Magnetic Measurements At SLAC

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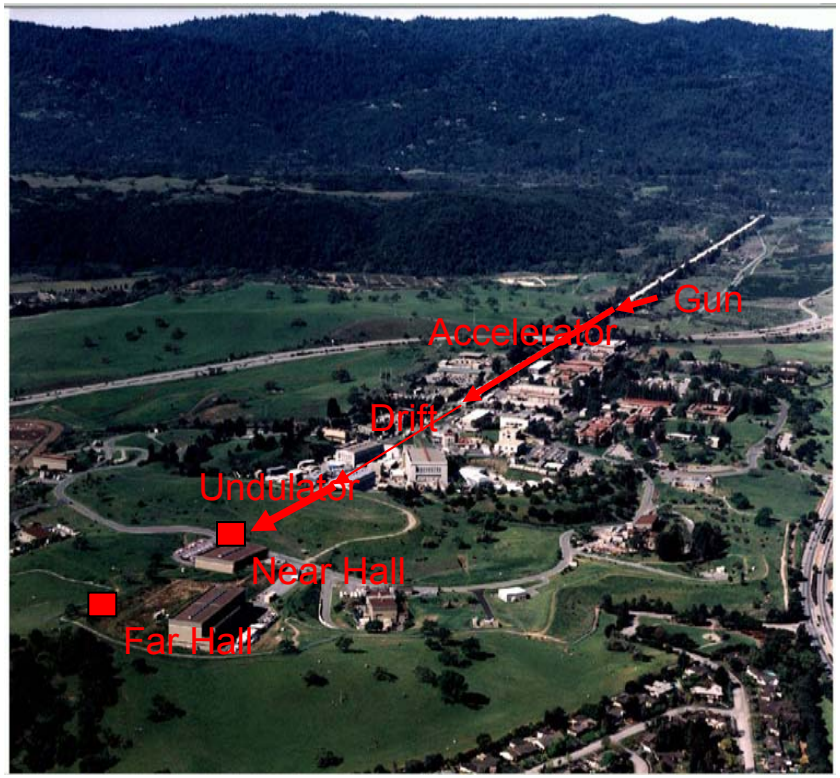
SLAC NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

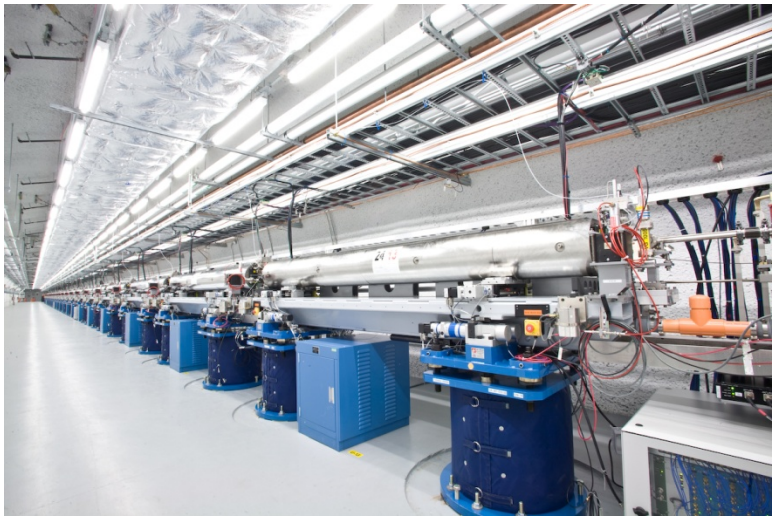
Overview Of Recent Efforts

- Conventional Magnets
  - We are between major projects
  - Just starting LCLS-II
- LCLS-I Undulators
  - Radiation damage checks – Yurii's talk
  - SHAB undulators
  - Self seeding magnets
- LCLS-II
  - Getting lab ready for construction
  - Designed and tested phase shifter
  - Designed and tested beam pipe corrector
- SSRL Undulator
  - Interesting coil straightness problem
- Delta Undulator
  - Building undulator
  - Measurement Challenges

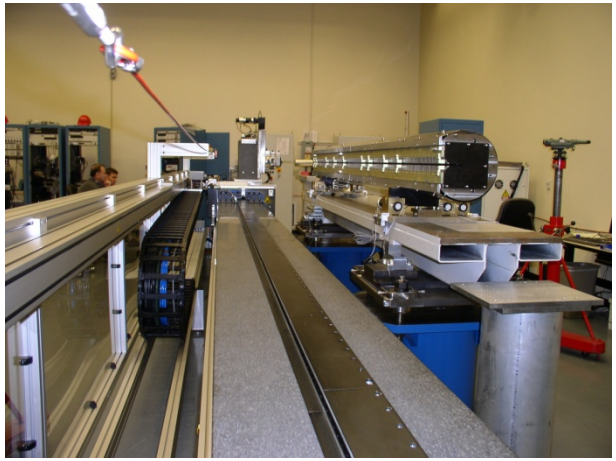
LCLS



Site Overview



Undulator Tunnel

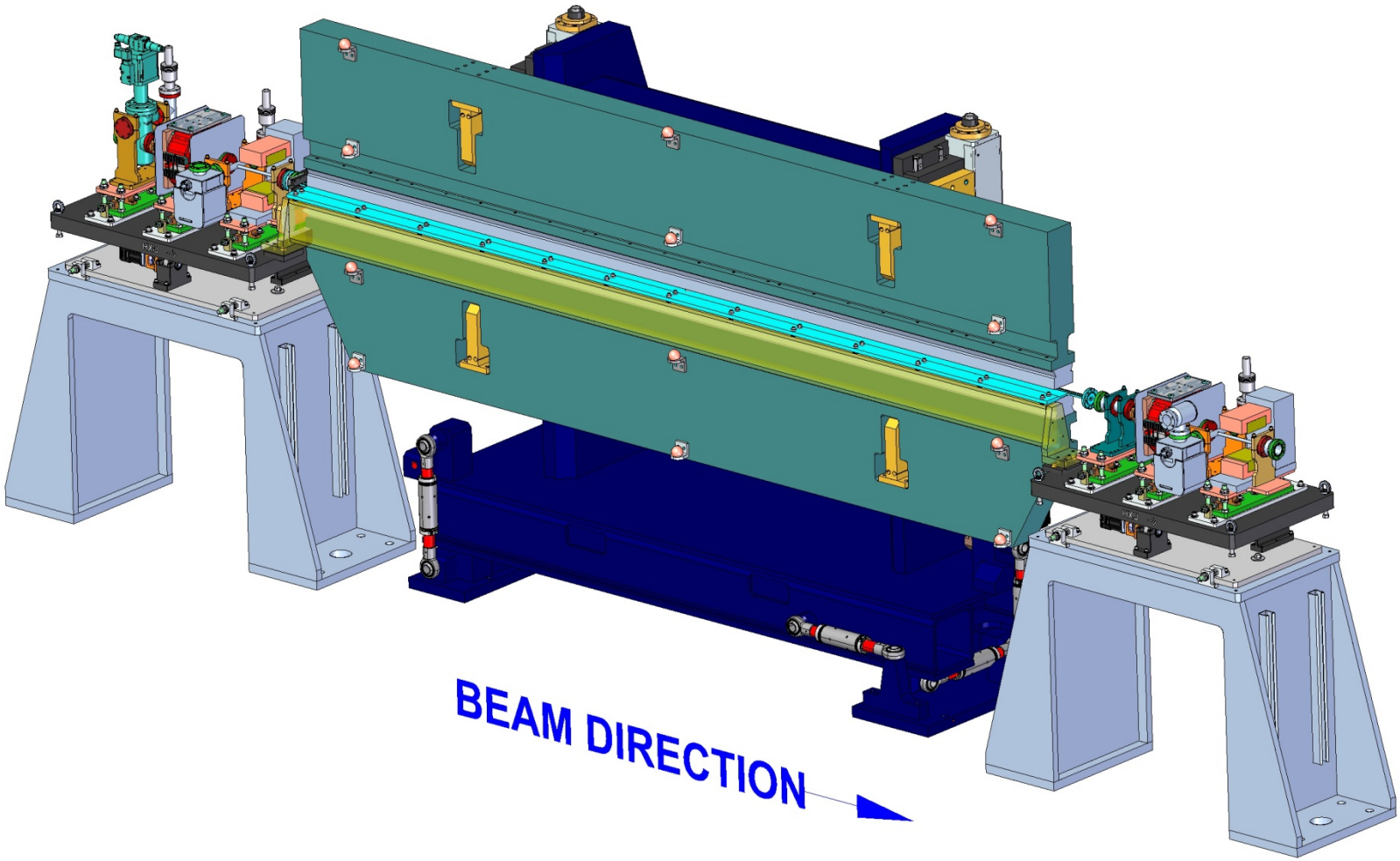


Measurement Lab

LCLS-II


Linac Coherent Light Source II
SLAC NATIONAL ACCELERATOR LABORATORY
Injector @ 1-km point
Sectors 10-20 of Linac (1 km) (with modifications)
Bypass LCLS Linac In PEP Xport Line (extended)
New Beam Transport Hall
BERKELEY LAB
SXR, HXR Undulators
X-ray Transport Optics/Diagnostics
New Underground Experiment Hall

LCLS-II Undulators



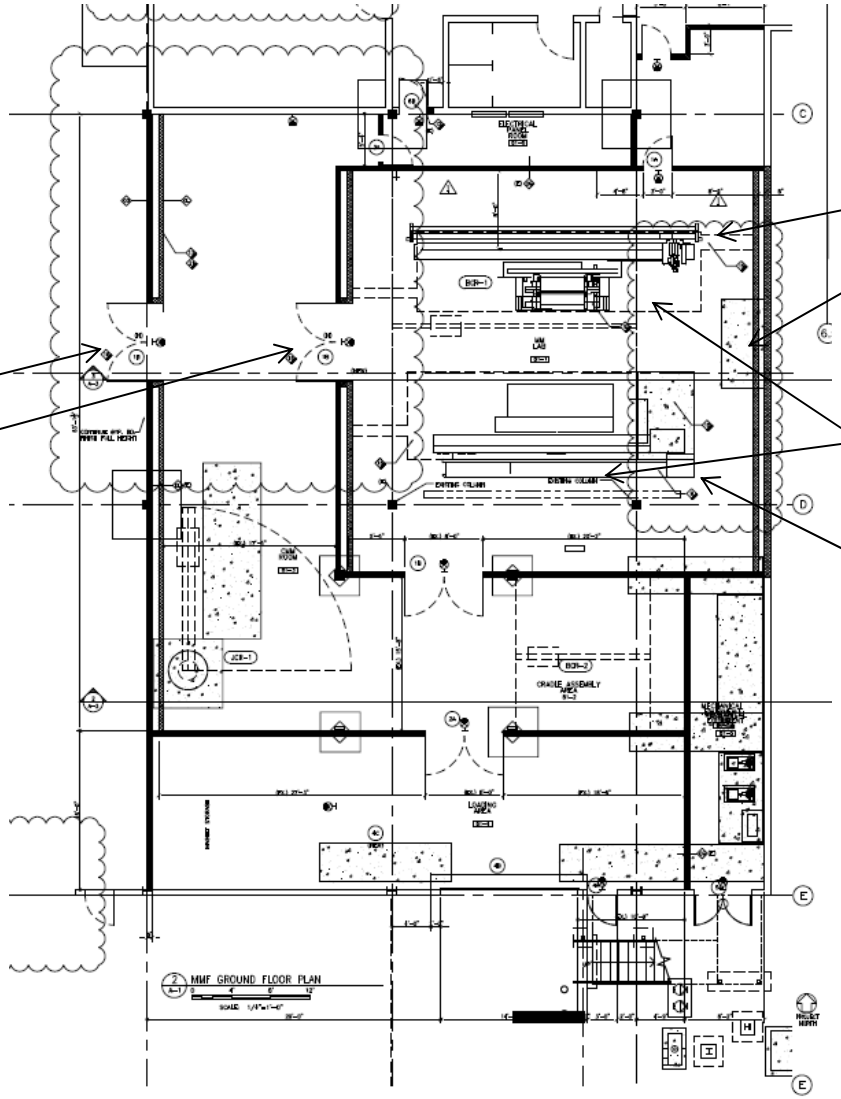
LCLS-II Undulators

Parameters:

Parameter	SXU Values	HXU Values	Unit
Number of undulator segments	15	20	
Segment length	3.4	3.4	m
Interspace length	1	1	m
Total magnetic undulator length	50.1	67.8	m
Total undulator length including interspaces	65	87	m

Parameter	SXU Values	HXU Values	Unit
Undulator period length (λ_u)	63	32	mm
Number of effective periods per segment (N_p)	52	104	
Number of poles per segment	108	212	
Undulator type	Planar	Planar	
Undulator magnet type	PM Hybrid	PM Hybrid	
Gap type	Variable	Variable	
Magnet material	$Nd_2Fe_{14}B$	$Nd_2Fe_{14}B$	
Wiggle plane	horizontal	horizontal	
Magnetic Field Symmetry	antisymmetric	antisymmetric	
Minimum operational gap height	7.2	7.2	mm
On-axis vertical effective field at min. oper. gap	>1.98	>1.26	T
K_{eff} at minimum operational gap	>11.63	>3.76	
Minimum full open gap height	200	200	mm

