

Towards sub-Micron Orbit Stability at NSLS-II



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for NSLS-II Accelerator Team
LER-2015, Grenoble, ESRF
September 16, 2015

12 Years Ago Here

Impact of Mini-Gap Undulators on Beam Dynamics and Operations at NSLS

Boris Podobedov (for the NSLS team)

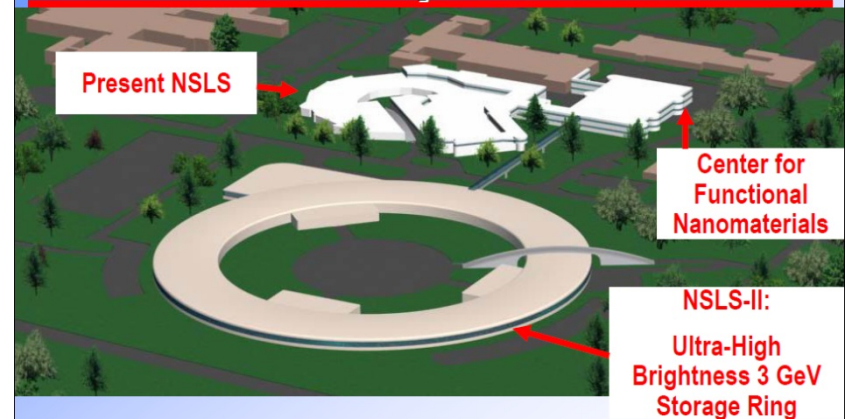
National Synchrotron Light Source
Brookhaven National Lab

Workshop on
Superconducting Undulators & Wigglers
ESRF, Grenoble, France
July 1, 2003

Brookhaven Science Associates
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Possible Site Layout for NSLS-II



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NSLS-II Motivation and Goals

Background:

- + The two rings at the NSLS are entering their 3rd decade of dedicated operation for 2500 users!
- + Brighter sources exist in the USA and abroad; in fact with the SPEAR3 upgrade will have the lowest brightness in USA
- + Bulk of the light source users reside in 5-20 keV
- + Brightness is the driver but average current / flux users are important as well

Goals:

- + 10³ increase in undulator brightness in the 5-20 keV range
- + without a significant reduction in flux
- + increase the insertion device capacity from 5 to ~20,
- + all done for a reasonable cost -> circumference & energy

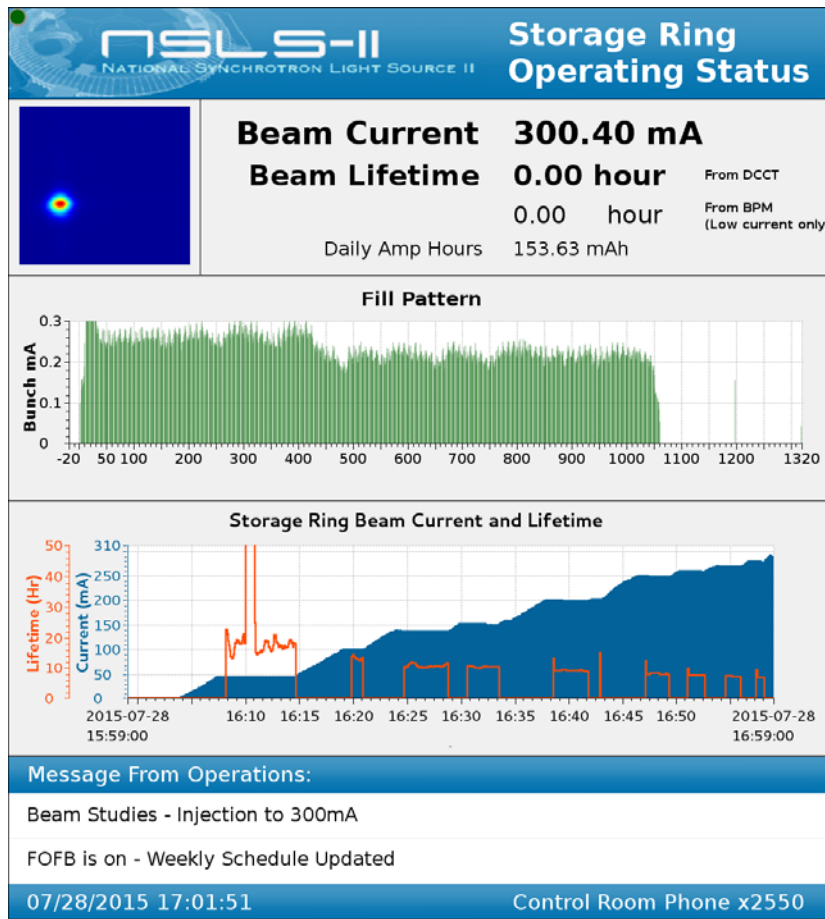
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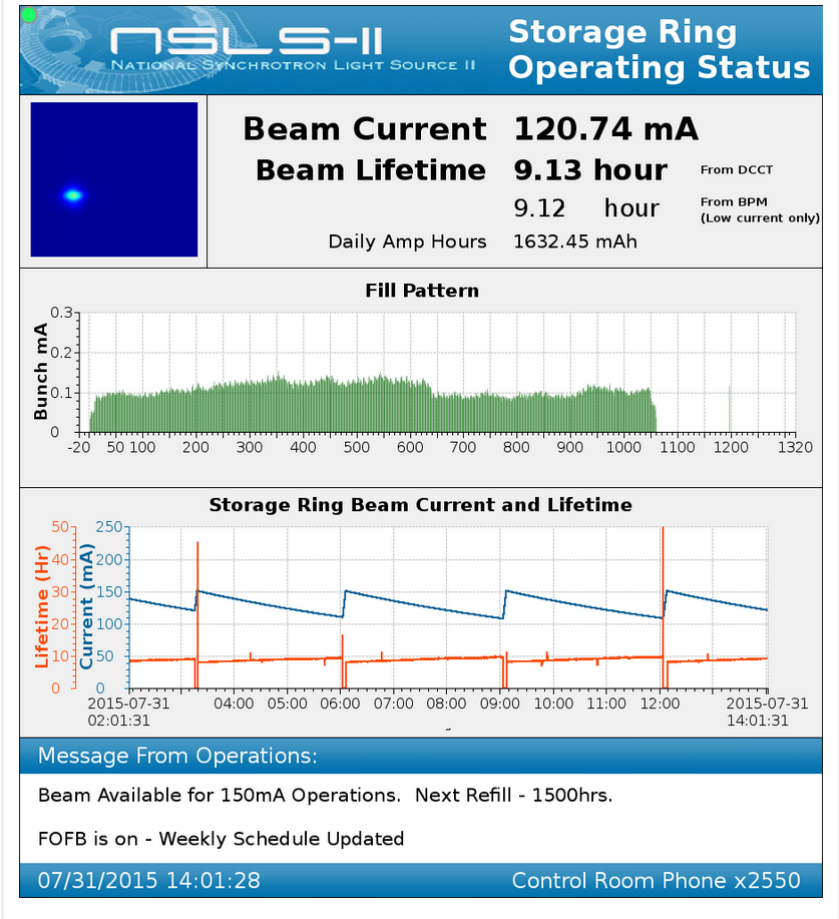
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The first talk that mentions NSLS-II

Recent NSLS-II Storage Ring Performance

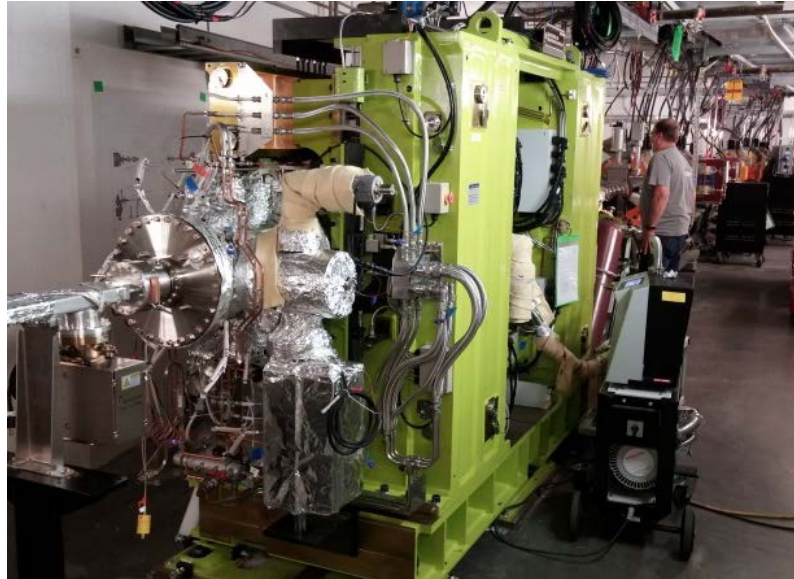


300 mA!



Routine Ops at 150 mA

Insertion Devices: ~15 Installed and More on the Way



Installation of In-Vacuum Undulator for ISR beamline, cell 4, this August

As of summer 2015:

- 7 IVUs
- 2 EPUs
- 3x2 DW

nsls-II
NATIONAL SYNCHROTRON LIGHT SOURCE II
ID & Frontend Main

Beamline Shutter Enable
DISABLE
ENABLE
Enabled
Beamline Control Restrict Permit

	FE Status - ID Gap, FE Flag, Shutters and Valves										Interlocks		ID Gap (mm)		Beamline Control		
	ID Gap	BMPS	GV1	Flag	Shutters	IDPS	FV	SSA	SSB	GV2&BL	Act Intlk	BeamDump	Detail	ID 1	ID 2	Slits & Gap	
ID3 HXN	Open	Closed	Closed	Out	Disabled	Closed	Open	Closed	Closed	Closed	Enabled	Normal	IVU20	40.00		Restricted	Permitted
ID5 SRX	Open	Closed	Closed	Out	Disabled	Open	Open	Open	Open	Closed	Enabled	Normal	IVU21	40.00		Restricted	Permitted
ID08	Open	Closed	Closed	None	Disabled	Closed	Closed	Closed	Closed	Closed	Disabled	Dumped	DW100	150.0	150.0		
ID10 IXS	Closed	Closed	Closed	Out	Disabled	Closed	Open	Closed	Closed	Closed	Enabled	Dumped	IVU22	5.50		Restricted	Permitted
ID11 CHX	Open	Closed	Closed	Out	Enabled	Closed	Open	Closed	Closed	Open	Disabled	Normal	IVU20	40.00		Restricted	Permitted
ID16	Open	Closed	Closed	Out	Enabled	Closed	Open	Closed	Closed	Open	Disabled	Dumped	IVU23	39.60			
ID17	Open	Closed	Closed	Out Out	Disabled	Closed	Closed	Closed	Closed	Closed	Enabled	Normal	IVU21	39.90	40.00		
ID18	Open	Open	Open	None	Disabled	Closed	Closed	Closed	Closed	Closed	Disabled	Normal	DW100	150.0	150.0		
ID23 CSX	Open	Closed	Closed	Out	Disabled	Closed	Open	Closed	Closed	Open	Enabled	Normal	EPU49	239.0	239.0	Restricted	Permitted
ID28 XPD	Open	Closed	Closed	Out	Enabled	Closed	Open	Closed	Closed	Open	Enabled	Normal	DW100	150.0	150.0	Restricted	Permitted

BTS Shutter Status Closed IOC status/reboot ID&FE Limits Front-end Flags Temp Monitoring

