Coupled bunch mode zero correction within the Orbit feedback bandwidth

Pavana Sirisha Kallakuri
N. Sereno, A. Brill, J. Carwardine, L. Emery

2023 International Beam Instrumentation Conference
11 Sept 2023

Work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-ACO2-O6CH11357.

Motivation

- The Advanced Photon Source Upgrade (APS-U) project at the Argonne National Laboratory will replace the existing 7-GeV, double bend storage ring lattice with a new 6-GeV hybrid 7 bend achromat lattice.

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

- 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.

- Large storage-rings such as APS (1.1-km circumference) would need longitudinal feedback system with high kick voltage capability for CBM0 suppression.
  - APS-U longitudinal feedback kicker is not strong enough to damp CBM0 oscillations.

Introduction

- New orbit to RF phase feedback configuration to suppress CBM0 oscillations,
  - Beam position measurements at dispersive bpms are dynamic inputs
  - Low level RF (LLRF) phase is used as actuator
  - Orbit feedback controller generates RF phase setpoint using energy induced component extracted from measured orbit.

- Proof of concept experiments using 7 GeV operations lattice[1]
  - Synchrotron frequency is outside the orbit feedback bandwidth
  - Demonstrated orbit feedback operation together with CBM0 correction in experiments and simulations

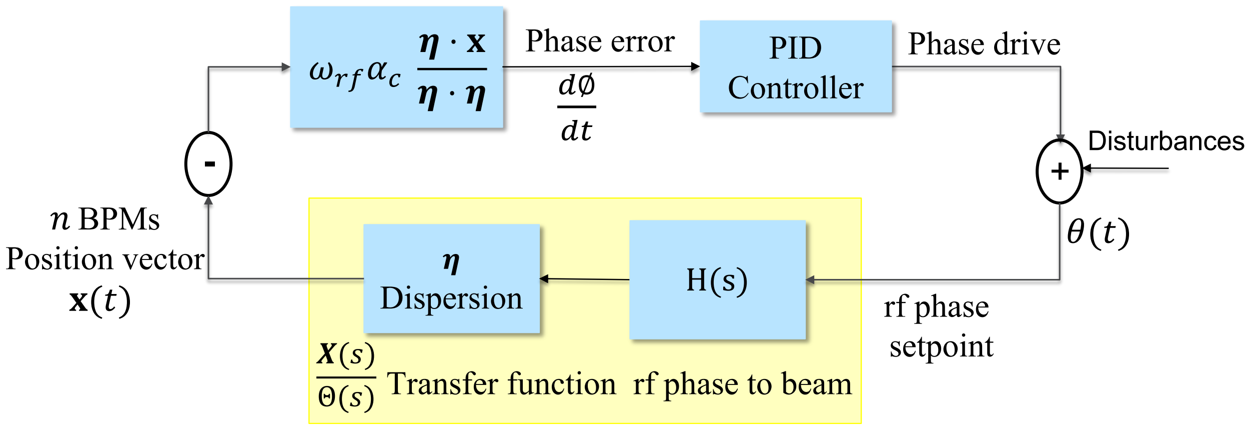
- Experimental study with 6 GeV low-alpha lattice configuration
  - Synchrotron frequency is inside the orbit feedback bandwidth resembling APS-U
  - Demonstrated CBM0 correction within the orbit feedback bandwidth