LCLS-II Lab Upgrade



Rotate bench

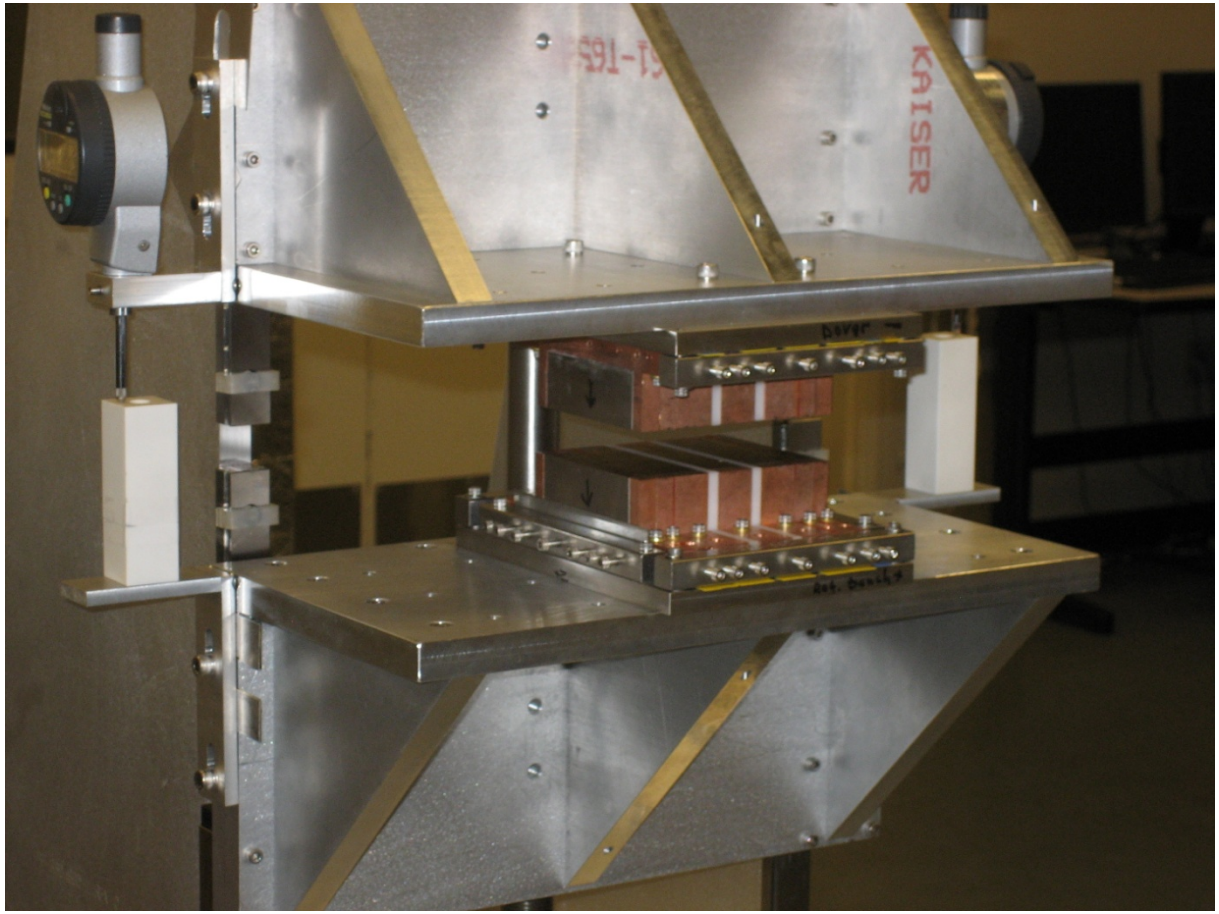
Pad for reference undulator

Two benches

Extend pad for bench

Add doors to
bring undulators in

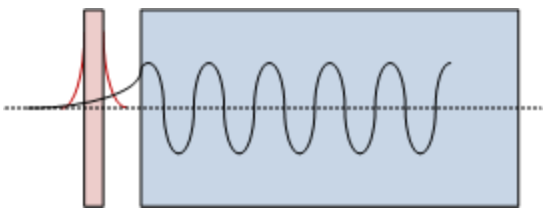
LCLS-II Phase Shifters



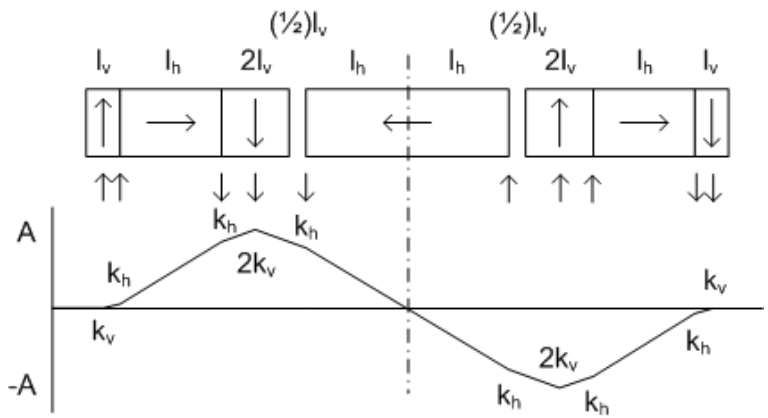
Magnet Assembly Prototype

LCLS-II Phase Shifters

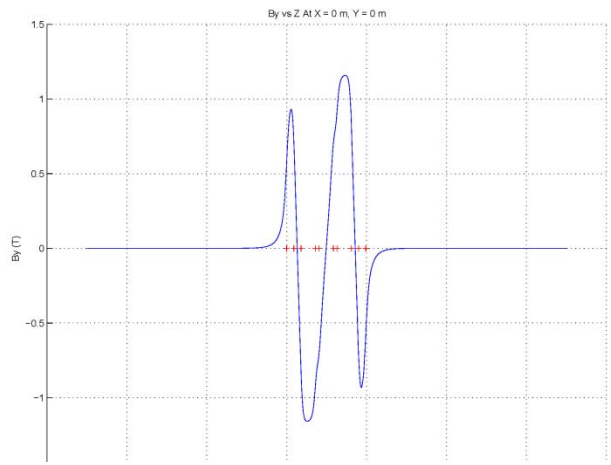
LCLS-TN-11-2, LCLS-TN-12-3



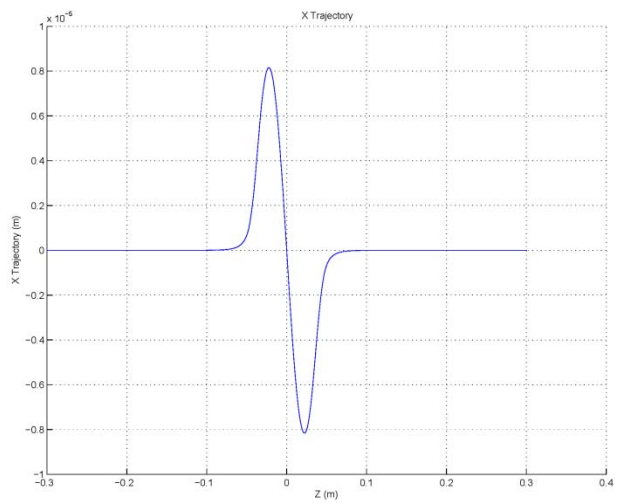
PPM, no coupling to undulator or quadrupole



