The BNL EBPM Electronics

High Performance for Next Generation Light Sources

Kurt Vetter

NAPAC16
Chicago, IL
October 9-14, 2016

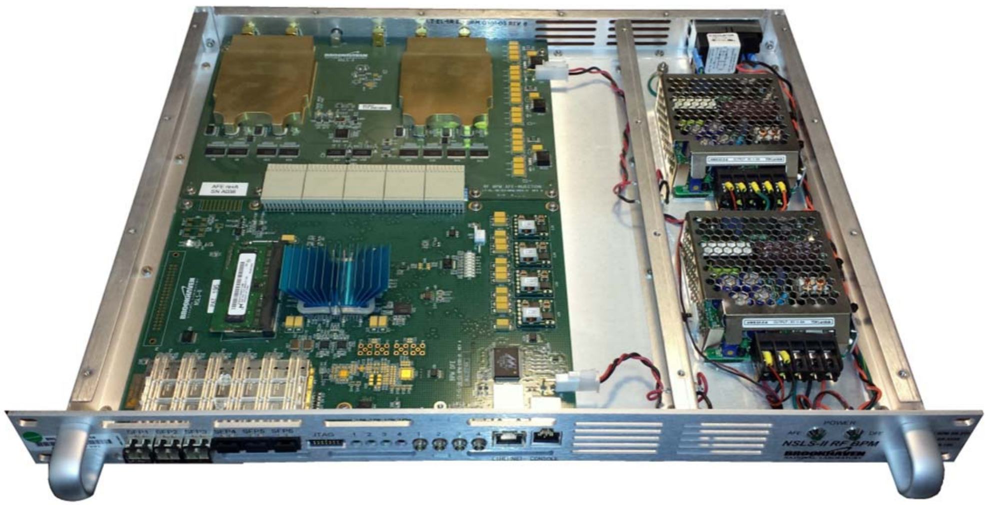
OAK RIDGE
National Laboratory

Outline

- Introduction
- EBPM design for sub-micron performance
- Operational Performance
- Derivative Instruments
- Summary

Introduction: NSLS-II BPM Receivers

Data Type	Mode	Max Length
ADC Data	On-demand	256Mbytes or 32M samples per channel simultaneously
Turn-by-Turn (TbT), Frev=379 kHz	On-demand	256Mbytes or 5 M samples Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd
Fast Acquisition (FA) , 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 (SA), 10Hz	Streaming and On-demand	80hr circular buffer Va,Vb,Vc,Vd, X,Y,SUM, Q, pt_va,pt_vb,pt_vc,pt_vd



- Development started August 2009
- First Beam Test at LBNL on ALS June 2010
- All requirements demonstrated February 2011
- Booster complete March 2012
- Storage Ring complete June 2013
- SR commissioning complete May 2014

"Commissioning of NSLS-II", F. Willeke, April 2015 BNL-107934-2015-CP

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Design for Sub-Micron Performance

1. Spatial Resolution and Signal to Noise Ratio (SNR)
2. Mapping required SNR into receiver dynamic range
3. Receiver design to achieve required spatial resolution
4. Optimal coherent sampling numerology
5. Design for stability

Design for Sub-Micron Performance

1. **Spatial Resolution** and **Signal-to-Noise Ratio (SNR)**

Design for Sub-Micron Performance

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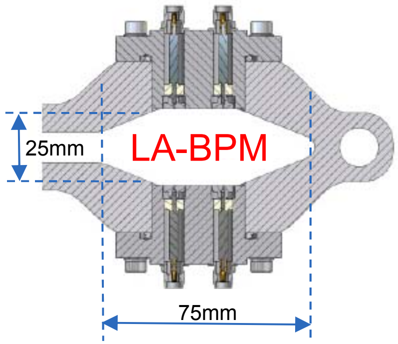
$$Resolution = \frac{1}{2\sqrt{2}}\frac{aperture}{\sqrt{SNR}}$$

Intrinsic resolution, assumes Gaussian noise, consider **75mm aperture (X-plane)**



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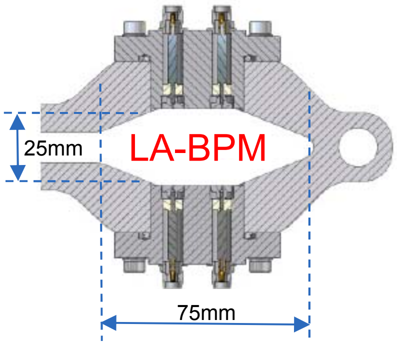

$$SNR\ Required \sim \frac{75 \cdot 10^{-3}}{200 \cdot 10^{-9}} = \mathbf{102dB}\ \ (for\ 200nm\ resolution)$$

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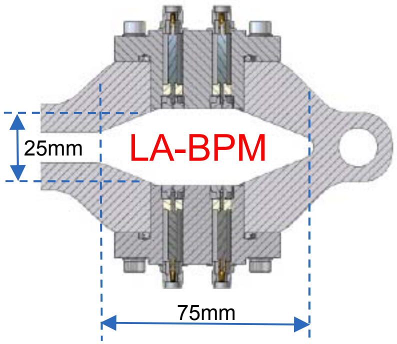

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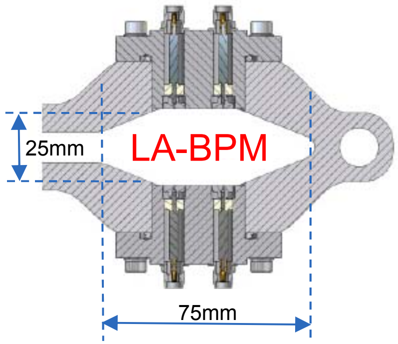

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Coasting Beam 80% Fill

$$SNR = SNR\ ADC + \underbrace{PG_{Turn} + PG_{TbT/10KHz} + PG_{10KHz/2KHz}}_{42dB} = 102dB = \mathbf{200nm}$$

Design for Sub-Micron performance

2. Mapping required **SNR** into **Receiver Dynamic Range**

Power level relative to ADC input

Design for Sub-Micron performance

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ADC Full Scale (FS) = +10dBm

ENOB = 10b = 60dB SNR (ADC instantaneous dynamic range, measured)

ADC FS – ENOB SNR = -50dBm (in ADC nyquist bandwidth)

Power level relative to ADC input

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ENOB = 10b = 60dB SNR (ADC instantaneous dynamic range, measured)

ADC FS – ENOB SNR = -50dBm (in ADC nyquist bandwidth)

Processing Gain = 42dB (required for 200nm resolution)

Power level relative to ADC input

Design for Sub-Micron performance

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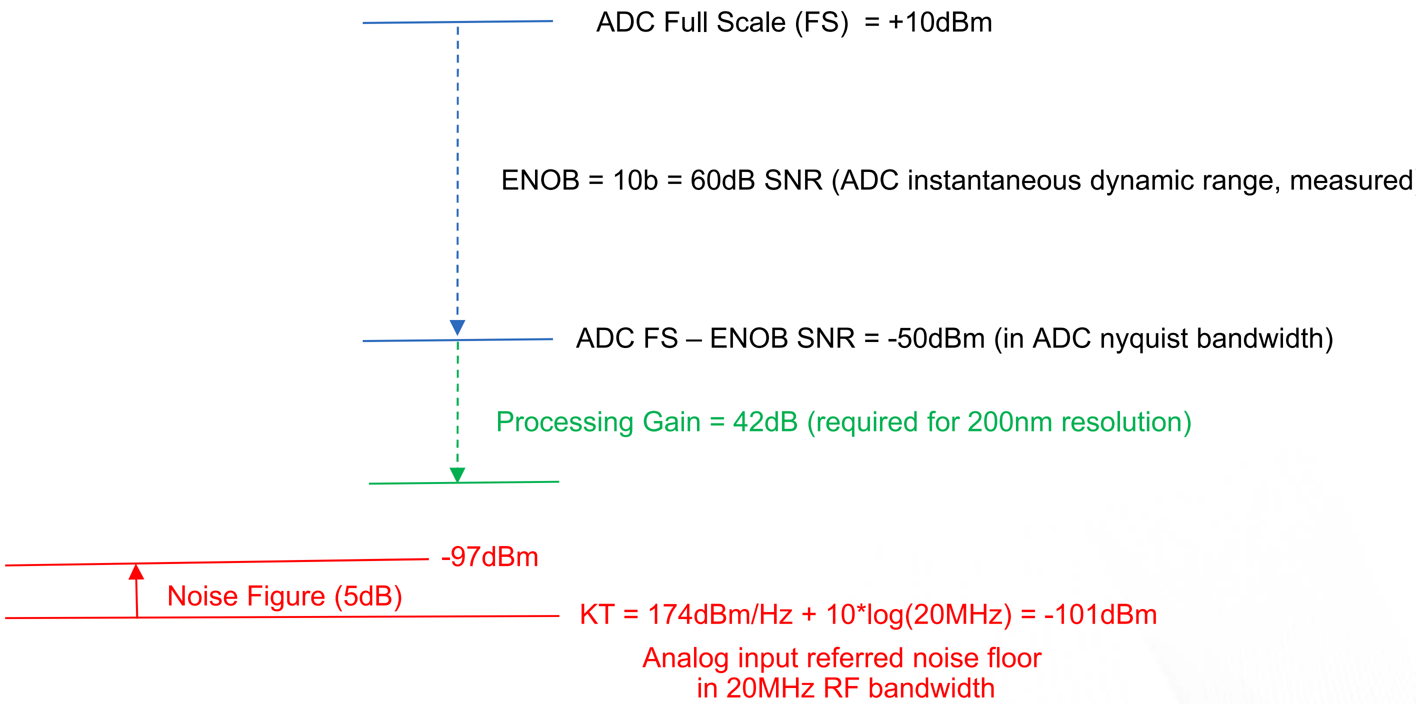

