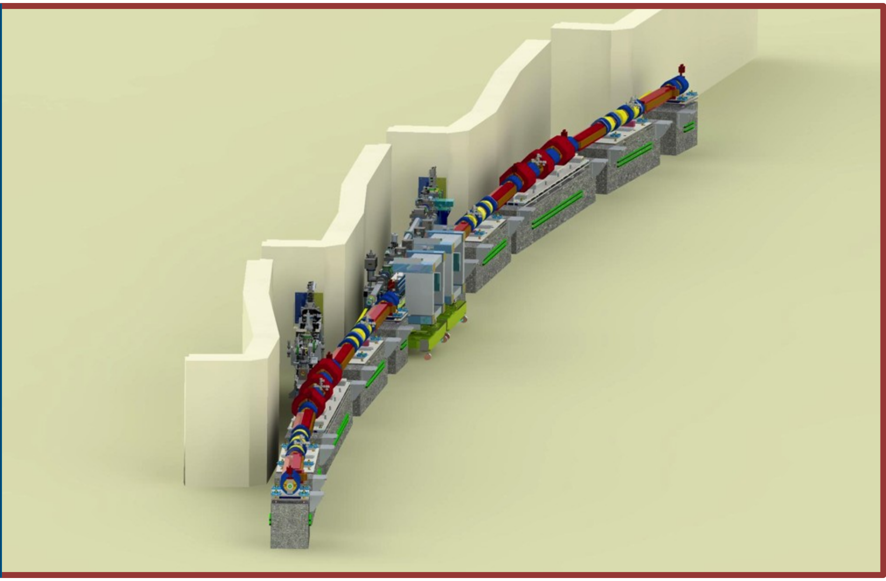
Fast Orbit Feedback at the APS



Nick Sereno
Diagnostics Group Leader
APS/Argonne National Laboratory
For the APS Beam Stability Team

BES Light Sources Beam Stability Workshop
Lawrence Berkeley National Laboratory
November 1, 2018

APS Beam Stability Team

Many Groups Working on Beam Stability and Diagnostics*

- ASD – Diagnostics:
  - R. Blake, A Brill, H. Bui, P. Dombrowski, L. Erwin, R. Keane, B. Lill, N. Sereno, X. Sun, B. X. Yang, P. Weghorn, R. Zabel
- AES – Controls:
  - N. Arnold, T. Fors, **S. Kallakuri, D. Paskvan, A. Pietryla, S. Shoaf, S. Xu
- ASD – Power Supplies:
  - B. Deriy, J. Wang
- APS Upgrade Vacuum:
  - H. Cease, B. Stillwell, J. Lerch
- ASD – Accelerator Operations and Physics
  - L. Emery, V. Sajaev, M. Sangroula, H. Shang, A. Xiao
- APS Upgrade Project:
  - J. Carwardine, G. Decker, U. Wienands
- ANL Facilities:
  - M. Kirchenbaum, S. Stewart, G. Kailus

* J. Carwardine, Invited Talk TUOCO2 IBIC 2018, Shanghai, China
** S. Kallakuri modelling and simulations

Outline

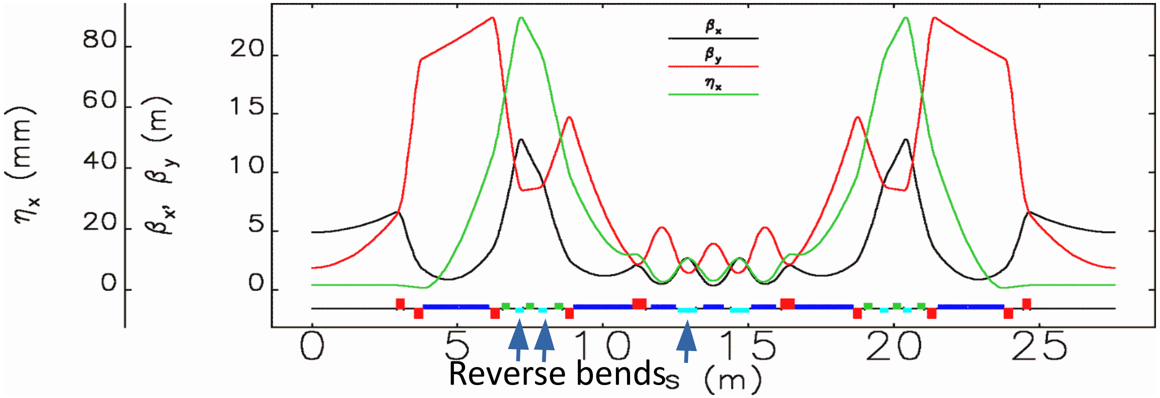
- Diagnostics for the MBA Ring
- Beam Stability Requirements
- Orbit Feedback System Design
  - Present Operations System
  - System Architecture
  - APS-U Feedback Controller (FBC) Hardware
- Orbit Feedback System R&D
  - Goals in terms of present orbit motion
  - APS-U R&D in Sector 27 and 28 of APS SR
  - Orbit feedback modelling and experimental results
  - Simultaneous operation of longitudinal and orbit feedback
  - Unified feedback Idea
  - Unified feedback experimental results and movie
- Summary

Diagnostic Systems For the MBA Ring

Diagnostic	Quantity/Sector	Total
Arc RF BPMs	12	480
ID RF BPMs (A:P0, B:P0)	2	80
Canted ID RF BPMs (C:P0)	1	10
Orbit Feedback System	N/A	1
Mechanical Motion Systems	1	35
Current Monitors	N/A	2
Bunch Current Monitor	N/A	1
Beam Size Monitors	N/A	3
Transverse and Longitudinal Multi-bunch Feedback	N/A	1
X-Ray BPM Electronics GRID	1	35

Major Systems Interfaced to Fast Orbit Feedback

MBA Ring Design



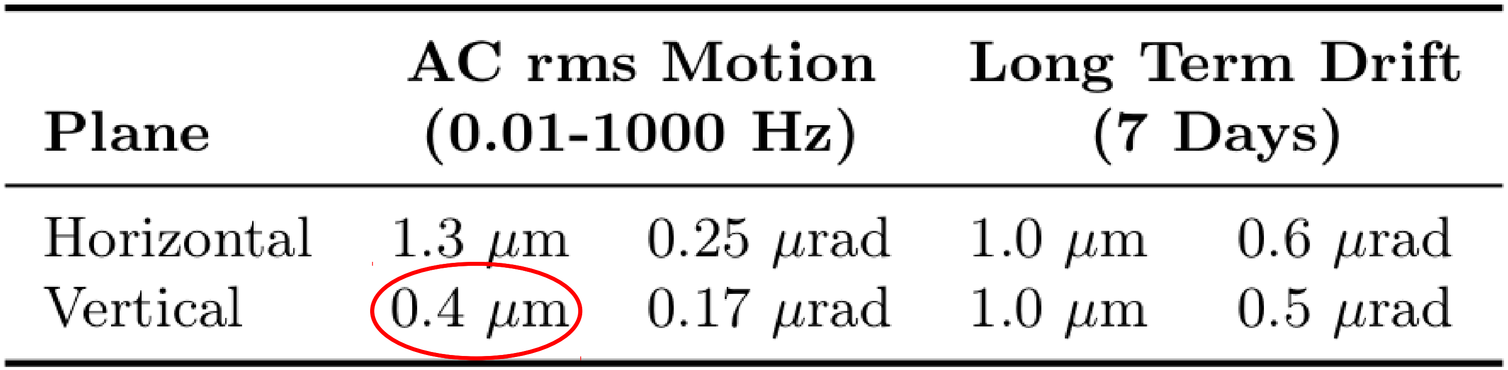
Invited Talk: THXGBD1
Aimin Xiao

Quantity	**APS Now**	**APS MBA Timing Mode**	**APS MBA Brightness Mode**	**Units**
Beam Energy	7	6		GeV
Beam Current	100	200		mA
Number of bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.130	%
Bunch Spacing	153	77	11	ns
Horizontal Emittance	3100	32	42	pm·rad
Emittance Ratio	0.013	1	0.1	
Horizontal Beam Size (rms)	275	12.6	14.5	μm
Vertical Beam Size (rms)	11	7.7	2.8	μm
Betatron Tune	35.2, 19.27	95.1, 36.1		
Natural Chromaticity	-90,-43	-130, -122		

- Diagnostics for the MBA Ring driven by small beam size

Beam Stability Requirements

- Beam stability requirements are set at a fraction of the particle beam phase space (x, x’, y, y’) dimensions, typically 10% at the ID source points



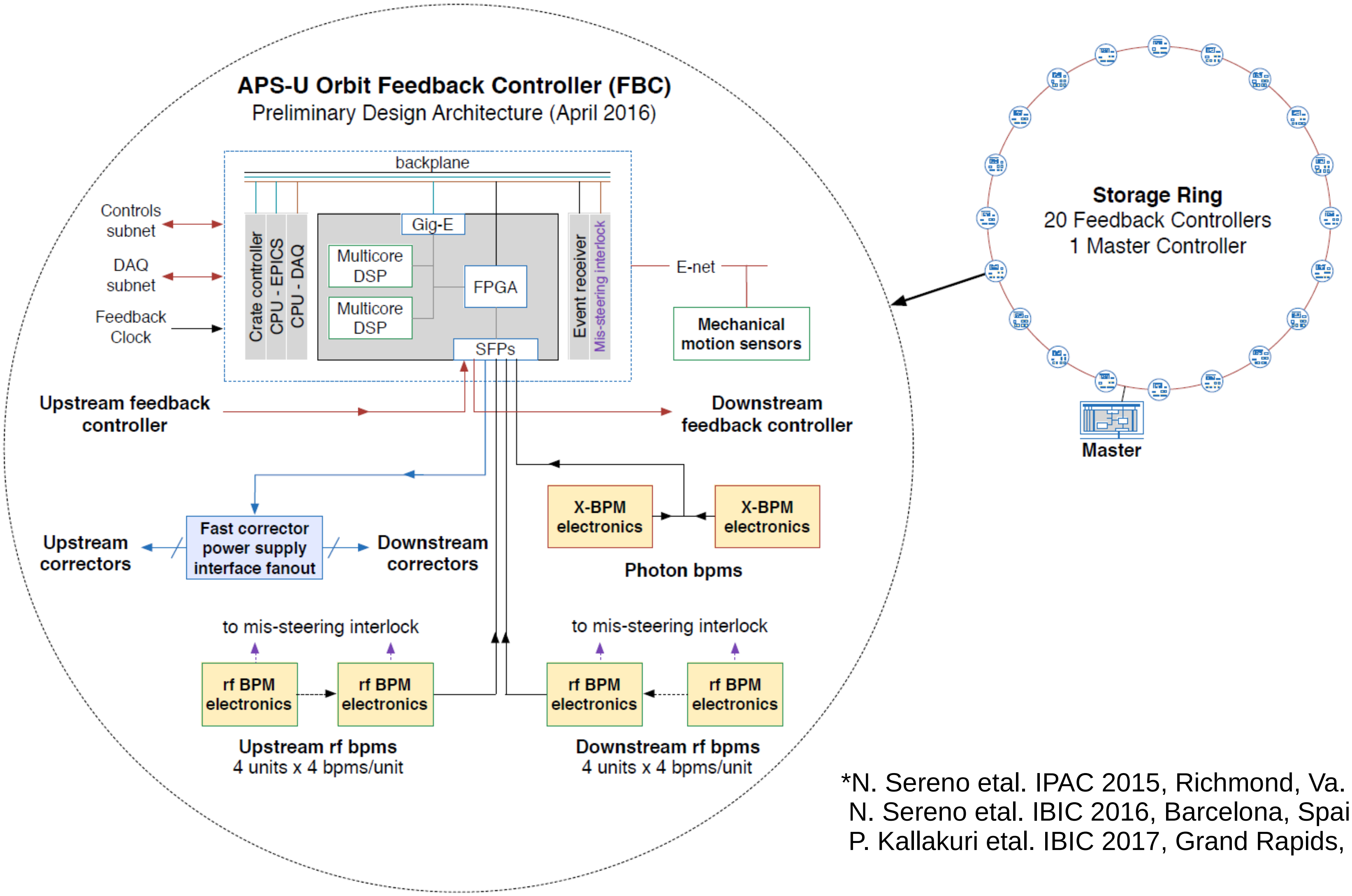
Plane	**AC rms Motion (0.01-1000 Hz)**		**Long Term Drift (7 Days)**	
Horizontal	1.3 μm	0.25 μrad	1.0 μm	0.6 μrad
Vertical	0.4 μm	0.17 μrad	1.0 μm	0.5 μrad