Magnetic design based on trajectory kicks

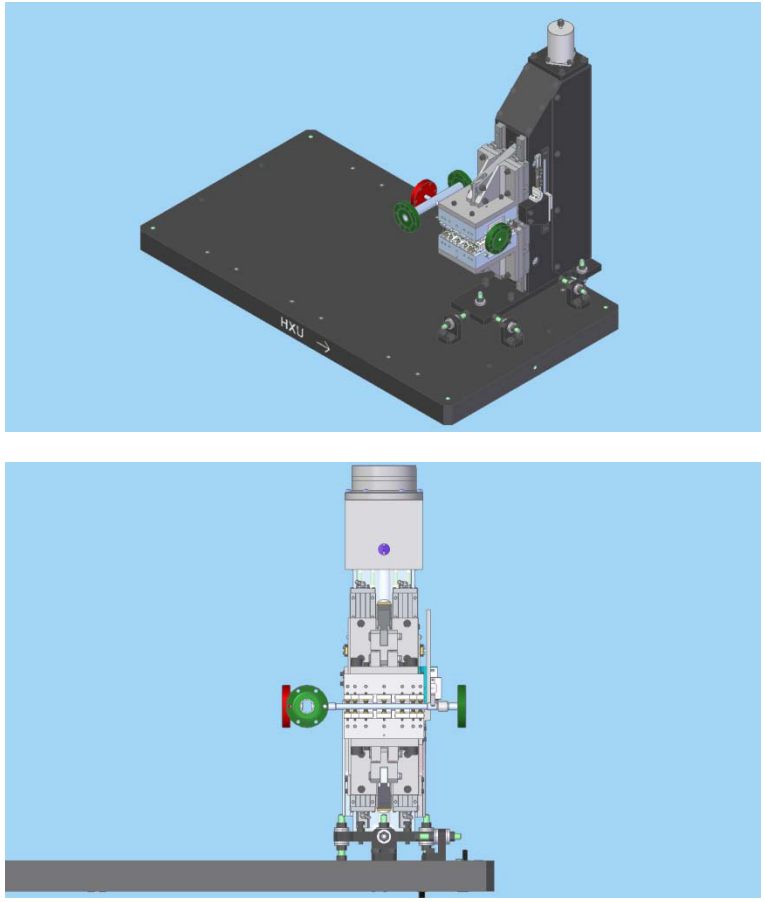


Simulated By vs z

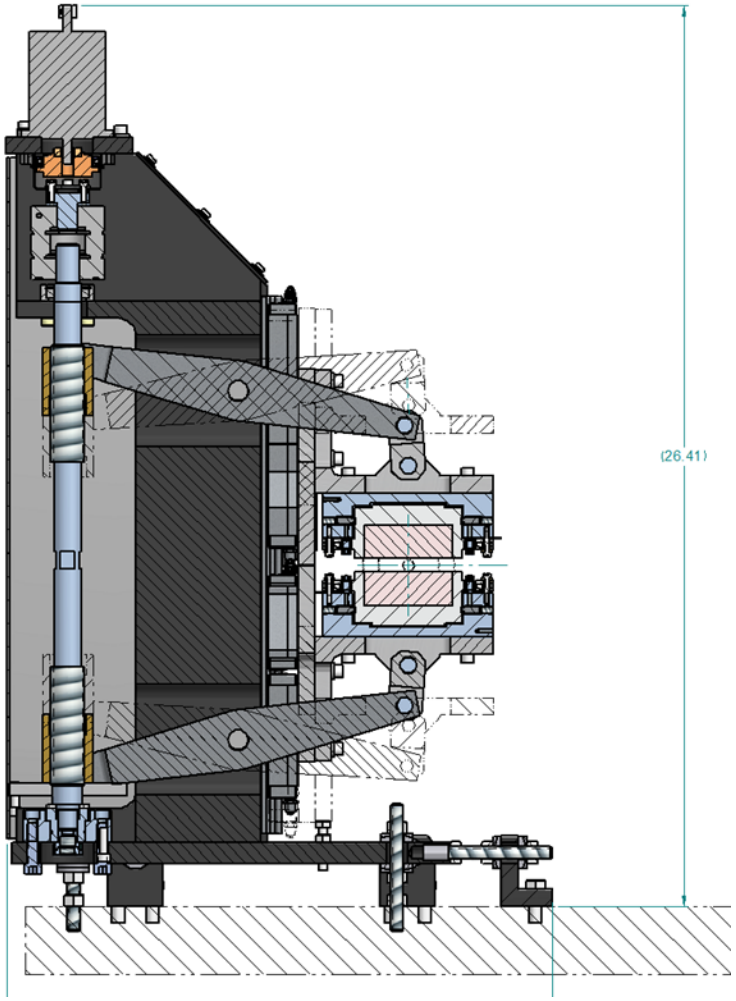


Simulated X-trajectory

LCLS-II Phase Shifters



Phase shifter on interspace stand

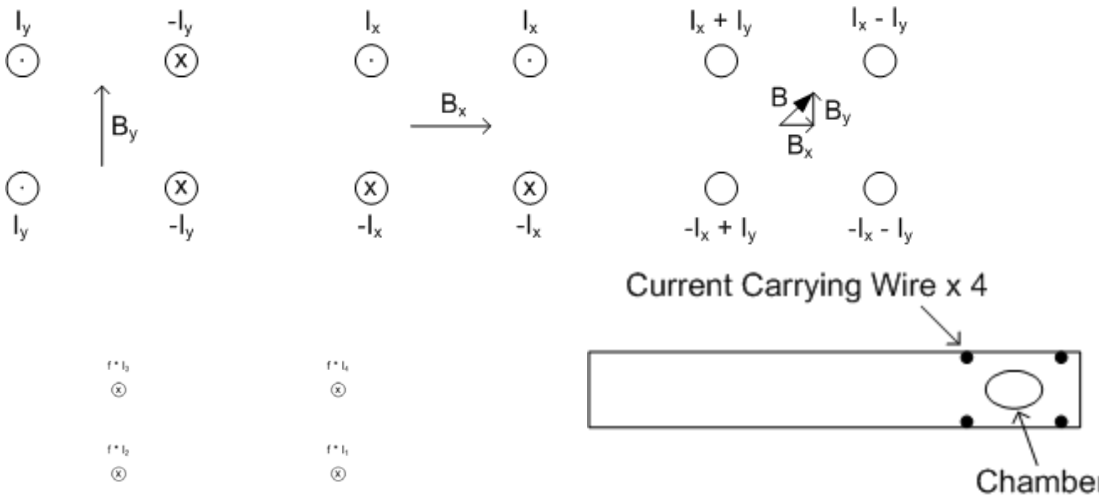


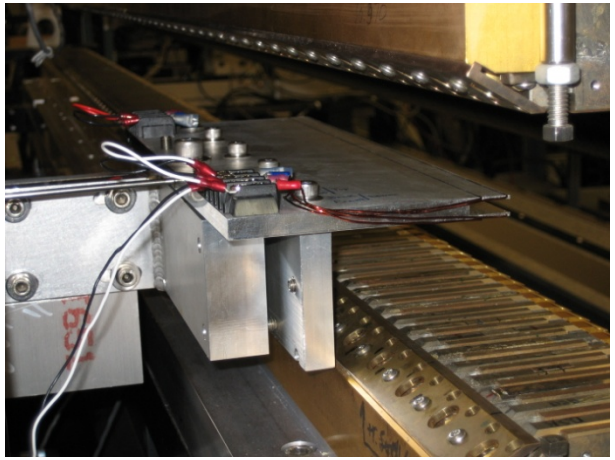
Moment-free drive

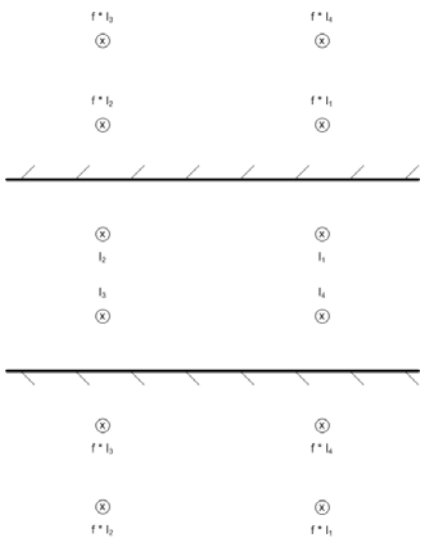
LCLS-II Beam Pipe Corrector

LCLS-TN-12-1

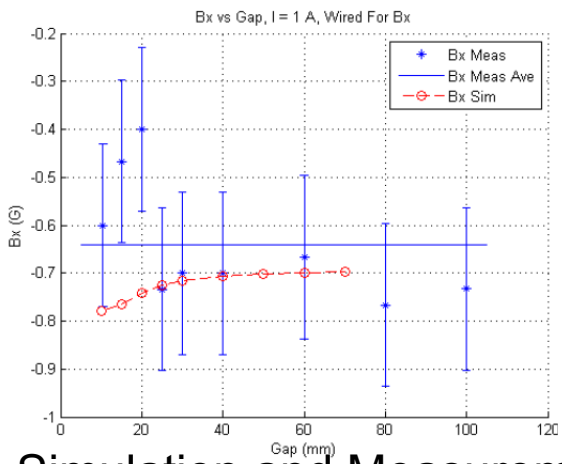
2 Power Supplies For Bx and By

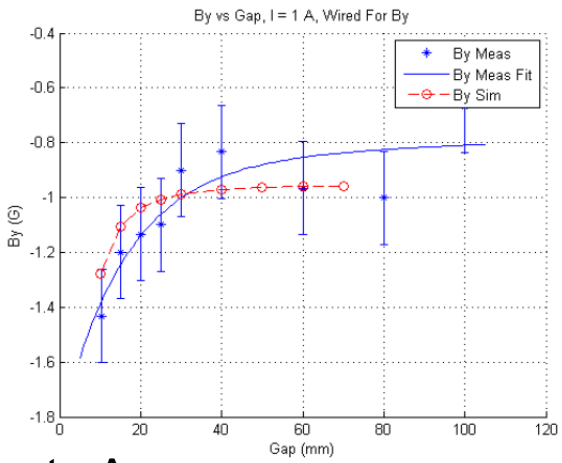






Included image currents in simulation

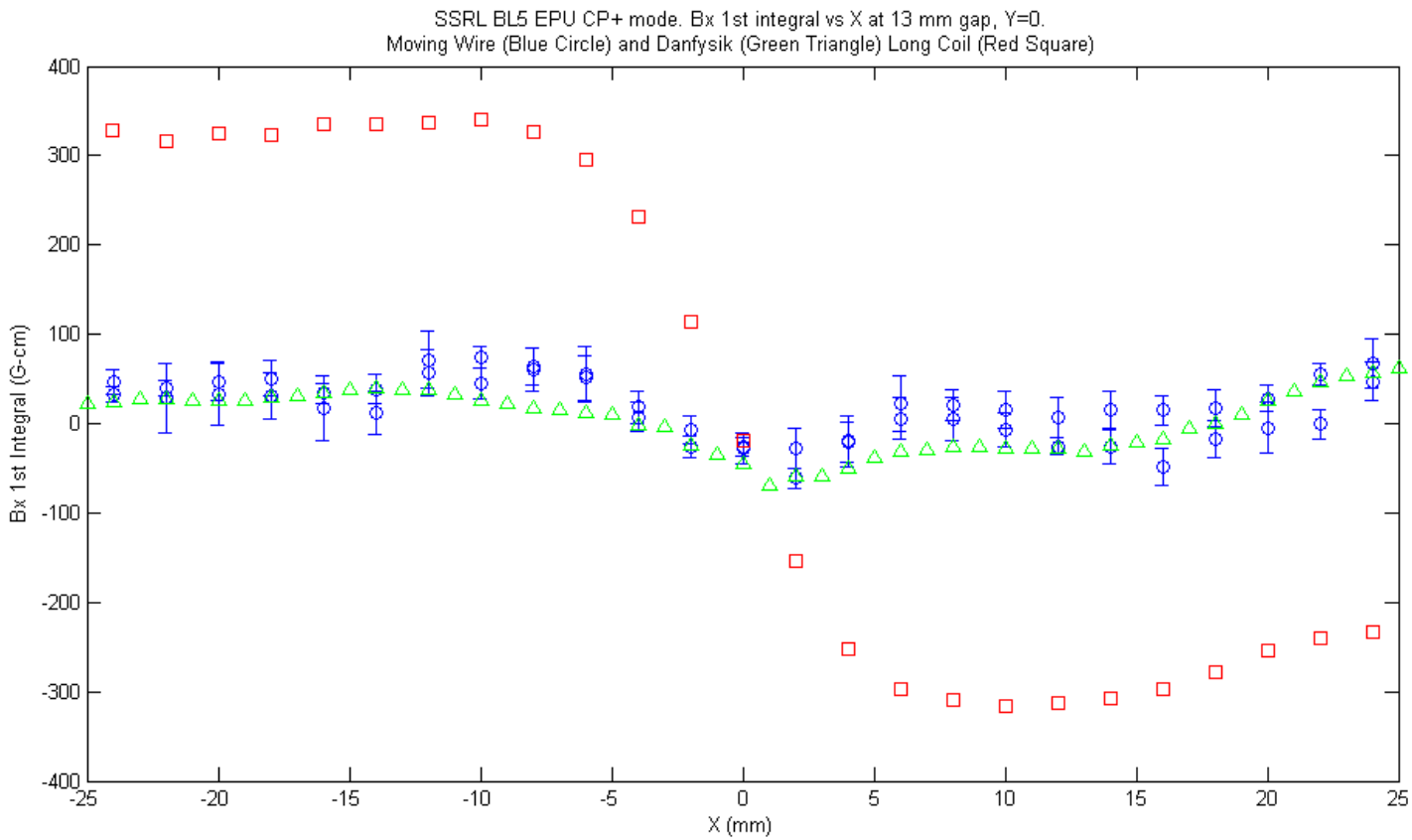




Simulation and Measurements Agree

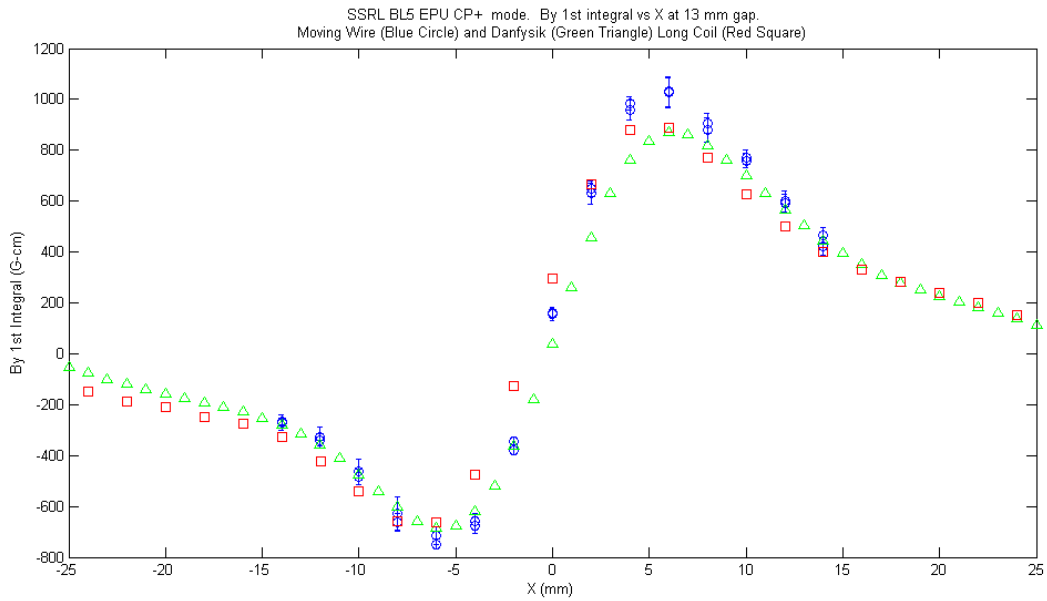
SSRL BL5 Undulator

Bx Field Integral Measurements



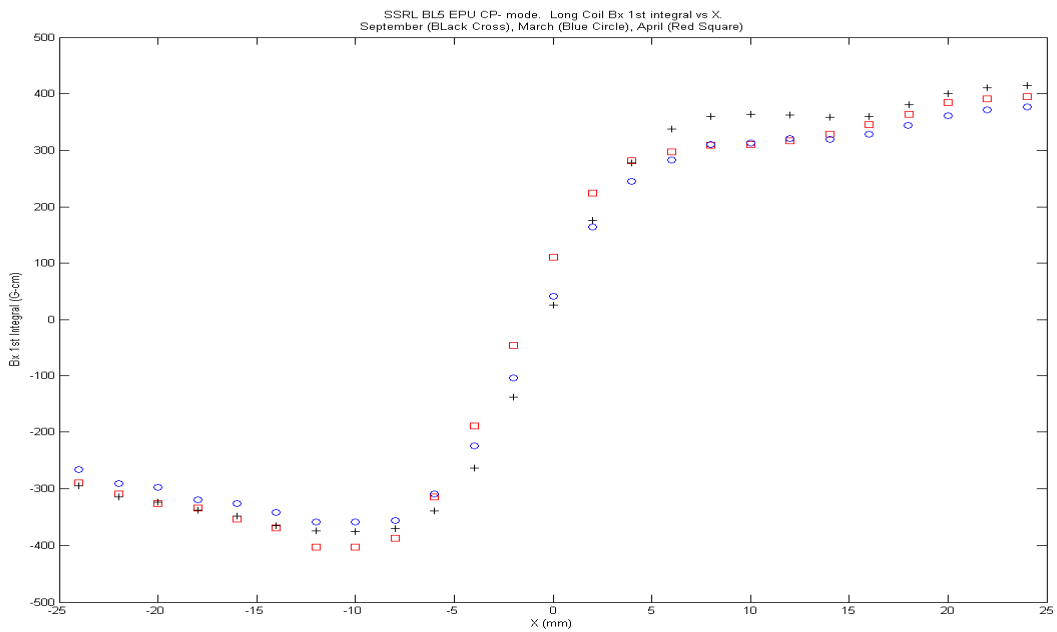
SLAC long coil Bx field integral measurements did not agree with Danfysik measurements. Started investigation to find out why.

Problem Only In Bx, Not By



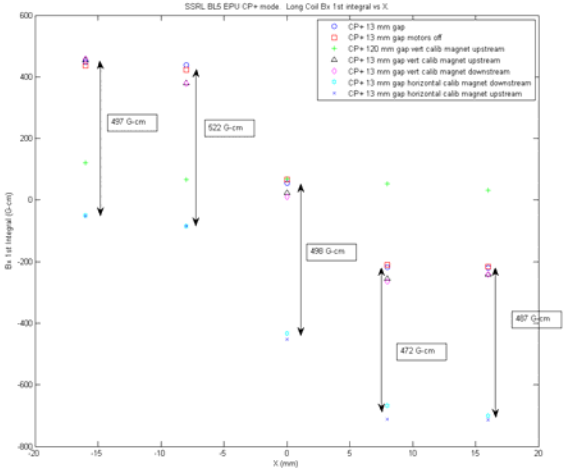
By integrals agreed. Only Bx integrals did not agree.

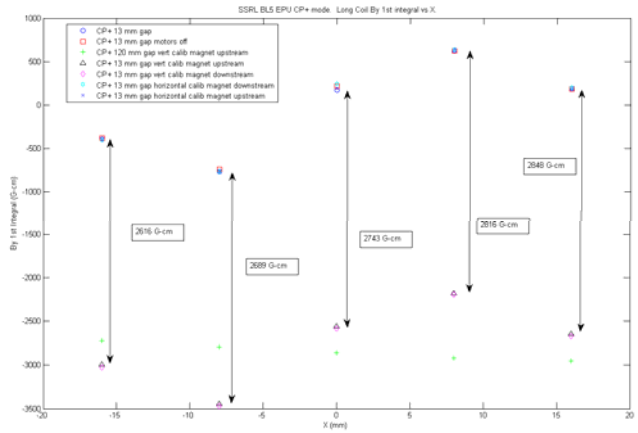
Measurements Repeatable

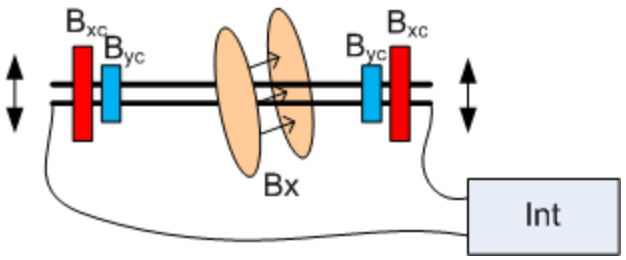


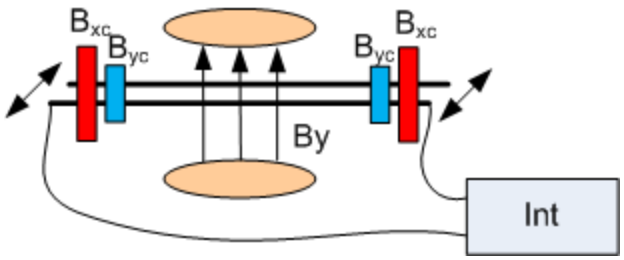
The odd looking Bx integral measurements were very repeatable.
They also were consistent with Maxwell's equations.

Calibration Magnet Checks



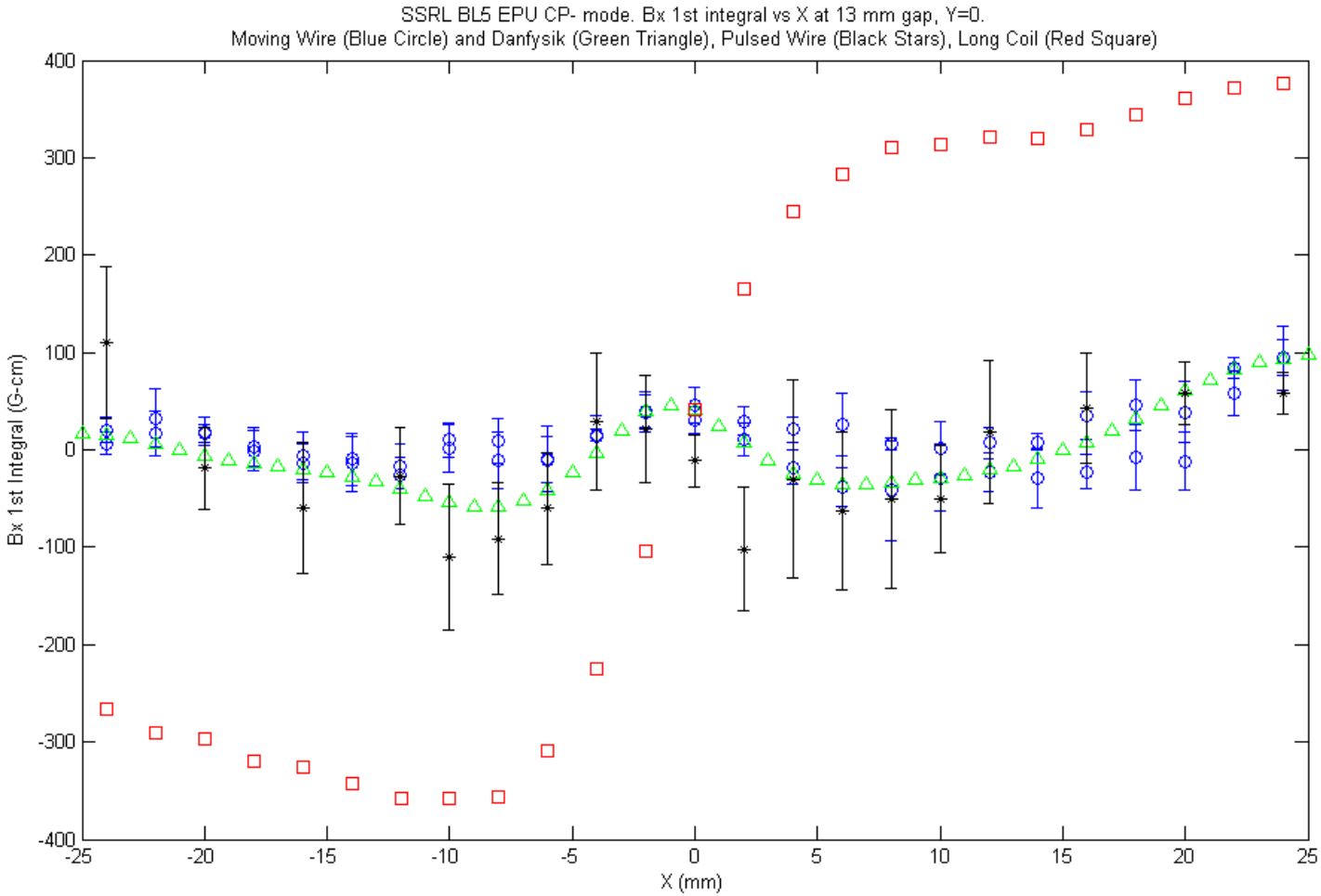






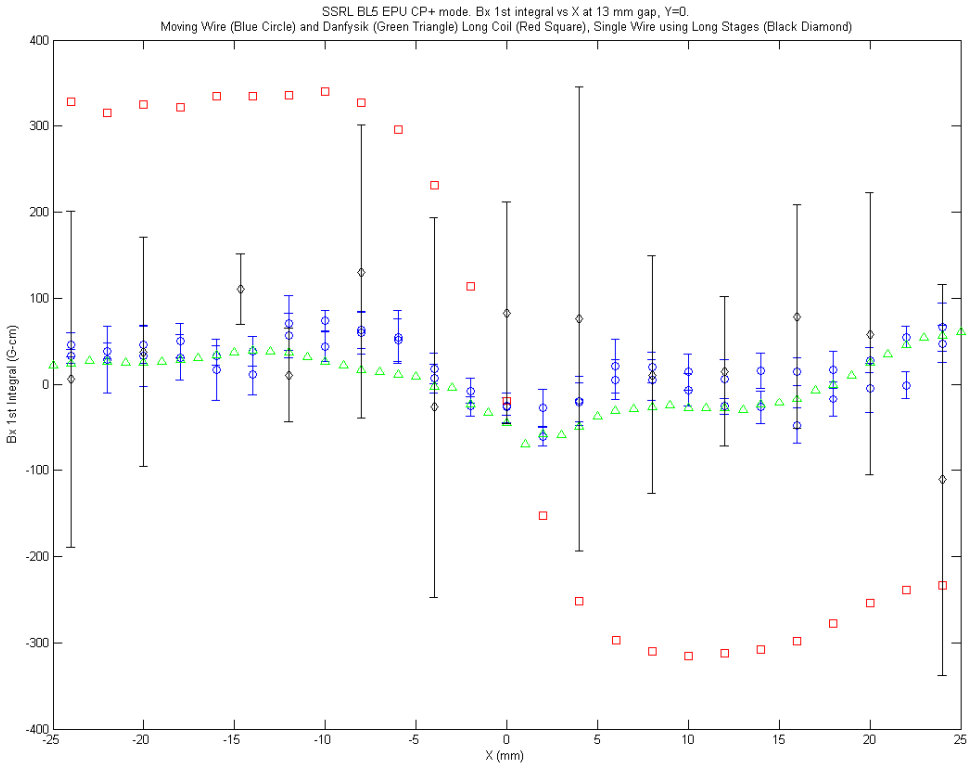
When a calibration magnet was added, the field integrals changed by the right amount. Implies stages moving ok, software correct, calibration correct. When undulator motors off, measurements don't change. Not noise problem.

