

Advances in Orbit Feedback Control for Enhancing Beam Stability at Advanced Photon Source

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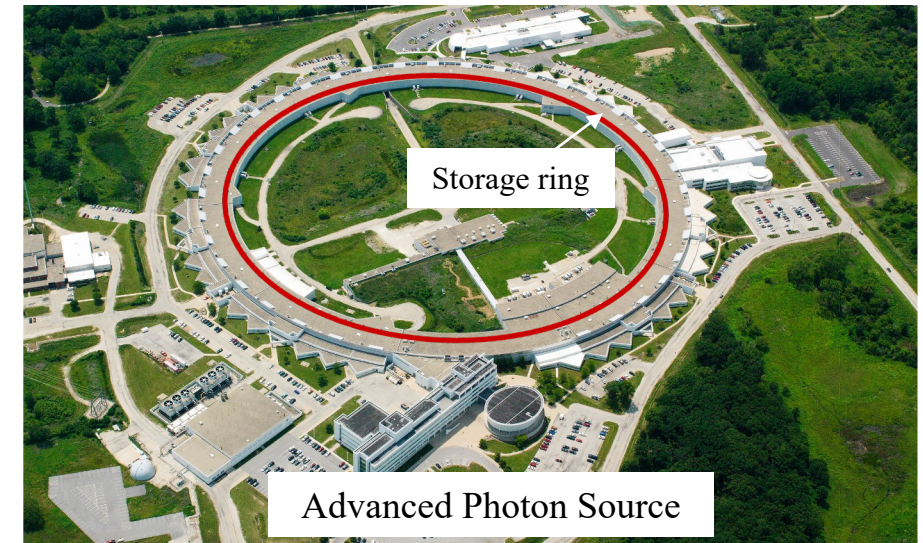
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Outline

1. Fast orbit feedback for electron beam stability.
2. Feedback methodologies for unified operation of fast and slow correctors in a single algorithm.
3. Orbit feedback controller with RF phase actuator for coupled bunch mode zero suppression.
4. Conclusions and Future work.

Advanced Photon Source - Beam Stability Goals

- Recently upgraded^[1] Advanced Photon Source (APS) at Argonne National Laboratory is a synchrotron source of high energy, high brightness x-rays.
 - Enables experiments for fundamental and applied research of a wide variety of academic and industrial users.
 - Need to stabilize movement of the beam centroid distorted by the environmental disturbances.
- **Beam stability engineering requirements** are AC rms motion tolerances for beam centroid within a frequency band.
 - AC rms motion up to 1 kHz: $1.25\ \mu\text{m}$ (*horizontal*), $0.4\ \mu\text{m}$ (*vertical*)



Fast Orbit Feedback (FOFB) for beam stabilization

- **Beam Position Monitors (BPMs)** are the sensors .
- Dipole magnets known as **correctors** are the actuators.
- System under development with an array of **560 BPMs**, **160 fast** and **160 slow correctors** per plane
- Distributed network of 20 feedback processors
 - Receives positional data from around the ring and provides drive inputs to the local corrector magnets.

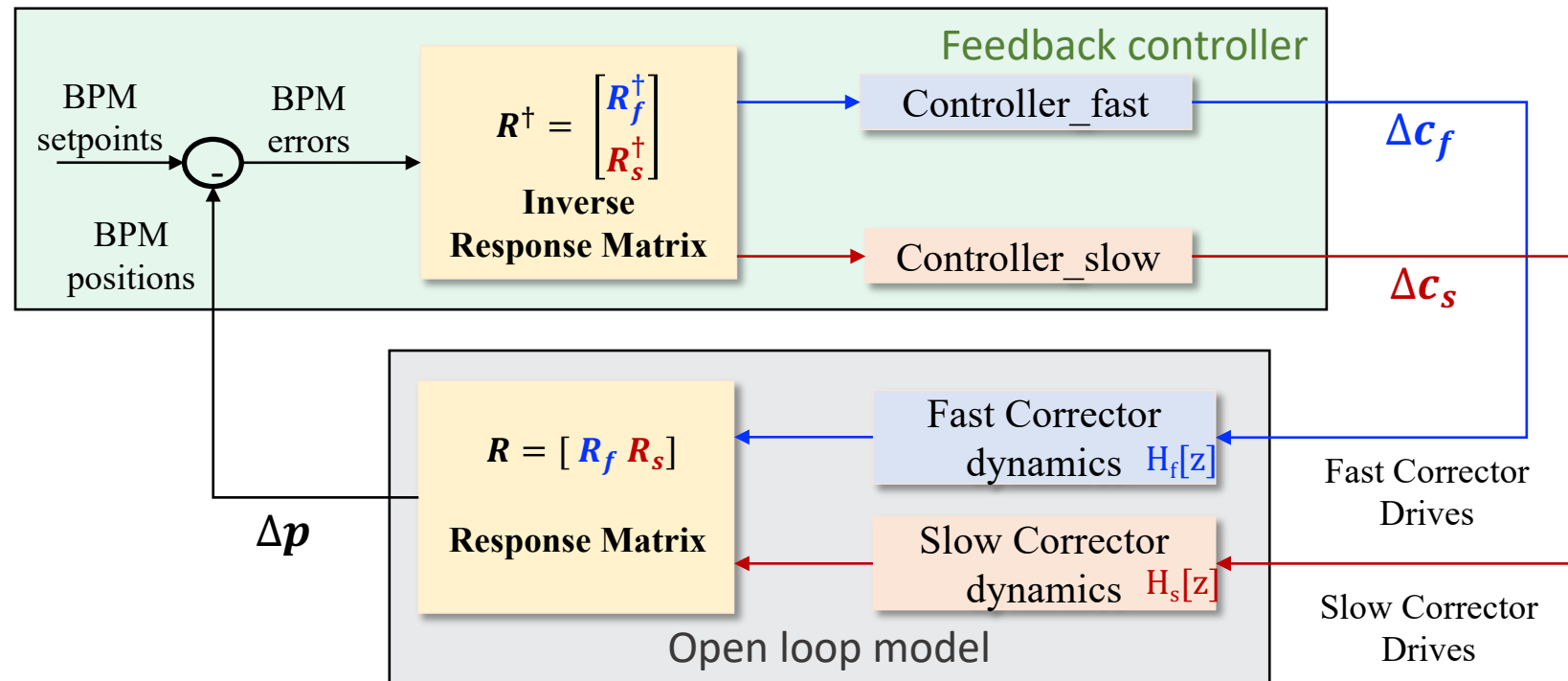
^[1]Fornek, Thomas E, doi:10.2172/1543138.