Present APS has ~5 times these values with bandwidth up to ~100 Hz

PARAMETERS – PRESENT APS ORBIT FEEDBACK SYSTEM (1995)

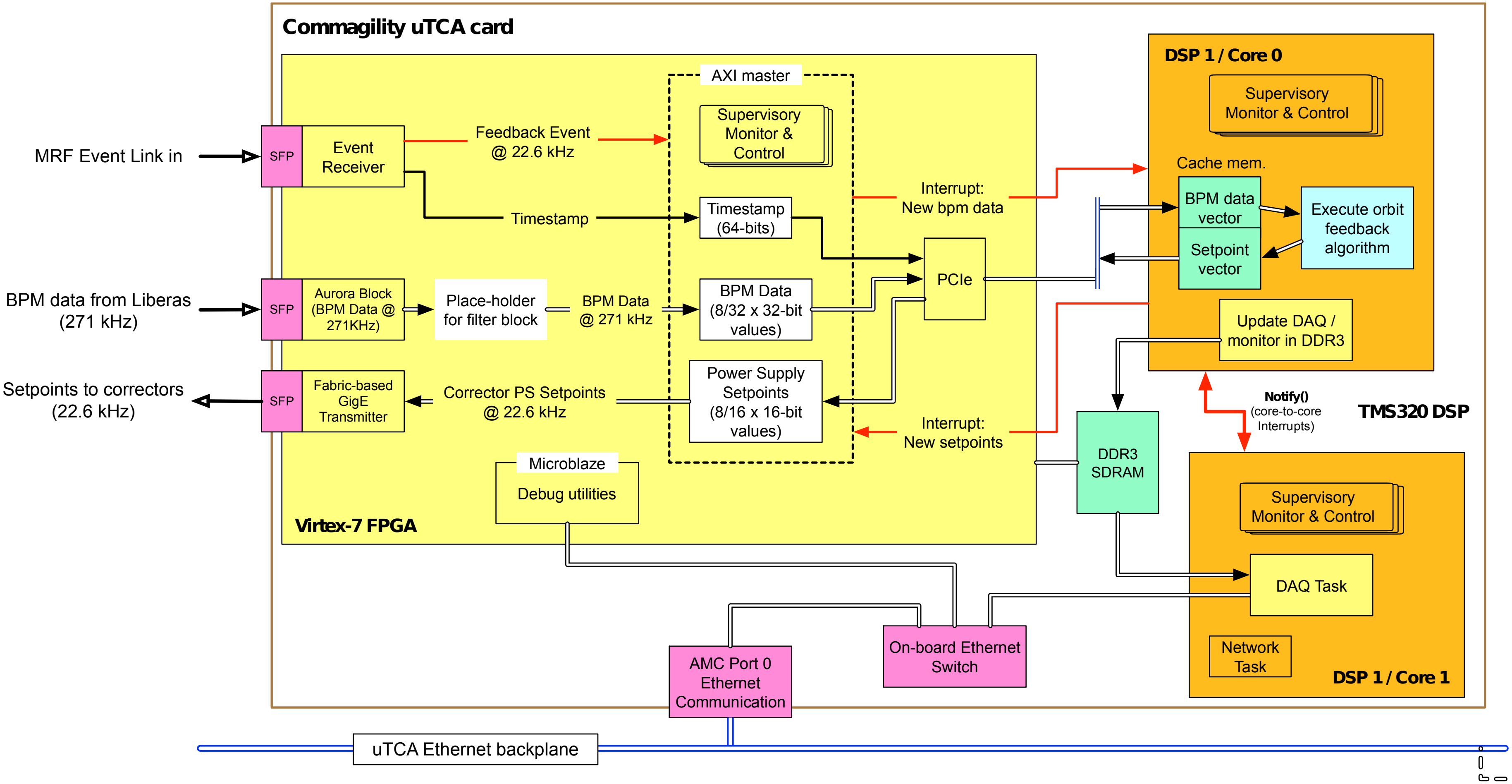
Parameter		**‘Datapool’**	**RTFB**
Algorithm implementation		Separate DC and AC systems for slow and fast correctors	
BPM sampling & processing rate		10 Hz	1.6 kHz
Corrector ps setpoint rate		10 Hz	1.6 kHz
Signal processors (20 nodes)		EPICS IOC	DSP (40 MFLOPS)
Num. rf bpms / plane		360	160 (4 per sector)
Fast correctors / plane		-	38 (1 per sector)
Slow correctors / plane		282	-
Fast corrector ps bandwidth		-	1 kHz
Fast corrector latency		-	~250 usec
Closed-loop bandwidth		DC - 1 Hz	1 Hz - 80 Hz

Orbit Feedback System Architecture



*N. Sereno etal. IPAC 2015, Richmond, Va. 2015
N. Sereno etal. IBIC 2016, Barcelona, Spain. 2016
P. Kallakuri etal. IBIC 2017, Grand Rapids, MI 2017

PROTOTYPE FAST ORBIT FEEDBACK PROCESSOR DATAFLOW



- FPGA manages bpm and corrector data-streams
- DSPs perform orbit feedback computations

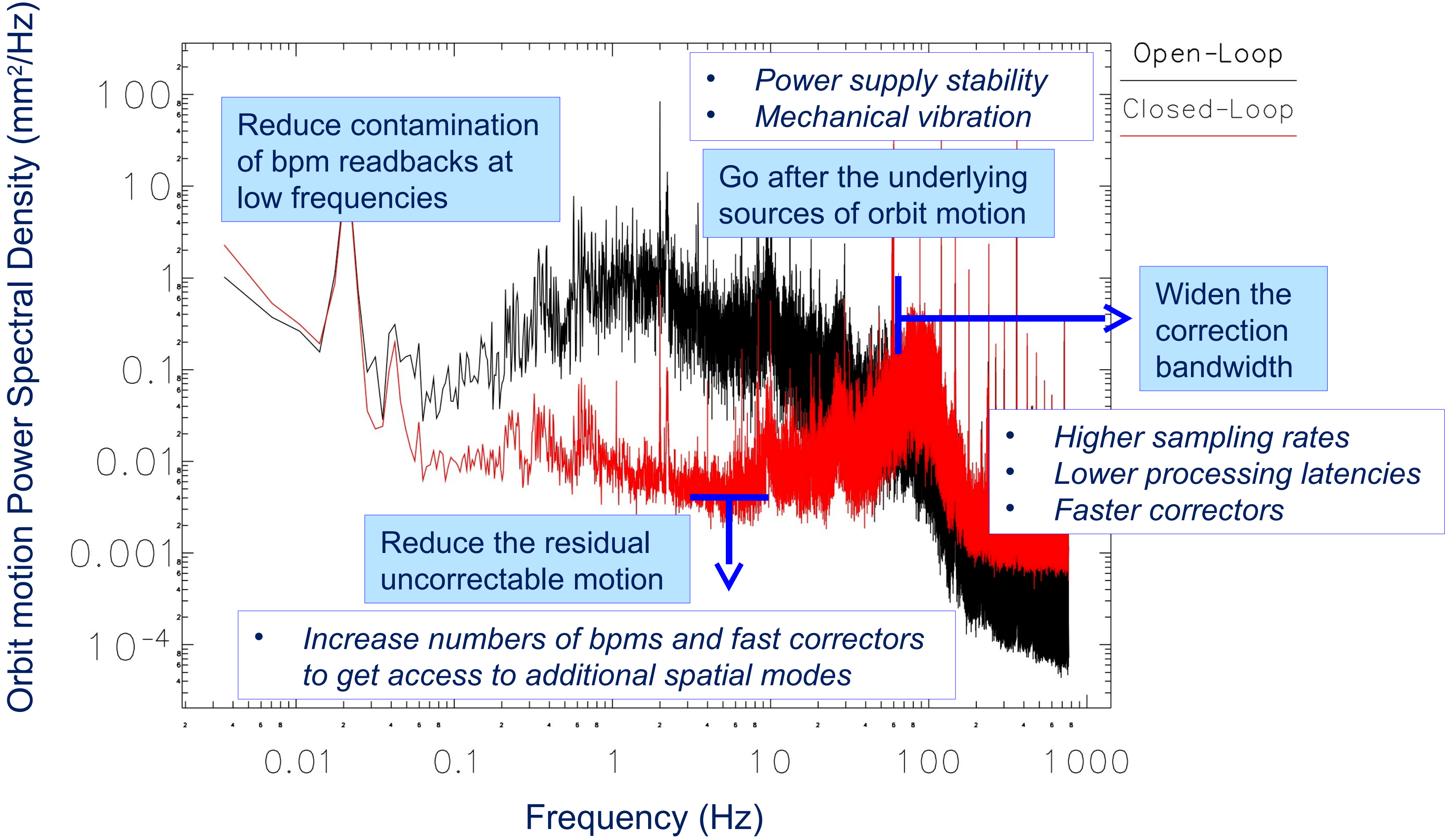
PARAMETERS – COMPARISON OF PRESENT AND NEW