Moving Wire and Pulsed Wire Check



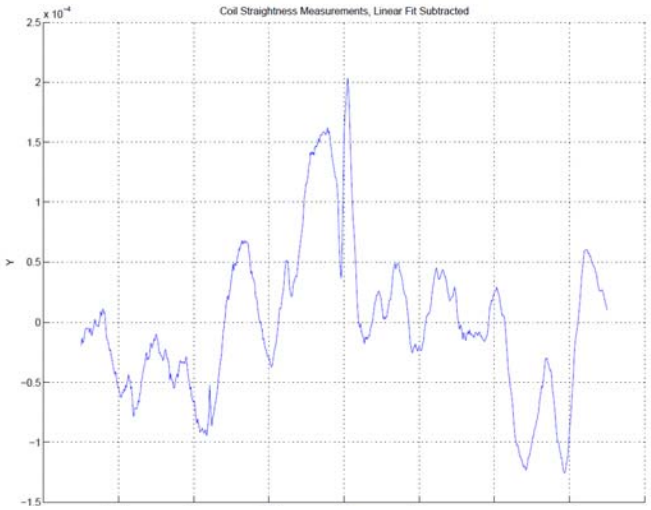
Set up moving wire and pulsed wire measurements to find the right answer.
The Danfysik measurements were correct.

Replace Coil With Single Wire

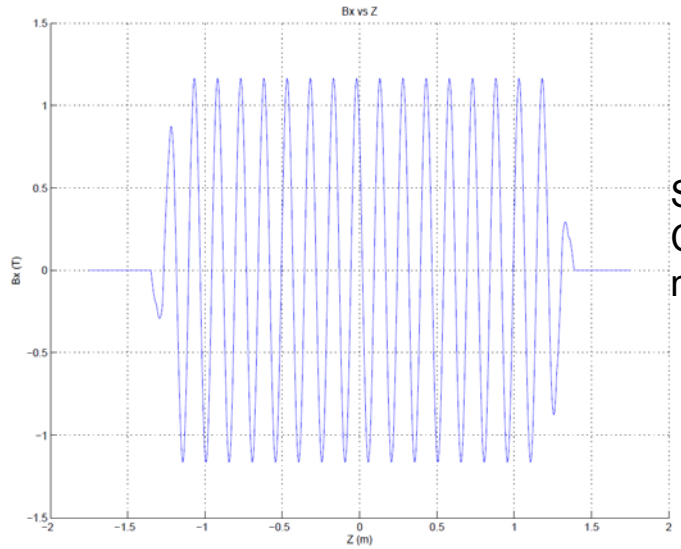


Replaced long coil with a single wire. Odd behavior is coming from the coil.

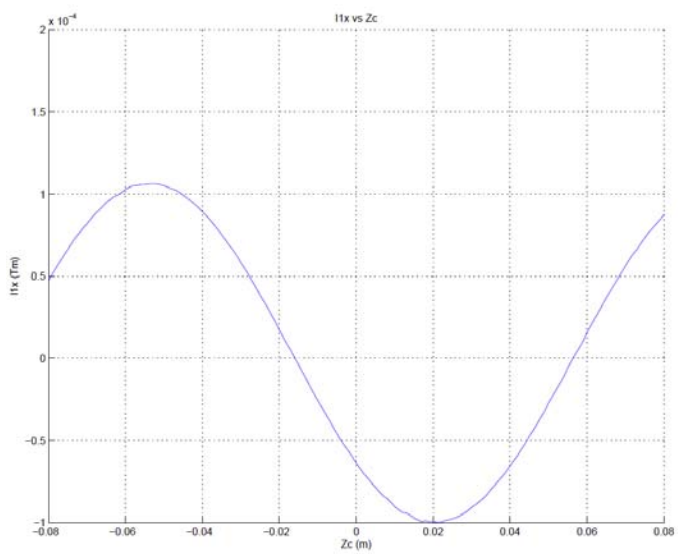
Coil Straightness Plausible Explanation



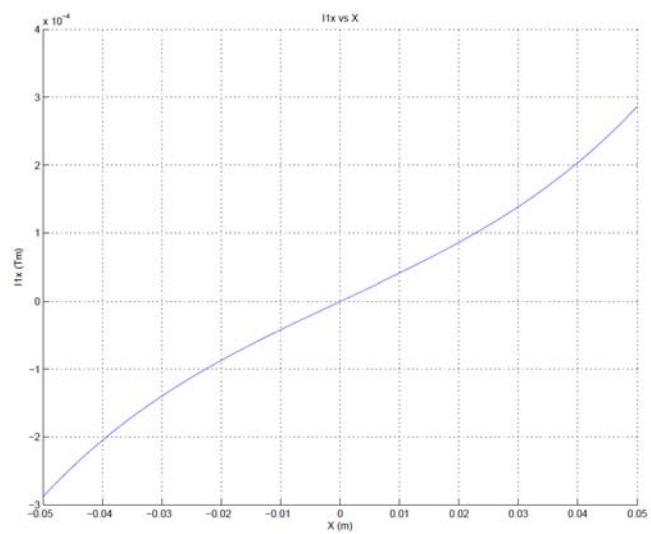
Coil Straightness In y



Simulated CP Field, no L-shims



Scan Coil Position In z



Bx Integral vs x

Changes Sign At Center

Delta Undulator

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

Delta undulator for Cornell energy recovery linac

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(Received 17 October 2008; published 11 December 2008)

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.

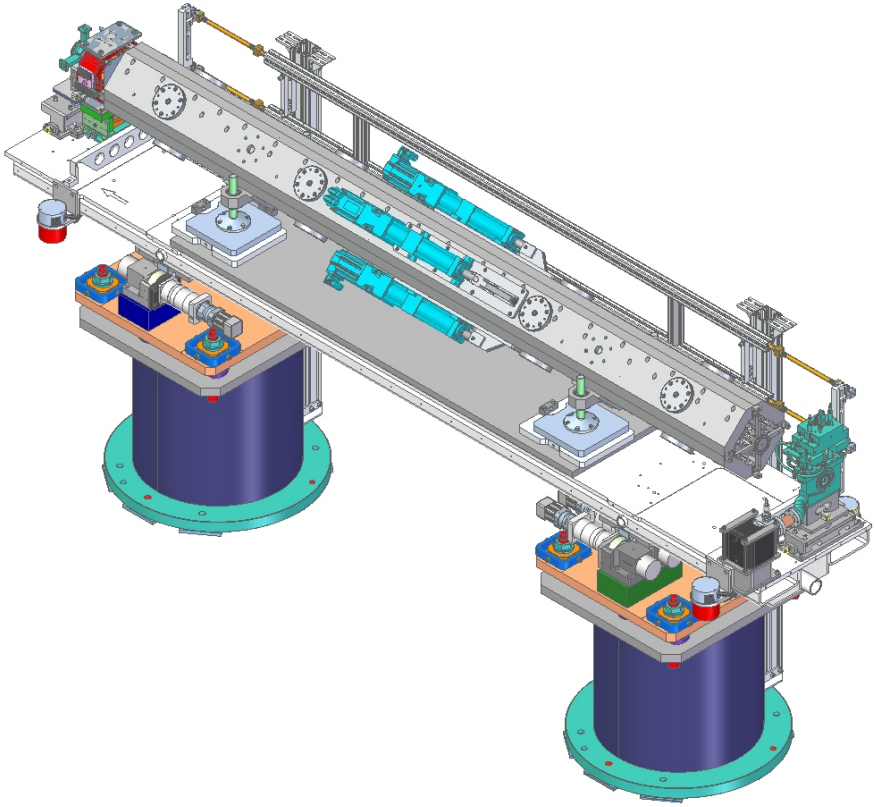
DOI: 10.1103/PhysRevSTAB.11.120702 PACS numbers: 85.70.−w, 41.60.−m, 07.85.Qe

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

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].

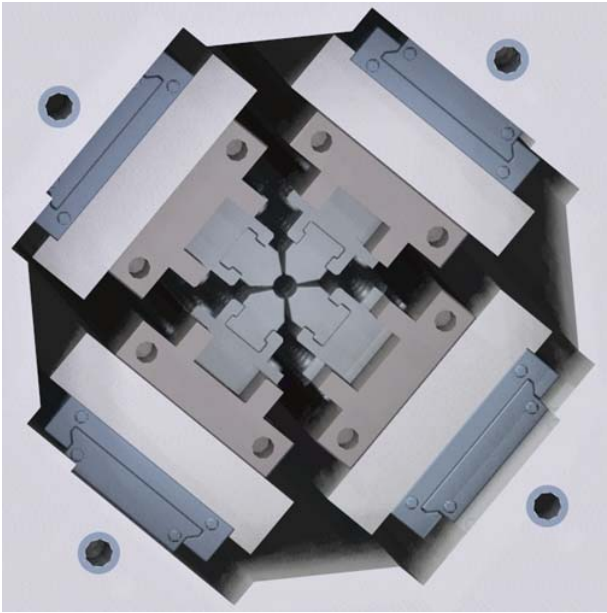
The round bore allows the design of a highly symmetric

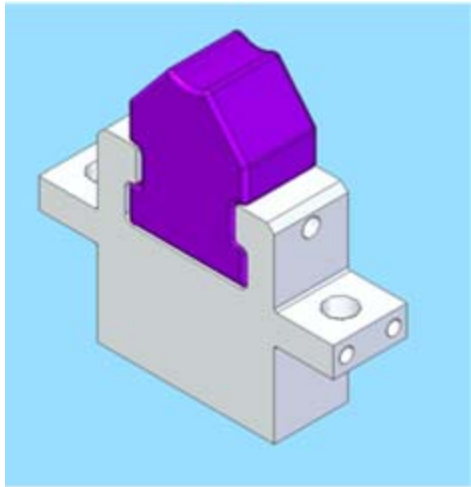


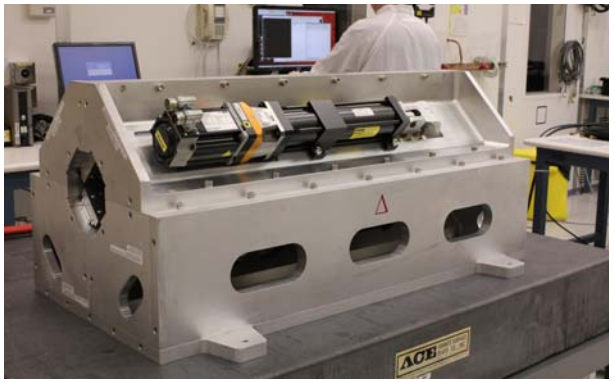
EPU in a package compatible with LCLS

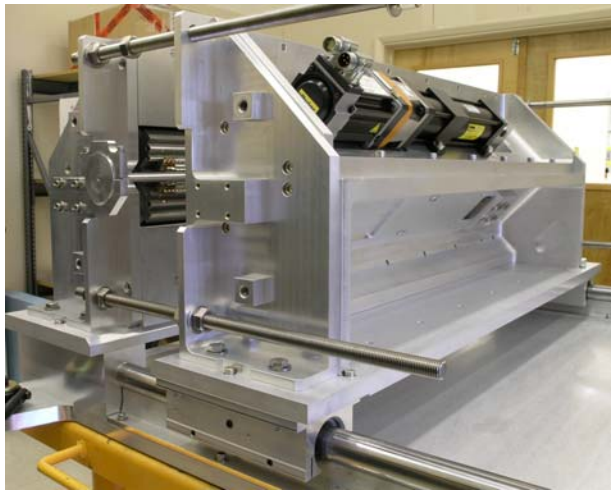
Delta Undulator

Prototype under construction







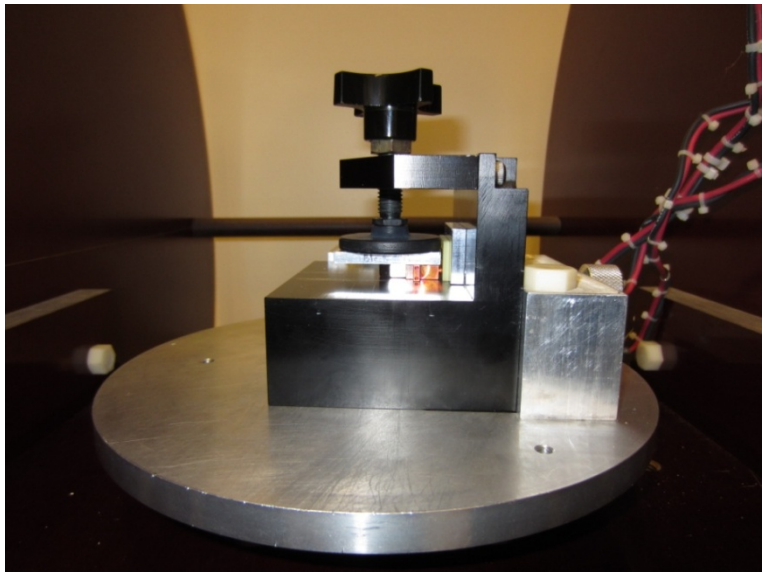


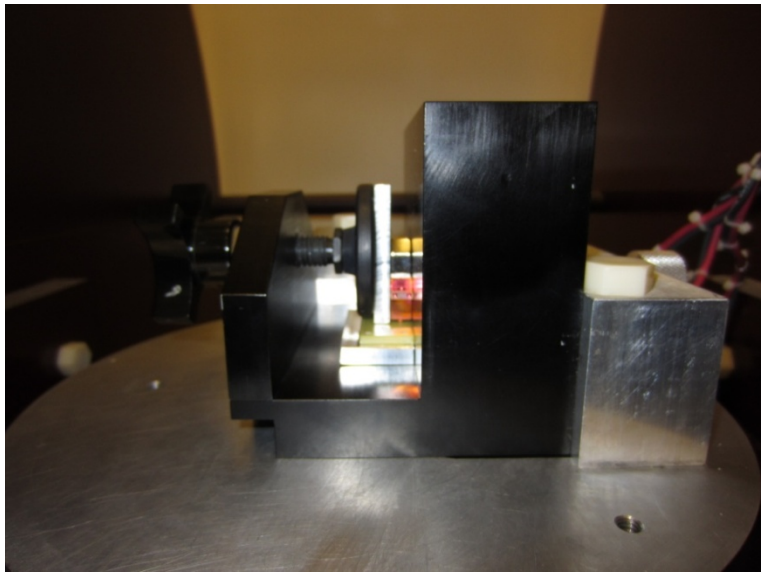
Delta Magnetic Measurements

- The measurements of the Delta undulator are an R&D effort. Eventually, we wish to make measurements with LCLS accuracy in the 6.6 mm diameter bore of a 3.2 m long undulator with no side access.
- We anticipate making an FEL from Delta undulators in the future.
- Our goal is to achieve FEL type measurement accuracy:
  - trajectories straight to 2 microns
  - rms phase errors below 10 degrees
  - phase matching errors below 10 degrees
  - first field integrals below 40 μTm
  - second field integrals below 50 μTm^2
  - K value accurate to 10^{-4}, measured at many row phases
  - beam axis fiducialized to 20 μm
- We measure on the curved path of a guide tube in the assembled undulator, not on the beam axis.
- We can only tune quadrants. The assembled undulator can only only be measured. Do as much tuning as possible before assembly.

