Fast Orbit Feedback (FOFB) System Design and R&D for the APS Upgrade (APS-U)

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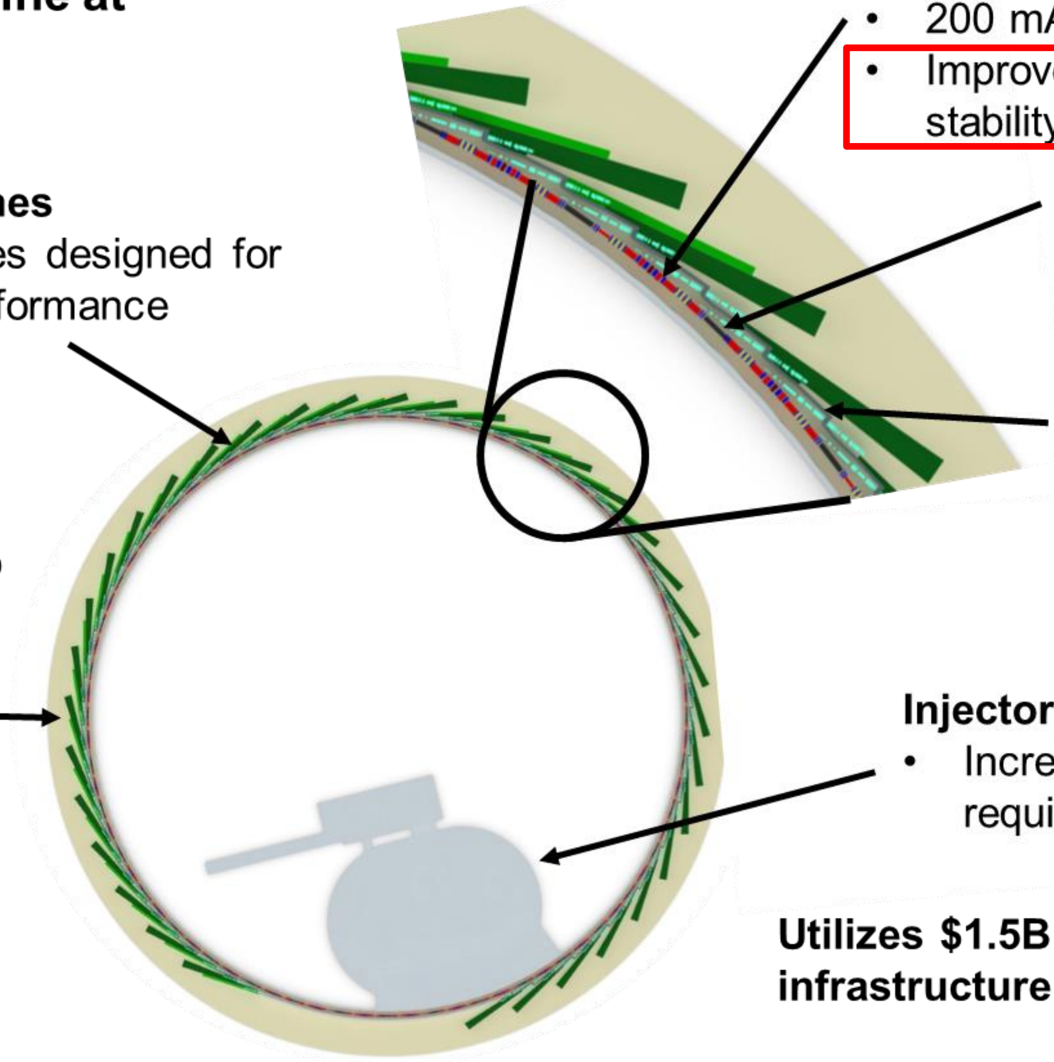
JLAB Seminar 10-19-2023

APS-U Scope

All existing beamlines incorporated in plans to come back online at conclusion of APS-U



New Storage Ring

- 6 GeV MBA lattice
- 200 mA current
- Improved electron/photon stability

New Insertion Devices

- Incorporate SCUs on selected beamlines

Feature beamlines

Suite of beamlines designed for best-in-class performance

New/upgraded Front-ends

- Common design for maximum flexibility

Beamline Enhancements: improvements to make beamlines “Upgrade Ready”

Injector improvements

- Increase performance as required to meet APS-U needs

Utilizes $1.5B in existing infrastructure

APS-U Serves Many User Communities

- Brightness-driven experiments (imaging, spectroscopic, micro/nanoprobes)[1]
- Coherence driven experiments (lensless imaging, correlation techniques) [1]
  - "Traditional" SAXS, PDF, GIXS,… are transformed by coherence to give local rather than average structure
- Optimization to deliver high-energy photons
  - High-pressure, *in situ*, *operando* environments realize enormous gains from combination of all of these enhancements
- Flux-driven experiments (including inelastic scattering, general purpose diffraction)
  - Pinhole flux increases
  - Brightness allows many of these techniques to become microscopies
- Communities served by bending magnets have same or better (~2x) performance
- Timing community
  - Timing mode preserved with greatly improved single-bunch brightness, >2x flux. Ok to lose hybrid mode
  - Fe Mossbauer requires chopper development (under way)
- Macromolecular Crystallography (MX) community
  - APS-U will match beam size to increasingly small crystals
  - Opens possibility for room-temperature serial crystallography

[1] D. Carbone, O. Bikondoa, NIM-B 539, 127-135, 2023

APS-U Performance Goals[1]

- Increase brightness and coherent flux for hard x-rays (>20 keV) of at least 2 orders of magnitude beyond the original APS machine capability
- Increase single bunch brightness for time resolved experiments one to two orders of magnitude beyond the original APS machine capability
- Increase the average flux to twice the original APS machine capability
- Exploiting the use of novel insertion devices (SCUs, Revolvers, Compact HPMU)
- Trade-offs in timing performance are acceptable (longer bunches, shorter bunch spacing)

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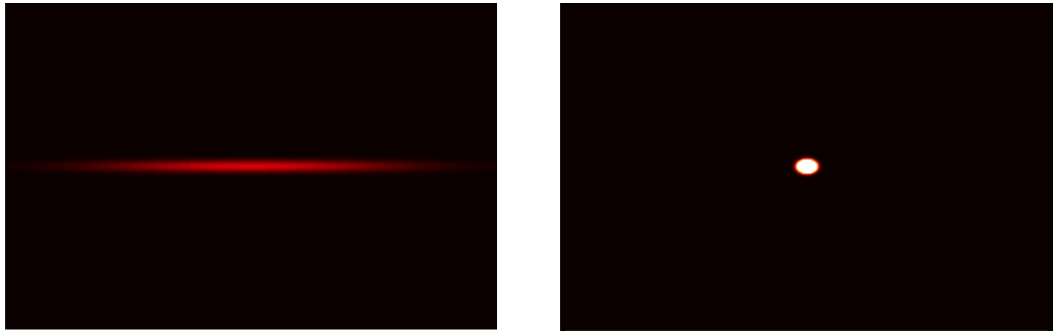
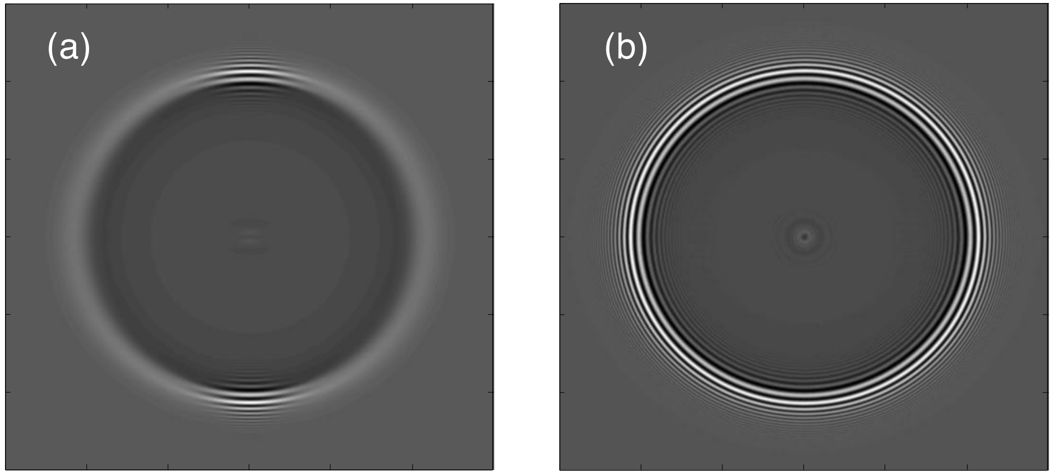
[1] APS-U Final Design Report - https://publications.anl.gov/anlpubs/2019/07/153666.pdf

Flat vs Round Source

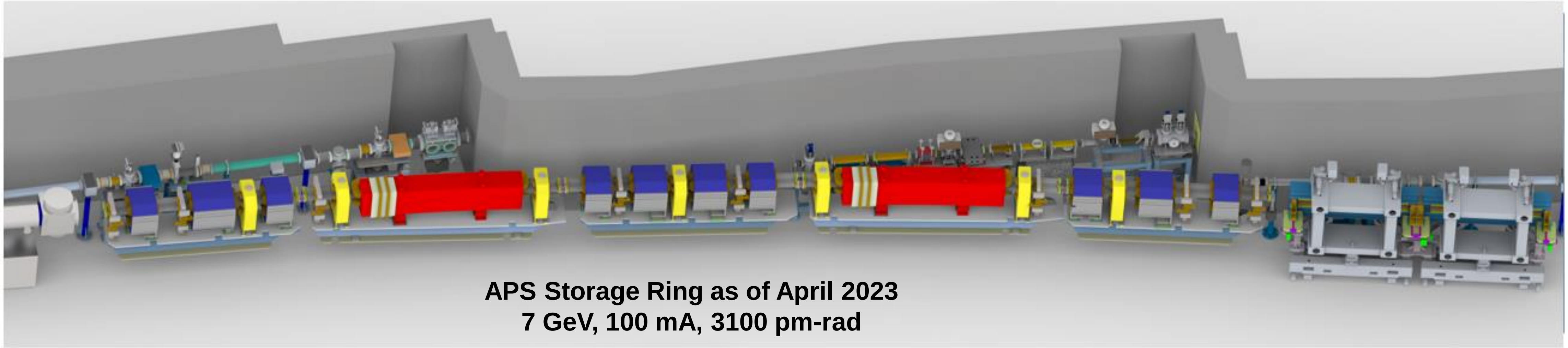
- Flat beams
  - Still have this mode for APS-U
  - Maximizes brightness (50 % increase)
  - Good for 1D focusing and grazing incidence experiments
- Round Beams
  - Ideal for imaging (same spatial resolution in both dimensions with no loss of flux)
  - Same contrast in horizontal and vertical directions
  - Simulated image of water droplet with an air bubble inside (a) with the original APS beam (b) with the APS-U beam



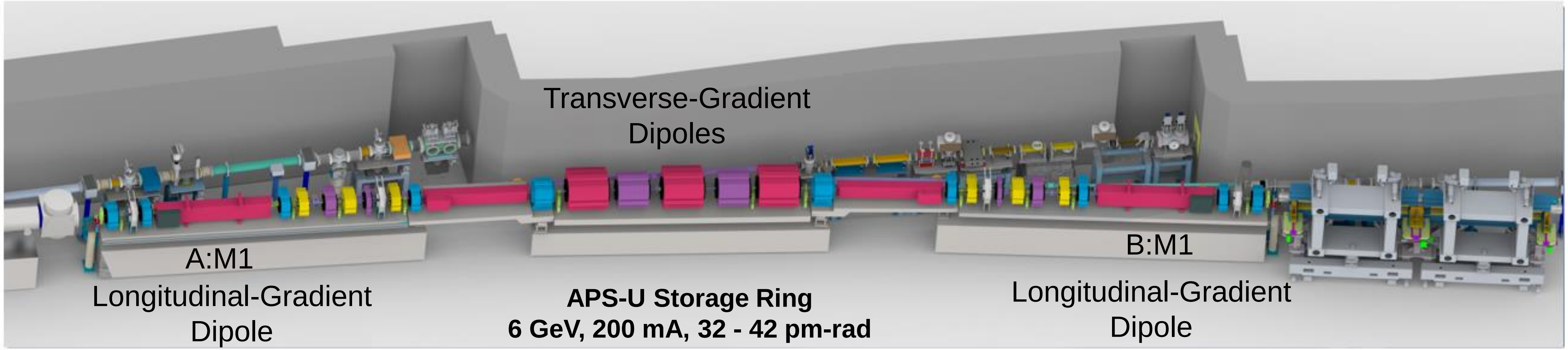
Original APS **APS-U**



APS-U Accelerator Scope



APS Storage Ring as of April 2023
7 GeV, 100 mA, 3100 pm-rad



Transverse-Gradient
Dipoles

A:M1
Longitudinal-Gradient
Dipole

APS-U Storage Ring
6 GeV, 200 mA, 32 - 42 pm-rad

B:M1

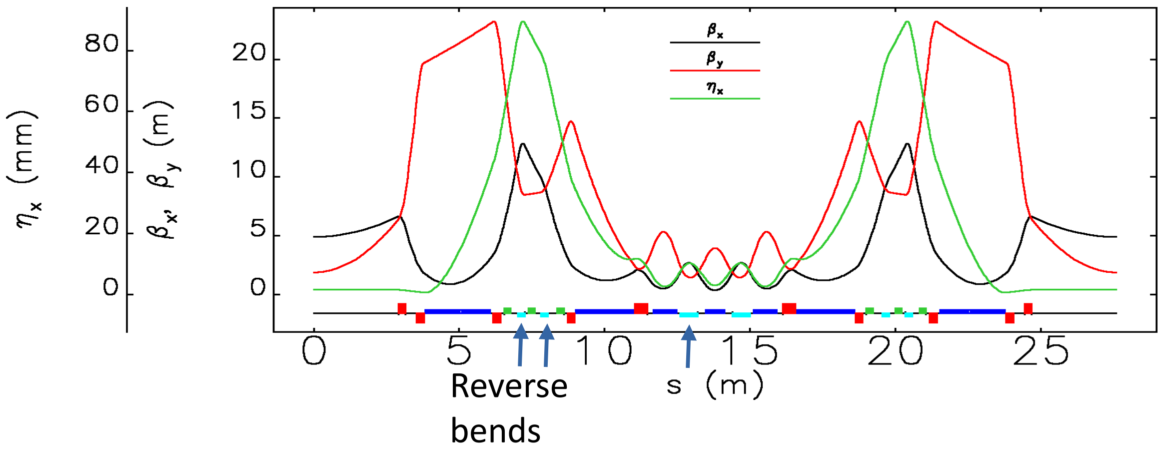
Longitudinal-Gradient
Dipole

Electron Beam Size and Divergence

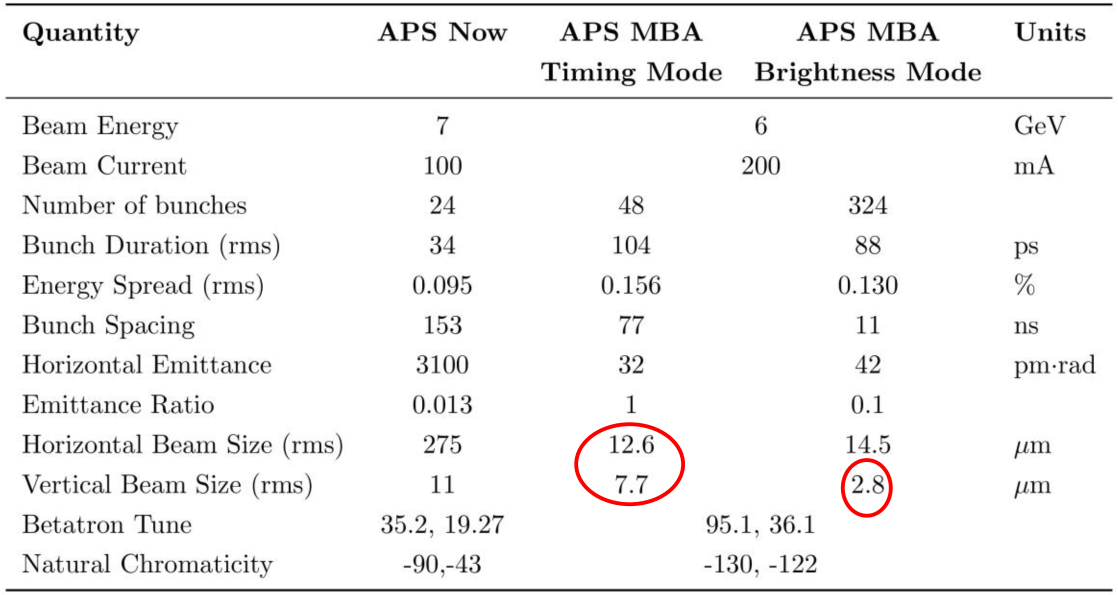
- 4^{th} generation light source beam stability requirements are driven small beam size

$$\sigma = \sqrt{\beta\epsilon + \sigma_E^2\eta^2} \qquad \sigma' = \sqrt{\frac{\epsilon}{\beta}}$$