		Present system (circ. 1995)	
Parameter	**APS-U design***	**‘Datapool’**	**RTFB**
Algorithm implementation	‘Unified feedback’ algorithm	Separate DC and AC systems for slow and fast correctors	
BPM sampling & processing rate	271 kHz (TBT)	10 Hz	1.6 kHz
Corrector ps setpoint rate	22.6 kHz	10 Hz	1.6 kHz
Signal processors (20 nodes)	DSP (320 GFLOPS) + FPGA (Virtex-7)	EPICS IOC	DSP (40 MFLOPS)
Num. rf bpms / plane	570 (14 per sector)	360	160 (4 per sector)
Fast correctors / plane	160 (4 per sector)	-	38 (1 per sector)
Slow correctors / plane	320 (8 per sector)	282	-
Fast corrector ps bandwidth	10 kHz	-	1 kHz
Fast corrector latency	<10 us	-	~250 usec
Closed-loop bandwidth	DC to 1 kHz	DC - 1 Hz	1 Hz - 80 Hz

* Goal of R&D was to demonstrate key parameters in beam studies at APS

TARGETS FOR APS-U ORBIT FEEDBACK R&D IN TERMS OF ORBIT MOTION SPECTRA

Open- vs closed-loop PSDs with present RTFB (x-plane)



Reduce contamination of bpm readbacks at low frequencies

- *Power supply stability*
- *Mechanical vibration*

Go after the underlying sources of orbit motion

Widen the correction bandwidth

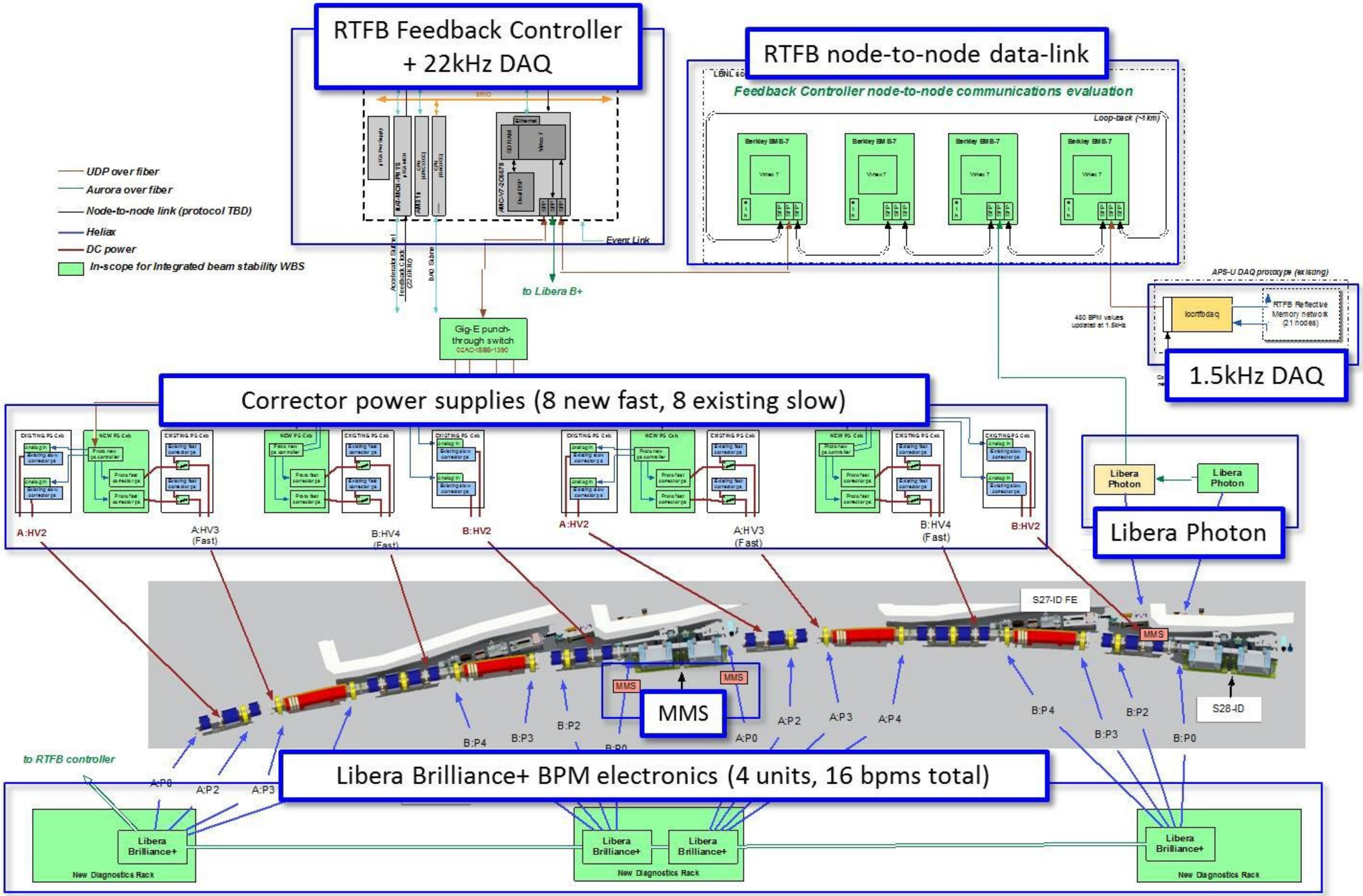
- *Higher sampling rates*
- *Lower processing latencies*
- *Faster correctors*

Reduce the residual uncorrectable motion

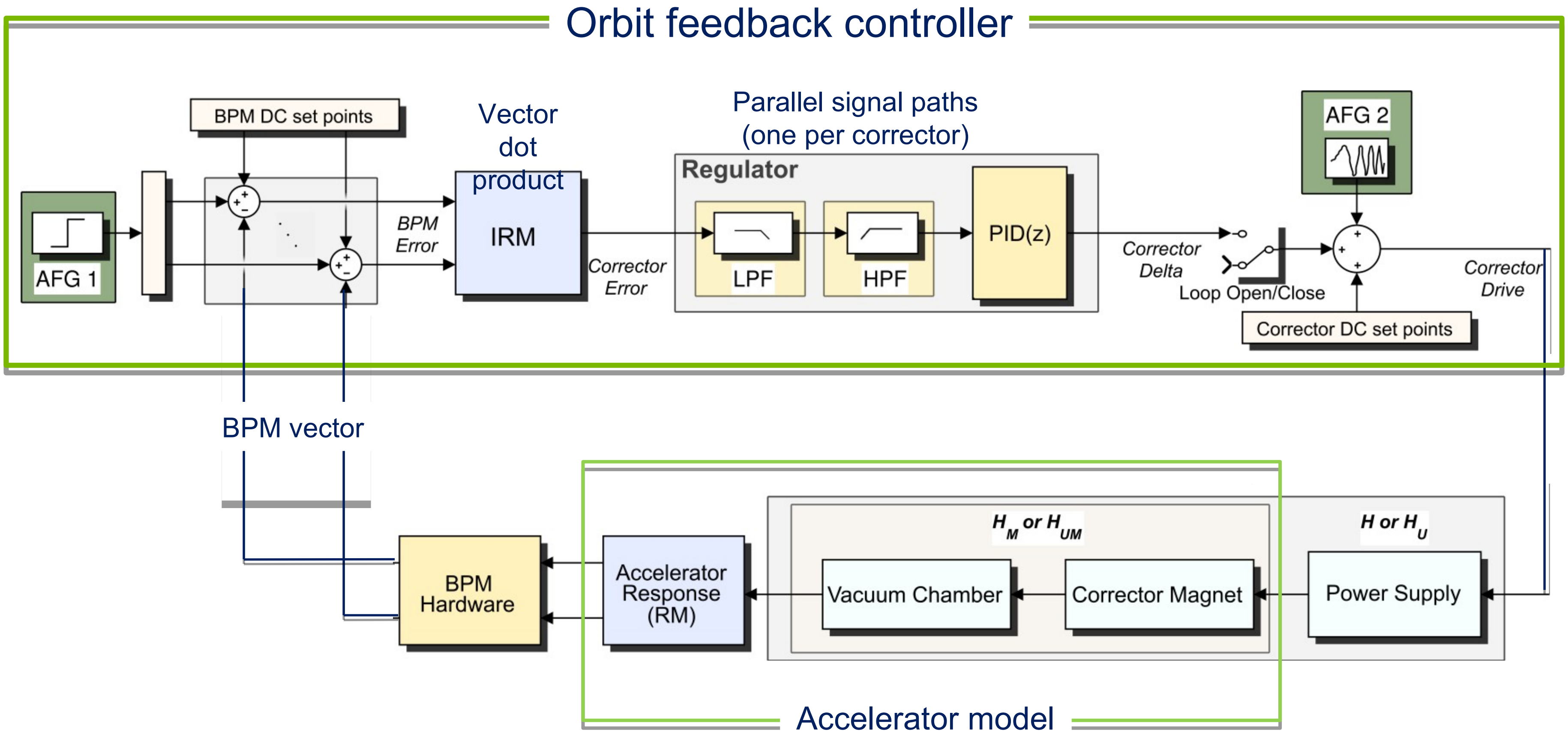
- *Increase numbers of bpms and fast correctors to get access to additional spatial modes*