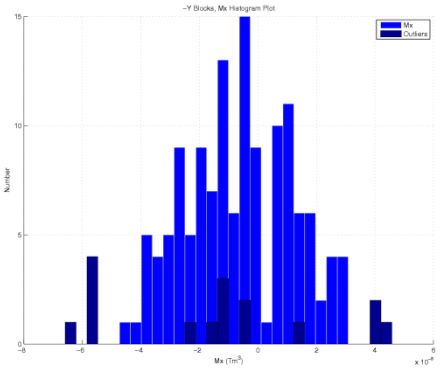
Magnet Block Sorting

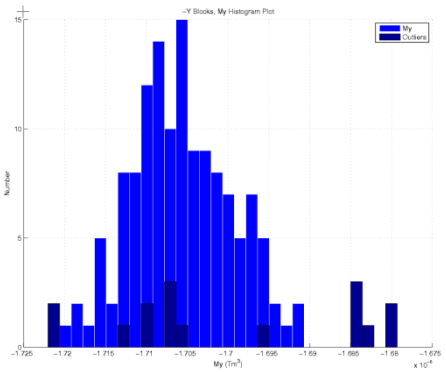
LCLS-TN-13-1

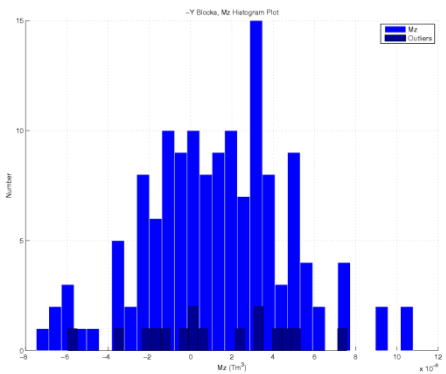




Measure:
- Mx
- My
- Mz



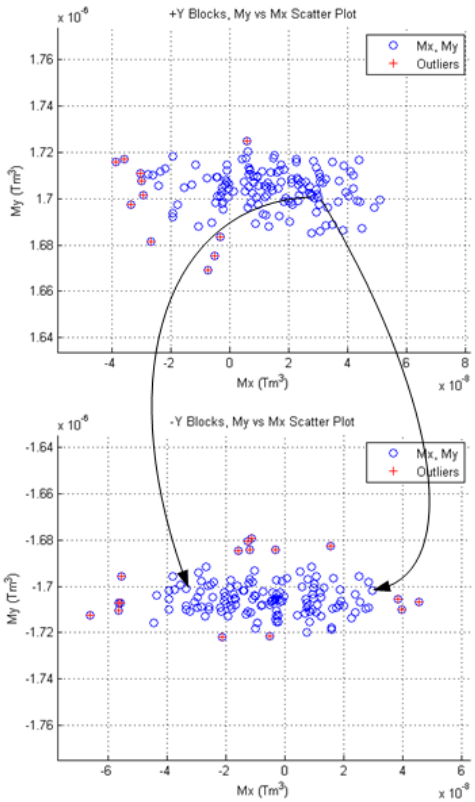


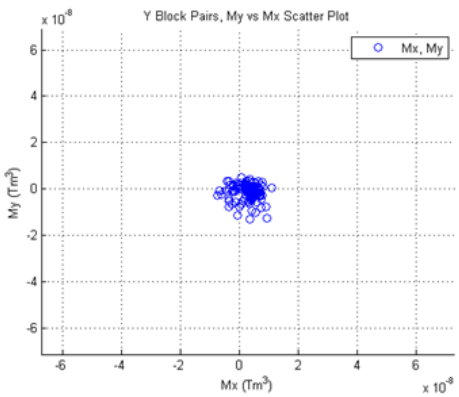


Block Sort, Vertical Blocks

Pair blocks and put pairs into periods to match My (no steering in a period) and cancel Mx (no vertical kicks in a period).

Put pairs into quadrants so quadrants can be tuned. Place strong pairs in a period next to weak pairs to minimize phase errors.

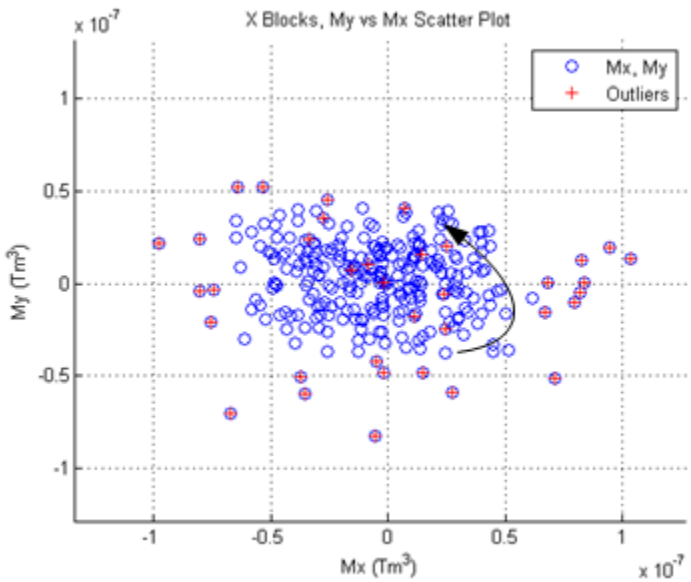


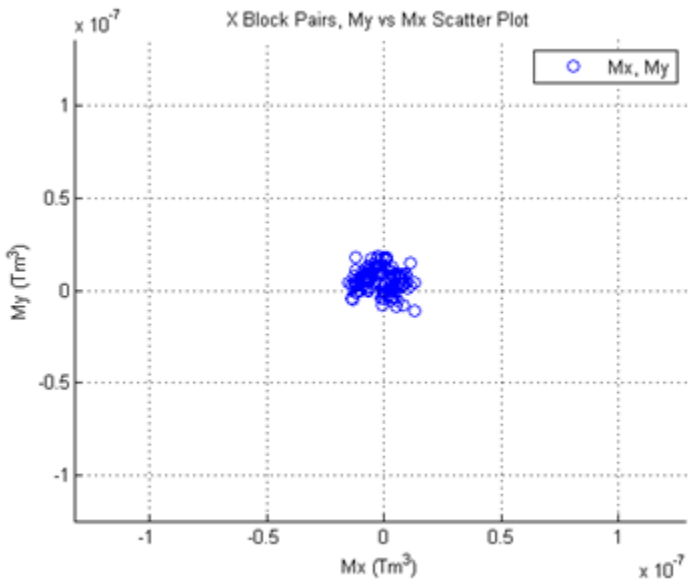


(all plots have same scale)

Block Sort, Horizontal Blocks

Horizontal blocks are paired to cancel My and Mx. Pairs are put into undulator periods. The periods are assembled to make the quadrants.





(both plots have same scale)

Assemble Quadrants

```
SLAC Magnetic Measurements
Date: 11-28-2012
Time: 17:13:15

Magnet Block Placement Analysis
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Magnet Block Placement Parameters:
Input file directory = c:\magdata\aa_int block sort results
Output file directory = c:\magdata\aa_int block sort results
Number of periods = 28
```
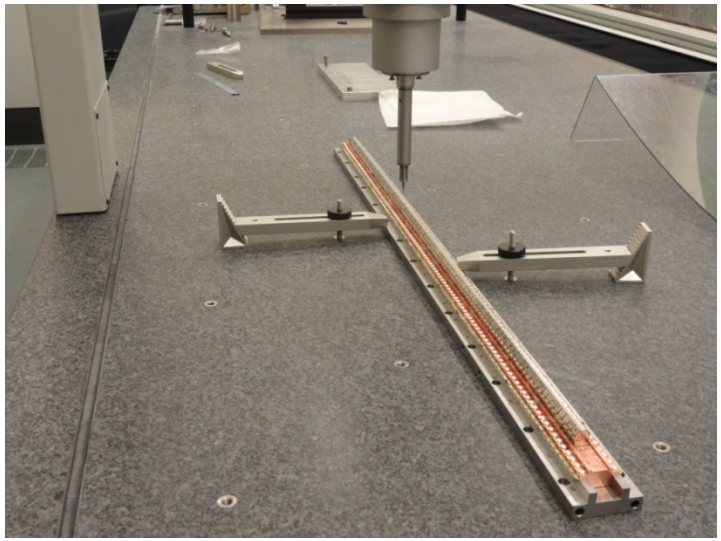

Magnet Block Placement

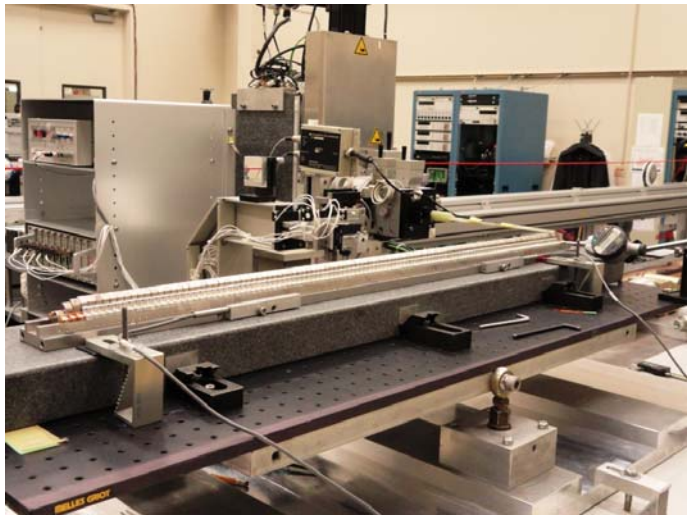
Quadrant 1			Quadrant 2			Quadrant 3			Quadrant 4		
Pos #	Name	Flip y/n	Pos #	Name	Flip y/n	Pos #	Name	Flip y/n	Pos #	Name	Flip y/n
1	blank	0	1	blank	0	1	blank	0	1	blank	0
2	blank	0	2	blank	0	2	blank	0	2	blank	0
3	blank	0	3	blank	0	3	blank	0	3	blank	0
4	C02_277	0	4	C02_262	0	4	C02_250	1	4	C02_074	1
5	B02_069	0	5	B02_020	0	5	A02_028	0	5	A02_104	0
6	C02_085	1	6	C02_124	1	6	C02_068	0	6	C02_049	0
7	A02_038	0	7	A02_026	0	7	B02_095	1	7	B02_093	1
8	C02_177	0	8	C02_235	0	8	C02_103	1	8	C02_252	1
9	B02_094	0	9	B02_046	0	9	A02_050	0	9	A02_045	0
10	C02_137	1	10	C02_191	1	10	C02_200	0	10	C02_105	0
11	A02_062	0	11	A02_134	0	11	B02_097	0	11	B02_017	1
12	C02_106	0	12	C02_203	0	12	C02_119	1	12	C02_221	1
13	B02_091	0	13	B02_105	0	13	A02_016	0	13	A02_089	0
14	C02_097	1	14	C02_218	1	14	C02_159	0	14	C02_090	0
15	A02_081	0	15	A02_080	0	15	B02_047	1	15	B02_109	0
16	C02_180	0	16	C02_150	0	16	C02_055	1	16	C02_175	1
17	B02_086	0	17	B02_076	1	17	A02_125	0	17	A02_053	0
18	C02_046	1	18	C02_028	1	18	C02_153	0	18	C02_128	0
19	A02_031	0	19	A02_131	0	19	B02_040	1	19	B02_051	1
20	C02_130	0	20	C02_217	0	20	C02_096	1	20	C02_081	1
21	B02_101	0	21	B02_116	1	21	A02_083	0	21	A02_093	0
22	C02_162	1	22	C02_069	1	22	C02_185	0	22	C02_063	0
23	A02_105	0	23	A02_124	0	23	B02_100	0	23	B02_008	1
24	C02_173	0	24	C02_276	0	24	C02_061	1	24	C02_110	1
25	B02_068	1	25	B02_131	0	25	A02_061	0	25	A02_129	0
26	C02_048	1	26	C02_122	1	26	C02_032	0	26	C02_138	0
27	A02_025	0	27	A02_073	0	27	B02_136	0	27	B02_004	1
28	C02_088	0	28	C02_195	0	28	C02_035	1	28	C02_270	1
29	B02_134	1	29	B02_045	1	29	A02_099	0	29	A02_136	0
30	C02_008	1	30	C02_236	1	30	C02_207	0	30	C02_078	0
31	A02_005	0	31	A02_006	0	31	B02_003	1	31	B02_125	0
32	C02_272	0	32	C02_015	0	32	C02_198	1	32	C02_268	1
33	B02_028	0	33	B02_081	0	33	A02_014	0	33	A02_030	0
34	C02_064	1	34	C02_024	1	34	C01_001	0	34	C02_006	0
35	A02_032	0	35	A02_047	0	35	B02_006	1	35	B02_054	1
36	C02_190	0	36	C02_123	0	36	C02_229	1	36	C02_216	1
37	B02_033	0	37	B02_117	1	37	A02_019	0	37	A02_106	0
38	C02_239	1	38	C02_014	1	38	C02_002	0	38	C02_208	0
39	A02_034	0	39	A02_048	0	39	B02_140	1	39	B02_058	0
40	C02_047	0	40	C02_019	0	40	C02_134	1	40	C02_073	1
41	B02_031	0	41	B02_012	0	41	A02_060	0	41	A02_069	0
42	C02_083	1	42	C02_027	1	42	C02_100	0	42	C02_156	0
43	A02_090	0	43	A02_035	0	43	B02_126	1	43	B02_014	0
44	C02_260	0	44	C02_184	0	44	C02_240	1	44	C02_010	1
45	B02_128	0	45	B02_027	1	45	A02_079	0	45	A02_009	0
46	C02_089	1	46	C02_053	1	46	C02_036	0	46	C02_264	0
47	A02_012	0	47	A02_058	0	47	B02_073	0	47	B02_087	0
48	C02_244	0	48	C02_243	0	48	C02_071	1	48	C01_002	1
49	B02_114	0	49	B02_072	1	49	A02_070	0	49	A02_072	0
50	C02_094	1	50	C02_269	1	50	C02_020	0	50	C02_172	0
51	A02_002	0	51	A02_059	0	51	B02_132	0	51	B02_075	0
52	C02_278	0	52	C02_056	0	52	C02_012	1	52	C02_082	1
53	B02_080	0	53	B02_021	1	53	A02_128	0	53	A02_066	0
54	C02_247	1	54	C02_091	1	54	C02_158	0	54	C02_001	0
55	A02_051	0	55	A02_094	0	55	B02_009	0	55	B02_037	1
56	C02_197	0	56	C02_059	0	56	C02_232	1	56	C02_169	1
57	B02_044	0	57	B02_127	0	57	A02_092	0	57	A02_042	0
58	C02_187	1	58	C02_132	1	58	C02_052	0	58	C02_116	0
59	A02_091	0	59	A02_037	0	59	B02_005	1	59	B02_059	1
60	C02_139	0	60	C02_109	0	60	C02_157	1	60	C02_060	1
61	B02_084	1	61	B02_085	1	61	A02_018	0	61	A02_054	0
62	C02_228	1	62	C02_093	1	62	C02_179	0	62	C02_062	0
63	A02_068	0	63	A02_011	0	63	B02_137	1	63	B02_041	0
64	C02_107	0	64	C02_201	0	64	C02_222	1	64	C02_223	1

