NSLS-II BPM & Fast Orbit Feedback

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NSLS-II Instrumentation

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Outline

- Overview
- RF BPM
  - Detector/ support
    - RF button optimization
    - Chamber HOM coupling
    - Button chamber support
  - Electronics – AFE,DFE,PTC
  - Controls architecture
  - Performance with beam
  - Integrated tests
- Fast Orbit Feedback
  - Noise sources
  - AC functional requirement
  - Fast & slow correctors
  - FOFB Implementation
    - Algorithm/ model
    - Cell Controller
    - Cell/ Global topology
    - Hardware
- Summary

NSLS- II Key Parameters

GUN
100 kV Electron Gun
40-150 bunches;
2 ns Bunching systems

LINAC

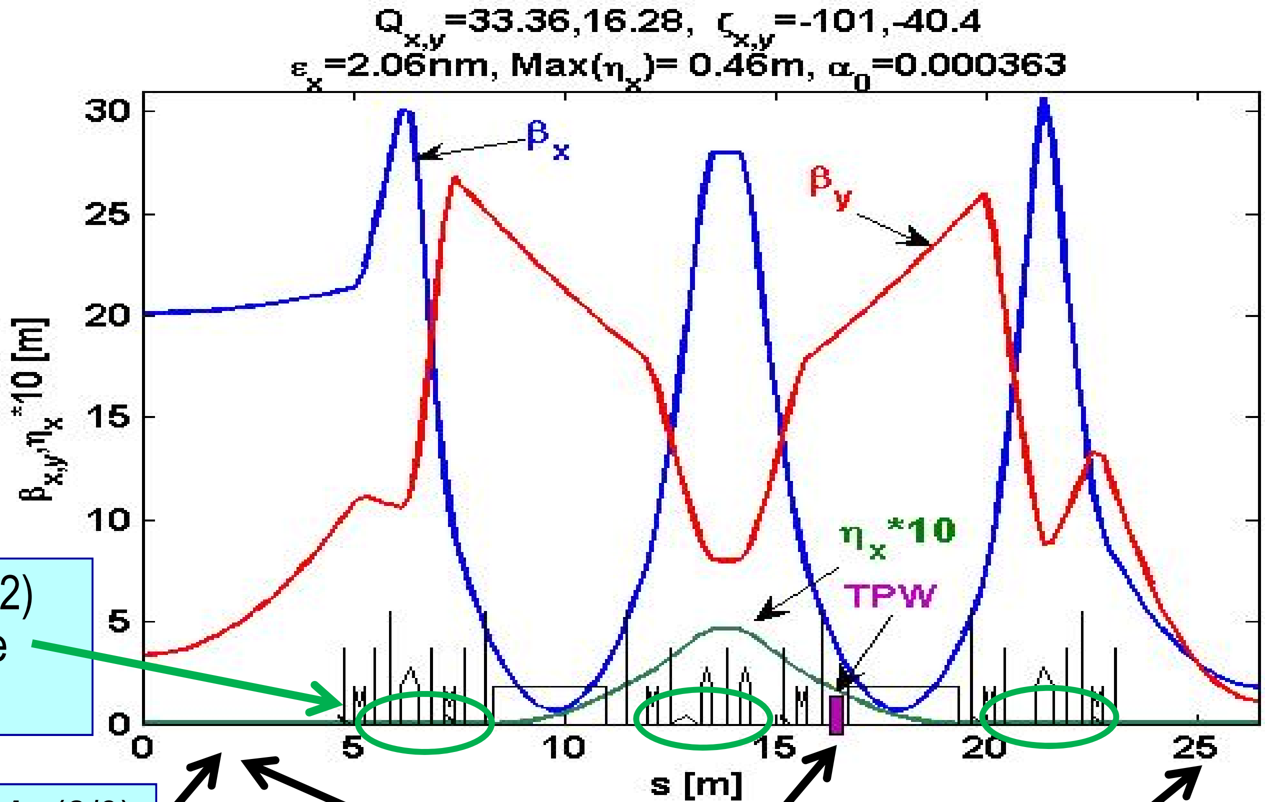
Energy	200MeV
Single-bunch Charge	10 pC-0.5 nC
Multi-bunch Charge	20 nC
Emittance	55 mm-mrad
Energy spread	0.5% - 1.0 %
Turn key	

Booster

Circumference	158m
Harmonic Number	264
Revolution Time	0.528 μs
Ramp Cycle	1 Hz
Ramp Energy	200 MeV -3GeV
Bunch Length (σ)	15ps
Semi-turn key	

Storage Ring	Nominal Value
Energy	3.0 GeV
Stored Beam (top up > 1 minute)	500 mA; $\Delta I/I = 1\%$
RF frequency	499.68 MHz
Circumference	792 m
Revolution period, T_0	2.642 μs
Harmonic number	1320
Number of bunches filled - (bunch to bunch variation = 20%)	1056 (~80%)
Tunes - Q_x, Q_y	33.36, 16.28
Emittance Bare Lattice ε_0 (H/V)	2.0 /0.01 nm-rad
Emittance with 8-DWs ε (H/V)	0.60/0.008 nm-rad
Bunch length – (3rd Harmonic bunch length cavity)	15-30 ps
Long & short straight sections – (2 RF & 1 injection in long SS)	15/15 (30 cells)

SR Lattice & Electron Beam sizes/divergences



Lattice Functions

Standard BPMs (2) on each multipole chambers

High stability BPMs (2/3) on ID straight chambers

Electron Beam Sizes & Divergences

Types of source	Long ID	1-T 3-Pole wiggler	Bend magnet	Short ID
σ_x (μm)	108	175	44.2	29.6
$\sigma_{x'}$ (μrad)	4.6	14	63.1	16.9
σ_y (μm)	4.8	12.4	15.7	3.1
$\sigma_{y'}$ (μrad)	1.7	0.62	0.63	2.6

Most challenging Beam stability Requirements = ~ 0.31 μm

NSLS-II BPM Performance Requirements

Injection System

- Rep Rate = 1Hz
- Bunch Spacing = 2ns
- B. Frev= 1.89MHz

Parameters/ Subsystems	Conditions	Vertical	Horizontal
Injector - single bunch	0.05 nC charge	300 µm rms	300 µm rms
	0.50 nC charge	30 µm rms	30 µm rms
Injector - mult-bunch (80-150 bunches) **(measured)**	15 nC charge	10 µm rms **(3 µm rms)**	10 µm rms **(4 µm rms)**

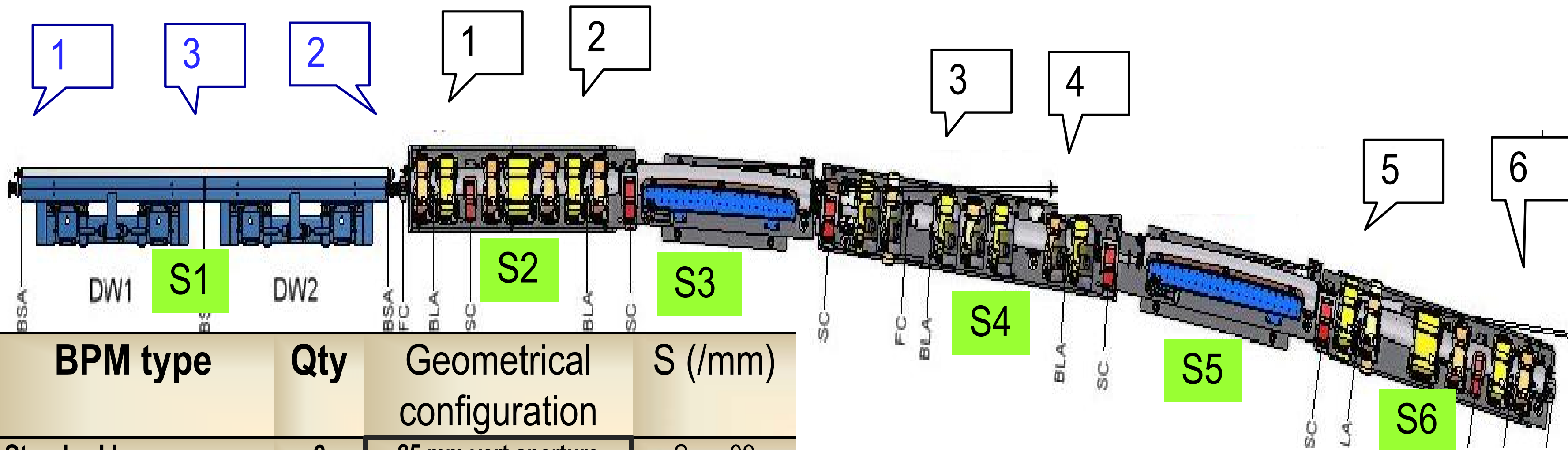
Parameters/ Subsystems		**Conditions**	***Multipole chamber RF BPM Resolution Requirement @ *500mA stored current***	
			Vertical	**Horizontal**
BPM Receiver Electronics	Turn by Turn	Data rate = 378 kHz	3 µm rms	5 µm rms
	Assuming no contribution from bunch/ fill pattern effects	0.017 Hz to 200 Hz	0.2 µm rms	0.3 µm rms
		200 Hz to 2000 Hz	0.4 µm rms	0.6 µm rms
		1 min to 8 hr drift	**0.2 µm peak**	0.5 µm peak
	Bunch charge/ fill pattern effects only	DC to 2000 Hz	**0.2 µm rms**	0.3 µm rms
BPM button support assembly	Vibrations	50 Hz to 2000 Hz	10 nm rms	10 nm rms
		4 Hz to 50 Hz	25 nm rms	25 nm rms
	Thermal	1 min to 8 hr	0.2 µm peak	0.5 µm peak

* ID straight RF BPMS requires better resolution

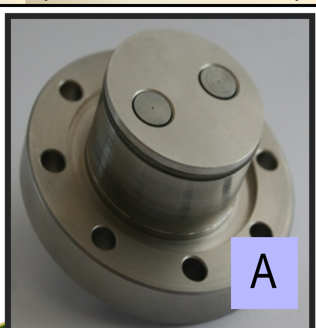
Storage Ring

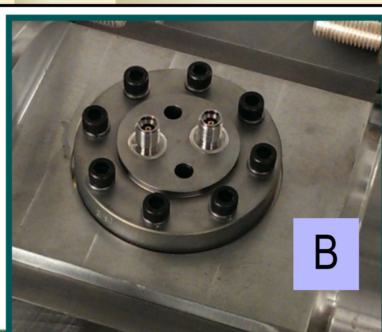
- Frev = 378KHz
- Frf = 499.68MHz

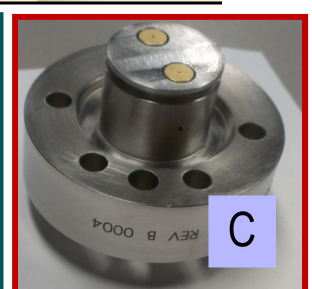
RF BPM Button – Geometric Optimization

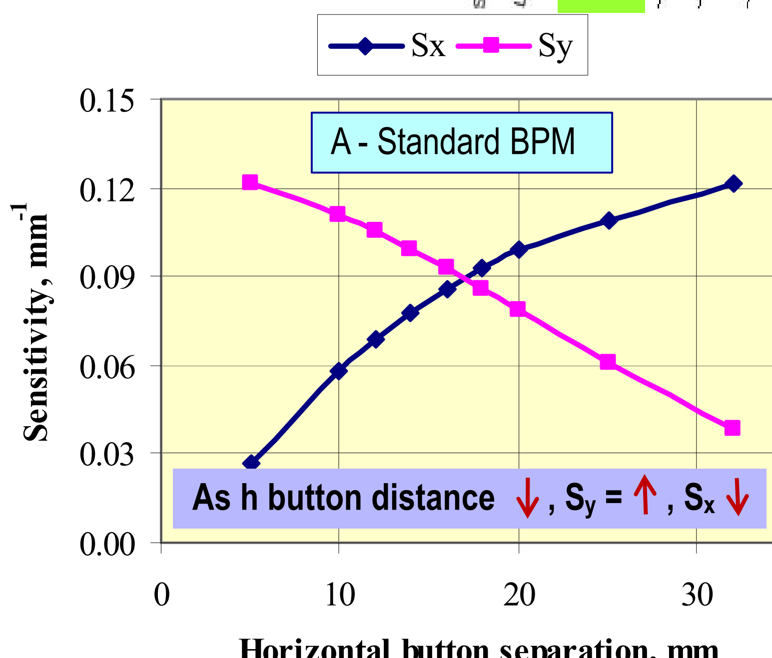


	BPM type	Qty	Geometrical configuration	S (/mm)
A	**Standard bpm – on Chambers – S 2, 4, 6**	**6**	**25 mm vert aperture 7 mm dia button 16 mm hor separation**	S_x = .09 **S_y = .08**
B	**IVU ID bpm – on S1 (Rotated RF Buttons)**	**2/3**	**25 mm vert aperture 7 mm dia button 7 mm hor separation**	S_x = .07 **S_y = .11**
C	**DW bpm – on S1 (Rotated RF Buttons) (9.6 mm w/o rotation)**	**2/3**	**11.5 mm vert aperture 4.7 mm dia button 5 mm hor separation**	S_x = .13 **S_y = .22**





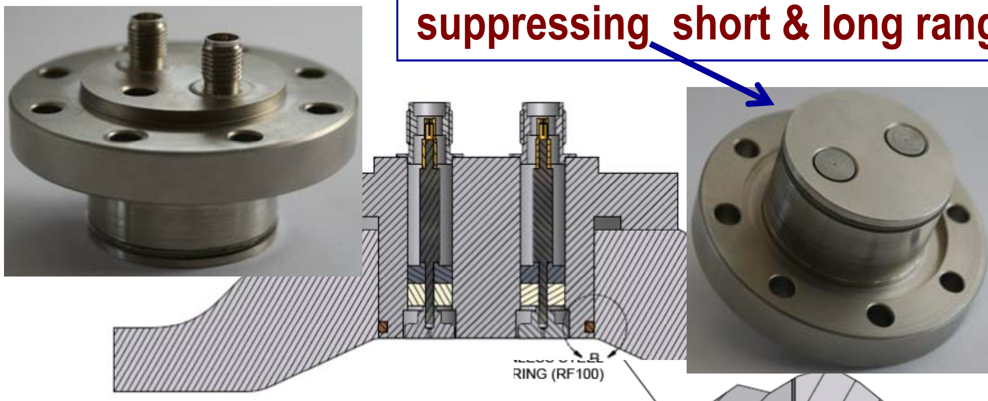


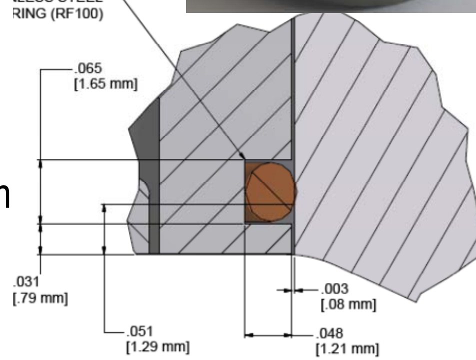


Qty = 500 - 7mm dia. Button;
Qty = 65 - 4.7mm dia. Button

BPM Heating/ Coupled bunch instability issues

RF shield in groove shorts the gap between bpm flange & vacuum chamber, suppressing short & long range wake-potential and impedance



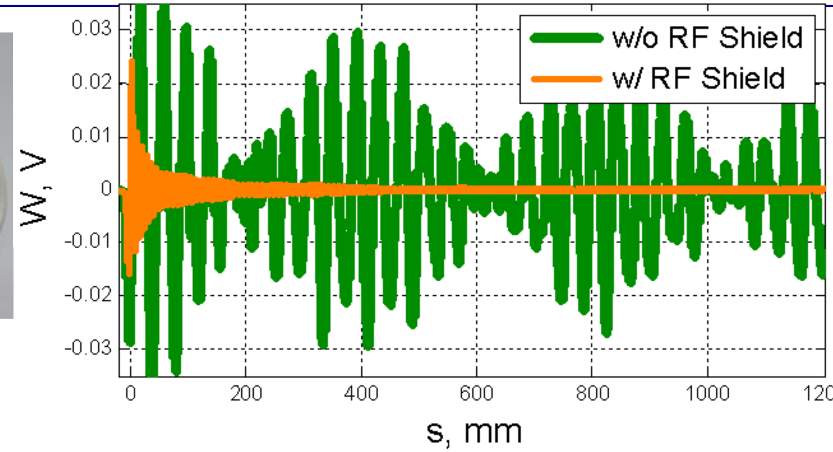


Geometric parameters:

g=100um and h=2mm

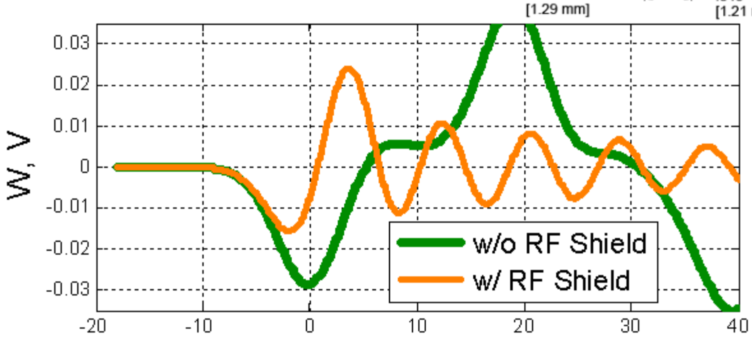
d1=30.5mm and d2=30.6mm

2a=76mm and 2b=25mm

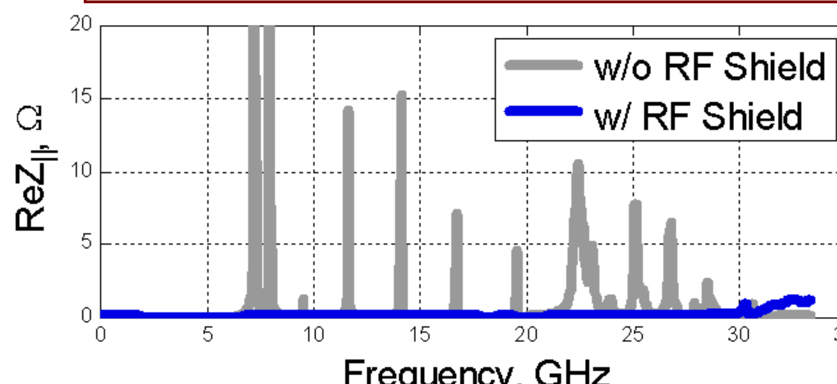


Longitudinal long-range wakepotential

$\kappa_{loss}(\sigma_s=3mm)$ = 0.7mV/pC (w/ RF Shield)

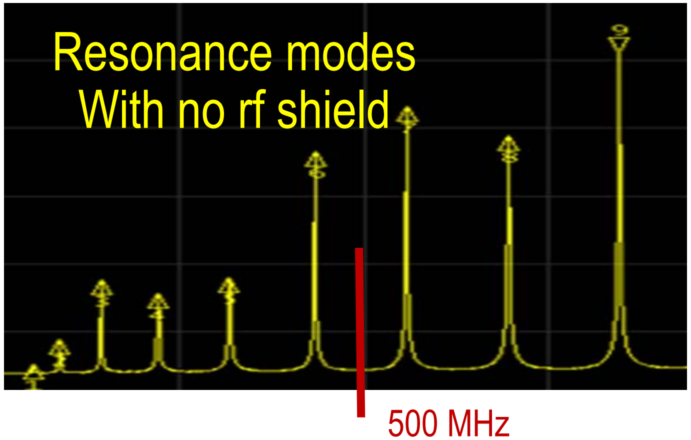


Longitudinal short-range wakepotential

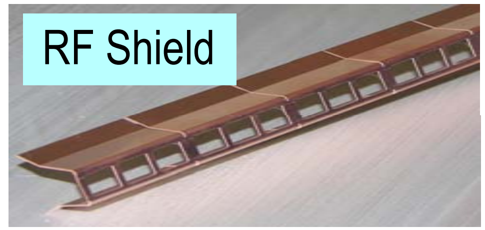


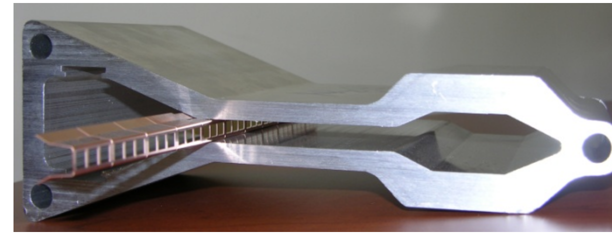
Real part of the longitudinal impedance

Multi-pole Chamber - Resonance modes optimization(RF shield)