Summary ID3 HXN ID5 SRX ID08 ID10 IXS ID11 CHX ID16 ID17 ID18 ID23 CSX ID28 XPD

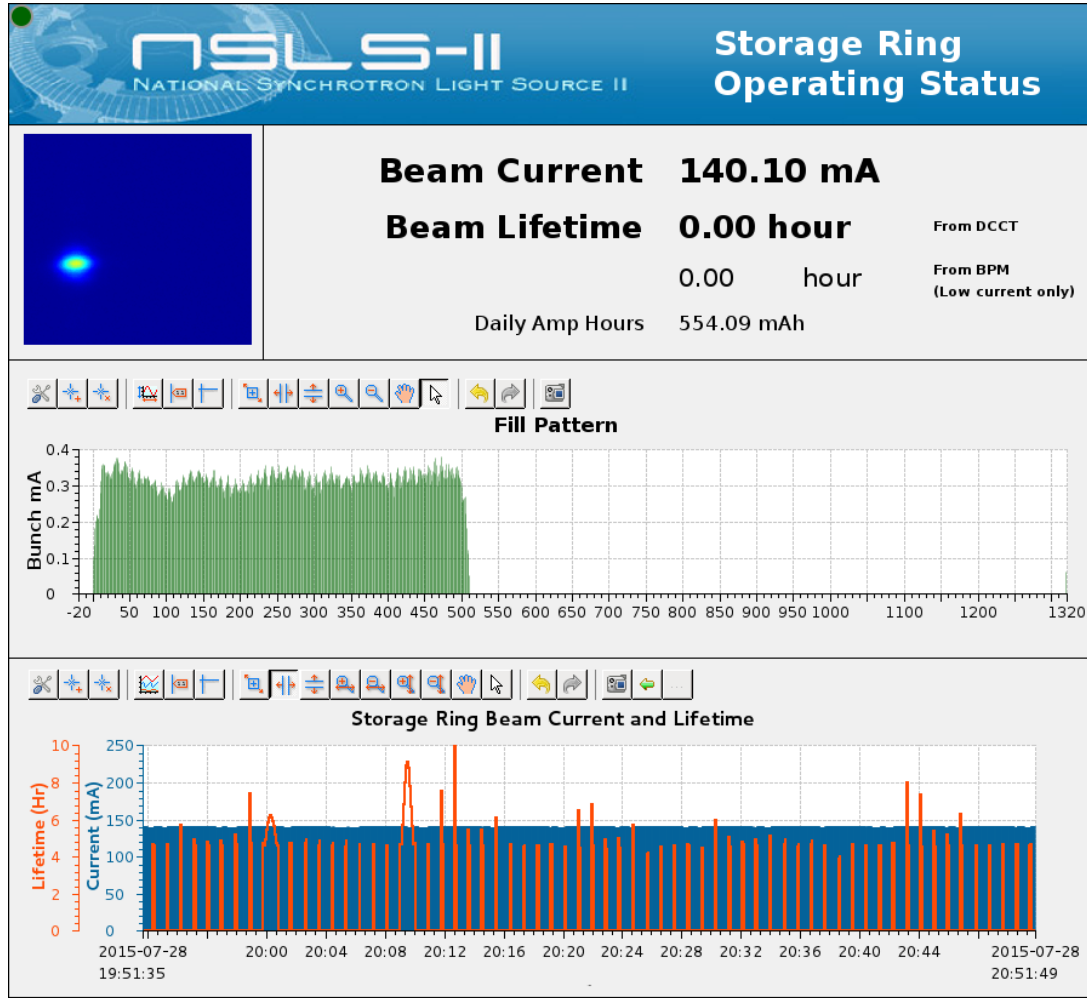
Open DWs STOP

IVU	Gap (mm)				Elevation (mm)				PS Sum	
	Setpoint	Readback	Min	Max	Setpoint	Readback	Min	Max	Power	Mode
C03	40.00	40.00	5.20	40.10	0.00	-0.00	-2.45	2.45	On	Auto
C05	40.00	40.00	6.40	40.10	0.00	-0.00	-2.75	2.75	On	Auto
C10	5.50	5.50	5.50	40.05	-3.78	-3.78	0.00	0.00	On	Auto
C11	40.00	40.00	5.20	40.10	0.00	-0.01	-2.45	2.45	On	Auto
C16	39.60	39.60	0.00	0.00	0.20	0.20	0.00	0.00	On	Auto
C17-1	39.90	39.90	6.40	40.10	0.00	0.00	-2.00	2.00	On	Auto
C17-2	40.00	40.00	6.40	40.10	0.00	-0.00	-2.00	2.00	On	Auto

EPU	Gap (mm)				Phase (mm)				PS Sum		
	Setpoint	Readback	Min	Max	Mode	Setpoint	Readback	Min	Max	Power	Mode
C23-1	239.00	239.00	11.50	239.00	Parallel TO-BI	0.00	0.00	-24.60	24.60	On	Auto
C23-2	239.00	239.00	12.00	239.00	Parallel TI-BO	0.00	-0.00	-24.60	24.60	On	Auto

DW	Gap DW1 (mm)				DW1 PS Sum		Gap DW2 (mm)				DW2 PS Sum	
	Setpoint	Readback	Min	Max	Power	Mode	Setpoint	Readback	Min	Max	Power	Mode
C08	150.00	150.00	15.00	150.1	On	Auto	150.00	150.00	15.00	150.1	On	Auto
C18	150.00	150.00	15.00	150.1	On	Auto	150.00	150.00	15.00	150.1	On	Auto
C28	150.00	150.00	15.00	150.1	On	Auto	150.00	150.00	15.00	150.1	On	Auto

Next Step: Top-off Operations



Preparation for Top-Off operation continues at a good pace.

- ✓ 20% bunch-to-bunch variation has been achieved (ignoring the leading and trailing bunches)
- ✓ 0.5% variation in ring current has also been achieved.

The Top-Off Safety System fabrication and installation is continues on schedule.

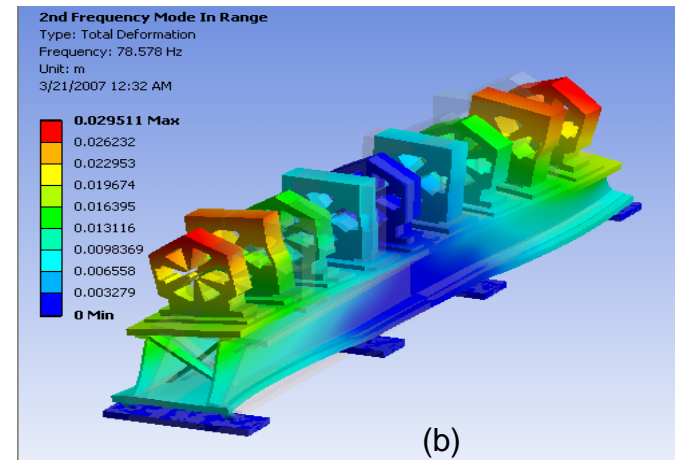
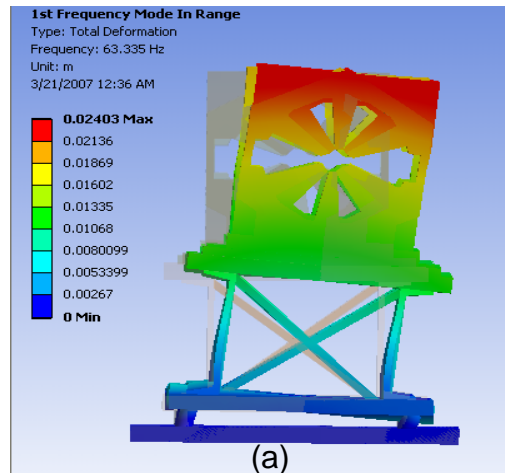
Ray Filler

Results from Top-Off Injection Studies on July 28th

High Stability Design Approach

- Most NSLS-II systems were designed and built with high stability in mind
- Stringent specs on most electrical and mechanical systems (PS regulation, vibration, thermal regulation, girder design, etc.)
- Many studies verifying the design, i.e. vibration analysis
- High resolution and stable BPMs designed and built
- Fast orbit feedback system (FOFB).

Sushil Sharma



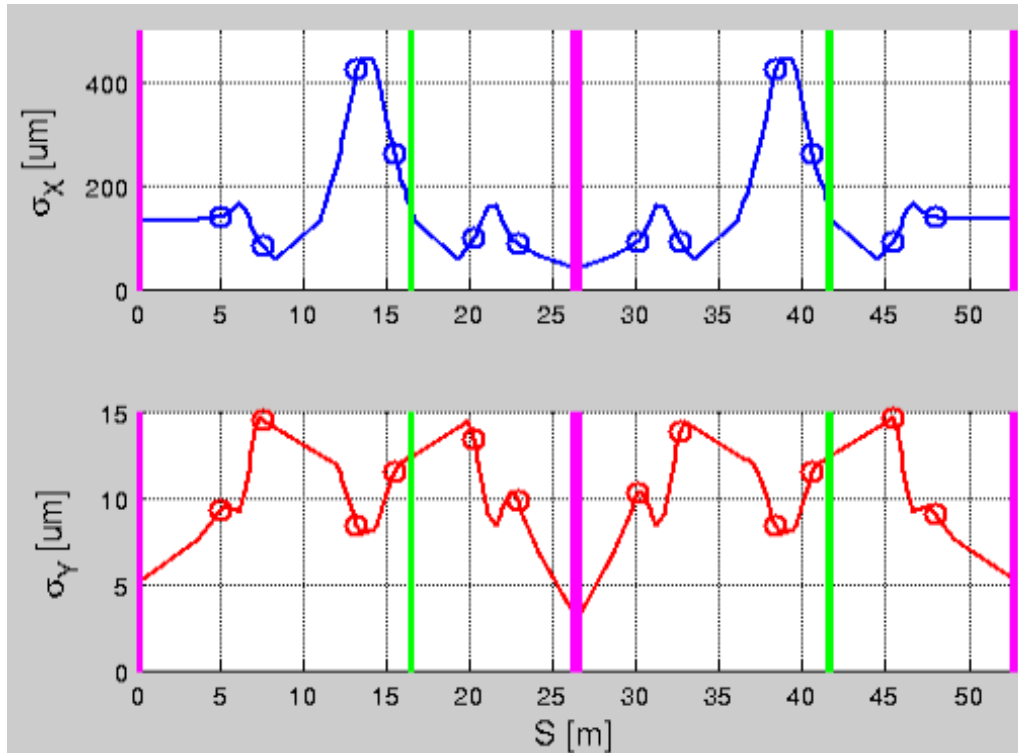
Natural modes of vibration for the girder-magnets assembly

These efforts have largely payed off

NSLS-II Storage Ring Design Parameters

Energy	3.0 GeV	RF Frequency	499.68 MHz
Circumference	792 m	Harmonic Number	1320
Number of Cells	30 DBA	RF voltage	4.8 MV
Number of Super-periods	15	RF Bucket Height	4.1%
Length ID Straights	6.6 & 9.3m	RMS Bunch Length	11.5ps
Emittance with DW (h/v)	0.9 nm/ 8 pm	Average Current	500 mA
Momentum Compaction	.00037	Current per Bunch	~0.5 mA
Dipole Bend Radius	25m	Touschek Lifetime	>3hrs
Energy Loss per Turn (with DW)	0.675MeV	Top-Off Injection Freq	1/min
Energy Spread (with DW)	0.094%	Charge from one injection	7.3nC
		Stability requirement	<10% beam size

RMS Beam Sizes and Orbit Stability Specs



Lines: RMS sizes
Ver. bars: user source points
Circles: RF BPMs (total 180)

Not shown: ID RF BPMs (2-3 per ID straight)
XBPMs (photon BPMs, 4 so far)

- Calculated beam sizes for $\varepsilon_x=0.9$ nm, $\varepsilon_y = 8$ pm, $\delta E/E=0.09\%$
- Smallest beam size in the center of low- β straight $\sigma_x=41$ μm , $\sigma_y = 3.1$ μm
- Our goal to have orbit stable to 10% of these values, i.e. <0.3 μm rms
- Most stringent angular stability is at the high- β straight, $0.1\sigma_y'=0.15$ μrad

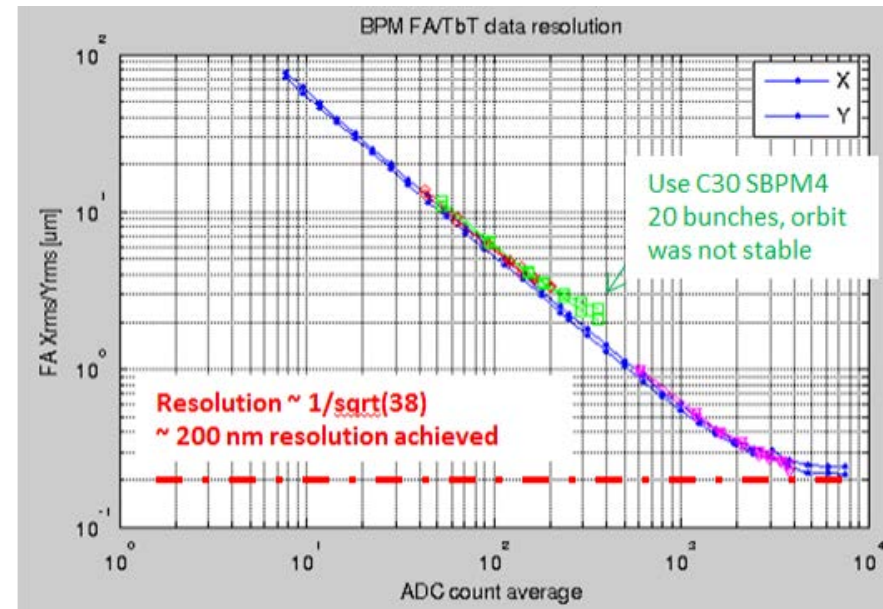
NSLS-II BPMs

Data Type	Mode	Max Length
ADC Data	On-demand	256Mbytes or 32M samples per channel simultaneously
Single-Pass	Streaming	800hr circular buffer (1Hz Injection)
TbT	On-demand	256Mbytes or 5 M samples Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
FOFB 10KHz	Streaming via SDI Link & on demand	Streaming - X,Y,SUM; For on demand: 256 Mbytes or 5 Msamples. Va,Vb,Vc,Vd, X,Y, SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
Slow Acquisition 10Hz	Streaming and On-demand	80hr circular buffer Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
System Health	Streaming & on-demand	80hr circular buffer AFE temp, DFE temp, FPGA Die temp, PLL lock status, SDI Link status



J. Mead, W. Cheng

- Original NSLS-II development (by Kurt Vetter et al.)
- Resolution specs of 1 μm turn-by-turn (TbT) and 200 nm in 10 kHz (FA) mode were verified with beam
- FA is used for fast orbit feedback