- Use matched pairs in each period to minimize local errors and overall field integrals
- Use strong pair, then weak pair to minimize phase errors
- Produce printout of what block goes in each slot, indicate block flips

Delta Quadrant Tuning



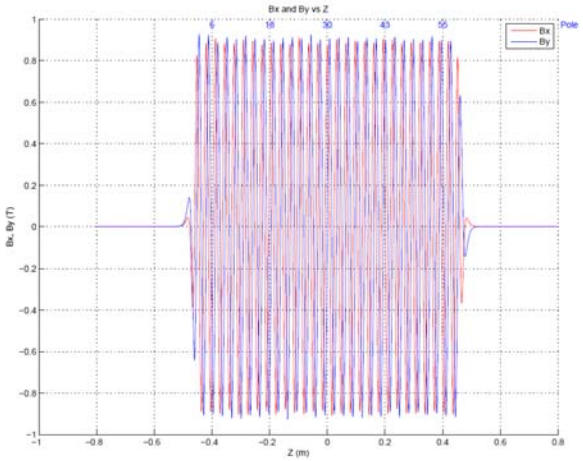
Mechanically align blocks using CMM.

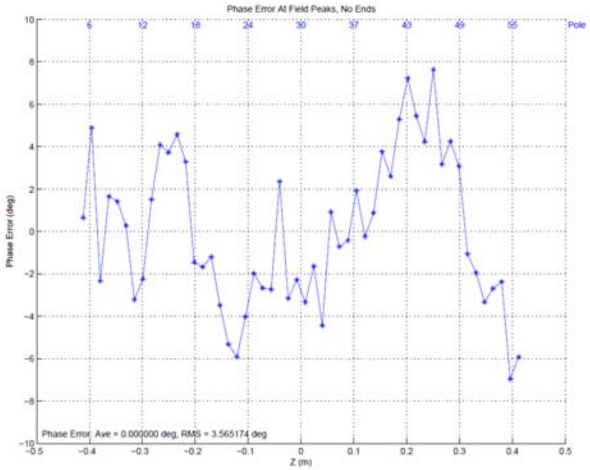


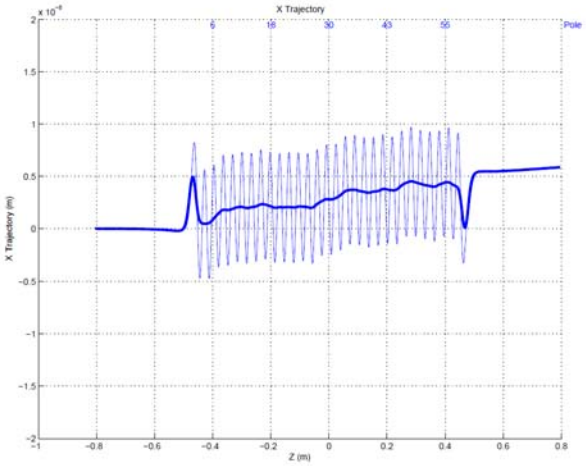
Move blocks using magnetic measurements to straighten trajectories and minimize phase errors.

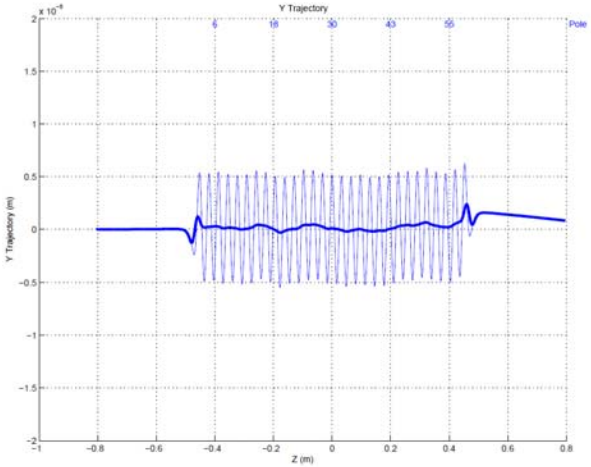
In Software Superpose Quadrant Fields To Simulate Assembled Undulator

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



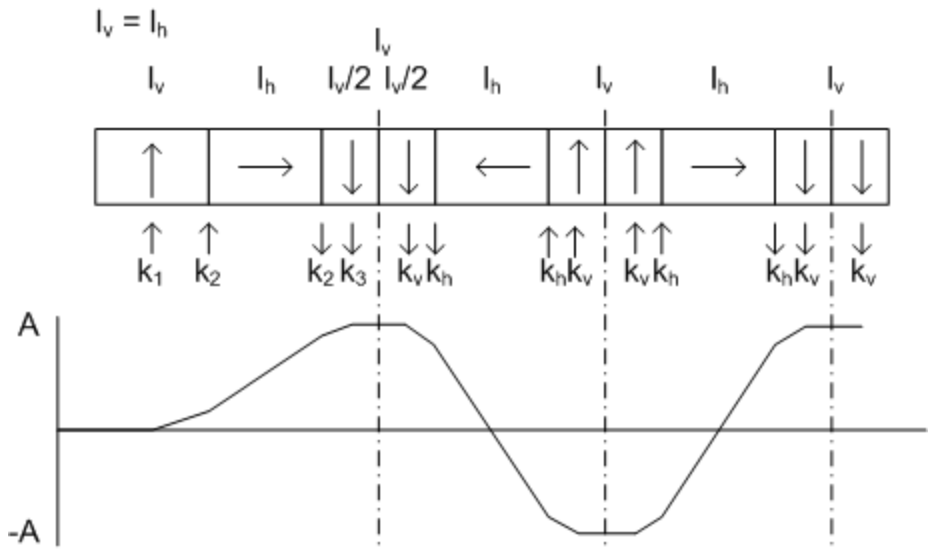




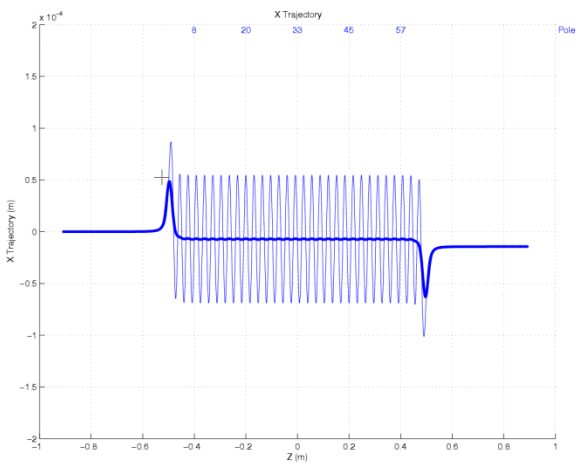


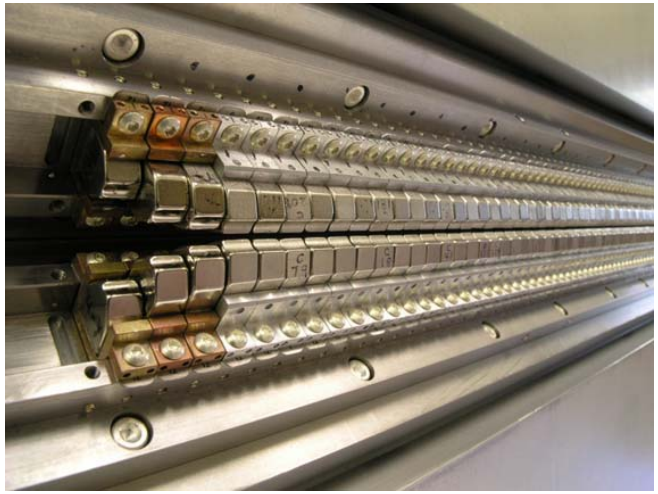
Delta Ends

LCLS-TN-13-2



Simulation





If K_v is kick from full vertical block and K_h is the kick from a full horizontal block:

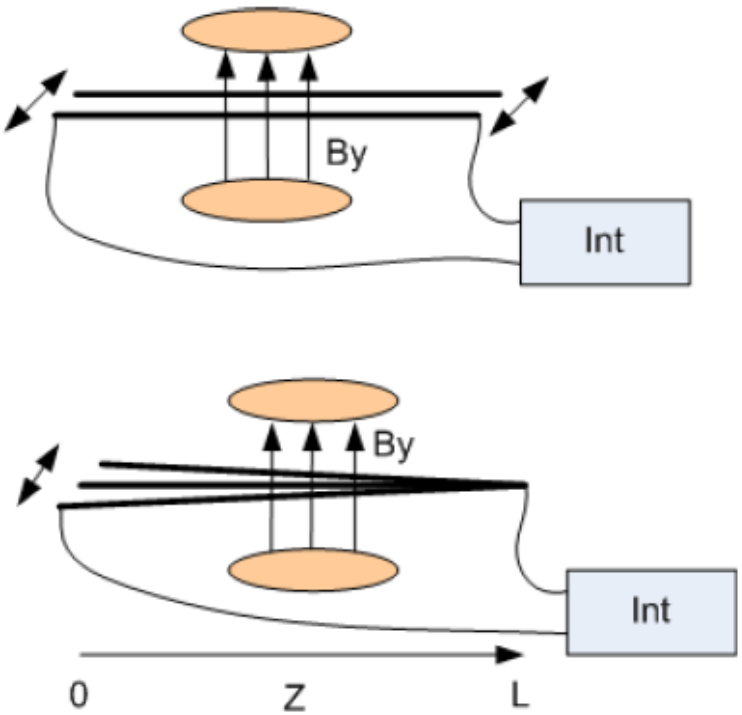
$k_1 = (3/14)K_v$

$k_2 = (1/2)\ K_h$

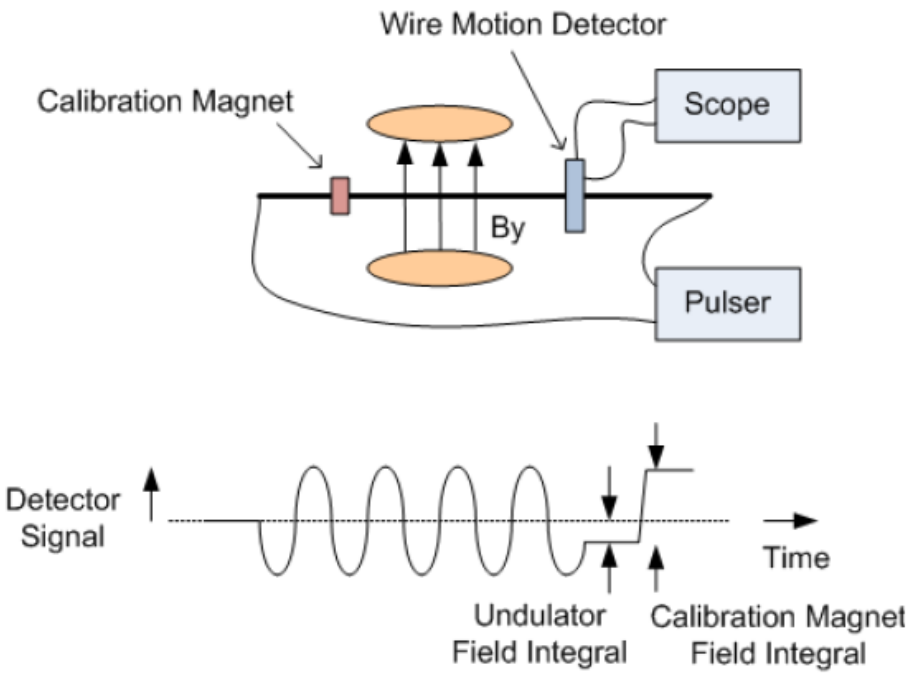
$k_3 + k_v = (5/7)\ K_v$

Block 3 homogenizes the two half blocks, this leaves a small trajectory offset. Correct by shifting block 2.

Delta Field Integrals



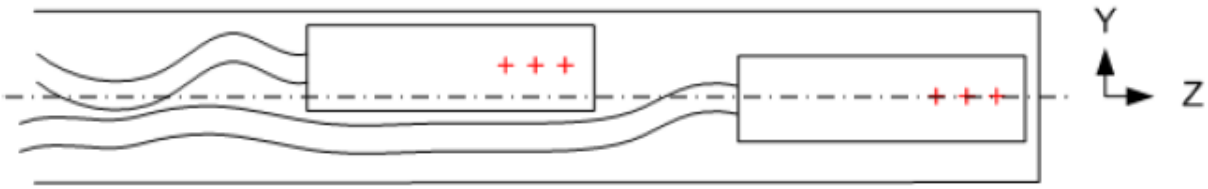
Moving Wire



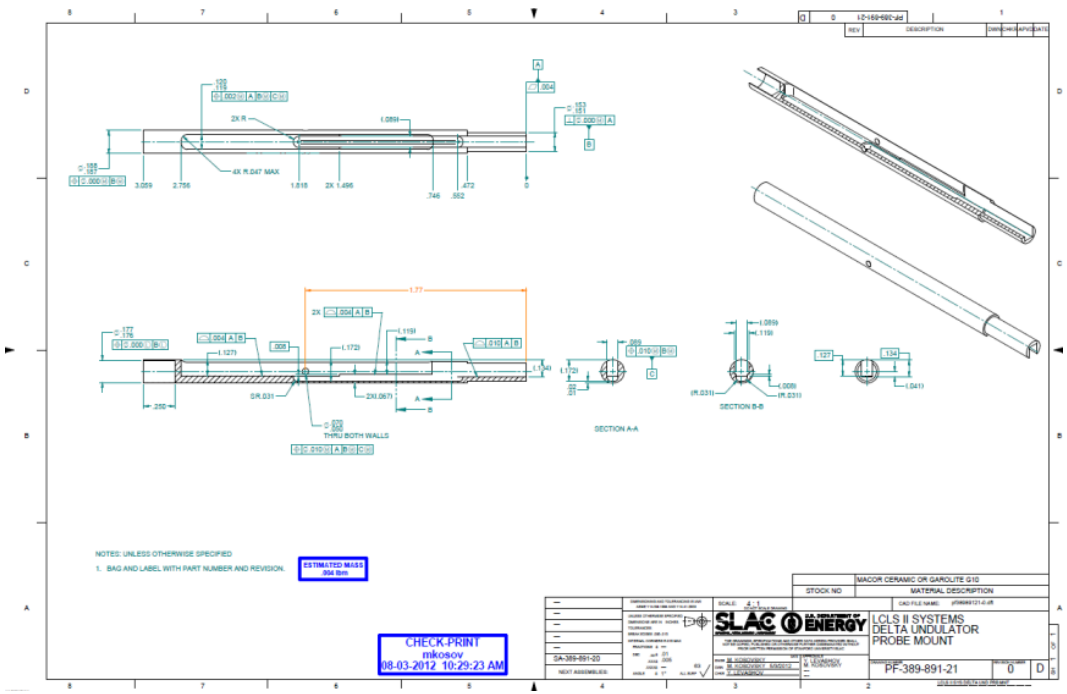
Pulsed Wire

Two Senis Probes To Measure Fields

Each probe measures Bx, By, and Bz.