Unified Orbit Feedback Configuration

- Open loop model is a two-dimensional process since the variations are continuous in both time and space.

$$\begin{bmatrix} \Delta p \end{bmatrix} = \underbrace{\begin{bmatrix} R_f & R_s \end{bmatrix}}_{\text{Spatial response}} \underbrace{\begin{bmatrix} H_f[z] & 0 \\ 0 & H_s[z] \end{bmatrix}}_{\text{Dynamic response}} \begin{bmatrix} \Delta c_f \\ \Delta c_s \end{bmatrix}$$

- The feedback controller will be a series combination of Inverse response matrix (IRM) and dynamic controller.
- In unified feedback configuration both slow and fast correctors are operated in a single feedback algorithm.
- Developed two methods for unified operation of fast and slow correctors in orbit feedback control.



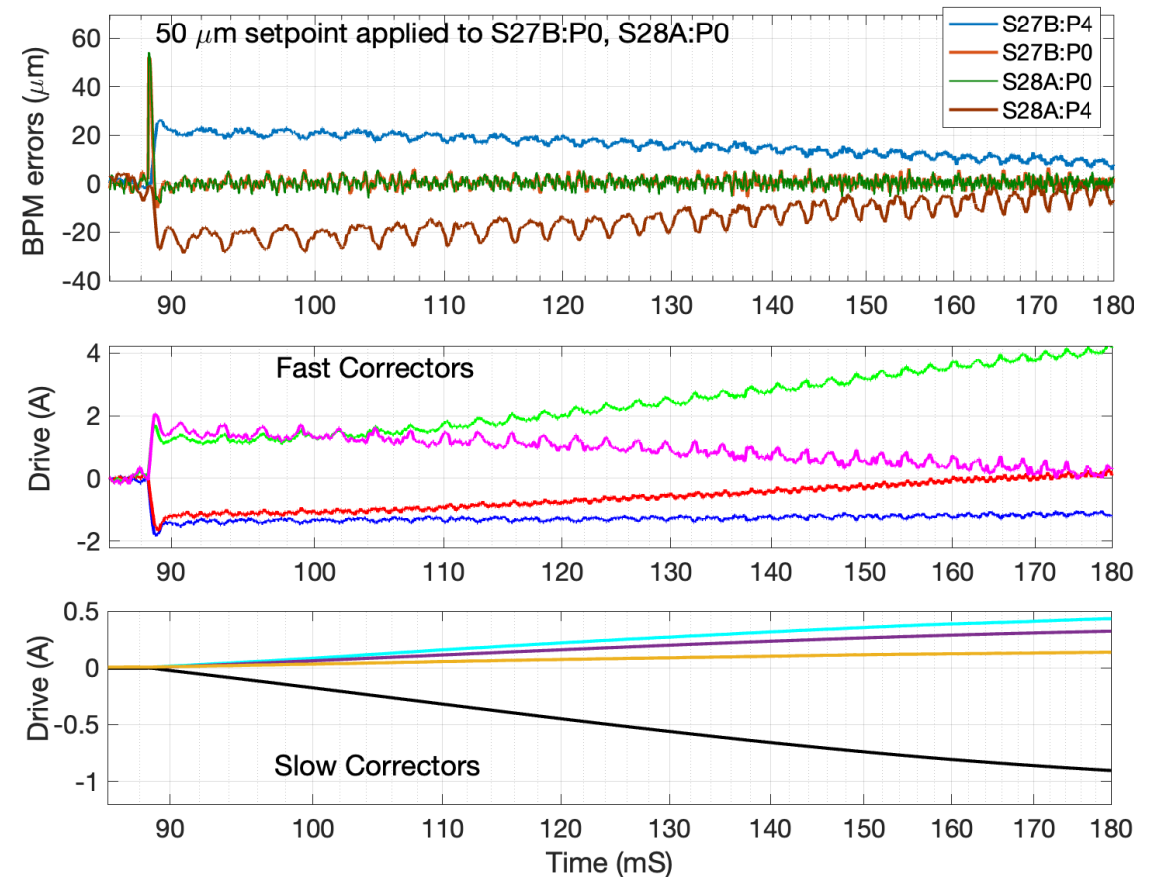
Modified slow response matrix for unified operation^[2,3]