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Design for Sub-Micron performance

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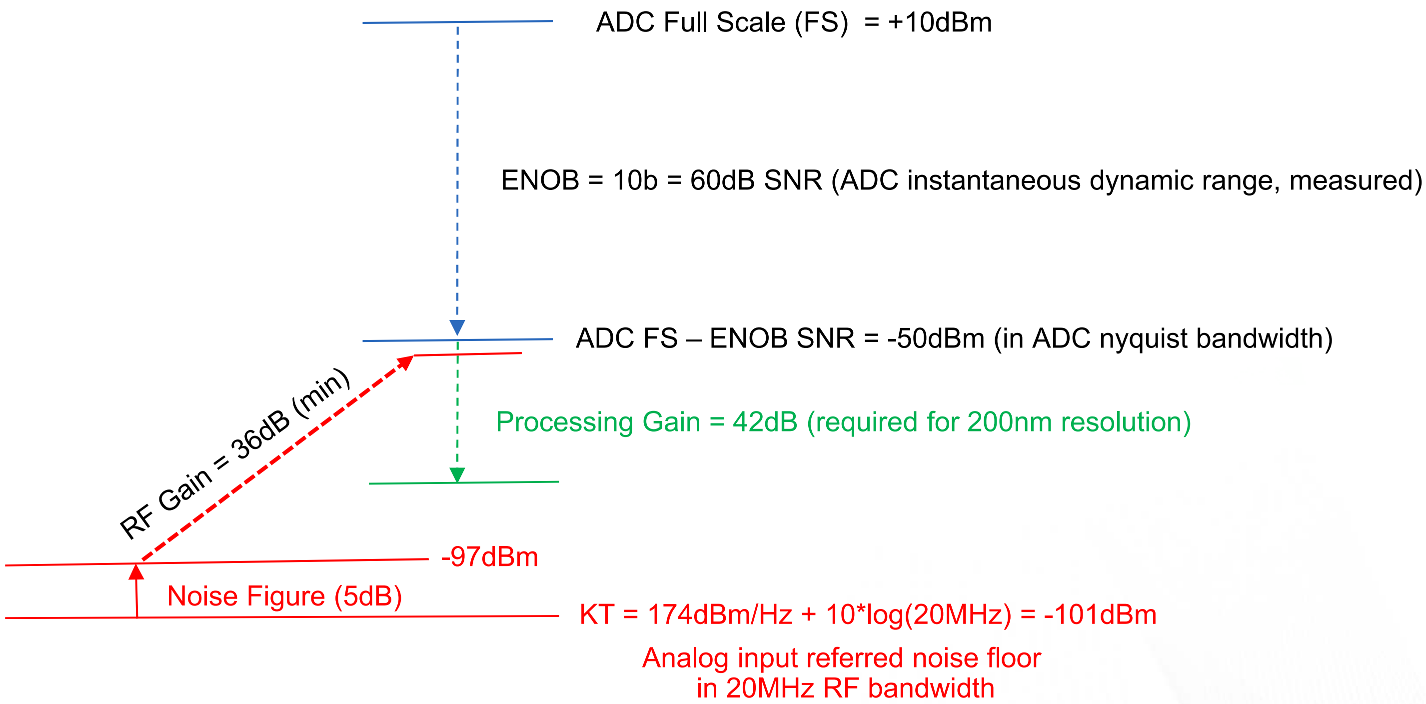


Power level relative to ADC input

Design for Sub-Micron Performance

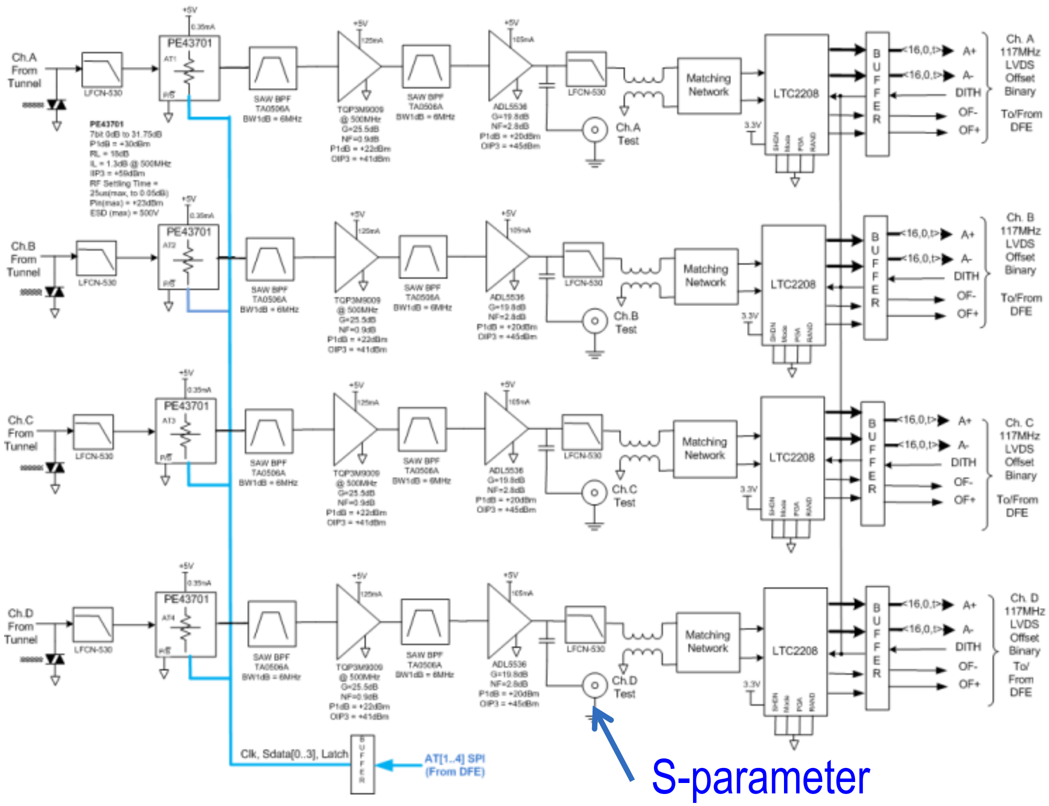
3. **Receiver Design** to achieve required **Spatial Resolution**

Design for Sub-Micron Performance

3. **Receiver Design** to achieve required **Spatial Resolution**

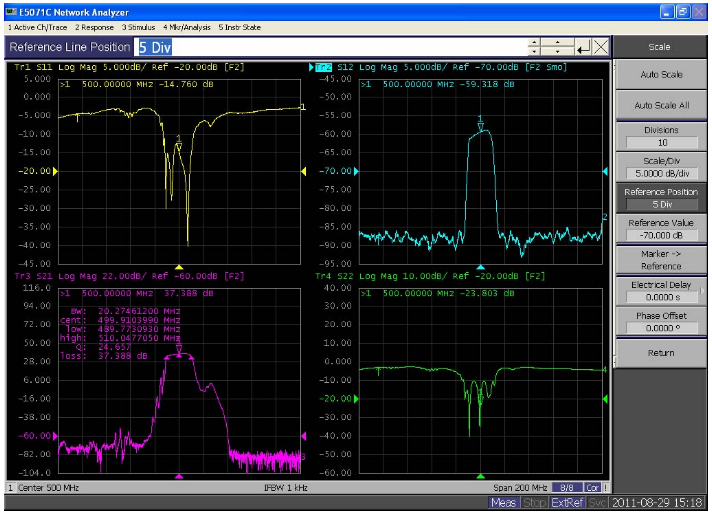
- Set RF bandwidth to enable true TbT processing
  - Sufficiently large (20MHz) to let energy decay to zero within turn
- Select ADC for 500MHz RF subsampling such that
  - Sufficient analog full-power bandwidth
  - Sufficient sample rate
  - 10b ENOB performance (min)
- Set RF gain to properly map to ADC noise floor
- Ensure receiver has sufficient linearity
  - P1dB compression sufficiently above ADC full-scale peak
  - IP3 sufficiently high to ensure IP3 products at noise floor