APS-U MBA Twiss Parameters



APS 3^{rd} Generation and MBA Comparison

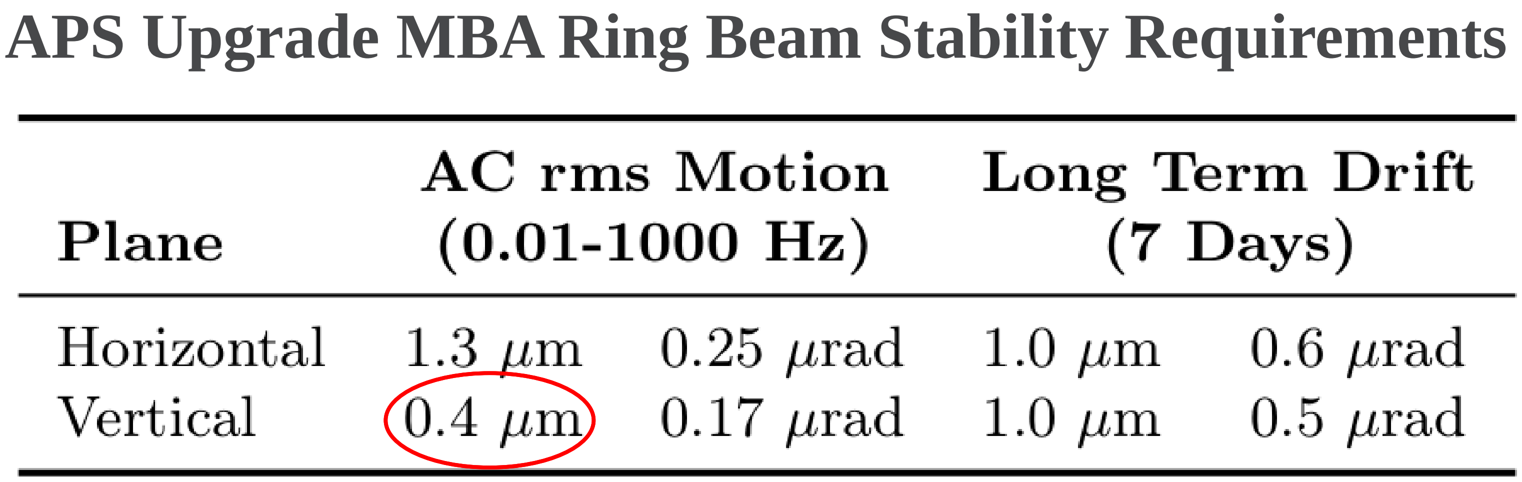


Quantity	APS Now	APS MBA Timing Mode	APS MBA Brightness Mode	Units
Beam Energy	7	6		GeV
Beam Current	100	200		mA
Number of bunches	24	48	324	
Bunch Duration (rms)	34	104	88	ps
Energy Spread (rms)	0.095	0.156	0.130	%
Bunch Spacing	153	77	11	ns
Horizontal Emittance	3100	32	42	pm·rad
Emittance Ratio	0.013	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		

- 3^{rd} generation light source horizontal beam size is typically an order of magnitude larger
  - However vertical beam size is comparable
- Energy/phase oscillations due to coupled bunch modes (CBM) can be a problem due to the dispersion (particularly CBM0 which can be driven by the rf system itself)

Beam Stability Requirements from Beam Size and Divergence

- Beam stability requirements are set at a fraction of the beam size and divergence at insertion device (ID) source points typically ~10 %
- Divided into fast (short) and slow (long-term) rms motion: User experiments are affected by both, in general, depending on type of experiment



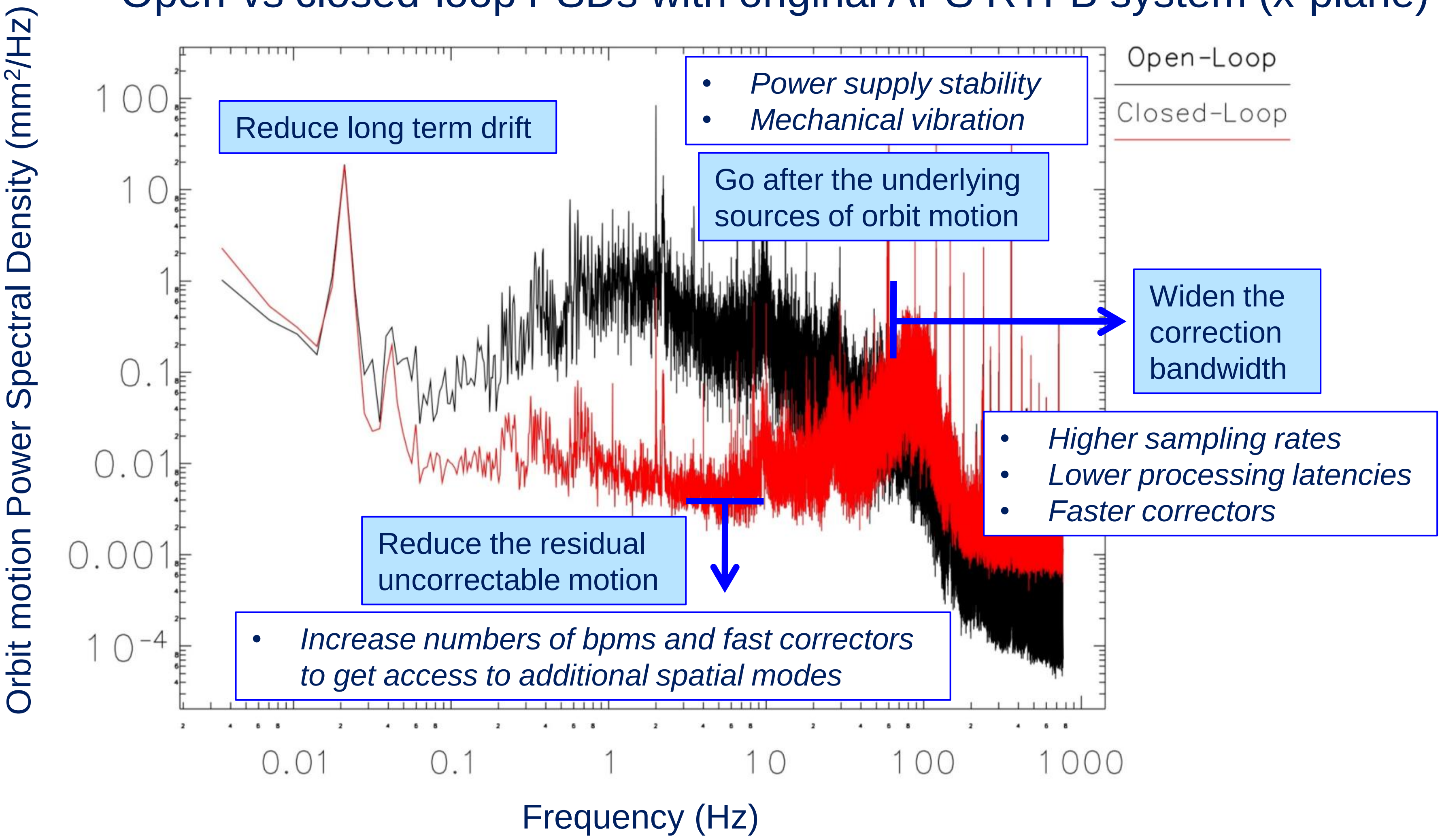
APS Upgrade MBA Ring Beam Stability Requirements

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

Original APS ring had ~5 times these values with bandwidth up to ~100 Hz

FOFB R&D Program Scope

Open-vs closed-loop PSDs with original APS RTFB system (x-plane)



Reduce long term drift

- *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*

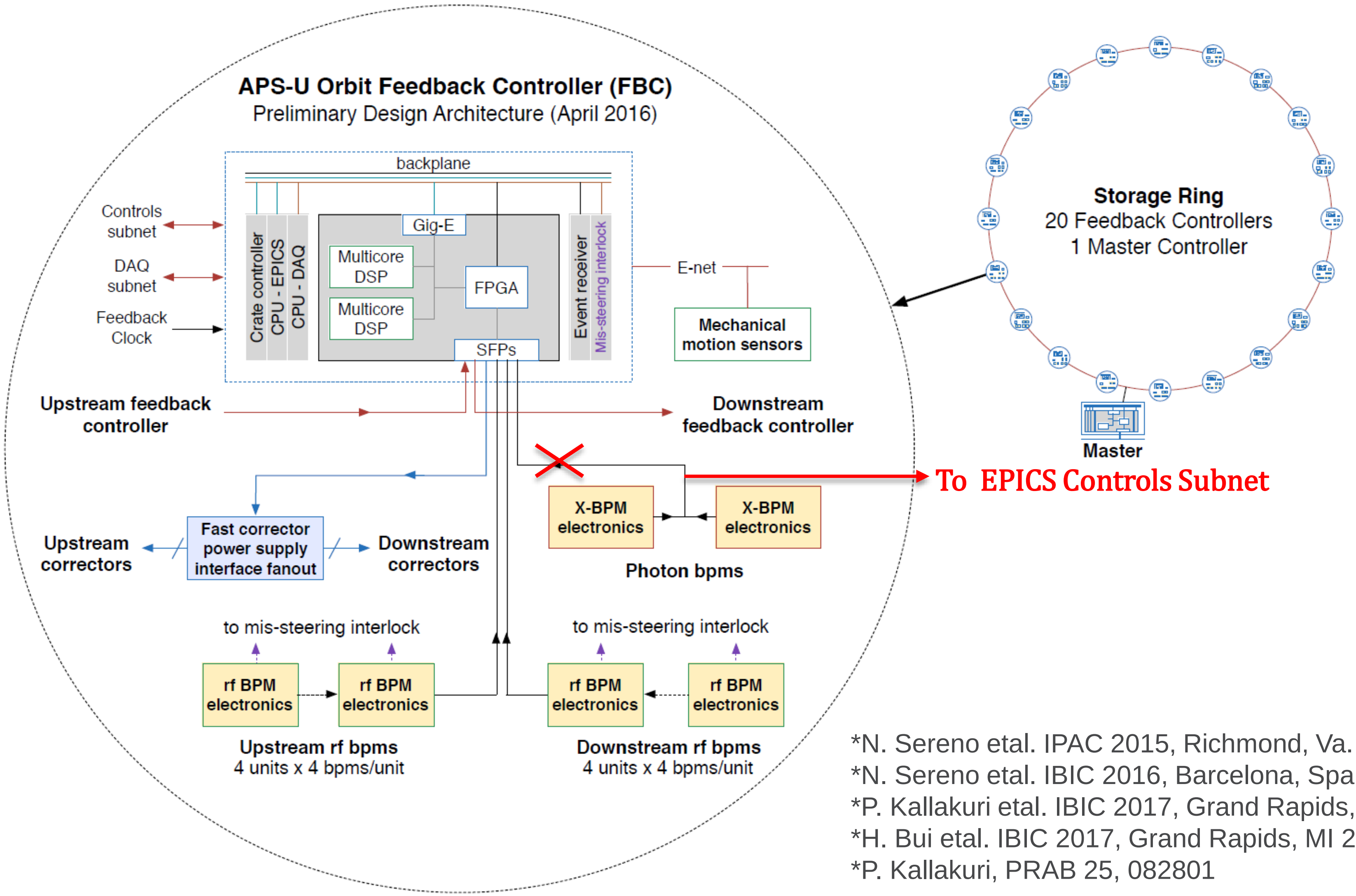
- Typical “original” APS orbit motion spectrum

FOFB High Level Requirements

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	160 (4 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

- Comparison of FOFB requirements to original APS slow and fast 'Datapool' and Real Time Feedback (RTFB) systems

APS-U FOFB 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
*H. Bui etal. IBIC 2017, Grand Rapids, MI 2017
*P. Kallakuri, PRAB 25, 082801

- “Double sector” FOFB architecture

FOFB R&D Program Scope

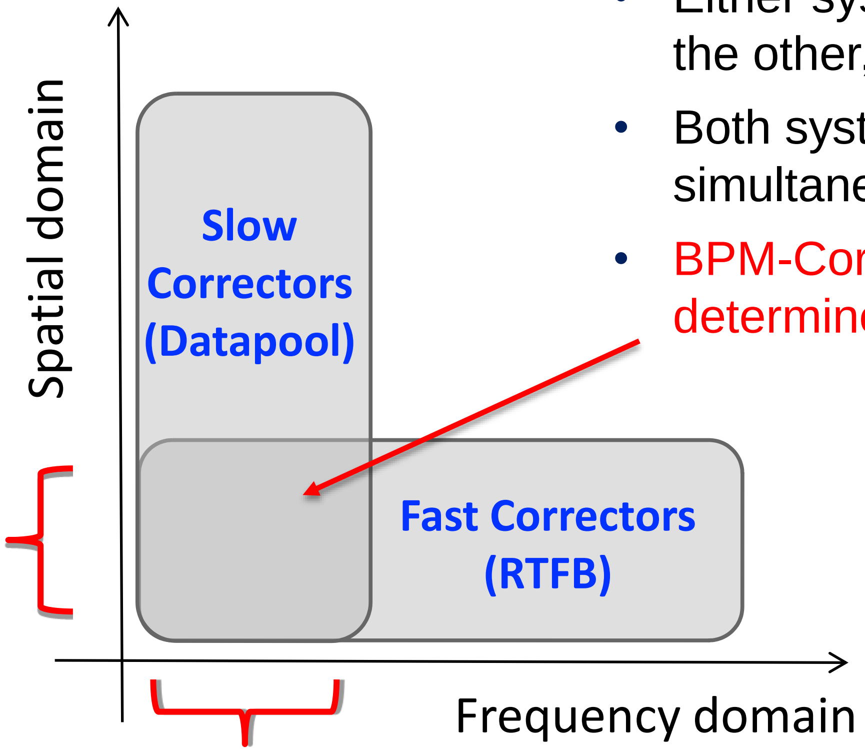
- Tested many of the APS-U feedback system functionality and hardware features using a double sector prototype in sectors 27 and 28 of the original APS
  - Prototype FOFB system feedback controller
  - Libera Brilliance+ bpms
  - New fast and slow power supply controllers
  - Use existing fast and slow correctors in the original APS

- Tested two algorithms using the prototype system and original APS “datapool” and RTFB systems
  - Unified Feedback algorithm combining fast and slow correctors in a single correction scheme at 22.6 kHz
  - Coupled Bunch Mode 0 (CBM0) correction using the FOFB system

R&D program demonstrated the ability of the FOFB architecture, hardware and algorithms to achieve APS-U beam stability requirements

Unified Algorithm - Problem Statement

- Either system can operate stably without the other, **but**
- Both systems go unstable if operating simultaneously
- BPM-Corrector spatial modes are determined by the response matrix (RM)



Both systems have access to this vector space

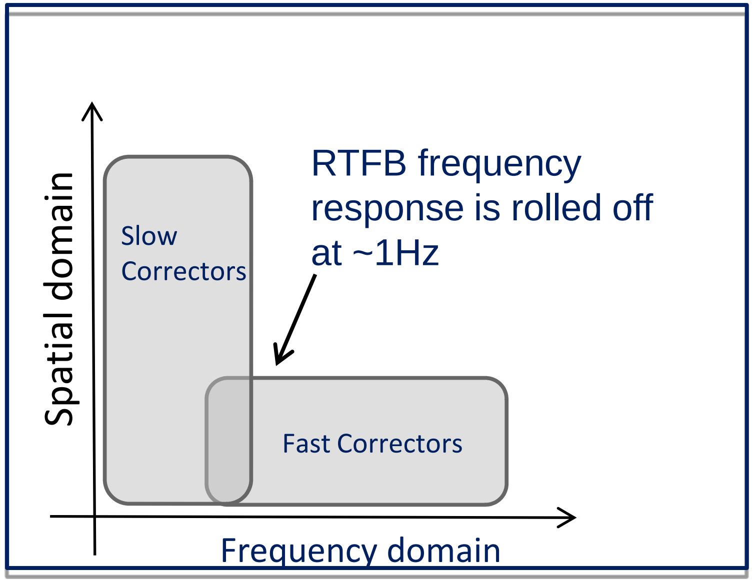
Both systems can respond over this frequency range

- Overlap in spatial and frequency domains for both types of correctors results in instability

Unified Algorithm - Concept

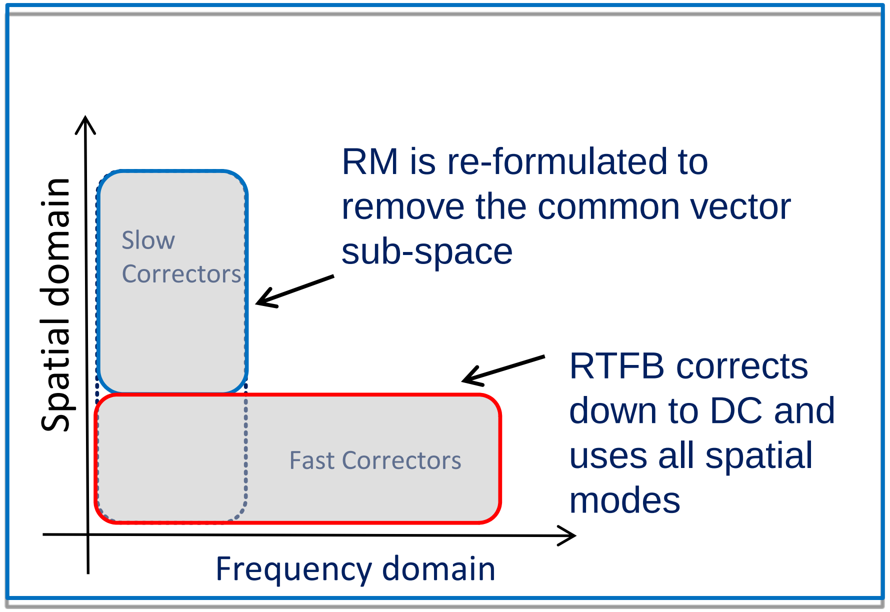
Issue: combination of slow + fast systems is unstable

- Original scheme: Separate into high and low frequency systems (‘woofer/tweeter’ concept)
- Unified scheme: Orthogonalize vector spaces