- The unified response matrix is characterized by replacing \mathbf{R}_s with unified slow response matrix, a subspace that is orthogonal to the space defined by the columns of \mathbf{R}_f .

$$\mathbf{R}_{us} = \mathbf{R}_s - \mathbf{R}_f \mathbf{R}_f^\dagger \mathbf{R}_s = \mathbf{P}_{\mathbf{R}_f}^\perp \mathbf{R}_s$$

$\mathbf{P}_{\mathbf{R}_f}^\perp$ - Orthogonal Projection Matrix of \mathbf{R}_f

- Prototype fast orbit feedback system is used for testing the effectiveness in experiments and simulations.
 - 4 fast correctors, 4 slow correctors, 16 BPMs
 - 22.6 kHz sampling rate
 - PID is the only option with the prototype
- Stable closed loop operation with fast and slow correctors in single algorithm.
- Fast correctors operate all the way to DC.
 - Suitable for applications where cost of fast input is not a concern.

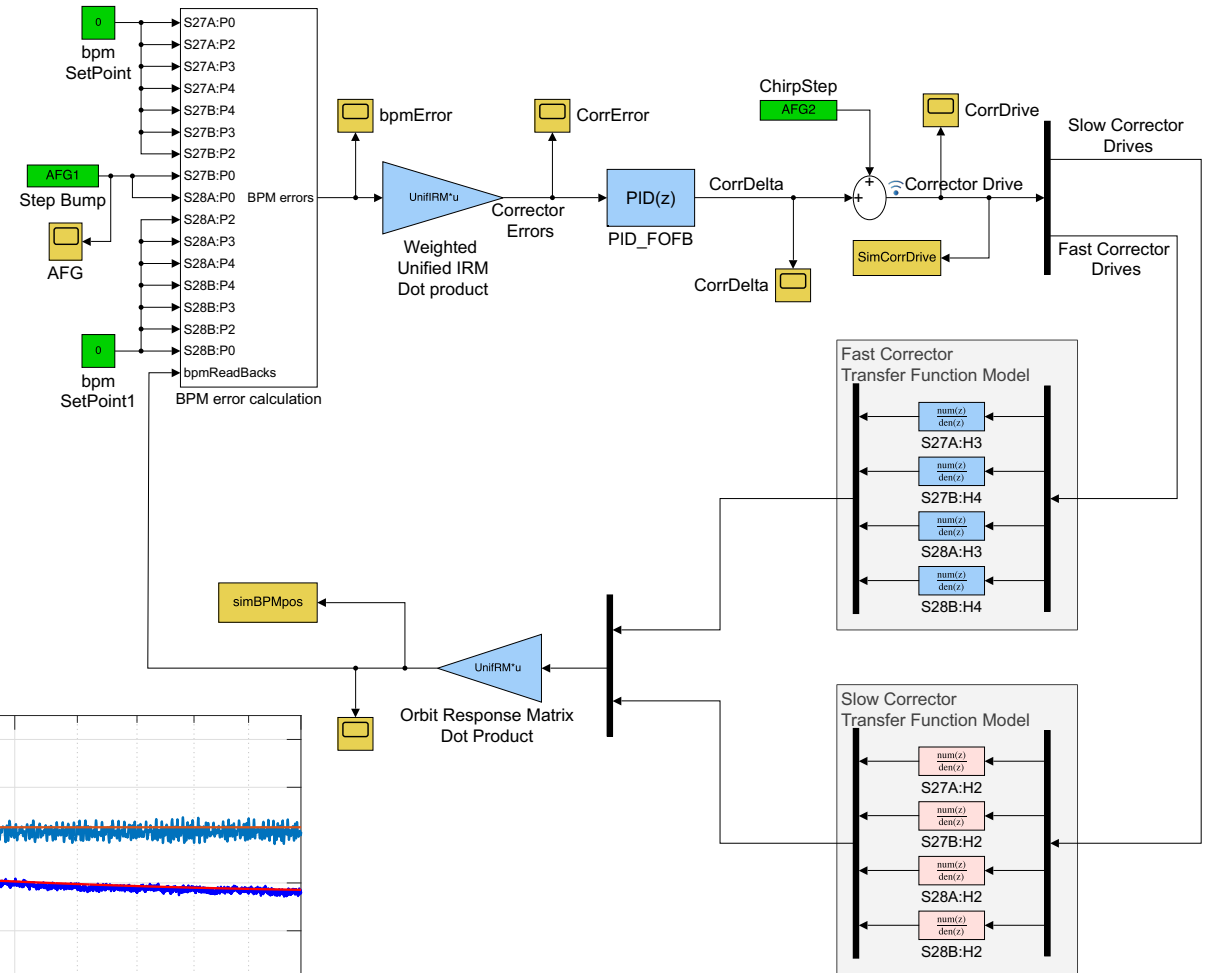
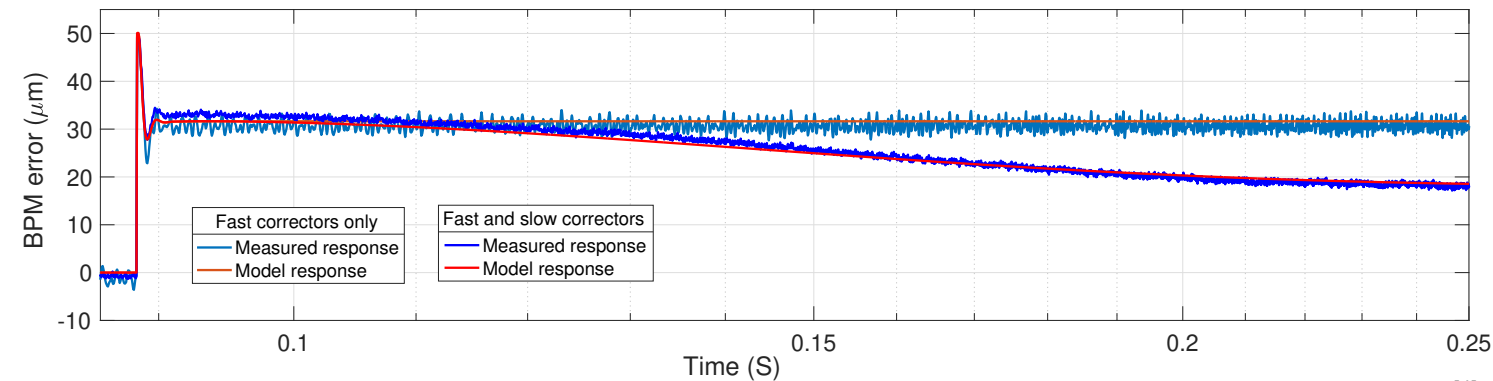
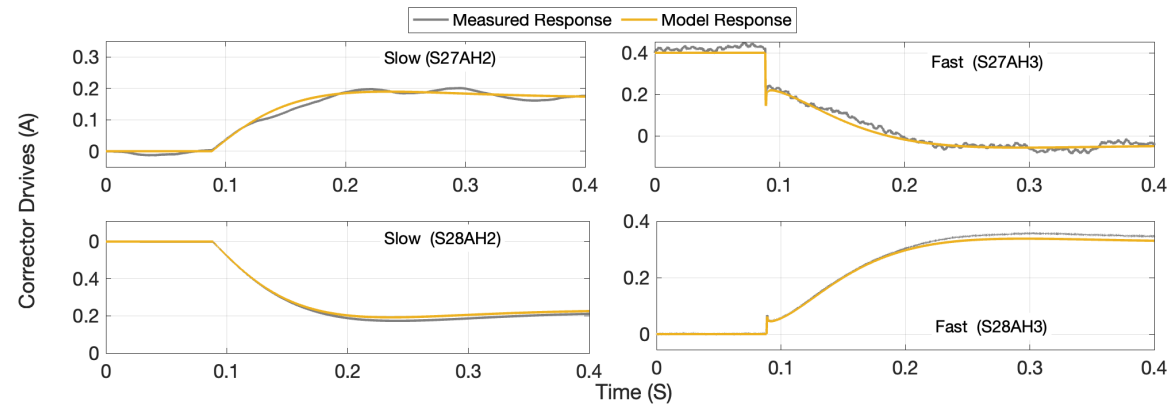