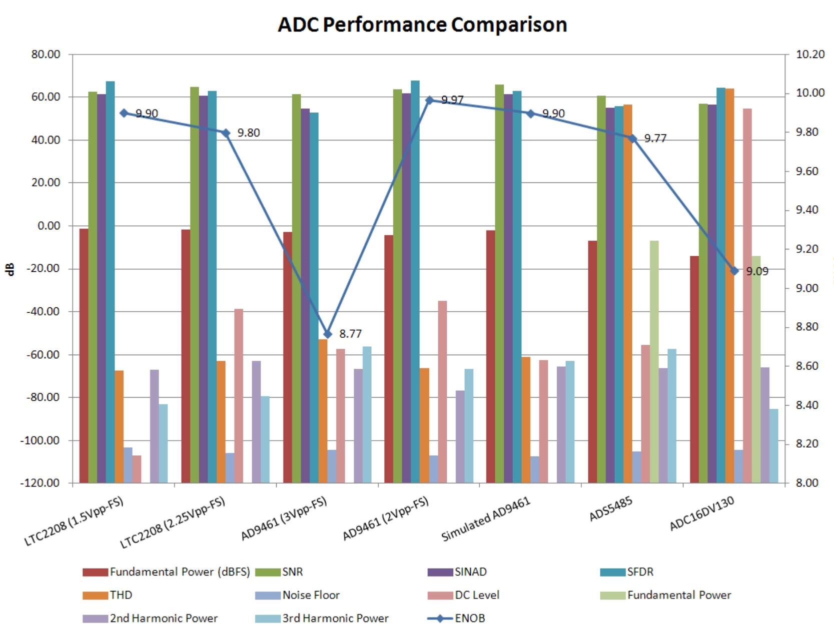
Design for Sub-Micron Performance (AFE)



S-parameter test connector

Receiver S-Parameter Characterization





Receiver RF Parameters:

- P1dB = +19dBm (at ADC Input)
- IP3 = +43dBm (at ADC input)
- NF = 5.3dB
- Channel-channels Isolation = 60dB (min)

Design for Sub-Micron Performance

4. Optimal **Coherent Sampling** numerology

Design for Sub-Micron Performance

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$$h_{sample} = 310 \ \ (\# \ of \ ADC \ samples \ per \ revolution)$$

$$f_s = f_{rev} \cdot h_{sample} = \frac{frf}{h} \cdot h_{sample} = \frac{499.68MHz}{1320} \cdot 310 = 378.55KHz \cdot 310 = 117.35MHz$$

$$f_{IF} = frf - 4 \cdot f_s = 499.68MHz - 469.396MHz$$

$$f_{IF} = f_{rev} \cdot (h - 4 \cdot h_{sample})$$

$$f_{IF} = f_{rev} \cdot h_{IF} = 378.55KHz \cdot (1320 - 4 \cdot 310) = 378.55KHz \cdot 80 = 30.284MHz$$

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↑

"Single Bin" DFT @h_{IF}

Design for Sub-Micron Performance

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Frf	499.68 MHz	499.68 MHz	499.6398 MHz
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Design for Sub-Micron Performance

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Beam Revolution Harmonic Relationships

✓ Integer relationship of NSLS-II SR and Booster allow for common ADC sampling clock (310*Frev)

Design for Sub-Micron Performance

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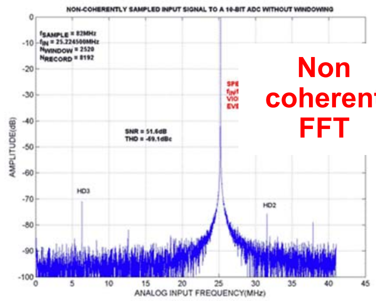

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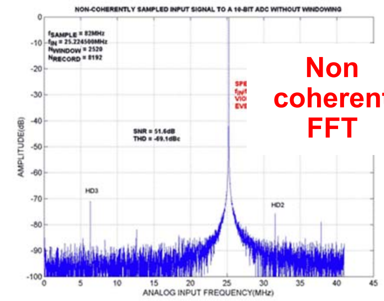

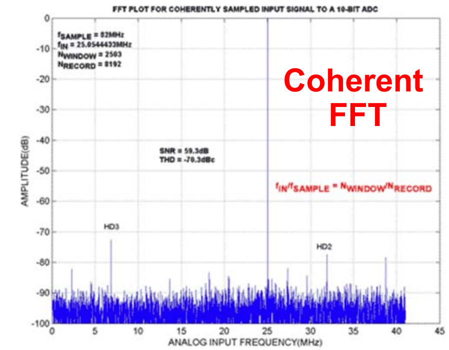

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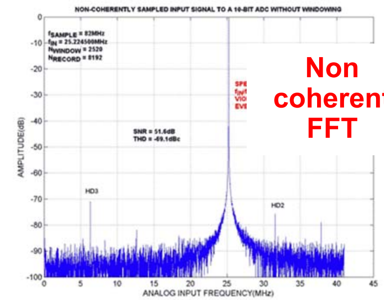
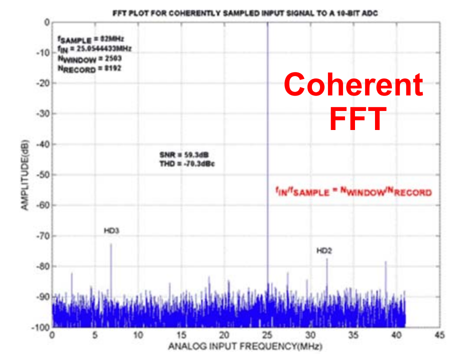
"Single Bin" DFT @h_{IF}

Integer harmonic relationship collapses signal energy into a single DFT bin





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Design for Sub-Micron Performance

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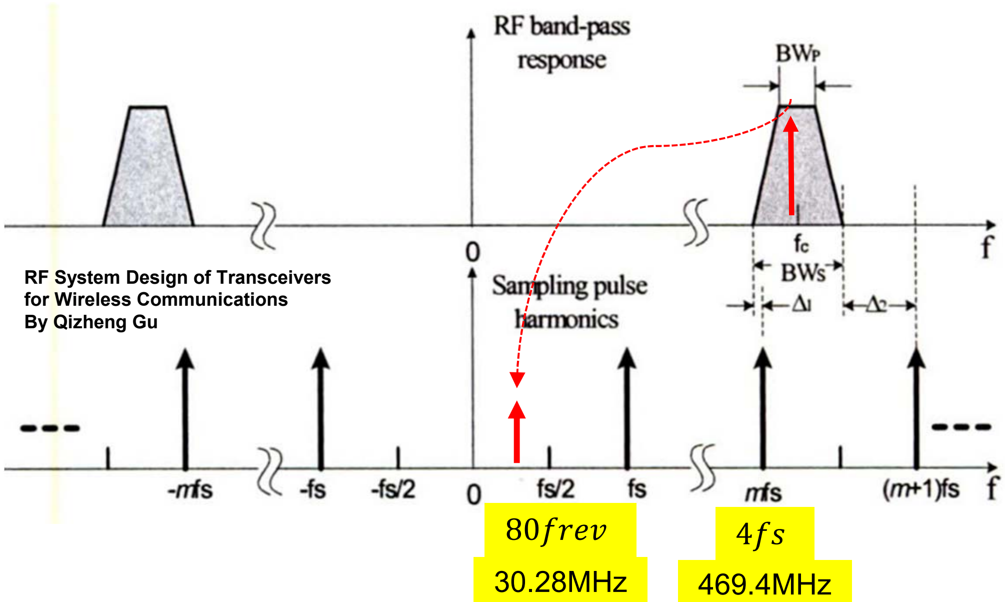
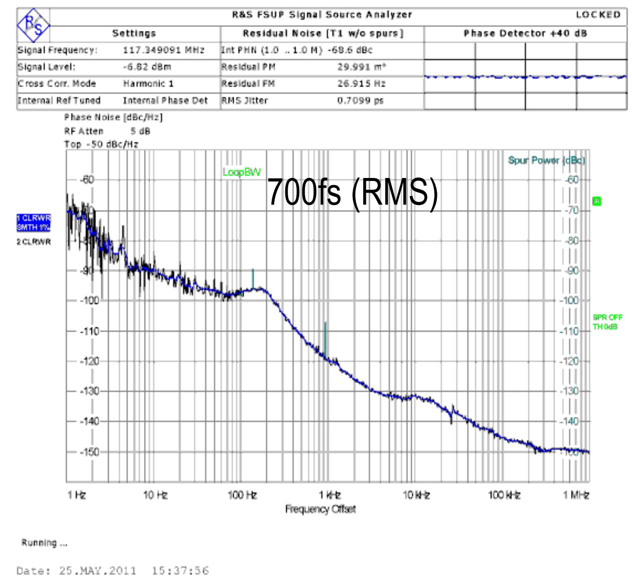
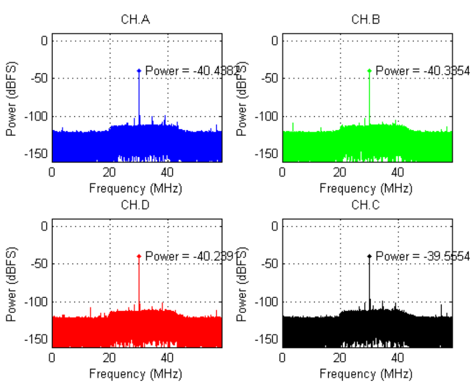


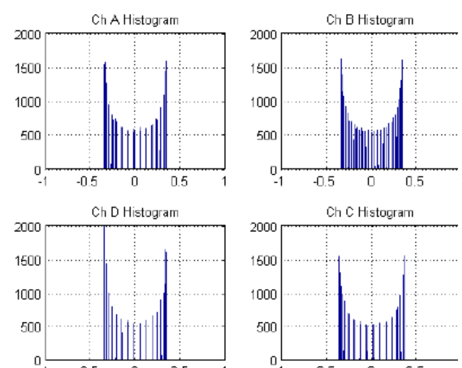
RF System Design of Transceivers
for Wireless Communications
By Qizheng Gu



