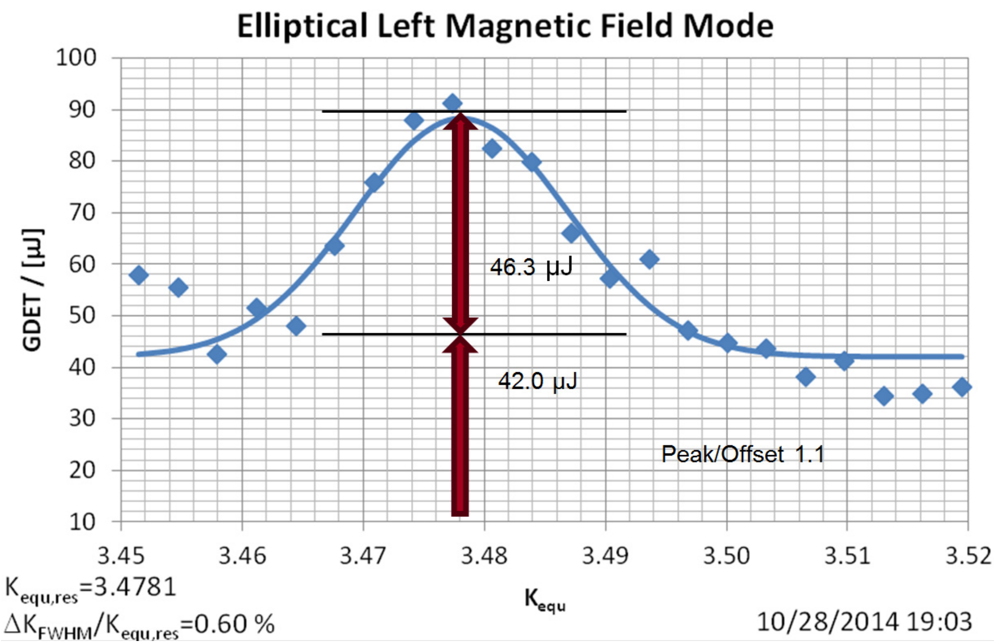
- **Commissioning with beam started on 10/14/2014**
- **Images show spontaneous radiation of linear and circularly polarized configuration at 9.2 keV.**
- **The observed patterns and intensities agree with calculations by J. MacArthur.**



Delta in Regular Afterburner Configuration at 930 eV

SLAC



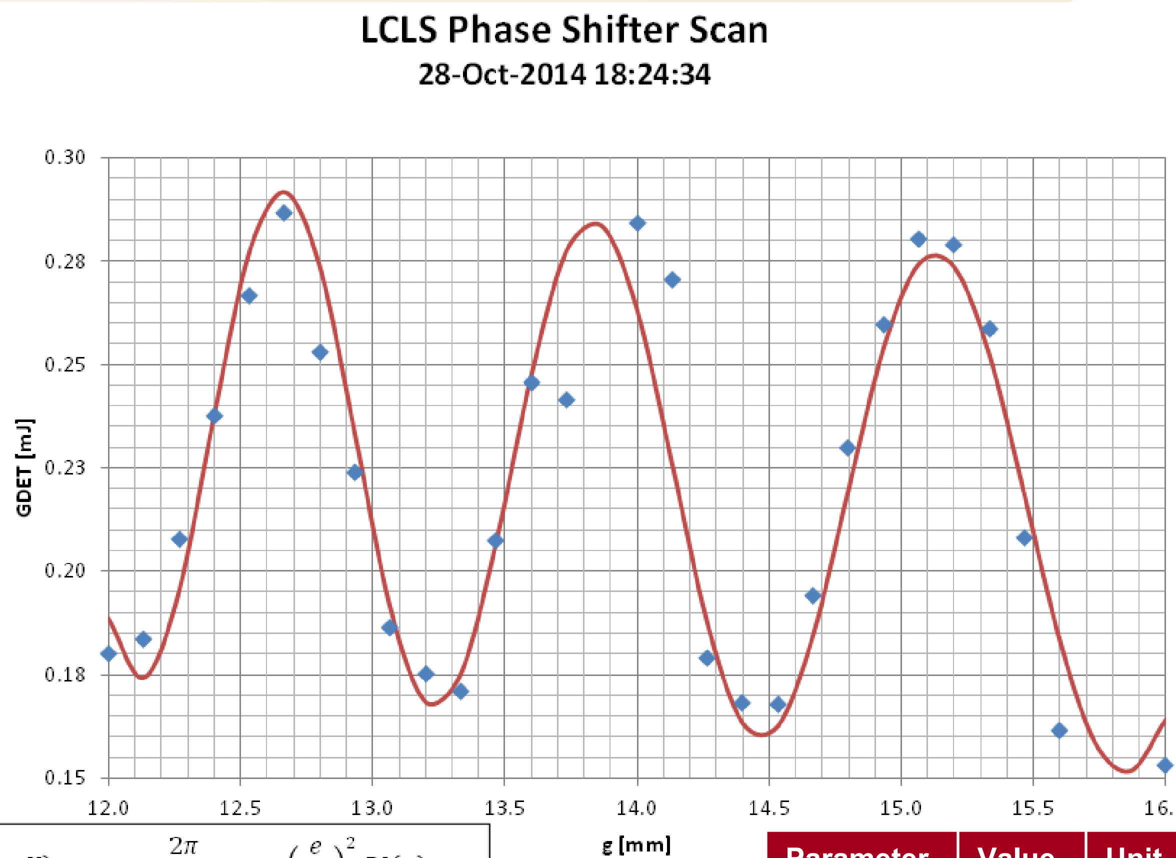


Peak Current around 1.5 kA

- 42 µJ with Delta off
- 88 µJ with Delta on

First Phase Shifter Scan

SLAC



$$\varphi(g,K) = \frac{2\pi}{0.030\ m\ (1+\frac{K^2}{2})}\left(\frac{e}{mc}\right)^2 PI(g)$$