^[2] N. Sereno et.al., <https://doi.org/10.18429/JACoW-IPAC2018-TUZGBD3>

^[3] J. Carwardine et.al., https://proceedings.jacow.org/ibic2018/talks/tuoc02_talk.pdf

Prototype Simulation Model in MATLAB/Simulink^[4]

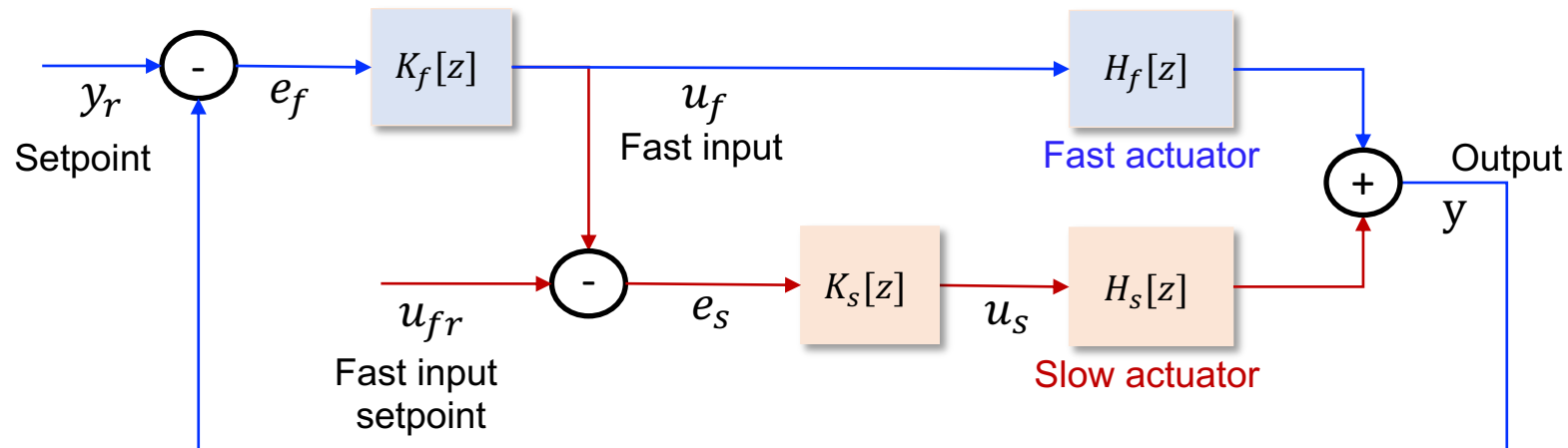
- Simulation model is developed for the FOFB prototype controller in MATLAB/simulink.
- Simulated responses are in good agreement with the measured data.