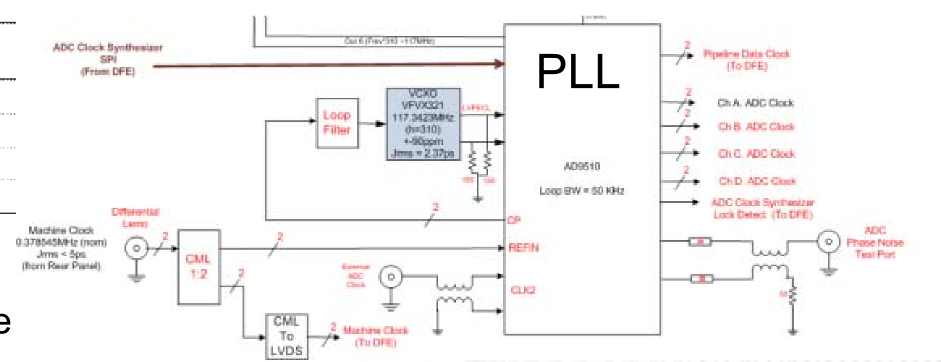
Phase Noise of ADC Clock
Measured directly at PLL output



Sinewave test tone
1Mpt FFT



Sinewave Histogram
Coherent discrete structure



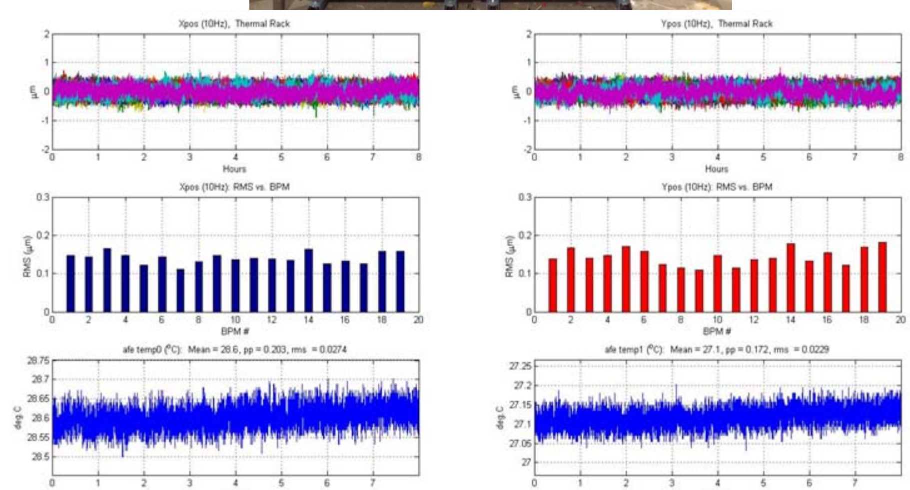
Design for Sub-Micron Performance

5. Design for **Stability**

- Original stability concept included pilot-tone
- Measured performance in thermally controlled racks ($0.01°C$) demonstrated sub 200nm 8hr stability.
- NSLS-II does not utilize pilot tone for operations.
- Pilot tone is used for test

✓ **No perturbations to beam spectrum**

Thermal Test Rack
20 BPMs in Burn-in



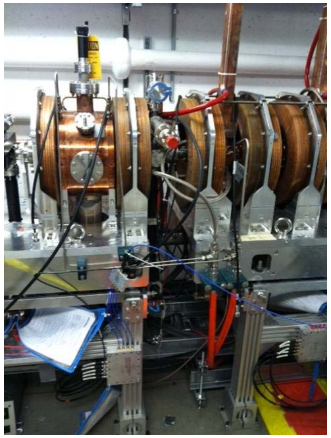
19 BPMs 8hr data set (all BPMs in both planes below 200nm RMS)

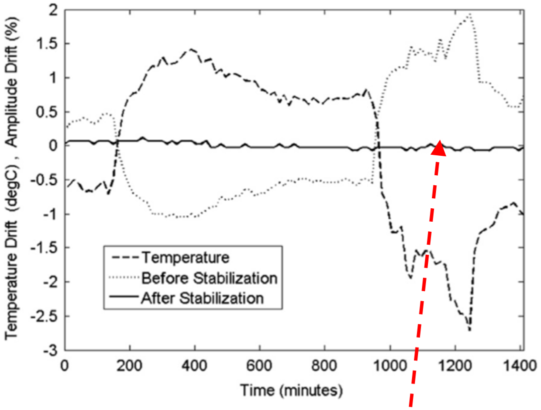
Design for Sub-Micron Performance

5. Design for **Stability**

Pilot Tone

- In-band sinewave
- Average over n-turns
- Apply correction in DSP





Pilot tone maintains drift to < 0.1%

An offset tone based gain stabilization technique for mixed-signal RF measurement systems

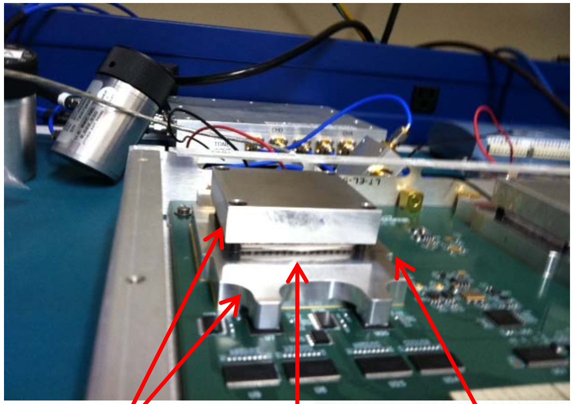
Gopal Joshi [a,*], Paresh D. Motiwala [a], G.D. Randale [a], Pitamber Singh [a], Vivek Agarwal [b], Girish Kumar [b]

[a] BARC, Mumbai 400085, India
[b] IIT Bombay, Powai, Mumbai 400076, India

Nuclear Instruments and Methods in Physics Research A 795 (2015) 399–408

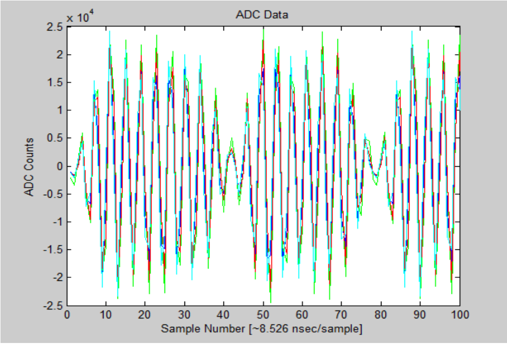
Thermal Electric Control

- Fairly crude TEC with PID feedback lab experiment demonstrated 35hr stability of 400nm RMS. Lab thermal cycle 8°C pp
- Significant room for improvement.

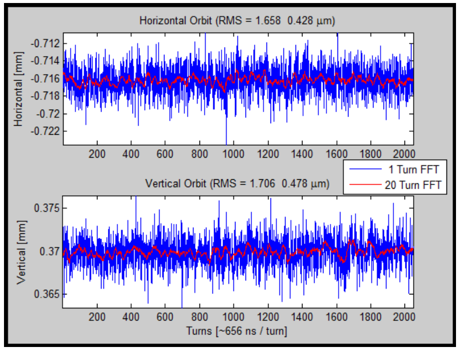


Beam Tests – ALS
Noise Measurement – Combiner/Splitter (2011)

500mA Dual-Cam User Beam

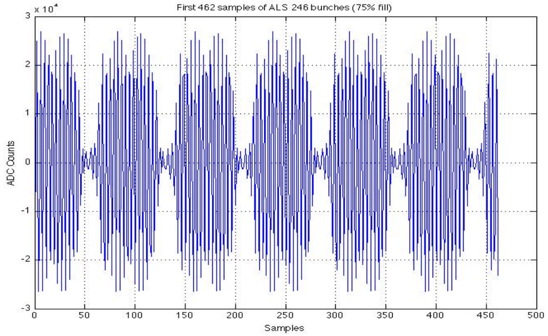


ADC Data – 4-channel overlay

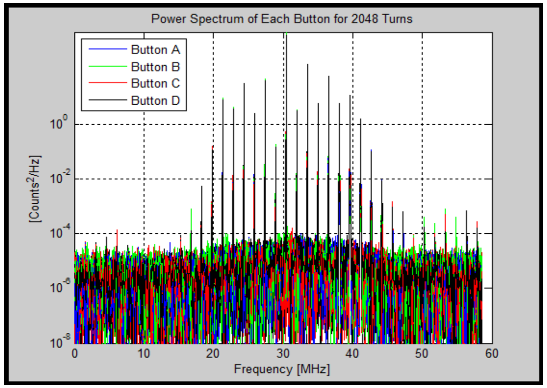


X=1.6um (TbT), 0.428um (20-turns)
Y=1.7um (TbT), 0.478um (20-turns)