RTFB frequency response is rolled off at ~1Hz

Original APS scheme using Datapool and RTFB



RM is re-formulated to remove the common vector sub-space

RTFB corrects down to DC and uses all spatial modes

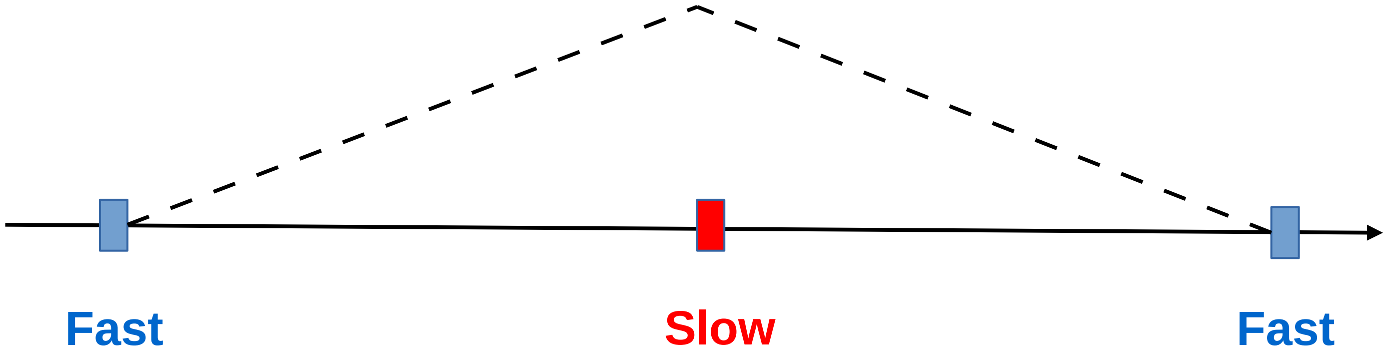
Unified algorithm

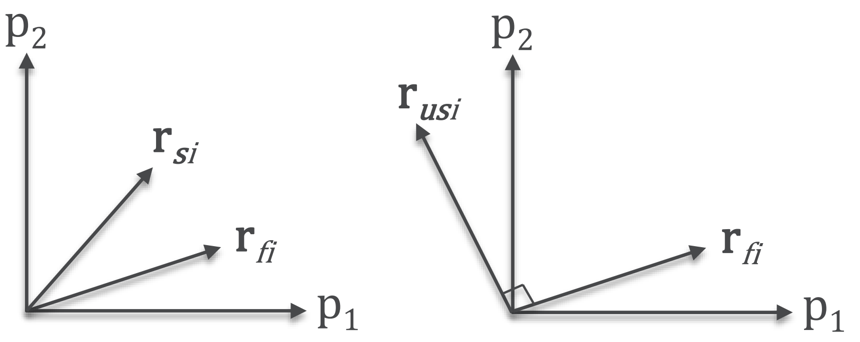
- Unified algorithm: Remove access to the common bpm vector space from the slow corrector response matrix

Unified Algorithm - Response Matrix

- How to modify the response matrix to achieve correction down to DC? First, took an experimental approach:
  - Run the fast corrector system using standard inverse response matrix but down to DC
  - Measure the response matrix for the slow system *with the fast system running down to DC*
  - Invert the measured slow system response matrix and use to run the slow system
- Can calculate the “unified” slow system RM from the calculated or measured RM
- First tested unified algorithm with RTFB and Datapool[1]

$$\begin{bmatrix} R_{ff} & R_{fs} \\ R_{sf} & R_{ss} \end{bmatrix} \begin{bmatrix} \mathbf{c}_f \\ \mathbf{c}_s \end{bmatrix} = \begin{bmatrix} \mathbf{p}_f \\ \mathbf{p}_s \end{bmatrix} \qquad \begin{matrix} \mathbf{c}_f = (R_{ff})^+ \mathbf{p}_f \\ \mathbf{c}_s = (R_{us})^+ \mathbf{p}_s \end{matrix}$$





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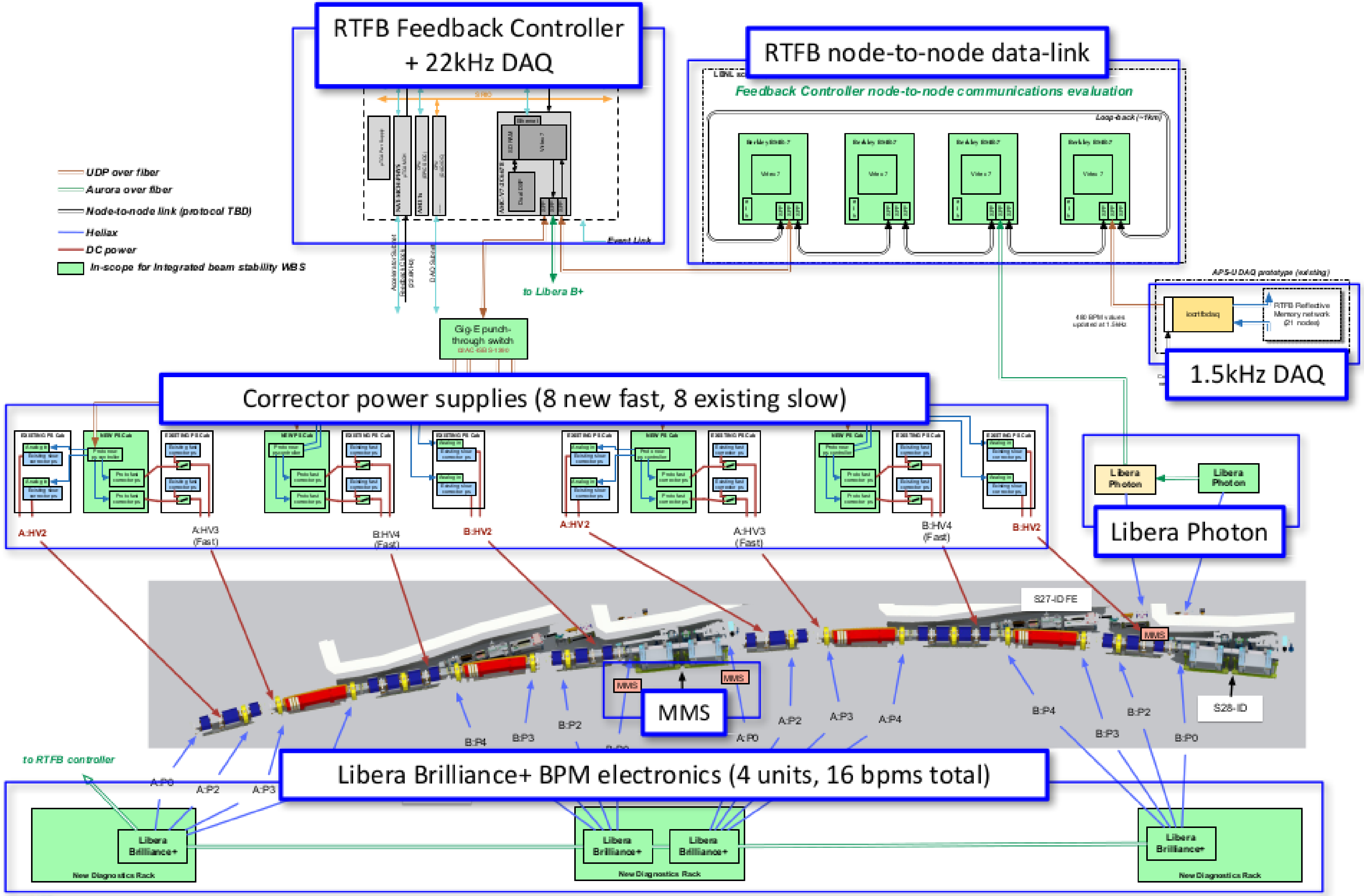
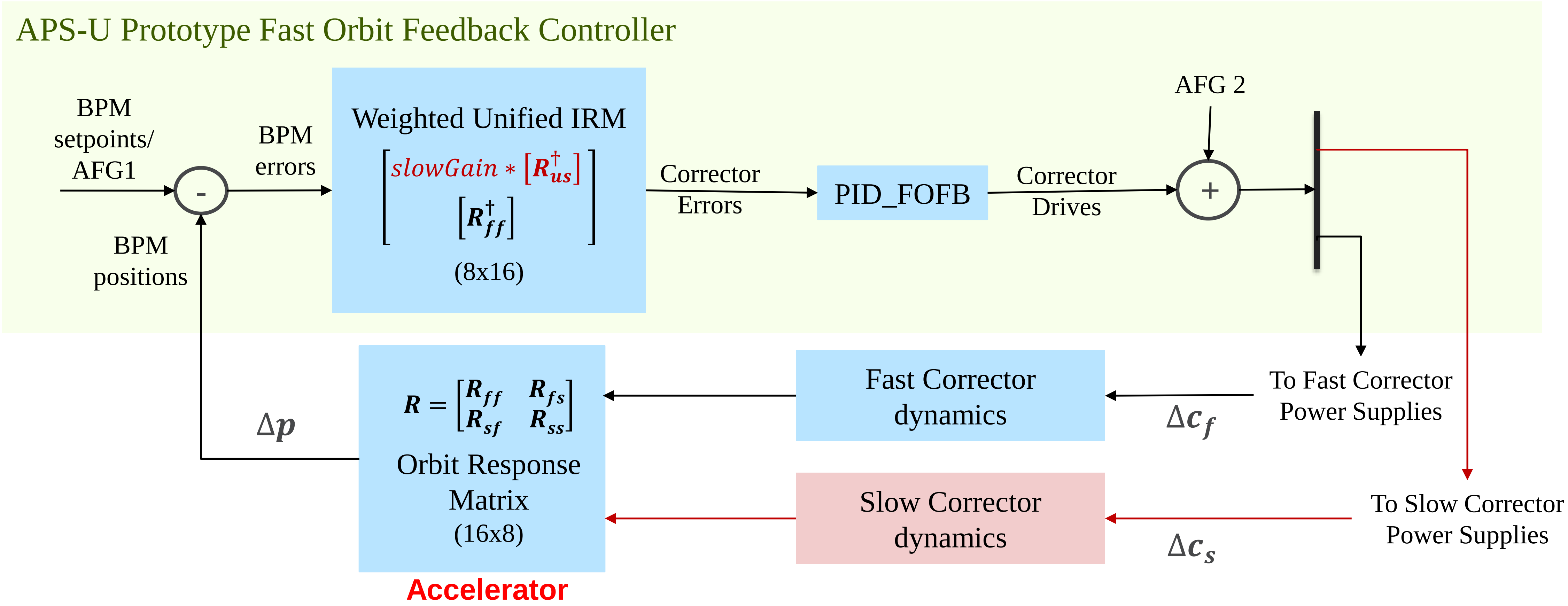
[1] N. S. Sereno etal., “Beam Stability R&D for the APS MBA Upgrade,” IPAC 2015

APS Sector 27, 28 FOFB Prototype System

- Prototype feedback controller
- Libera Brilliance+ BPMs (16)
- New Fast and Slow Corrector Power supply controllers (8 fast, 8 slow)
- Existing APS machine fast and slow correctors
- Fast and slow correctors updated at 22.6 kHz



Unified Feedback Test – Closed loop Experimental Setup and Model[1]

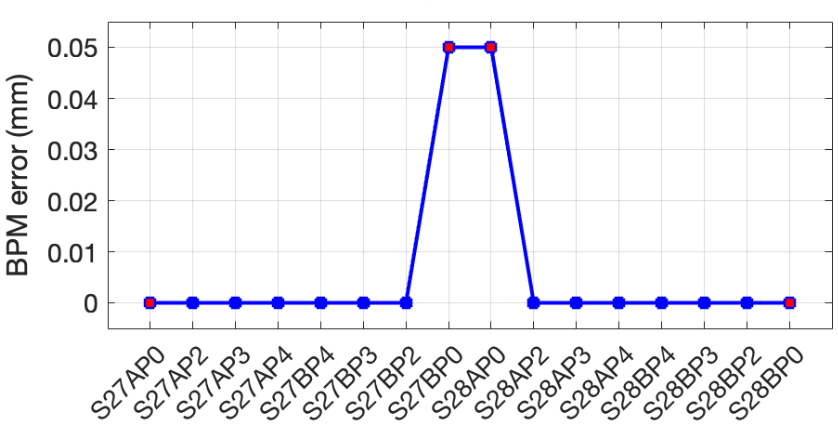


- Single PID controller is used for both fast and slow corrector loops.
- Weighting slow correctors with "slowGain", allows us to use different controller gains for slow and fast correctors.
- First the fast corrector closed loop is stabilized with optimum Ki while keeping slowGain zero.
- The factor slowGain is then ramped up to optimum value, both fast and slow correctors are now used in the feedback loop *receiving their setpoints at 22.6 kHz.*

[1] N.Sereno et.al, DIAG-TN-2018-002

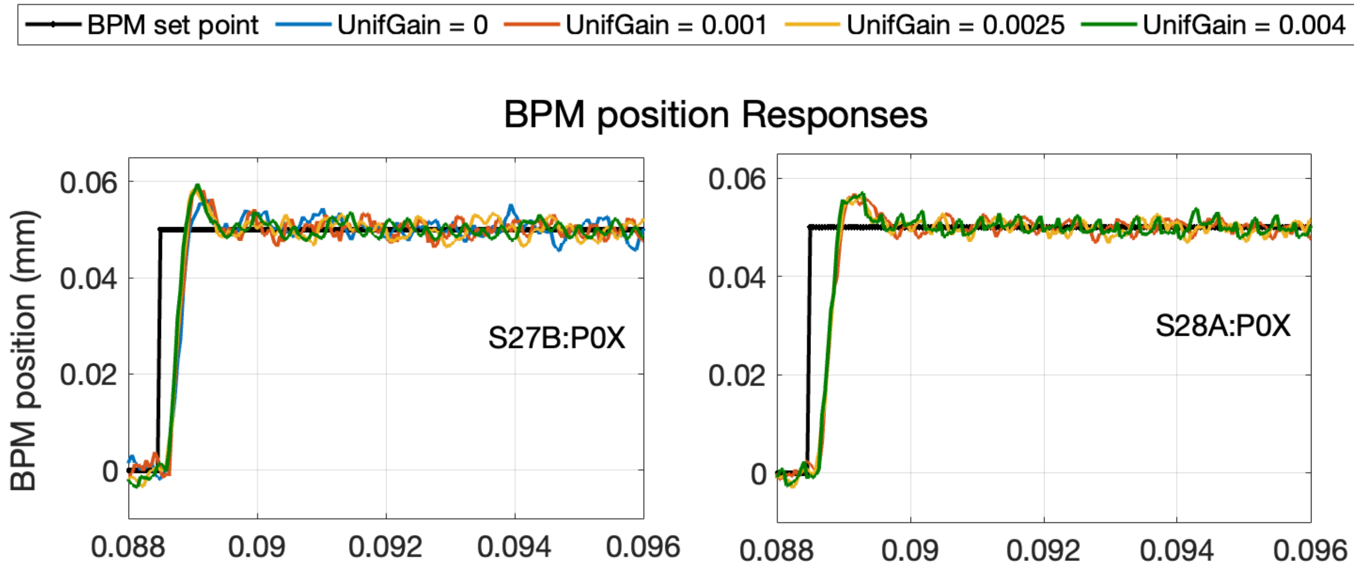
Unified Feedback Test - Horizontal closed loop with 4x4 fast, 4x16 slow IRM – Integral gain only

- Stable closed loop with 4x4 fast IRM, and 4x16 unified slow IRM.
- Ki = 0.2, tried different slowGains upto 0.004.
- Offset and angle bump responses are measured.
- Applied setpoints for 2 P0 bpms are reached.
  - Steady state errors are close to zero.
- Fast system corrects P0s, slow correctors contribute to all 16 BPMs error correction.