Integrated Beam Stability R&D in APS Sector 27

Major systems tested: BPM Electronics, Fast Corrector PS, Feedback Controller

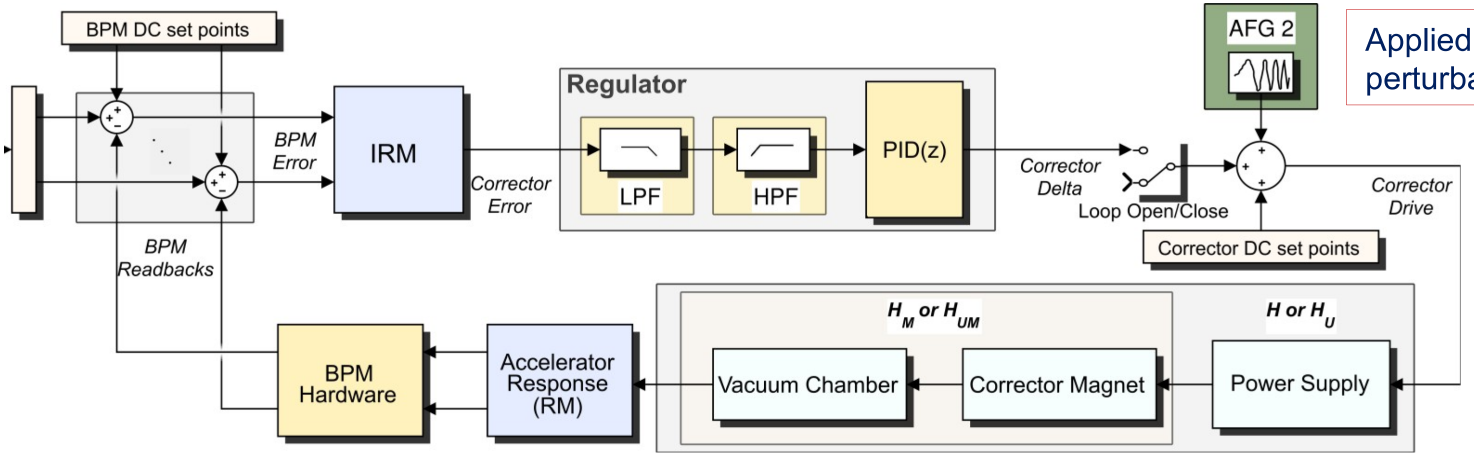


ORBIT FEEDBACK SYSTEM MODEL



BUILT-IN DYNAMIC-SYSTEM ANALYZER

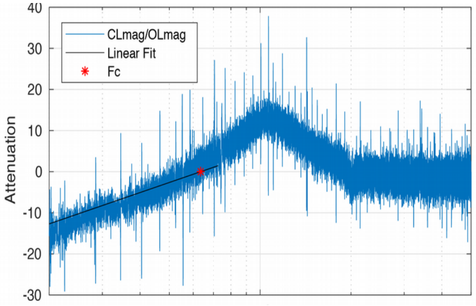
- Need a means of evaluating effects of latency and regulator tuning
  - Method of dividing open-loop and closed-loop PSDs is noisy and imprecise
  - Dynamic-system analyzer approach: measure response to known excitation


BPM DC set points
BPM Error
IRM
Corrector Error
Regulator
LPF
HPF
PID(z)
Corrector Delta
Loop Open/Close
AFG 2
Corrector Drive
Corrector DC set points
BPM Readbacks
H_M or H_{UM}
H or H_U
BPM Hardware
Accelerator Response (RM)
Vacuum Chamber
Corrector Magnet
Power Supply

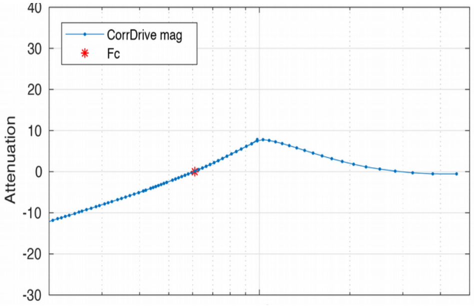
Applied perturbation

Residual perturbation

Compute ratio of PSDs (Noisy, imprecise)



Measure response to applied perturbation

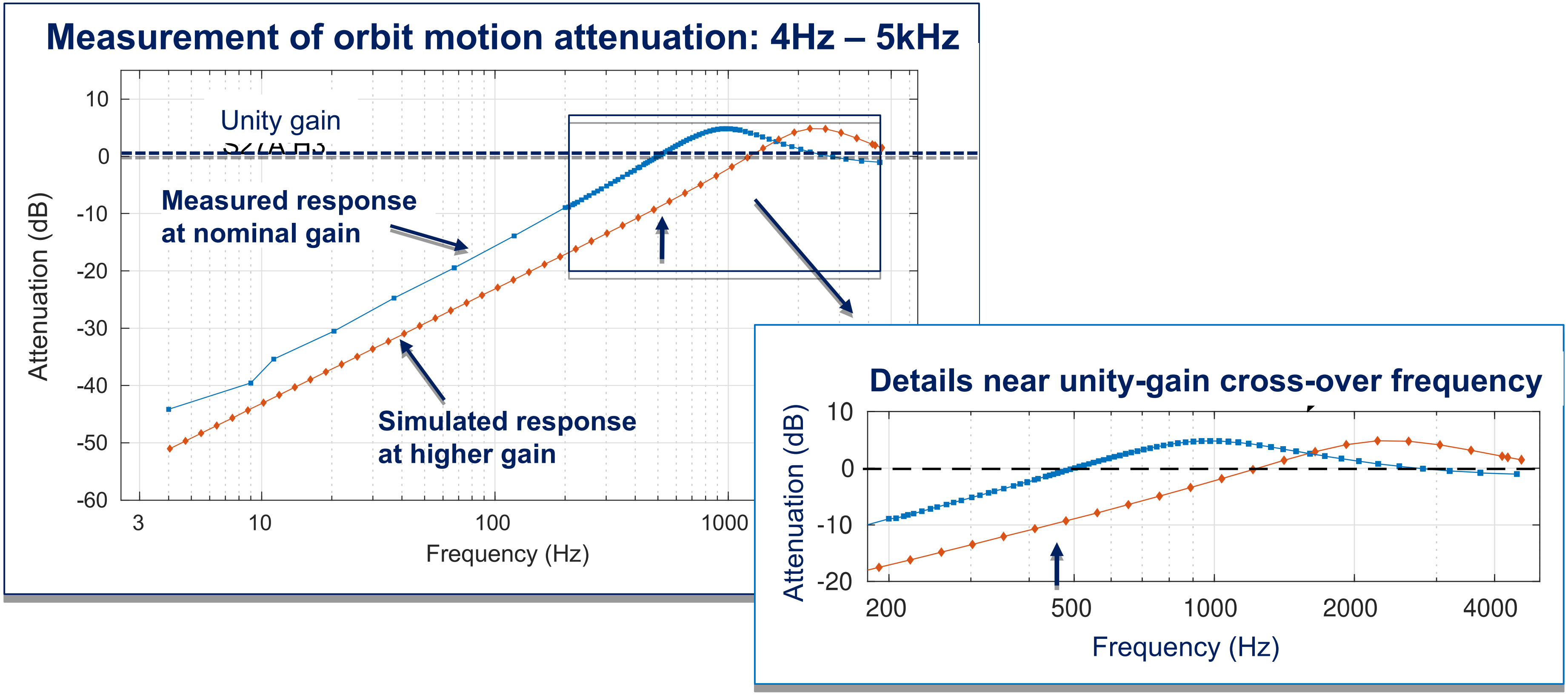


- Multiple simultaneous measurement channels
- Beam-based measurement of frequency- and time-domain responses
- Resolve differences in transfer-function to <10Hz
- Closed-loop Response Matrix measurements

MEASURING ORBIT FEEDBACK EFFECTIVENESS

Plots show the attenuation response (fraction of motion remaining with feedback enabled)

- At low frequencies, there is more than 40dB attenuation.
- Amplification at higher frequencies corresponds to overshoot in the step response.