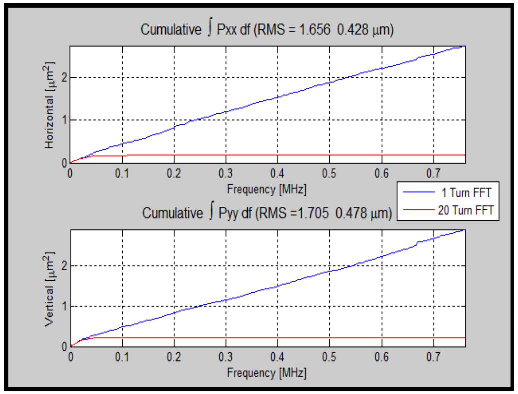
246 Bunch (75%) fill @ 500mA



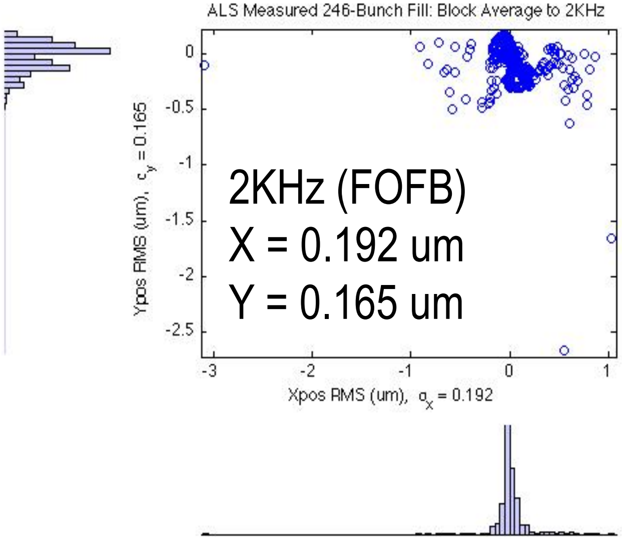
TbT = 1.6um (RMS)



Spectrum – 4 channel Overlay



Integrated PSD: 1-turn, 20-turns



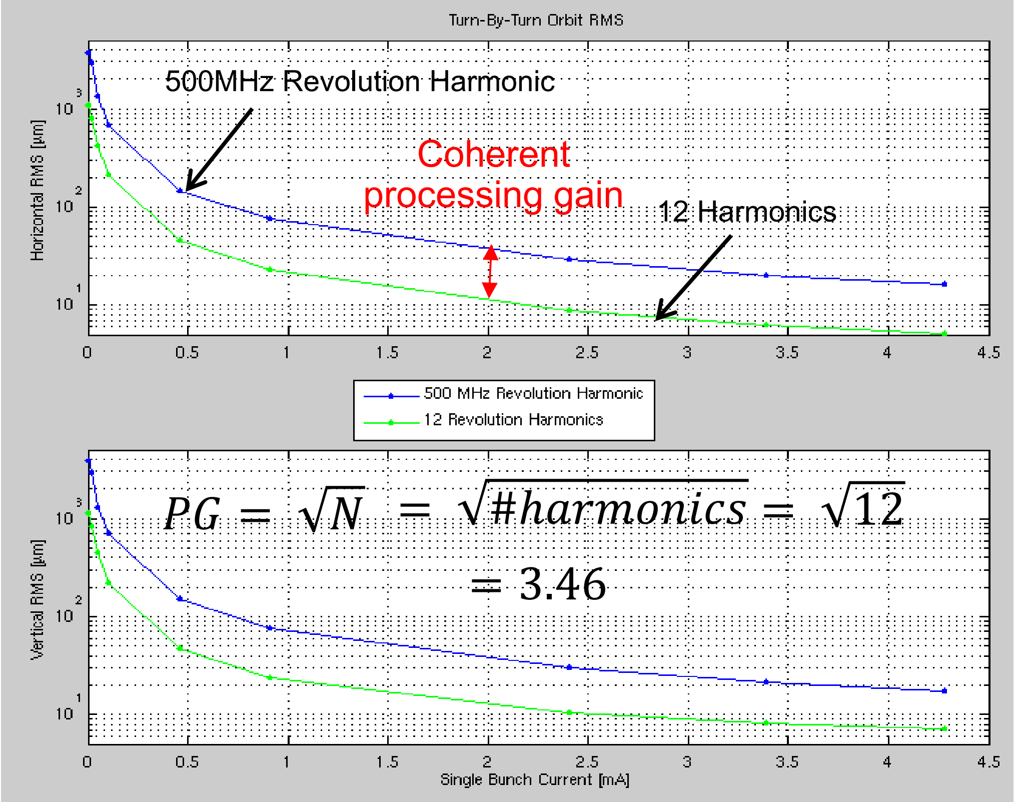
Greg Portmann, K.Vetter

These results served as basis to justify project PCR to use custom EBPM

OAK RIDGE National Laboratory

Single-Bunch TbT Coherent Processing Gain (Frequency Domain)

- ALS beam experiments conducted by **Greg Portmann** first demonstrated coherent **processing gain** utilizing Fourier processing of 12 revolution harmonics within EBPM RF passband
- Coherent processing gain is realized by coherent addition of Fourier revolution harmonic, and quadrature addition of noise component



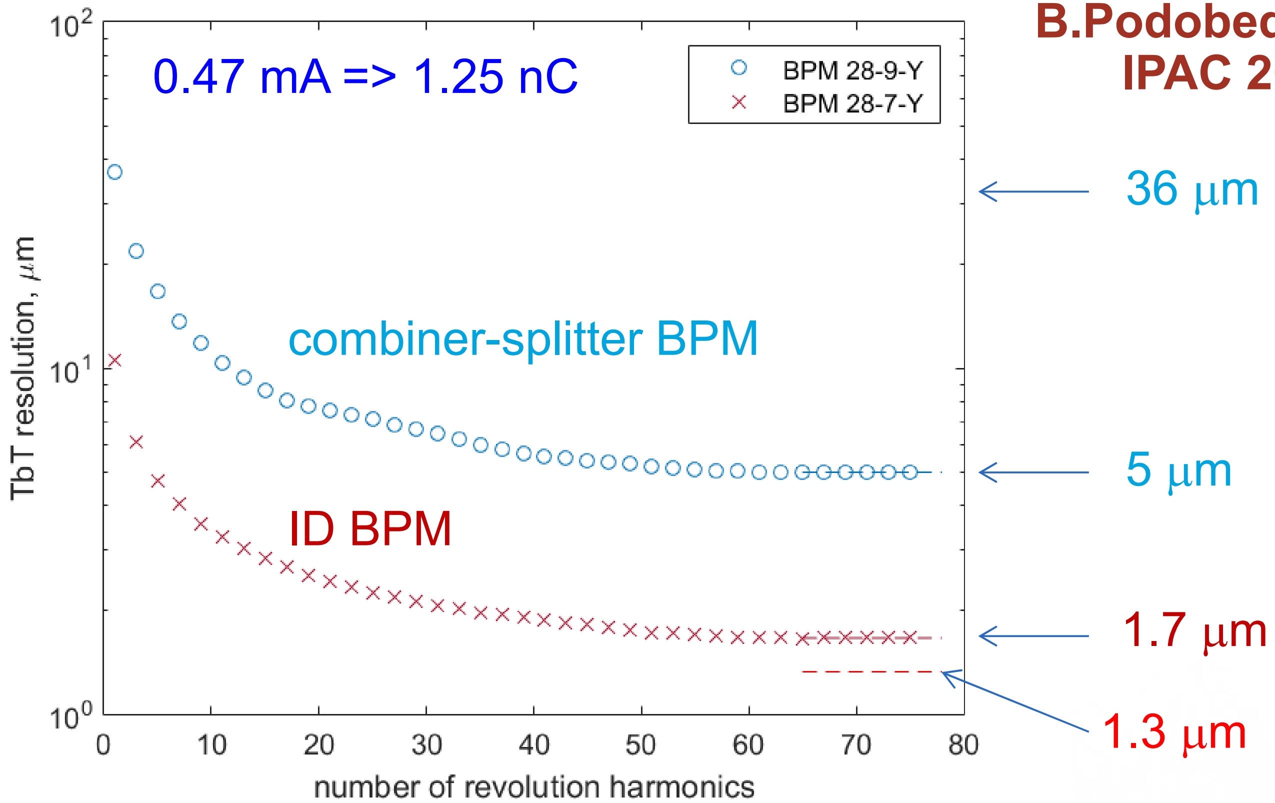
$$PG = \sqrt{N} = \sqrt{\#harmonics} = \sqrt{12} = 3.46$$

Greg Portmann
June 21, 2012
ALS beam experiment with NSLS-II EBPM

Measurement Number	Beam Current [mA]	Horizontal RMS [µm]		Vertical RMS [µm]	
		500 MHz	*12 harmonics*	*500 MHz*	*12 harmonics*
1	No beam	3731.136	1095.387	3858.981	1121.546
2	0.019	2916.476	791.274	2951.289	820.819
3	0.048	1332.762	425.028	1317.234	442.208
4	0.102	687.204	210.955	705.075	218.336
5	0.461	147.137	45.847	151.327	47.552
6	0.908	75.041	23.028	76.928	24.075
7	2.404	28.701	8.876	30.160	10.591
8	3.390	20.179	6.339	21.479	8.181
9	4.283	16.523	5.127	17.388	7.267

Single-Bunch TbT Coherent Processing Gain (Frequency Domain)