[4] P. Kallakuri et.al., doi:10.18429/JACoW-NAPAC2019-WEPLM11

Mid-rangng Control Theory

- Class of control problems where two or more inputs each exerting distinct dynamic effects are used to regulate a single output^[5,6].
- The control scheme seeks to manipulate all inputs upon an upset but then gradually resets or mid-ranges the fast input to its DC set-point.



- Extensively established for Two Input Single Output (TISO) configuration.
- Design criterion is obtaining,
 - Desired response from y_r to y
 - Desired response from u_{fr} to u_f
 - Decoupled response from u_{fr} to y

[5] Allison BJ, Ogawa S. doi:10.1191/0142331203tm072oa

[6] Gayadeen S, Heath W. <https://doi.org/10.3182/20090712-4-TR-2008.00087>

Multi variable approach to mid-ranging Control^[7]

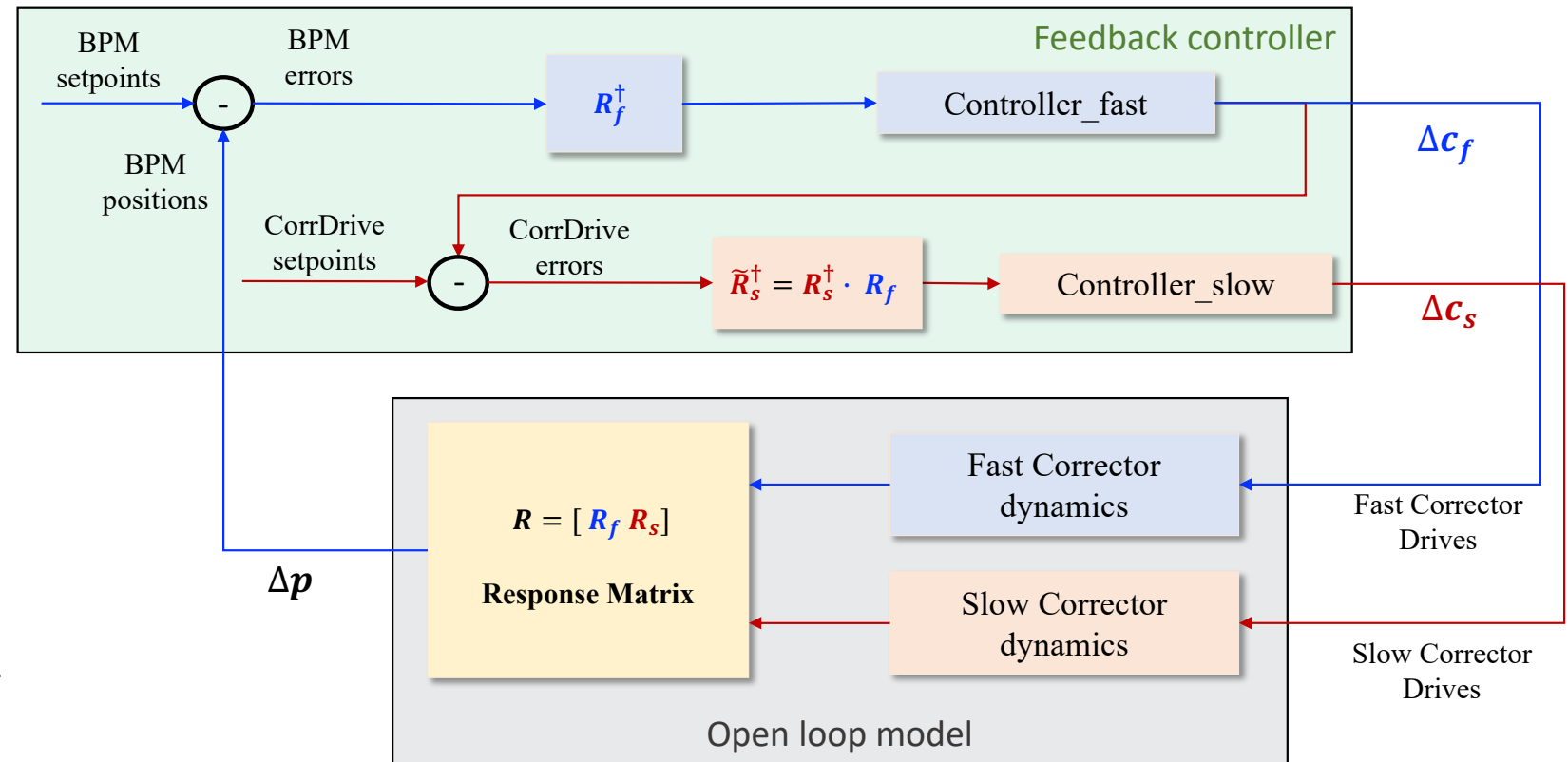
- Input to fast feedback loop is the BPM error. And input to slow feedback loop is the fast corrector drive setpoint.
- The fast dynamic controller generates fast corrector drives to correct the BPM error as in general case.