Measurement of orbit motion attenuation: 4Hz – 5kHz

Unity gain

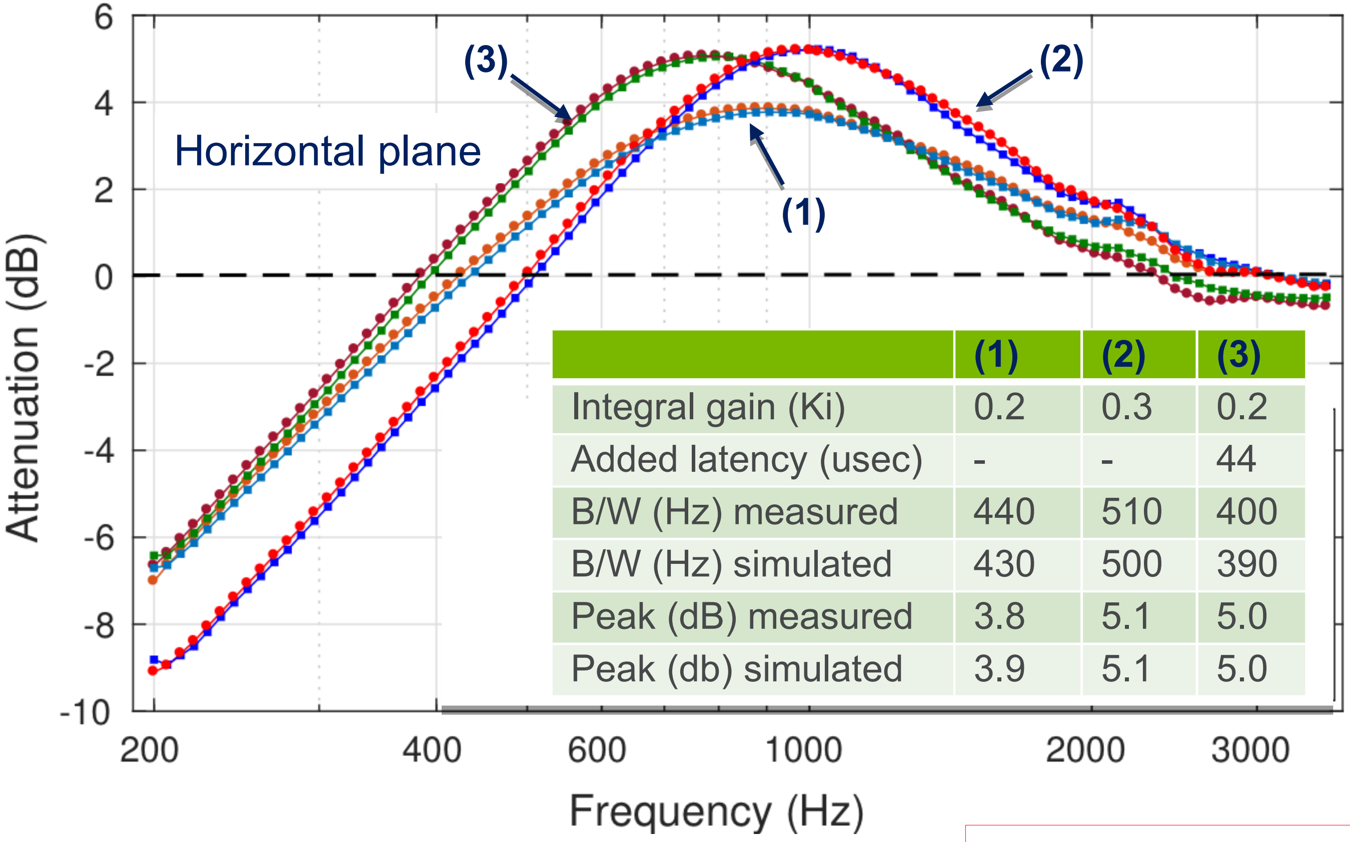
Measured response at nominal gain

Simulated response at higher gain

Details near unity-gain cross-over frequency

BEAM-BASED MEASUREMENT OF CLOSED-LOOP PERFORMANCE VS PROCESSING LATENCY

Attenuation responses with/without added latency

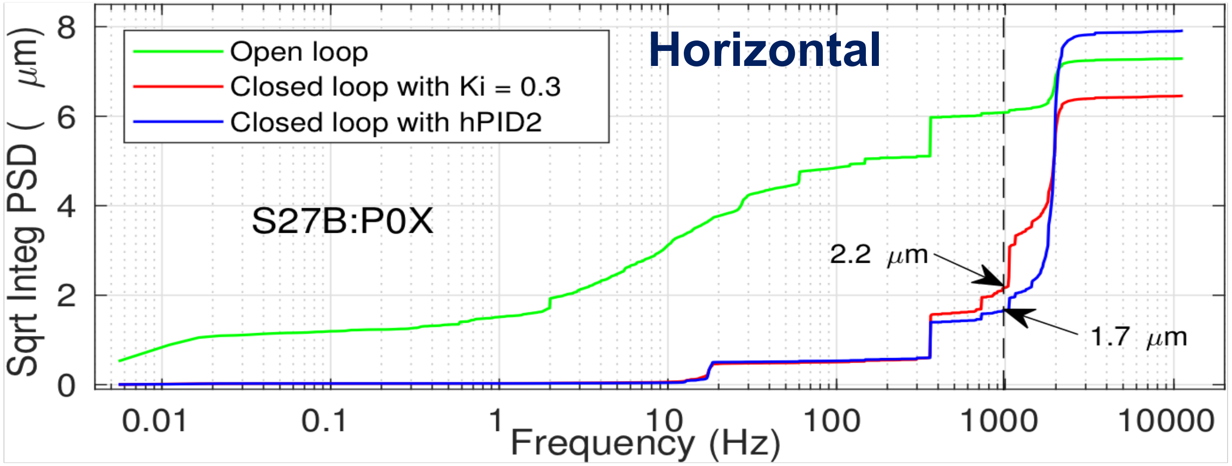


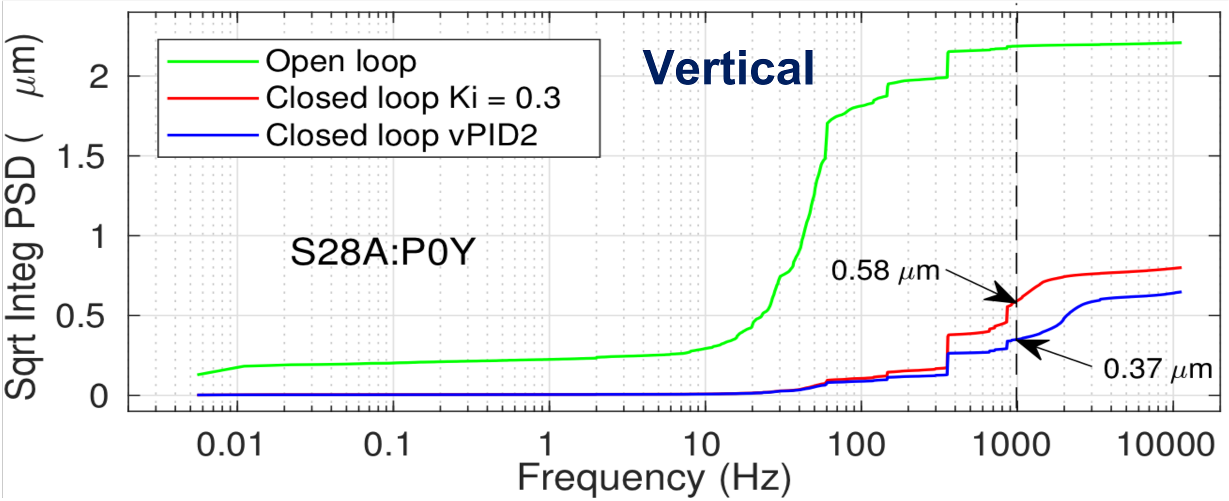
	(1)	(2)	(3)
Integral gain (Ki)	0.2	0.3	0.2
Added latency (usec)	-	-	44
B/W (Hz) measured	440	510	400
B/W (Hz) simulated	430	500	390
Peak (dB) measured	3.8	5.1	5.0
Peak (db) simulated	3.9	5.1	5.0

44 usec (1 tick) of added processing latency costs ~100Hz in bandwidth

MEASURED PERFORMANCE:
REDUCTION IN CUMULATIVE RMS MOTION

RMS beam stability goals for APS-U have been demonstrated on APS





Plots show cumulative RMS motion up to 11 kHz:
- Open-loop
- Ki regulator
- Ki+Kp+Kd regulator

Large source of orbit motion at 1.8kHz is due to synchrotron motion

J. Carwardine, et., al. International Beam Instrumentation Conference, 9-14 Sept. 2018, Shanghai

PARAMETERS – COMPARISON OF PRESENT AND NEW

Present system (circ. 1995)

Parameter	APS-U design	'Datapool'	RTFB
Algorithm implementation	'Unified feedback' algorithm ✓	Separate DC and AC systems for slow and fast correctors	
BPM sampling & processing rate	271 kHz (TBT) ✓	10 Hz	1.6 kHz
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Fast corrector ps bandwidth	10 kHz ✓	-	1 kHz
Fast corrector latency	<10 us ✓	-	~250 usec
Closed-loop bandwidth	DC to 1 kHz ✓	DC - 1 Hz	1 Hz - 80 Hz

✓ Demonstrated

✔ Demonstrated in a double-sector

Simultaneous Operation of Longitudinal and Orbit Feedback for APS-U

- The problem: Frequency overlap of Orbit Feedback and Longitudinal Feedback systems for the MBA ring
  - Orbit feedback bandwidth: 0.01 to 1000 Hz
  - [1] Synchrotron frequency (2 kHz in present APS):
    - 560 Hz with Higher-Harmonic Cavity (HHC) off
    - 100 Hz +/- 100 Hz with HHC on
- Orbit feedback fast correctors have a bandwidth >~ 1 kHz
  - Could very quickly add to the net dipole field around the ring
  - For a fixed rf frequency this will change the beam energy quickly
- *Orbit feedback correctors should never attempt to correct a dispersive orbit or equivalently add to the net ring dipole field*

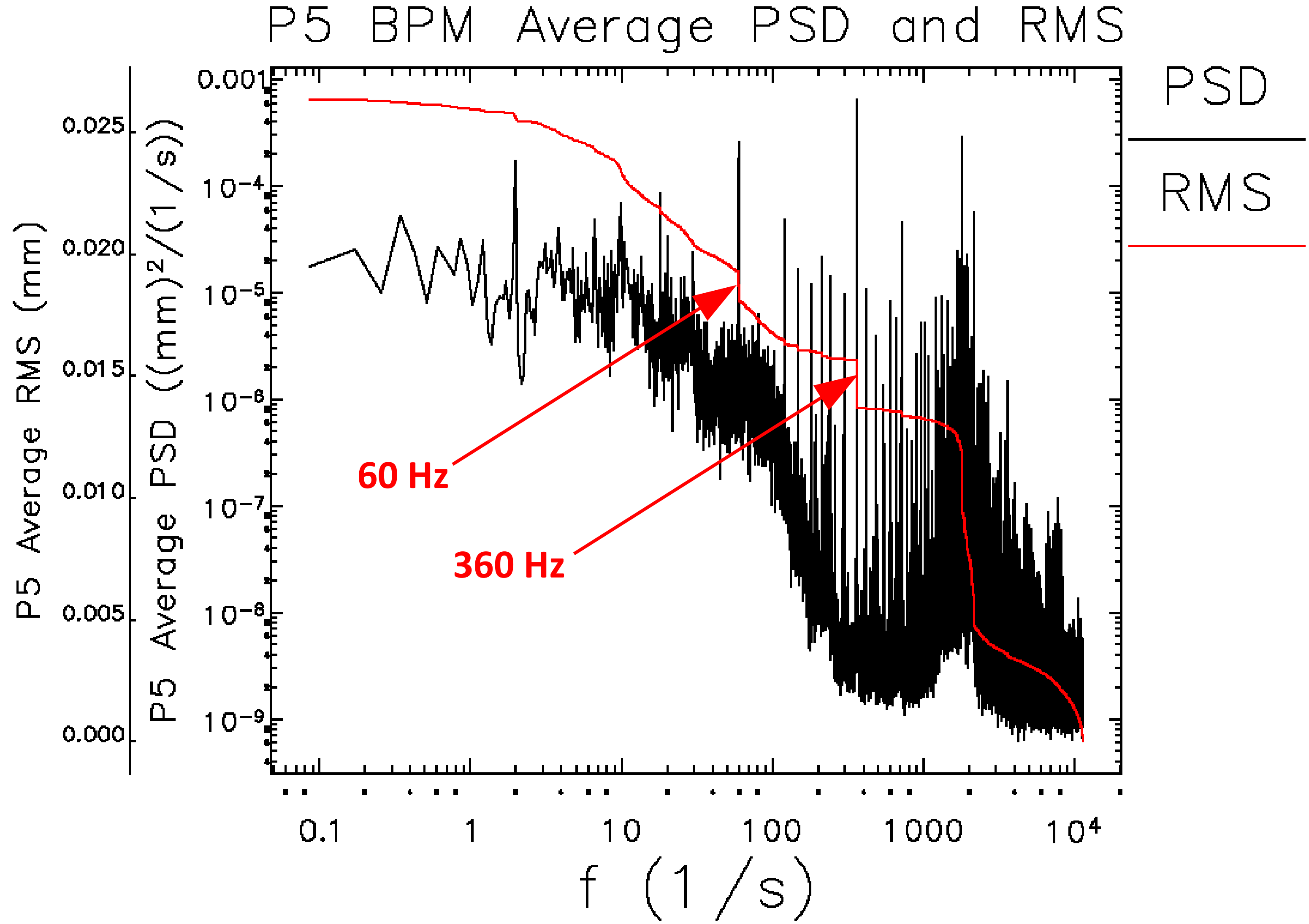
[1] APS Upgrade Project Preliminary Design Report table 4.36

