Experience with ID Magnet Measurement, Commissioning and Optimization of their Radiation at NSLS-II

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U.S. DEPARTMENT OF ENERGY | Office of Science

High-Brightness Synchrotron Light Source Workshop
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BROOKHAVEN NATIONAL LABORATORY | National Synchrotron Light Source II

Outline

- Overview of NSLS-II Insertion Devices
- Magnetic Field Measurement Lab
- ID Commissioning Experience
    - Residual field integrals & Orbit feedforward
    - Current strips feedforward
    - Coupling feedforward
    - Photon beam optimization

NSLS-II Insertion Device List (Project IDs)

Beam Line	Type	Design	Beam port	Location	Length [m]	Period [mm]	Peak Field [T]	K_{max}	Canting Angle [mrad]	Vac Aper [mm]	Fund. [eV]	Total Power [kW]
CSX1 /CSX2	EPU49	PPM	Low-β_x	23-ID	4 (2×2)	49	0.57 (heli) 0.94 (Lin) 0.72 (vlin) 0.41 (45d)	2.6 (heli) 4.3 (Lin) 3.2 (vlin) 1.8 (45d)	0.16	8.0	230 (heli) 180 (Lin) 285 (vlin) 400 (45d)	7.3 (heli) 9.9 (Lin) 5.5 (vlin) 1.7 (45d)
IXS	IVU22	Hybrid	High-β_x	10-ID	6 (1×3) center	22	1.52	1.52	0	7.2	1802	4.7x2
HXN	IVU20	Hybrid	Low-β_x	3-ID	3	20	1.03	1.83	0	5.0	1620	8.0
CHX	IVU20	Hybrid	Low-β_x	11-ID	3	20	1.03	1.83	0	5.0	1620	8.0
SRX /(XFN)	IVU21	Hybrid	Low-β_x	5-ID	1.5 downstream	21	0.90	1.79	2.0	6.2	1570	3.6
XPD /PDF	DW100	Hybrid	High-β_x	28-ID	6.8 (2×3.4)	100	1.8	~16.5		11.5		64.5

- Total 7 Insertion Devices (IDs) installed and commissioned as part of NSLS-II Project

NSLS-II Insertion Device List (NEXT, ABBIX, Partner)

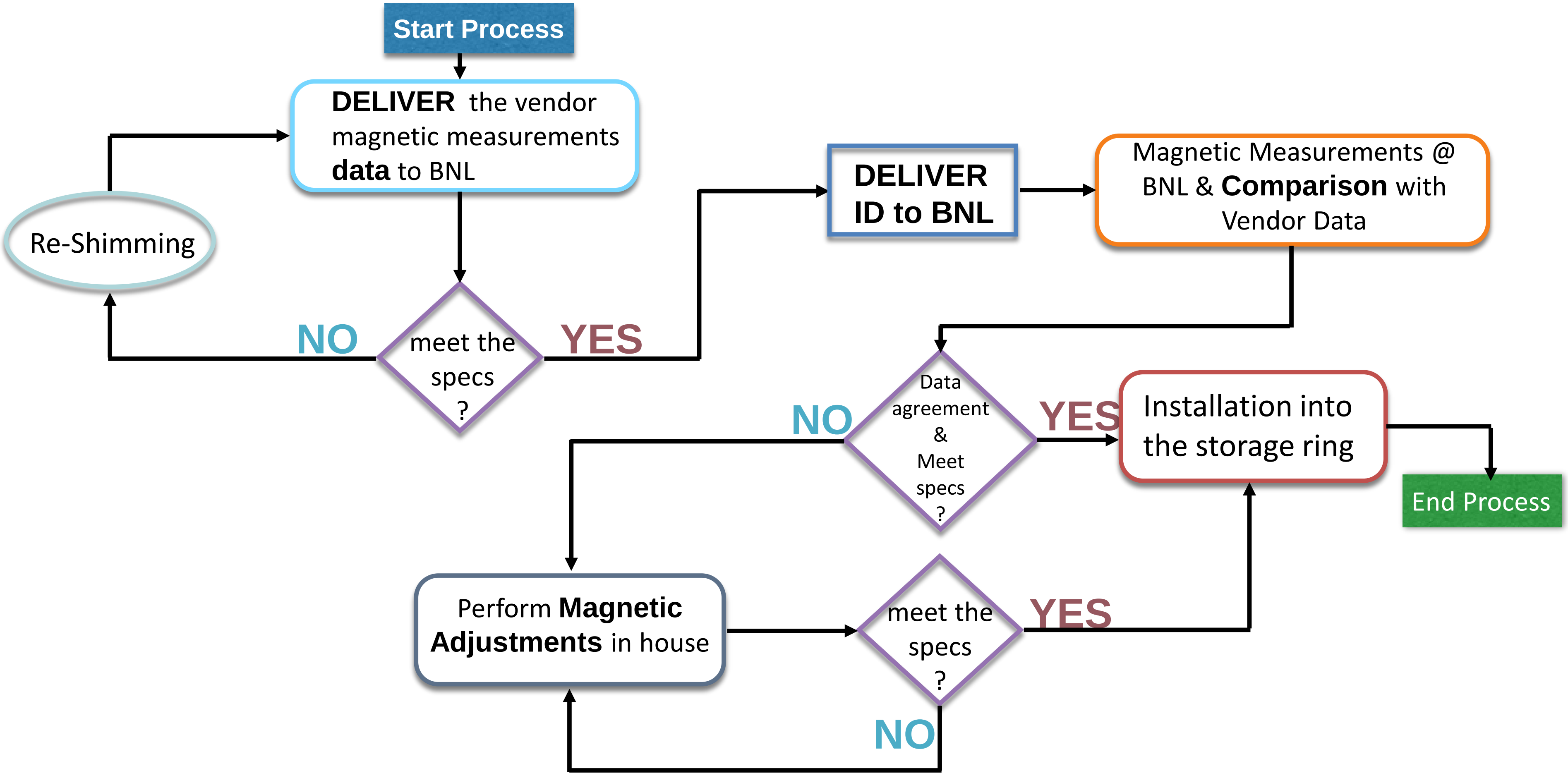
Beam Line	Project	Type	Design	Beamport	Location	Length [m]	Period [mm]	Peak Field [T]	K_{max}	Canting Angle [mrad]	Vac Aper [mm]	Total Power [kW]
ESM	NEXT	EPU105/ EPU57	PPM	Low-β_x	21-ID	2.7/1.4	105/49	0.74/0.57 (heli) 0.90 (vlin) 1.14/0.83 (Lin)	7.23/3.55 (heli) 7.23/3.06(vlin) 11.2/4.4 (Lin)	2.0		4.22/1.2 (heli) 4.22/0.86 (vlin) 10.1/2.0 (Lin)
SIX	NEXT	EPU57	PPM	High-β_x	2-ID	7.0 (2×3.5)	57	0.57 (heli) 0.83 (Lin)	3.55 (heli) 4.41 (Lin)	0		4.4 (heli) x2 6.8 (Lin) x2
ISR	NEXT	IVU23	Hybrid	High-β_x	4-ID	2.8	23	0.95	2.05	2.0	6.0	
SMI	NEXT	IVU23	Hybrid	High-βx	12-ID	2.8	23	0.95	2.05	2.0	6.0	
ISS+XFP	NEXT	DW100	Hybrid	High-β_x	18-ID	6.8 (2×3.4)	100		~16.5		11.5	64.5
FXI	NEXT	DW100	Hybrid	High-β_x	8-ID	6.8 (2×3.4)	100		~16.5		11.5	64.5
LIX	ABBIX	IVU23	Hybrid	High-β_x	16-ID	2.8	23	1.02	2.2	0	5.5	
FMX/AMX	ABBIX	IVU21	Hybrid	Low-β_x	17-ID	1.5 x 2	21	0.90	1.79	2.0	6.2	3.6
SST	Partner	U42	Hybrid	Low-β_x	7-ID	1.6	42	0.82	3.27	2.0	8.0	3.2
	Partner	EPU60	PPM	Low-β_x	7-ID	0.89	60	0.73 (heli) 1.02 (Lin)	4.1 (heli) 5.7 (Lin)		8.0	1.8 (heli) 2.7 (Lin)
NYX	Partner	IVU18	Hybrid	Low-β_x	19-ID	1.0	18	0.95	1.55	0	5.4	2.5
HEX	Partner	SCW55	EM	Low-β_x	27-ID?	1.0	55	4.2	21.6	0	10	49.7

- 10 additional IDs installed so far (9 commissioned) as part of 3 different projects
- 2 more IDs soon to be installed
- 2 SCWs (HEX & MRE) planned
- 2 commissioned 3PWs (3 more coming + 1 prototype)

Magnetic Measurements and Retuning @ NSLS-II

All IDs at NSLS-II were procured as a "turn-key" devices from main ID companies (Danfysik, HITACHI and Kyma).