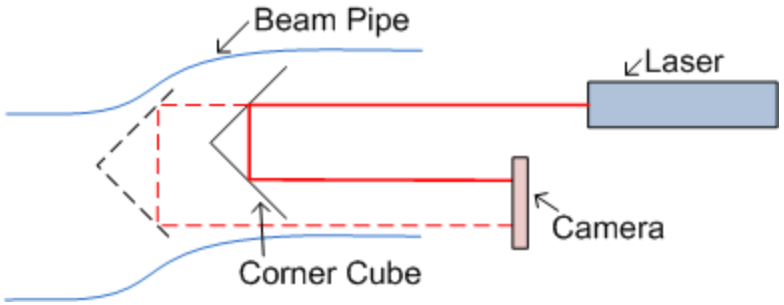


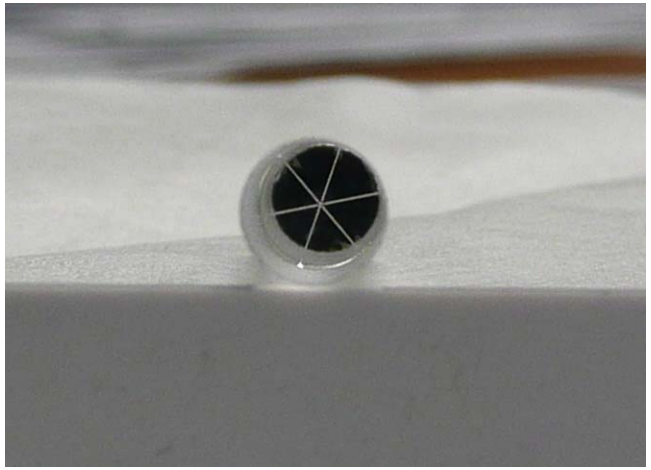
2 Senis probes
Small planar hall effect
Accurate measurements
Δy = 200 microns
Take out Δz in software

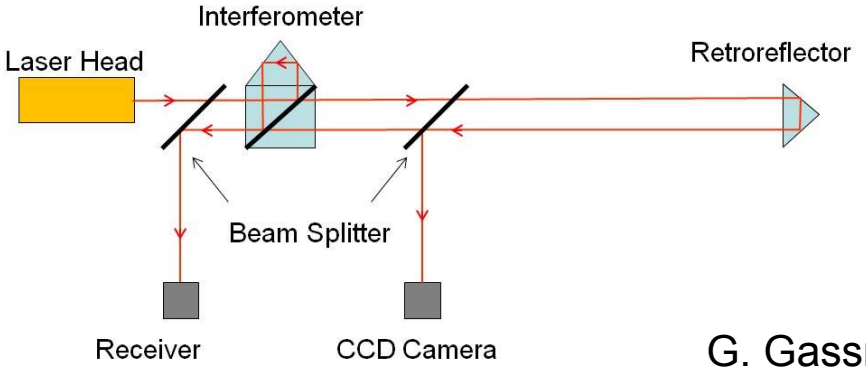


Probe Location

Transverse location from corner cube. Longitudinal location from interferometer.

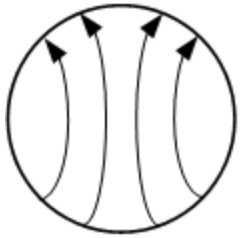


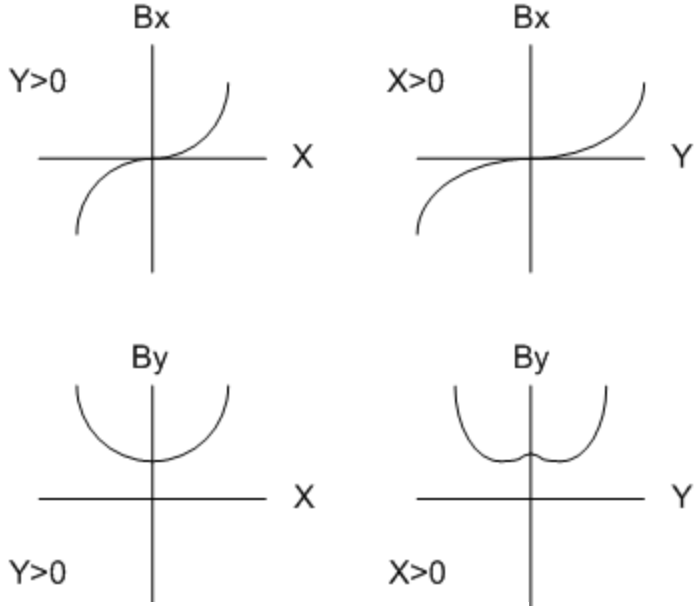




G. Gassner

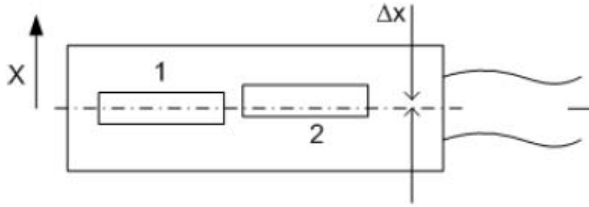
Locate Magnetic Center

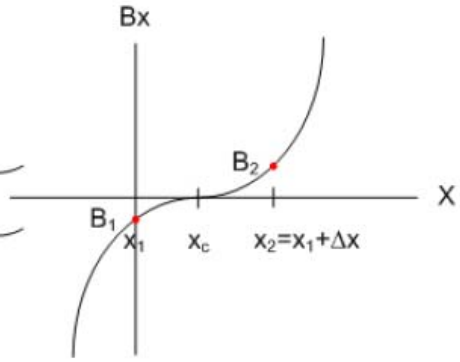


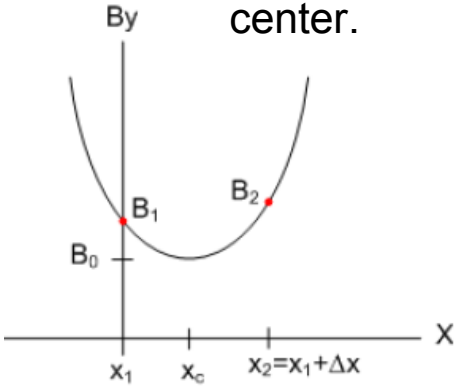


Center relative to probes.
Use linear field mode.
Measure Bx and By.
Can rotate probes to measure
at two points along x or y.

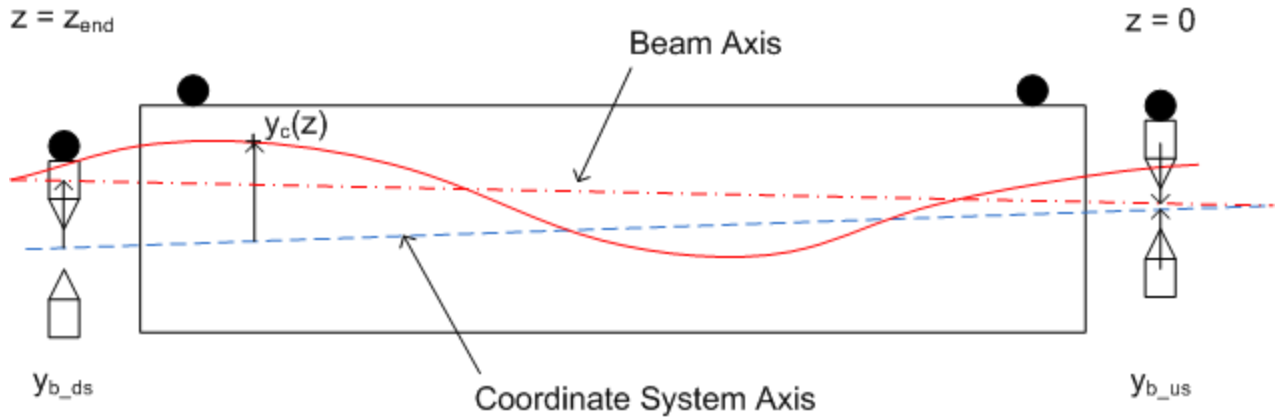
Assume field shape is first term in field expansion near the center.







Calculate Fields On Beam Axis



LCLS-TN-13-4

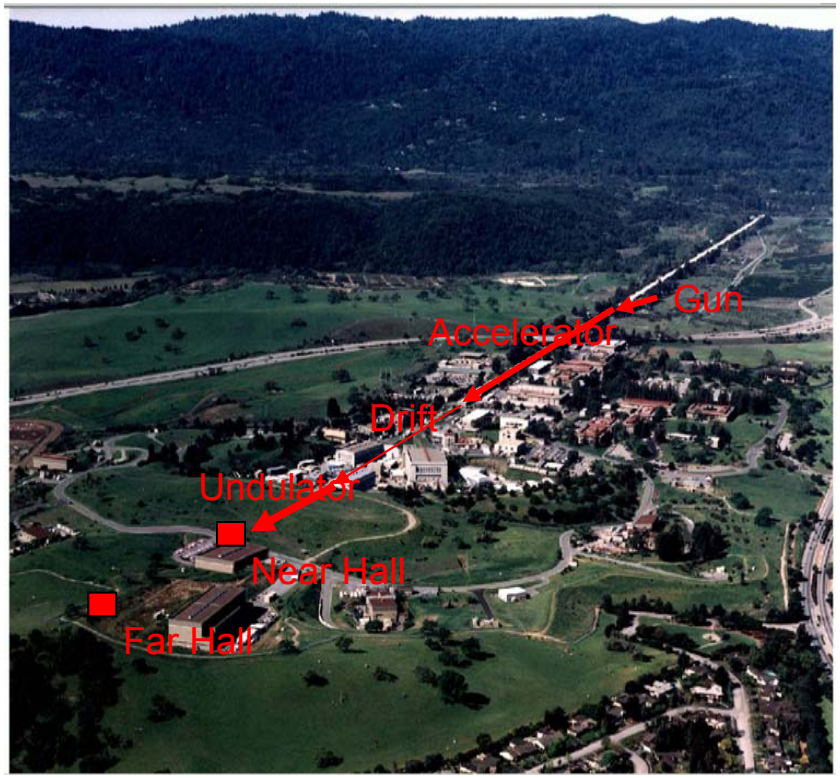
- Measure on curved trajectory
- Find magnetic center relative to probes
- Find probes relative to straight line
- Find magnetic center relative to straight line
- Fit magnetic centers with line to get beam axis
- Fiducialize beam axis
- Assume that close to the magnetic center, the field has the form of the fundamental term in the field expansion
- Calculate the field on the beam axis from the field at the measurement location, the location of the magnetic center, and the form of the field

Conclusion

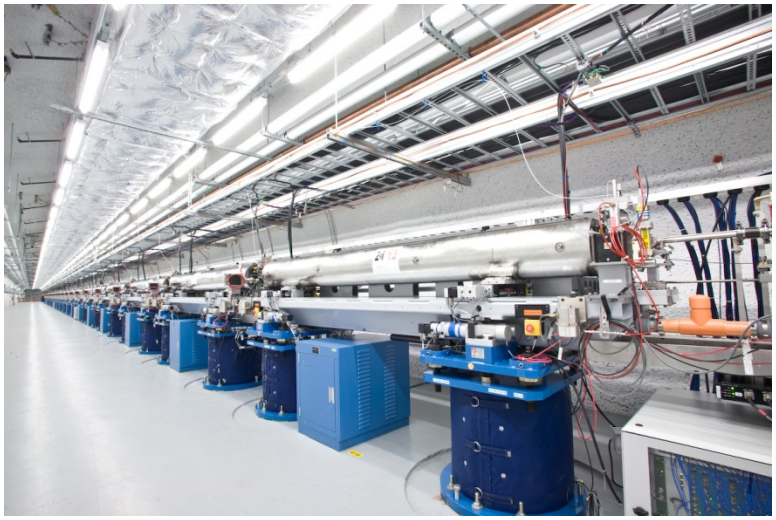
- LCLS-I measurements continue to check for radiation damage and to do experiments such as opening the gap for the second harmonic.
- We are preparing to upgrade the lab to handle the large LCLS-II undulators.
- We are working on the LCLS-II phase shifter. We built a magnetic test piece that we successfully tuned. We are starting to build a prototype.
- We simulated and tested an LCLS-II beam pipe corrector.
- We are building a Delta undulator. A 1 meter prototype is built. We are starting to measure it. This involved measuring the magnetic moments of the blocks and sorting them. Mounting the blocks in keepers, mechanically adjusting them, and tuning the quadrants. We just put the 4 quadrants together.
- We have a plan to accurately determine the fields in the Delta undulator on the beam axis. Our goal is to make measurements accurately enough to someday make an FEL out of Delta undulators.