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

Proposed orbit to rf phase feedback configuration

- 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,

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



Closed loop schematic of proposed orbit to RF phase feedback method

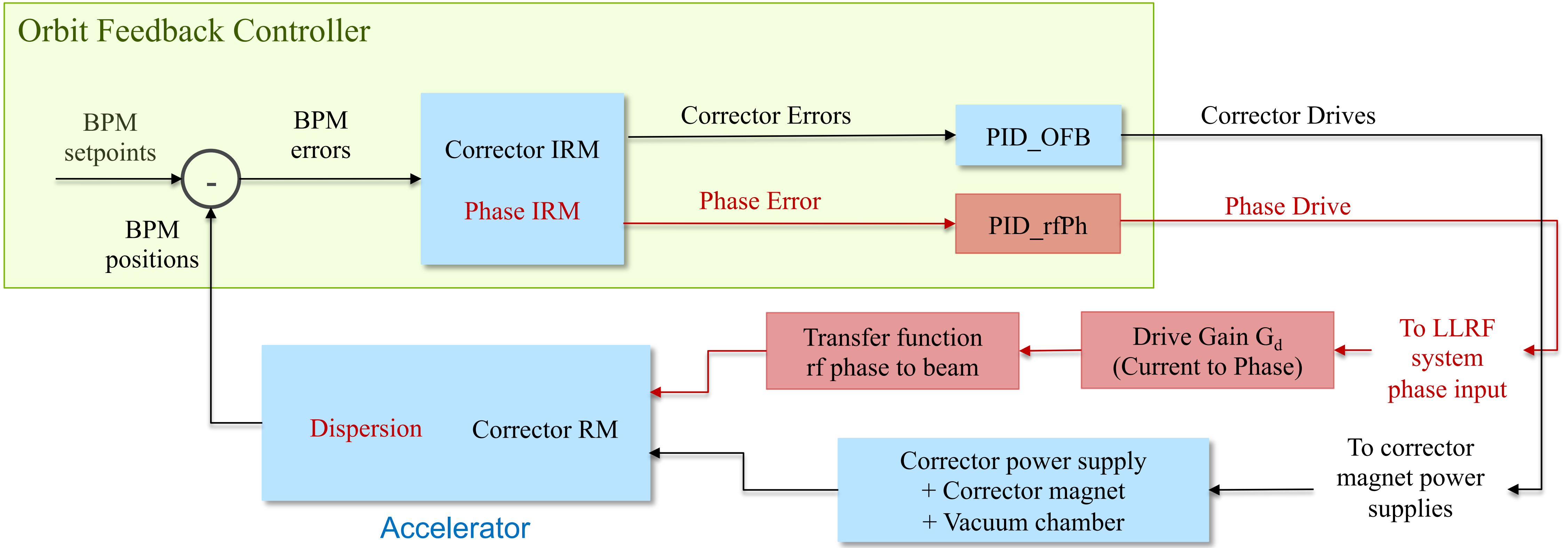
$\mathbf{x}$	-	*Horizontal position deviation*
$\boldsymbol{\eta}$	-	*Dispersion*
Φ	-	*Beam phase*
ω_{rf}	-	*RF frequency*
α_c	-	*Momentum compaction factor*
α_s	-	*Damping rate*
Ω	-	*Synchrotron frequency*
θ	-	*RF phase noise*

- 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.

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

Argonne NATIONAL LABORATORY

Experimental setup – Orbit feedback controller with RF actuator

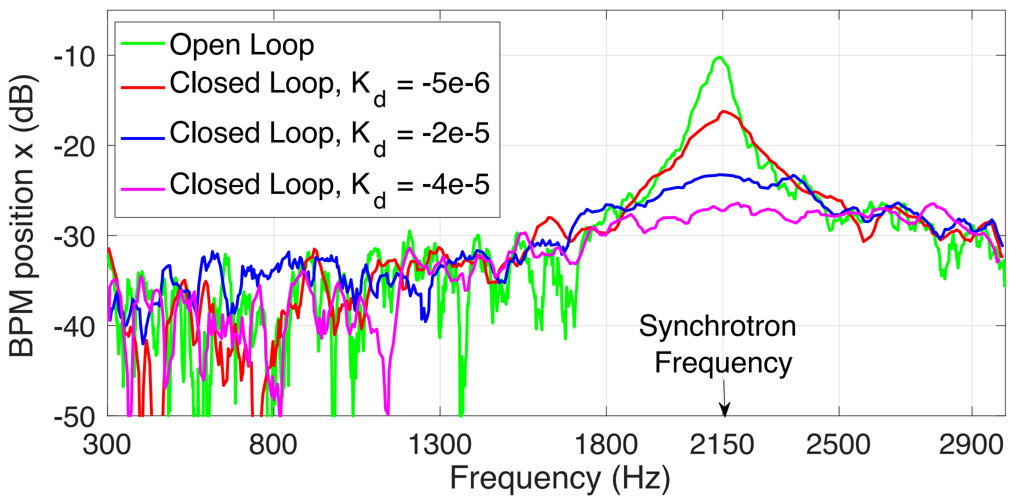


- Orbit feedback algorithm used for corrector drives is used to generate RF phase setpoints.
- Phase computations are incorporated as an additional row in Inverse Response Matrix (IRM) dot product.