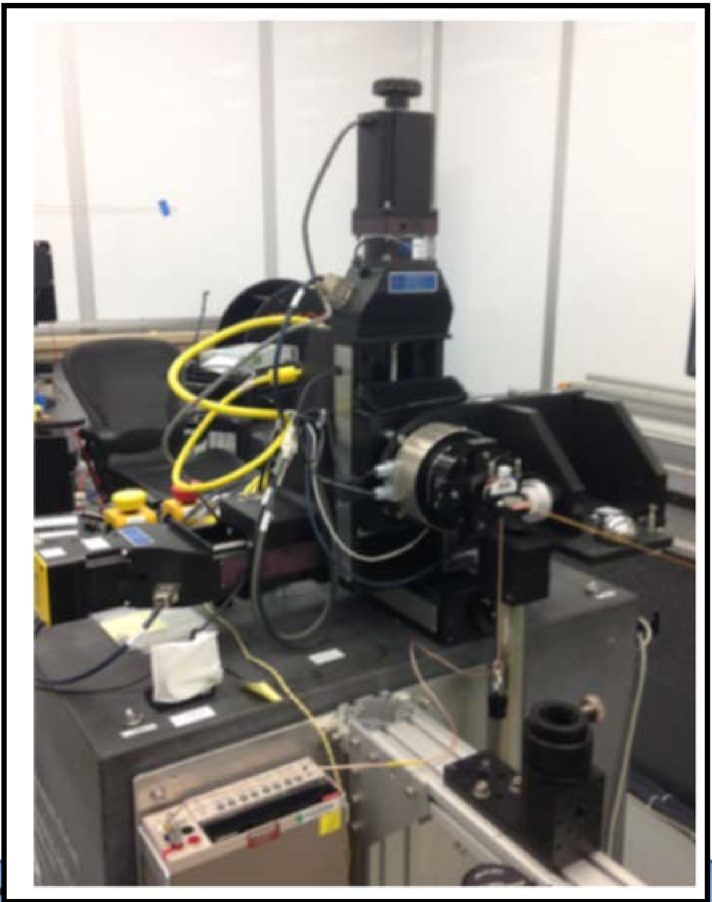
In order to validate that IDs delivered to NLSL-II meet the tight specifications, they are accurately surveyed before installation into the storage ring.



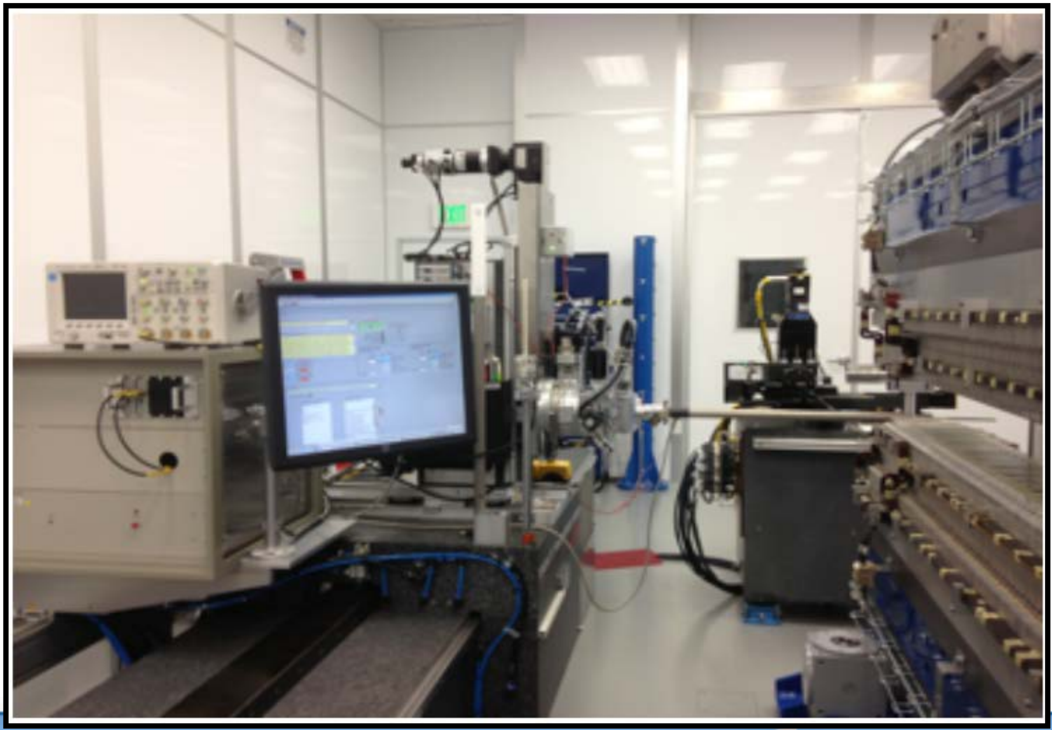
NSLS-II Magnetic Measurement Facility

- Our magnetic measurements are the final verification of the complex design and fabrication process, so that proper certification of device can be made.

Integrated Field Measurement System by ADC USA Inc



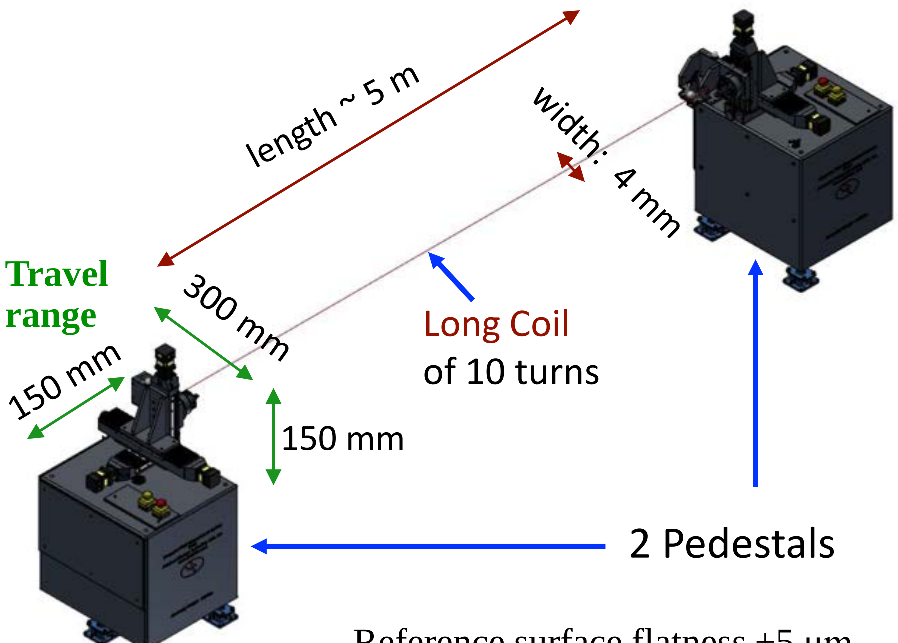
3D Hall probe-mapping bench MMB-6500 by Kugler, GmbH



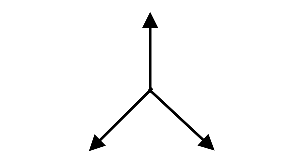
Courtesy of T. Tanabe

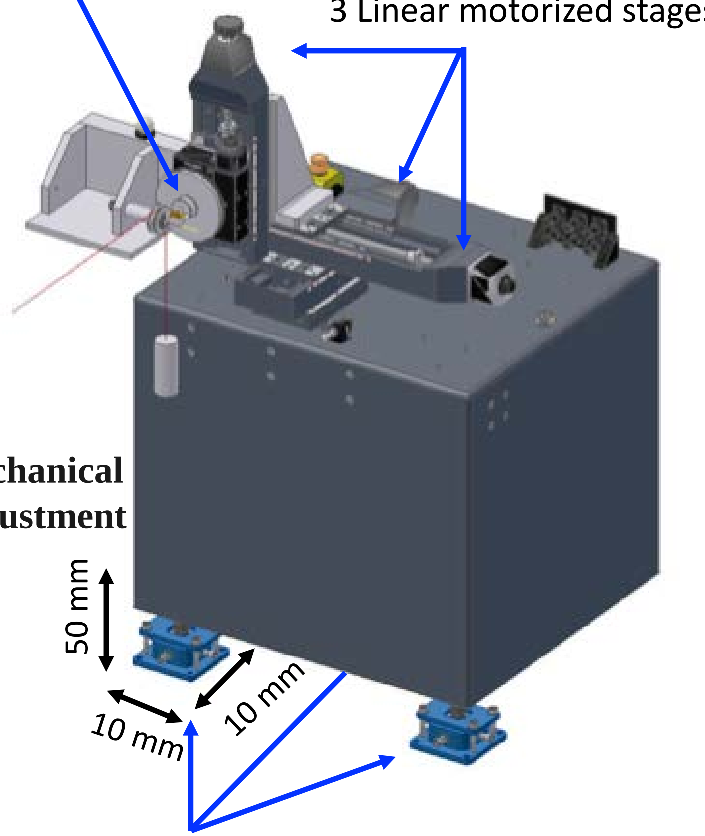
IFMS: Integrated Field Measurement System

A set of three field integral measurement systems: a stretch wire, a moving wire and a **flip coil**