- Slow feedback controller generates slow corrector drives that correct fast corrector drive errors.

- Corrector drive computations in feedback controller,

$$\Delta c_f = K_f[z] \cdot R_f^\dagger \cdot \Delta p$$

$$\Delta c_s = K_s[z] \cdot R_s^\dagger \cdot R_f \cdot \Delta c_f$$

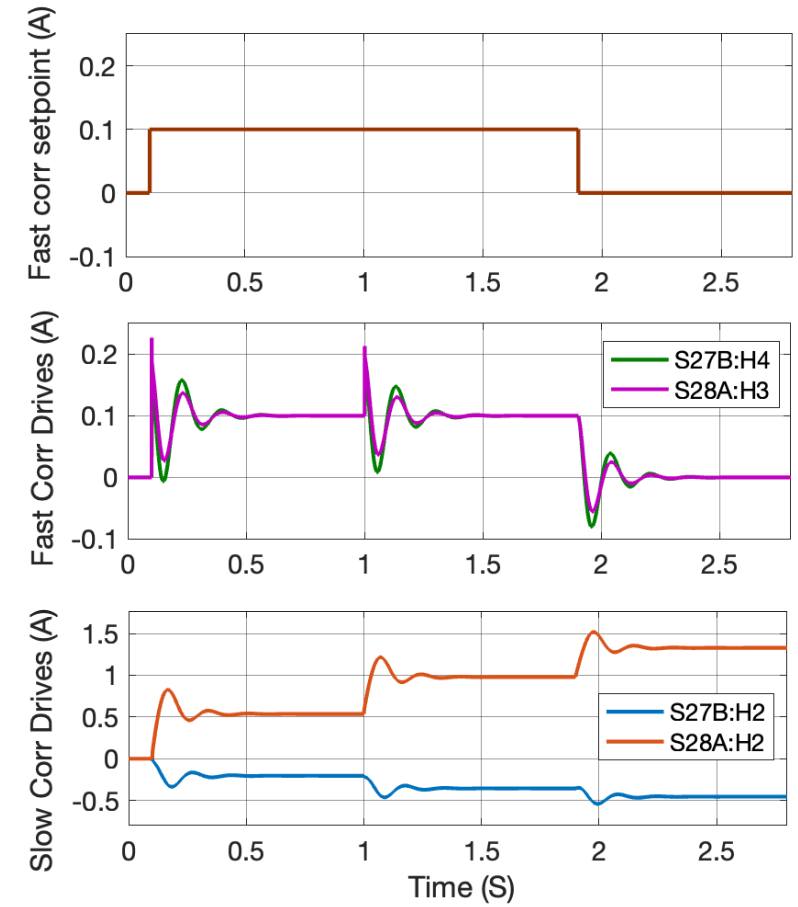
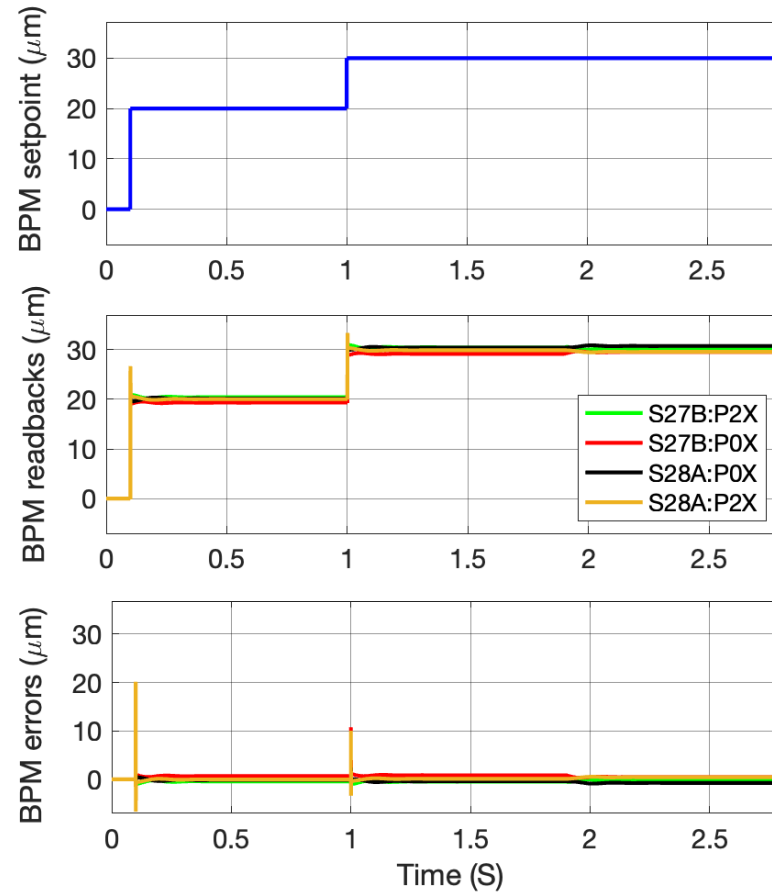