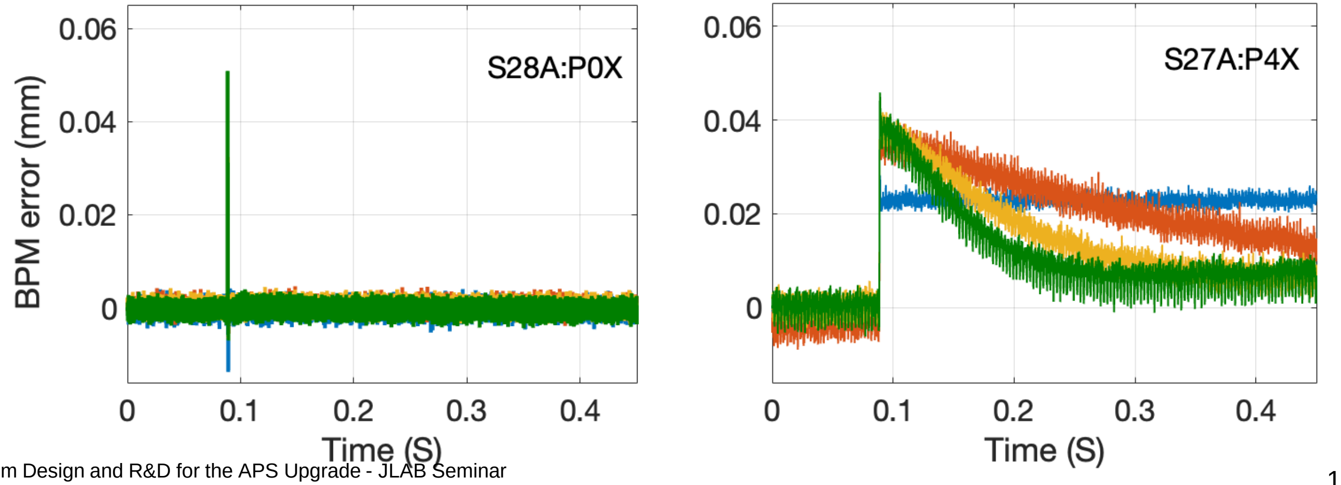


50 um offset bump @S27B:P0X, S28A:P0X

Closed Loop Offset-bump Responses

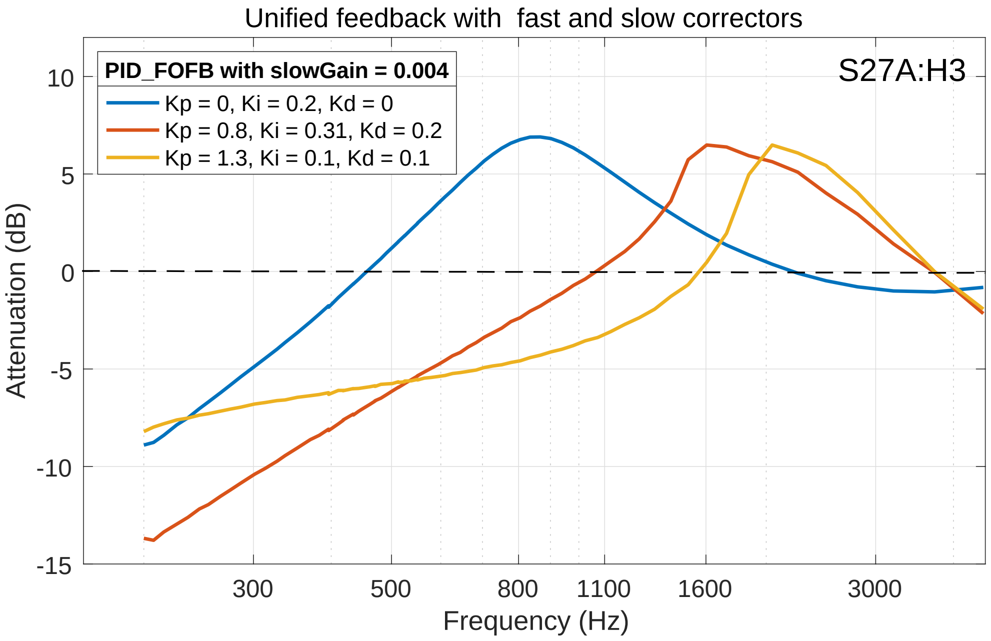


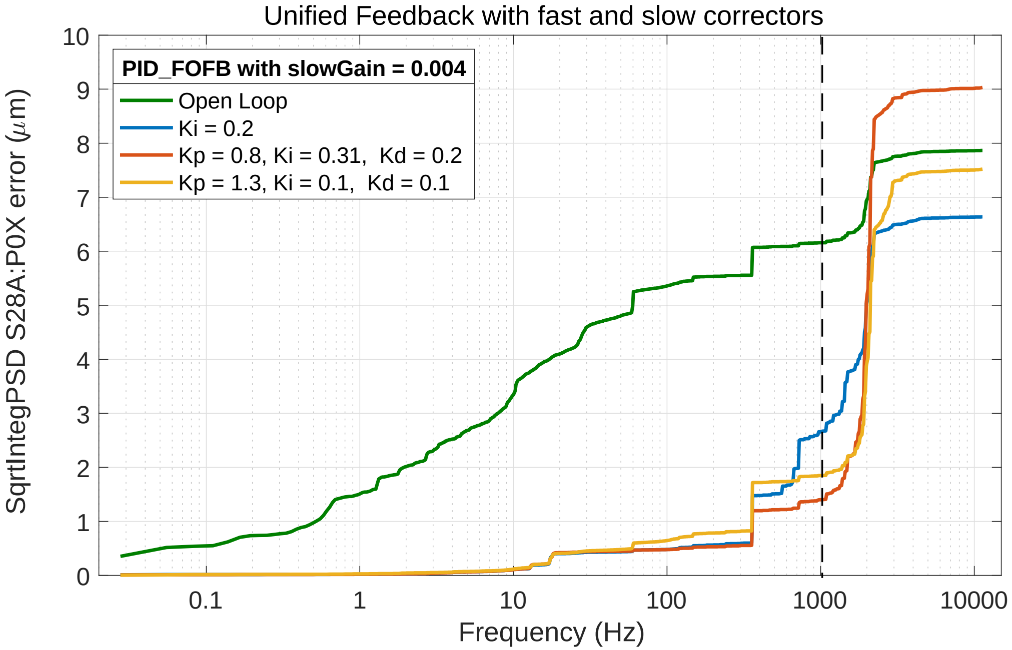
BPM Error Responses



Unified Feedback - Orbit (disturbance) Attenuation Measurements - full PID

- Closed loop bandwidth is obtained from input disturbance attenuation responses.
- Closed loop bandwidth for Ki = 0.2 is ~490 Hz
- With full PID controller we could increase it to more than 1300 Hz
- Simulated with Matlab/Simulink with excellent agreement with experiment