BPM Signals in the Present APS Storage Ring

- BPMs (Libera Brilliance+) average orbit position of bunches over a single turn
  - Time domain: ADC sampling/rms over one turn for each button signal
  - I/Q DDC: For each button signal (ITECH recommended operations mode)
  - Both modes have been tested in the APS storage ring[1]
- BPMs are not sensitive to position of individual bunches in operations modes (48 and 324 bunch)
- Dispersion orbits due to longitudinal motion of all bunches together (common mode) are most easily measured in the horizontal plane
- Sources of longitudinal motion:
  - RF Frequency error (DC drift due to earth tides, temperature drifts)
  - RF phase errors (AC mostly harmonics of 60 Hz)
  - Coupled bunch mode 0 (AC at the synchrotron tune)
- Implies two fundamental RF actuators to correct common mode longitudinal motion

[1] Libera Brilliance+ Noise Measurements in Sector 27, DIAG-TN-2016-001

BPM Signals in the Present APS Storage Ring



- High dispersion “P5” BPM PSD and RMS Using BSP-100 BPMs in 12 turn average mode

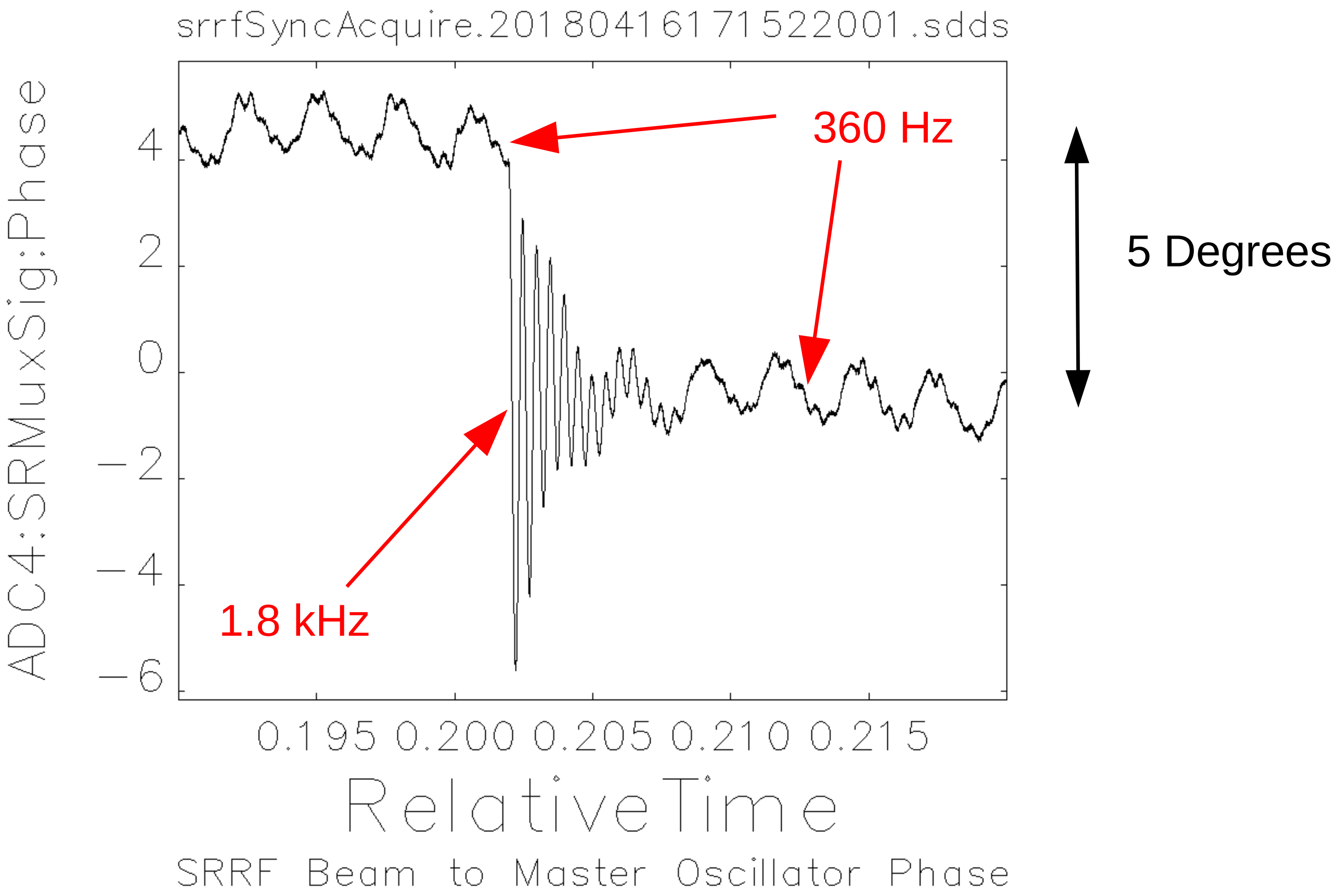
Response Matrix with RF Actuators

- One can combine correctors and rf actuators in the response matrix

$$R \Delta c = \Delta p$$
$$R = (r_1 r_2 \ldots r_{n-1} rf_n)$$
$$R = U S V^T$$

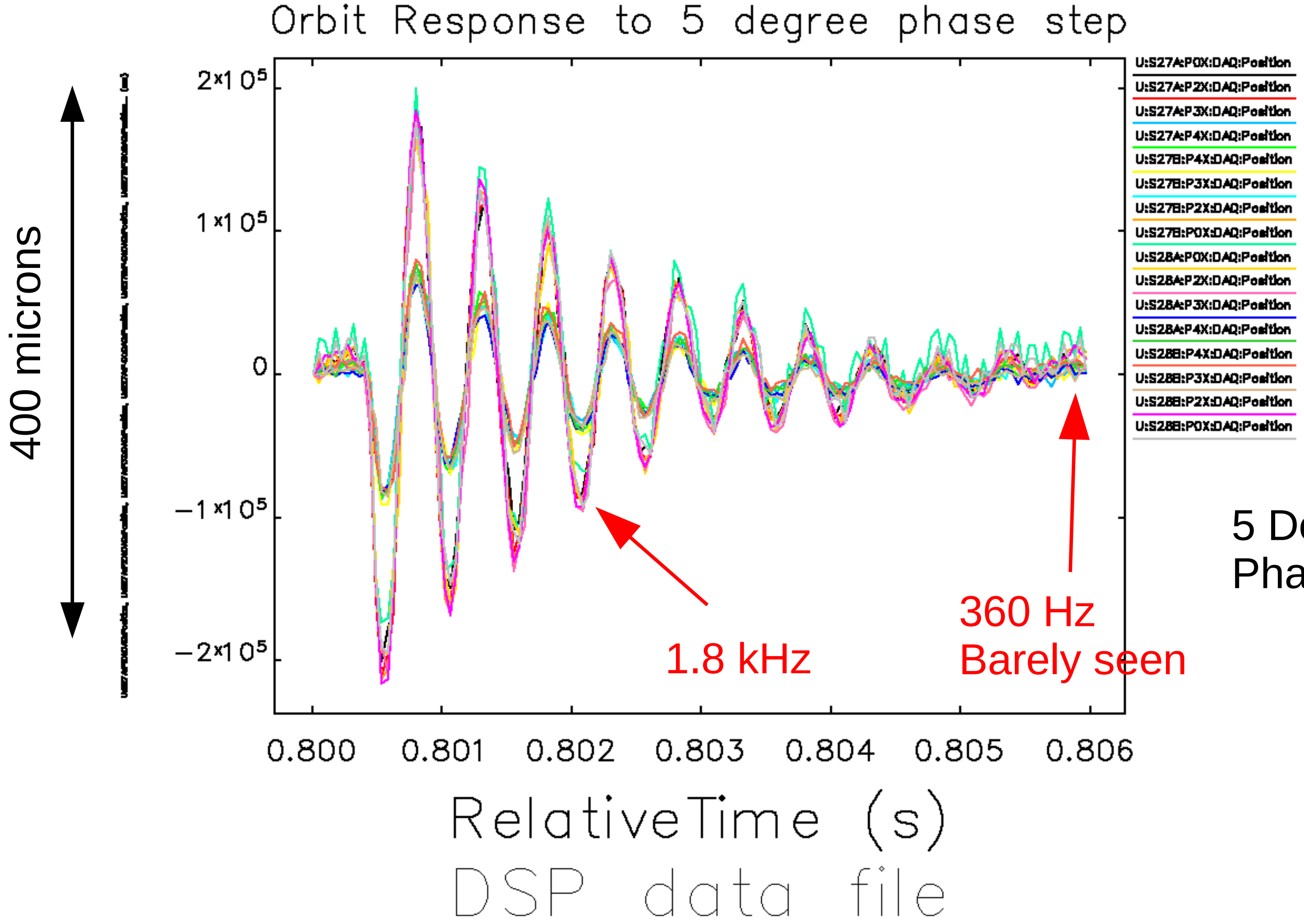
  - Column vectors r_i are normal fast corrector response columns
  - Column vector rf_n has the shape of the dispersion orbit
- The (normalized) column vector rf_n is also one of the eigen-orbits in the U matrix
- The rf actuator response is selected by the inverse response matrix (U^T) from the dispersive part of the orbit
- Ultimately implement by sending a phase signal from the orbit FBCs to the rf phase actuator
- Did an rf phase step response experiment to demonstrate the concept using the operations RTFB and sector 27, 28 FBC DAQ systems

RF Phase Step Response Measurement



- Phase Step Response: Phase detector output measured using a bpm sum signal and master oscillator as the phase reference (rf DAQ has 271 kHz sampling rate)

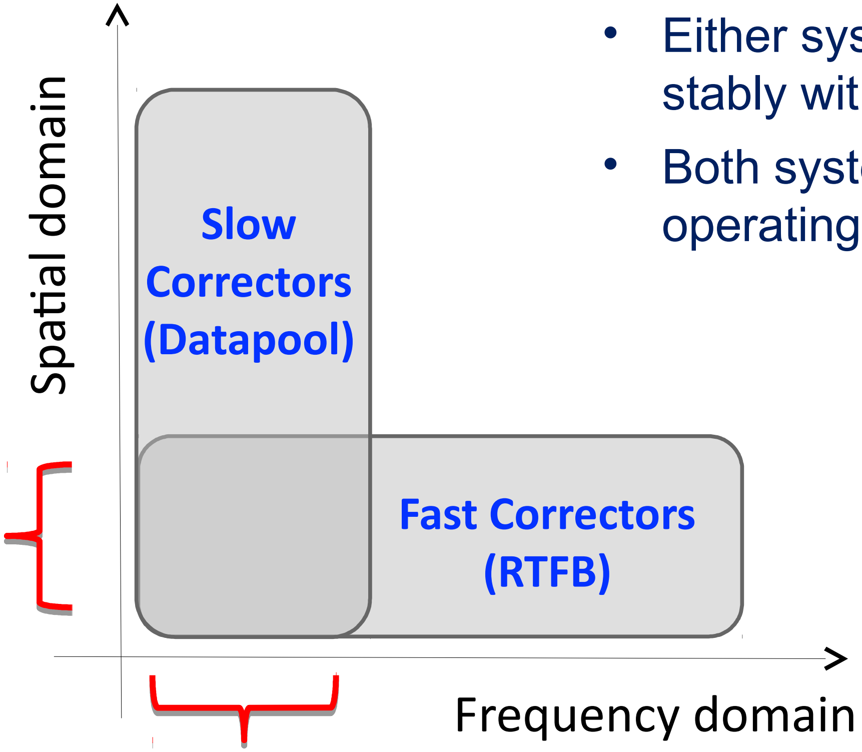
RF Phase Step Response Measurement cont.