Fit: $$GDET = A\sin(\varphi(g,K)+B) + C\,g + D$$

rms = 14.3 μJ

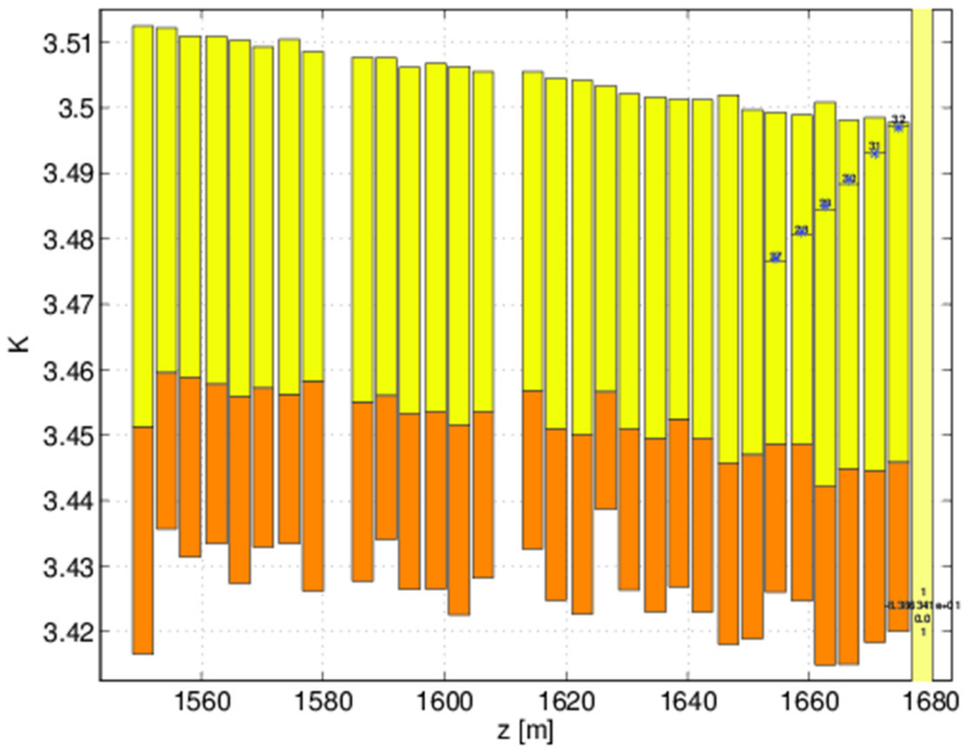
Parameter	Value	Unit
K	3.4710	
A	0.06054	mJ
B	-1.24898	rad
C	-0.00606	mJ/mm
D	0.30799	mJ

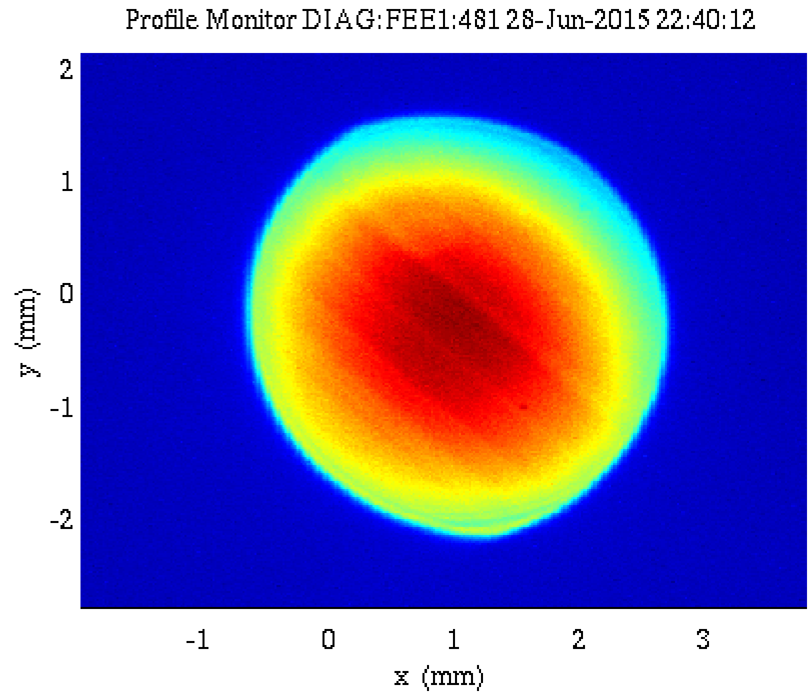
Delta in Enhanced Afterburner Configuration at 710 eV

SLAC

Reverse Taper

E.A. Schneidmiller, M.V. Yurkov, "Obtaining high degree of circular polarization at X-ray FELs via a reverse undulator taper", arXiv:1308.3342 [physics.acc-ph]