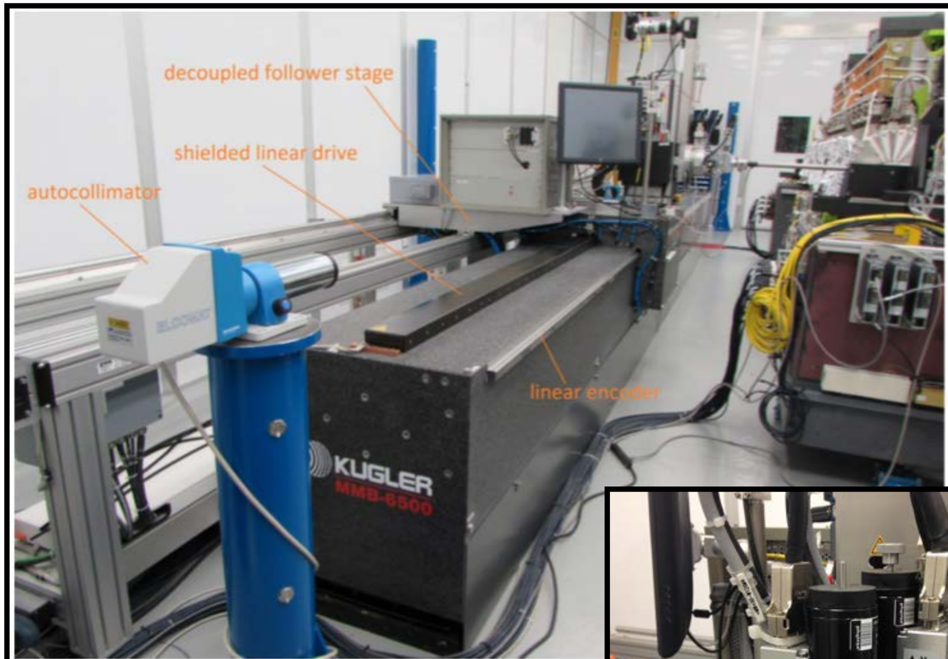
- Reference surface flatness ±5 µm.
- Weight of each granite support: 1580 kg





Hall Probe Bench Overview (1/2)

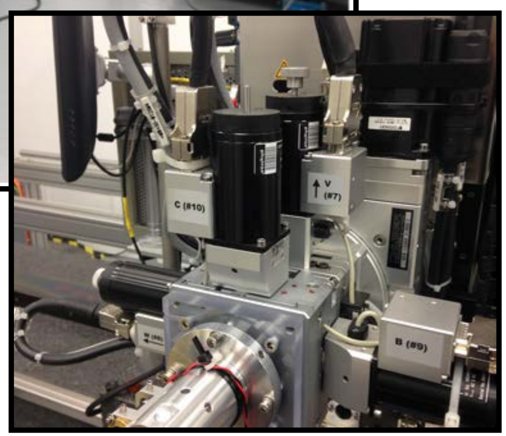
3D Hall probe-mapping bench MMB-6500 built by Kugler, GmbH



Total Z-axis travel is 6.5 m.

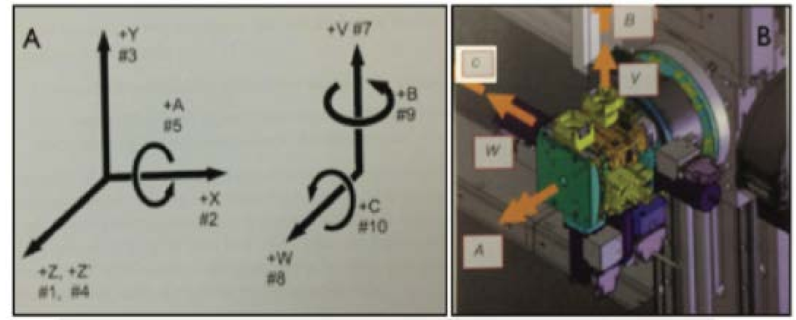
A Heidenhain linear encoder provides position feedback for Z-axis closed loop control.

A Renishaw laser linear encoder is used as a trigger for on-the-fly measurements.



A and **C** secondary axes are particularly useful for fine angular positioning of the B_y Hall sensor

- Granite guide-beam length: 7.7 m
- Flatness deviation < ± 3 μm
- Positioning accuracy: ± 1 μm



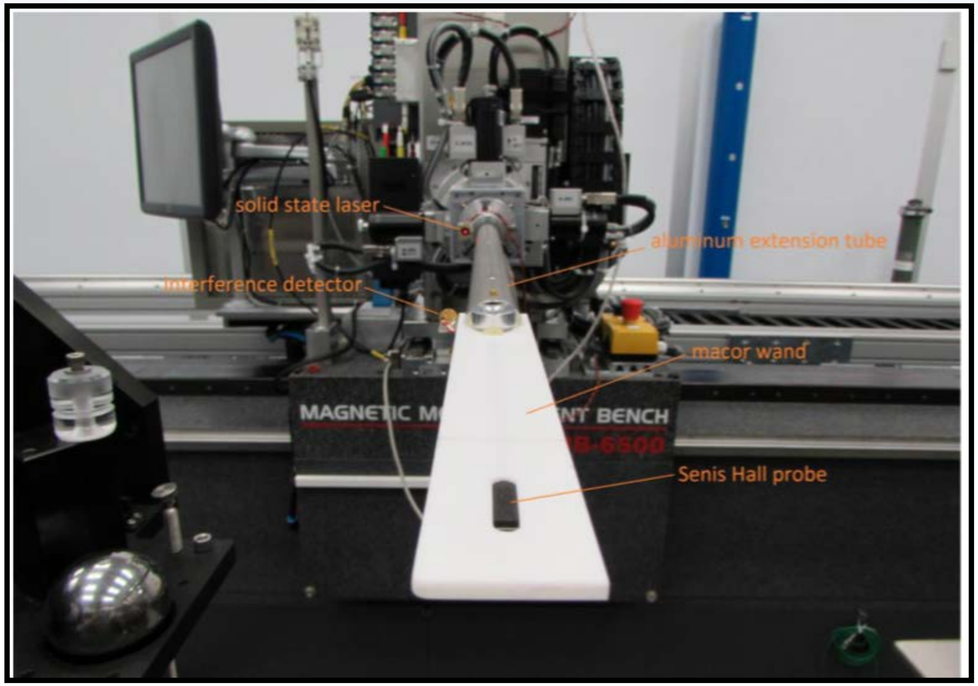
- **9 Motion Controlled Axes**

4 Primary Axes
- **Z** master axis and **Z’** follower axis
- **Y** axis and **X** axis

5 Secondary Axes
- **A** rotary axis
- **V** linear axis
- **W** linear axis
- **B** goniometer axis and the **C**

Hall Probe Bench Overview (2/2)

SENIS 3D Hall Probe



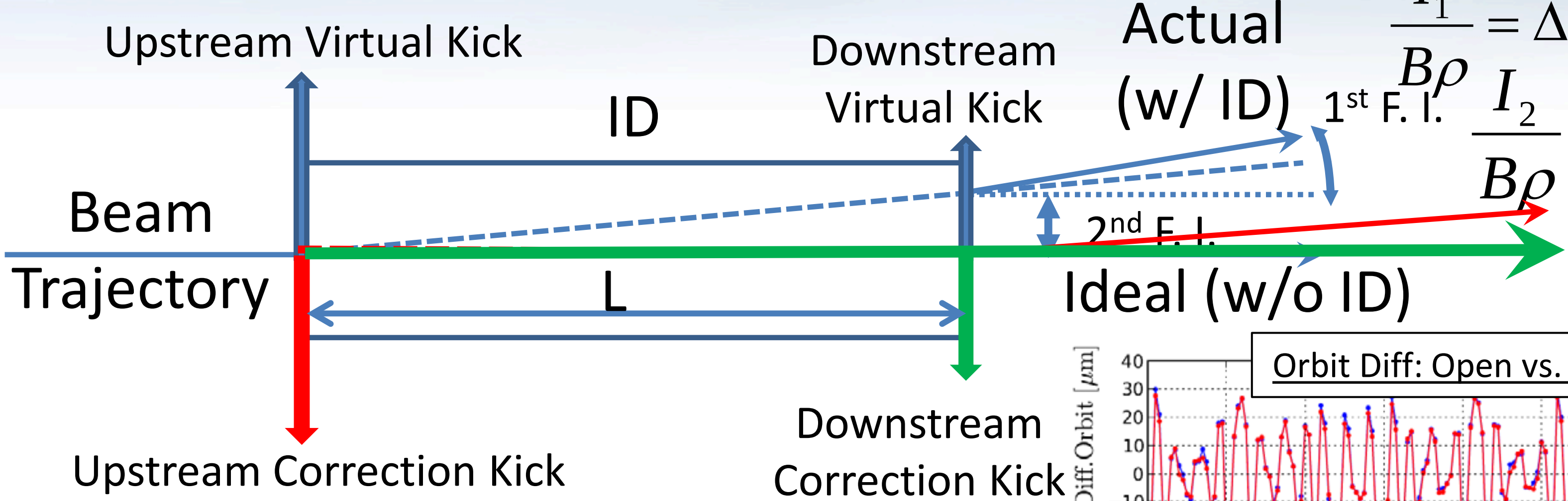
- Hall sensors X, Y and Z are arranged along longitudinal axis
- The SENIS 3D probe is mounted into a macor wand.
- The probe extends ~800 mm from the C stage
- Magnetic field sensitive volume of 150 x 1 x 150 μm
- Linearity error is 0.15% (up to 2 T)
- Good angular accuracy with an orthogonality error < 2°

NI CompactRIO real-time Programmable Automation Controller is utilized for on-the-fly Hall probe data acquisition.