5 Degree
Phase Step

- Beam Response: Sector 27 and 28 Libera Brilliance+ response using the FBC DAQ (22.6 kHz sampling rate)

OVERLAP IN COVERAGE OF SLOW AND FAST ORBIT FEEDBACK SYSTEMS



- Either system can operate stably without the other, **but**
- Both systems go unstable if operating simultaneously

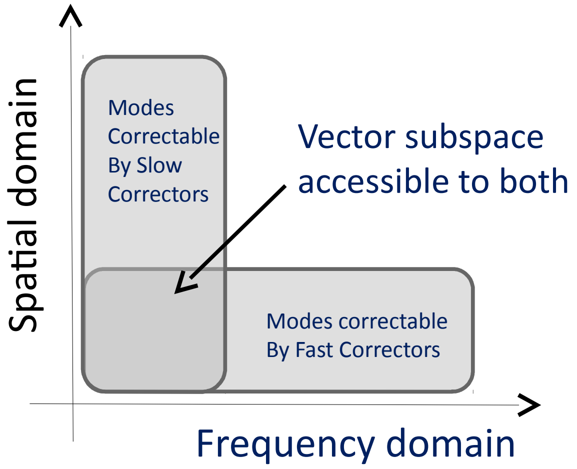
Both systems have access to this vector space

Both systems can respond over this frequency range

J. Carwardine, et., al. International Beam Instrumentation Conference, 9-14 Sept. 2018, Shanghai

UNIFIED FEEDBACK ALGORITHM CONCEPT:

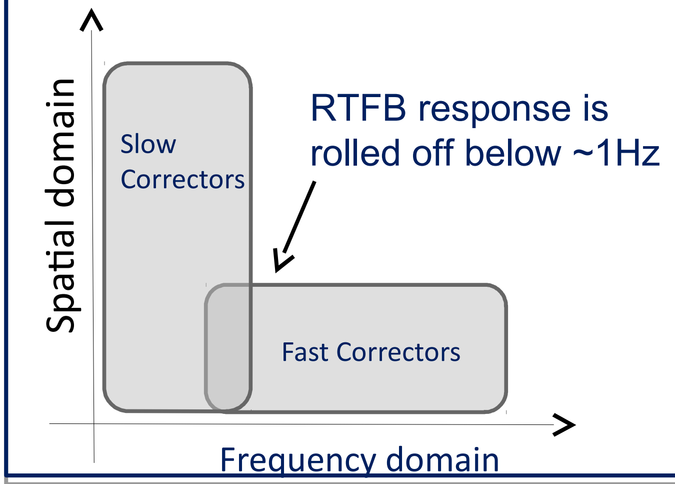
SPATIAL- VS FREQUENCY-DOMAIN ORTHOGONALIZATION



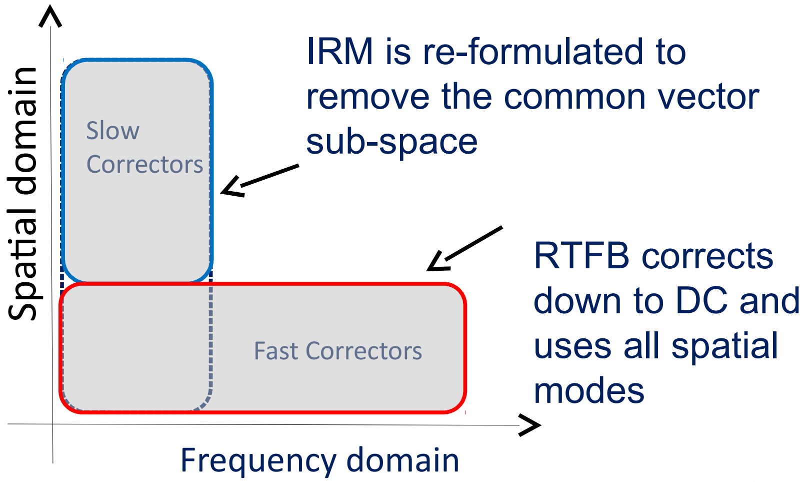
Issue: combination of slow + fast systems is unstable

- Present scheme: separate into high- and low-frequency systems ('woofer/tweeter' concept)
- Unified scheme: orthogonalize vector spaces

Present scheme

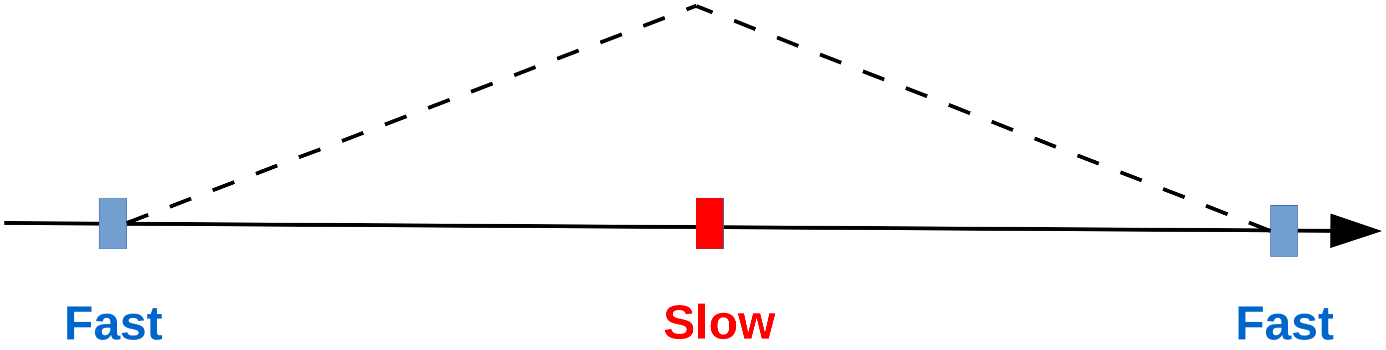


Unified algorithm



Unified Feedback Illustration

- Problem is to utilize both fast and slow correctors down to DC without the system becoming unstable
- How to modify the response matrix to achieve correction down to DC: First, took an experimental approach
  - Run the fast corrector system (RTFB) using standard inverse response matrix but down to DC
  - Measure the response matrix for the slow system (DP)
  - Invert and run the measured slow system using this measured response matrix



Fast correctors can't correct DC perturbations inside the 3-bump

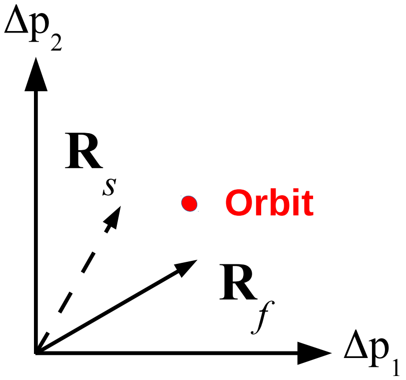
Unified Feedback Illustration

- The slow corrector response matrix exactly calculable from the standard machine response matrix
- Imagine a very simple orbit feedback system consisting of two bpms and two correctors: one fast and the other slow
- The standard response matrix is:

$$\left[\boldsymbol{R}_f\,\boldsymbol{R}_s\right]\boldsymbol{\Delta\,c}=\boldsymbol{\Delta\,p}$$

$$\boldsymbol{\Delta\,p}=\begin{bmatrix}\Delta\,p_1\\ \Delta\,p_2\end{bmatrix}$$

$$\boldsymbol{\Delta\,c}=\begin{bmatrix}\Delta\,c_f\\ \Delta\,c_s\end{bmatrix}$$



Standard orbit feedback

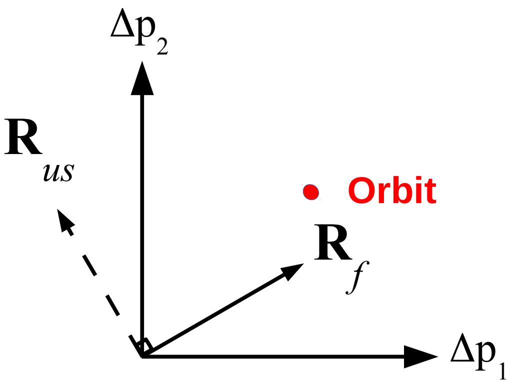
Unified Feedback Illustration

- The unified response matrix for slow correctors is orthogonal to that for the fast correctors (assuming the response matrix is full rank):
- Or in general the unified response matrix is that part of the slow corrector magnet response matrix column space orthogonal to that for the fast correctors

$$\left[\boldsymbol{R}_f \, \boldsymbol{R}_{us}\right] \boldsymbol{\Delta c} = \boldsymbol{\Delta p}$$