- X-ray growth suppressed during reverse taper

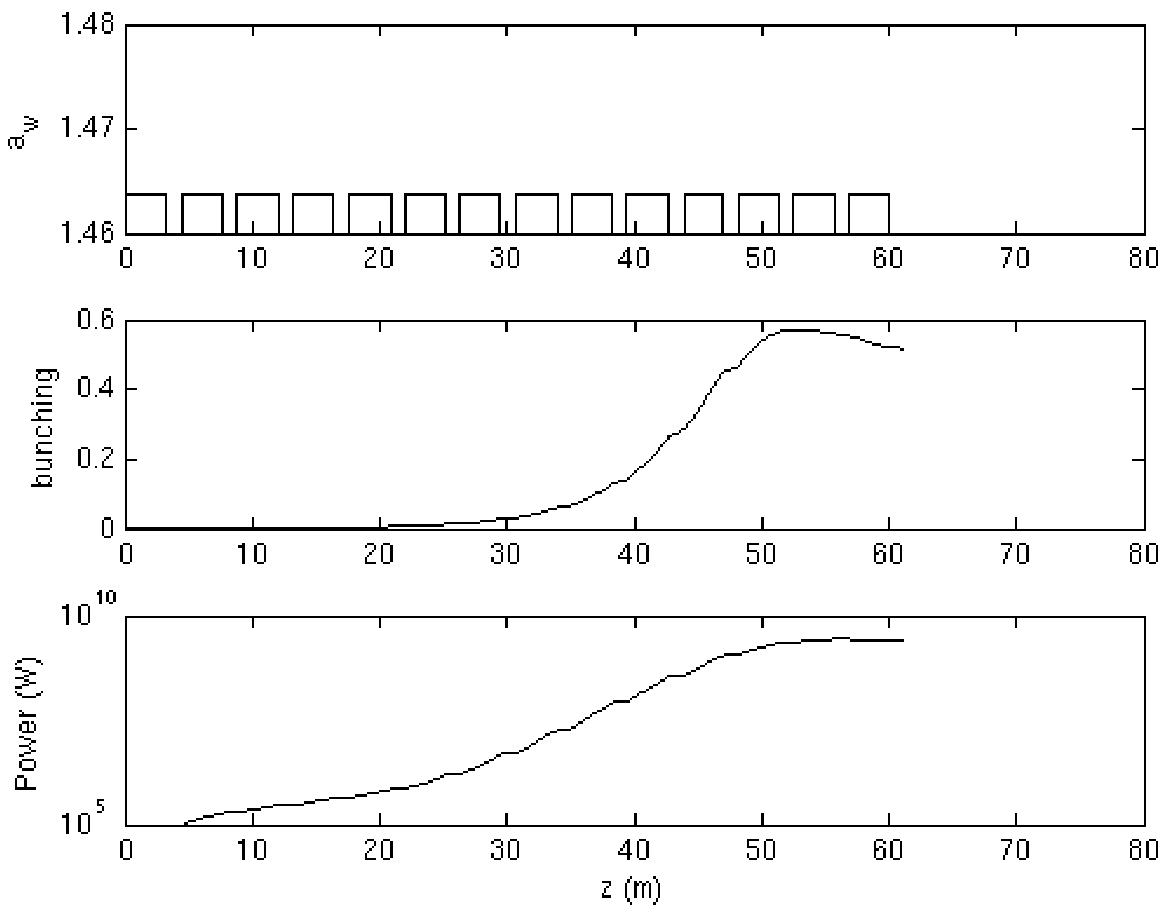
- 30 µJ with Delta off
- 510 µJ with Delta on