Insertion Device Commissioning Steps

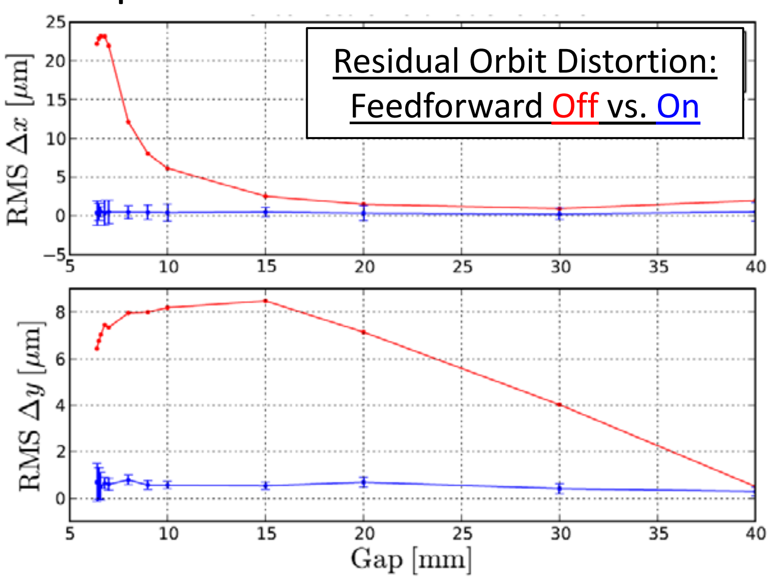
- Commission canting magnets (if any)
- Commission new ID BPMs (e.g., BBA)
- Active interlock check
- Front end flag photon beam alignment
- Radiation survey
- Physical aperture scan with local bumps
- ID Elevation scan
- Orbit feedforward table generation / validation
- Current strips table validation (for EPUs)

Beam-based Field Integral Measurements

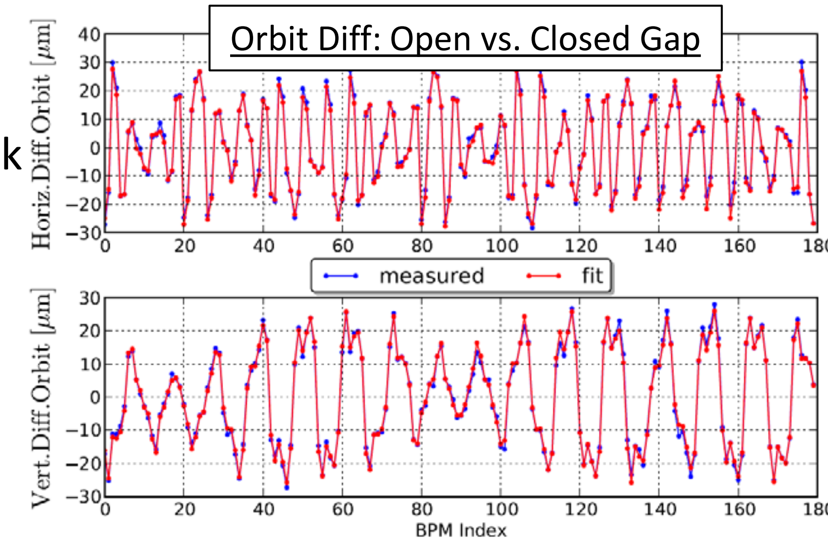


$$\frac{I_1}{B\rho} = \Delta\theta_x = \theta_{\mathrm{US}} + \theta_{\mathrm{DS}}$$

$$\frac{I_2}{B\rho} = \Delta x = L\theta_{\mathrm{US}}$$



- Orbit feedforward system applies opposite kicks at both ends to minimize orbit disturbance outside ID.



- Treat ID as drift & fit US & DS virtual kick angles that produce measured COD difference
- Simple formula to estimate I_1 & I_2

$$I_1 = B\rho\left(\theta_{\mathrm{US}} + \theta_{\mathrm{DS}}\right) \quad I_2 = B\rho \cdot L\theta_{\mathrm{US}}$$

Field Integrals: Beam-based vs. Flip Coil Meas.

Device	Location	Date	Gap [mm]	Coil ΔI_x [G.cm]	Coil ΔI_y [G.cm]	e-beam ΔI_x [G.cm]	e-beam ΔI_y [G.cm]	RMS Δx [μm]	RMS Δy [μm]
IVU20	C3	2/25/15	6.7	-105.6985	77.558	-11.086	-3.363	1.152	0.501
IVU20	C11	2/25/15	6.7	-33.3001	11.608	17.963	32.457	1.187	0.593
IVU21	C5	11/15/14	6.2	-71.37575	79.664	-104.454	102.777	1.417	1.084
		2/25/15 **	6.5	-170.118	259.042	-81.194	88.924	1.199	2.787
IVU22	C10 (LS)	11/21/14	6	17.743	214.844	-24.237	-15.945	2.419	1.189
		2/25/15	7.2	-394.663	93.299	-63.984	-18.226	2.534	3.014
DW	C8U	12/20/14	15	-22.9726	-51.3981	-105.159	-99.38	8.818	4.485
		2/25/15	15			-62.961	-79.578	5.546	4.252
	C8D	1/23/15	15	137.6943	158.2675	59.702	215.524	6.066	6.634
		2/25/15	15			42.042	199.967	10.021	5.955
	C18U	12/17/14	15	-21.0953	12.2921	-144.666	-76.481	5.795	6.456
		2/25/15	15			-96.179	-67.754	4.659	3.454
	C18D	12/20/14	15	2.4744	-9.4423	-187.691	95.166	5.464	5.249
		2/25/15	15			-213.981	79.656	5.950	9.544
	C28U	12/8/14	15	-95.9395	-24.267	140.991	-57.057	5.106	6.544
		2/25/15**	15			-67.869	-53.881	4.564	3.326
	C28D	12/8/14	15	-95.9395	-24.267	-290.004	178.495	5.134	17.54
		2/25/15 **	15			-205.97	160.369	7.758	6.311

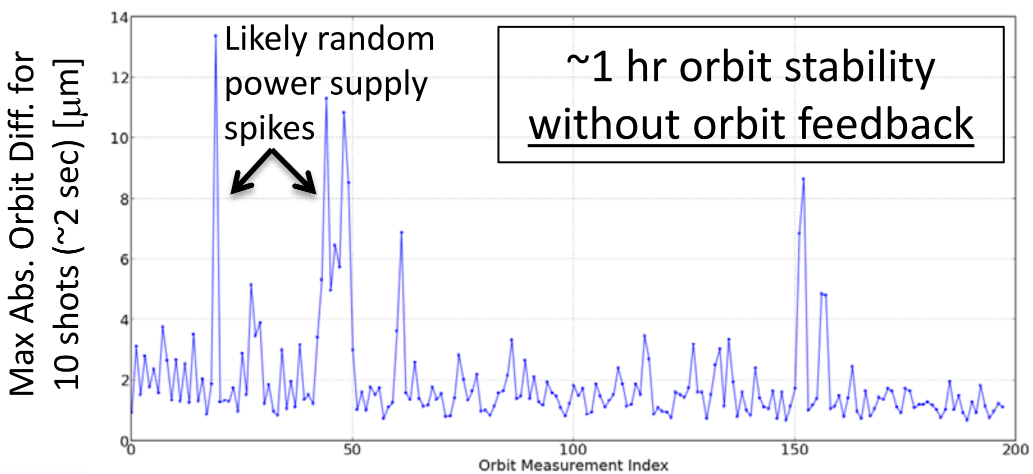
T. Tanbae et al., Synch. Rad. News, 28 (2015)

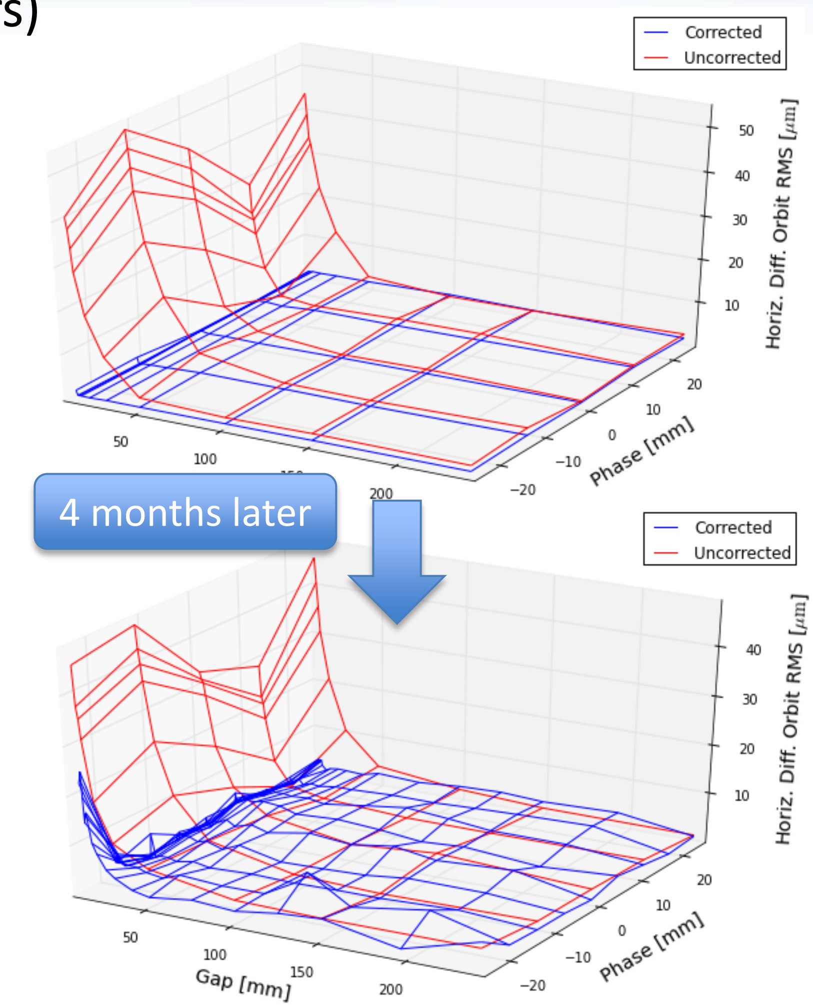
** Realigned after year-end shutdown in 2014