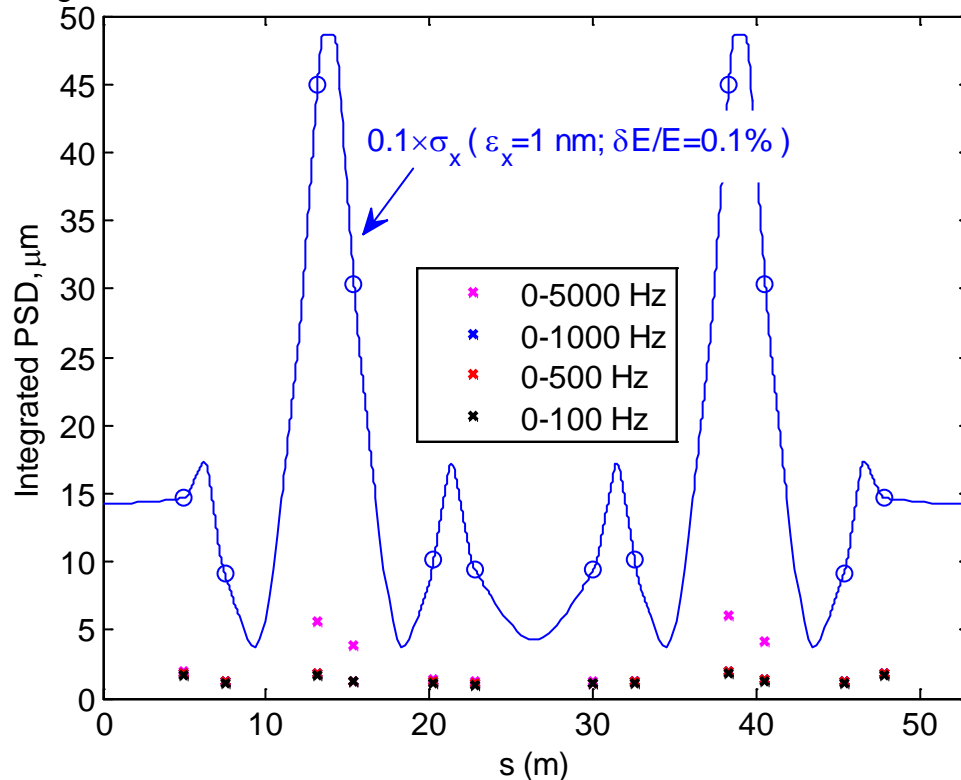


What We Understand about Orbit Noise

Horizontal Orbit Stability without Feedback

- July 2014, 1 sec of 10 kHz (FA) data

Integrated BPM-FA-X Noise and 10% Beam-size Goal; Jul 11, 18:47, 47 mA



Line: 10% beam sizes

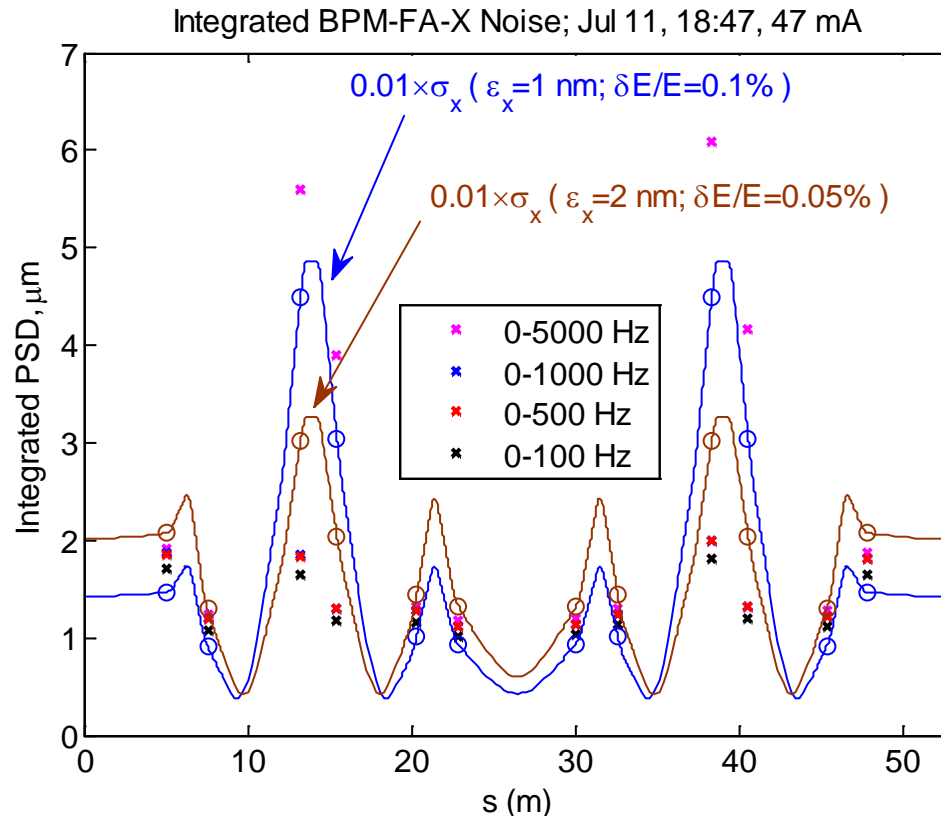
Circles: BPM locations

Crosses: Measurements

- Horizontal orbit stability is a lot better than the 10% beam size spec.

Horizontal Orbit Stability without Feedback

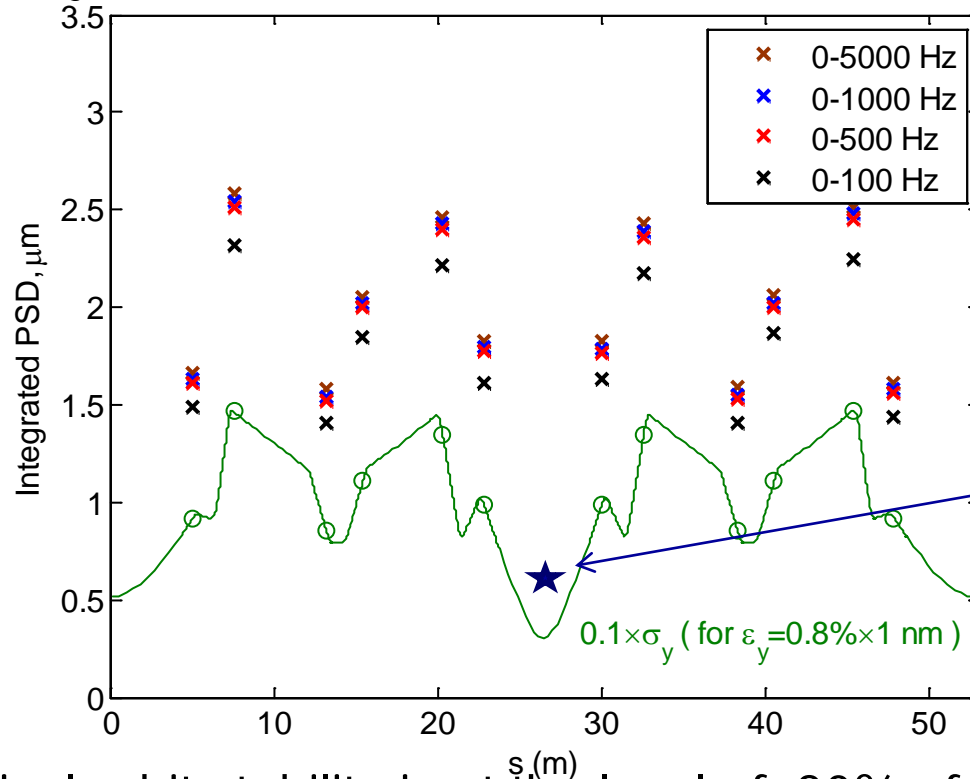
- Same data, x10 finer vertical scale



- Hor. orbit stability is at the level of $\sim 1\%$ beam size.
- Except for dispersion BPMs most of the noise is below 100 Hz.

Vertical Orbit Stability without Feedback

Integrated BPM-FA-Y Noise and 10% Beam-size Goal; Jul 11, 18:47, 47 mA



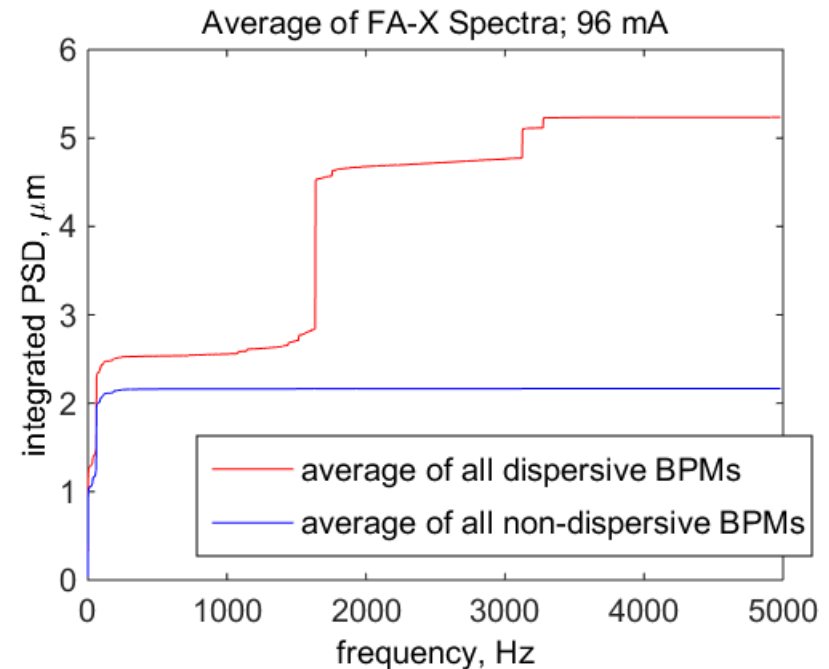
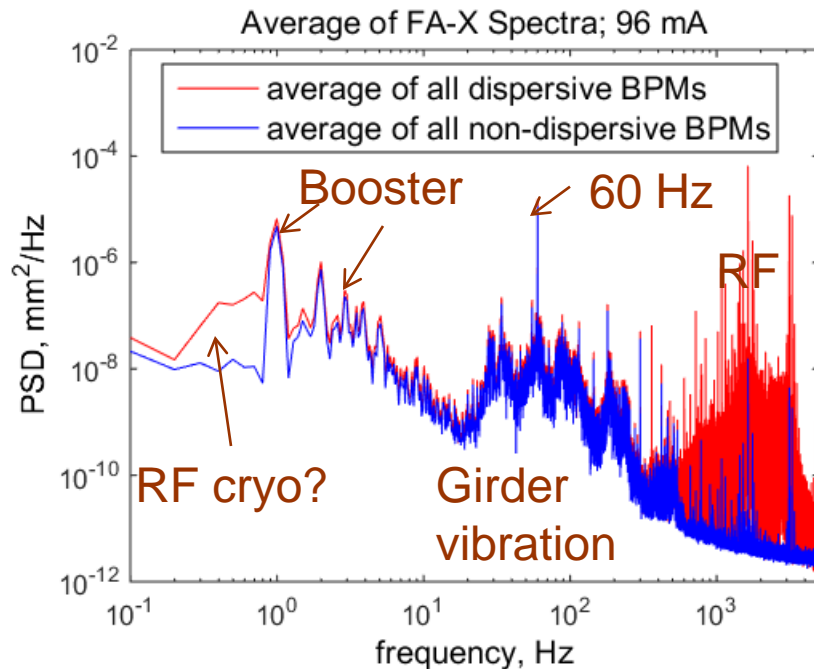
Mar, 2015, Ops
C05 ID BPM
0.6 μm full BW

- Full BW vertical orbit stability is at the level of 20% of beam size.
- Need only a feedback gain of ~ 2 in 0-100 Hz BW to get to the spec.
- \Rightarrow a fairly simple feedback digital filter design should work.
- Integrated PSD approx. correlates with $(\beta_y(s))^{1/2}$.