Peak Current increased above 4 kA

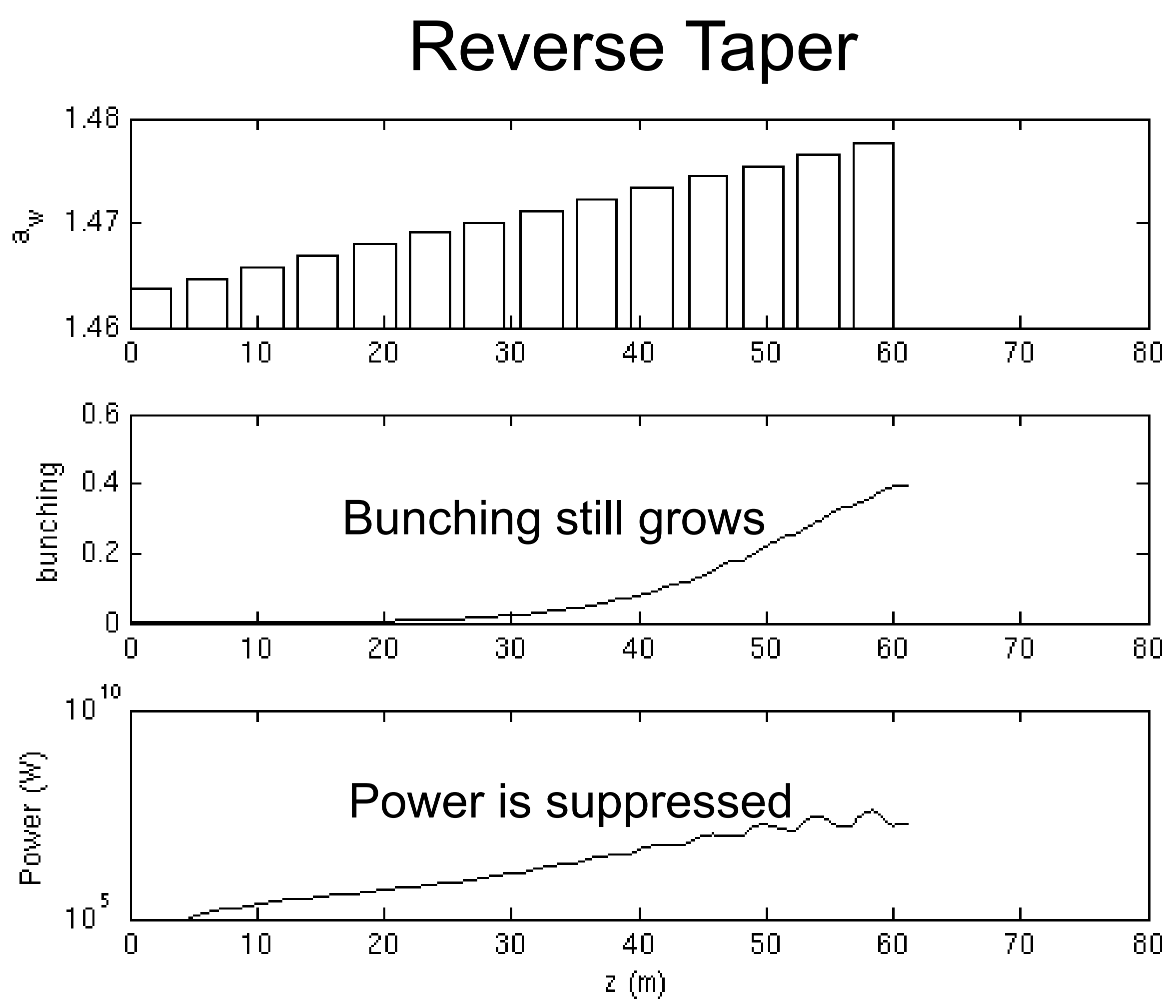
James MacArthur WEP004

Reverse Taper Simulation

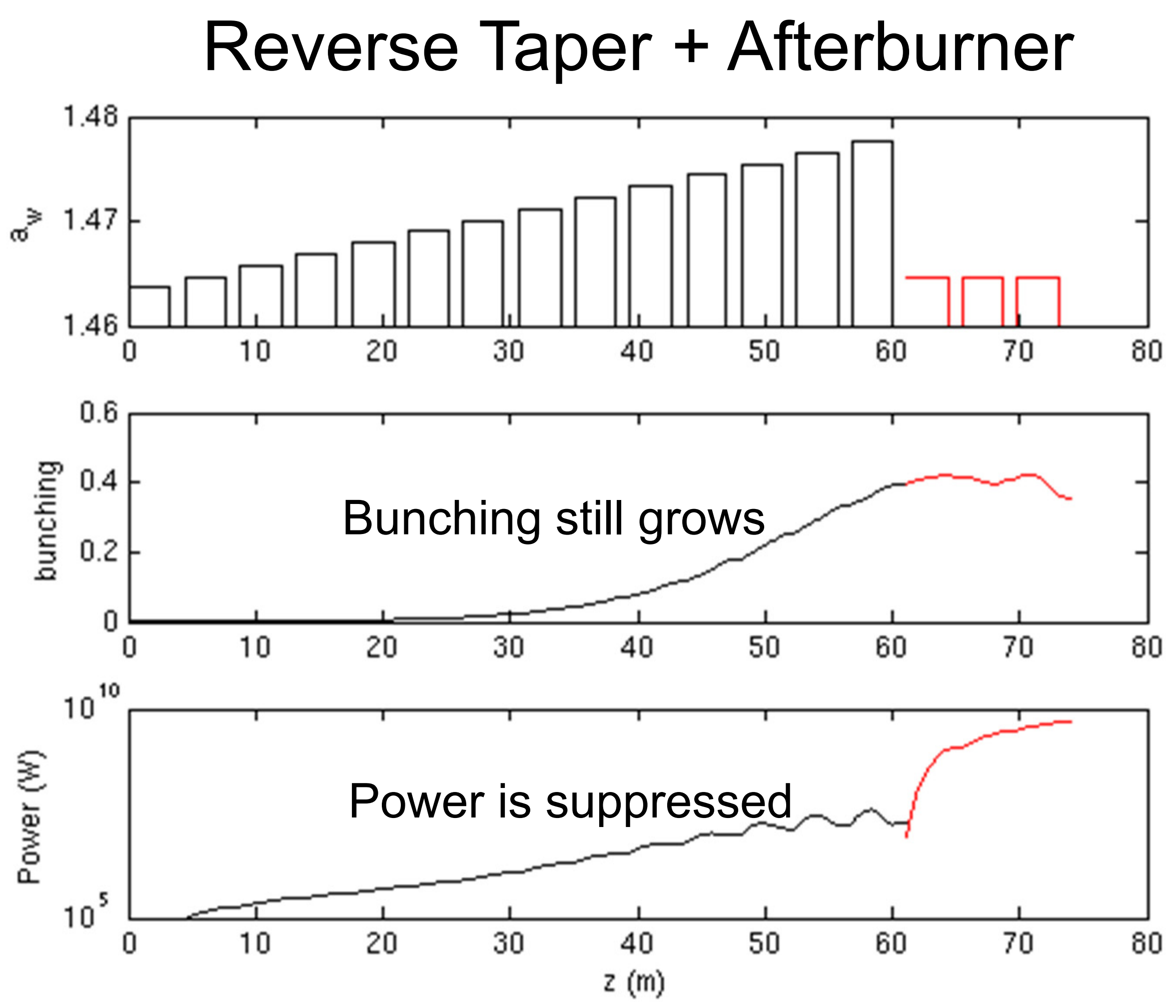
Regular Taper



Reverse Taper Simulation



Reverse Taper Simulation

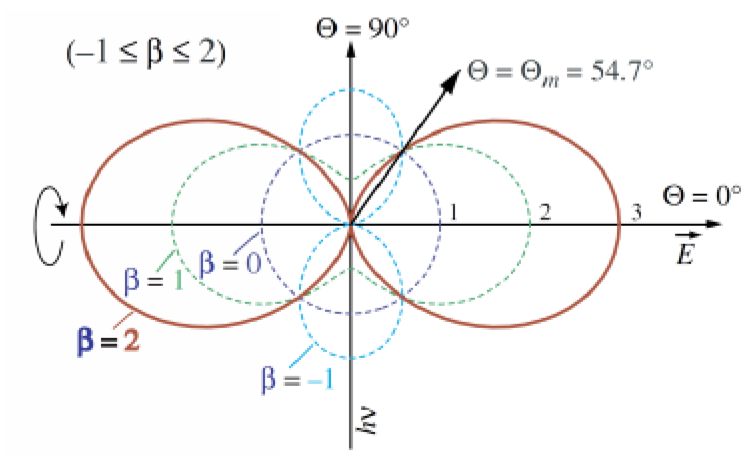