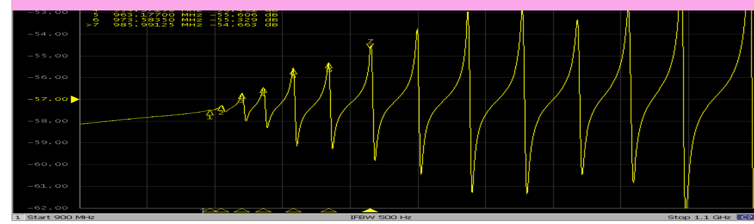


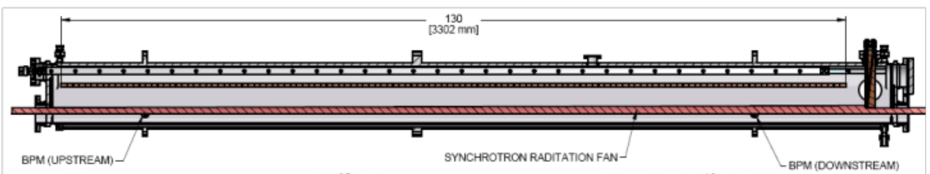
Flexible BeCu RF fingers with 50% of opening space



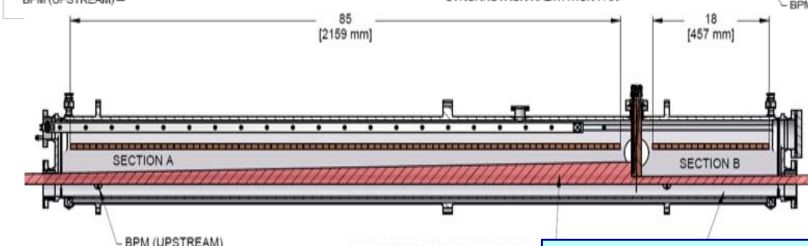


- S2 & S4 → shifts modes to > 800 MHz



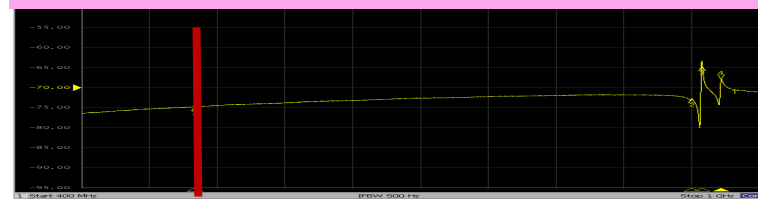


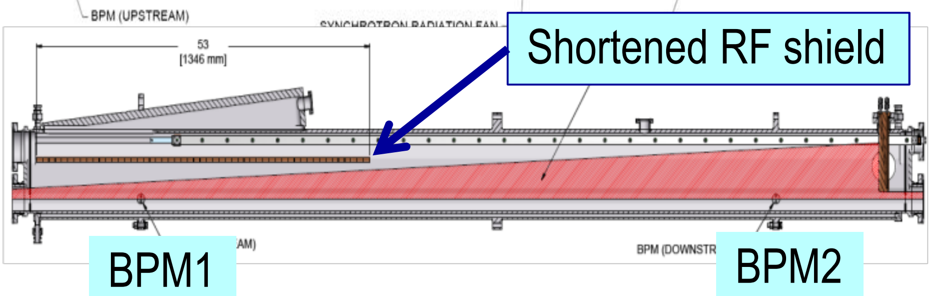
S2



S4

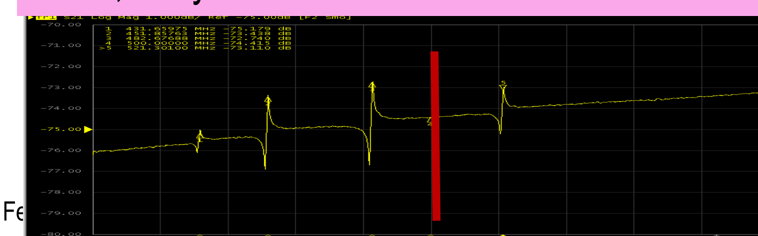
- S6 upstream → shifts modes to > 800 MHz



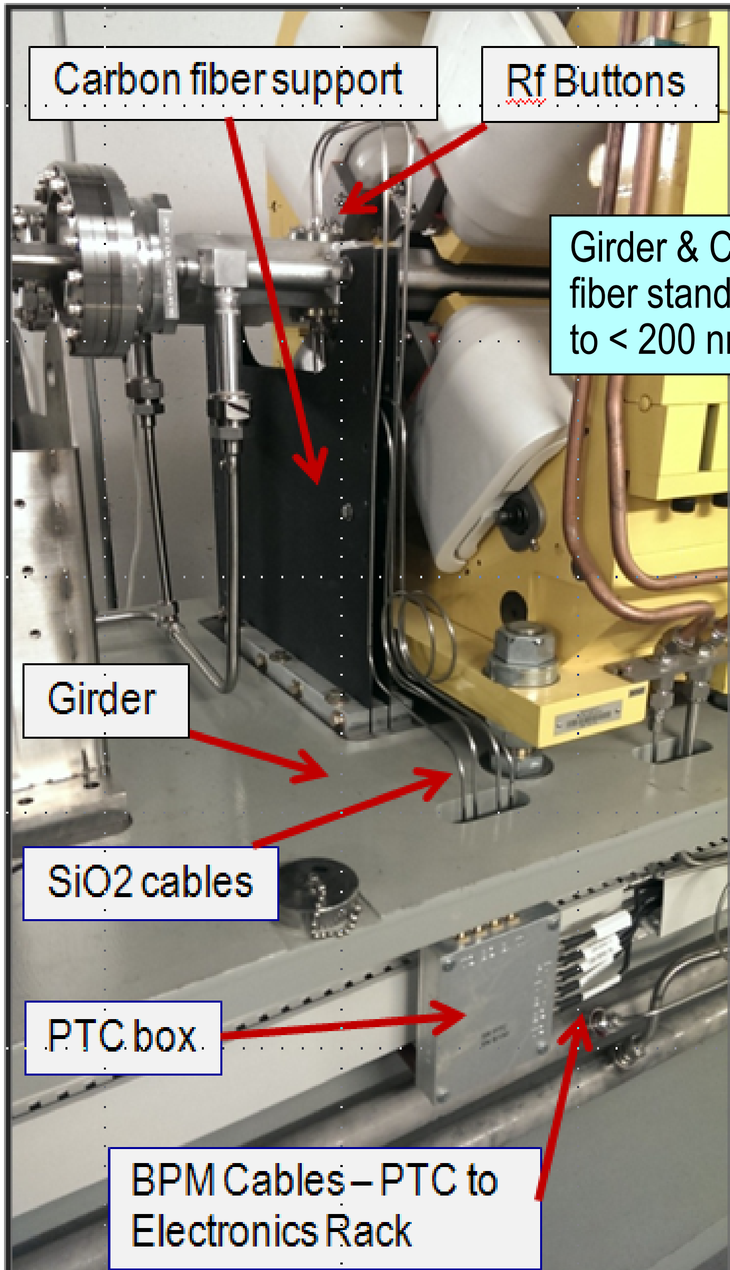


S6

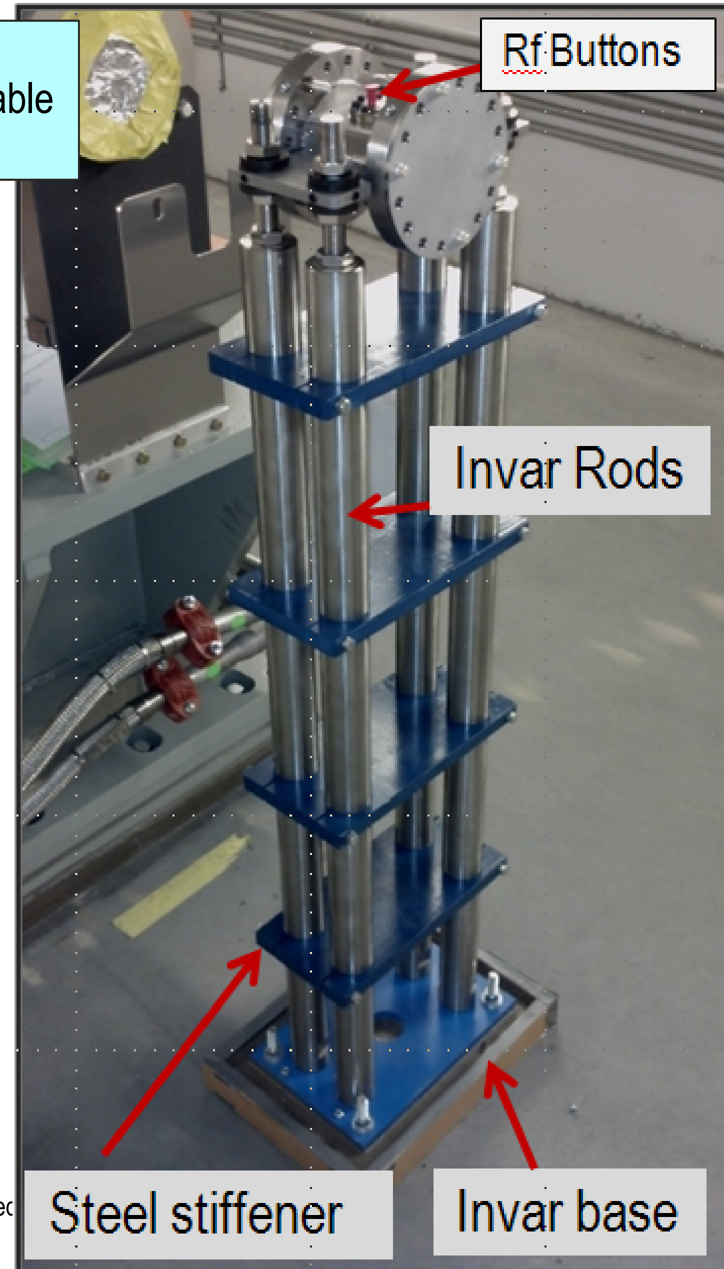
- S6 downstream → does not shift out of band, may not be available



RF buttons assembly support - thermal optimization



High stability Invar stand stable to < 100 nm

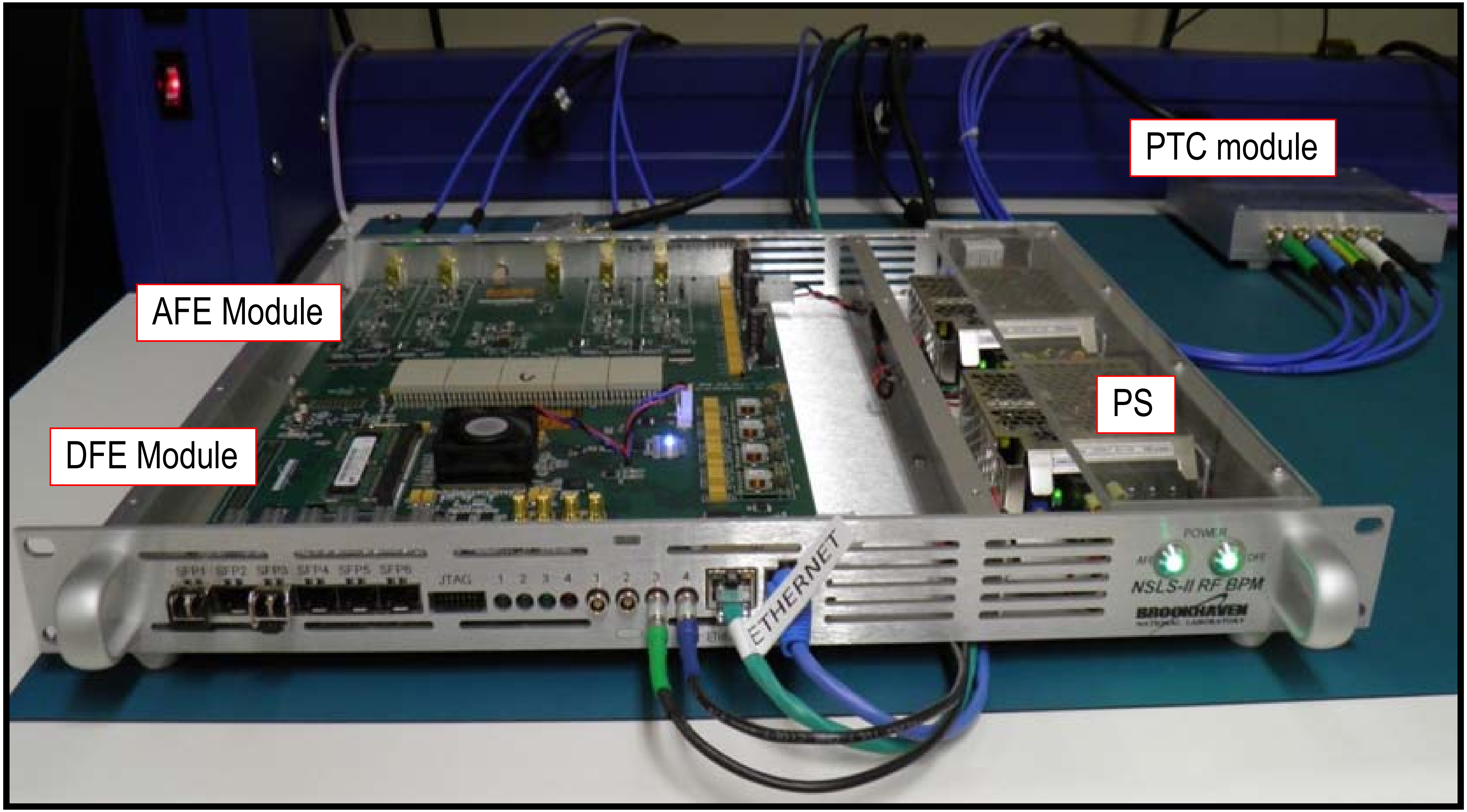


In- House Electronics

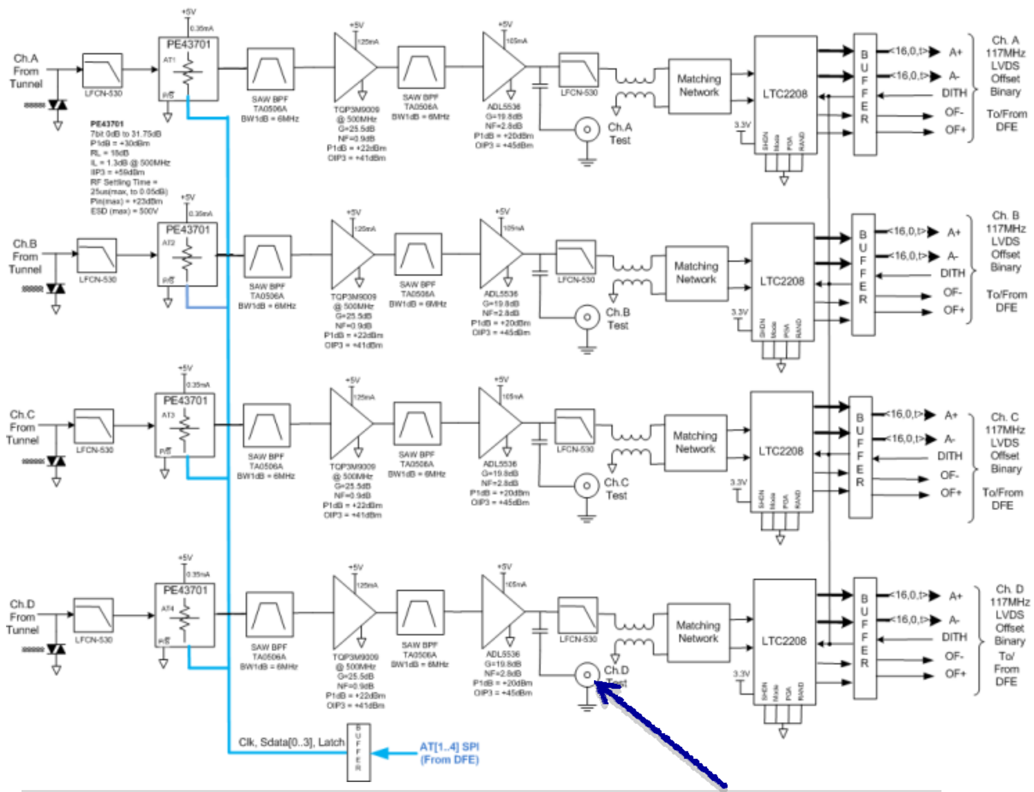
- Motivation – Why design our own BPM?
  - Technology → Use latest technology for World Class Synchrotron
  - System Architecture → Create generic architecture
  - In-House Expertise → Expertise resides in-house for all system aspects
- Design Decisions
  - Build two separate boards → AFE and DFE
  - Integrated test tone – Pilot tone combiner (PTC)
  - No Fan → Leverage NSLS-II thermally stable racks, +/- 0.1°C
  - Long-Term Stability → Combination of stable thermal rack and tunnel
  - Use Soft-Core Microprocessor → Design Portability
  - TCP/IP Interface → Direct EPICS and Matlab communication
- Time Line – Start program in August 2009

		Injection	Storage Ring
1	Production start	August, 2011	January, 2012
2	Installation/ Integration completion	April, 2013	November, 2013
3	Commissioning start	November, 2013	March, 2014