- Beam-based fitting is worse (RMS Δx & Δy) for DWs than for IVUs
  - Stronger focusing effect of wigglers, sensitive to vertical orbit centering
  - Large horiz. wiggling motion => path lengthening
- Many show large discrepancies
  - Potential causes: Earth field variation, nearby ferromagnetic structures, stray B-field, misalignment during installation

Orbit Feedforward Correction Limitation

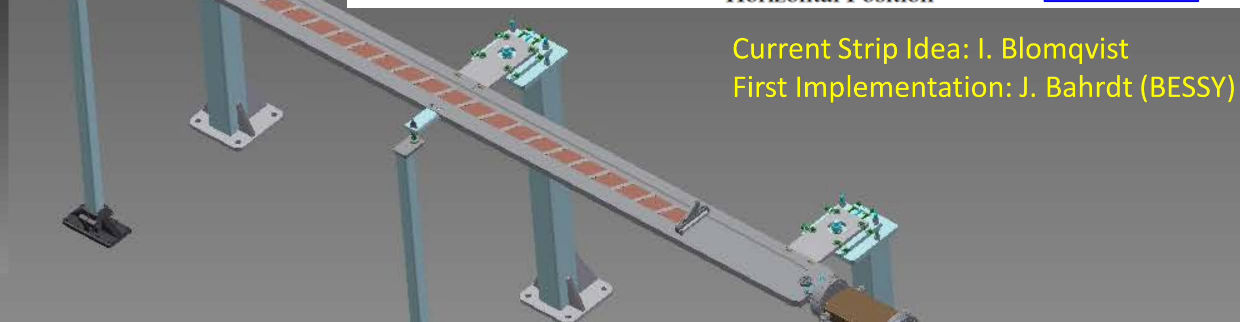
- Long-term drift (e.g., settlement, environmental change, local bump change request from users)
- Orbit jitters w/o feedback => best-case orbit feedforward correction of 1-2 μm
- Table generation/validation very time-consuming for EPUs (e.g., C23 CSX):
  - 2D table for each mode:
    - ORM meas. required at each gap
    - Meas. COD & ORM ~40 min. (10 gaps & 5 phases)
    - Refine computed table ~40 min.
  - 2 parallel & 2 anti-parallel modes (for each of 2 devices)

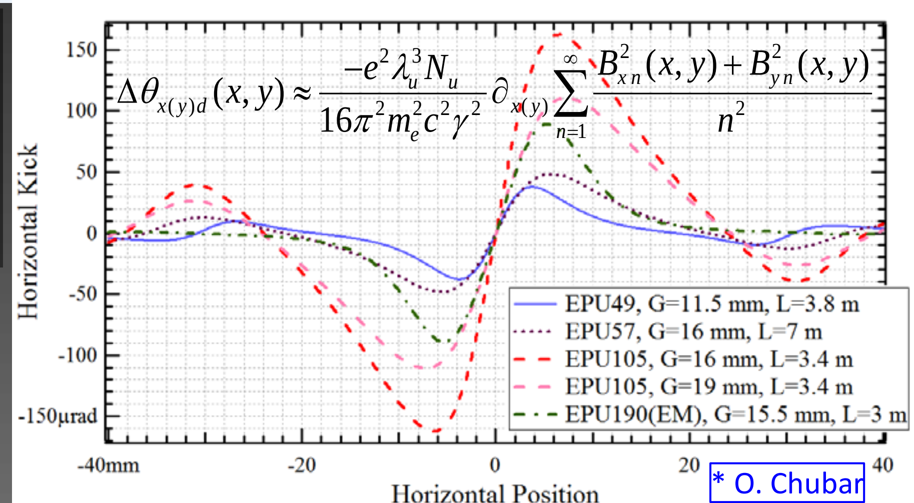




Current Strips for 2nd-Order Kick Correction

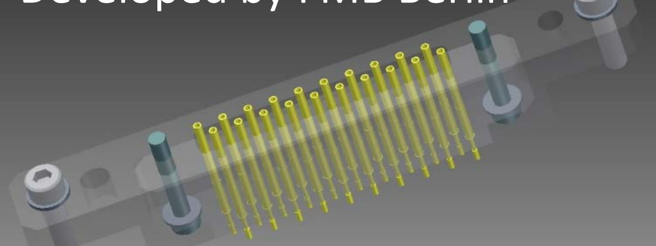
SIX: 26 wires x 2 per EPU
Wire x-sec 2mm (W)x 0.3 mm (H)x 3500 mm (L)
Space separation between wire 0.5 mm
Max current <3A



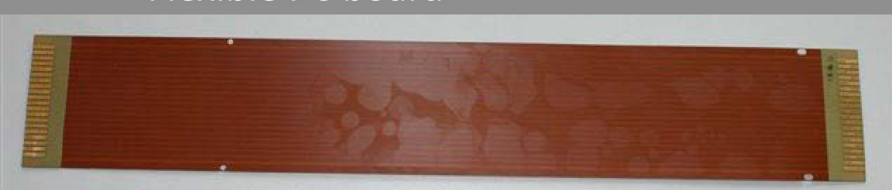


Current Strip Idea: I. Blomqvist
First Implementation: J. Bahrdt (BESSY)