Unified Feedback - Movie

- Movie of insertion device (ID) P0 BPMs 50 μm offset step disturbance-
  - MPL Motif movie: mpl_motif -interval 0.001 < CL_S27B:P0_S28A:P0_Horiz_Unified_50um_Off_X_Orbit_Rise.mpl
  - sddsplot movie:

```
sddsplot -group=page,request -sep=page,request -split=page -layout=1,2 \
    -graph=symb,sca=2,conn -subticksettings=yDivisions=5 -same=y \
    -col=BPMName,X CL_S27B:P0_S28A:P0_Horiz_Unified_50um_Off_X_Orbit_Rise.sdds \
    "-title=Orbit Evolution During Offset Bump Rise" \
    -string=@X_RMSString,p=0.1,q=0.90 \
    -string=@dspFastKiString,p=0.7,q=0.90 \
    -string=@dspSlowKiString,p=0.7,q=0.10 \
    -topline=@TimeString \
    -col=ControlName,H CL_S27B:P0_S28A:P0_Horiz_Unified_50um_Off_H_Corrs_Rise.sdds -mode=y=offset \
    -string=@H_RMSString,p=0.1,q=0.90 \
    "-title=Corrector Evolution During Offset Bump Rise" \
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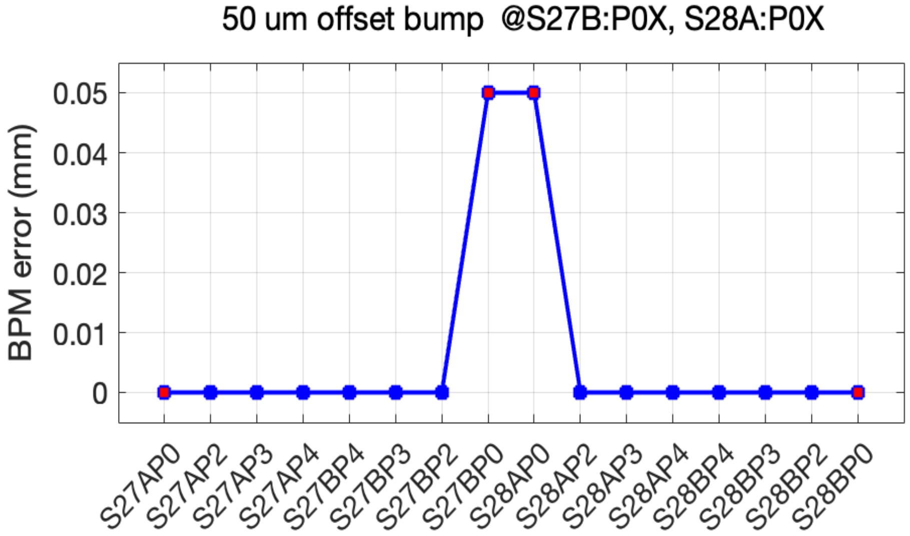


Unified Feedback Algorithm Summary

- Achieved beam stability requirements with this algorithm using original APS fast correctors with ~800 Hz BW (horizontal and vertical planes)
- New fast correctors have a bandwidth of 3.5 kHz
- New fast corrector power supplies have a small signal bandwidth of 10 kHz (keep phase response flat out past 1 kHz)
- Tested more configurations of bpms and fast/slow correctors using this algorithm
  - 4x16 fast correctors used for $\boldsymbol{R}_{ff}$ and 4x16 slow correctors used for $\boldsymbol{R}_{ss}$
  - Tested both horizontal and vertical planes
- First tested with two completely different hardware/software systems: Datapool at 10 Hz and RTFB at 1.5 kHz
- Final test in sectors 27 and 28 used the prototype FBC updating both slow and fast correctors at 22.6 kHz
- A drawback is that the fast correctors operate down to DC and sometimes they are not very strong (NSLS-II)
- Testing a “mid ranging” configuration that keeps the fast corrector DC level near 0 A.

CBM0 Correction using FOFB - Motivation

- Coupled bunch mode 0 (CBM0) oscillations where energy/phase oscillations of all bunches are in-phase with each other, induce horizontal orbit motion at synchrotron frequency.

- The BPMs are sensitive to CBM0 induced motion since they sample all bunch positions and average over 1 turn to give beam position on a Turn-By-Turn (TBT) basis

- The Fast orbit feedback (FOFB) bandwidth in APS-U will be DC-1000 Hz while the synchrotron frequency will lie anywhere between 100 and 560 Hz.
  - This frequency overlap places CBM0 induced horizontal position offsets within the orbit feedback bandwidth range, potentially affecting our ability to achieve APS-U goals for beam stability.
  - Longitudinal feedback kicker amplifier is not strong enough to damp CBM0 oscillations especially those induced by rf system phase and amplitude noise

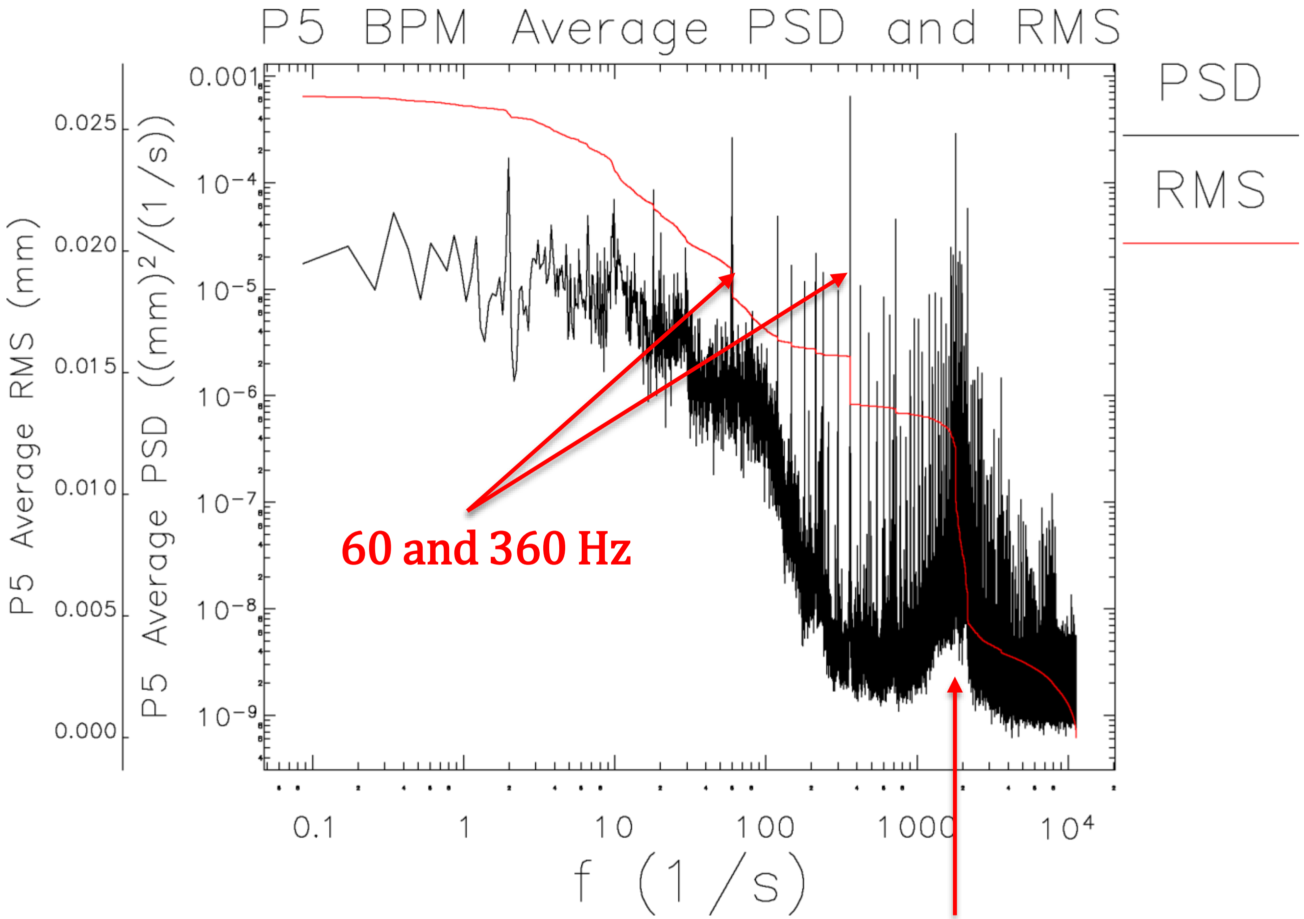
- Comment from Longitudinal Feedback System PDR January 2018 (similar recommendations and comments from Diagnostics CDR and PDRs)

Coupling between the LFB and fast orbit feedback needs to be further investigated analytically and studied on the APS. In particular, how fast orbit motion may couple into synchrotron motion needs to be understood. The prototype fast orbit feedback system at Sector 27 has sufficient bandwidth that the coupling mechanism could be studied at APS, even though the synchrotron tune is much higher than for APS-U.

CBM0 Impact on Orbit Motion in Original APS

- Coupled bunch mode 0 (CBM0) in original APS is primarily due to rf phase noise from 100 kV power supplies for 1 MW klystrons
- This generates large (horizontal) beam motion at the synchrotron frequency ~2.2 kHz
- Phase noise is largest at 360 Hz but is present for all harmonics of 60 Hz
- Our approach is to feedback to the LLRF system klystron phase setpoint to reduce the synchrotron motion
- Suppression of 60 Hz harmonics is planned by addition of a notch-filter noise suppression system in the LLRF for APS-U (test of prototype hardware completed in the original APS)

Horizontal BPM "P5" Motion Spectrum in Sector 27



60 and 360 Hz

Synchrotron Frequency

CBM0 Experiment and Simulation Outline

- New orbit to RF phase feedback configuration to suppress CBM0 oscillations,
  - Beam position measurements at dispersive bpms are dynamic inputs
    - CBM0 effect shows up on each dispersive bpm as a position oscillation at the synchrotron frequency.
  - Low level RF (LLRF) phase is used as actuator
    - Feedback controller generates RF phase setpoint using energy induced component extracted from measured orbit.

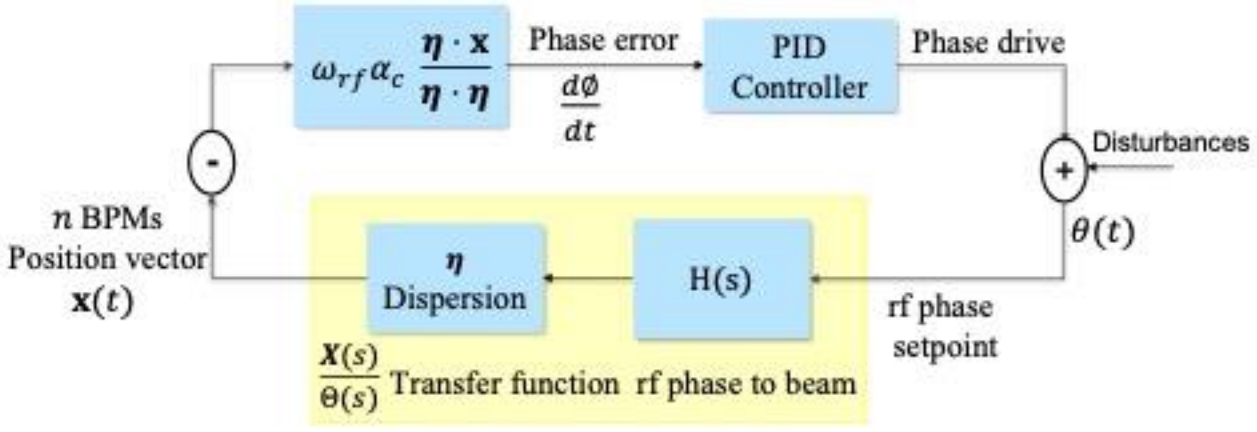