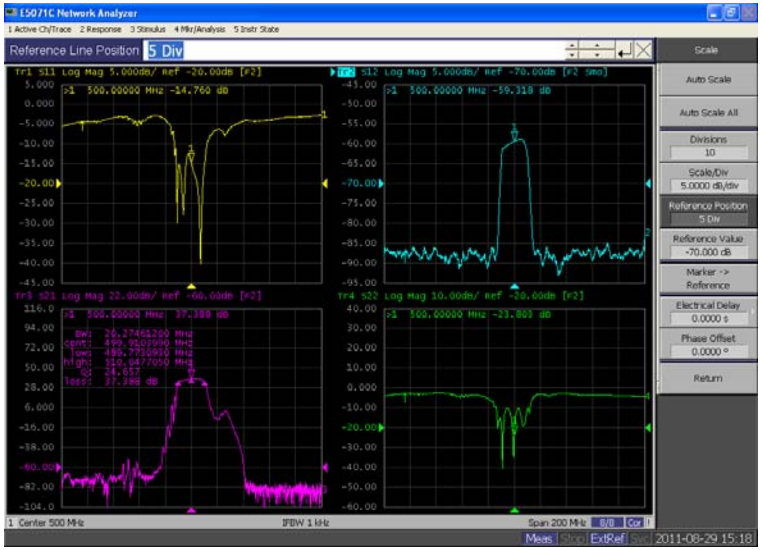
RF BPM Hardware



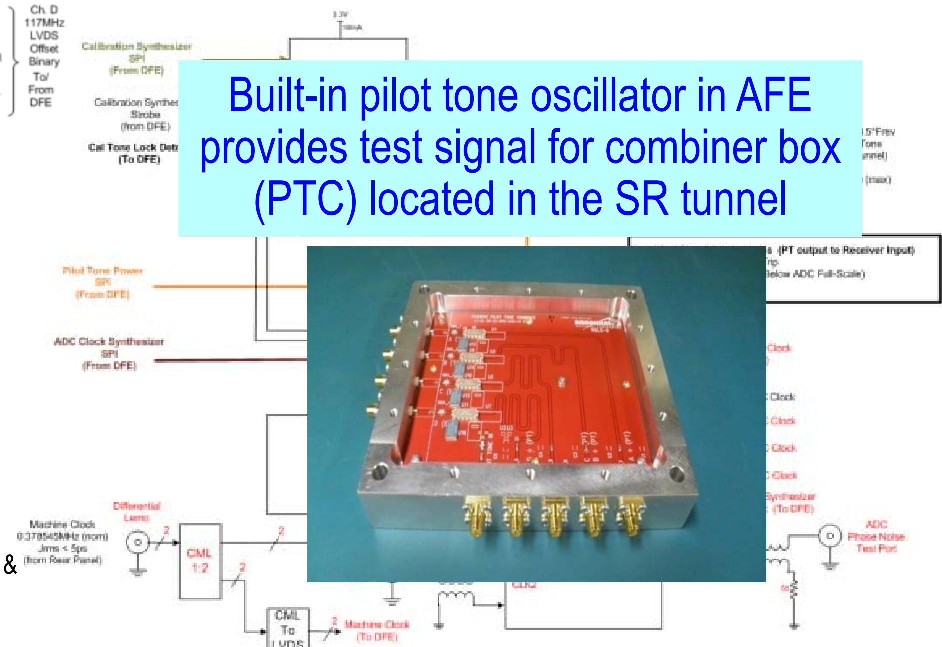
System Architecture - AFE



Receiver S-Parameter Characterization



Built-in pilot tone oscillator in AFE provides test signal for combiner box (PTC) located in the SR tunnel



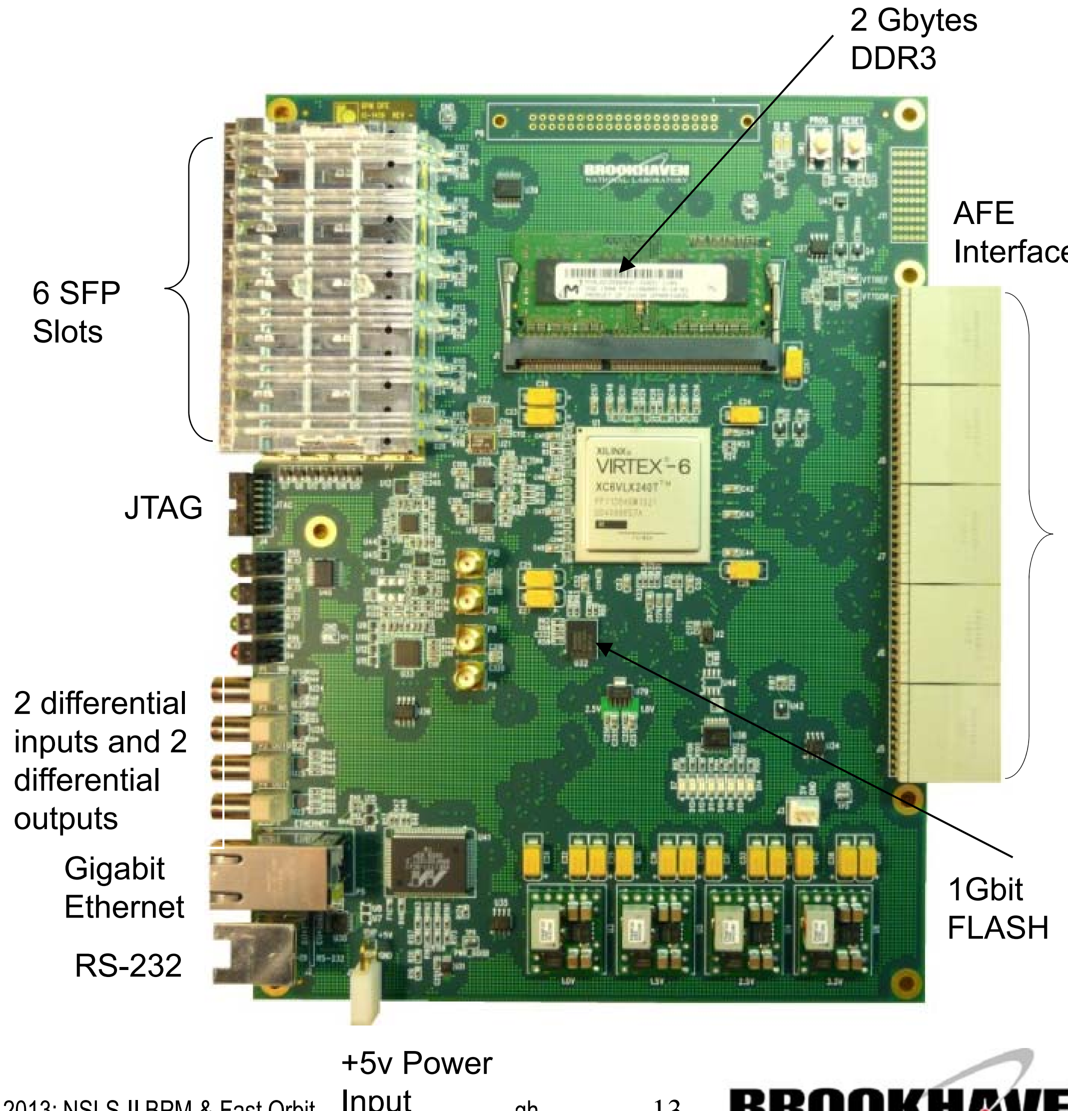
Receiver RF Parameters:

- P1dB = +19dBm (at ADC Input)
- IP3 = +43dBm (at ADC input)
- NF = 5.3dB (dominated by LPF and SAW filter)
- Channel-channels Isolation = 60dB (min)

Digital Front End Board (DFE)

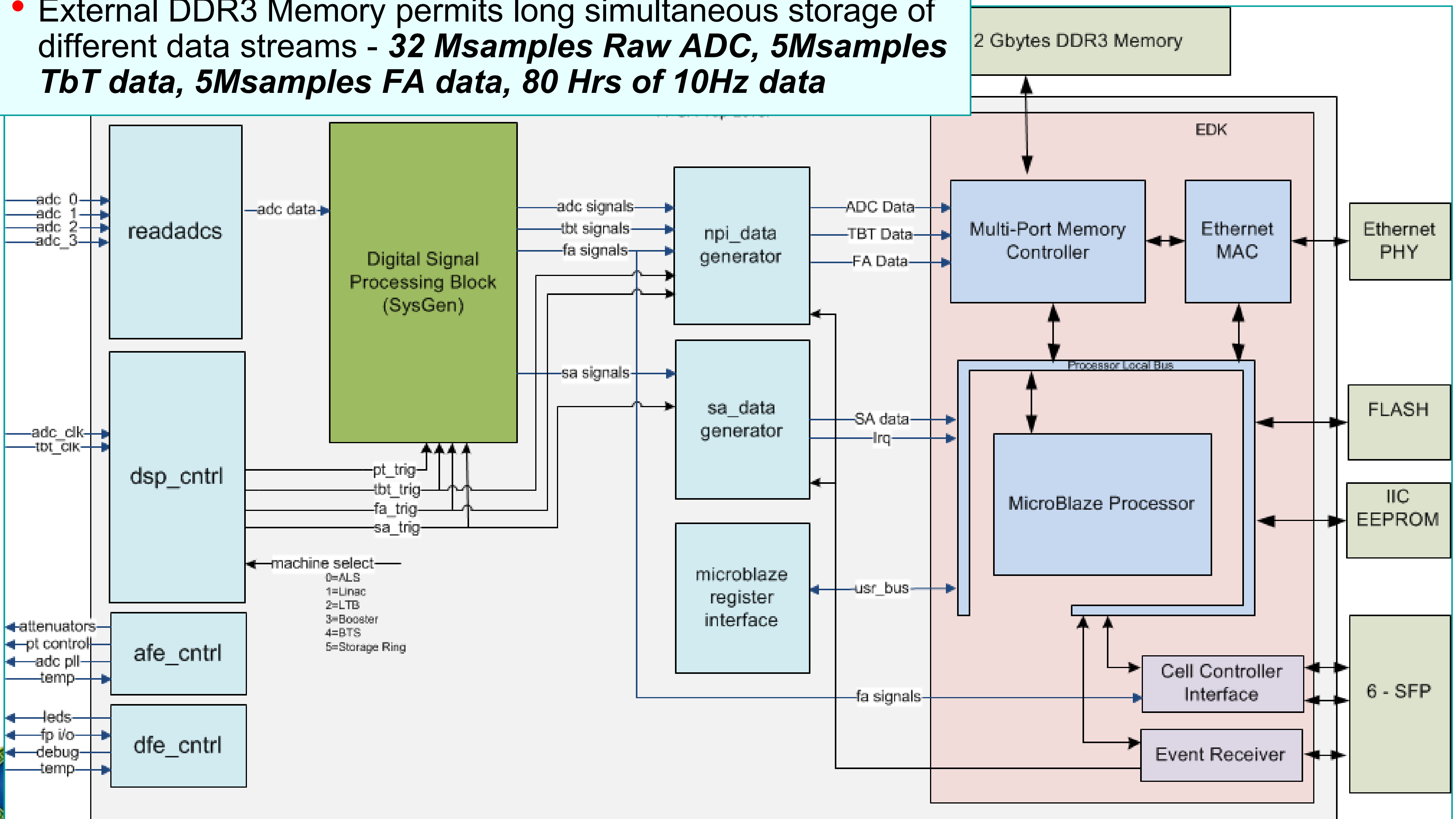
Features:

- Virtex-6 FPGA (LX240T)
- Embedded MicroBlaze soft core µP
  - Xilkernel OS and lwIP TCP/IP stack
- Gigabit Ethernet
- 2Gbyte DDR3 SO-DIMM
  - Memory throughput = 6.4 GBytes/sec
- Six 6.6Gbps SFP modules
  - Embedded Event Receiver
  - Fast Orbit Feedback
- Fixed Point DSP Engine
- 1Gbit FLASH memory
- **Utilized in Cell Controller and FOF processor**
- Currently upgrading to 7-Series Zynq part for Photon BPM
  - Hard 1GHz Dual Core ARM Cortex A9 Processor



System Architecture – DFE FPGA

- FPGA Implemented using a combination of VHDL, Verilog, System Generator (for DSP block) and EDK for Microblaze processor - *Digital Signal Processing implementation using Matlab-Simulink Model Based design flow.*
- External DDR3 Memory permits long simultaneous storage of different data streams - ***32 Msamples Raw ADC, 5Msamples TbT data, 5Msamples FA data, 80 Hrs of 10Hz data***

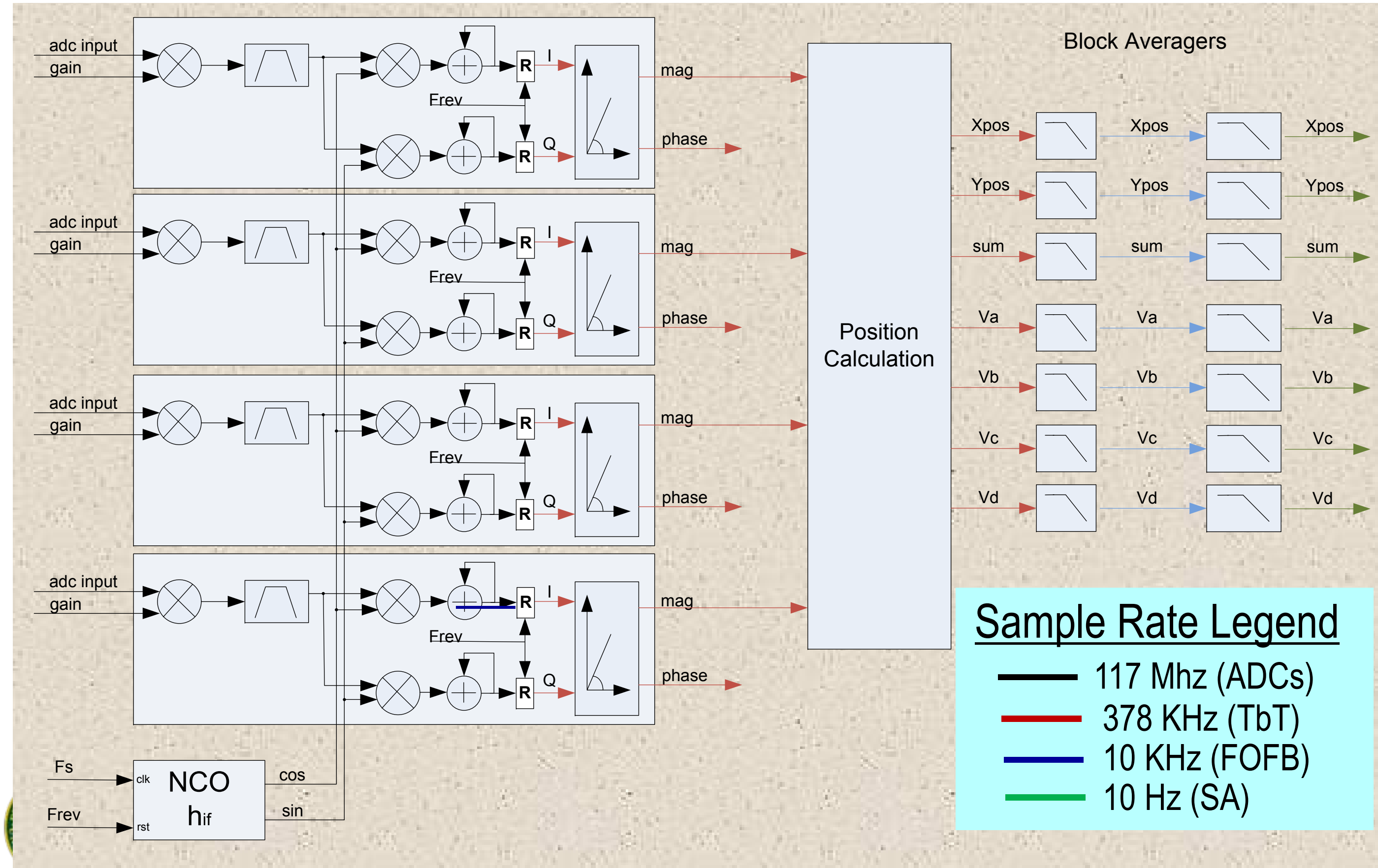


System Architecture – FPGA Signal Processing

- Under-sample 500 MHz RF signal generated by "ringing" band-pass filter.
- Coherent Signal Processing – phase locked to Frev
- "Single bin" DFT position processing at TbT rate

$$X[h_{IF}] = \sum_{n=0}^{hSample-1} x[n] \cdot e^{\frac{-i \cdot 2\pi \cdot h_{IF} \cdot n}{h_{Sample}}}$$

$$n = 0..h_{Sample} - 1$$

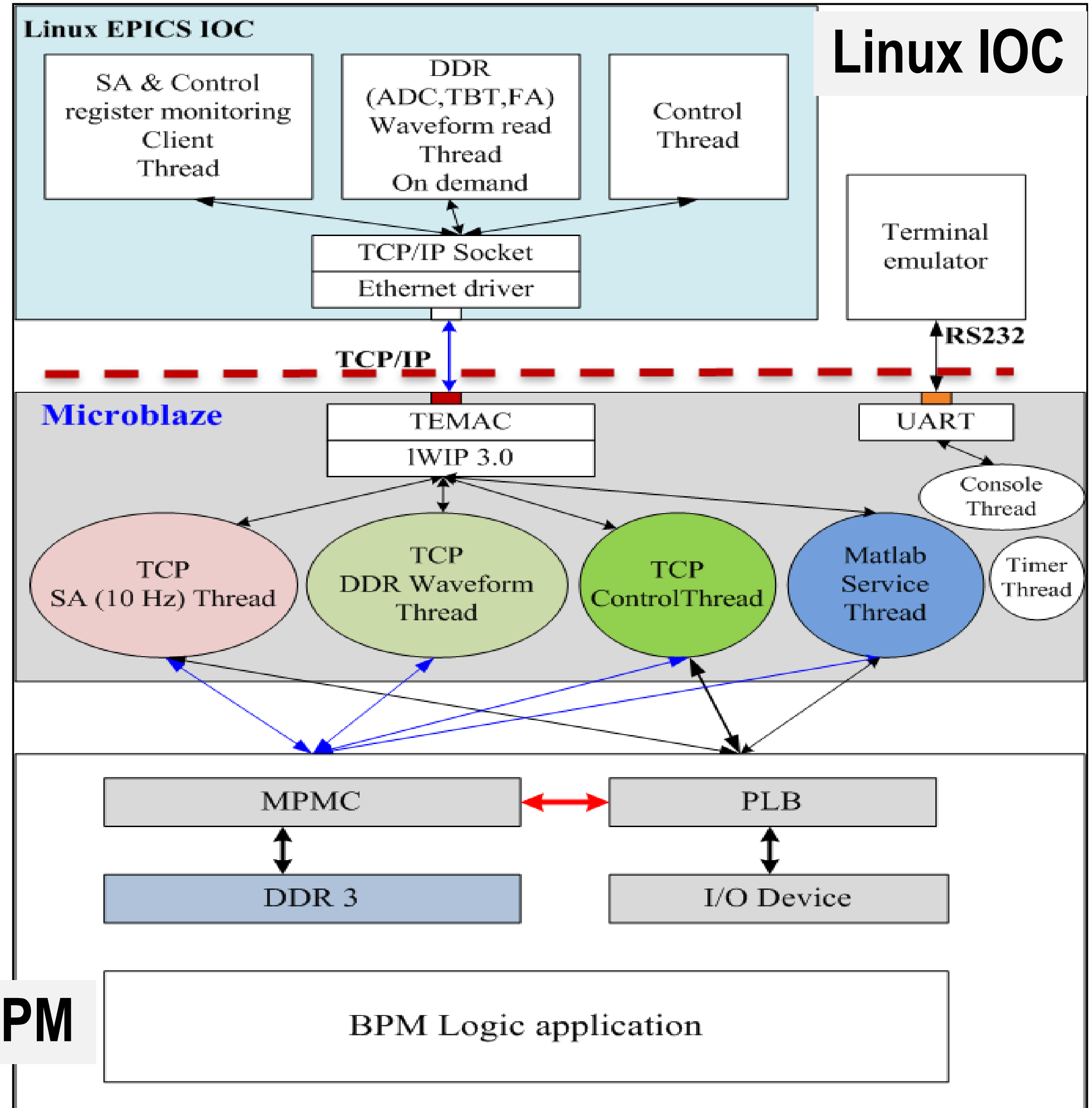


Example numerology:

Parameter	NSLS-II Storage Ring	NSLS–II Booster
Frf	499.68 MHz	499.68 MHz
h	1320	264
hsample	310	62
hIF	80	16