Identification of Orbit Noise Sources

Short-Term Orbit Stability: Horizontal

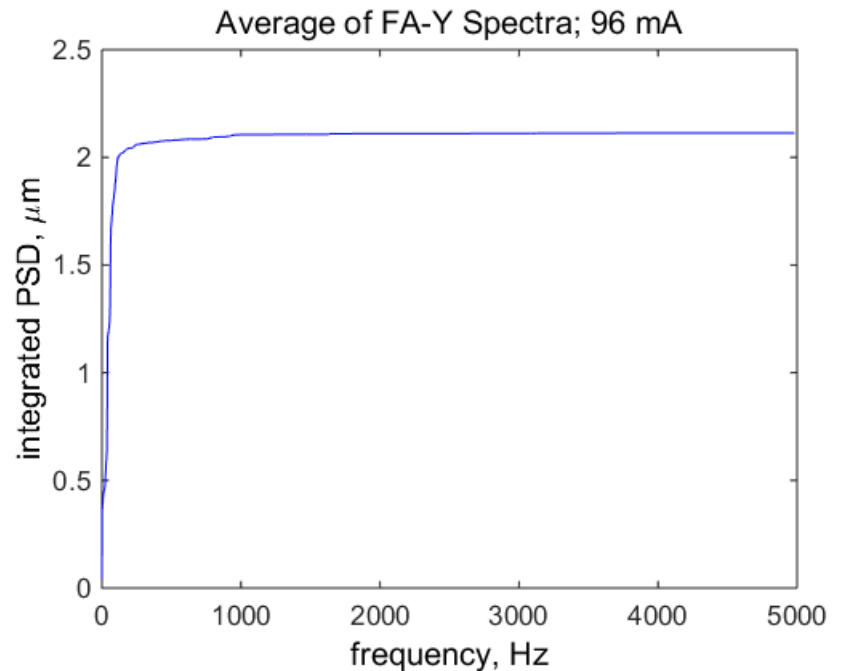
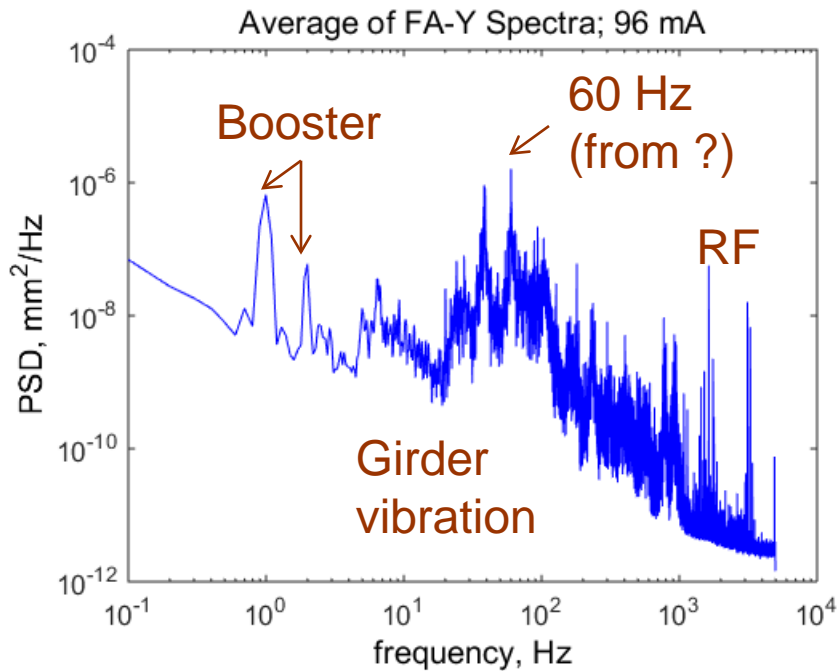
- All 180 BPMs sampled for 10 sec at 10 kHz; orbit feedbacks off
- Plot ring-average BPM spectra (psd and integrated)



- Plenty of spectral features; but integrated levels are very small

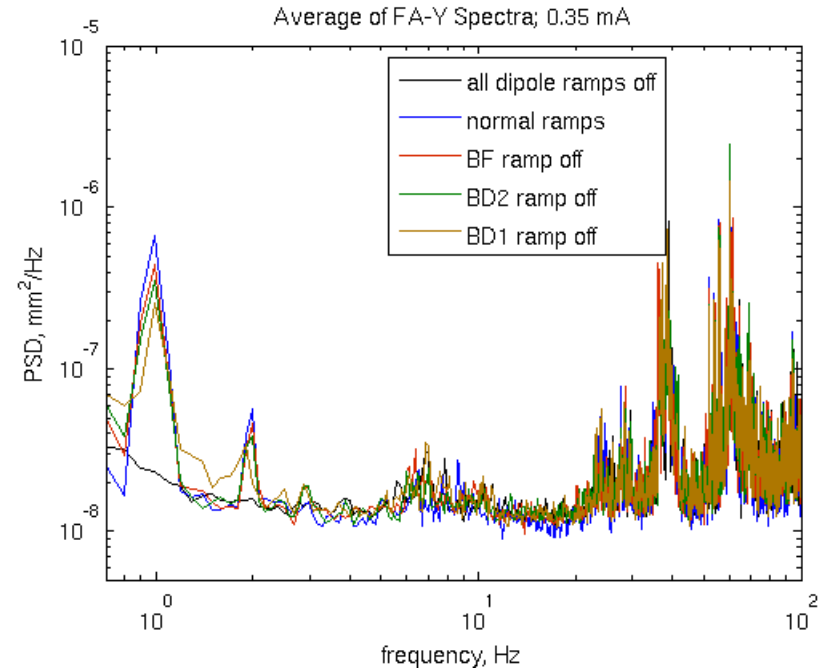
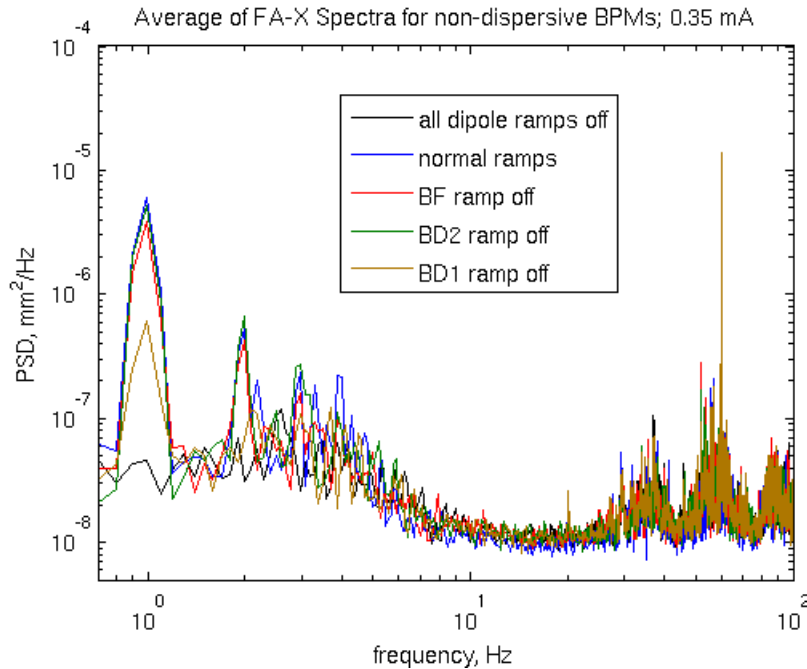
Short-term Orbit Stability: Vertical

- Same plot for the vertical



- Plenty of spectral features; but integrated level is very small

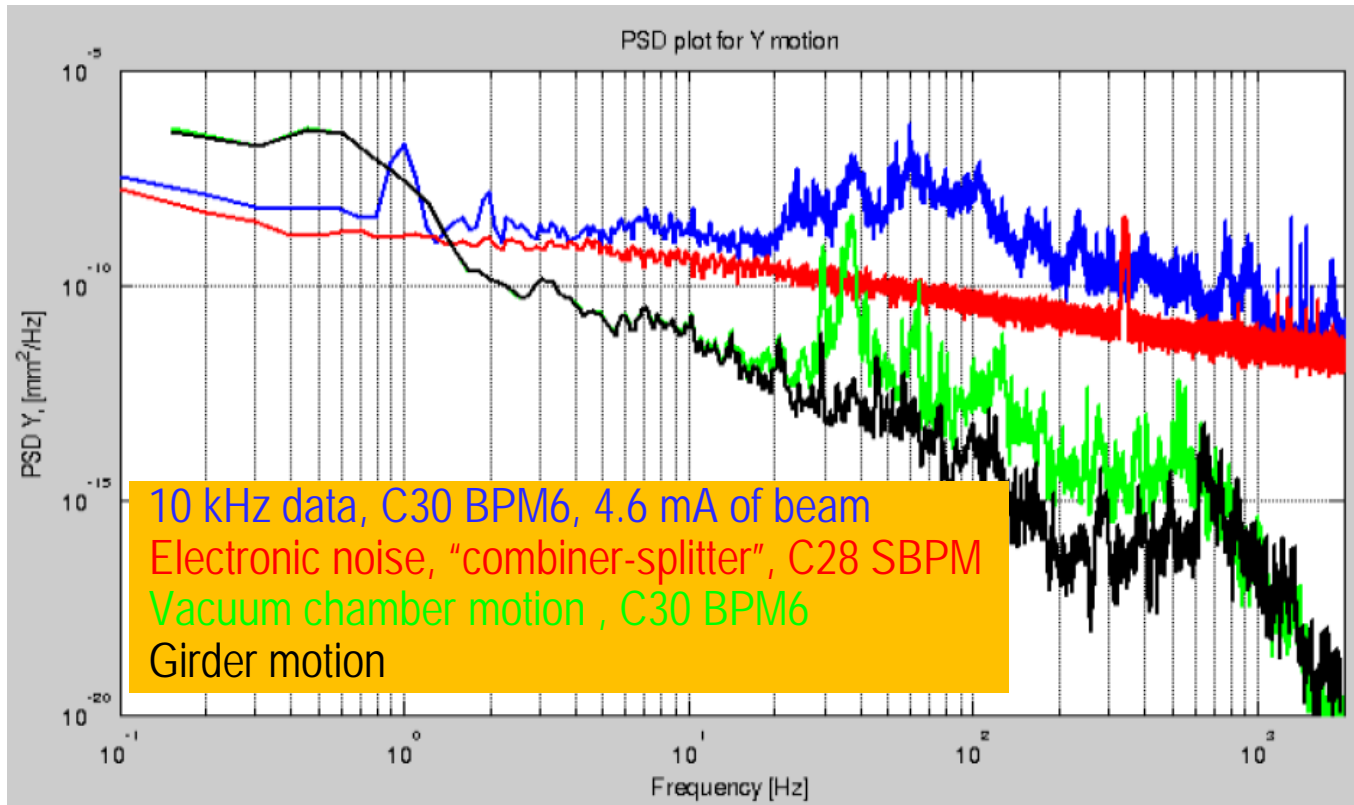
Booster Ramp Harmonics



- Booster magnet ramps (mainly BD1) induce 1 Hz orbit noise + harmonics
- Turning them all off (black curve) eliminates this noise completely
- This noise is reproducible, easily fixable by a simple feedforward system
- Or can be taken out by the FOFB.

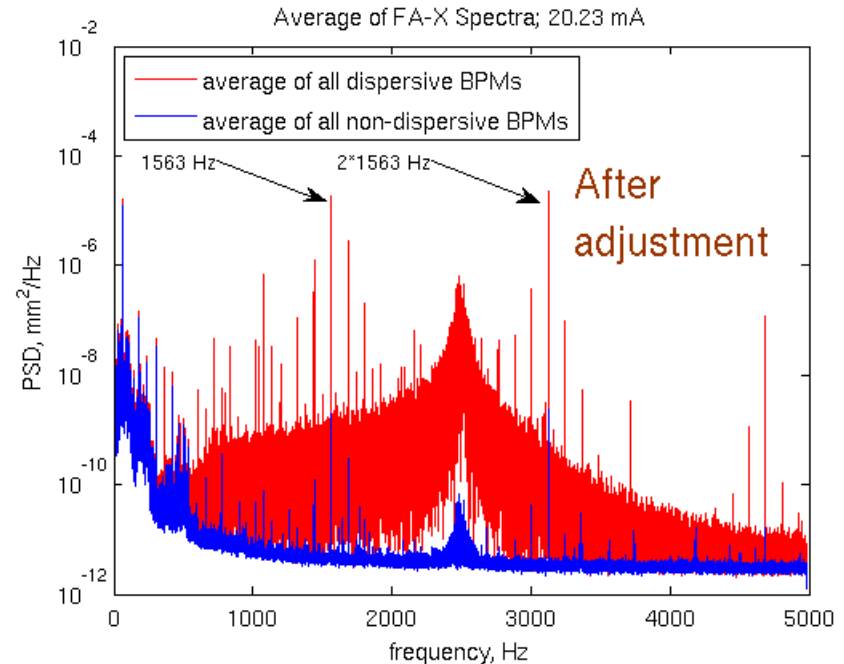
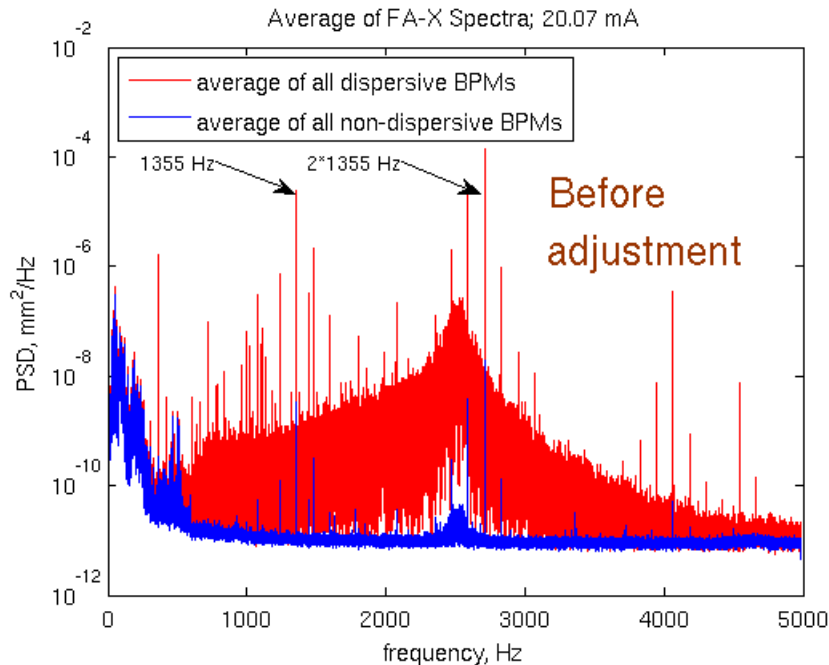
Correlations with Vacuum Chamber and Girder Vibrations