- Proof of concept experiments using 7 GeV operations lattice (20 bunches, 20 mA)
  - Synchrotron frequency is outside the orbit feedback bandwidth
  - Demonstrated orbit feedback operation together with CBM0 correction in experiments and simulations

- Experimental study with 6 GeV low-alpha lattice configuration (using APS RTFB, 20 bunches 14 mA
  - Synchrotron frequency is inside the orbit feedback bandwidth resembling APS-U
  - Demonstrated CBM0 correction within the orbit feedback bandwidth

Orbit to RF Phase Feedback Configuration[1]

- Feedback model to suppress CBM0 oscillations is developed based on synchrotron oscillation theory.
- Derivative of phase error is computed using dispersion and measured position at dispersive bpms,

$$\frac{d\emptyset}{dt} = \omega_{rf}\alpha_c \frac{\boldsymbol{\eta} \cdot \mathbf{x}}{\boldsymbol{\eta} \cdot \boldsymbol{\eta}} \ldots (1)$$



Closed loop schematic of proposed orbit to RF phase feedback method

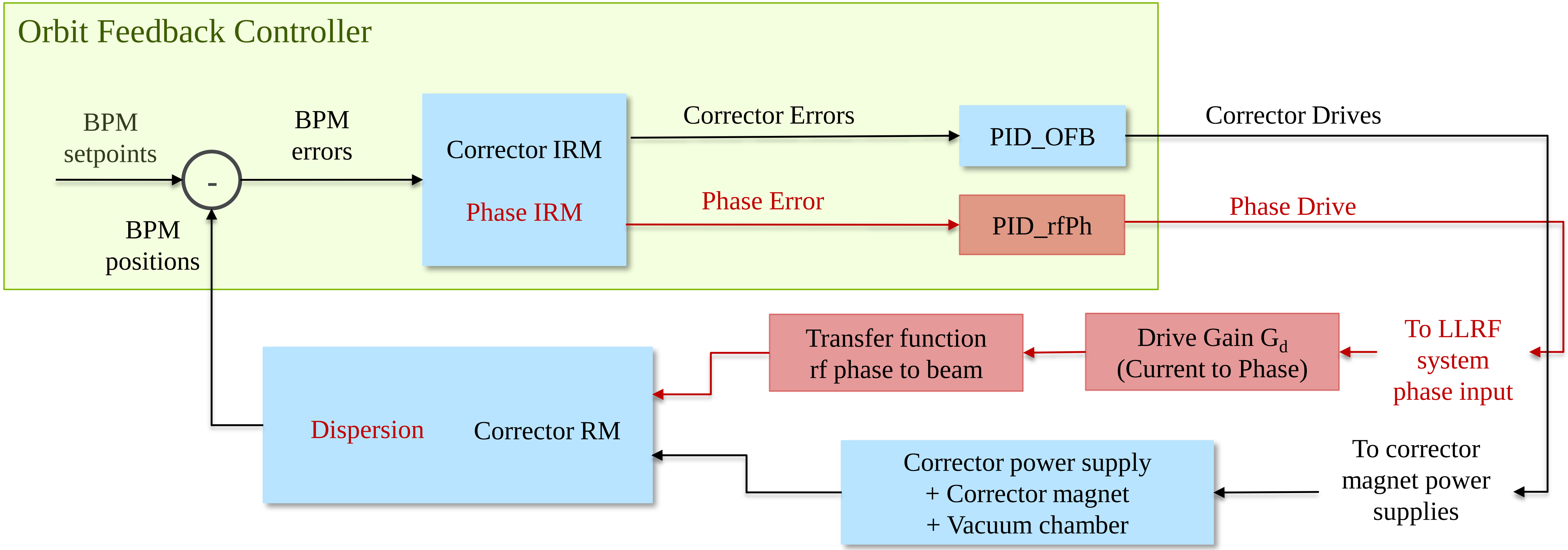
$\mathbf{x}$ - *Horizontal position deviation*
$\boldsymbol{\eta}$ - *Dispersion*
Φ - *Beam phase*
ω_{rf} - *RF frequency*
α_c - *Momentum compaction factor*
α_s - *Damping rate*
Ω - *Synchrotron frequency*
θ - *RF phase noise*

- Transfer function from rf phase noise to beam position deviation represents the open loop dynamics.
  - Under damped harmonic oscillator with resonant peak at synchrotron frequency.

$$H(\mathrm{s}) = \frac{\Omega^2}{\omega_{rf}\alpha_c} \frac{s}{s^2 + 2s\alpha_s + \Omega^2} \ldots (2)$$

1. P. Kallakuri et al., PRAB **25**, 082801

Experimental setup – Orbit feedback controller with RF actuator

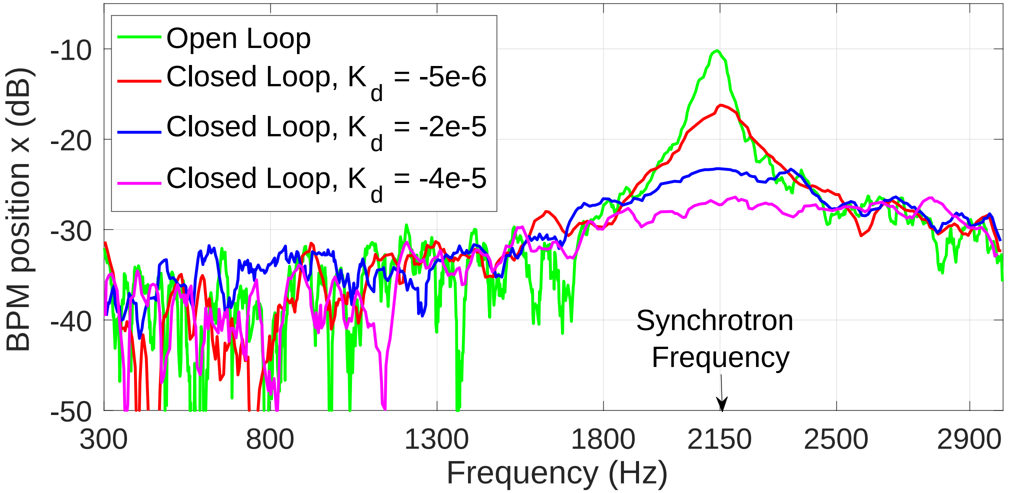


- Phase computations are incorporated as additional row in Inverse Response Matrix (IRM) dot product.
- RF phase control signal is generated as if it were another corrector drive in the orbit feedback algorithm.

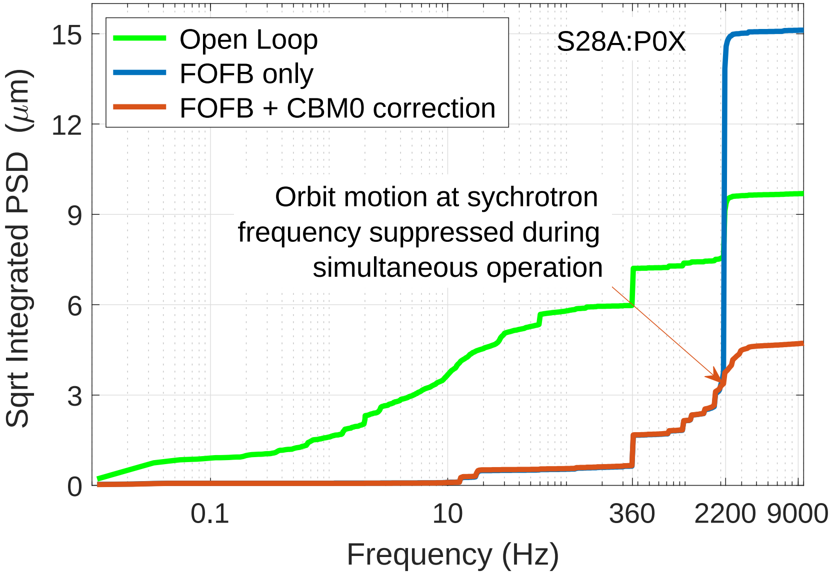
Proof of concept experiments with operations lattice using FOFB Prototype:

Synchrotron frequency outside orbit feedback bandwidth

- Coupled bunch mode zero correction is demonstrated using,
  - APS-U prototype FOFB system (sectors 27 and 28 of original APS) with 22.6 kHz sampling rate, 4 fast correctors and 12 BPMs.
  - Operations lattice where synchrotron frequency (2.2 kHz) is outside the FOFB bandwidth (920 Hz).



Chirp responses showing synchrotron frequency suppression



Orbit motion at sychrotron frequency suppressed during simultaneous operation

Comparison of measured AC rms orbit motion

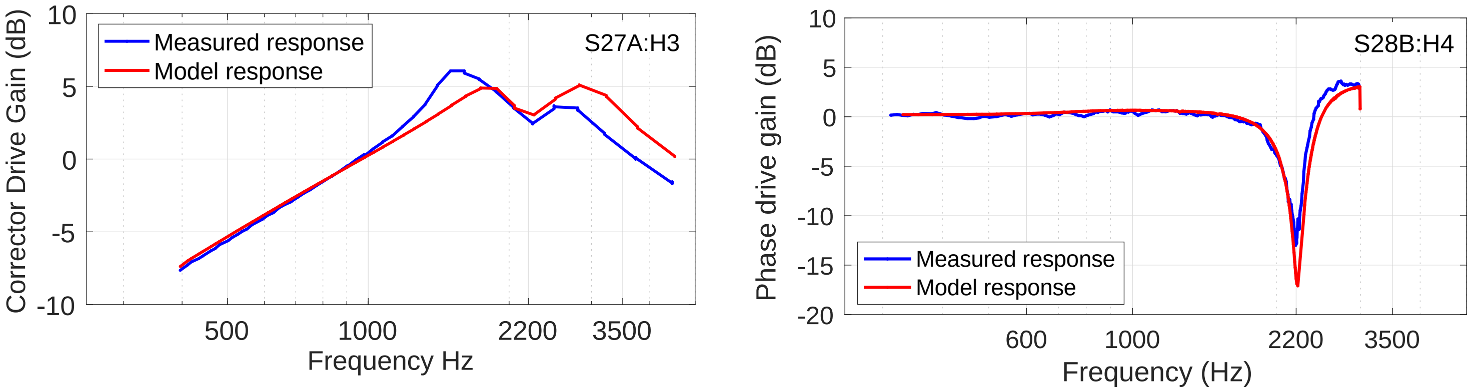
- Achieved significant suppression around synchrotron frequency with orbit to RF phase feedback.
- Stable FOFB + CBM0 correction
  - Retained 920 Hz orbit feedback bandwidth.

PRAB **25**, 082801

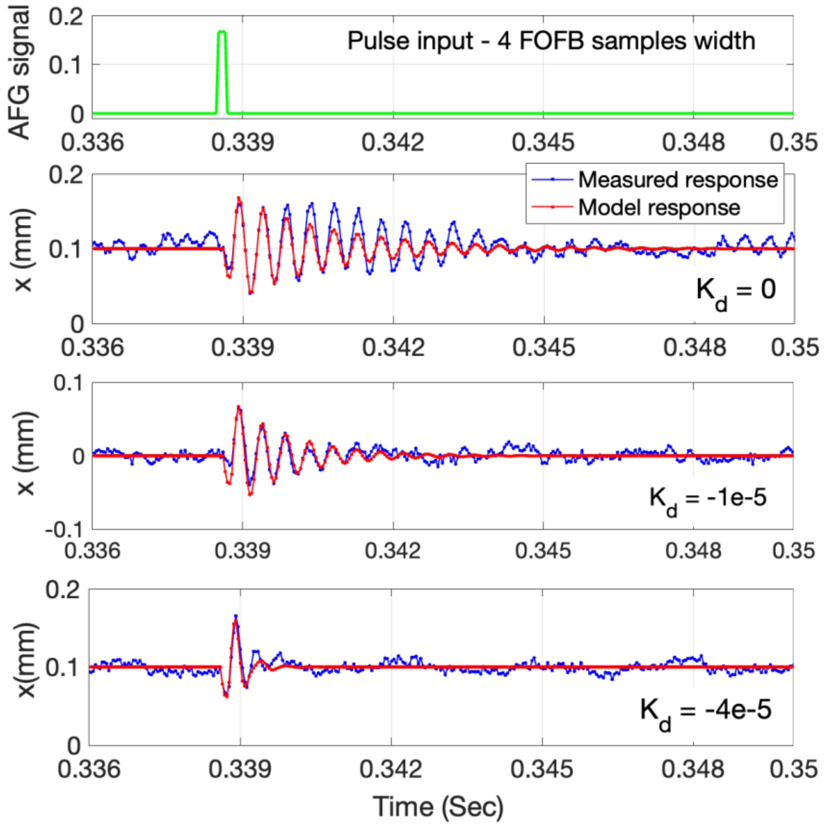
Simulation model for prototype FOFB + CBM0 correction

- Developed a MATLAB/simulink model for prototype FOFB+CBM0 correction setup using theoretical knowledge and measurement-based system identification.
- Open loop and closed loop simulation models are validated by comparing model responses against measurements.
- Used 4 fast correctors and 12 BPMs

Simulation responses are in good agreement with measurements.



Simulation vs Measurements – Input disturbance attenuation at corrector and phase drives



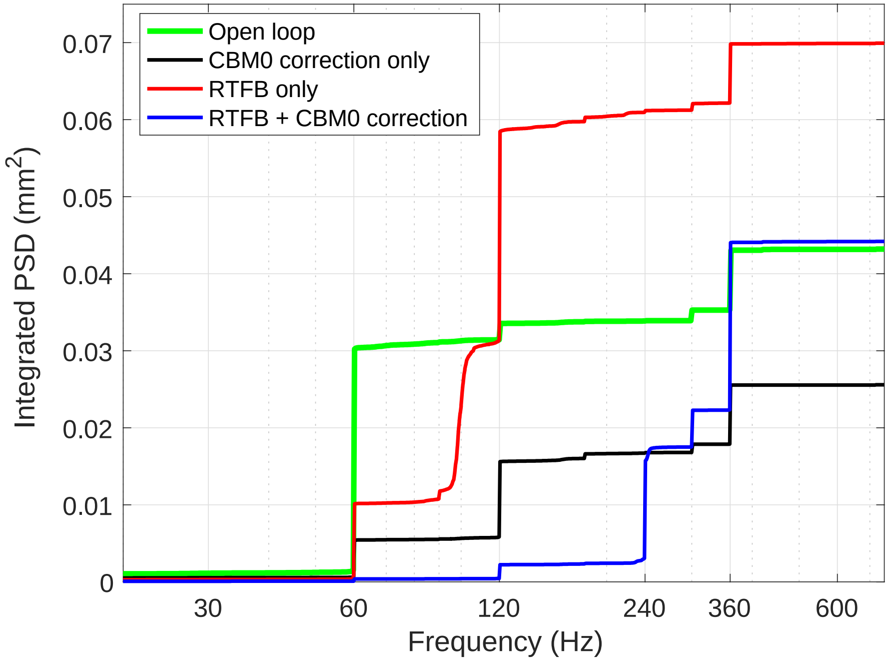
Simulation vs Measurements - Horizontal position responses to pulse input at Phase drive

PRAB **25**, 082801

Coupled bunch mode zero correction within orbit feedback bandwidth:

Experimental study with low-alpha lattice

- 6 GeV low-alpha lattice configuration: Synchrotron frequency (60 Hz) is within the orbit feedback bandwidth (90 Hz).
  - RF system noise at 360 Hz and other 60 Hz harmonics is larger compared to operations lattice.
- Real time feedback system (RTFB) is used - Orbit feedback system for APS operations
  - 38 fast correctors and 154 BPMs to deal with large noise in low-alpha lattice.



Cumulative mean square orbit motion with different feedback configurations

- Stable combined operation of RTFB + CBM0 correction.
- Orbit to RF phase feedback and RTFB are correcting respective energy and betatron 60 Hz components when operated individually.
- More suppression at 60 Hz with both feedbacks running together due to the combined effect.

CBM0 Correction Algorithm Summary

- Successfully demonstrated CBM0 correction:
  - With APS standard lattice where the FOFB bandwidth is < synchrotron frequency
  - With APS low-alpha lattice where the synchrotron frequency (60 Hz) is within RTFB system bandwidth