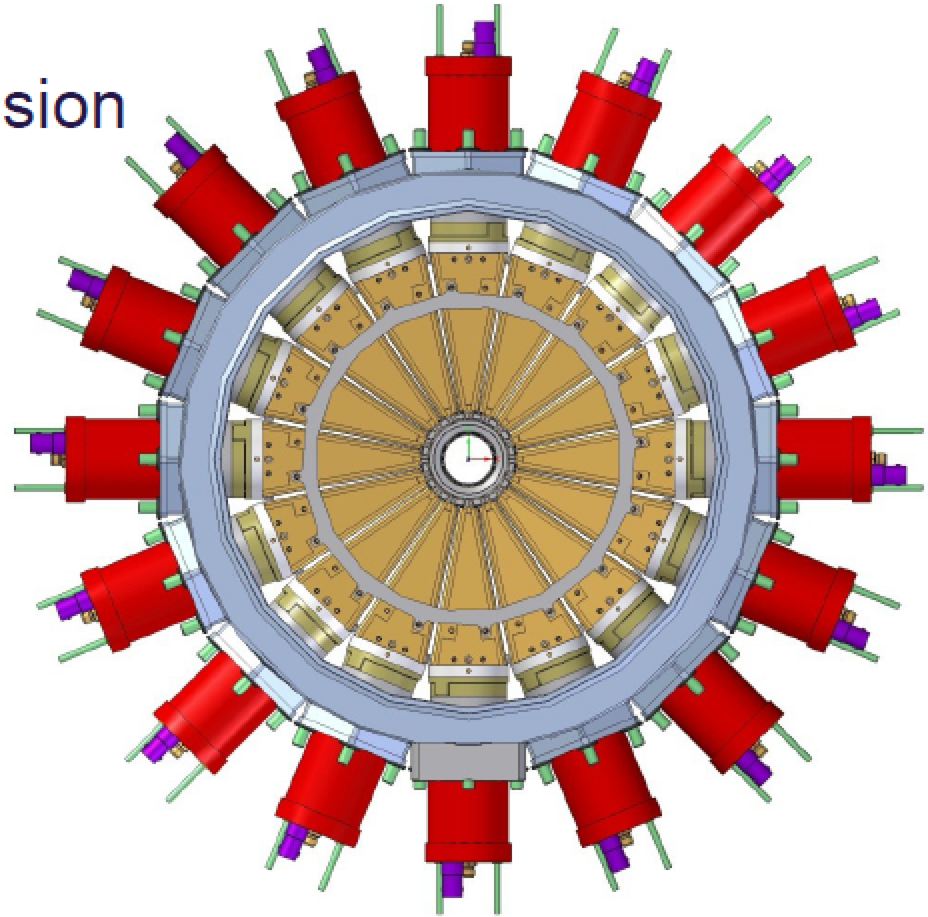
Rapid increase in power

TOF Polarimeter – DESY / EXFEL

- 16 channels (max.) ⇒ Angular resolution
- Analysis of dipole photoemission

  ⇒ Linear polarization

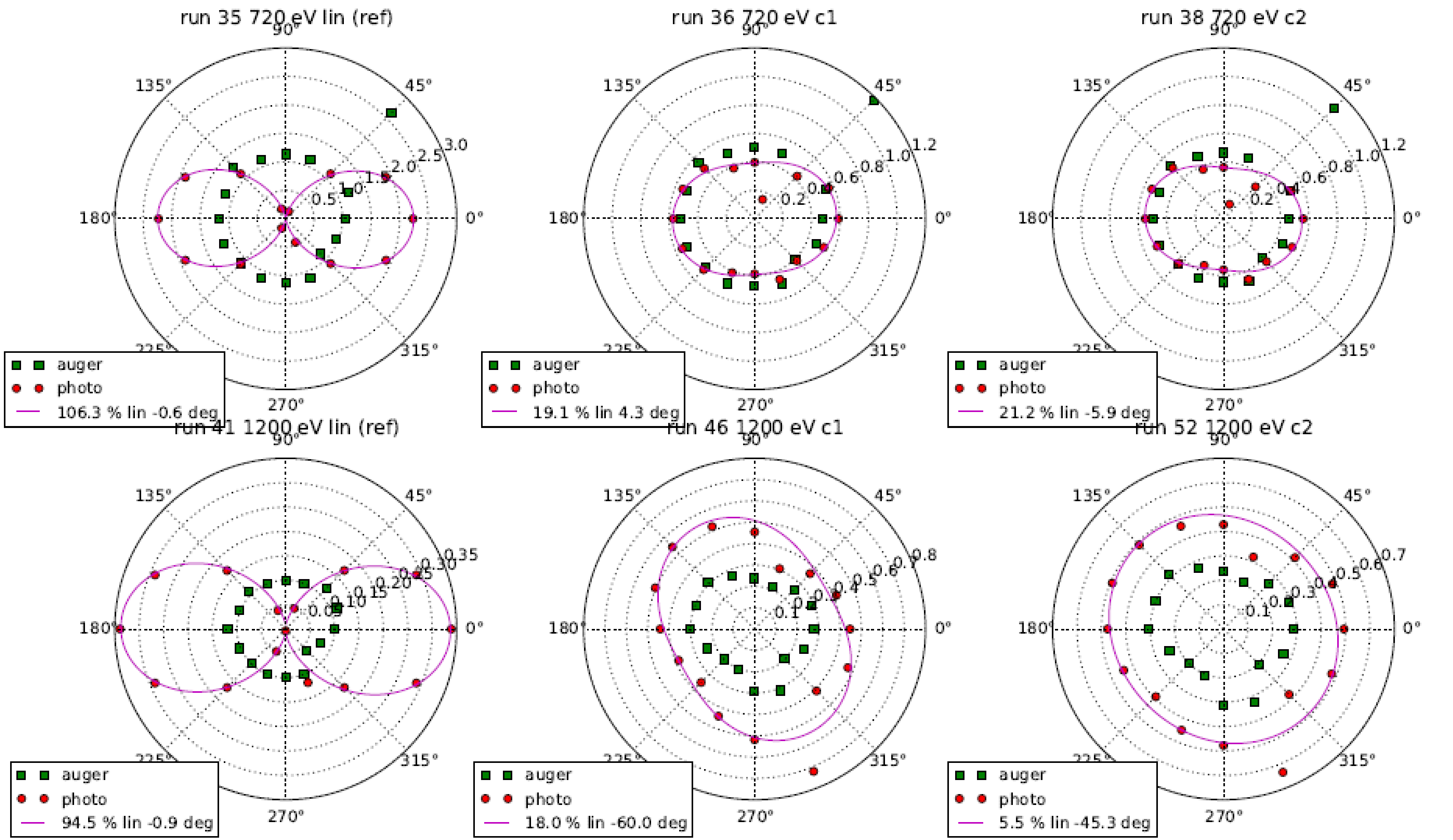