Developed by FMB Berlin

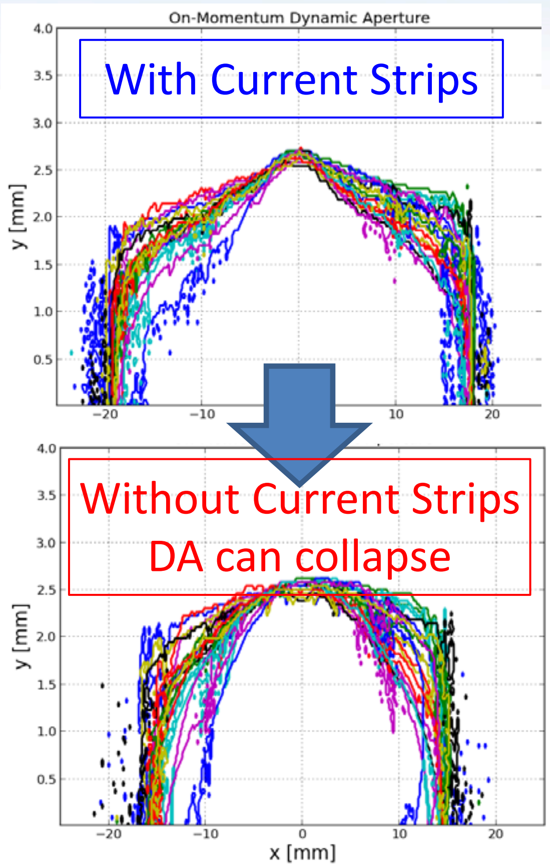


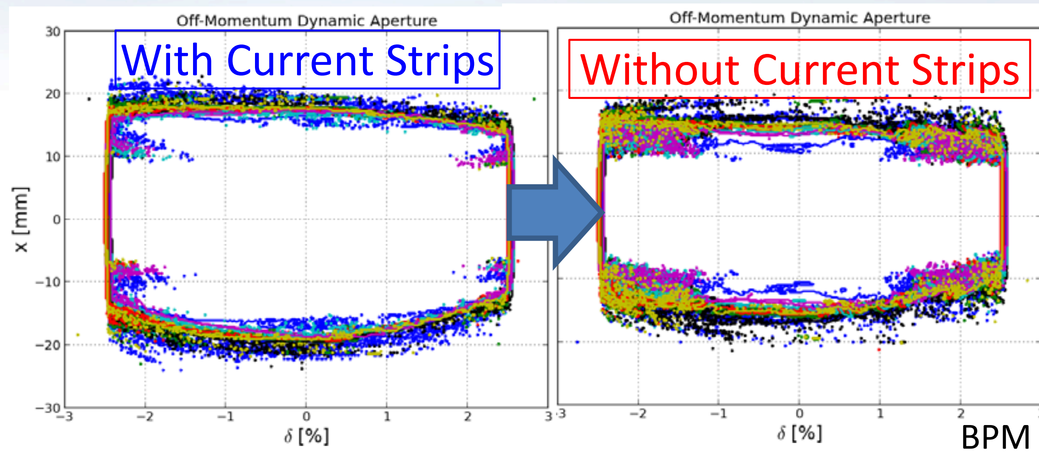
Flexible PC board



Courtesy of C. Kitegi

2nd-Order Kick Impact from EPUs on Beam Dynamics

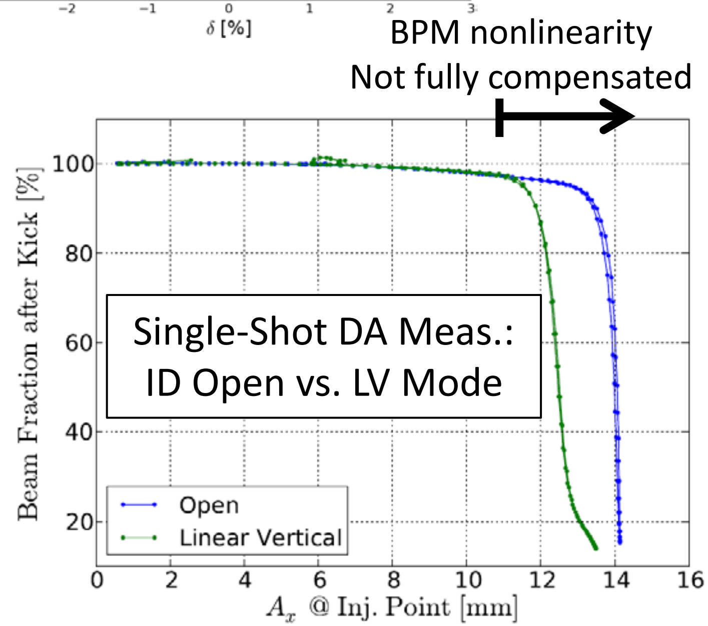




SIX @ 16 mm gap & 28.5 mm phase (Linear Vertical Mode)

On-Axis Tune Shift w/o CS

	Measured	Expected
$\Delta\nu_x$	-0.01241	-0.01302
$\Delta\nu_y$	+0.00403	+0.00405

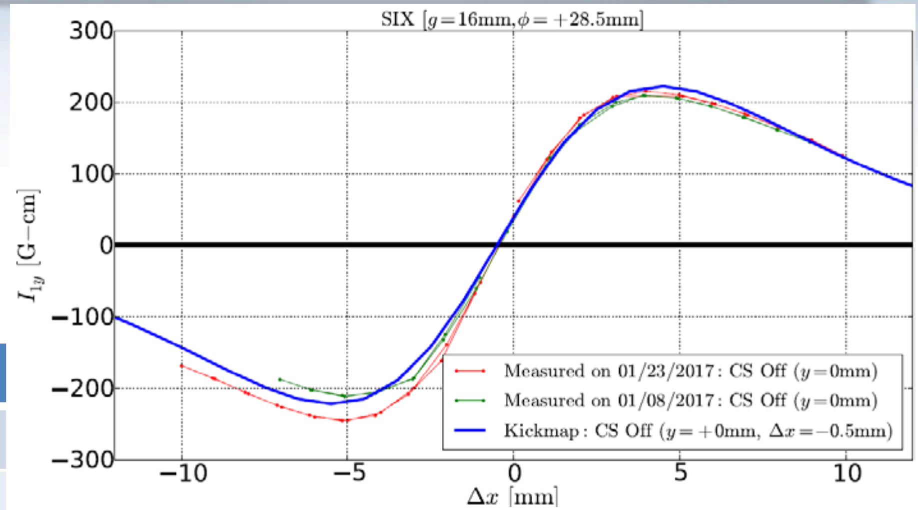


	ID Open	ID Closed w/o CS
Measured Injection Eff.	~90%	~40%

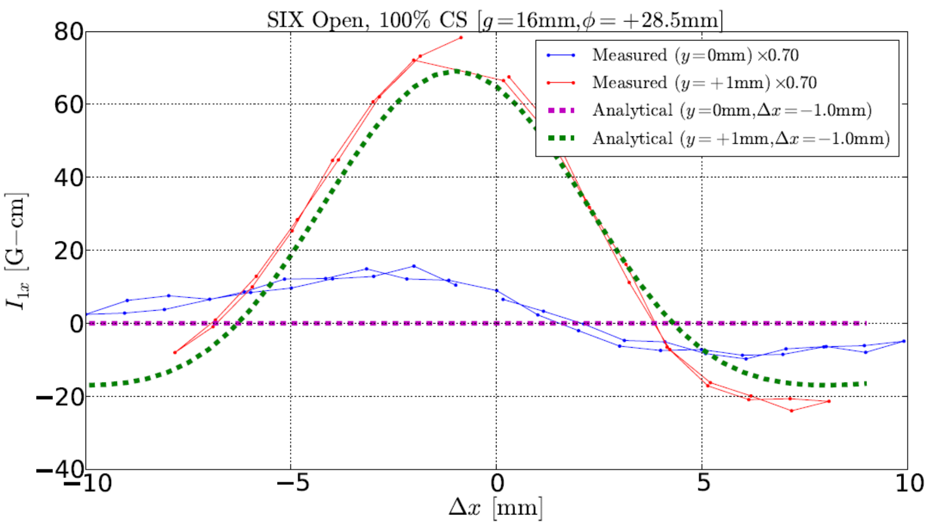
Direct Meas. & Correction of 1st and 2nd-Order Kicks

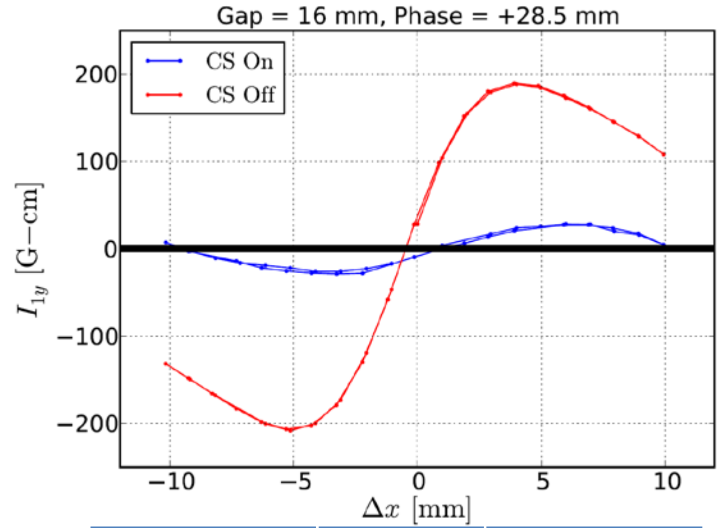
- Utilize same technique used in orbit feedforward table generation to measure beam-based field integrals with different horizontal orbit bumps.
- Compensation confirmed for SIX (But only 70% expected correction applied)

	Peak 1st Fld. Int.	Inj. Eff. [%]
Without CS	~200 G-cm	70.7±11.5
With CS	~20 G-cm	96.1±3.8



- Potential as beam alignment diagnostic tool

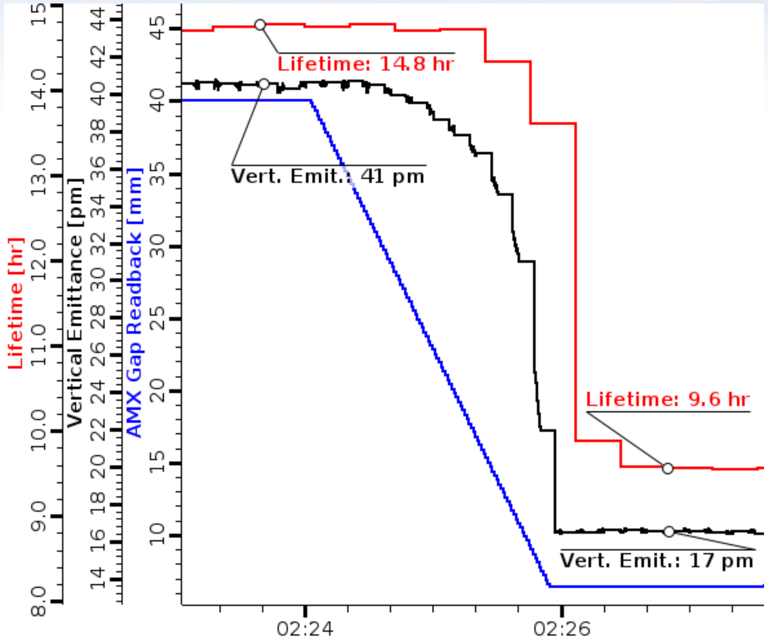




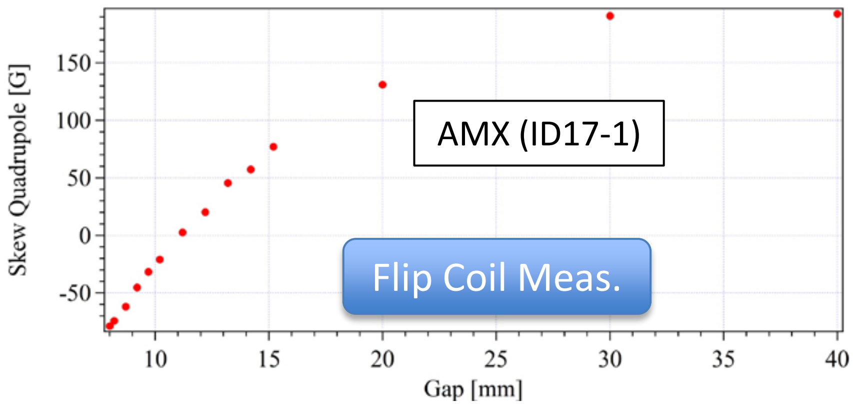
	w/o CS	w/ CS
Measured $\Delta\nu_x$	-0.01242	-0.00151
Expected $\Delta\nu_x$	-0.01302	-0.00036
Measured $\Delta\nu_y$	+0.00407	+0.00213
Expected $\Delta\nu_y$	+0.00405	+0.00170