- Energy component of beam motion is extracted from the measured orbit and an rf phase control signal created and applied to klystron LLRF to correct CBM0 motion
- The combination of CBM0 correction and RTFB was significantly more effective in suppressing synchrotron frequency.
- Cannot correct amplitude and phase errors in the LLRF/Klystron system at various 60 Hz harmonics:
  - Developing a dedicated LLRF notch filtering system for this
- Can remove the CBM0 energy oscillation part of the beam motion at each bpm even if this idea is not used in feedback
- We plan on having an SFP fiber link from FOFB to the LLRF for APS-U for an application in the future

Summary

- Successfully demonstrated a unified feedback algorithm in sector 27 and 28 of the original APS ring based on modification of the response matrix
- Successfully demonstrated CBM0 correction within the orbit feedback bandwidth via experiments with standard and low-alpha lattices
- Tested many other systems required to meet APS-U beam stability specifications:
  - Mechanical motion sensing system
  - X-ray bpms and associated electronics
  - FOFB fast fiber data network
  - Data acquisition systems at 22.6 kHz and TBT (271 kHz) rates for diagnostics, power supply and rf systems
  - Libera Brilliance+ BPMs for the storage ring
  - KEK rf switch and Libera Sparks for single bunch injection position measurements
  - Prototype APS-U button bpm assembly and Libera Brilliance+ bpm electronics
  - Tunnel air and water temperature stability systems

Acknowledgements

ASD Diagnostics

P. Kallakuri, N. Sereno, A.Brill, H. Bui, R. Blake, P. Dombrowski,
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ASD Physics

L. Emery, V. Sajaev, M. Borland, M. Sangroula, H. Shang, A. Xiao

ASD Controls

S. Shoaf, N. Arnold, S. Xu, G. Shen, S. Veseli, T. Fors, D. Paskvan, A. Pietryla

ASD RF group

T. Berenc, T. Madden, D. Horan

ASD Power Systems

J. Wang, B. Deriy

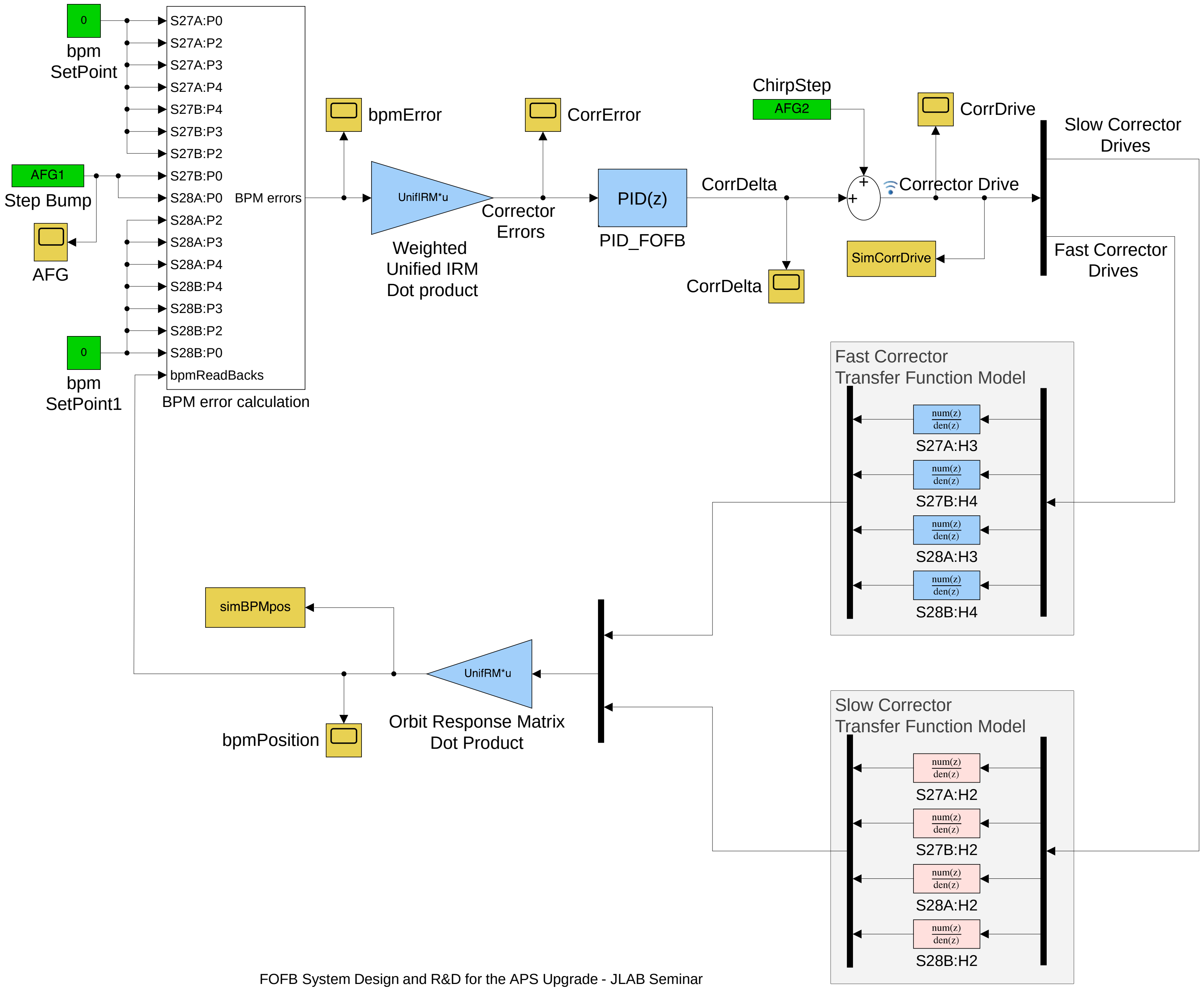
ANL Facilities

M. Kirchenbaum, S. Stewart, G. Kailus, D. Kazenko

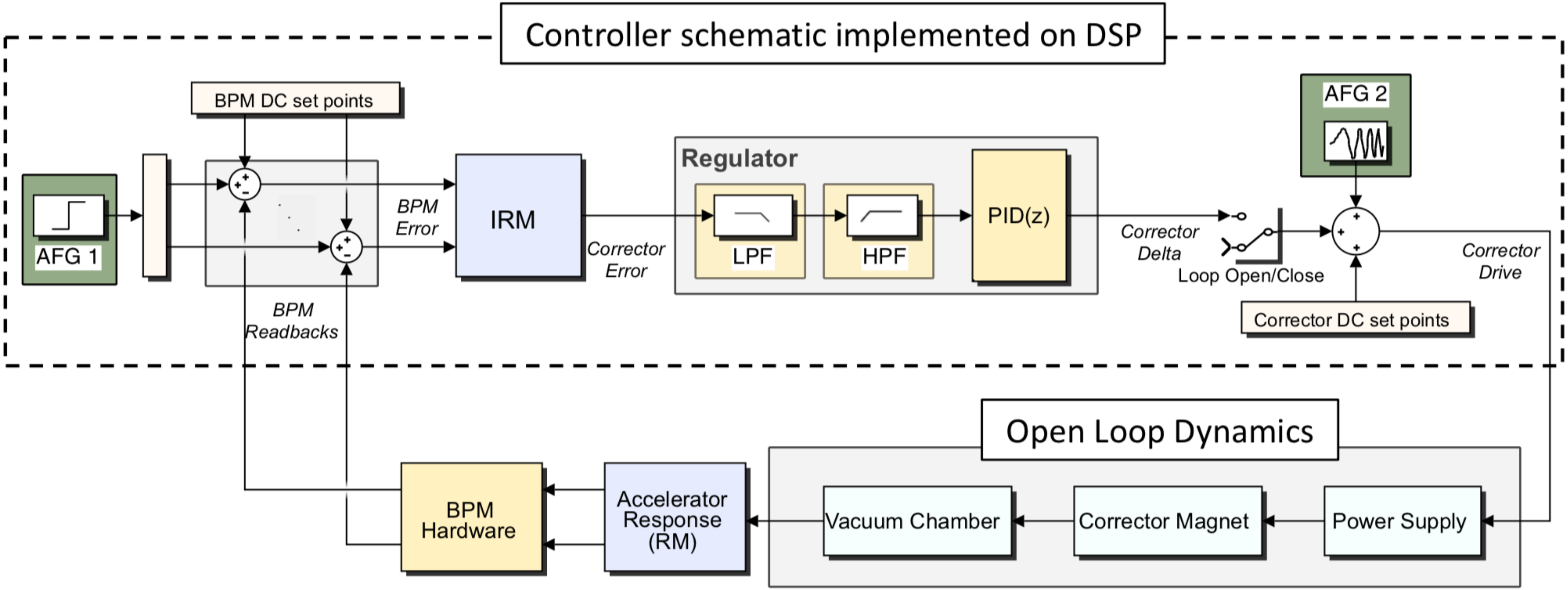
Extra Slides

Matlab/Simulink Modelling and Validation
S27 prototype in unified feedback configuration
-Horizontal plane results (Sirisha Kallakuri)

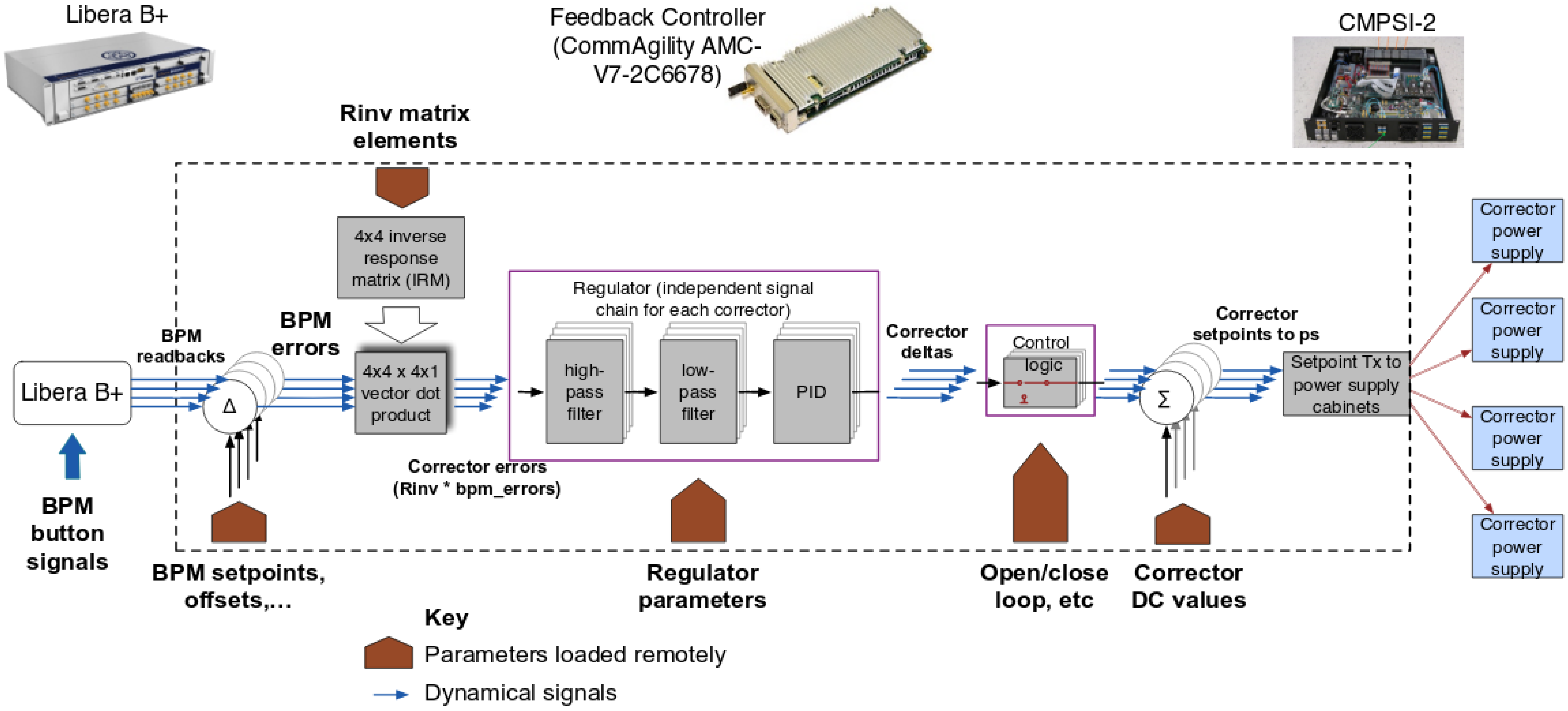
Matlab/Simulink model Unified Feedback for S27 prototype



Feedback Loop Main Blocks for Modelling



Prototype System Hardware/Configuration



Libera B+

Feedback Controller
(CommAgility AMC-
V7-2C6678)

CMPSI-2

Rinv matrix elements

4x4 inverse response matrix (IRM)

Libera B+

BPM readbacks

Δ

BPM errors

4x4 x 4x1 vector dot product

Corrector errors (Rinv * bpm_errors)

Regulator (independent signal chain for each corrector)

high-pass filter

low-pass filter

PID

Corrector deltas

Control logic

Σ

Corrector setpoints to ps

Setpoint Tx to power supply cabinets

Corrector power supply

Corrector power supply

Corrector power supply

Corrector power supply

BPM button signals

BPM setpoints, offsets,…

Regulator parameters

Open/close loop, etc

Corrector DC values

Key

▨ Parameters loaded remotely

→ Dynamical signals

Matlab/Simulink model for prototype FOFB + CBM0 correction

- Open loop dynamics of orbit to rf phase feedback $\widetilde{H}_d[z]$ are modeled using measurements and storage-ring parameters.
  - Continuous transfer function model

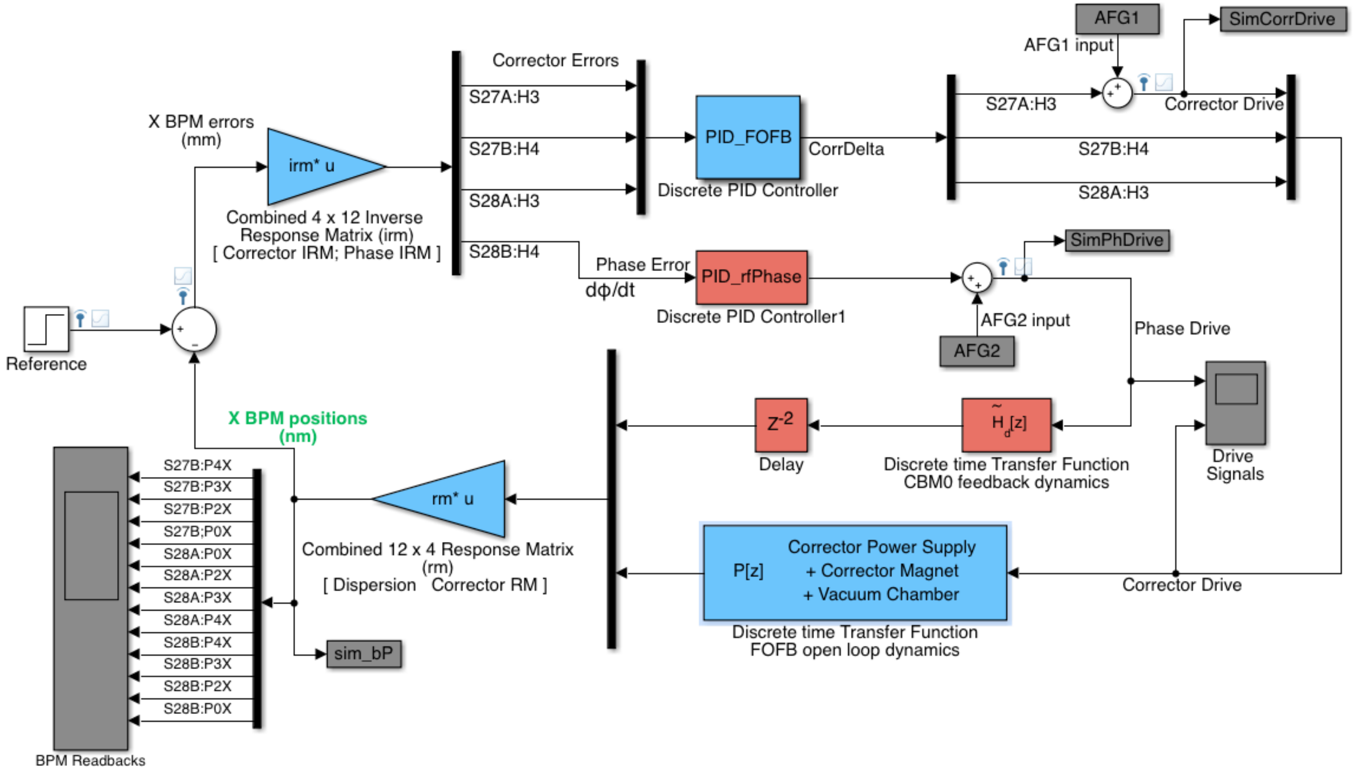
$$\widetilde{H}(s) = -\frac{\pi}{180}\,\frac{G_d}{\omega_{rf}\alpha_c}\,\frac{s\cdot\Omega^2}{s^2+2\,\alpha_s s+\Omega^2}\;e^{-T_d s}$$

  - Discrete transfer function for simulation

$$\widetilde{H}_d[z] = 6.939e^5\,\frac{1-z}{z^2-1.649z+0.9818}\;z^{-2}$$

- The open loop dynamics of orbit feedback system *P[z]* are estimated using beam based time and frequency measurements[1,2].

- Combined response matrix, concatenation of dispersion and corrector respose matrix.



Matlab/Simulink model of S27 prototype for FOFB + CBM0 correction

1. P. Kallakuri et al., IBIC2017-TUPCF02
2. P. Kallakuri et al., NAPAC2019-WEPLM11

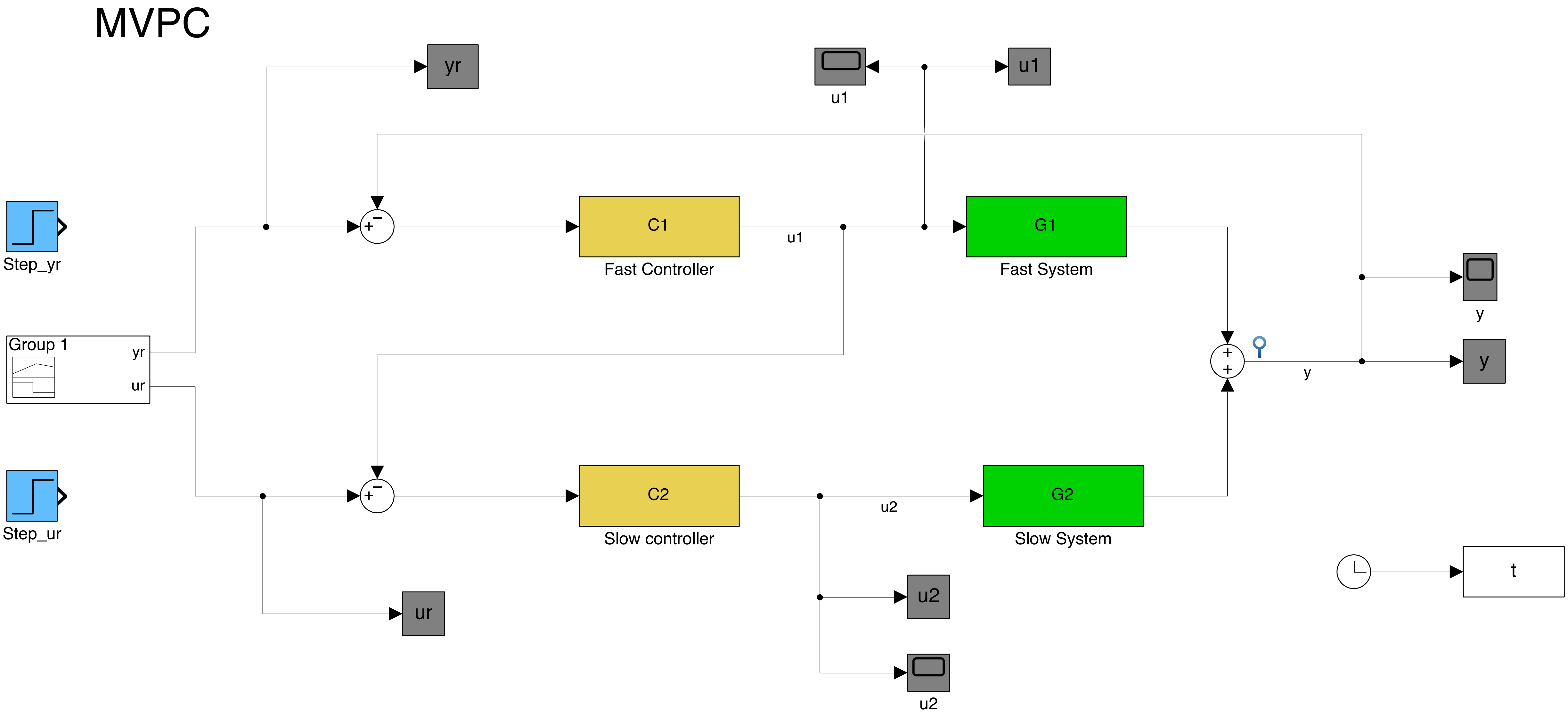
Mid-Ranging feedback control Simulation

- Simulating results from,
  - Design and tuning of valve position controllers with industrial applications,

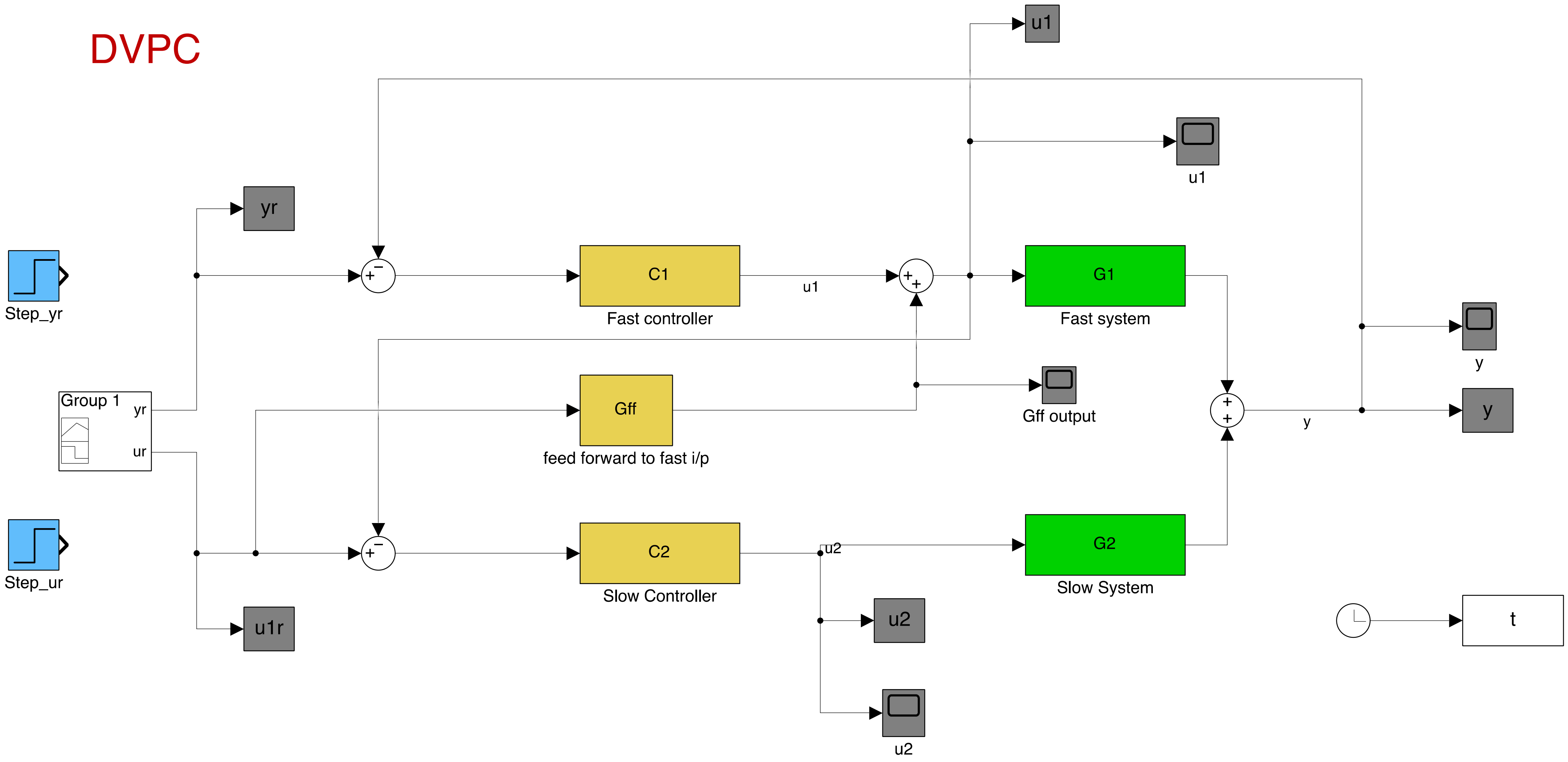
    Bruce J. Allison[1] and Shiro Ogawa, in *Transactions of the Institute of Measurement and Control* 25,1 (2003) pp. 3–16

- DVPC - Direct synthesis valve position control
- MVPC - Modified valve position control

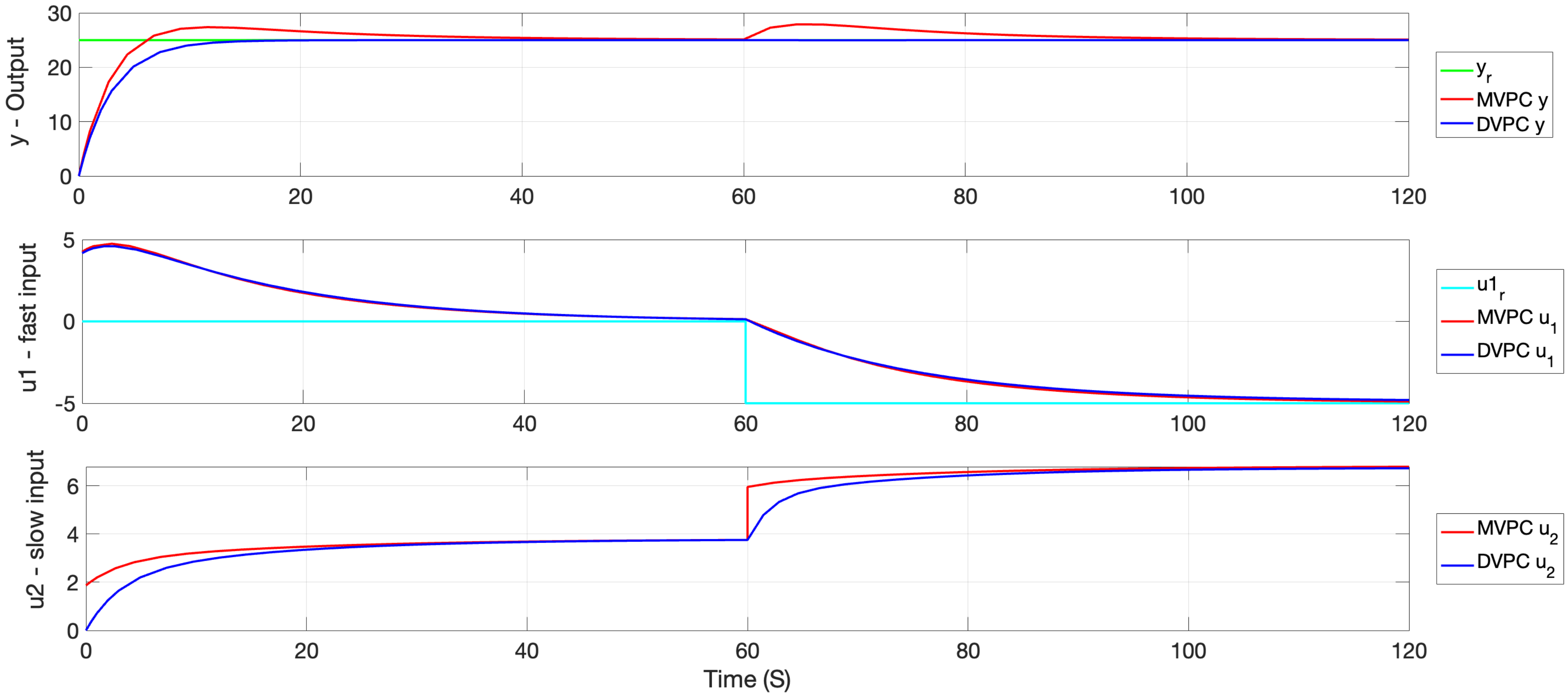
Modified Valve Position Control



Direct Synthesis Valve Position Control



Simulation Results – Closed loop output, fast and slow actuator inputs