B.Podobedov et.al
IPAC 2016

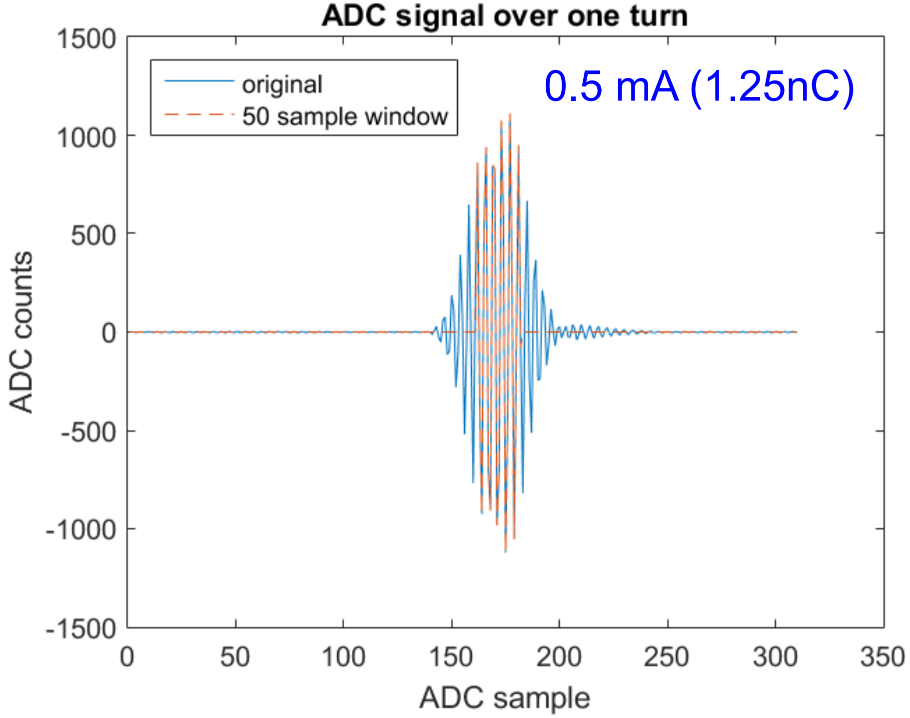


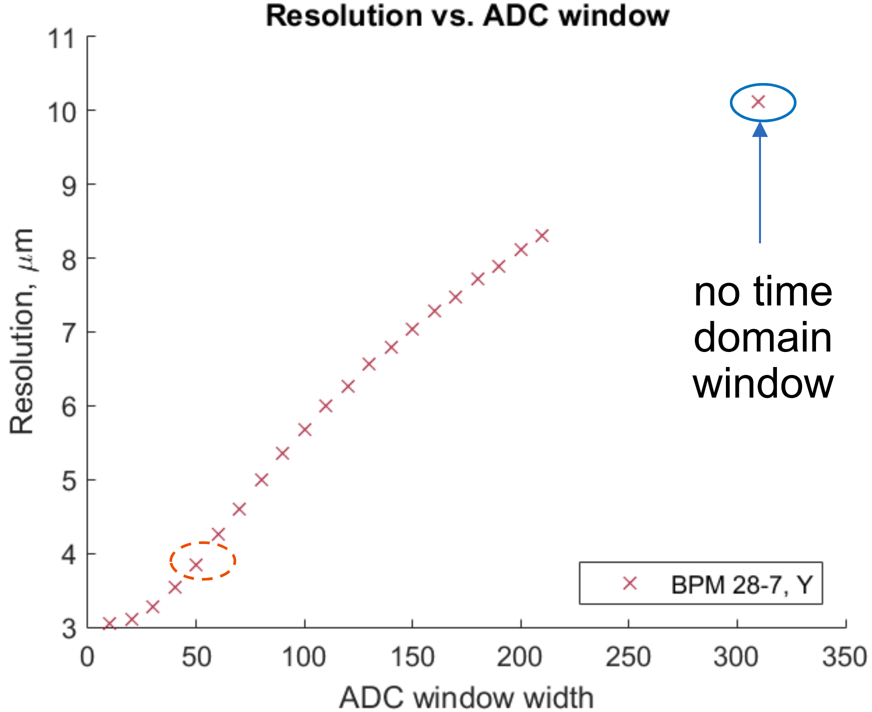
- On ID BPMs directly measured resolution reaches 1.7 μm, or 1.3 μm when scaled from combiner-splitter BPM (1.7um measurement includes beam motion)

✓ **Achieve Single-Bunch TbT resolution on order of 1um at ~1nC/bunch**

Single-Bunch TBT Coherent Processing Gain (Time Domain)

B.Podobedov et.al
IPAC 2016

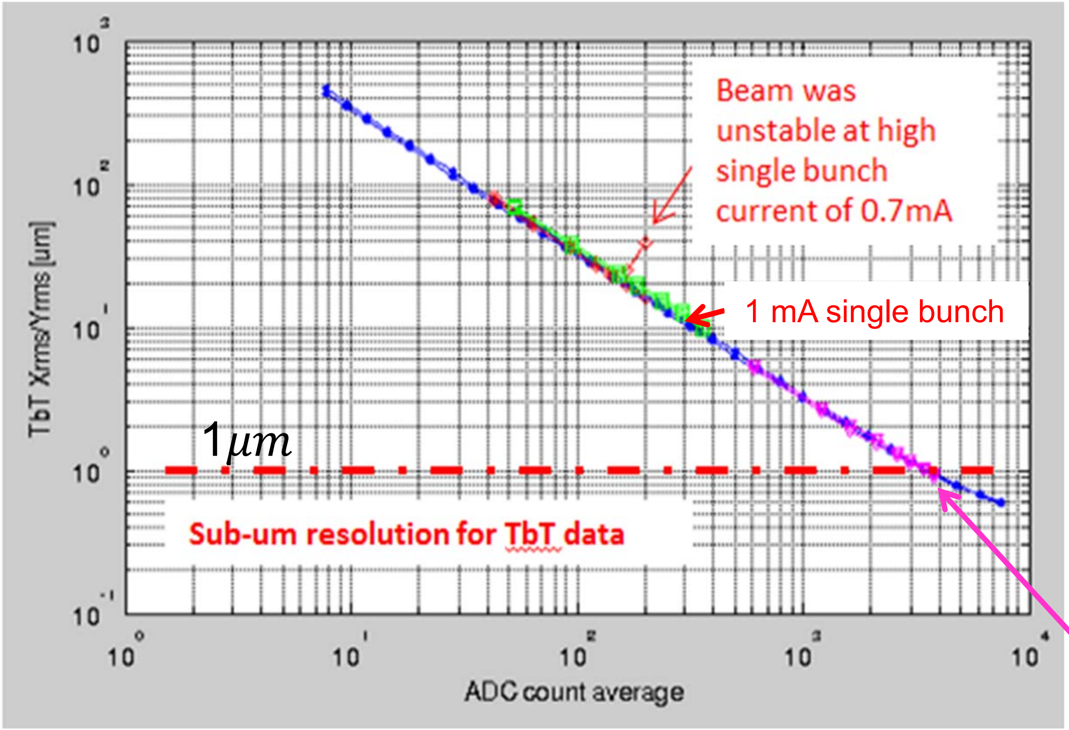




- Standard BPM processing looks at all 310 ADC channels (i.e. entire turn)
- Apply boxcar filter to single bunch ADC data every turn (maximize SNR)
- Processing gain = 3.3 (correlates closely with frequency domain)

OAK RIDGE National Laboratory

NSLS-II EBPM Turn-by-Turn Performance



- pilot tone test
- single bunch
- 20 bunch train
- 1,000 bunch train

~10 mA / 1,000 bunches

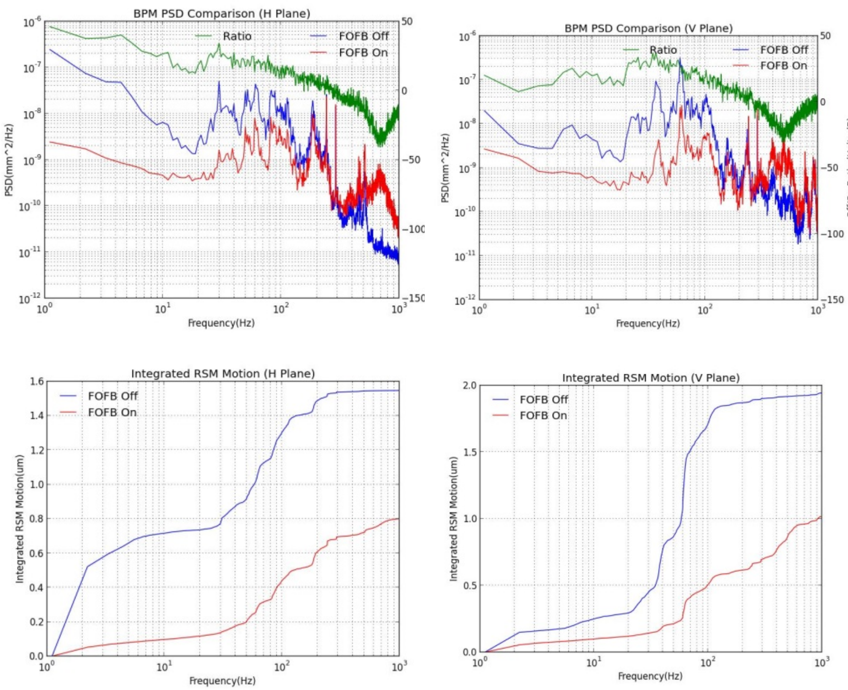
✓ **Sub-micron TbT resolution is routinely available for long bunch trains**

W. Cheng et al., IBIC'15

FOFB Performance

Y.Tian

Short term performance: PSD



FOFB short term stability (integrate to 500Hz):

→ H and V plane noises suppression up to 250Hz.