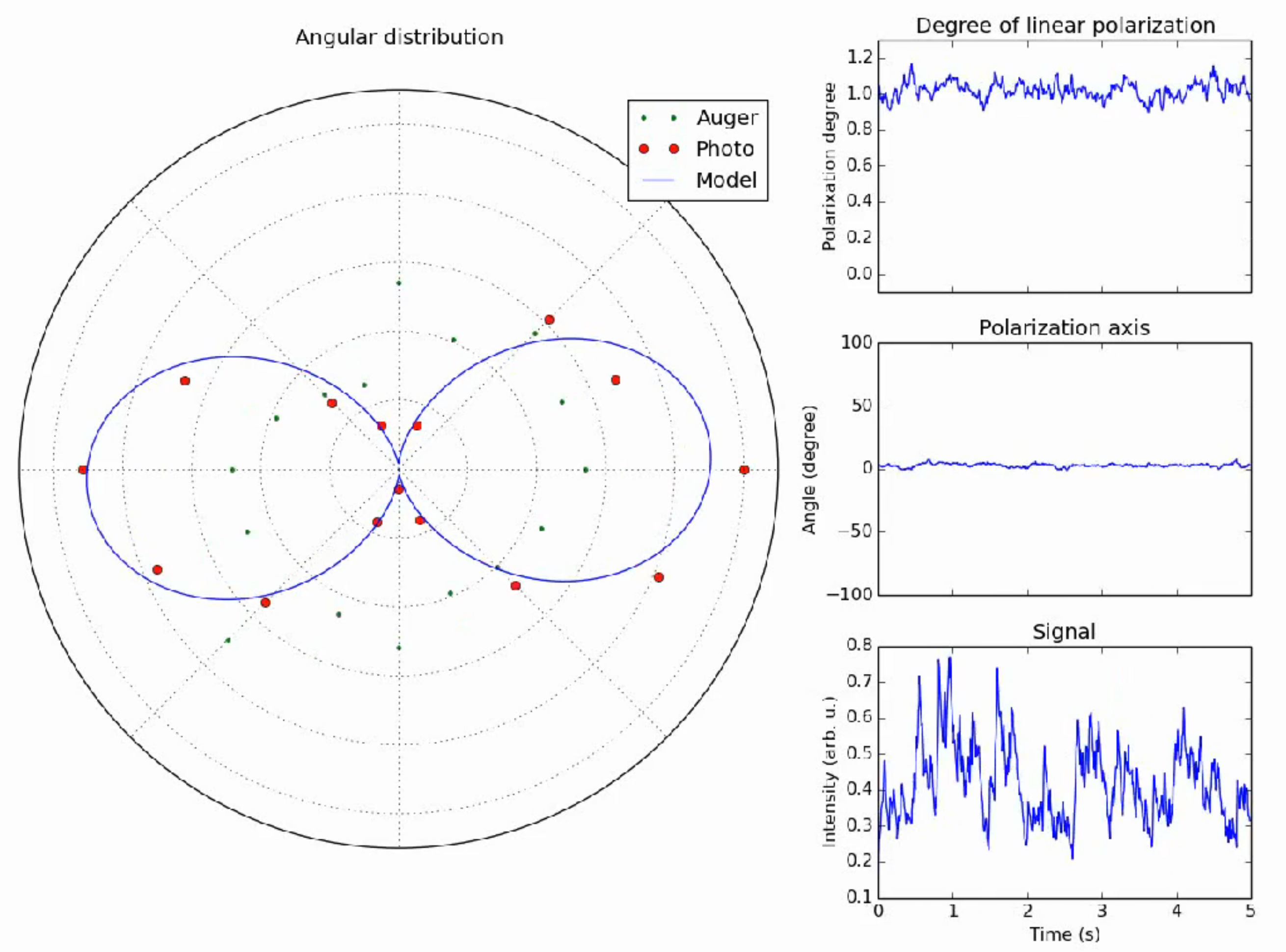
Jens Viefhaus WED02

TOF Polarimeter Displays

SLAC



Online Polarization Information



$$P(\theta) = 1 + \frac{\beta}{4} \cdot \left[1 + 3 \cdot P_{lin} \cdot \cos\left(2 \cdot (\theta - \psi)\right) \right]$$