Weixing
Cheng



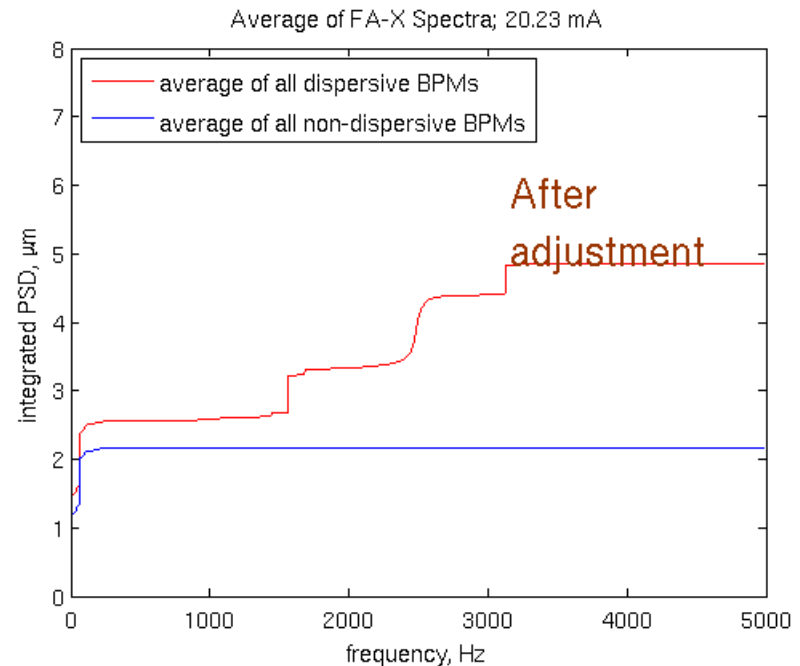
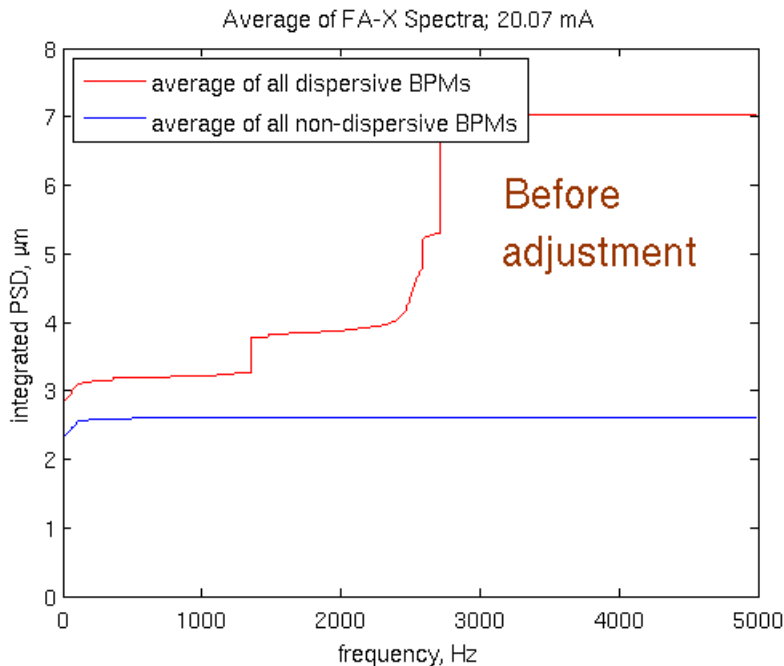
- All levels are pretty small
- Electronic noise \ll 4.6 mA beam except for the ~ 450 Hz peak (fixed now)
- Some correlation of mechanical motions and beam motion
- Some agreement to earlier mech. modelling and vibration measurements

RF Noise



- Dispersive BPM noise is dominated by RF, but it is still small!
- Recent adjustment of the switching frequency of the RF HVPS to have synchrotron peak in a “quieter region” i.e. between the switching frequency sub-harmonics (112 kHz/86 modules)
- Strongest switching frequency lines are down by a factor of ~ 6

RF Noise Cont'd

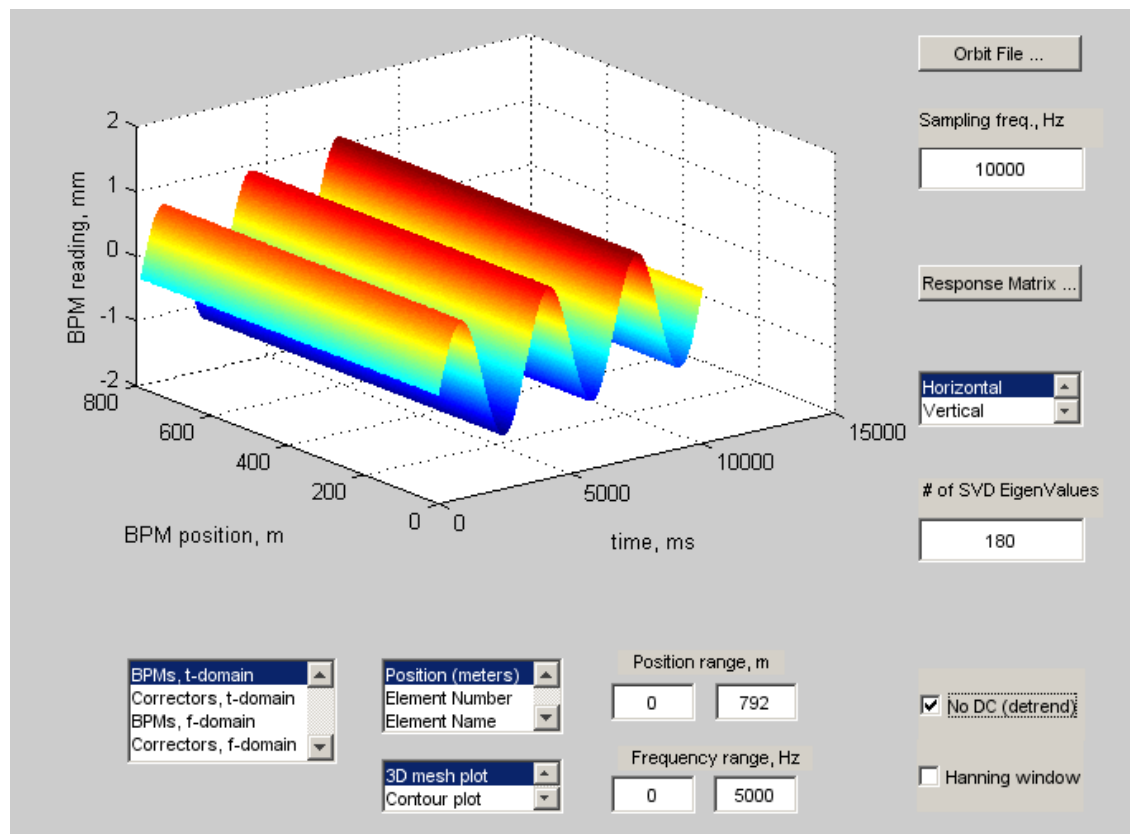


- The noise is a very small percentage of beam size
- The noise does not directly affect the (ID) users
- It cannot be cured by FOFB (frequency too high !)
- May need to revisit once IR beamlines come online

The Source of 60 Hz

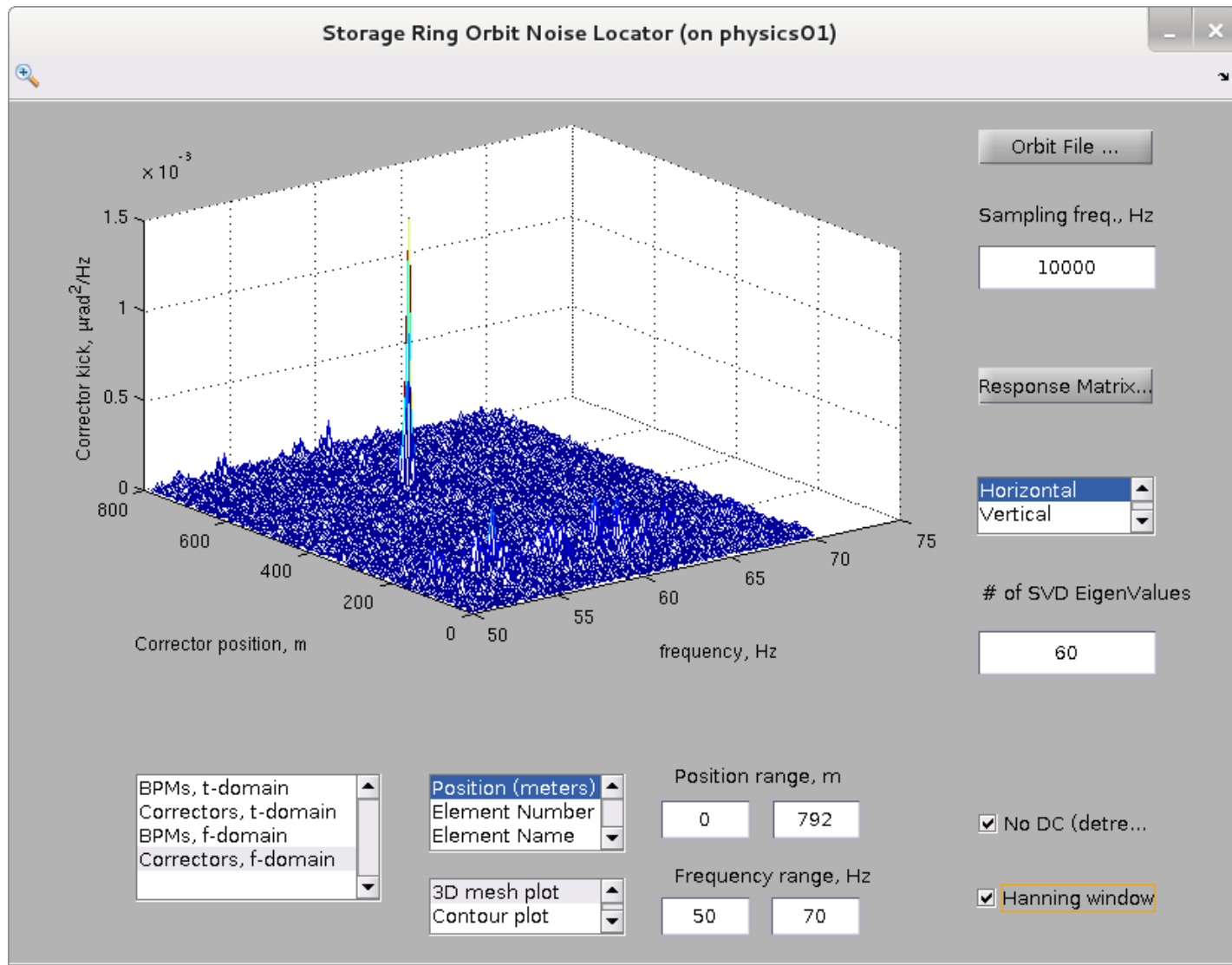
Noise Locator Tool for NSLS-II

- Uses Matlab Middle Layer by Greg Portmann
- Input is any sampled orbit data file, usually FA (10 kHz), or SA (10 Hz)
- The tool does display and analysis only (no machine control)
- Self-explanatory GUI interface



Found with the Noise Locator Tool

- Most of the 60 Hz noise coming from one single location, s~580 m



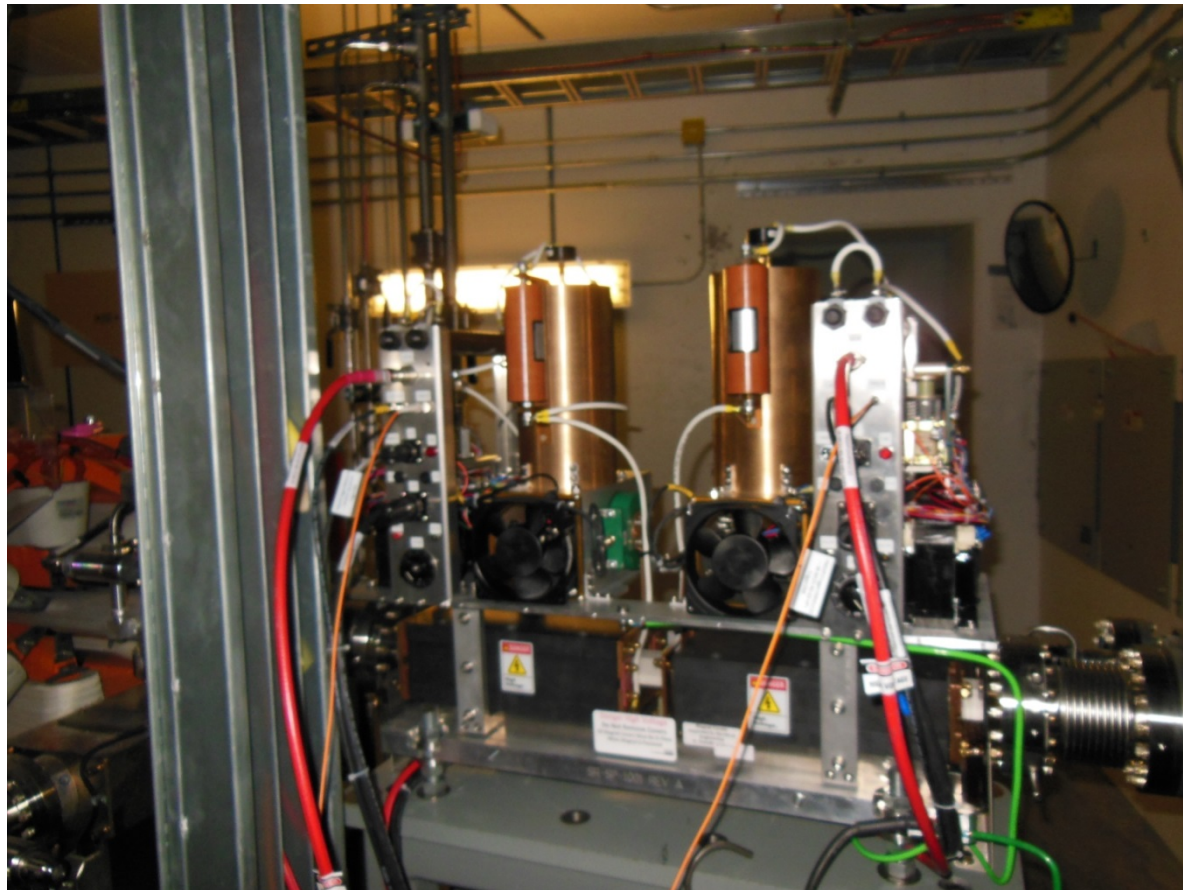
Pinger Magnets in the Ring

- Pinger magnets are located at $s=577.17$ m (h) and 577.54 m (v)