Extra Slides

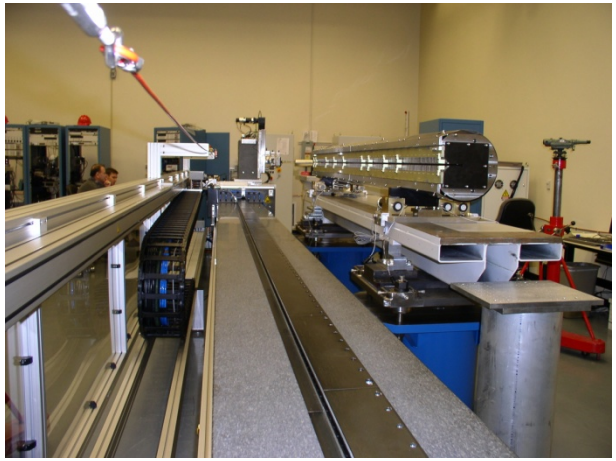
LCLS



Site Overview

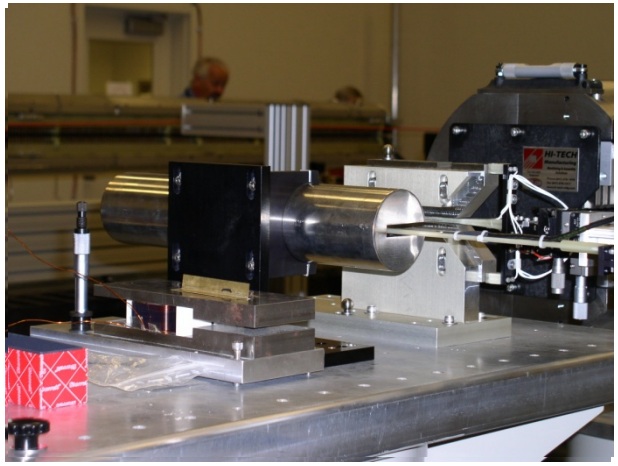


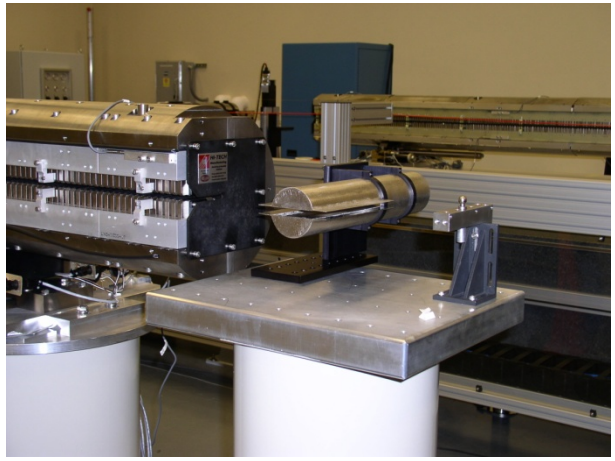
Undulator Tunnel

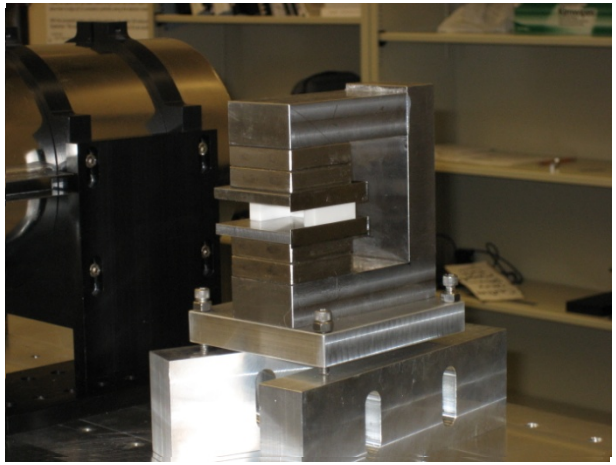


Measurement Lab

Hall Probe

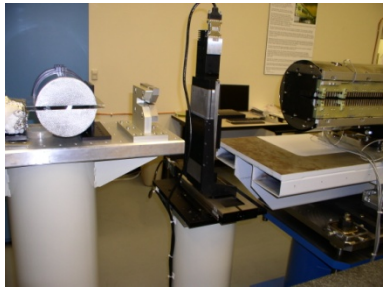




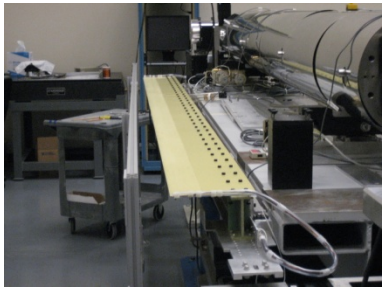


Hall probe measurements begin and end in a zero gauss chamber. Probe offsets are removed. The probes are periodically calibrated with an NMR system. A reference dipole which accepts an NMR probe is measured with each undulator to check for probe drift.

Coil Measurements



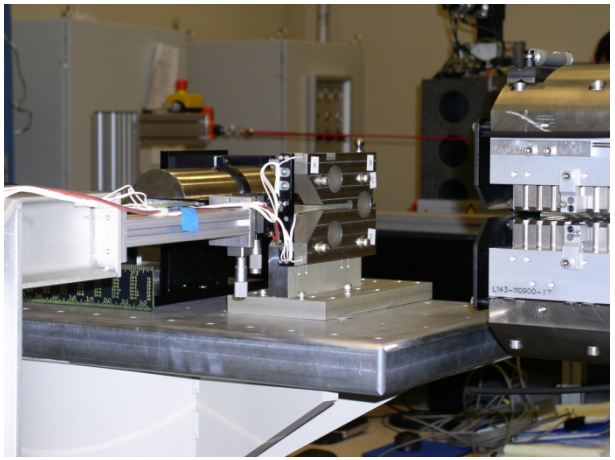
Short coils measure both the horizontal and vertical field. The measurements begin and end in a zero gauss chamber. The short coils are used to check the hall probe measurements.



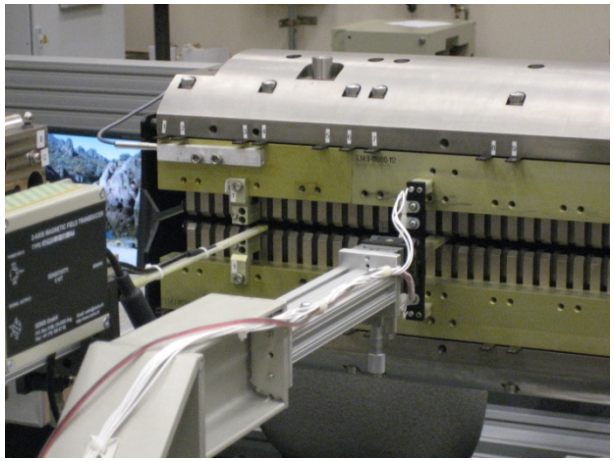
Long coil measurements are used to determine the field integrals. Integrator drift is minimized by the short measurement time. The field integrals are more accurate than those of other methods.

Long coil in use

Align Undulator To Bench



Capacitive sensor measurements start in a reference pole which determines the transverse position and roll. Pitch and yaw are set by making the undulator parallel to the bench.

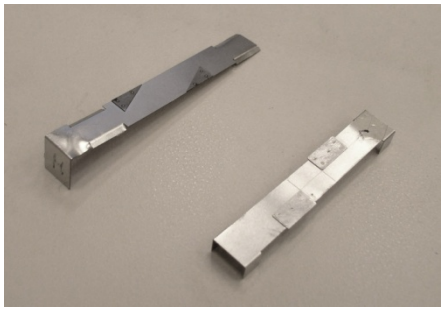


Capacitive sensors measure undulator position relative to the bench.

Cam movers move the undulator parallel to the bench, take out roll, and move to the proper transverse location.

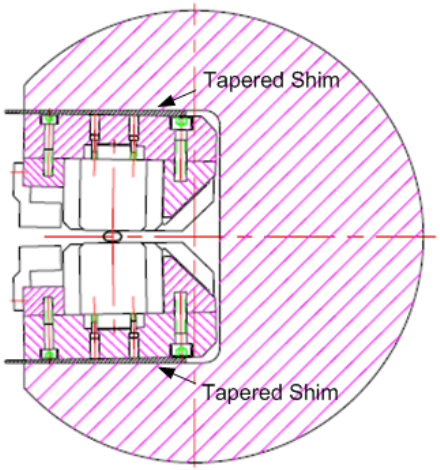
Undulator Shims

Horizontal trajectory shims.



Vertical trajectory shims.

Horizontal trajectory shim and phase shims.



Tapered shims.

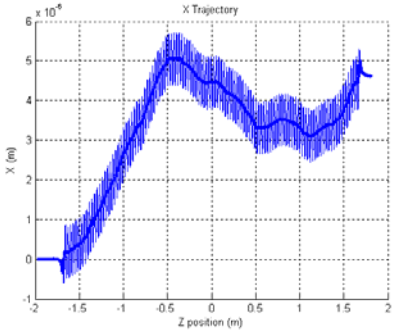
The horizontal trajectory shims weaken a pole, giving the beam a horizontal kick. Pole polarity determines the kick direction.

Vertical trajectory shims introduce a small horizontal field component, giving the beam a vertical kick.

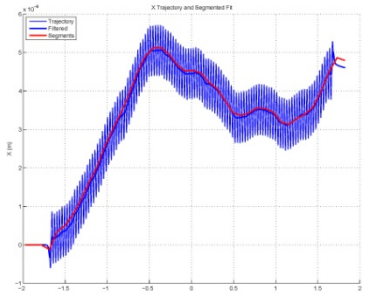
Phase shims weaken two poles, increasing the average forward velocity of the beam. This introduces a negative phase shift.

Tapered shims set the cant angle of the poles. They are used to adjust the gap in order to set the K value. Phase adjustments are also done with these shims.

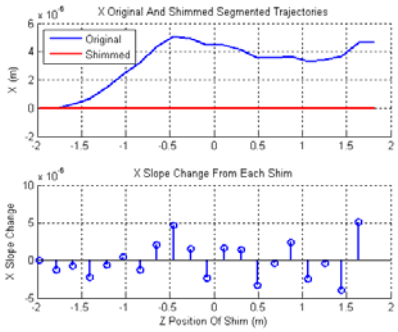
Tuning Automation



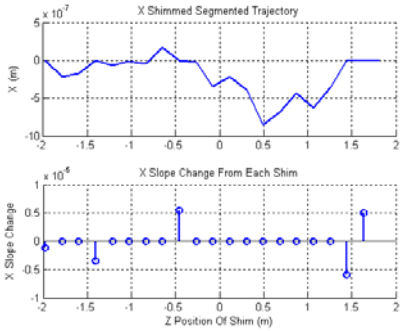
Measured x-trajectory



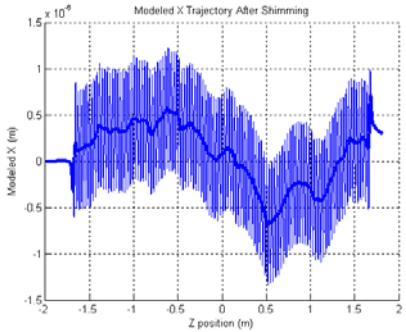
Line segments fit to the trajectory



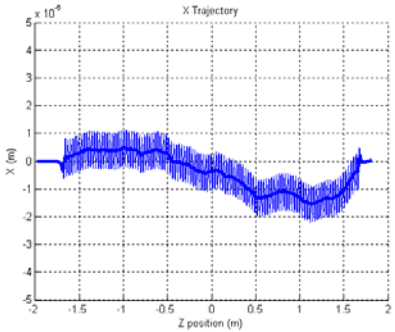
One shim per segment calculated to make the segments into a straight line



Shims combined to reduce their number



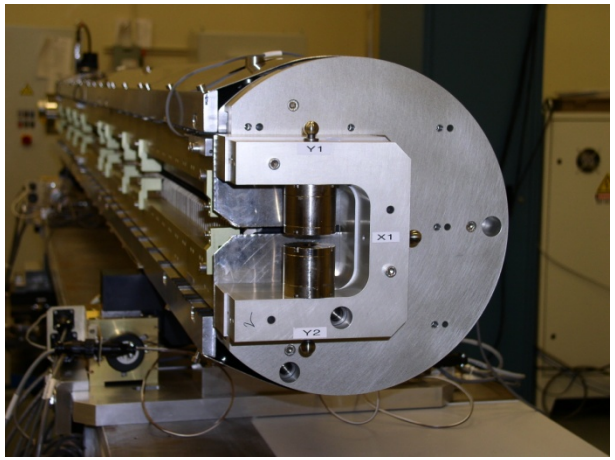
Trajectory modeled with shims applied

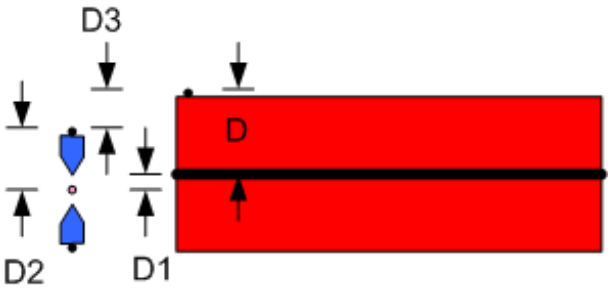


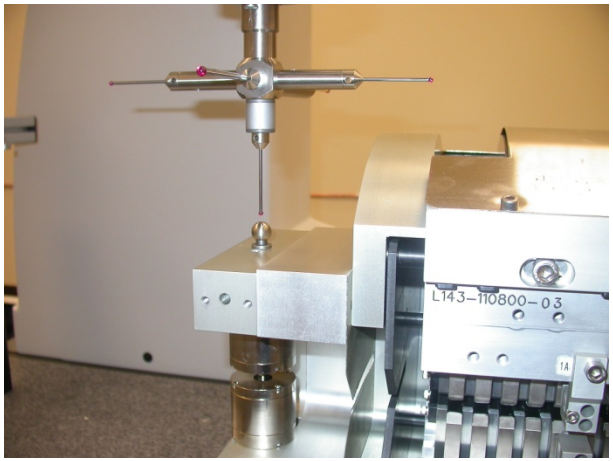
Trajectory measured after shims were applied

A number of straight line segments are fit to the measured trajectory. The slope change for each segment is calculated which makes the segments into a straight line. Shim strengths are calculated from the slope changes. Shims are combined to reduce their number, resulting in a trajectory which is no longer ideal, but it exceeds the tolerances. The trajectory with the added shims is modeled. The shims are added and the corrected trajectory is measured.

Fiducialization

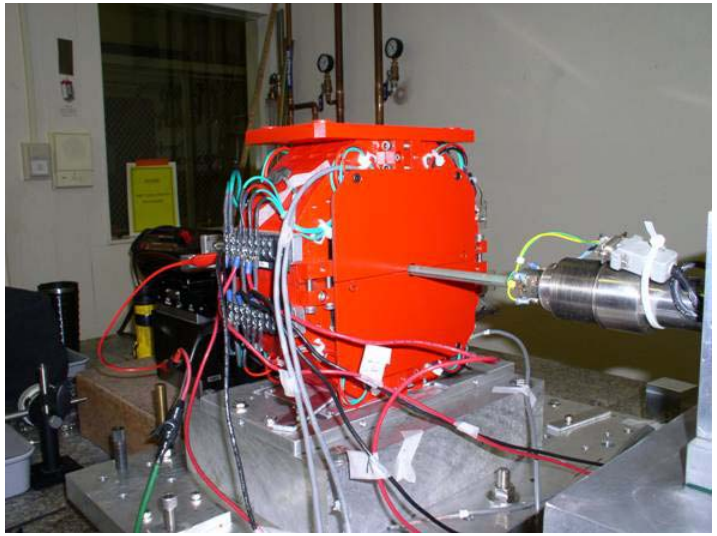




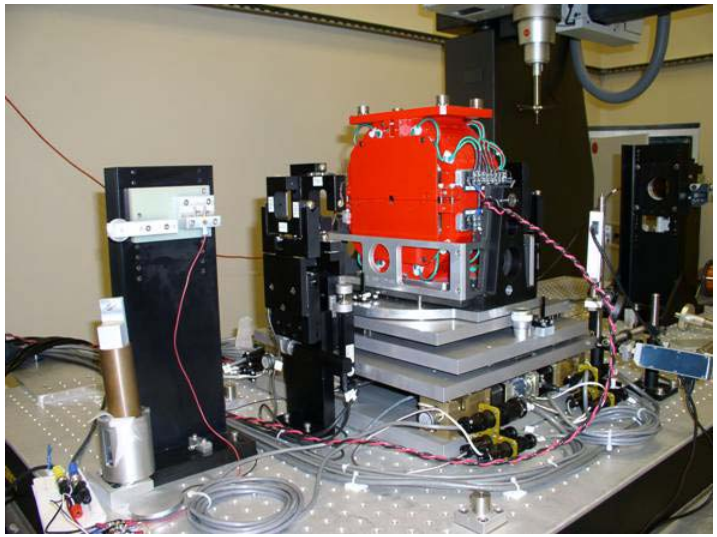


Pointed magnets with same sign poles are added to the ends of the undulator. These magnets have a well defined zero field point in the center. The distance from the measurement axis to the zero field point is determined. A calibration gives the distance from the zero field point to tooling balls on the pointed magnet fixture. The distance from the tooling balls on the pointed magnet fixture to tooling balls on the undulator is measured with a coordinate measuring machine.

Undulator Quadrupoles



Field Quality



Magnetic Center