- Online adjustment of correction currents also planned

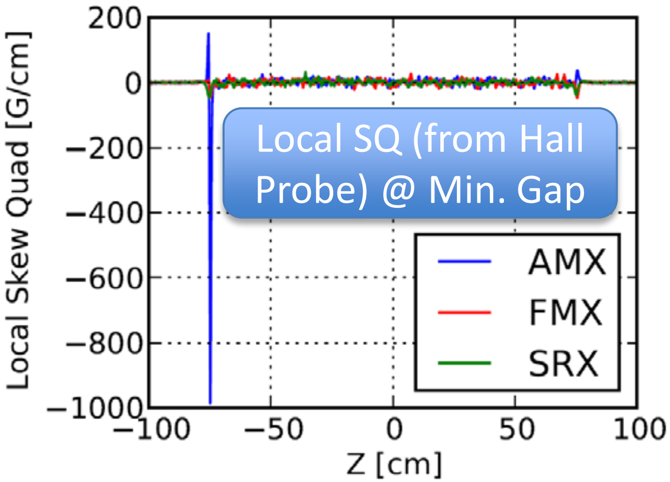
ID-induced Coupling Change



- Large lifetime jumps occasionally observed since March 2016 at NSLS-II.
- Correlated with ID gap motions, particularly with AMX, an IVU at Cell 17.

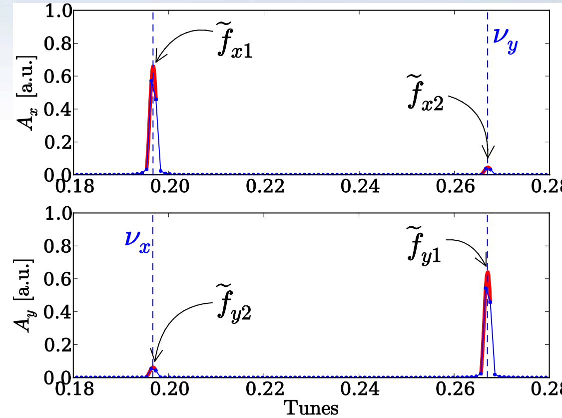


- AMX found to have:
  - Large SQ variation with gap (>15 mm gap outside of ±50 G spec).
  - Large localized skew quad. (SQ) component at min. gap



Beam-based Coupling Measurement

- SQ error estimates by DTBLOC (Driving-Terms-based Linear Optics Calibration) algorithm [Y. Hidaka et al. NAPAC 2016]
  - Based on RDTs formalism used by ESRF coupling correction [A. Franchi et al., PRSTAB 14, 034002 (2011)]
  - Also estimates normal quad errors as well as BPM gains/rolls/deformations (very important for coupling & η_y!)
  - Very fast (~2 min. data acq. [TbT + Dispersion], ~3 min. data proc. & fitting, for 1 iteration)



$$f_{\substack{1001\\1010}}(s) \cong \frac{\sum_w (\Delta a_2 L)_w \sqrt{\beta_x^w \beta_y^w}\, e^{i\left(\Delta\phi_x^{w,s} \mp \Delta\phi_y^{w,s}\right)}}{4\left(1 - e^{2\pi i\left(\nu_x \mp \nu_y\right)}\right)}$$

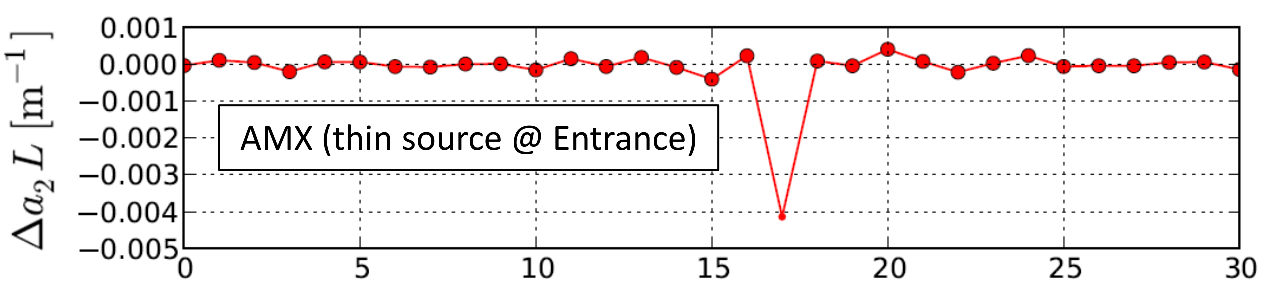
$$|f_{x1}| = \sqrt{2I_x\beta_{x0}} \qquad |f_{y1}| = \sqrt{2I_y\beta_{y0}}$$

$$|f_{x2}| = \sqrt{2I_y\beta_{x0}}\sqrt{\left(2\Im\{f_{1001}\} + 2\Im\{f_{1010}^H\}\right)^2 + \left(2\Re\{f_{1001}\} - 2\Re\{f_{1010}^H\}\right)^2}$$

$$|f_{y2}| = \sqrt{2I_x\beta_{y0}}\sqrt{\left(2\Im\{f_{0110}\} + 2\Im\{f_{1010}^V\}\right)^2 + \left(2\Re\{f_{0110}\} - 2\Re\{f_{1010}^V\}\right)^2}$$

AMX (ID17-1) @ gap 6.4 mm	Integ. SQ [G]	χ^2 reduc. factor
Thin @ Entrance	**-578.3**	101.1
Thin @ Center	-958.1	80.7
Thin @ Exit	-1529.2	50.7
Thick (1.5 m)	-974.6	61.8

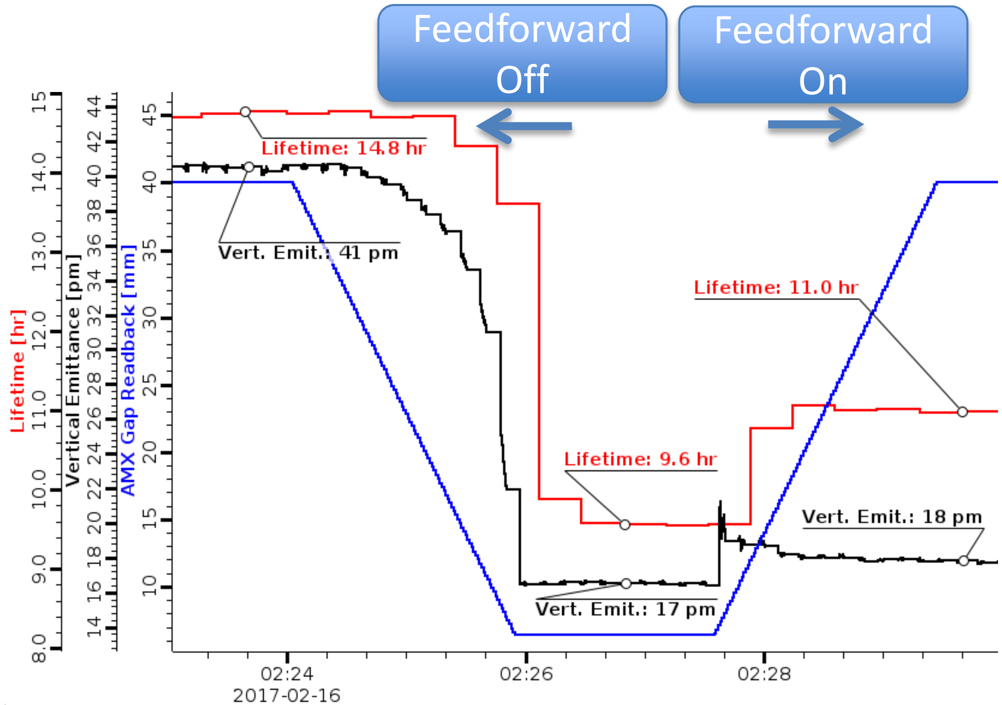
FMX (ID17-2) @ gap 6.4 mm	Integ. SQ [G]	χ^2 reduc. Factor
Thin @ Entrance	-304.5	16.4
Thin @ Center	-197.8	17.8
Thin @ Exit	-118.6	17.6
Thick (1.5 m)	**-171.6**	17.3



- Fits better (i.e. larger χ^2 reduction factor) if thin error source at entrance is assumed, which is consistent with the Hall probe measurement for AMX.

Global Coupling Feedforward System

- Recently implemented for stable operation in low-emittance mode.
- Use existing 15 correction SQs in non-dispersive sections to avoid vertical dispersion change.
- Currently only for AMX, but extendable to other ID-induced SQ errors.
- 1 iteration sufficient, which took only 25 min. data acq. & 25 min. proc. to generate full 12-gap feedforward table for AMX.