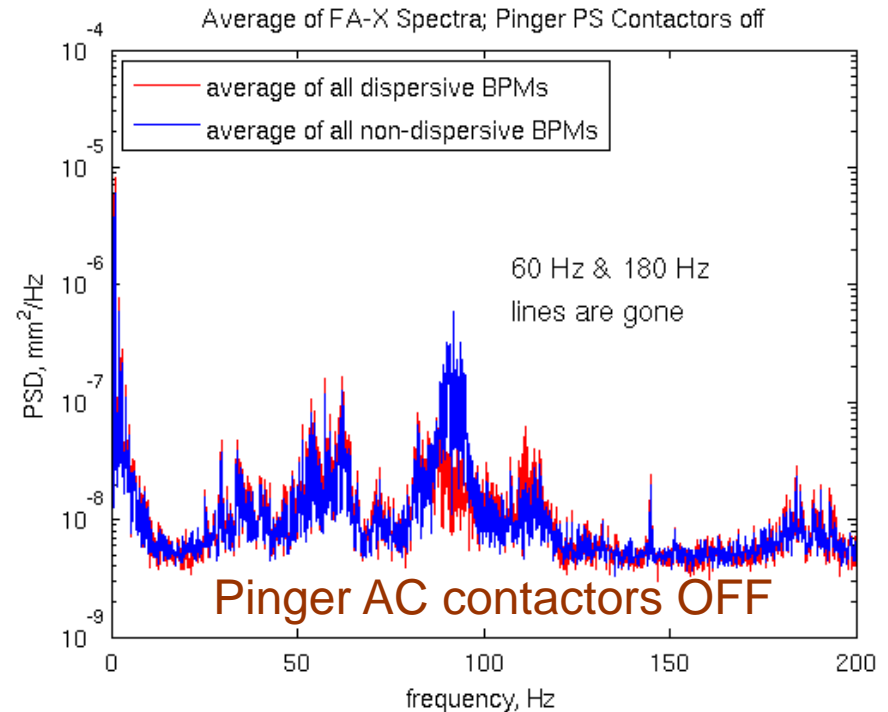
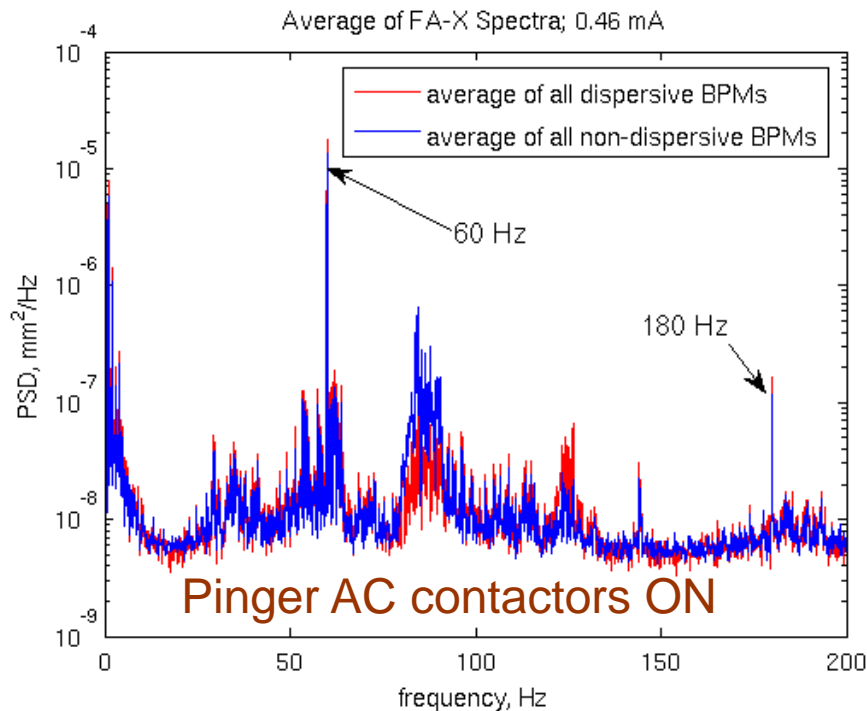


Pinger Magnets in the Ring

- A likely source of 60 Hz is one of the transformers close to the beam pipe
- Transformers are on even when high voltage is off (and no beam pinging)



Turning Pinger AC Contactors OFF...

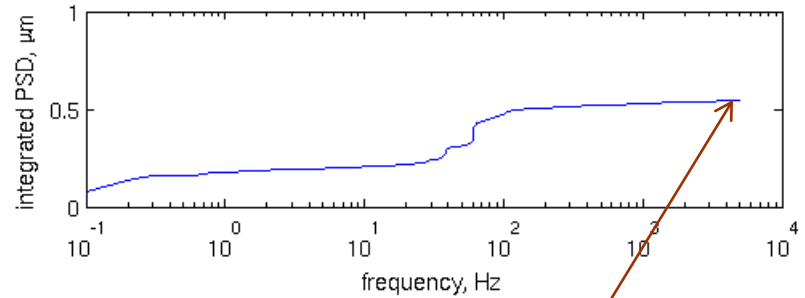
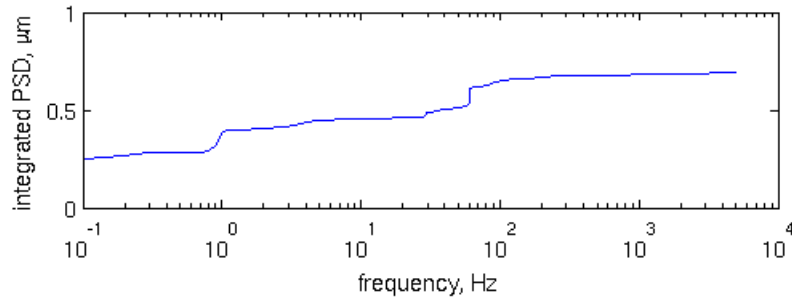
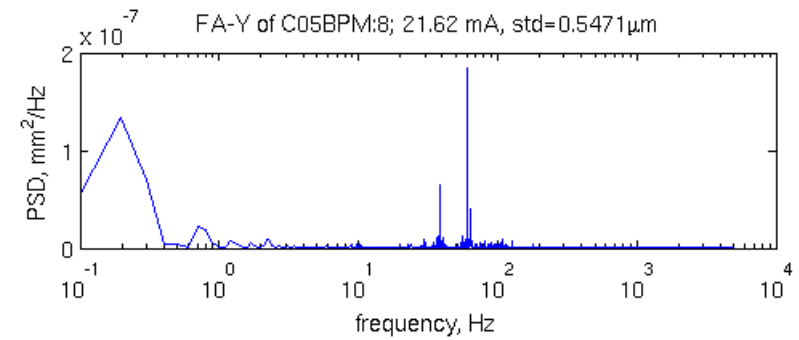
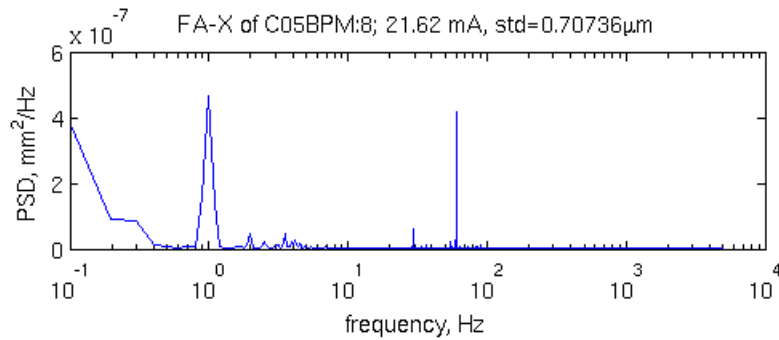


- ... kills the 60 Hz and its harmonics
- This is the simplest cure as we don't use pingers during ops anyway
- However, users don't seem to notice this noise so far (so we often ran with pinger AC contactors on)

Back to Overall Orbit Stability

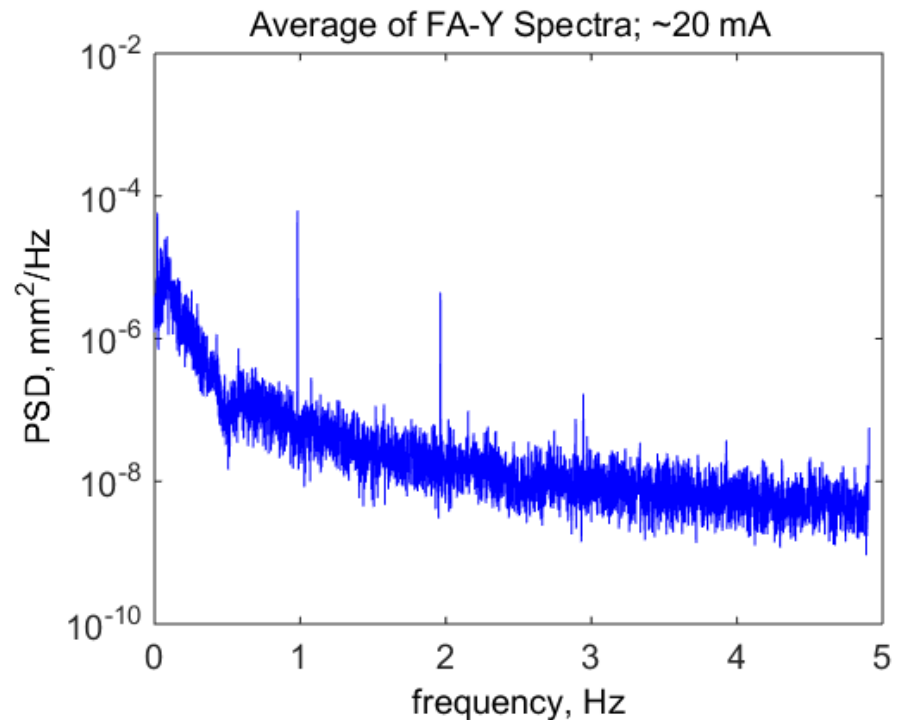
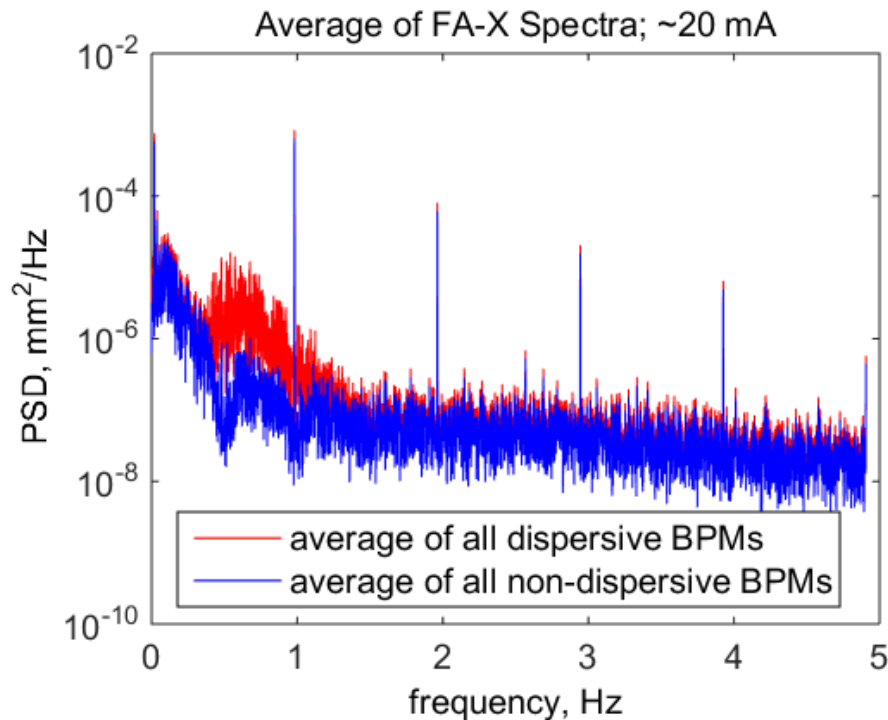
Short-term Orbit Stability: ID BPMs