System Architecture – Control System

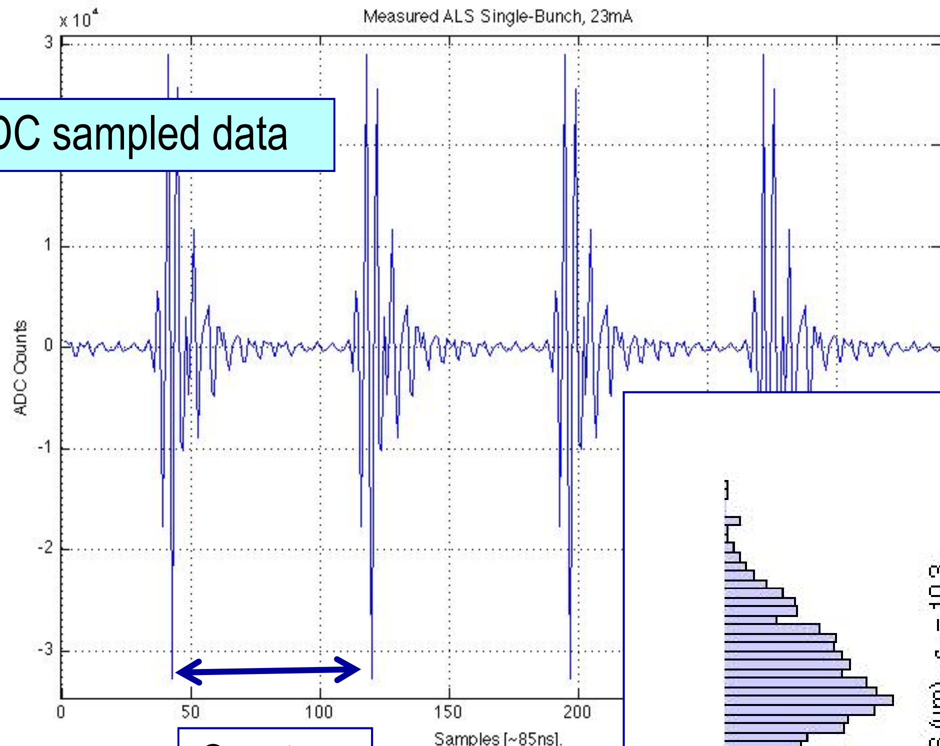
- IOC located outside of BPM in IBM Server
- GigE communication to BPM
- Serial terminal connection to BPM via RJ45
- Embedded Event Link Receiver in FPGA
- FOFB communication using 6Gbps SFP via bidirectional "SDI" Link
- TCP/IP communication via LWIP protocol stack
- Fully developed EPICS drivers
- Simultaneous EPICS and Matlab communication



Virtex-6 BPM

- Performance with beam
- Integrated Tests

BPM Performance – @ ALS (single bunch); 02/2011



ADC sampled data

One turn

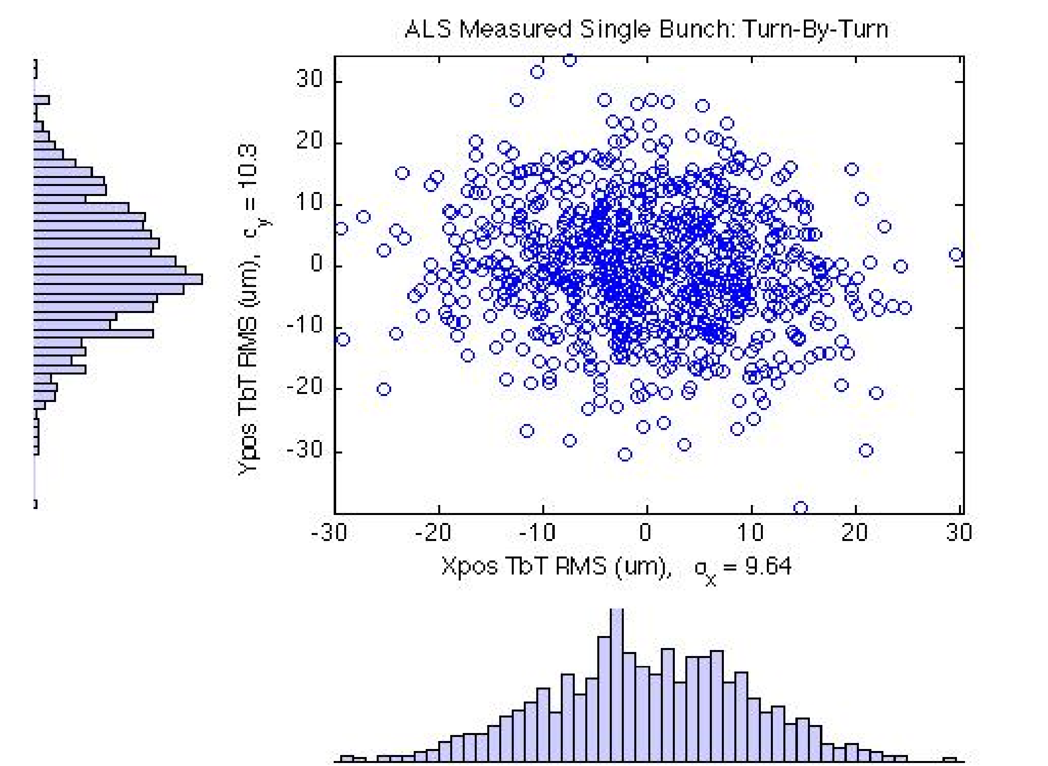
Test set up (Prototype)

- One SR Button to 1-4 splitter
- Splitter output to NSLS-II BPM
- Single bunch; I=23mA (15 nC)

Single bunch resolution

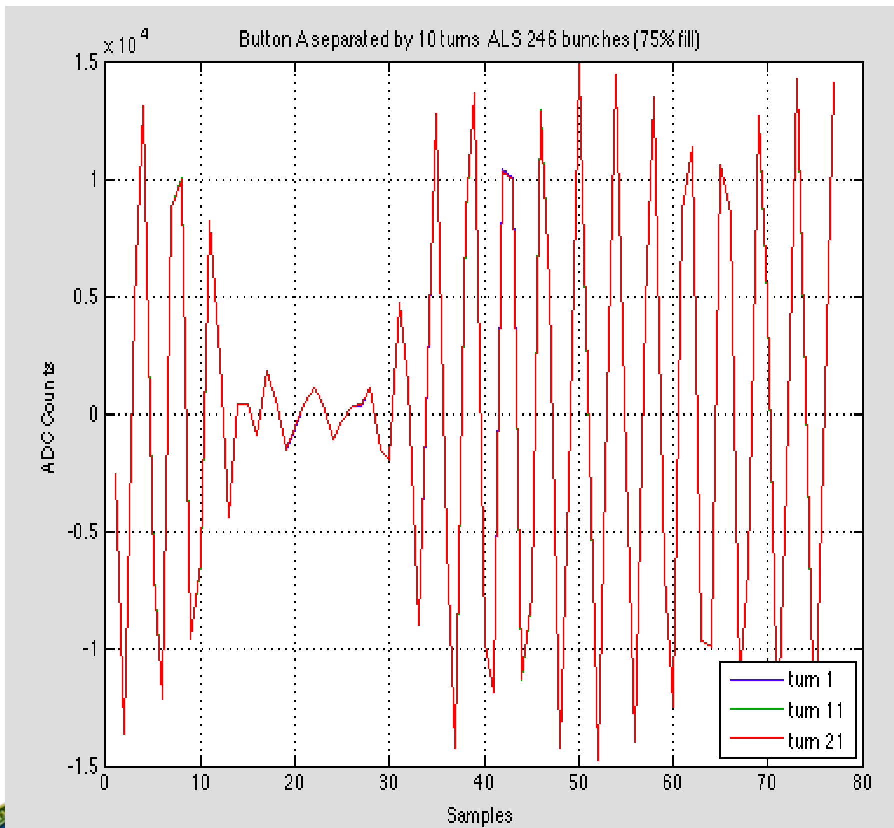
- σ_x = 9.64 microns
- σ_y = 10.3 microns

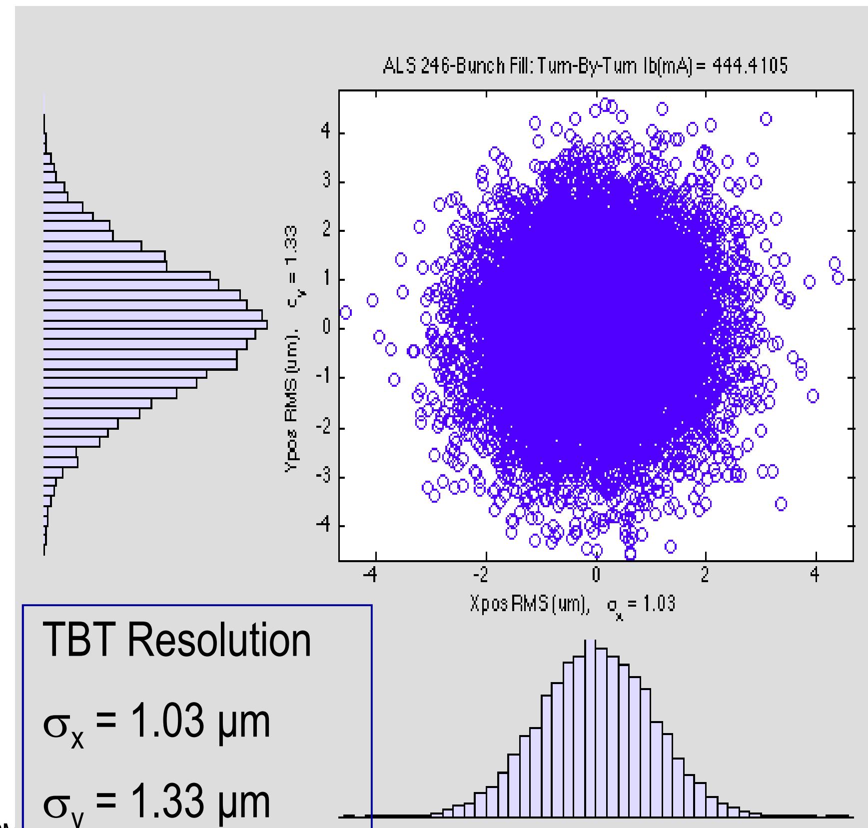
✓ Meets NSLS-II goals



BPM performance - @ ALS (80% fill - 246 bunch-10/2011)

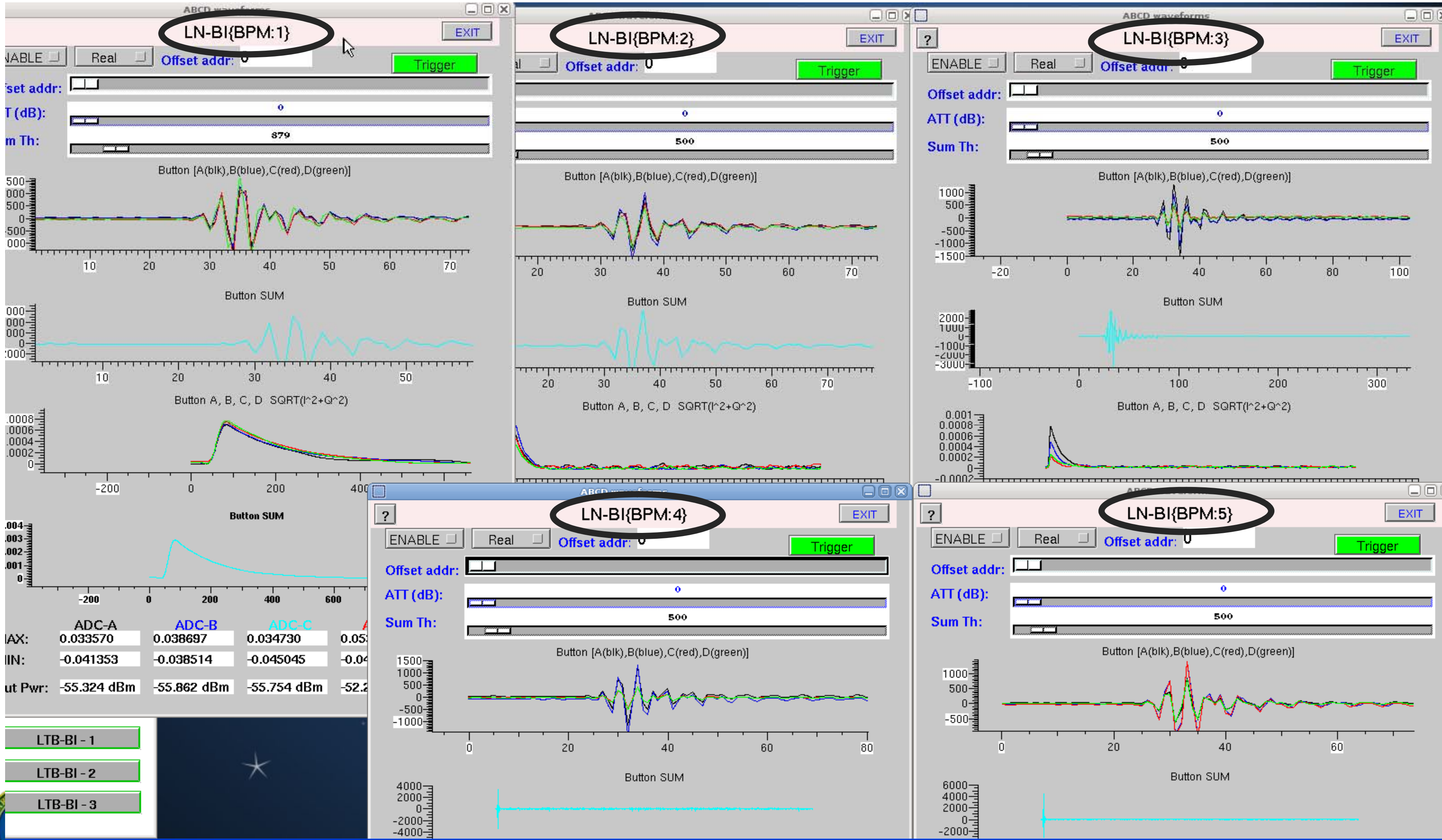
- Analysis of 1-million samples of raw ADC data
  1. NSLS-II RF BPM mounted in ALS rack with 10dB pad on each channel input at BPM
  2. Buttons combined and split in ring to remove beam motion



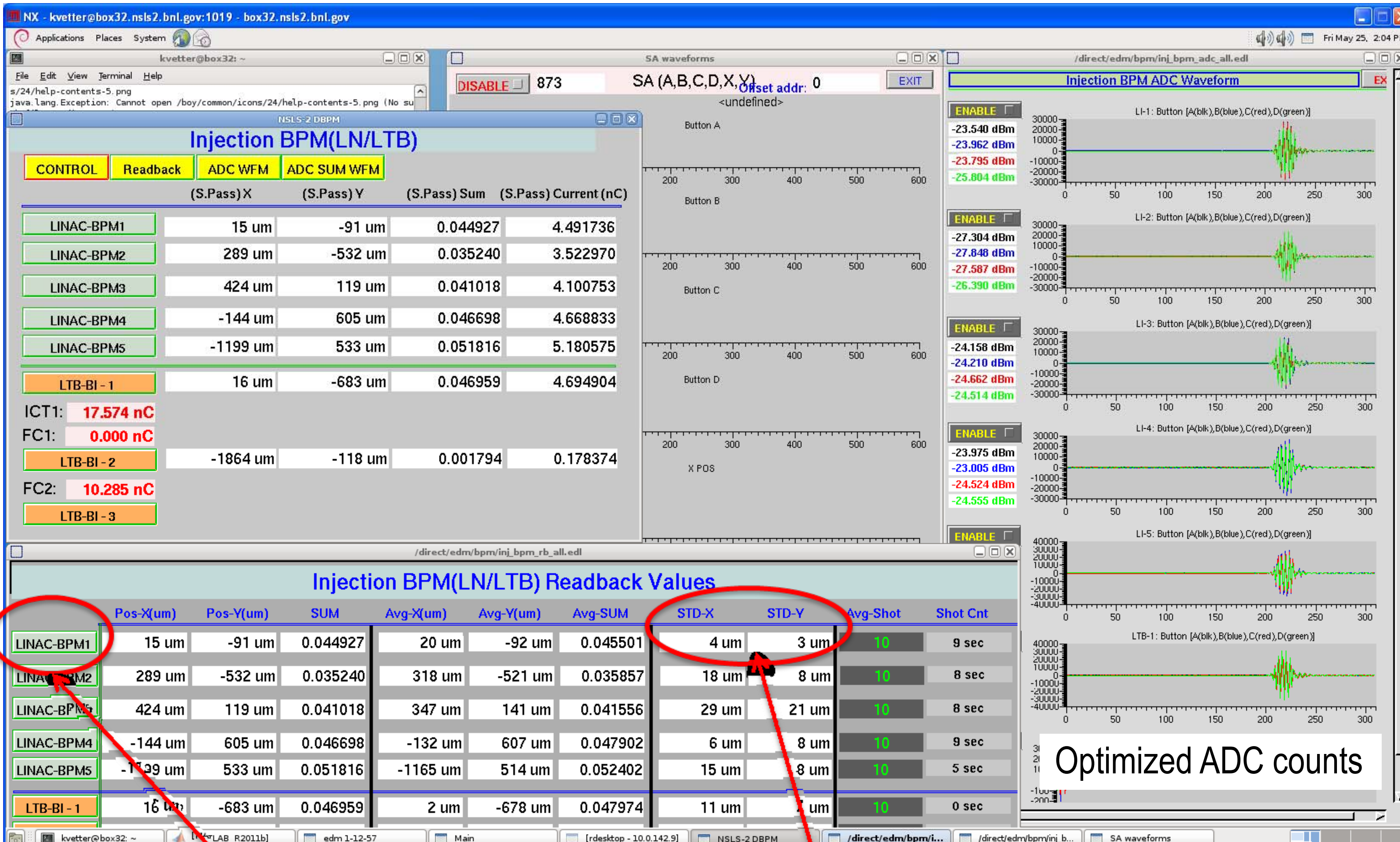


BPM Performance – @ NSLS-II Linac BPMs (04, 2012)

1st measured beam with RF BPM (all 5 LINAC BPMs)
120pC Single-Bunch - ~1200 Peak ADC Counts (4% FS)



BPM Performance - @ NSLS-II Linac multi-bunch 17nC; 5/2012



LINAC BPM1 Configured for "Noise" measurement (i.e. combiner/splitter)

ember

Performance < RMS Spec of 10um

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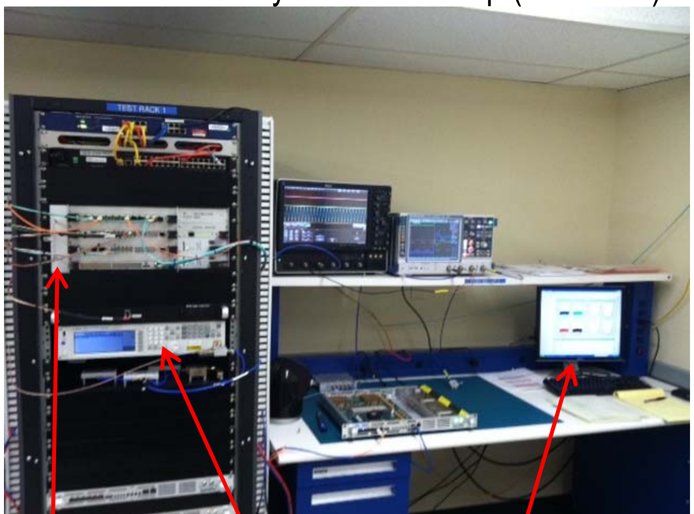
BROOKHAVEN SCIENCE ASSOCIATES

RF BPM Production - Test

RF BPM Laboratory Unit Test Setup (Bench #1)