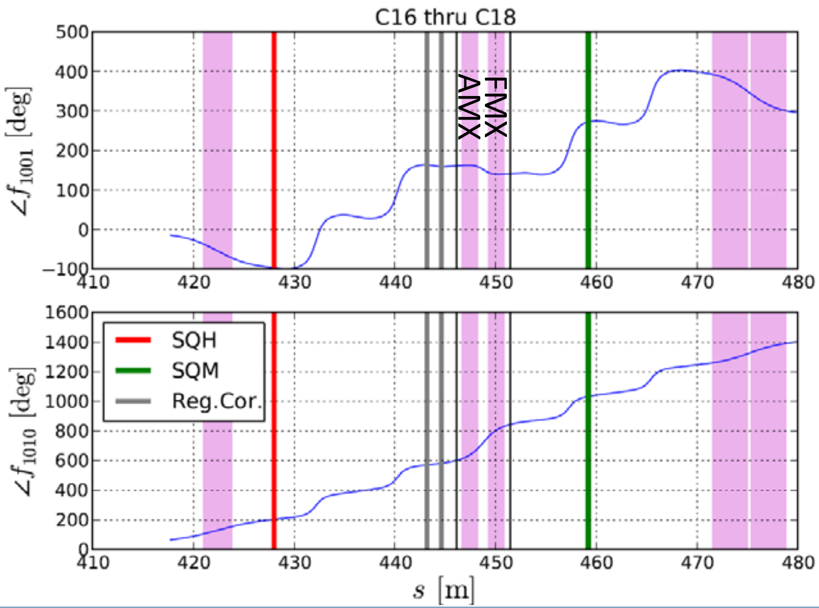


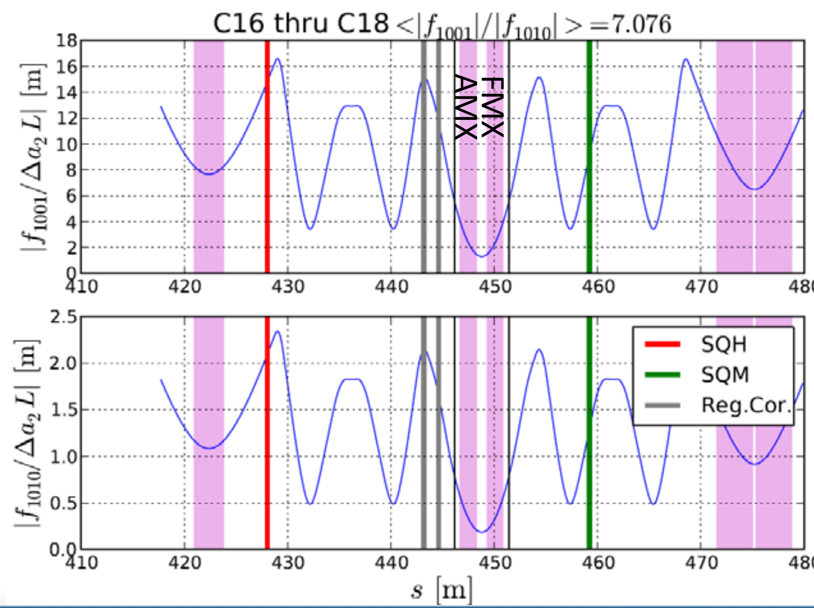
- With feedforward turned on under a nominal user operation condition (i.e., high current, moderate emittance):
  - $\Delta\sigma_y$ of 60% (260% in ε_y) => 4% (8%)
  - Beam-current-lifetime-product change of 53% reduced to 11%.
- Table generated at low current (2 mA) was equally effective at high current (250 mA).

More Coupling Variation Mitigations

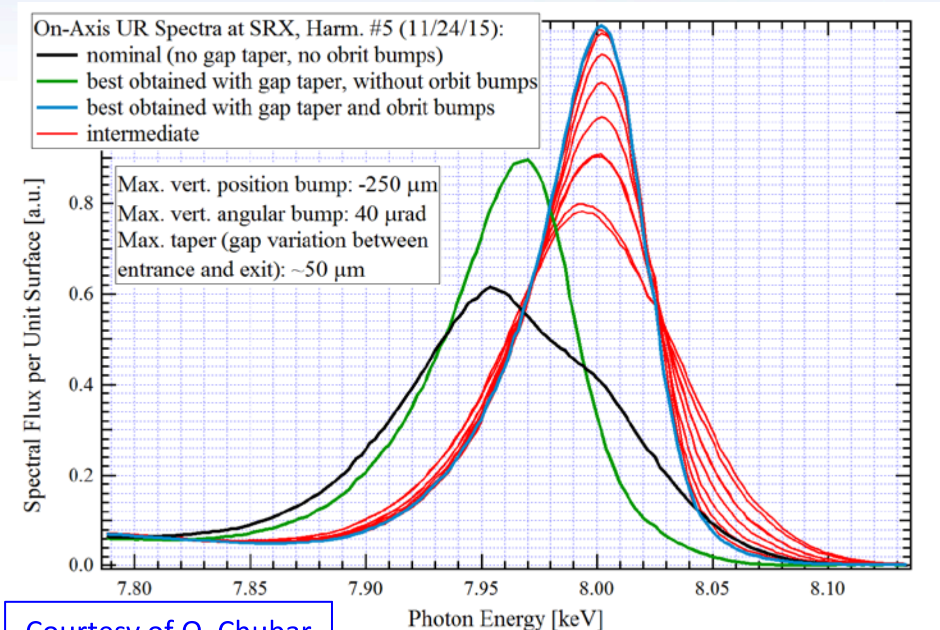
- Maximum gap reduced from 40 mm to 25 mm to limit skew component variation.
  - better also from impedance point of view
- More "local" compensation planned by introducing a new additional correction SQ near AMX.
  - Identified a slow orbit corrector upstream of AMX as a good candidate (right f_{1001} phase & large β-functions) for skew quad retrofitting (during this shutdown)

$$f_{\substack{1001\\1010}}(s) \cong \frac{\sum_w (\Delta a_2 L)_w \sqrt{\beta_x^w \beta_y^w}\, e^{i\left(\Delta\phi_x^{w,s} \mp \Delta\phi_y^{w,s}\right)}}{4\left(1 - e^{2\pi i\left(\nu_x \mp \nu_y\right)}\right)}$$

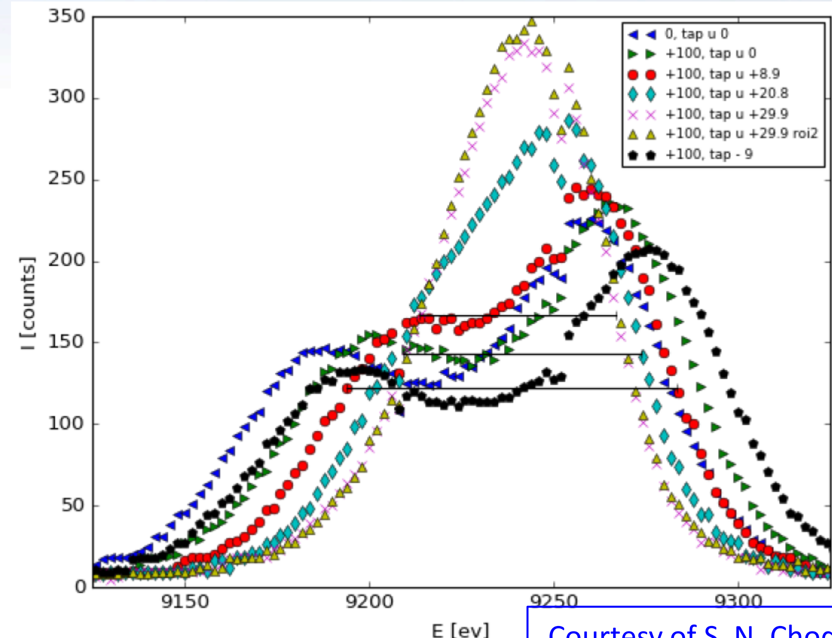




Improving Photon Beam Quality & Stability



Courtesy of O. Chubar



Courtesy of S. N. Chodankar

- Significant undulator radiation spectra improvement at SRX (C05 IVU) and LIX (C16 IVU) by applying e-beam orbit bumps, undulator gap tapering, and/or undulator elevation.
- Adjustment of elevation, undulator taper, and ID-mounted long-coil at SMI (C12 IVU).
- CSX (C23) EPU brake engage/disengage found to cause vertical orbit disturbance (~1 μm).
- Inclusion of ID BPMs into fast orbit feedback (FOFB) loop.
- Upgraded ID local bump programs to be compatible w/ FOFB (APS method).
- Cross-talk between upstream & downstream canted EPUs at CSX (C23) => larger canting angle may be needed.

Summary

- 3 different types (DWs, IVUs, EPUs), a total of 17 IDs have been successfully installed and commissioned at NSLS-II so far.
- ID Magnetic Field Measurement Lab was essential in certifying and improving ID field qualities before installation into the SR tunnel.
- Beam-based residual field integrals were found to differ substantially from flip coil measurements, likely due to environmental differences and sensitivity to beam orbit.
- Orbit feedforward system has been successfully implemented with up to a few micron residual orbit distortion, but long-term drift and short-term orbit jitters recognized as limitations.
- Preliminary results from current strips commissioning indicate their effectiveness to correct dynamic field integrals for most worrisome EPU in a large beta straight. More to be studied.
- Unexpected ID-induced coupling source has been successfully minimized by a global coupling feedforward system (DTBLOC, fast lattice correction tool, quite helpful), while more local coupling compensation solution is being implemented.
- Continue to optimize photon beam quality for user scientists.

Acknowledgments

- ID Group
- Other Groups in NSLS-II Accelerator Division
- NSLS-II Photon Science Division

Any Questions?