Angle between unit dispersion and betatron closed orbit

- Beam position at any given time is a linear combination of betatron and synchrotron orbit motion given by,

$$\mathbf{x} = \mathbf{x}_{\boldsymbol{\eta}} + \mathbf{x}_{\boldsymbol{\beta}}$$

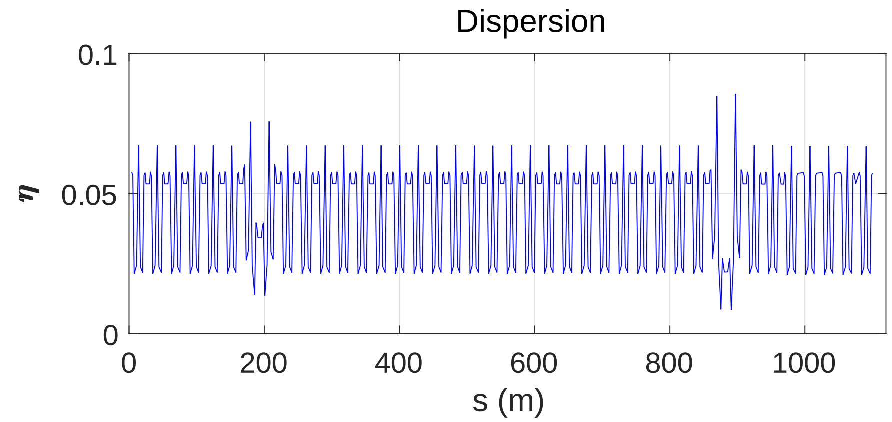
$\mathbf{x}_{\boldsymbol{\eta}}$ - is the orbit vector at all the BPMs due to all bunches oscillating in phase from CBM0.

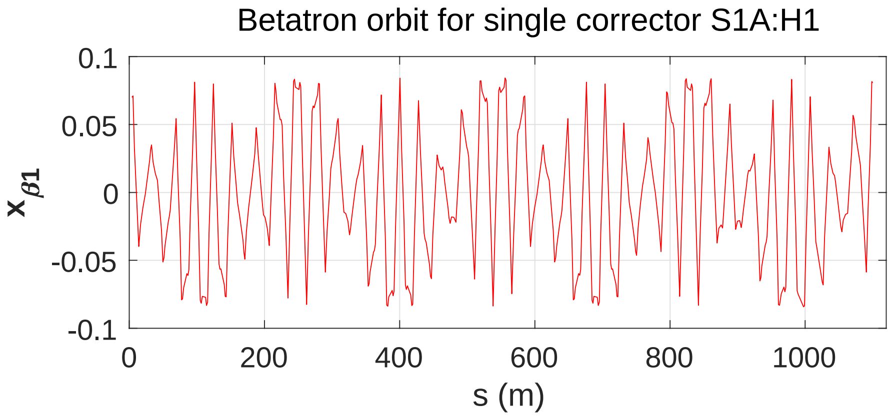
$\mathbf{x}_{\boldsymbol{\beta}}$ - is the orbit vector due to betatron orbit from all dipole errors around the ring is given by,

$$\mathbf{x}_{\boldsymbol{\beta}} = \sum_{\boldsymbol{i}} \mathbf{x}_{\boldsymbol{\beta}_{\boldsymbol{i}}}$$

$$\boldsymbol{\eta} \cdot \mathbf{x} = \boldsymbol{\eta} \cdot \mathbf{x}_{\boldsymbol{\eta}} + \boldsymbol{\eta} \cdot \mathbf{x}_{\boldsymbol{\beta}}$$

$$\boldsymbol{\eta} \cdot \mathbf{x}_{\boldsymbol{\beta}} = \sum_{\boldsymbol{i}} \boldsymbol{\eta} \cdot \mathbf{x}_{\boldsymbol{\beta}_{\boldsymbol{i}}} \quad \cong \ 0$$





- θ_{η_i} - is the angle between unit dispersion and betatron orbit of a single corrector

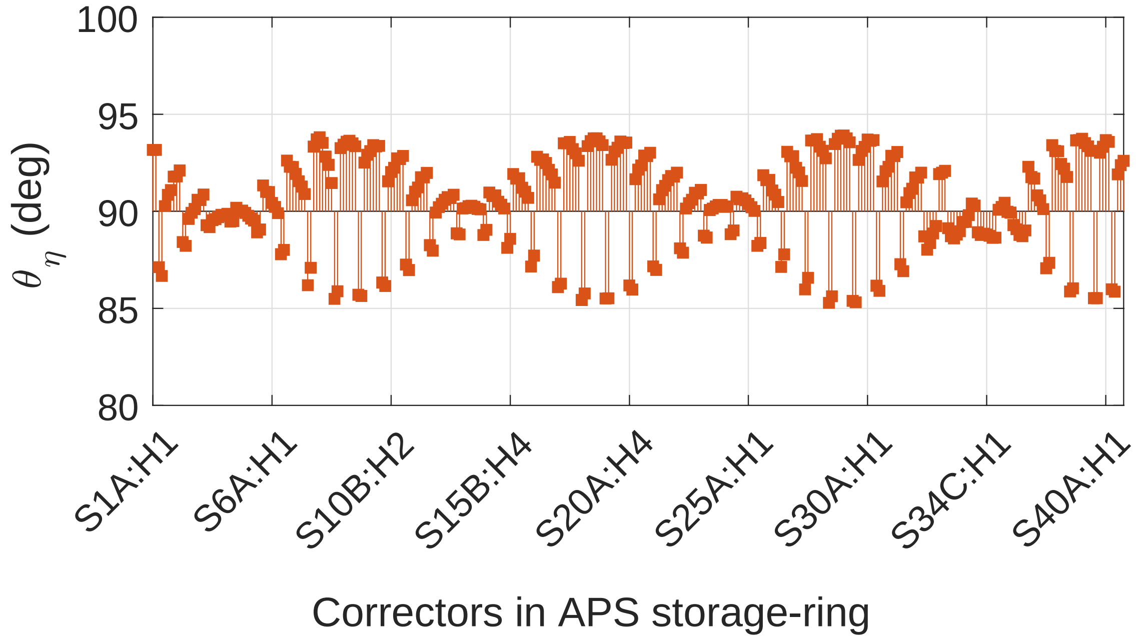
$$\theta_{\eta_1} = 93.37 \text{ deg}$$

$$\cos(\theta_{\eta_i}) = \frac{\boldsymbol{\eta} \cdot \mathbf{x}_{\boldsymbol{\beta}_{\boldsymbol{i}}}}{|\boldsymbol{\eta}||\mathbf{x}_{\boldsymbol{\beta}_{\boldsymbol{i}}}|}$$

Orthogonality between dispersion and betatron closed orbits[1]

- Beam position at any given time is a linear combination of betatron and synchrotron orbit motion.
- Phase error computation of the feedback model assumes dispersion and betatron orbit vectors are orthogonal.
  - Analyzed for all correctors in the APS storage-ring with a simulation study.

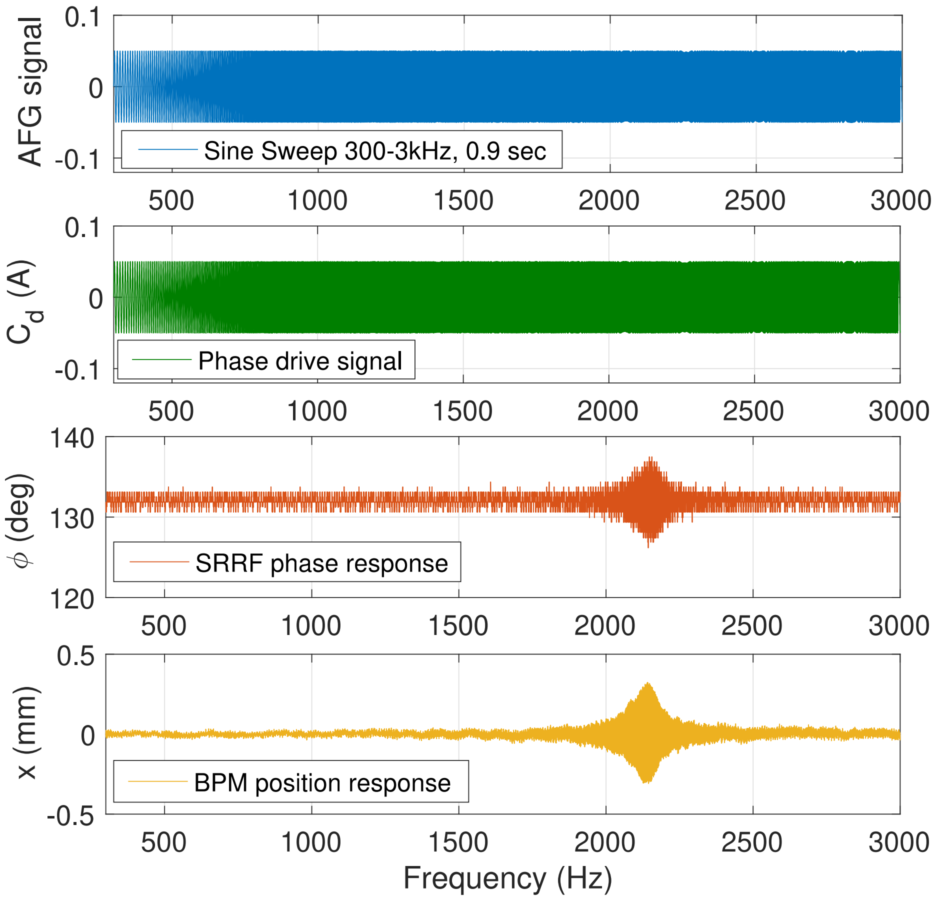
- When orbit is defined by 440 bpms near orthogonality is seen. Not as orthogonal when orbit is defined by 16 bpms.
- Provided enough bpms are used to measure the orbit, dot product $\boldsymbol{\eta} \cdot \mathbf{x}$ acts as a filter to remove betatron motion and ensures feedback only reacts to synchrotron motion.



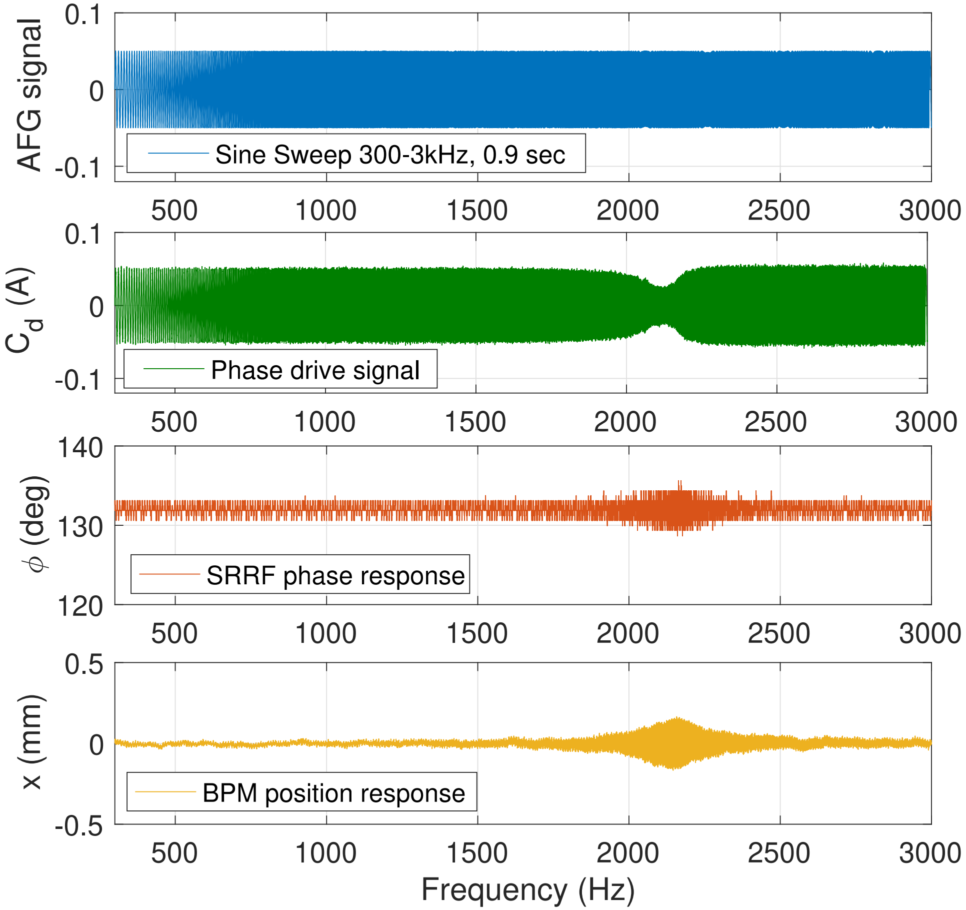
Angle between dispersion and betatron closed orbits

1. P. Kallakuri et al., PRAB **25**, 082801

Open loop Vs Closed loop chirp response measurements



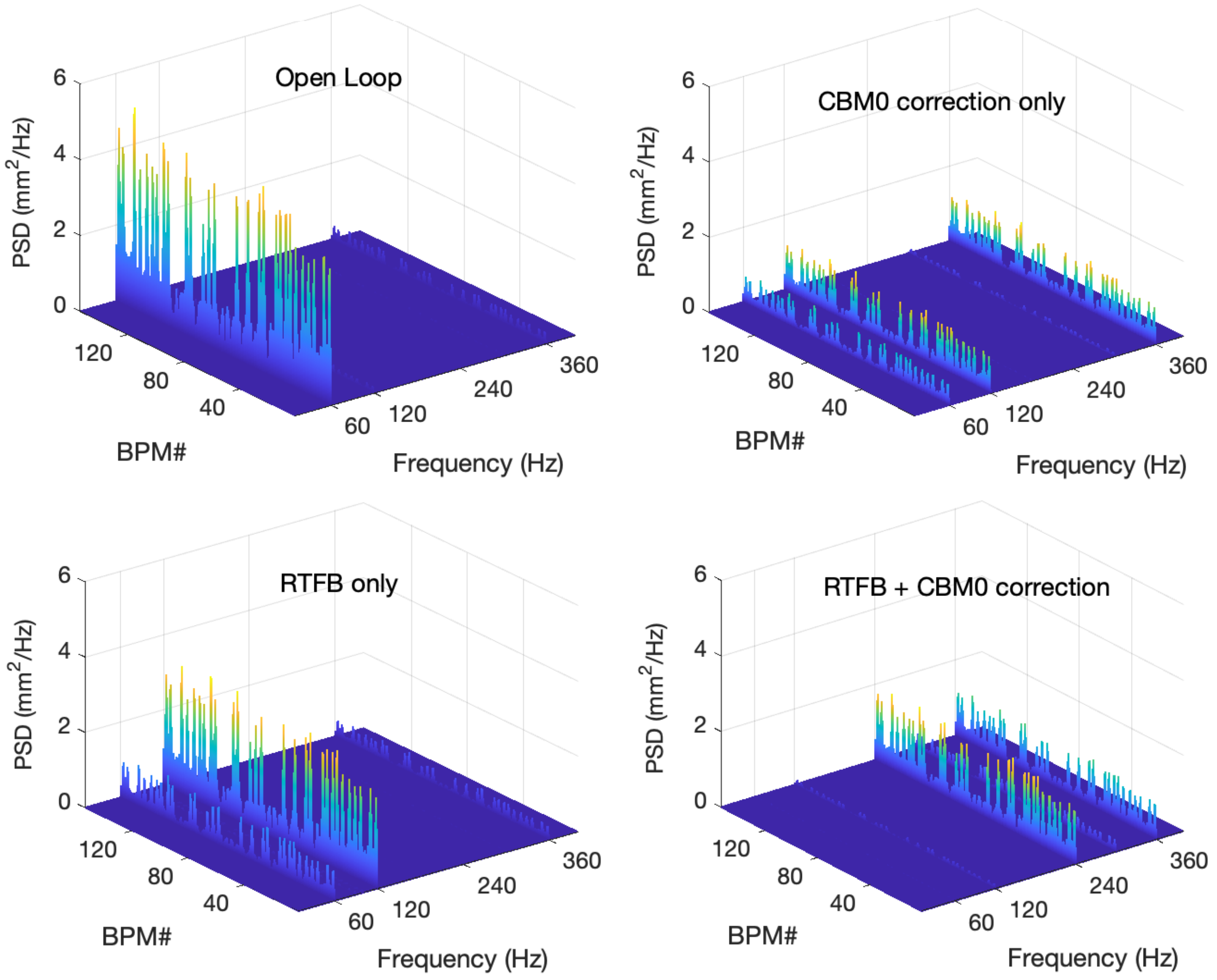
Open loop chirp responses, x-axis is instantaneous chirp frequency. Resonant peak at synchrotron frequency is observed in ϕ and x responses.



Closed loop chirp responses, x-axis is instantaneous chirp frequency. Resonant peaks are suppressed compared to open loop responses.

BPM responses measured at 154 BPMs around the storage-ring

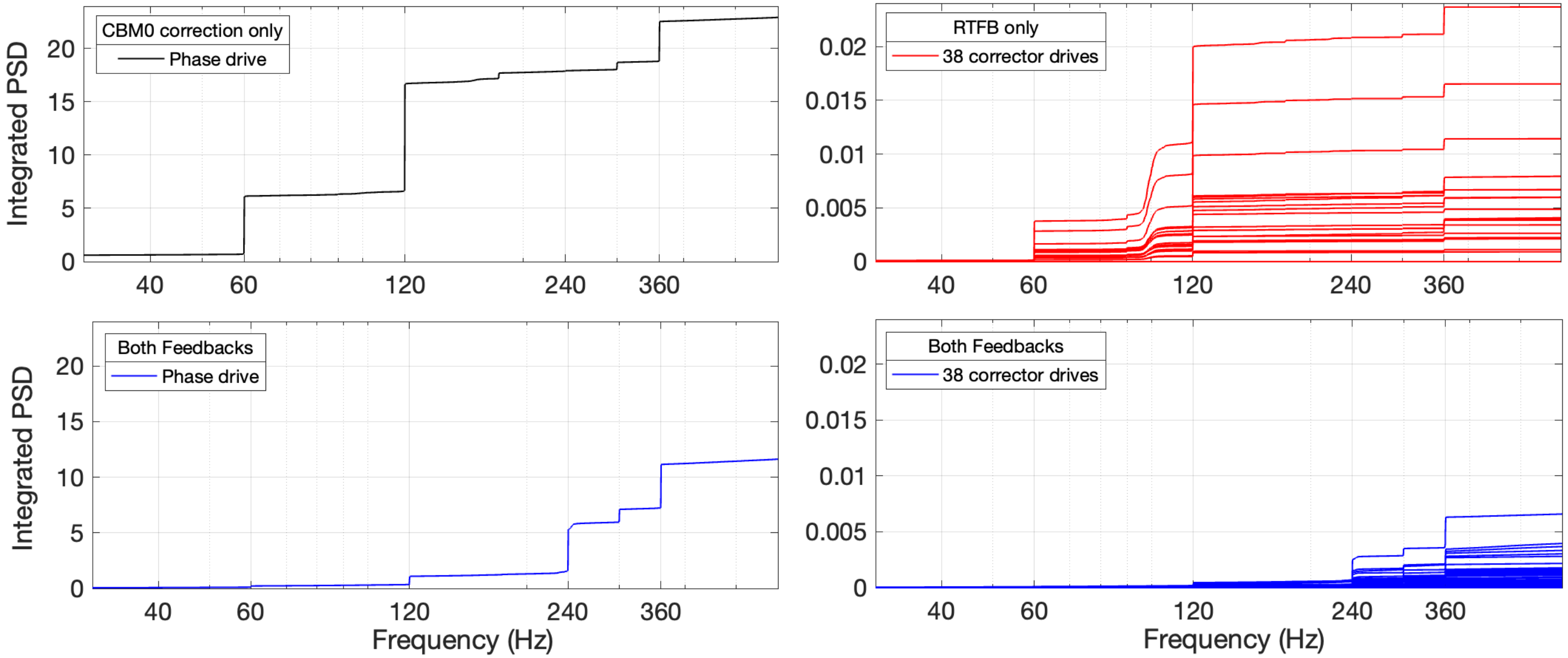
- BPMs in the high dispersion area has larger magnitudes compared to others.
- Individual operation of RTFB or CBM0 correction partially suppressed 60 Hz
  - Frequencies beyond 90 Hz are amplified.
- Narrow resonant increase of RF noise at 60 Hz harmonics when high frequency motion is amplified.
- RTFB + CBM0 correction
  - Significant suppression at 60 Hz
  - High frequency motion amplified by individual feedback operation is attenuated up to 240 Hz.



PSDs of BPM errors at all 154 BPMs in open loop and different closed loop configurations.

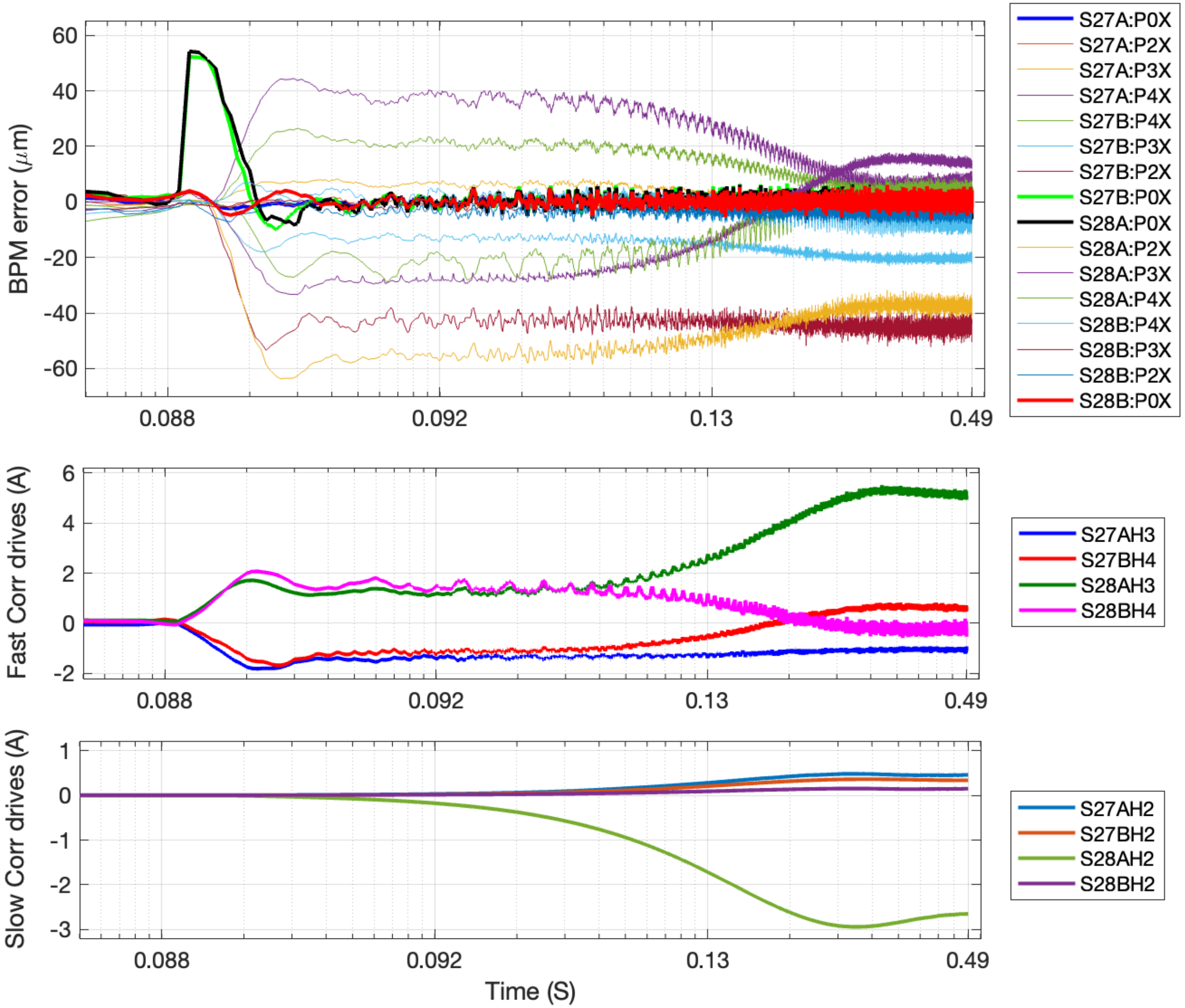
Reduced feedback control efforts during combined operation

- Corrector and phase drive signals indicate feedback control efforts required to perform necessary correction.
- During combined operation,
  - Energy and betatron components are corrected simultaneously, and feedback errors will be small.
  - Drive magnitudes are less compared to respective individual operation of each feedback.
  - More orbit motion suppression with less control effort from corrector and phase drives.

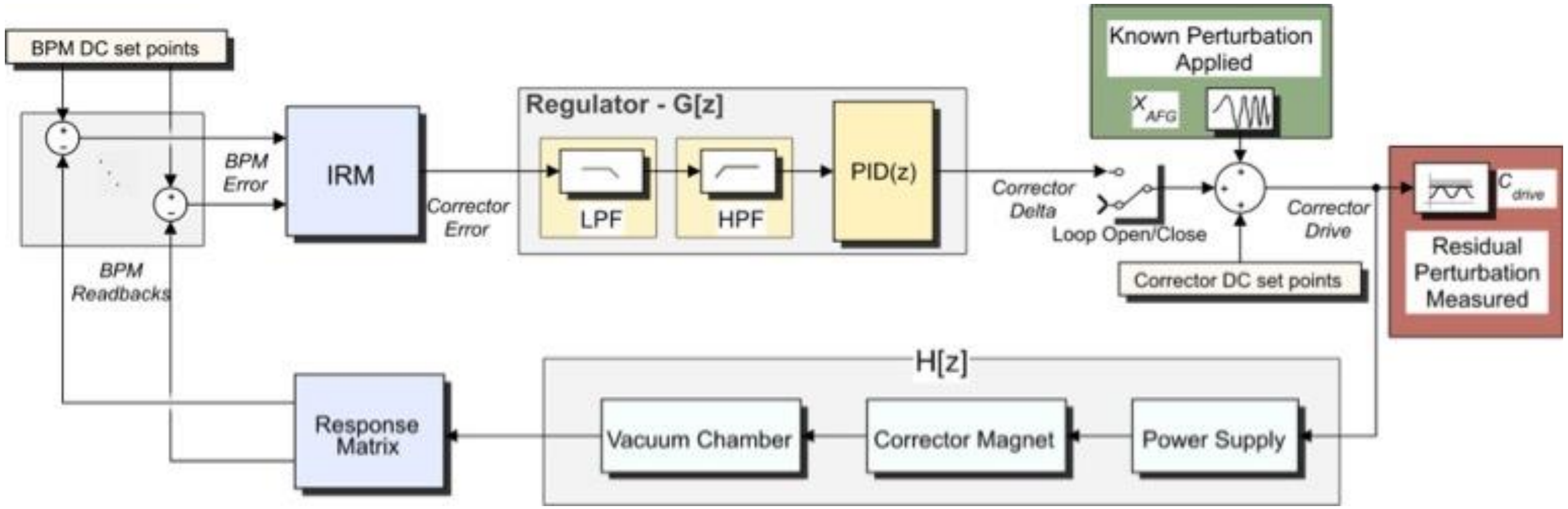


Comparison of drive efforts of each feedback individual operation with simultaneous operation.

BPM error and corrector drive responses to offset bump (in log scale)

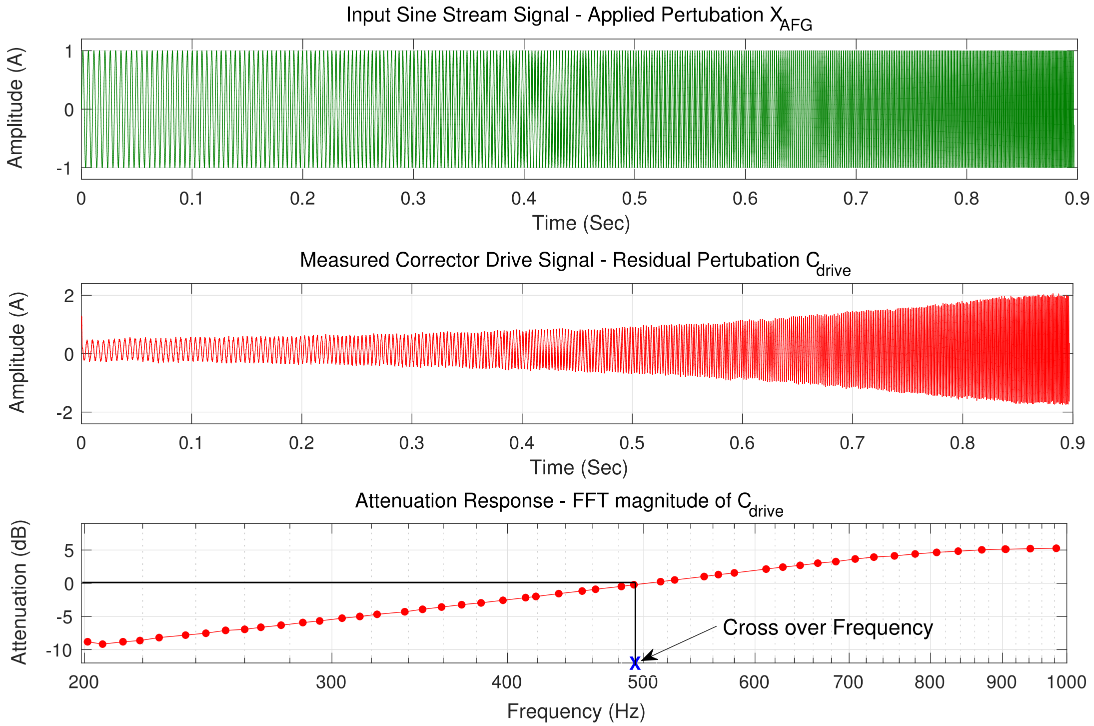


Input disturbance attenuation measurement – Dynamic signal analyzer approach



$$\frac{C_{drive}}{X_{AFG}} = \frac{1}{1+GH} \Leftarrow \mathit{Attenuation\ Transfer\ Function}$$

- FFT magnitude of corrector drive is attenuation response.
- 0 dB crossover frequency is the closed loop bandwidth.



Separating energy and betatron oscillations from horizontal BPM position data

Horizontal BPM position,

$$x(t) = x_\beta(t) + (\delta(t)\cdot \eta)$$

Energy oscillations,

$$\delta(t) = \frac{\eta\cdot x(t)}{\eta\cdot\eta}$$

Betatron oscillations,

$$x_\beta(t) = x(t) - (\delta(t)\cdot \eta)$$