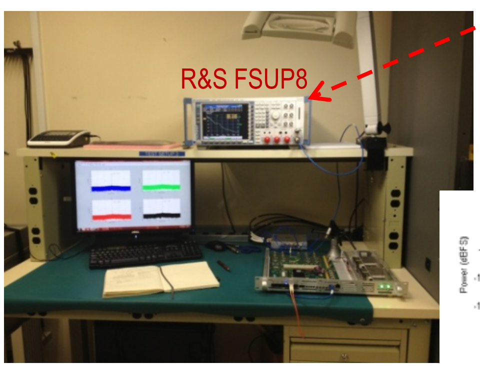


Timing System

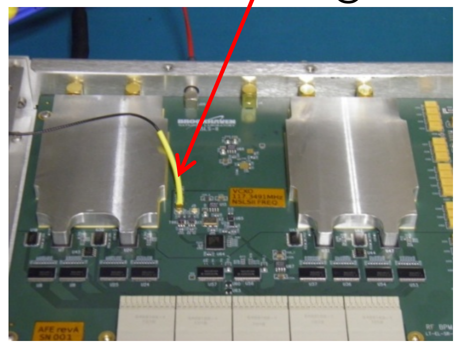
500MHz MO

Matlab – Generate test Report (15min test time)

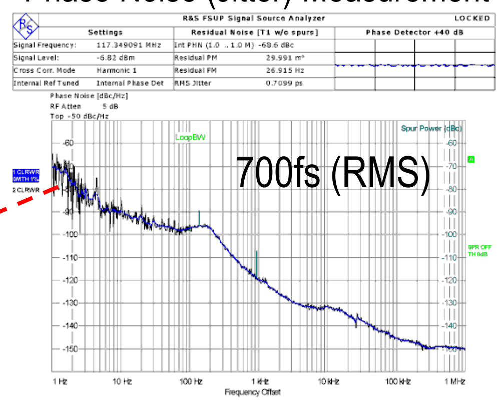
Test Bench #2



Phase Noise Test Port @ ADC

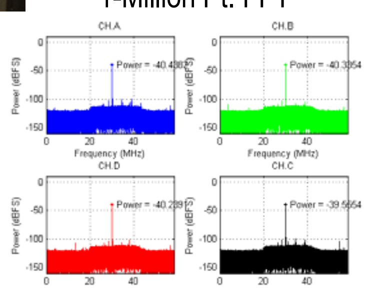


Phase Noise (Jitter) Measurement

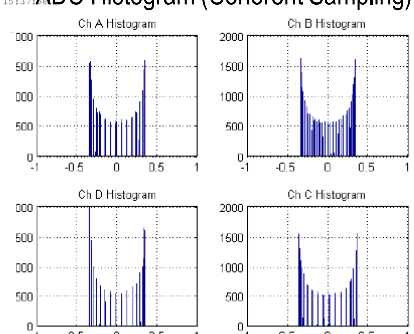


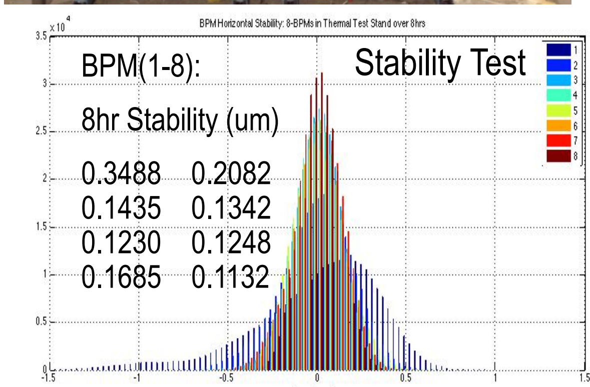
RF BPM Burn-In: “20-units” in Thermal Test Rack

1-Million Pt. FFT



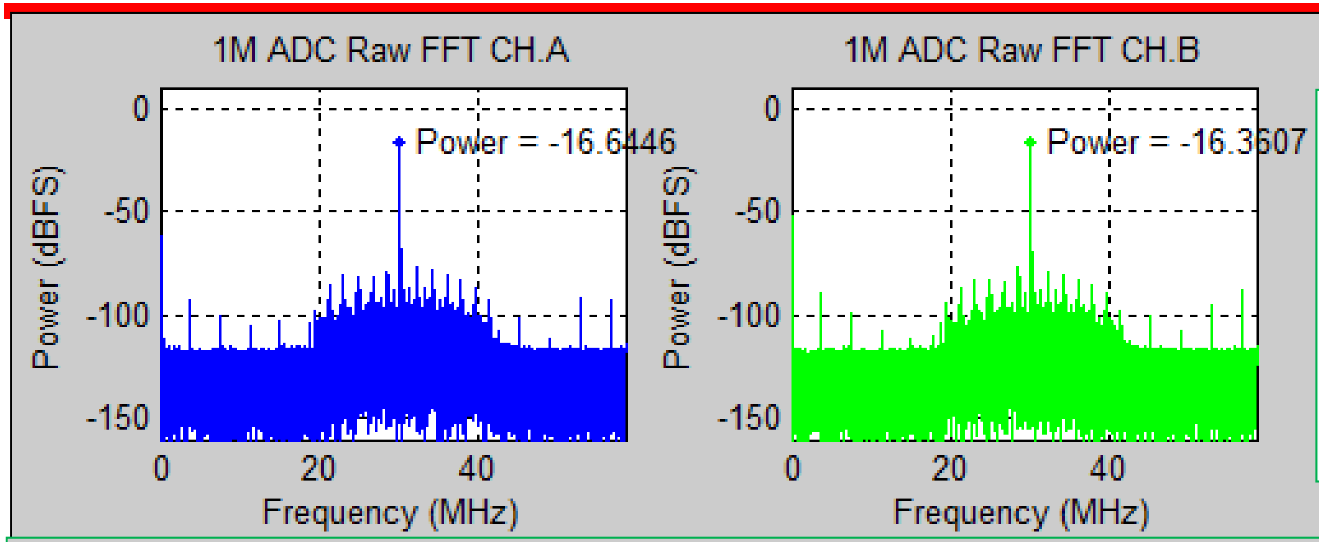
ADC Histogram (Coherent Sampling)



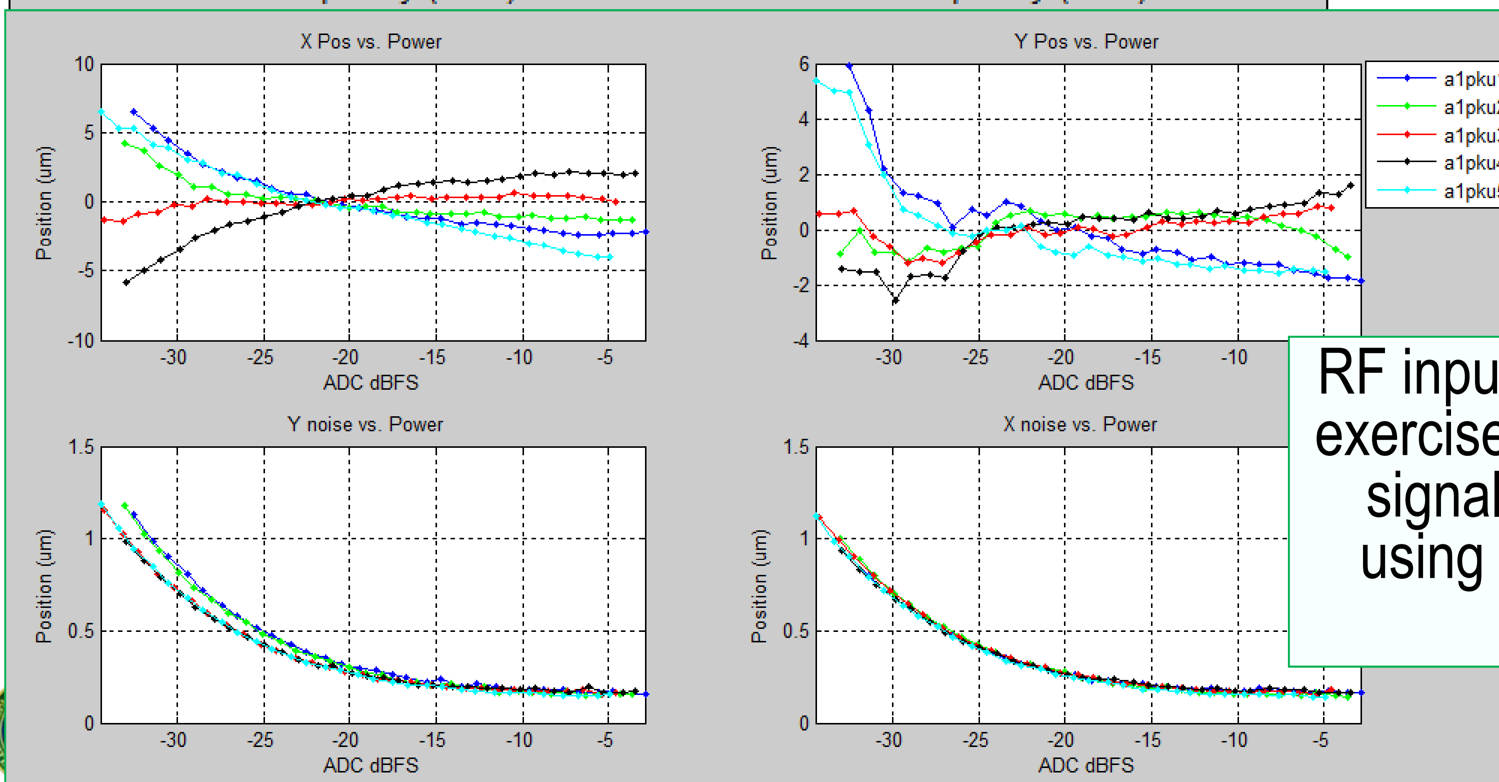


U.S. DEPARTMENT OF ENERGY

In-situ Integration Test using Pilot Tone

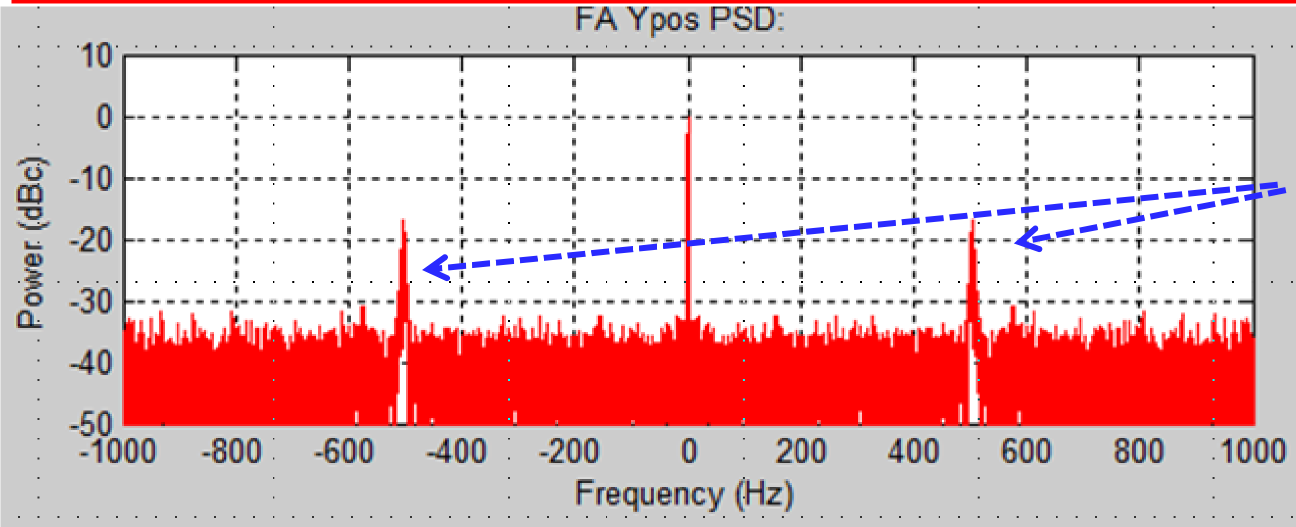


Pilot Tone signal has proved to be an excellent diagnostic tool for bpm health status check w/o beam.

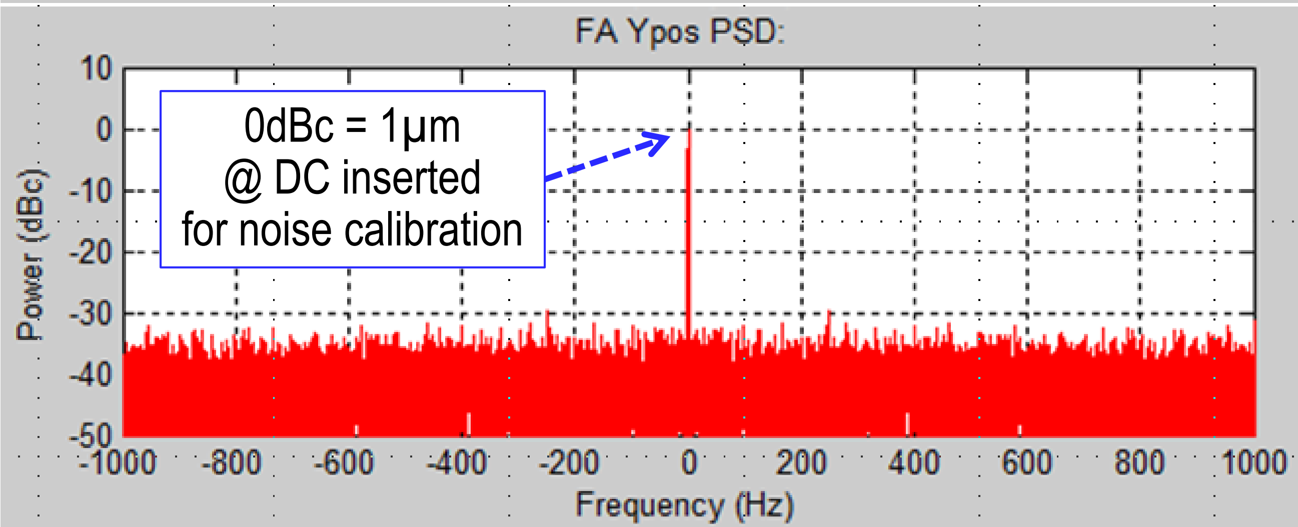


RF input chain can be exercised with various signal drive levels using pilot tone on AFE

In-situ noise observation & mitigation



The 500 Hz spurious signals at ~100 nm level are observed in the FA data spectrum due to noise pickup in AFE from DFE via metal top cover.



The spurious signals have been eliminated after installation of a 4”x6 “ micro-wave absorber onto the top cover.

Fast Orbit Feedback

Kiman Ha
Li-Hua Yu
Yuke Tian

External Noise Sources - Mitigations

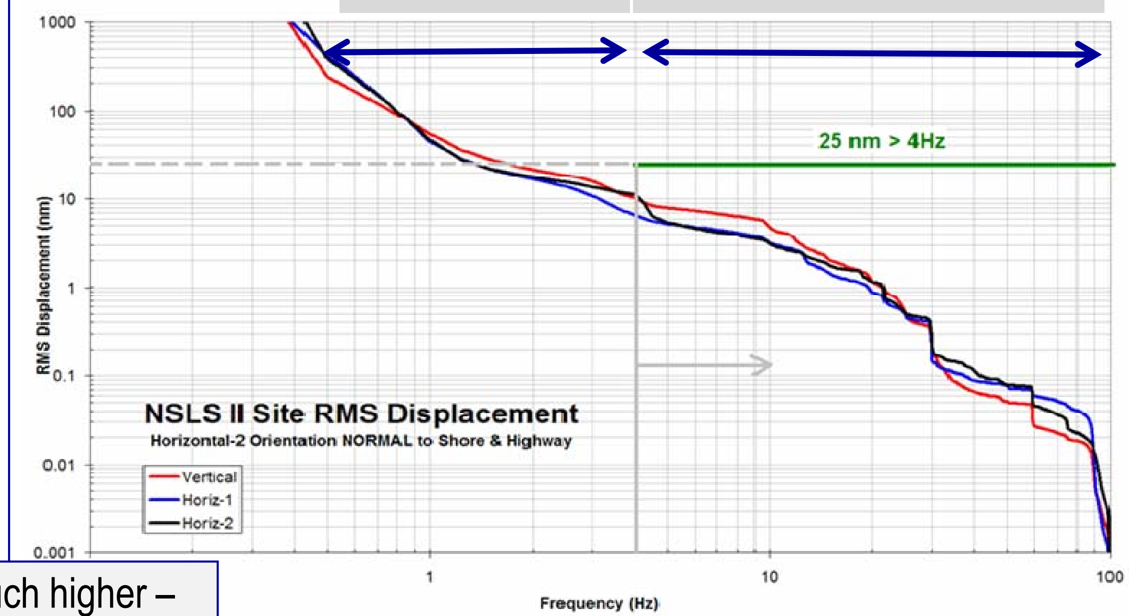
- Magnet & RF system power supply noise / ripple
- Thermal effects (Tunnel air / water temperature)

→ Mitigated by improved design & temperature regulation

- Earth tides – changes circumferences → RF frequency feedback
- Insertion device gap change effects due to magnetic field errors
- NSLS-2 site floor vibration –
  - measured in 2007

A fast orbit feedback system required to suppress noise due to last 2 types of noise sources