- 3/26, Ops with SOFB, Vertical ID BPM; Cell 5 center



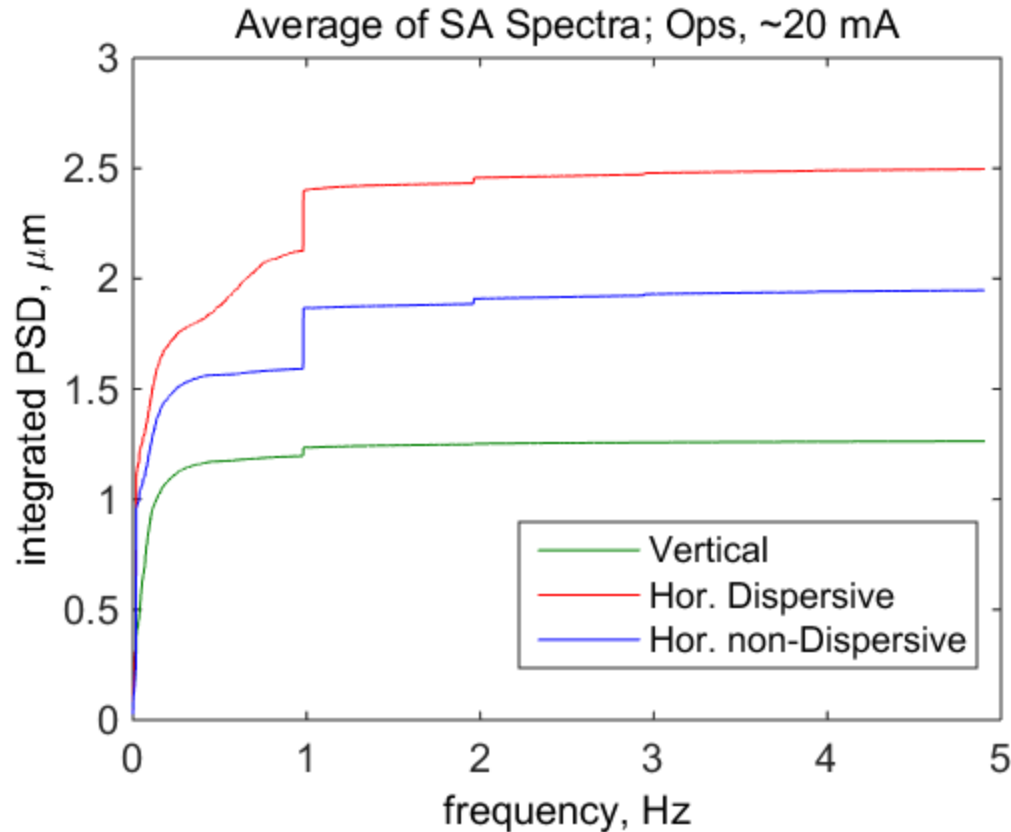
Less than 20% of the design beam size

Medium-term Orbit Stability: First Look at Buffered SA Data



- 10,000 points (= 16.7 mins) of 1 Hz orbit data from 180 RF BPMs
- Slow Orbit Feedback ON
- Not much spectral structure; just booster harmonics and “RF cryo?”

Medium-term Orbit Stability: First Look at Buffered SA Data Cont'd



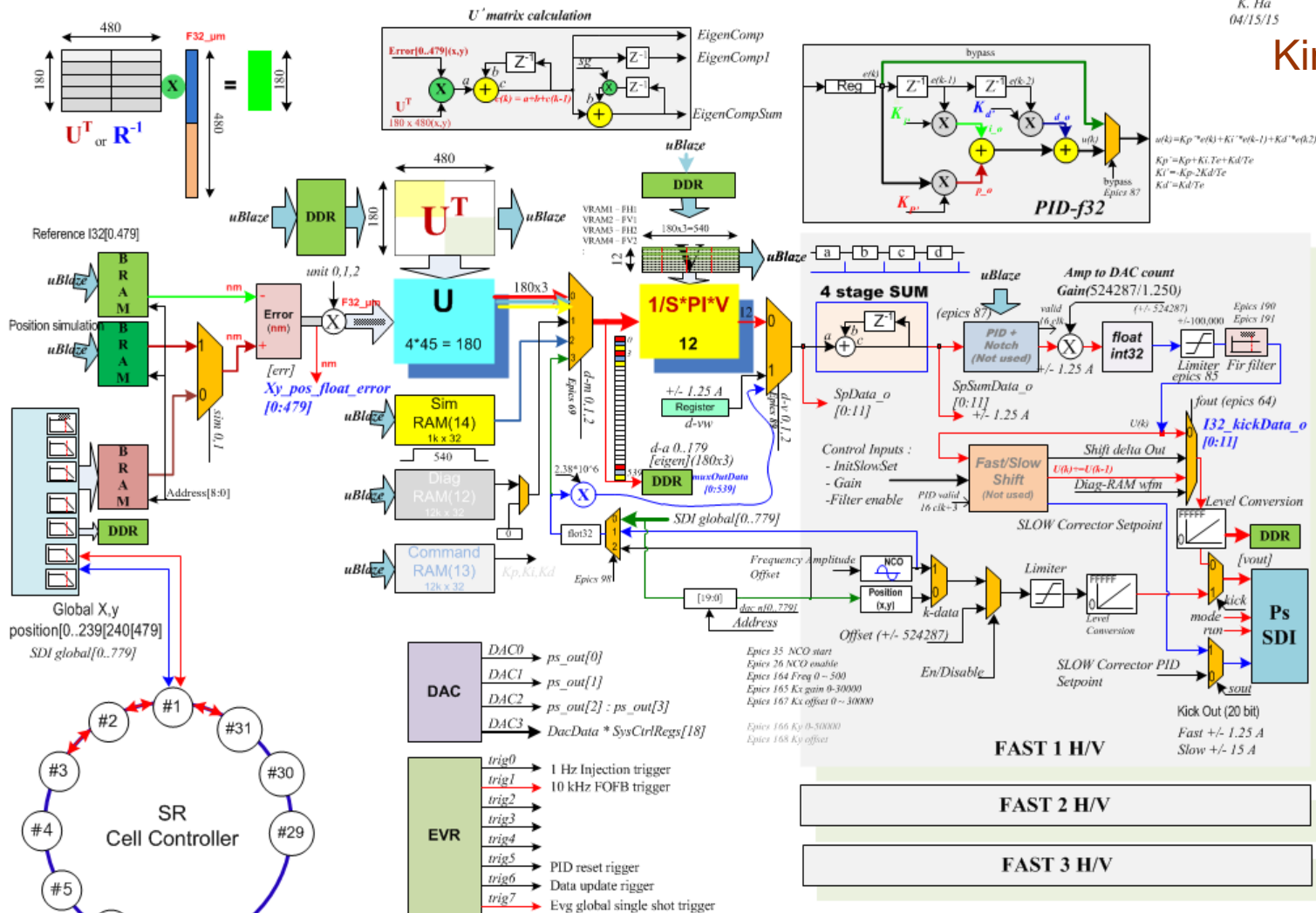
- Integrated PSDs for the same data
- Levels are pretty low

Fast Orbit Feedback

Fast Orbit Feedback Diagram

K. Ha
04/15/15

Kimann Ha



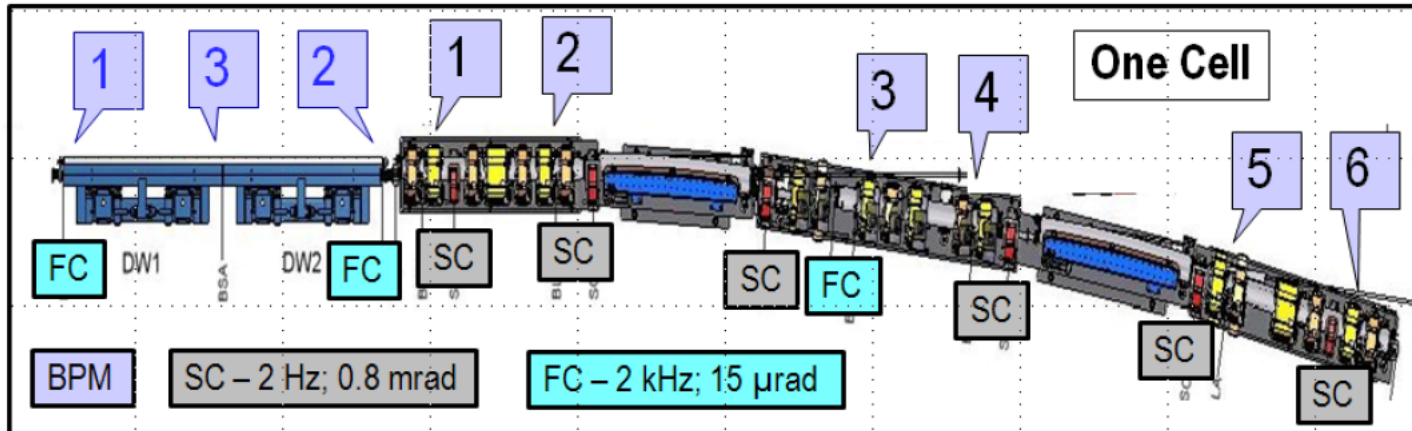
FPGA internal layout for FOFB calculation

assign ExtDout_pin[6] = sd12_0_NipStrobe;
assign ExtDout_pin[7] = ffo_wa_envelop;
assign ExtDout_pin[8] = sd12_cc_NipStrobe;



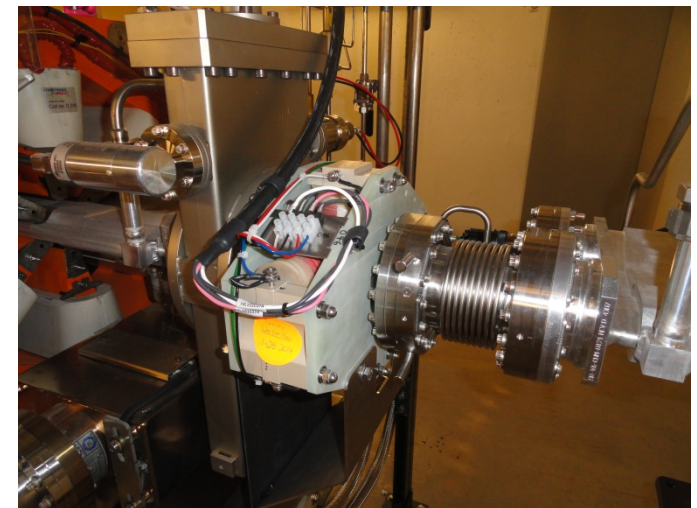
*Development Cell Controller at C28
10.0.132.42 4002 - 4003
10.0.133.61 - 10.0.133.90 for operation
06/15/15 Removed FIR filter

Fast Orbit Feedback



Om Singh
et al.
IBIC 2013

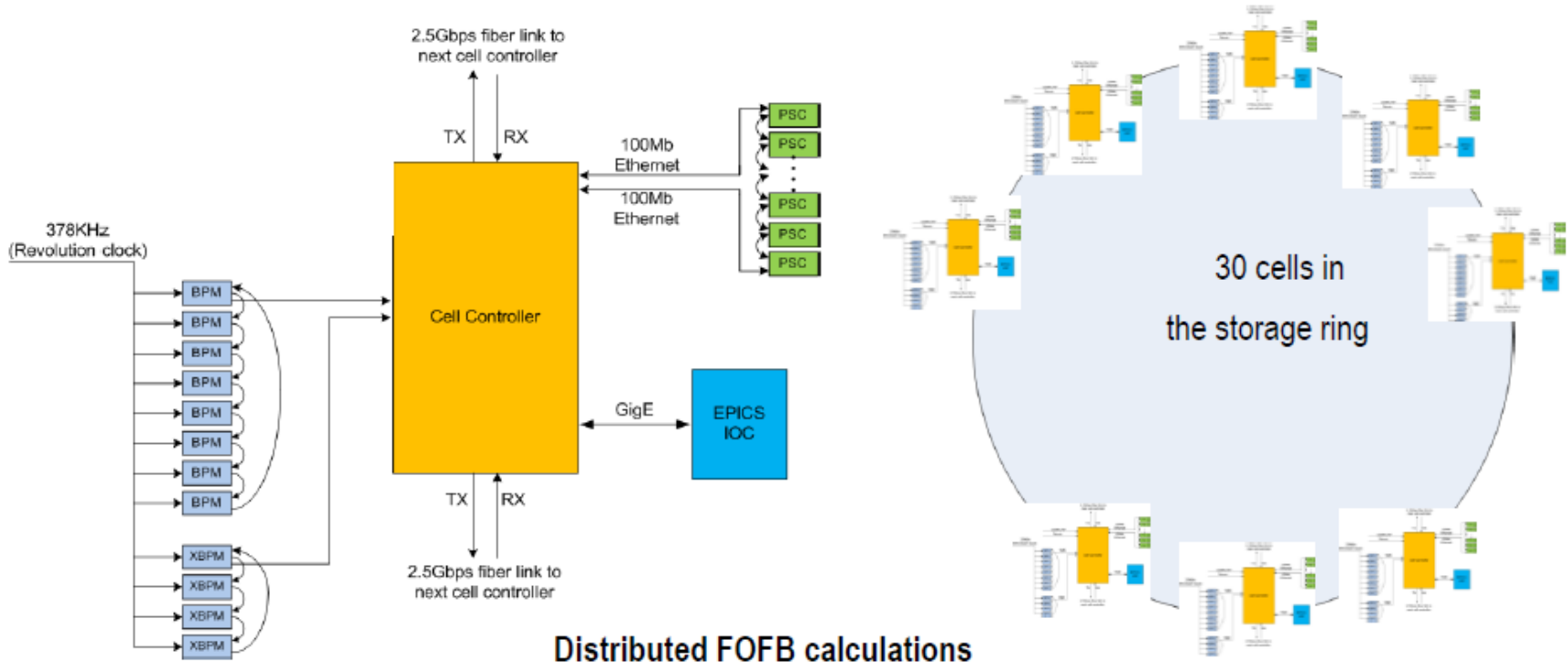
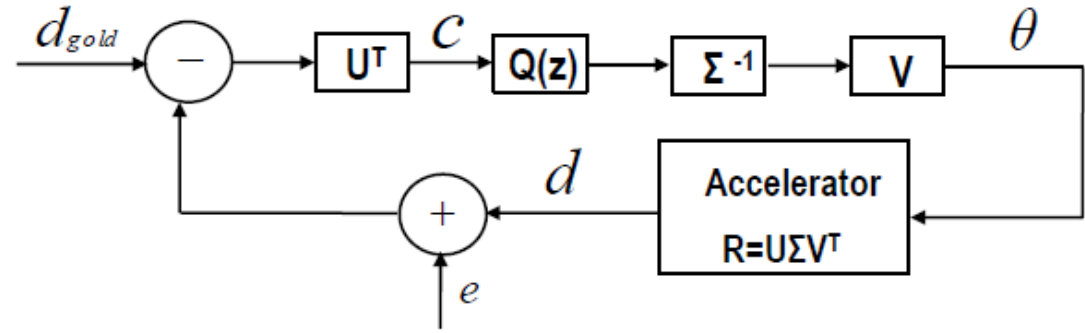
- 180 BPMs in each plane
- 90 fast correctors / plane with an option to offload accumulated kick effort to (strong) slow correctors
- Standard SVD algorithm
- Individual PID coefficients for each eigenvector