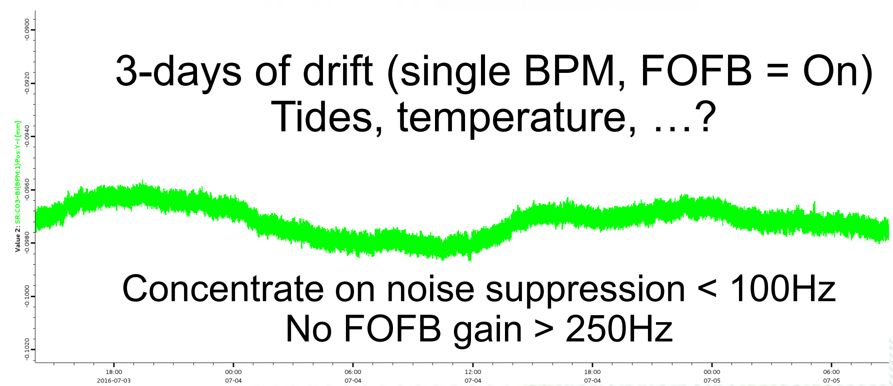
→ Integrated PSD in H plane (about 800nm), is within 1% of beamsize

→ Integrated PSD in V plane (about 550nm), is within 10% of beamsize

Long term performance (24 hours RMS data)

	Source point	Parameters	Values	10%	Measured RMS
X plane		ε (nm-rad)	0.86		
	Short Straight	β (m)	1.89		
		σx (μm)	**40.3**	**4.03**	**0.65**
		σxp (μrad)	21.3	2.13	0.72
	Long Straight	β (m)	19.16		
		σx (μm)	**128**	**12.8**	**1.27**
		σxp (μrad)	6.69	0.669	0.12
Y plane		ε (nm-rad)	0.008		
	Short Straight	β (m)	1.09		
		σy (μm)	**2.97**	**0.297**	**0.53**
		σyp (μrad)	3.29	0.329	0.086
	Long Straight	β (m)	3.2		
		σy (μm)	**5.35**	**0.535**	**0.525**
		σyp (μrad)	1.92	0.192	0.2

FOFB long term stability: within the 10% of stability requirement.

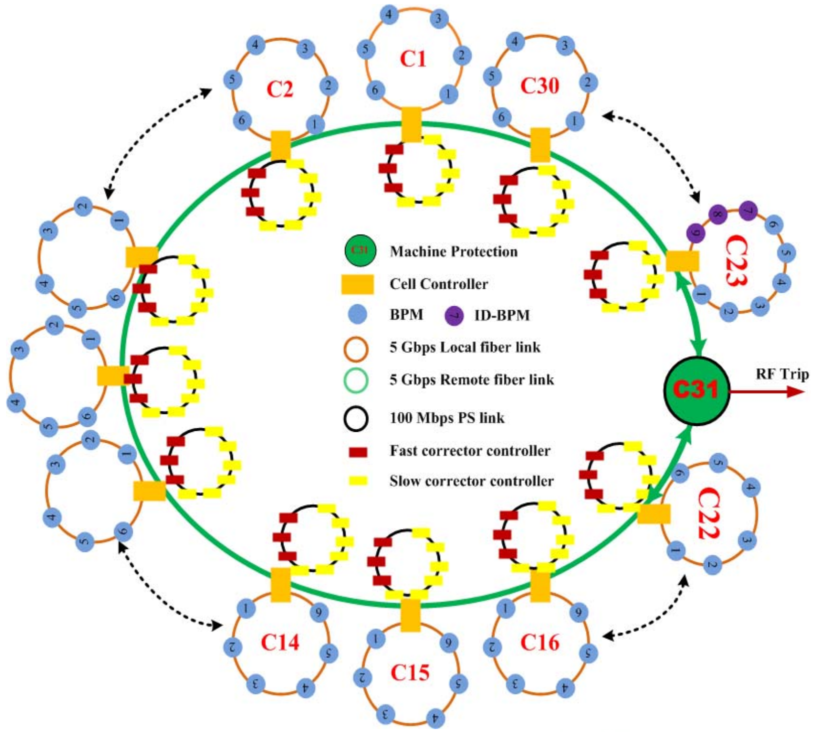


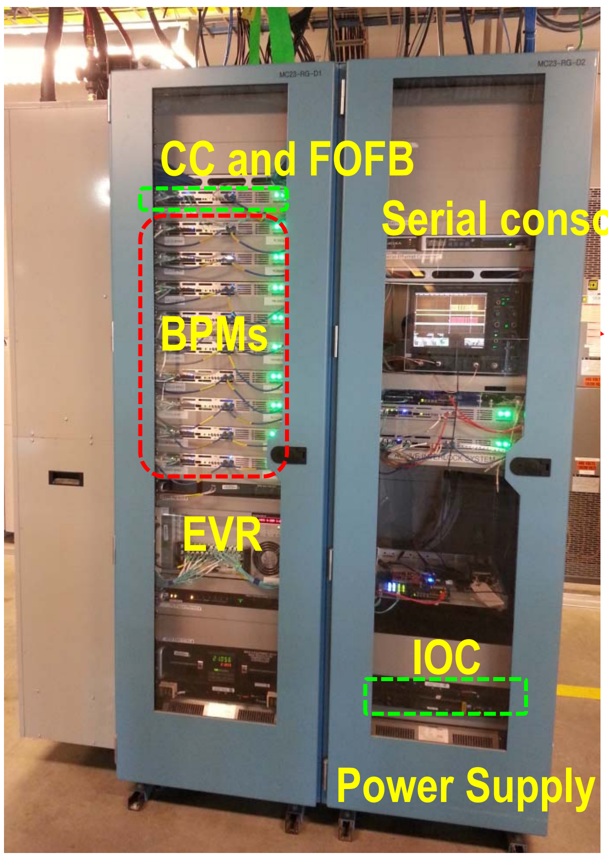
Derivative Instruments

- NSLS-II Cell Controller (FOFB and Active Interlock)
- NSLS-II Xray BPM (XBPM)
- NSLS-II Diamond Detector BPM (DBPM)
- LBNL EBPM

Cell Controller

- PID control based on SVD in FPGA
- 180 EPMs, 90 Correctors
- 10KHz update rate
- 1st generation DFE, custom AFE

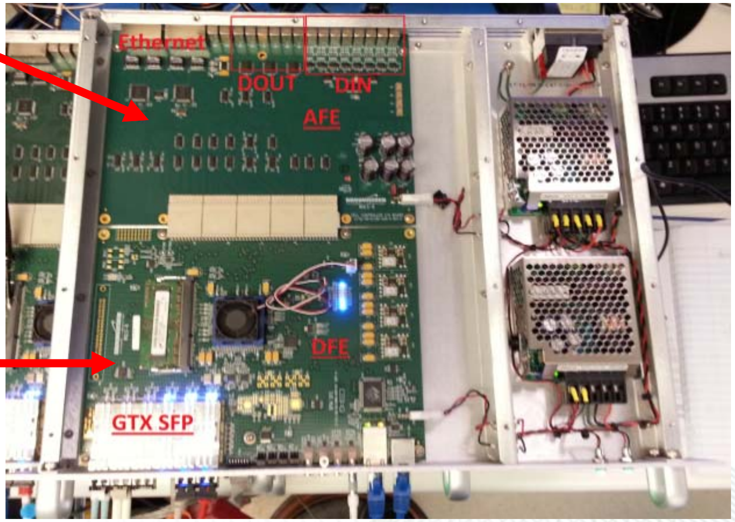




Custom DFE
Corrector Drive

15 urad, 20b PS res.
1 ppm step response
BW=2 kHz

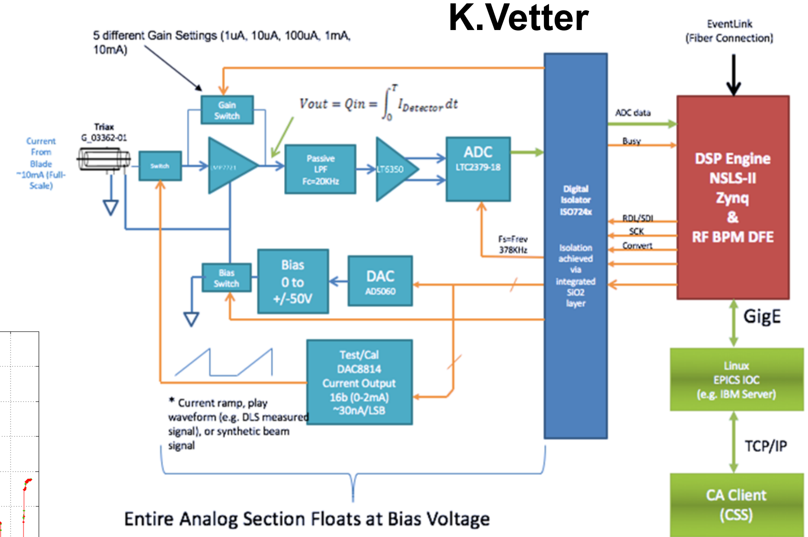
EBPM
DFE

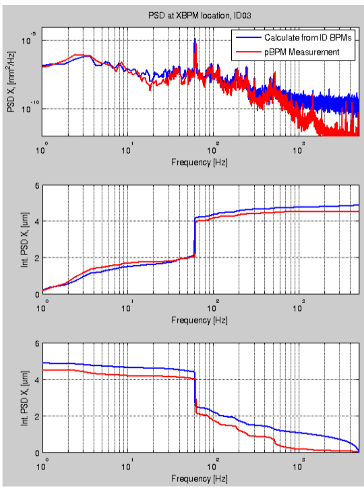


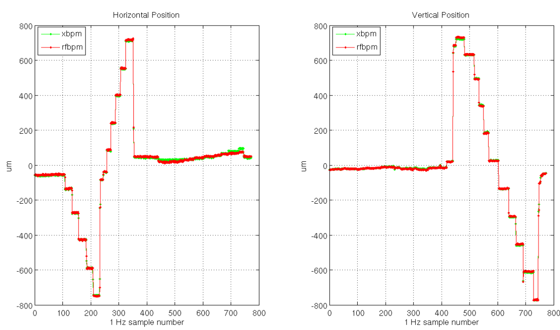
NSLS-II Xray BPM (XBPM)