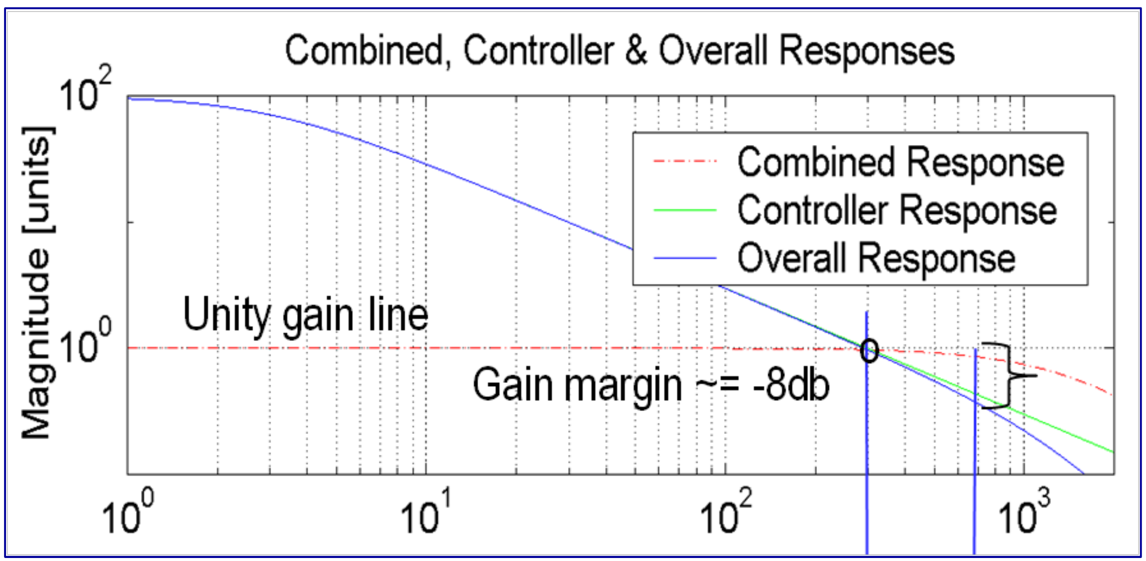
< 200 nm	< 25 nm
0.5-4 Hz	4-200 Hz



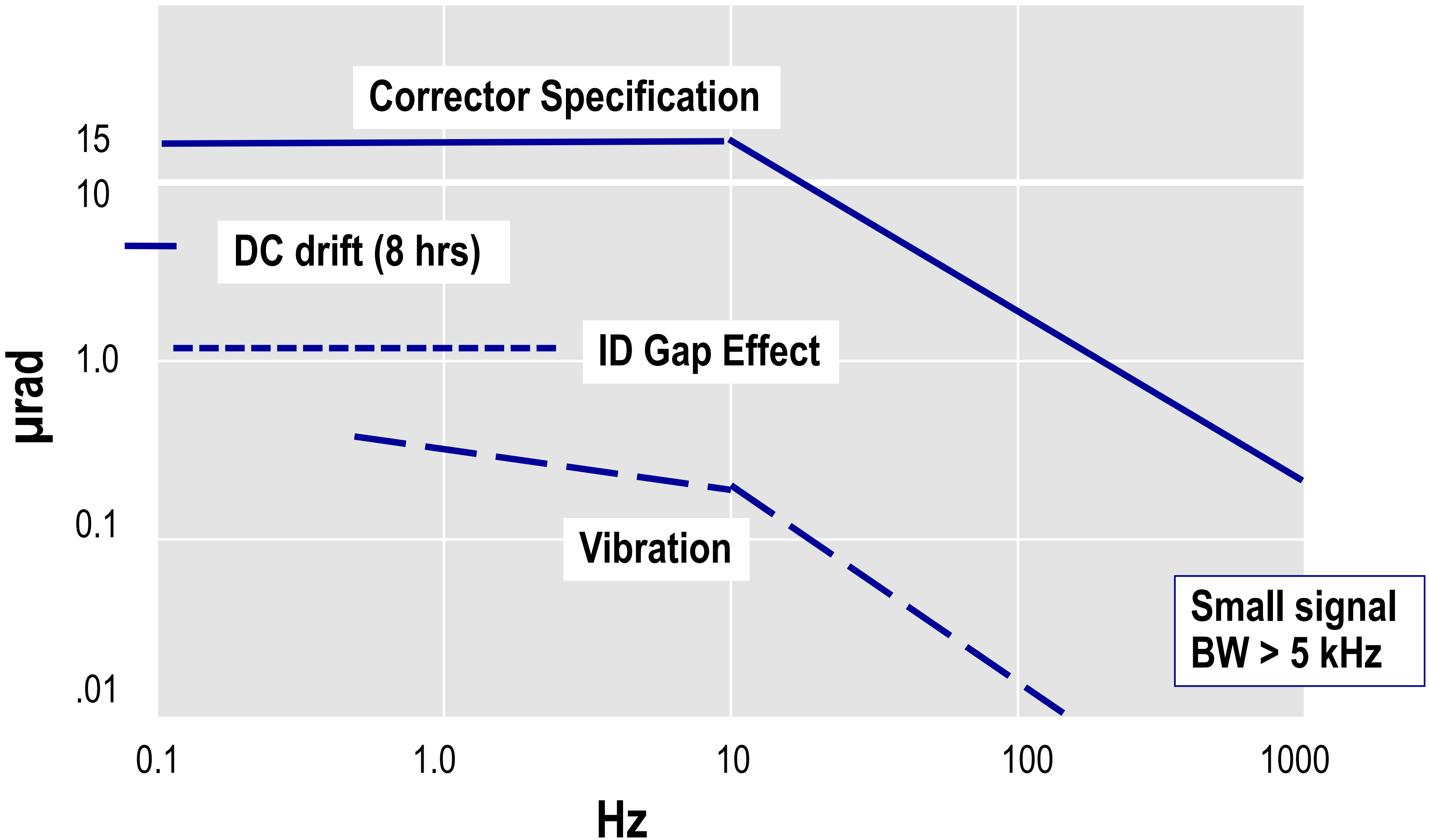
NSLS-II Floor vibration measured in 2013 much higher –
WEPC08 – W. Cheng, Floor vibration measurement

FOF AC Functional Requirements

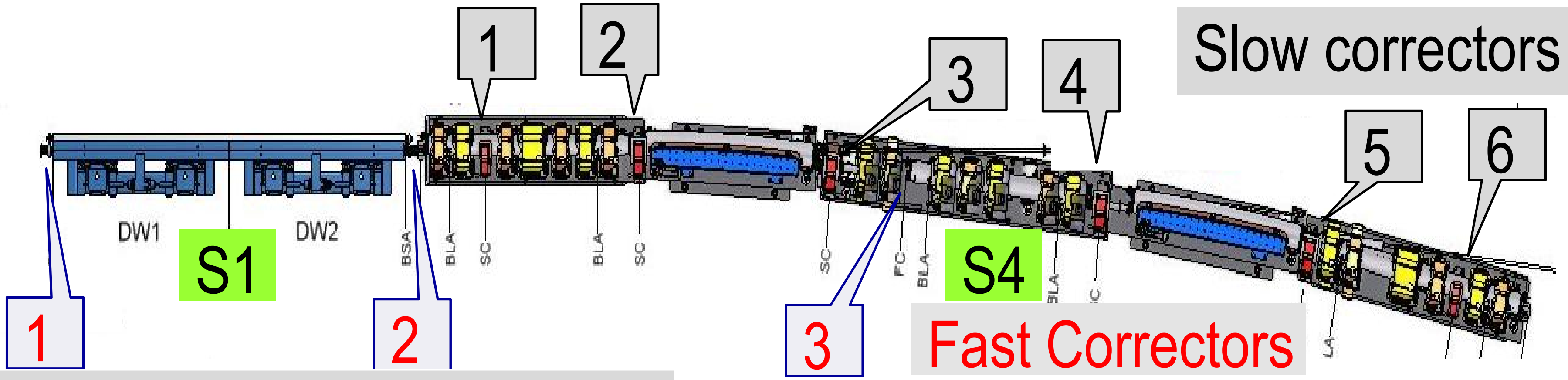
- Noise reduction @ low freq = 100 (DC gain ~= 100)
- Noise reduction @ 100 Hz > 2.5
- FOF gain cross over Frequency = 300 Hz



Fast Corrector Requirement vs Noise Sources



Orbit Correction Magnets

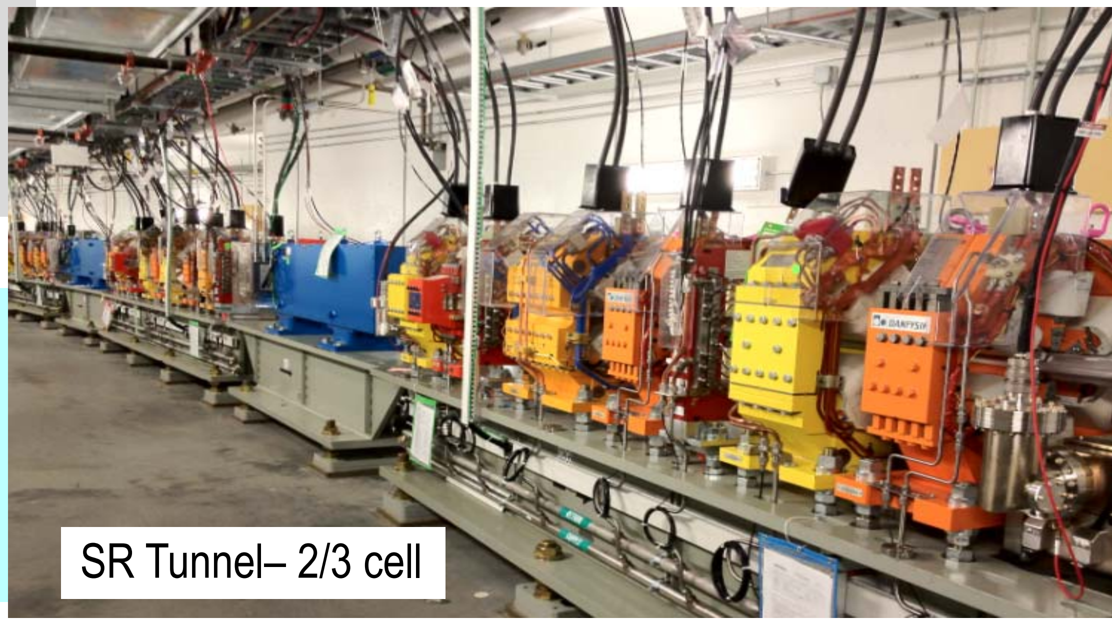


Slow corrector magnets (Qty=6)

- Slow response – 2 Hz
- Strong strength – 800 µrad
- Utilized for slow orbit fdbk

Fast corrector magnets (Qty=3)

- Fast response – 2 kHz
- Weak strength – 15 µrad
- Utilized for fast orbit feedback



SR Tunnel– 2/3 cell

NSLS-II FOFB algorithm – Compensation for each eigenmode

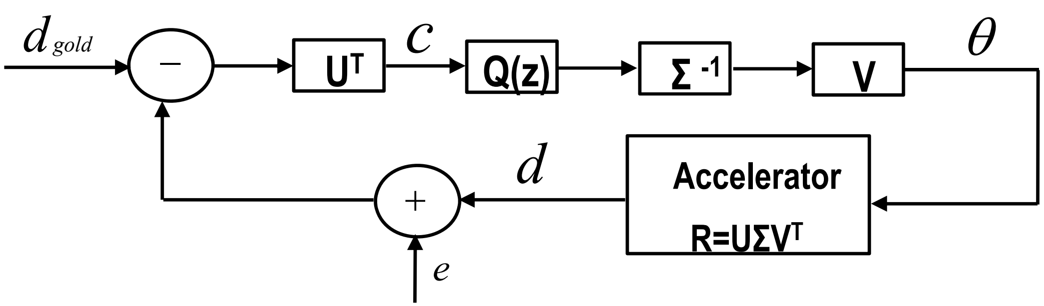
- Fast orbit feedback system is a typical multiple-input and multiple-output (MIMO) system. For NSLS-II, there are 180 BPM readings and 90 fast corrector set points in each plane. The BPMs and correctors are coupled together. One BPM reading is the results of many correctors. One corrector kick can also affect many BPM readings. It is difficult to design a compensator for all noises with different frequencies.

- It is desirable if we can decouple the BPM and corrector relationship so that the MIMO problem can be converted into many single input single output (SISO) problems, for which control theory has many standard treatments.

- Fortunately, SVD already provides a solution: it projects the BPMs input into the eigenspace, where each component is independent. We can design many SISO type compensators (one for each eigenmode) and apply the standard SISO control theory to treat each eigenmode problem in frequency domain without affecting other eigenmodes.

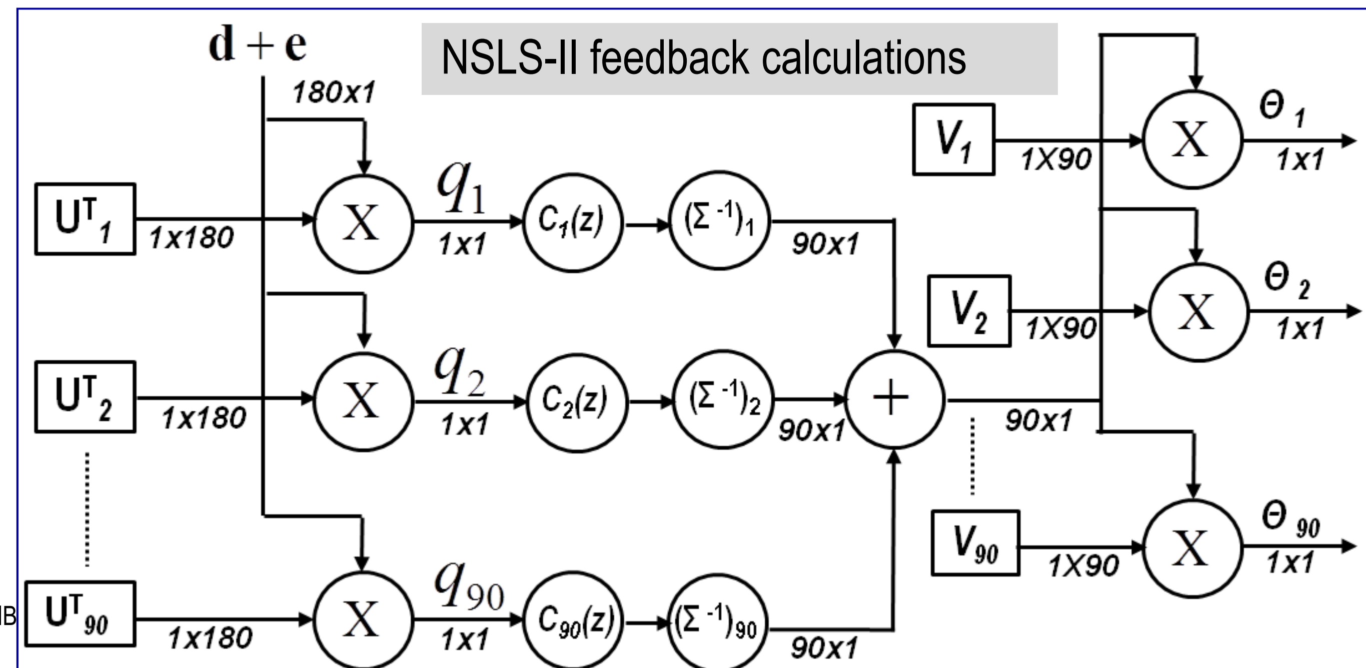
Model and solving the calculation problem

NSLS-II FOFB Model



$$Q(z) = \begin{bmatrix} Q_1(z) & 0 & 0 & 0 \\ 0 & Q_2(z) & 0 & 0 \\ . & . & . & . \\ 0 & 0 & 0 & Q_N(z) \end{bmatrix}$$

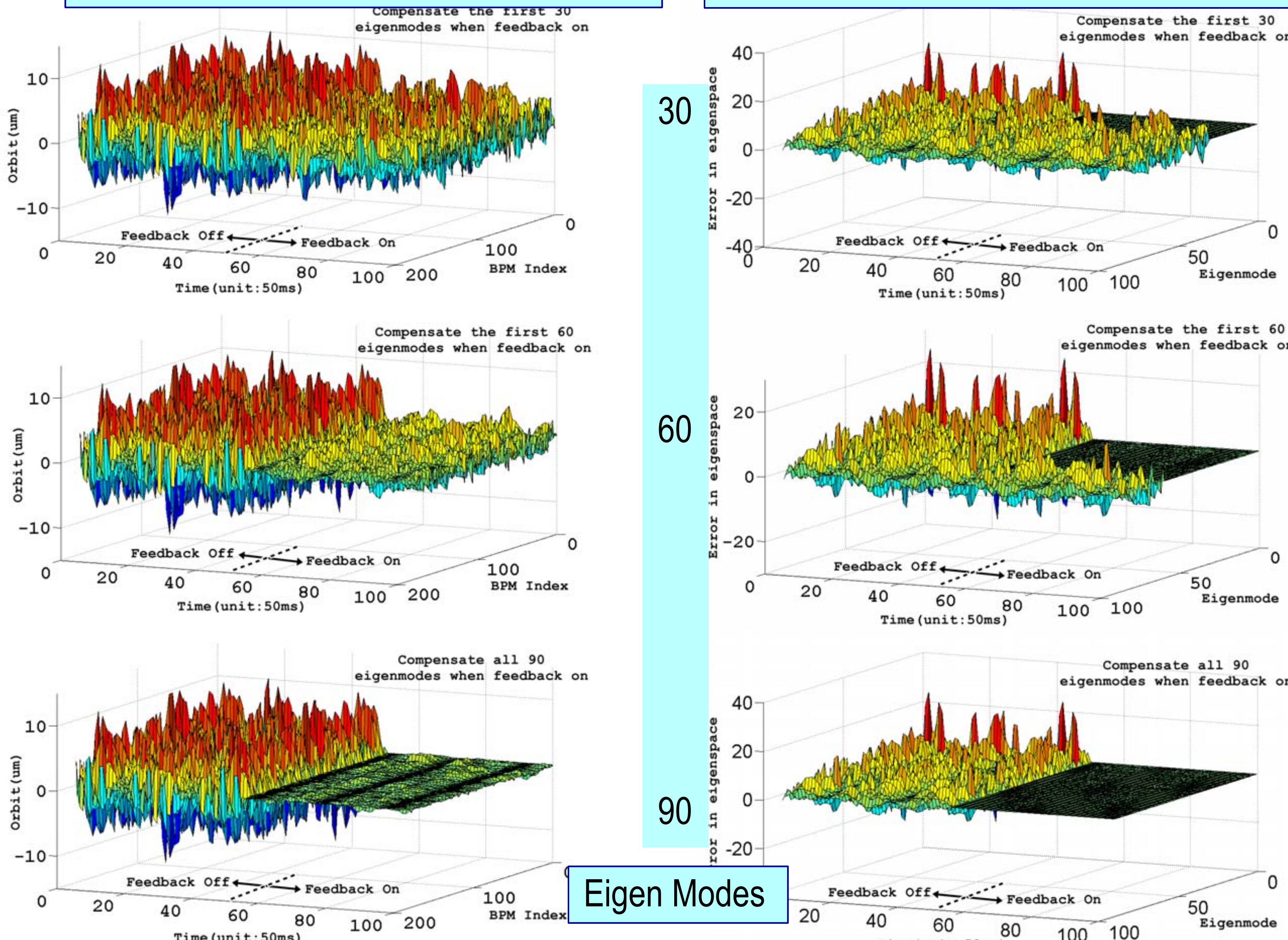
$c_1, c_2, \ldots, c_N$ is the input projections in the eigenspace.
$Q_1(z), Q_2(z), \ldots, Q_N(z)$ is the compensator for each eigenmode.