^[7] Kallakuri P, Sereno N. DOI: [10.18429/JACoW-IPAC2024-THPG29](https://doi.org/10.18429/JACoW-IPAC2024-THPG29)

Simulation Study with Multi Input Multi Output Configuration

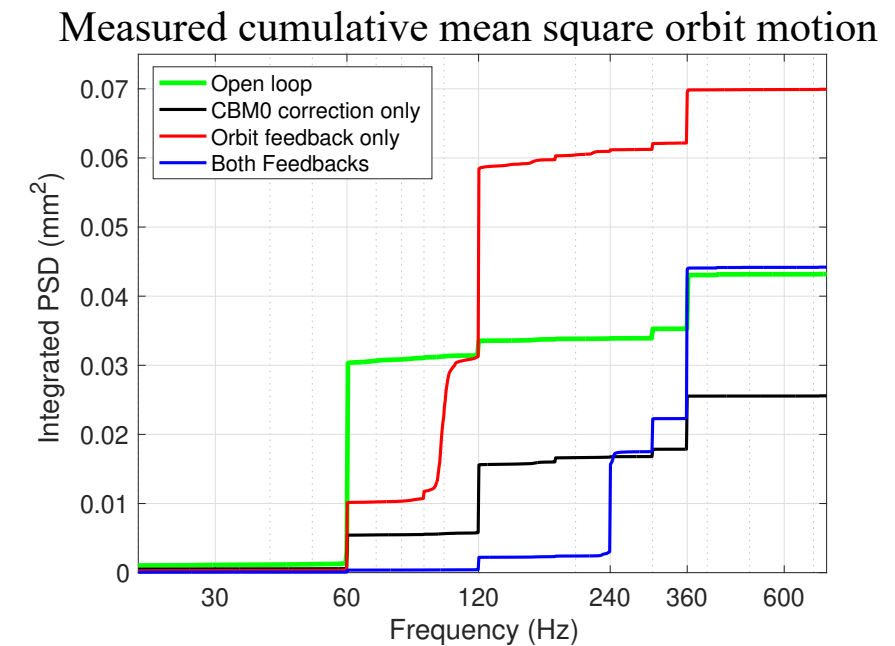
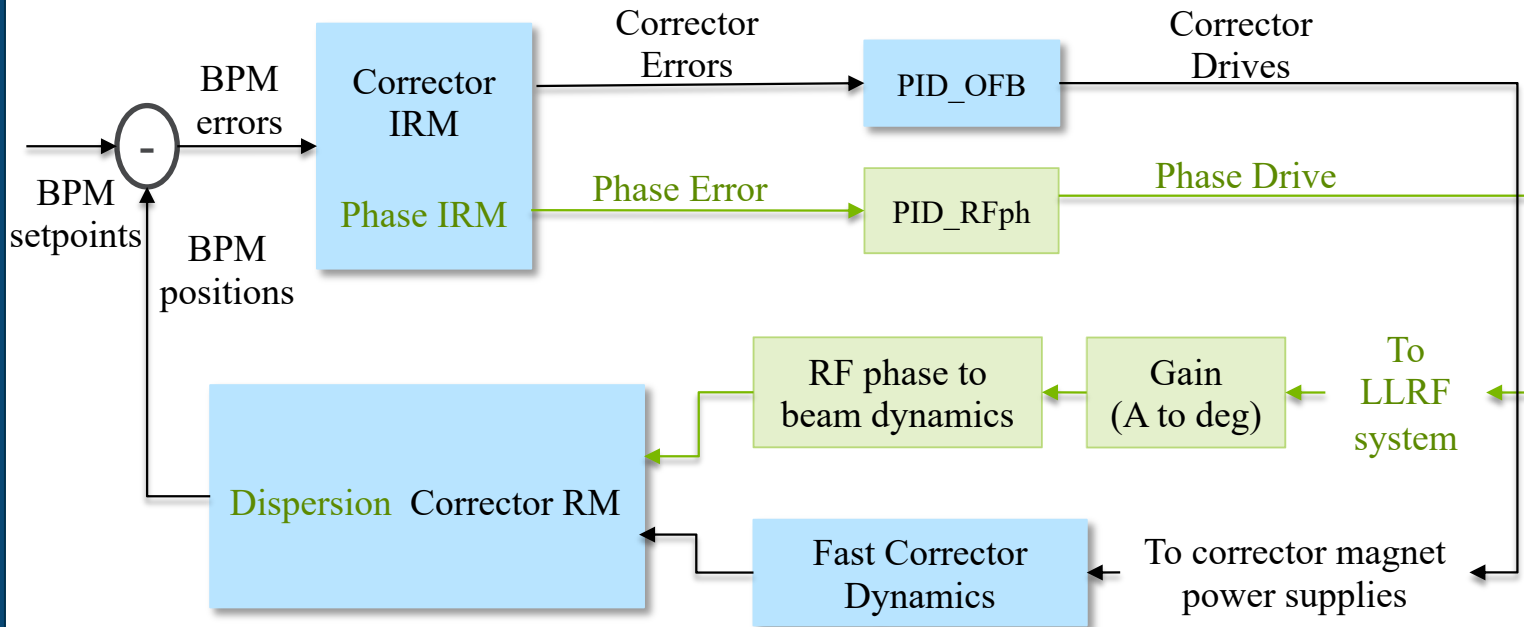
- Feedback configuration: 2 fast correctors, 2 slow correctors, 4 BPMs
- Closed loop is stable when both fast and slow correctors are used in single feedback algorithm.