- Photo emission blade detector
- Electrometer AFE with Zynq XC7Z045 FPGA based 2nd Gen.DFE

K.Vetter

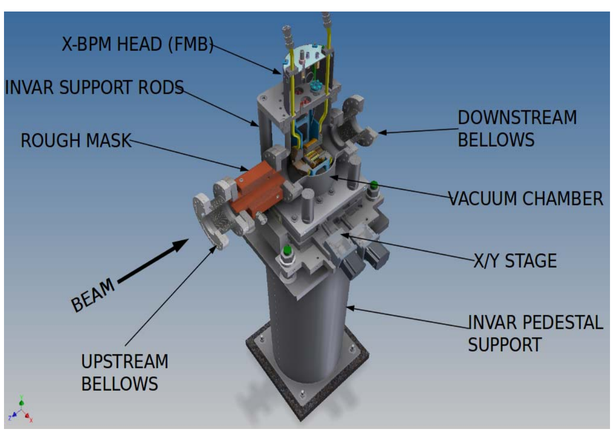






Manually swept local bump from -0.5mrad to +0.5mrad in Horizontal and Vertical planes XBPM position matches position calculated from 2 ID EBPMs

J.Mead

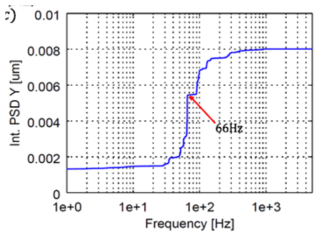


2nd Generation DFE

- Zynq XC7Z045 FPGA with hard dual-core ARM A9 processor.
- Debian based Linux OS
- Software development is now standard user space applications similar to software development on a standard Linux server.

Diamond BPM (DBPM)

- XBPM electronics are used as detector readout for CVD Diamond BPM
- Includes actuation drive to enable adaptive monochromator control
- **Developed in collaboration with Sydor Instruments via SBIR**



Measured vertical beam motion

ABSTRACT

The mechanical, optical, electronic and thermal properties of diamond make it an ideal material to address the x-ray beam monitoring needs of modern synchrotrons. Diamond Beam Position Monitors (DBPMs) have demonstrated to yield position resolutions of 25 nm for stable beams and a have shown linear flux responses of at least 11 orders of magnitude. Readout electronics tailored to suit the performance and integration needs of DBPMs are needed to fully harness the potential of the technology. Sydor Instruments LLC in collaboration with Brookhaven National Laboratory (BNL) has advanced a novel electronic readout system based on the electron Beam Position Monitor (eBPM) readout systems developed for the National Synchrotron Light Source II (NSLSII) storage ring. The developed system, SIEPA3P, is a 4-channel electrometer with an internal power supply, Ethernet based Experimental Physics and Industrial Control System (EPICS) controls and a Control System Studio (CSS) user interface to operate DBPMs. The system has been deployed at the NSLSII CHX beamline for x-ray beam diagnostics and stabilization. The SIEPA3P utilizes a Sydor Instruments' DBPM for beam characterization in conjunction with a horizontal mirror and a Double Crystal Monochromator for x-ray beam stabilization.

DIAMOND BPM OPERATION

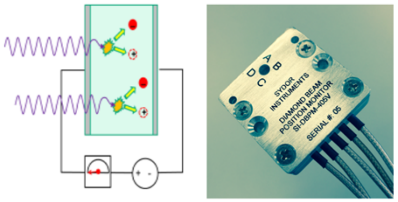
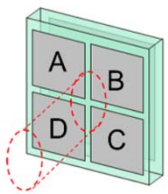


Fig. 1 Electron-hole pair production in CVD diamond (Left). Sydor DBPM (Right).



$$Y = G_y \frac{(A+D)-(B+C)}{A+B+C+D}$$

$$X = G_x \frac{(A+B)-(C+D)}{A+B+C+D}$$

Fig. 2 Quadrant Diamond BPM (Left). The charge collected by each quadrant is utilized to calculate the x-ray beam position via a difference over sum algorithm (Right)

BEAM POSITION STABILIZATION

In order to suppress the vertical x-ray beam drift, the SIEPA3P monitored the beam motion with the installed DBPM and controlled an upstream monochromator. The monochromator was controlled via the SIEPA3P DAC outputs and utilizing the unit's internal, user configurable PID controls loops. Figure 6 shows the effect of the beam stabilization at 1Hz when the feedback was enabled and disabled over a period of approximately 15 minutes.

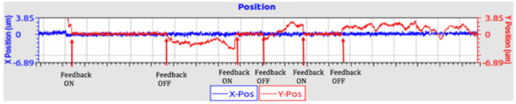


Fig. 6 Vertical x-ray beam motion when the SIEAPA3P feedback was enabled and disabled over a 15 minute period

A closer look into vertical beam stability over a period of 5 minutes showed a significant decrease in beam motion and closer overall beam centering on the DBPM when the SIEPA3P feedback control was enabled. This demonstrated that the SIEAP3P feedback control is effective is suppressing sub-Hertz beam motion (Figure 7).

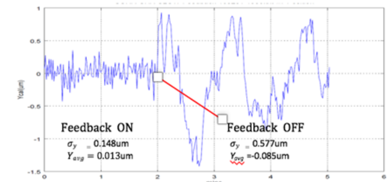


Fig. 7 Vertical beam stability with the SIEPA3P feedback control enabled and then disabled.

SIEP-A3P Electrometer

Jaime Farrington

SYDOR INSTRUMENTS
A SYDOR TECHNOLOGIES COMPANY

X-ray Beam Stabilization System Utilizing Diamond Beam Position Monitors

Andrei Fluerasu[a], Lutz Wiegart[a], Jaime Farrington[b]
[a]Brookhaven National Laboratory, Upton, NY 11973, [b]Sydor Instruments LLC, Rochester, NY 14624

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LBNL BPM

- MOU between BNL and LBNL to transfer EBPM technology
- Adapt 1st generation DFE – modify DSP and controls to optimize for ALS operation
- Evolve AFE to incorporate pilot tone using lumped filter technology
  - NSLS-II based on SAW filter technology, thermally sensitive (used in cell phones), not an issue for NSLS-II as a result of thermally stable racks (0.01C)

Greg Portmann et.al.

Summary

- The NSLS-II EBPM has been developed and commissioned in less than 5 years
- Single-bunch TbT resolution of ~1um (~1nC/bunch)
- Orbit stability (24hr.) <10% of beam size
- Four derivative instruments have been developed
  - NSLS-II Cell Controller (FOFB and Active Interlock)
  - NSLS-II Xray BPM (BPM)
  - NSLS-II Diamond Detector BPM (DBPM)
  - LBNL EBPM

Acknowledgements

- **The original EBPM Development team**
  - The success of this project would not have been possible without every member of the original developmnet team!
- **Boris Podobedov, Weixing Cheng, Joe Mead, Yuke Tian, Jaime Farrington**
  - Contributions to this presentation
- **Om Singh**
  - For championing the EBPM R&D Project
- **Ferdinand Willeke**
  - For funding the EBPM R&D
  - Having the confidence in the team to re-baseline project to include custom EBPM

Thank You for Your Attention!

Original Development Team

K. Vetter (Team Leader, System Architecture, RF, Algorithms)
A. DellaPenna – (RF)
K. Ha (Embedded Controls, EPICS)
M. Maggipinto – (Technical Support)
J. Mead (FPGA, DSP, DFE board design)
J.Delong (FPGA,Timing, Embedded Eventlink, SDI Link)
B.Kosciuk (Mechanical, thermal analysis)
I. Pinayev (physics)
Y.Tian (FPGA, Controls, Cell Controller, FOFB)
G.Portman – Collaborator, Beam Tests, Signal Processing (LBNL)
J.Sebek – Collaborator, Beam Tests, Signal Processing (SLAC)
J.Webber – Collaborator, FPGA (LBNL)

*__BOLD__ indicates full-time.

Oak Ridge National Laboratory