Simulation of Orbit Feedback results vs # of Eigen Modes

Orbit changes for different compensation

Error in Eigenspace for different compensation

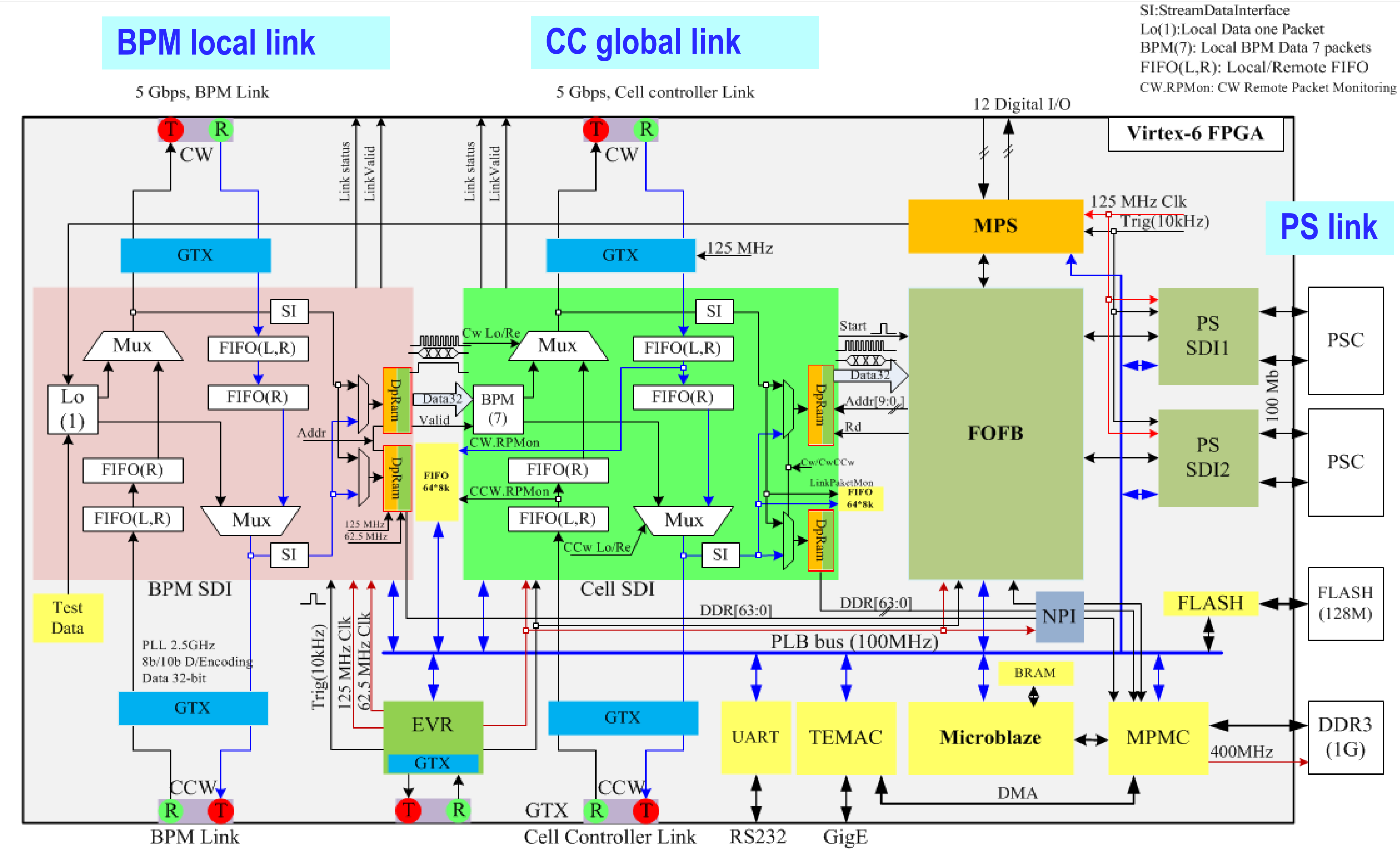


FOFB Key Requirements

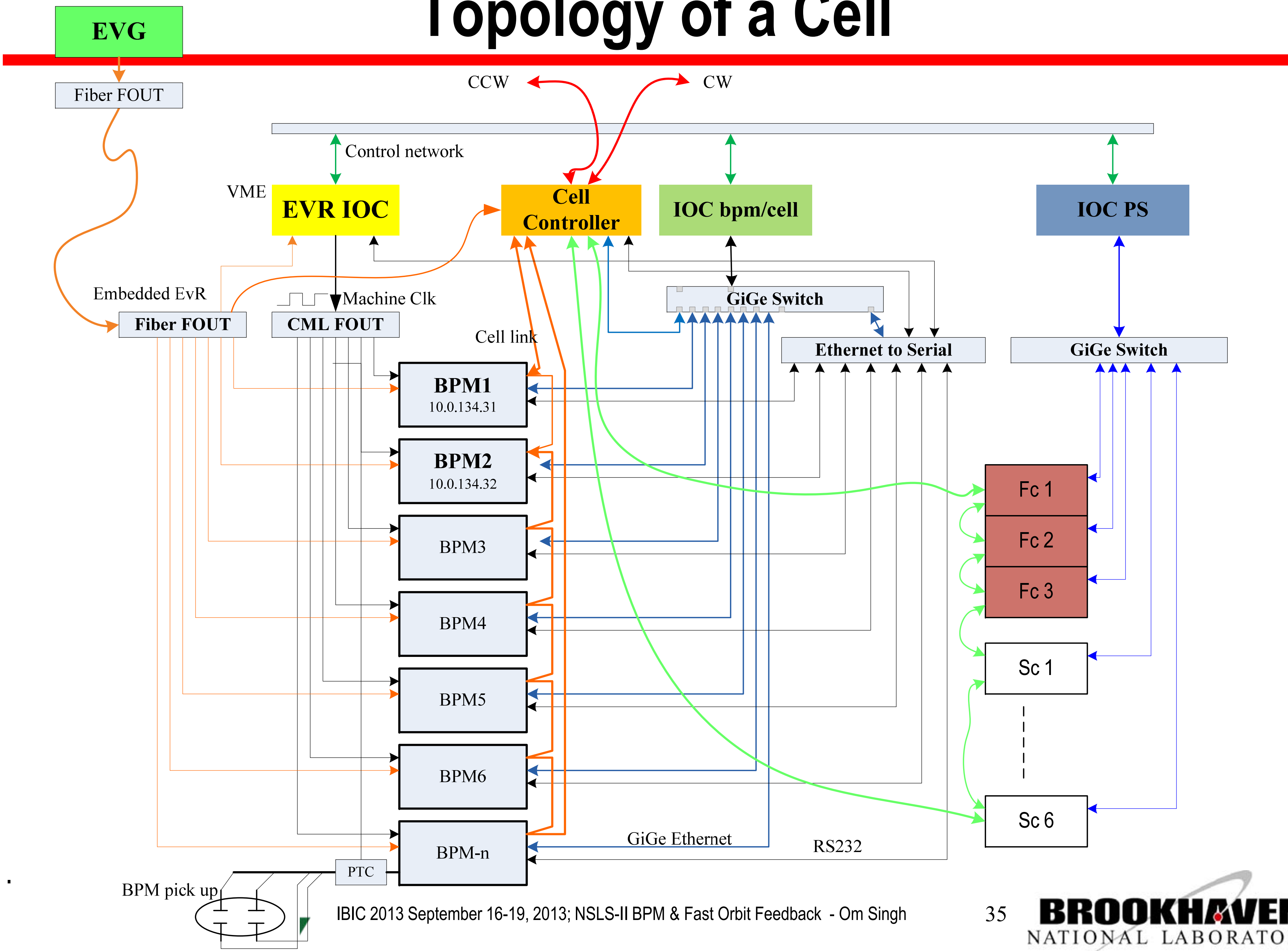
1. Goal is to deliver BPM data to a *place* that orbit calculation module have directly access.
2. Similarly, goal is to deliver corrector setpoint from a *place* that orbit calculation module have directly access.
3. It seems we need a *place* that can:
   → Receive local BPM data;
   → Tx/Rx BPM data to/for other cell;
   → Carry out FOFB calculation;
   → Tx corrector setpoints to PS control system.

A Cell Controller is designed for this purpose

Cell Controller Architecture



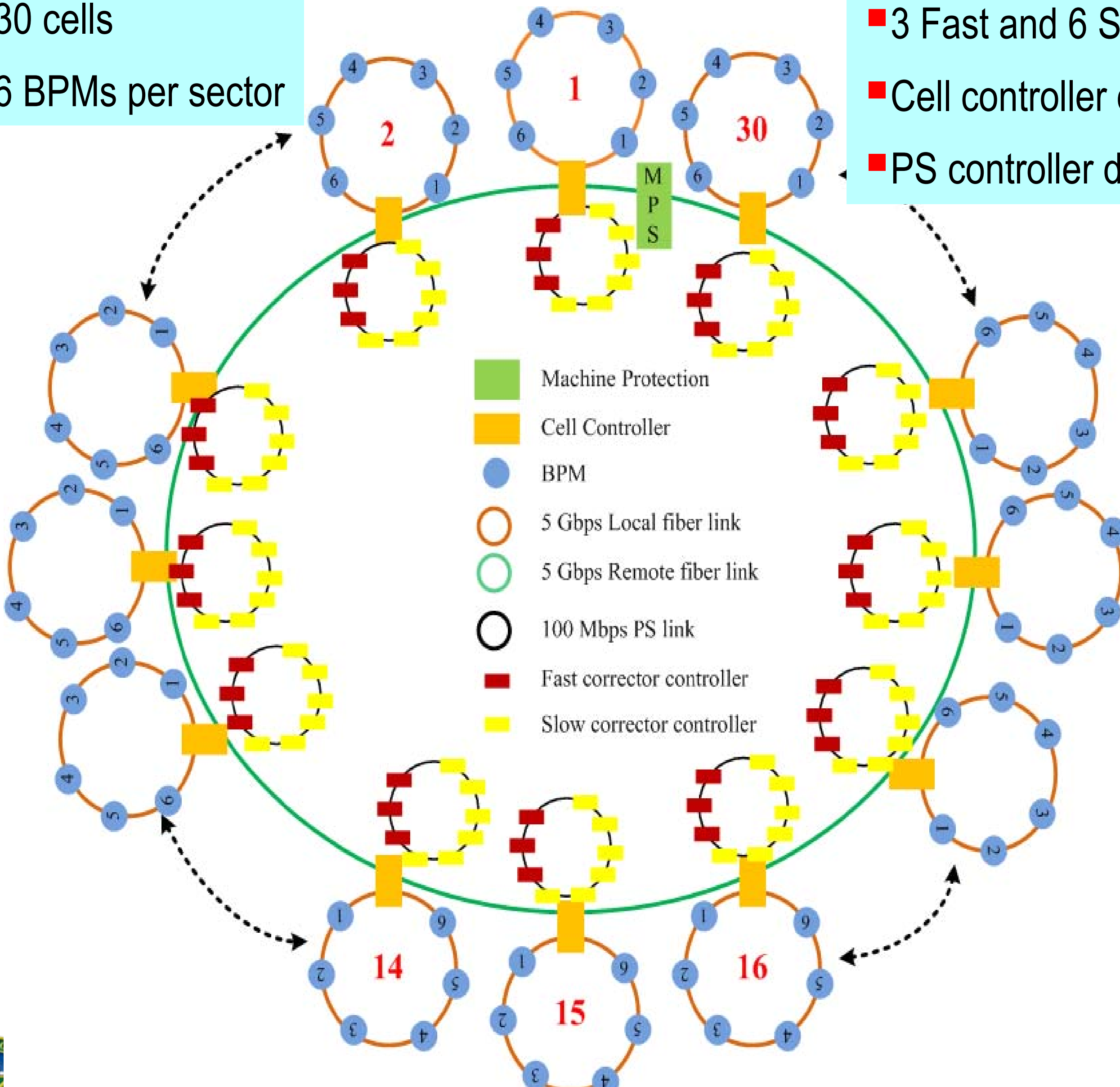
Topology of a Cell



Topology of the FOFB network

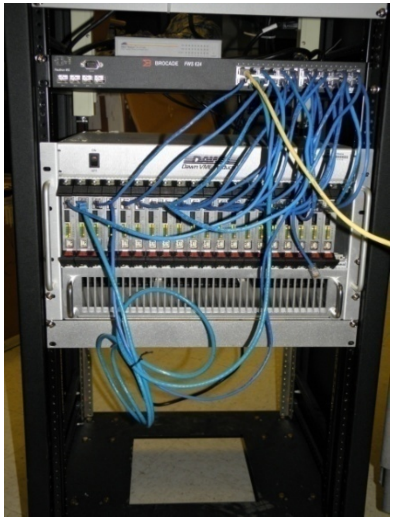
- 30 cells
- 6 BPMs per sector

- 3 Fast and 6 Slow H/V correctors per sector
- Cell controller distribution takes 15 us
- PS controller distribution takes 5 us

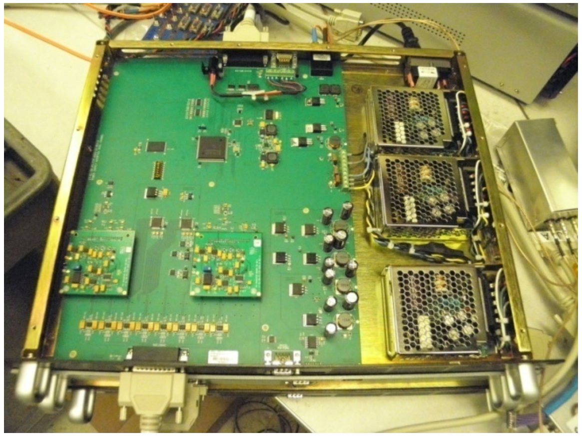


Power Supply Controller & Interface Hardware

PSC – power supply controller

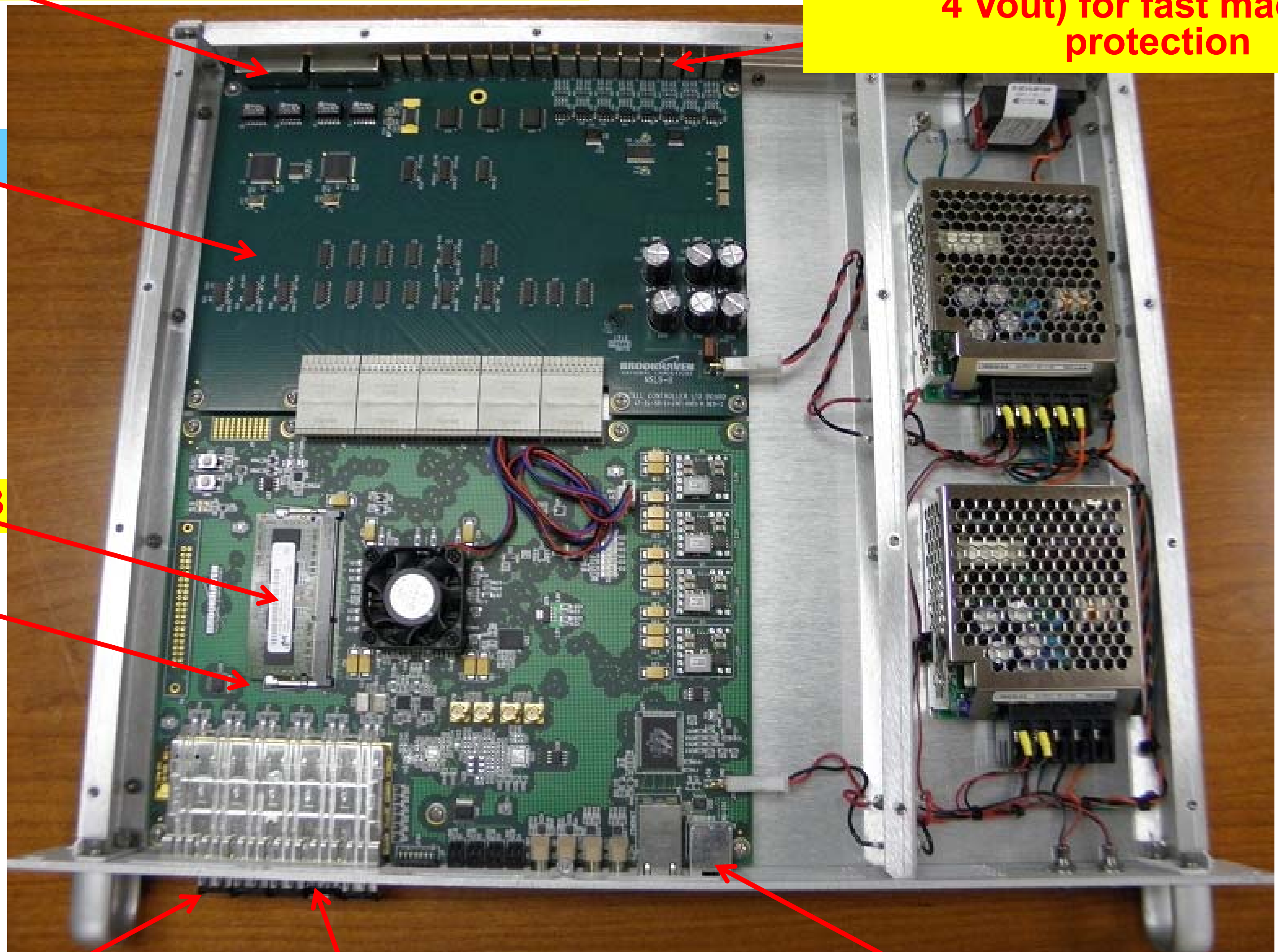


PSI Crate



PSI – power supply interface

Cell Controller Hardware



NSLS-II Fast Orbit Feedback Status

- The hardware design (PCB, chassis) for cell controller and PSC are all done. The production units are being installed in the storage ring.
- PSC, FPGA firmware, EPICS drivers and database development are all done.
- All cell controller blocks (SDI, FOFB etc) are all done. The cell controller integration is in progress.
- Since we have the fast fiber SDI to deliver data around the ring, cell controller's SDI link will also be used as fast machine protection system that deliver critical system (such as the vast valve signal from vacuum system) around the ring within much less than 1ms. This latency is impossible for PLC to achieve.

Summary – RF BPM

- RF BPM detector and support optimization carried out successfully
- The Multipole vacuum chamber RF buttons (LA) installed
- Insertion device RF buttons (SA) production unit delivery this month
- The RF BPM electronics
  - Injector installation/ integration completed
  - SR installation completed; integration to complete by 11/2013
- Performance results with beam at ALS & NSLS-II Linac/ Ltb are encouraging
- Commissioning/ plan
  - Linac/ Ltb transport line commissioning completed successfully on 5/2012
  - Remaining injector commissioning to start on 11/2013
  - SR commissioning to start on 3/2014

Summary - FOFB

- NSLS-II's stringent emittance requirements need a efficient fast orbit feedback system. The two tier communication structure and the FPGA-based fast orbit feedback calculation architecture is designed for achieve the requirements.
- Algorithm with individual eigenmode compensation is proposed. The typical MIMO feedback problem is converted into many SISO problems. This algorithm enables accelerator physicists to correct the beam orbit in eigenspace.
- We compared the calculations for FOFB with and without individual eigenmode compensation. We found that the proposed NSLS-II FOFB algorithm needs a large amount of calculations. However, benefited from NSLS-II FOFB architecture, the challenge can be conquered.
- We expect a successful application of the NSLS-II FOFB algorithm during the NSLS-II commissioning and daily operation.

Acknowledgments

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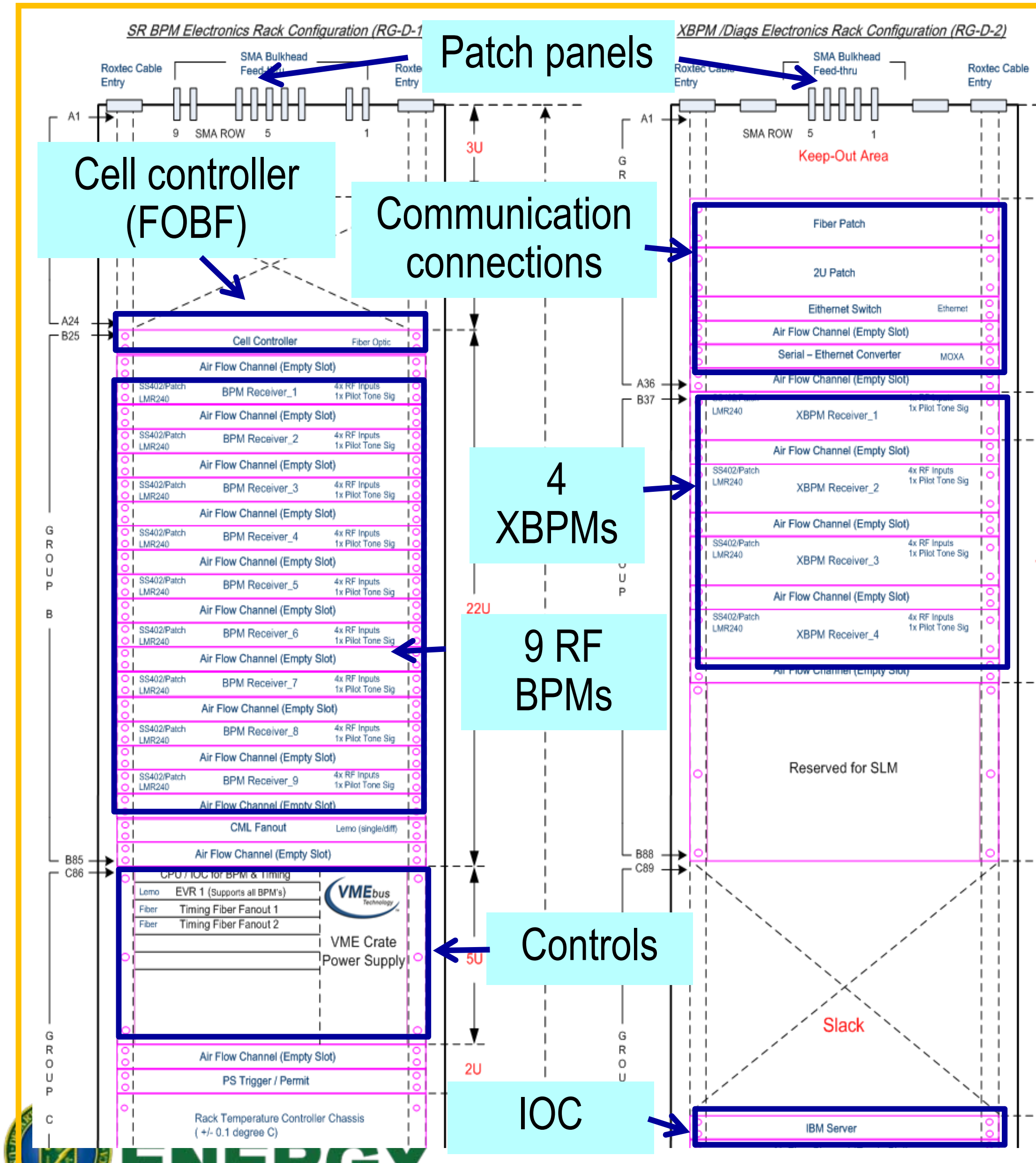
Collaborators – Mike Chin (LBNL), Greg Portman (LBNL), J. Sebek (SLAC), Jonah Webber (LBNL)

Thank you for your kind attention.