Fast Corrector

Fast Orbit Feedback

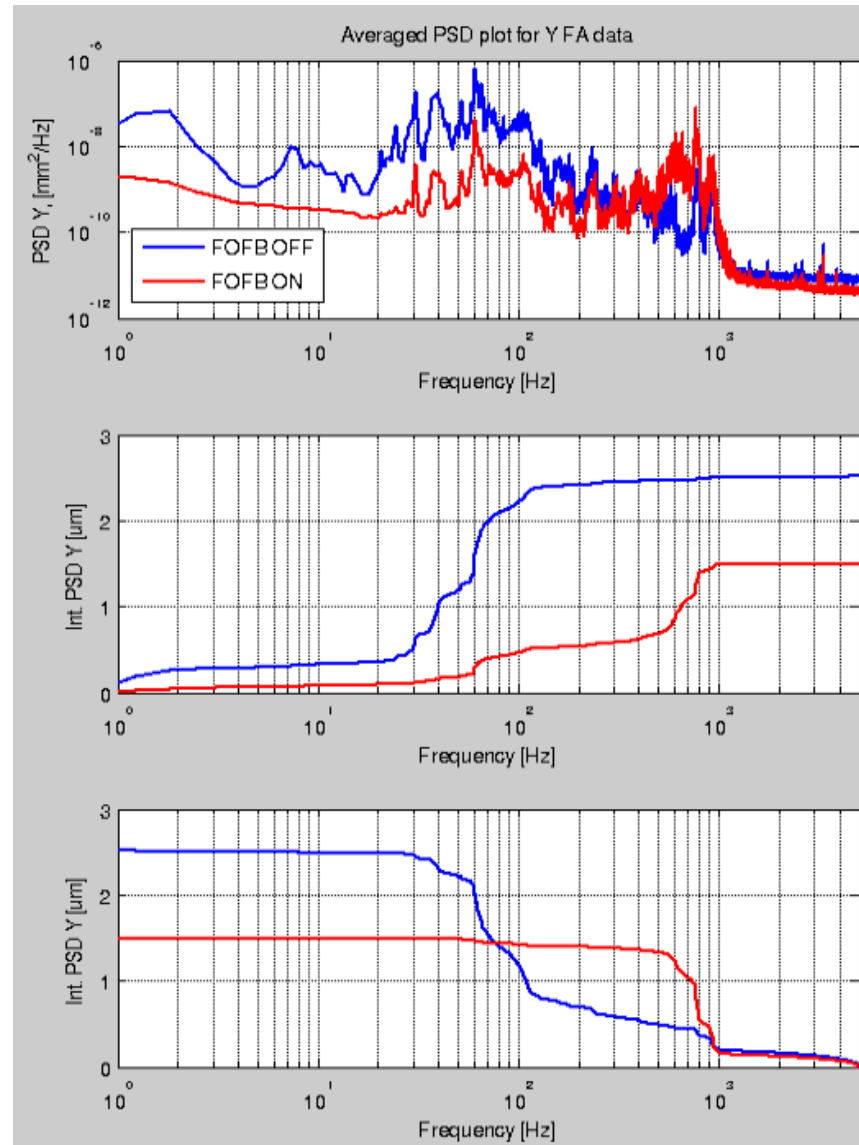
Yuke Tian
Li-Hua Yu



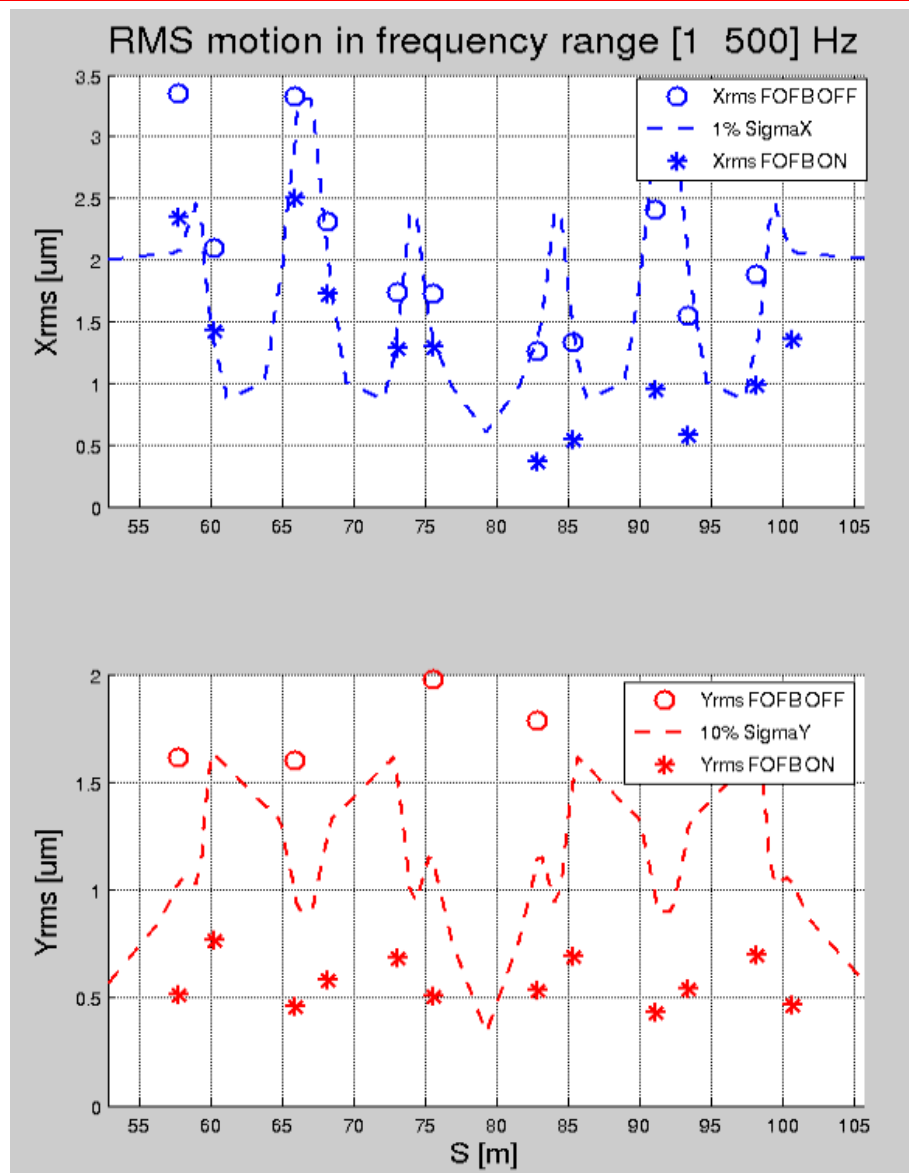
Distributed FOFB calculations

Stability with Fast Orbit Feedback

Weixing
Cheng



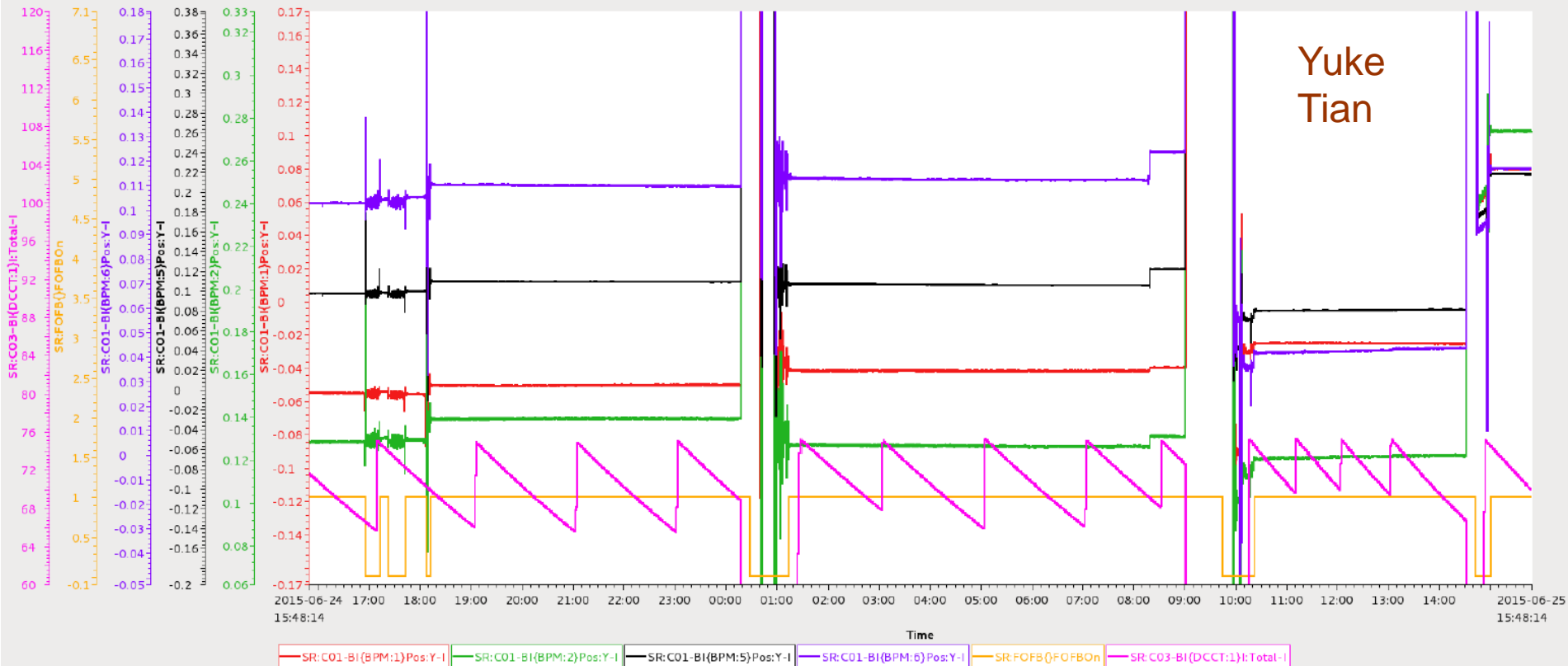
Stability with Fast Orbit Feedback Cont'd



Weixing
Cheng

Long Term Stability with FOFB

Yuke
Tian



- 4 non-dispersive vertical BPMs shown during "75 mA Ops" with FOFB
- Long term drift is less than $1 \mu\text{m}$
- Long term drift in the horizontal (not shown) is less than $5 \mu\text{m}$
- Further improvement is expected with top-off and FOFB optimization

Conclusions and Future Plans

- Even without orbit feedbacks NSLS-II orbit stability is quite good, thanks to the meticulous design efforts.
- Short term stability is brought within 10% of beam-size (sub- μm in the vertical) by using a fast orbit feedback system.
- Major noise sources have been identified and understood, especially the short-time scale ones.
- Longer term stability was less studied due to lack of time and rapid machine development. Typical orbit drifts in 8 hr period at the ID source points are sub- μm in the vert., single digit microns in hor.
- Further improvement is expected from top-off operations to start soon.
- Other developments will include commissioning X-ray BPMs, further optimization of orbit feedbacks, and joint studies with the users.

Thank you