Courtesy of Anton Lindahl

Online Polarization Information

$$P_{lin} \propto \sqrt{\frac{s_1^2 + s_2^2}{s_0^2}}$$

The degree of linear polarization as measured by the TOF polarimeter can be expressed in terms of the Stokes parameters

Scheme	E_{circ}/E_{lin}	P_{lin}	P_{circ}	E_{xray} (μJ)
Crossed Polarization			low	50[a]
Regular Afterburner	up to ~4	0.5	0.87	50[a]
Reverse Taper	up to ~15	0.3	0.96	480[b]
Split Beams	≳100		~1	220[b]

$$\begin{aligned} s_0 &= I_x + I_y \\ s_1 &= I_x - I_y \\ s_2 &= I_{45°} - I_{-45°} \\ s_3 &= I_{RCP} - I_{LCP} \end{aligned}$$

with

$$s_0^2 \geq s_1^2 + s_2^2 + s_3^2.$$

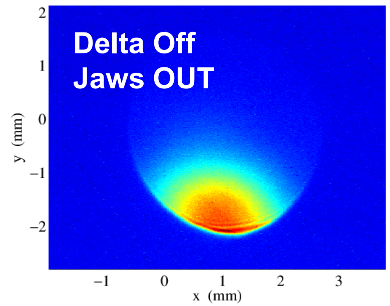
The equal sign applies if the light is fully polarized. Only in this case can the degree of circular polarization be deduced from the absence of linear polarization

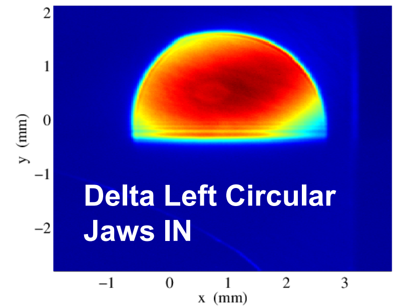
$$P_{circ} = \frac{|s_3|}{s_0} = \sqrt{1 - \frac{s_1^2 + s_2^2}{s_0^2}} = \sqrt{1 - P_{lin}{}^2}$$

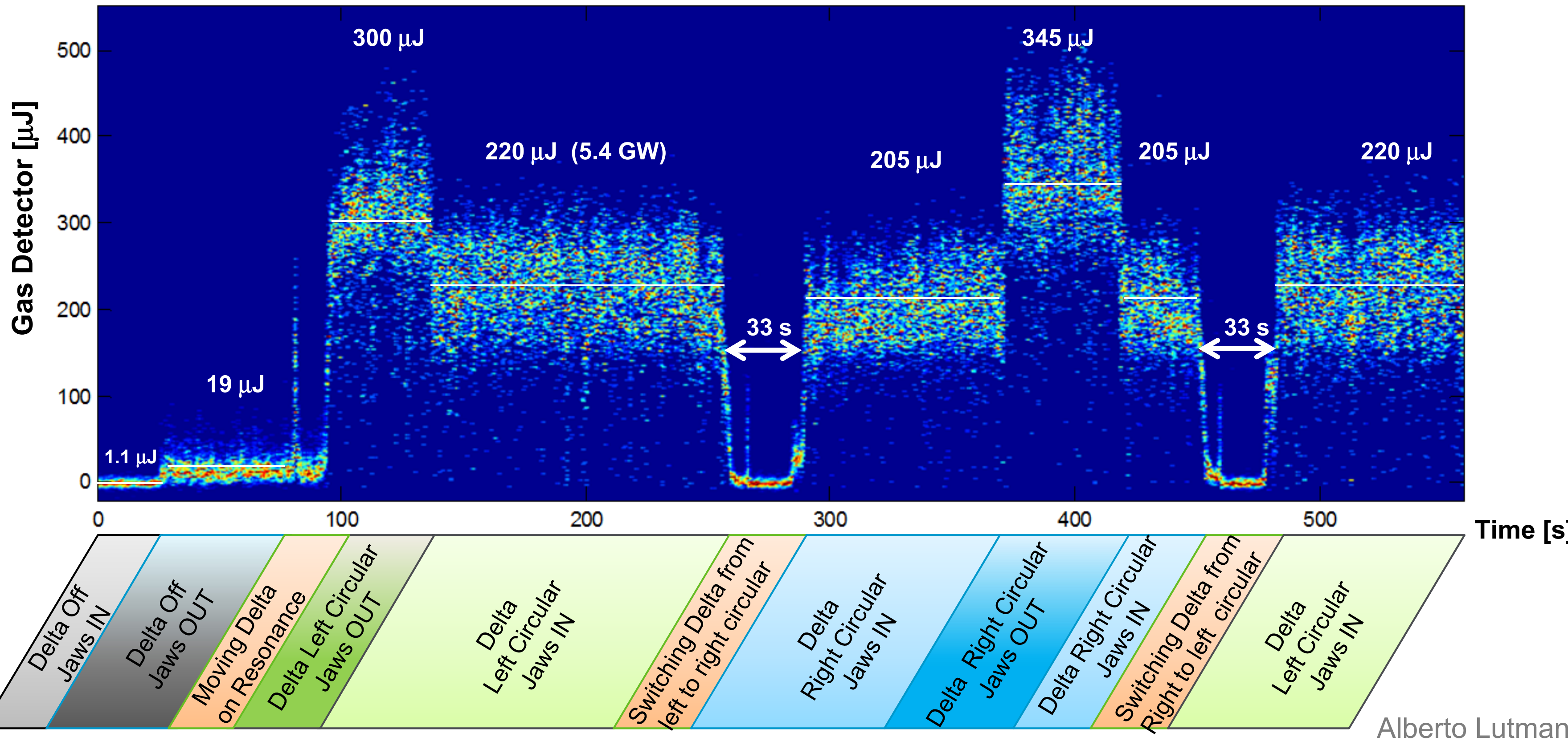
The actual degree of circular polarization has since been confirmed using x-ray magnetic circular dichroism (XMCD)