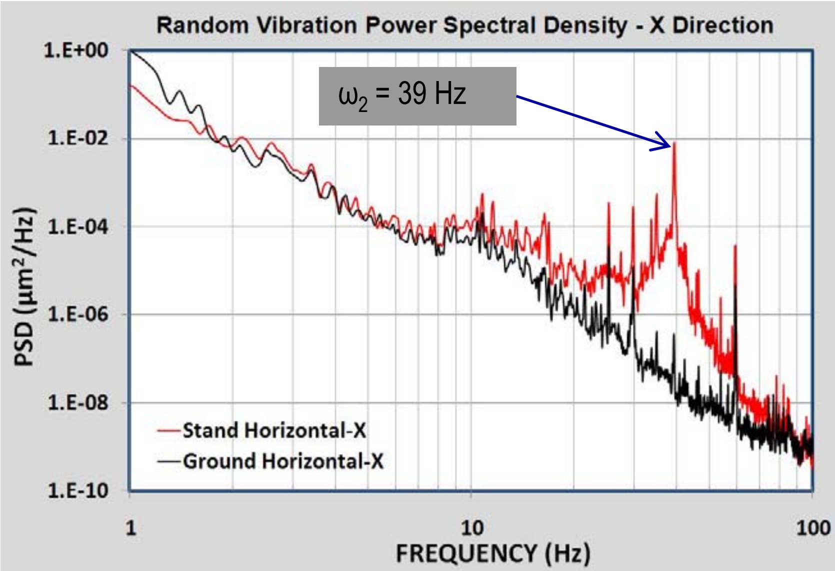
NSLS-II BPM & Fast Orbit Feedback

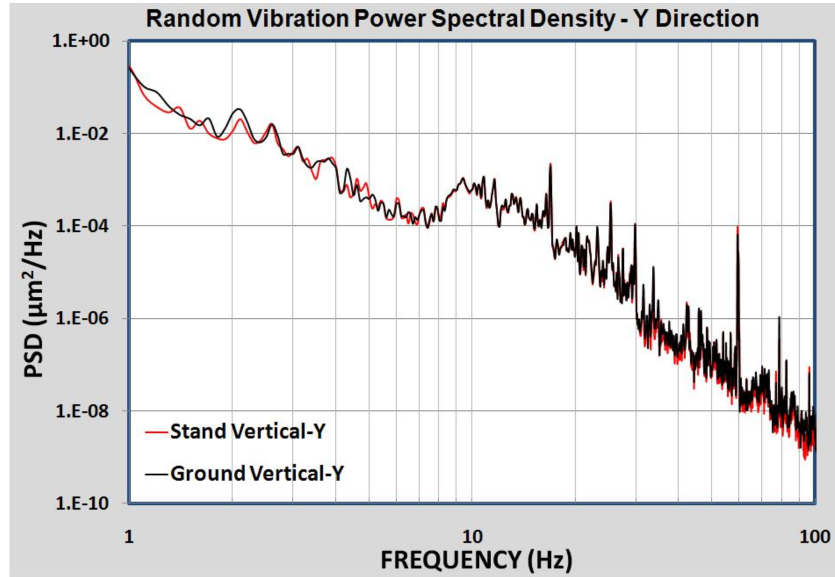
Om Singh
NSLS-II Instrumentation
IBIC2013, SBS, Oxford, UK

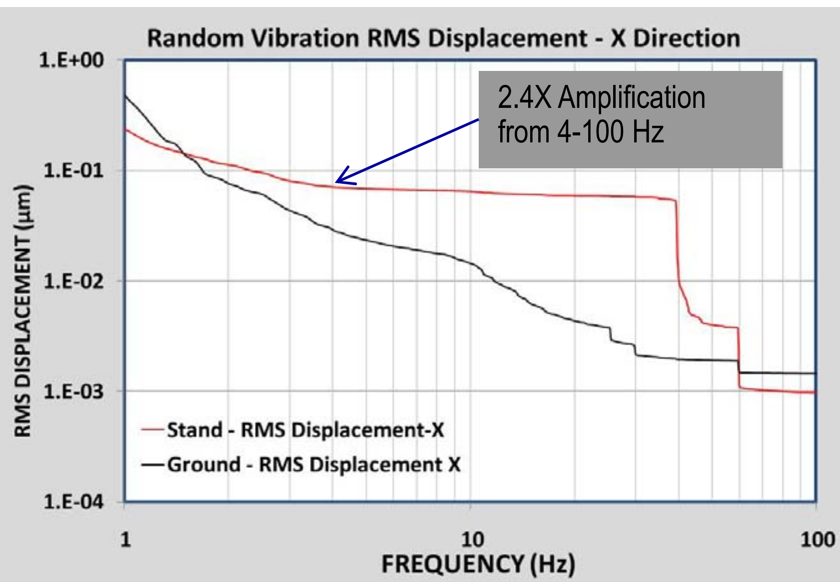
One Cell BPM/ Controller Rack

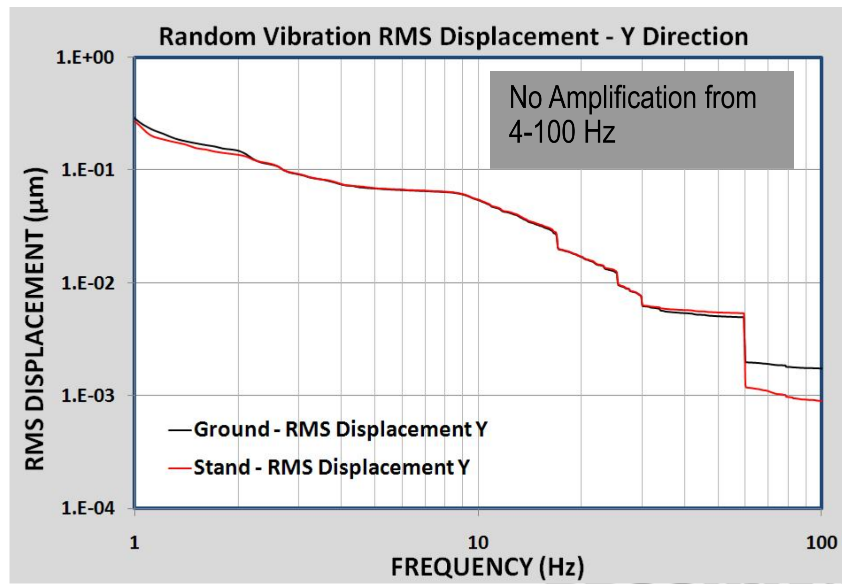


Vibration Test Results

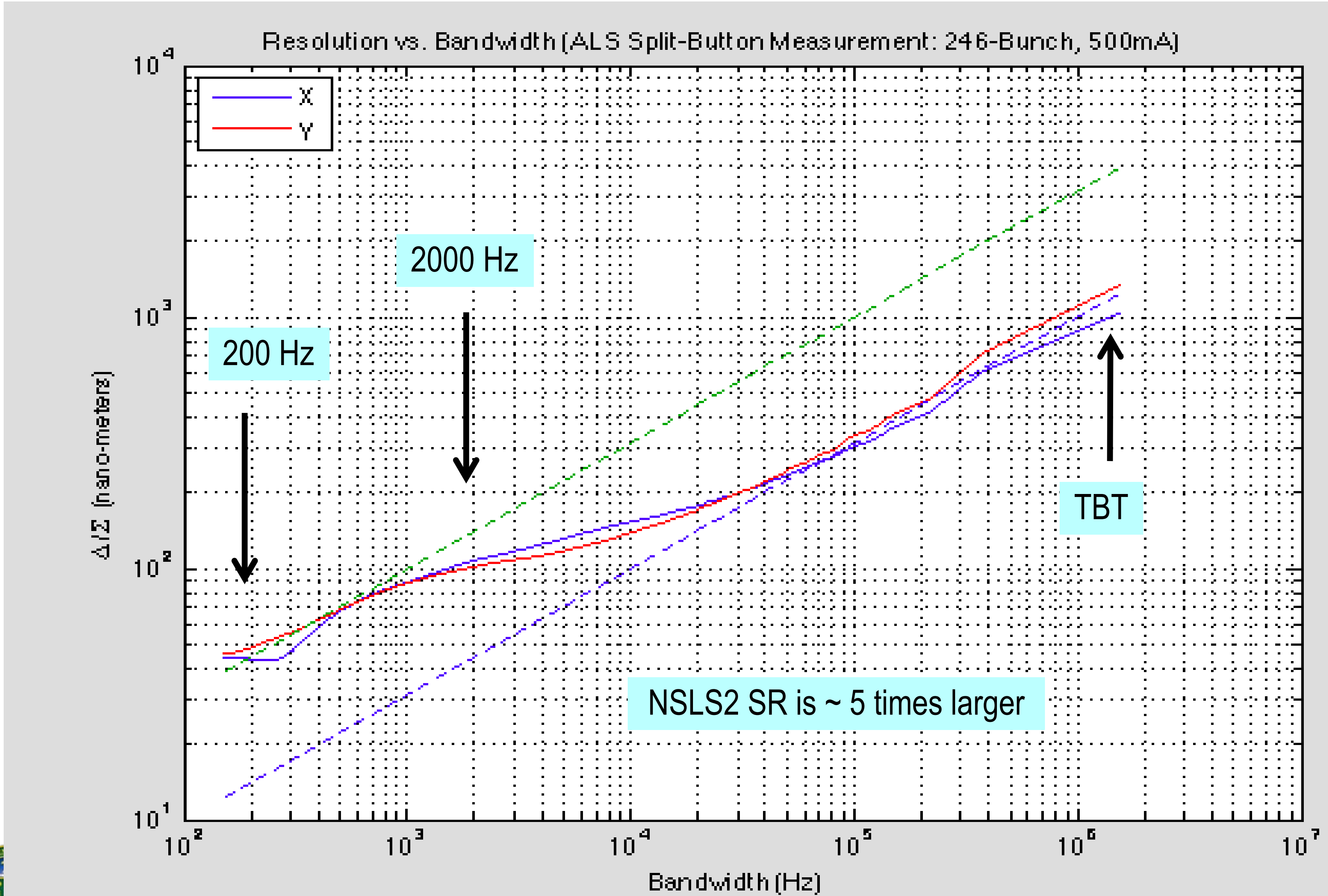




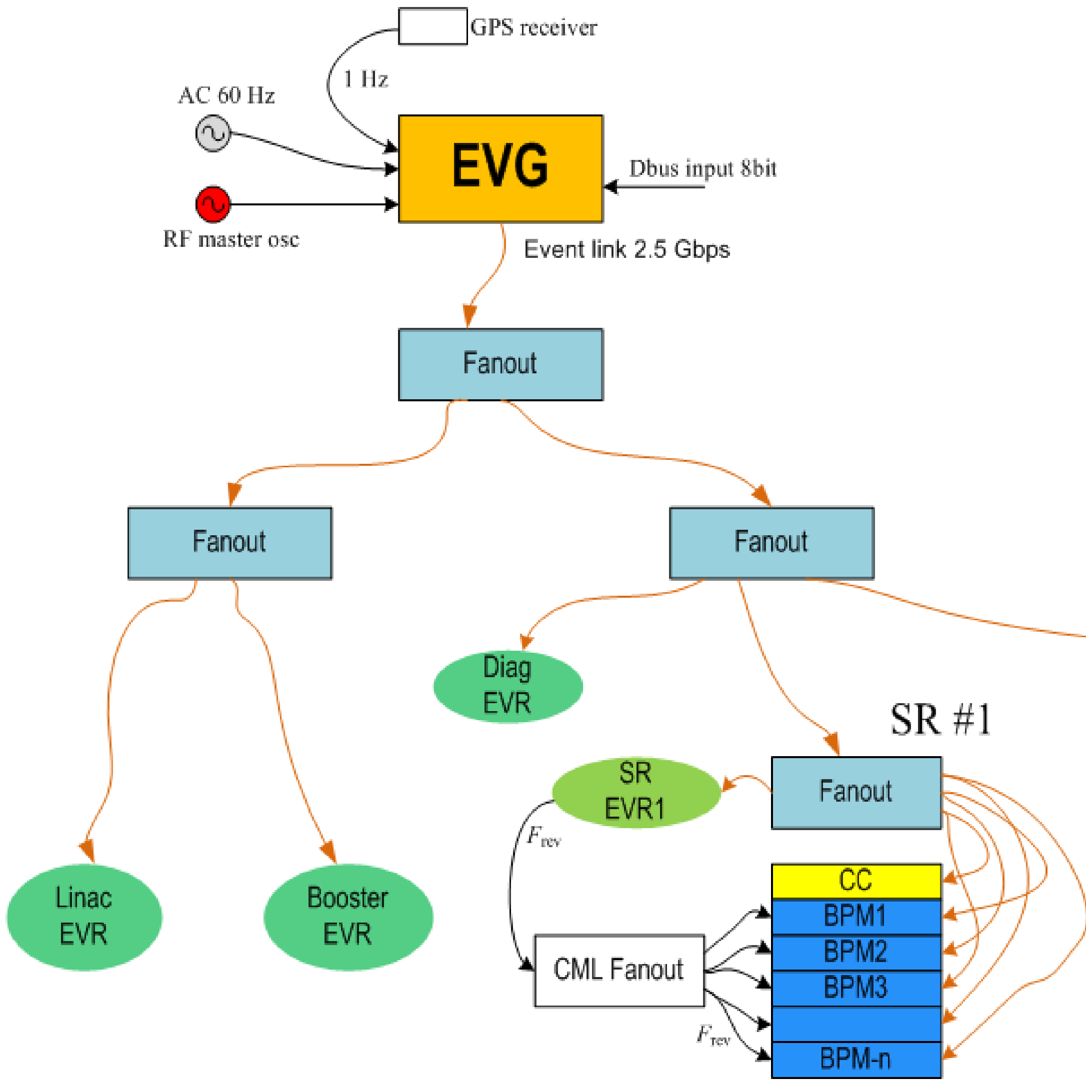




Resolution vs Bandwidth @ ALS SR

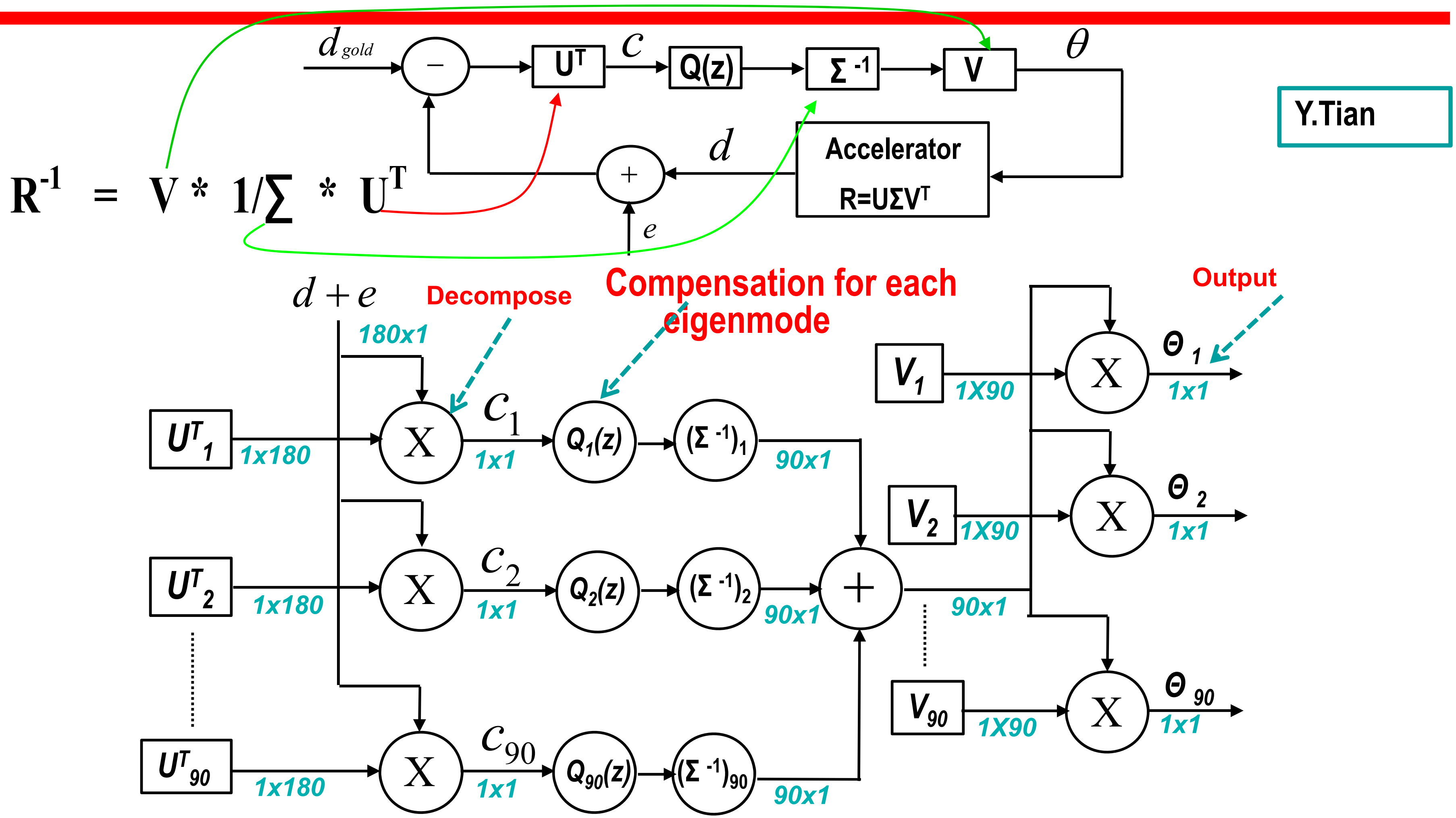


Timing Synchronizations



- MRF's EVG 230 – VME
- MRF's EVR-VME, cPCI, PMC
- BPM – Embedded EVR
- CC – Embedded EVR

Fast Orbit Feedback Algorithm – Implementation in FPGA



Use FPGA parallel computation features to implement the algorithm (assume 240 BPMs, 90 correctors)
U^T_1, U^T_2 … U^T_{90} : input matrix vector -- download from control system as waveform PV
V_1, V_2 ,…V_{90}: output matrix vector -- download from control system as waveform PV
$Q_1(z)$, $Q_2(z)$, …, $Q_{90}(z)$: compensator for each eigenmode -- parameters download from control system