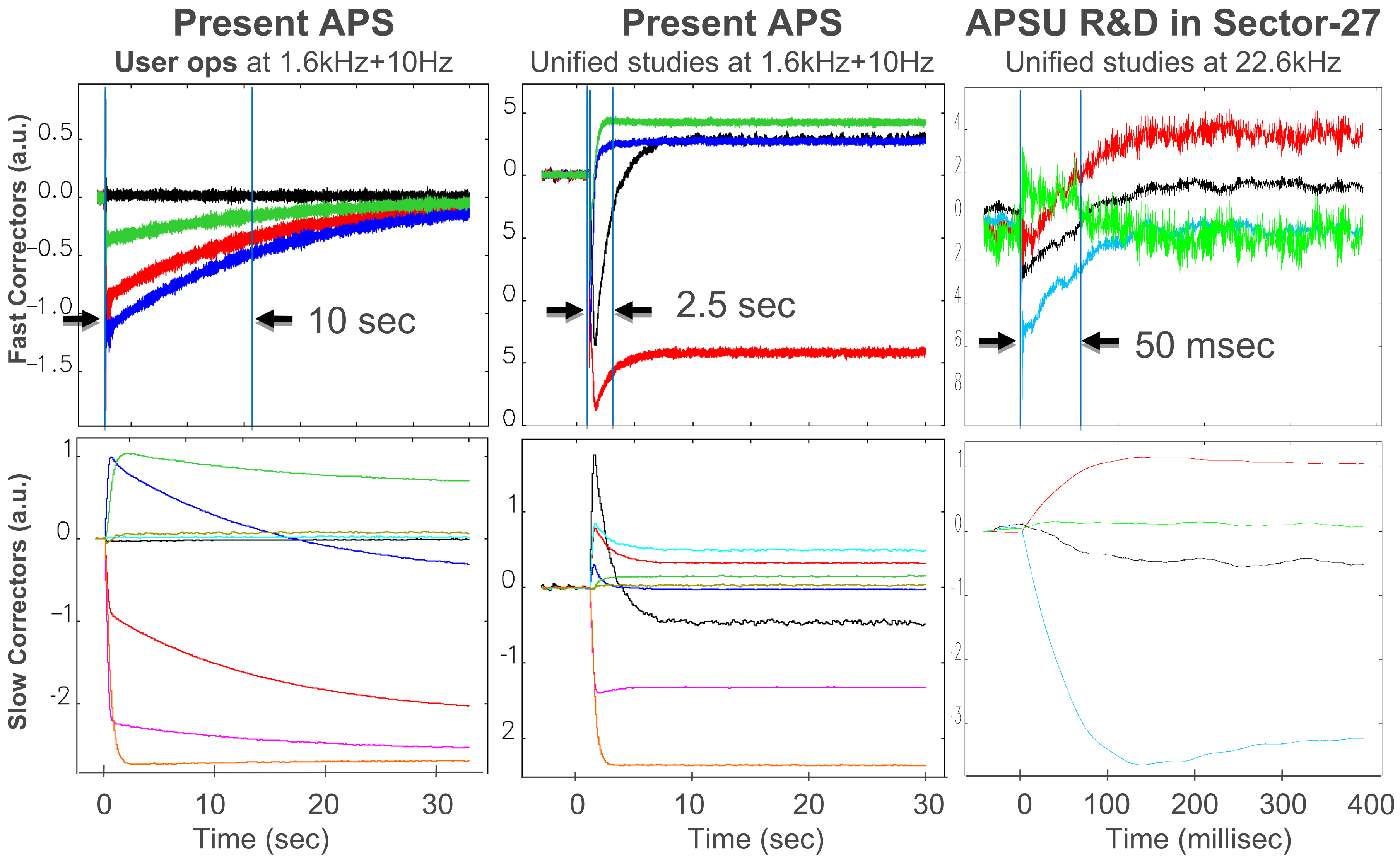
$$\boldsymbol{\Delta p} = \begin{bmatrix} \Delta p_1 \\ \Delta p_2 \end{bmatrix}$$

$$\boldsymbol{\Delta c} = \begin{bmatrix} \Delta c_f \\ \Delta c_s \end{bmatrix}$$



Unified orbit feedback

Improvements in orbit feedback settling times from the Unified Feedback Algorithm for Orbit Step Changes



Present APS
User ops at 1.6kHz+10Hz

Present APS
Unified studies at 1.6kHz+10Hz

APSU R&D in Sector-27
Unified studies at 22.6kHz

Unified Feedback Orbit Movie of Sector 28 ID Bump Step Response

- Step Height 50 microns
- 4 ID BPM and 4 fast correctors for the square “fast” response matrix
- 16 BPMs and 4 slow correctors for the “slow” system
- Each movie frame is 44 microseconds of time (22.6 kHz)
- Repeated for:
  - Angle Bumps
  - Vertical plane
  - 16x4 “fast and slow” response matrices

SUMMARY

Small APS-U beam sizes lead to very challenging orbit stability goals

- MBA orbit feedback system must deliver unprecedented beam stability
  - Integration and R&D in sector 27 and 28 has informed diagnostics design
  - R&D has have given the team confidence MBA requirements can be met
- APS-U fast orbit feedback system uses the same architecture and functionality as the 20-yr old APS RTFB, but is implemented using ‘modern’ components
  - 4000-fold increase in performance vs 1995-era processors
  - Hybrid DSP-FPGA processor chosen over FPGA-only implementation (DAQ, AFG, DSP code)
  - Use TBT data to minimize latency
  - Have to properly handle simultaneous operation of longitudinal and orbit feedback
- APS-U fast orbit feedback controller has been prototyped on the present APS
  - Unified feedback algorithm combines fast and slow correctors without compromising spatial or dynamical performance (replaces present ‘woofer/tweeter’ scheme).
  - 22.6 kHz orbit correction rate with 16 bpms and 4 fast correctors per sector per plane.
  - Unique diagnostic and measurement capabilities are built into the controller
  - Developed a model of the system and plan on testing ‘optimal’ control techniques.
  - All key parameters for APS-U fast orbit feedback system design have been demonstrated during beam studies, including 1kHz closed-loop bandwidth

Extra Slides

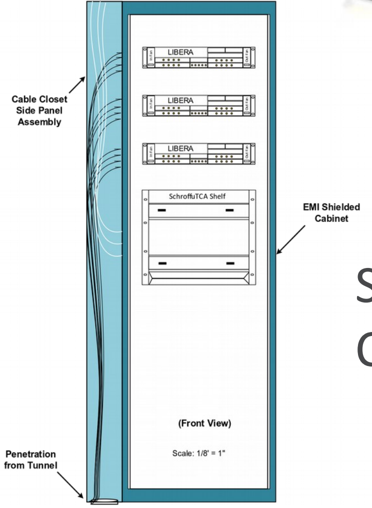
- RF and Xray bpm systems

RF BPMs*

- Baseline design uses Libera Brilliance+ by ITech
  - < 60 nm rms AC noise 0.01 to 1000 Hz
  - < 50 nm pk-pk drift over 7 days
  - < 30 μm single shot rms noise for 1 nC typical commissioning charge levels
- 40 Shielded EMI enclosures for BPMs and feedback system electronics.
- BPM pickup electrode assembly has integrated shielded bellows designed in coordination with vacuum design group.

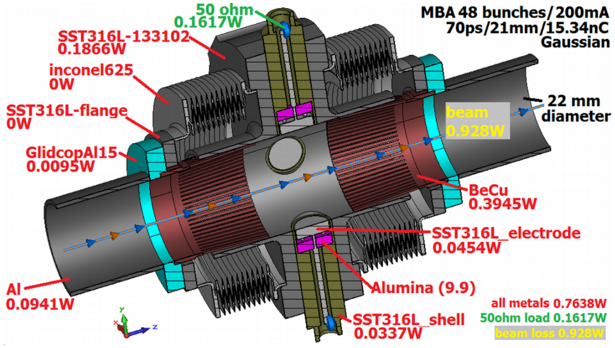
* R. Lill etal. IBIC 2016, Barcelona, Spain 2016
X. Sun etal. IBIC 2017, Grand Rapids, MI, 2017

Libera Brilliance Plus electronics

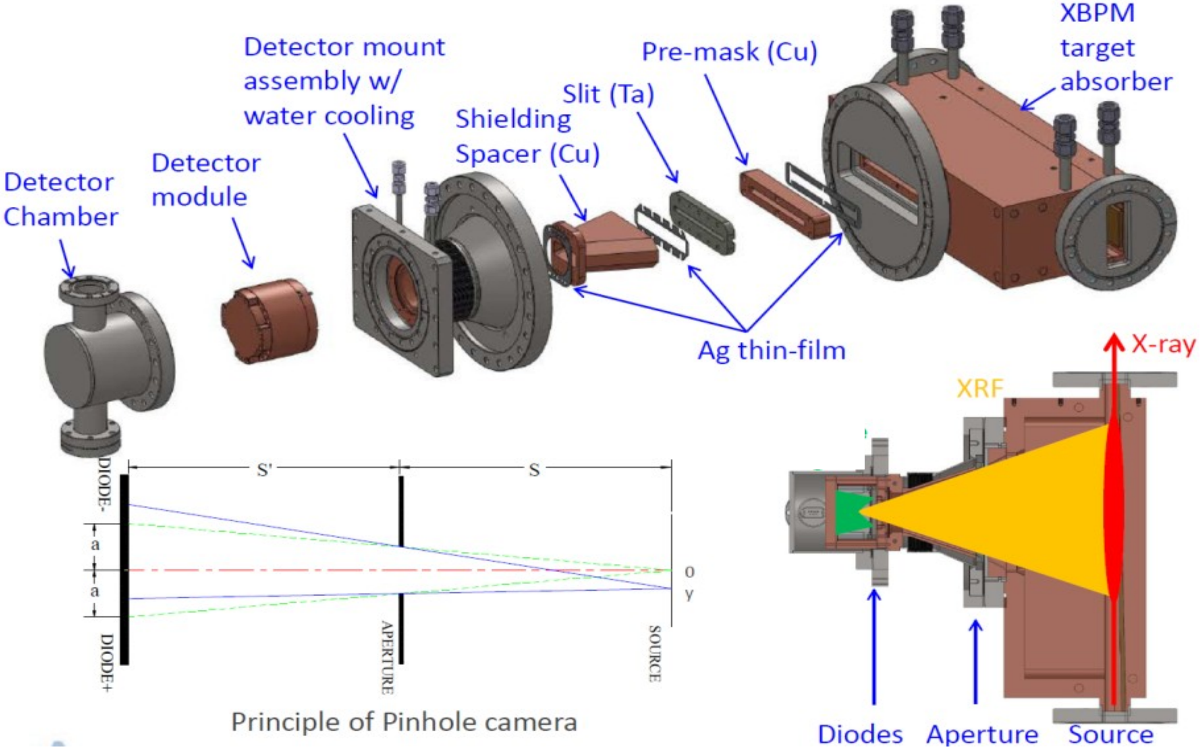


Shielded EMI Cabinets

BPM with integrated shielded bellows



GRID-XBPM Prototype Design*



Principle of Pinhole camera

- 27-ID GRID installed for R&D and User Operations since Summer 2015
- Based on interception of hard X-rays and fluorescence by Cu (GlidCop)
- Vertical position obtained from pinhole imaging by each detector assembly
- Horizontal position obtained from difference over sum between upstream and downstream detectors
- Final engineering of system underway due to higher energy/flux bend magnet/quad backgrounds in 42 pm emittance MBA ring

*B. X. Yang etal. IPAC 2015, Richmond, Va. 2015
B. X. Yang etal. IBIC 2016, Barcelona, Spain, 2016
G. Decker, PAC 2007, Albuquerque, NM, 2007