[a]Peak Current about 1500 A; [b] Peak Current above 4000 A

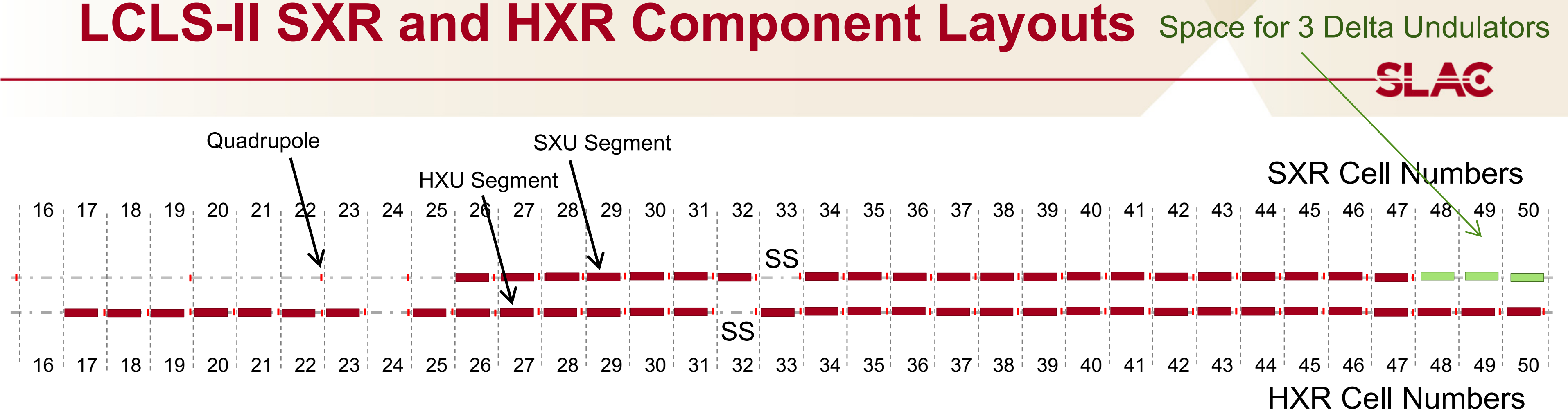
Operational Polarization Record



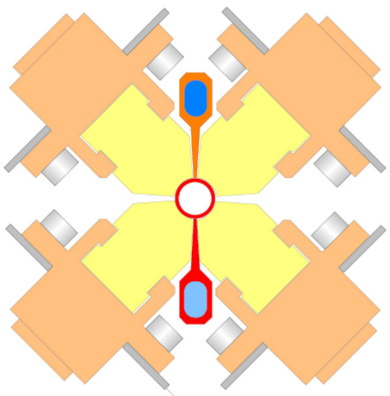


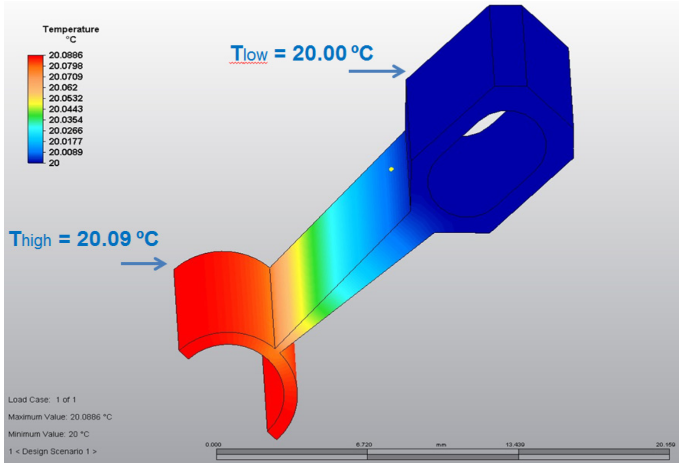


LCLS-II SXR and HXR Component Layouts



- Increased period length (39 mm) to match SXU segments
- Larger transverse block dimensions to reach
  SXU $K_{max} = 5.48$
- Improved carrier structure for increased stability and improved tuning.
- Water-cooled vacuum chamber.





Summary

- Adding the polarization control Delta undulator to the LCLS provides for the first time circularly polarized ultrafast x-ray pulses for experimental use.
- The final performance characteristics: nearly 100% degree of circular polarization and pulse intensities in excess of 0.2 mJ exceed expectations.
- Advanced modes of two colors with two polarizations with control of time and energy separations have already been demonstrated.
- A Delta undulator tailored for the new LCLS-II SXR line is being developed.

Acknowledgements

We thank **Leif Glaser, Frank Scholz, Jörn Seltmann, Ivan Shevchuk (DESY, Hamburg, Germany)** and **Jan Grünert (European XFEL)** for providing the polarimeter and excellent support with running the device during Delta machine development shifts.

Work was supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract DE-AC02-76SF00515. A.B. Temnykh is supported U.S. National Science Foundation awards DMR-0807731 and DMR-DMR-0936384.