- The steady state BPM errors are zero after the initial transients at the step changes.
- The fast correctors reached their DC set-points and Slow correctors will take over the correction in steady state.
- Fast corrector setpoint changes has very minimal effect on BPM positions and errors.



Orbit Feedback Controller with RF phase actuator^[8]

- Coupled bunch mode 0 (CBM0) oscillations where energy oscillations of all bunches are in-phase, induce horizontal orbit motion at synchrotron frequency that is inside the orbit feedback bandwidth.
- Orbit feedback controller infrastructure is used to generate RF phase setpoint based on energy induced component extracted from measured orbit.

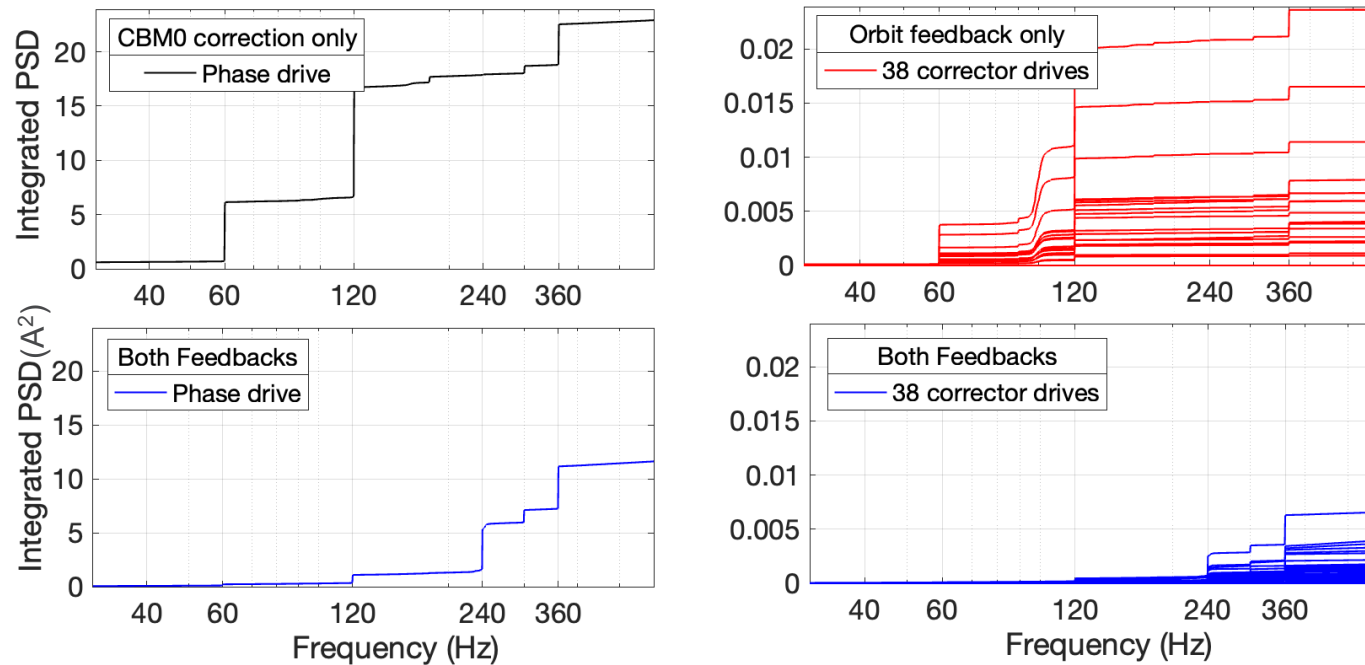


- Partial suppression at synchrotron frequency (60 Hz) when feedbacks are operated individually.
- Complete suppression at 60 Hz motion (betatron + energy components) with both feedbacks running together.

^[8] P. Kallakuri et.al., DOI: <https://doi.org/10.1103/PhysRevAccelBeams.25.082801>

Reduced feedback control efforts during combined operation^[9]

- 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

Conclusions

- To unify the operation of fast and slow correctors in a single algorithm we implemented two methodologies,
 - Modifying the slow response matrix
 - Employing a multi-variable mid-ranging control strategy
- We developed a novel feedback method for CBM0 correction using the fast orbit feedback framework with RF phase actuator
- These algorithms were validated through experiments and/or simulations using prototype fast orbit feedback system.

Ongoing efforts ...

- Development of fast orbit feedback system for upgraded APS user operations.
- Extending the prototype simulation model to full distributed controller configuration.
- Investigate distributed control implementation of tested unified feedback algorithms.
- Coupled bunch mode zero correction in a storage-ring with higher harmonic cavity.

Acknowledgements

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