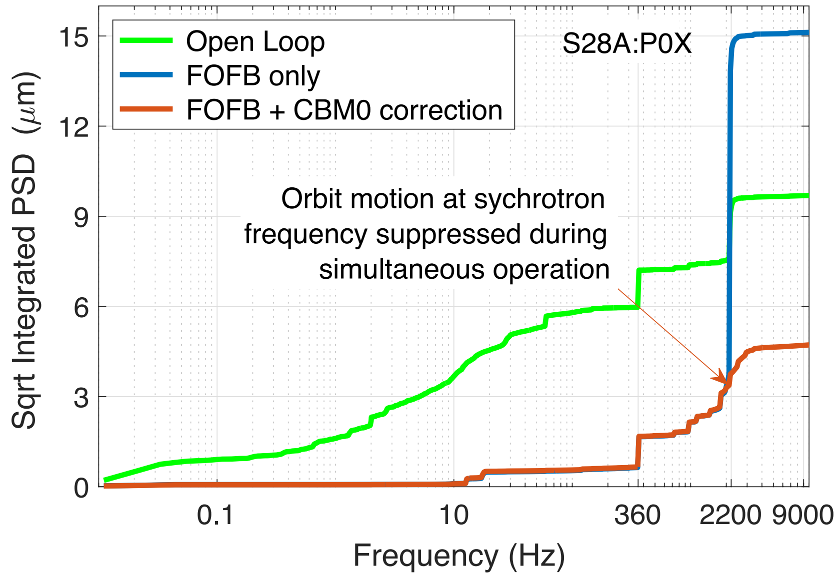
Proof of concept experiments with operations lattice

Synchrotron frequency outside orbit feedback bandwidth[1]

- Coupled bunch mode zero correction is demonstrated using,
  - APS-U prototype FOFB system 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



Comparison of measured AC rms orbit motion

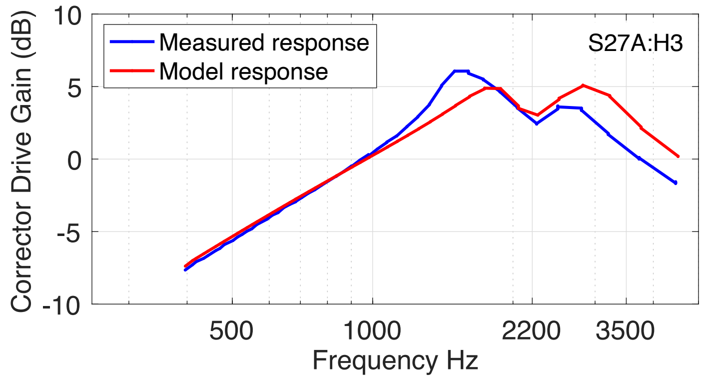
- Achieved significant suppression around synchrotron frequency with orbit to RF phase feedback.
- Stable FOFB + CBM0 correction
  - Retained 920 Hz orbit feedback bandwidth. Motion at 360 Hz is not affected.

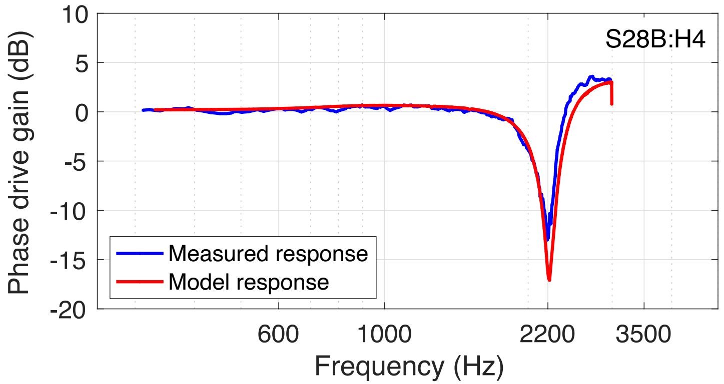
1. P. Kallakuri et al., PRAB **25**, 082801

Simulation model for prototype FOFB + CBM0 correction[1]

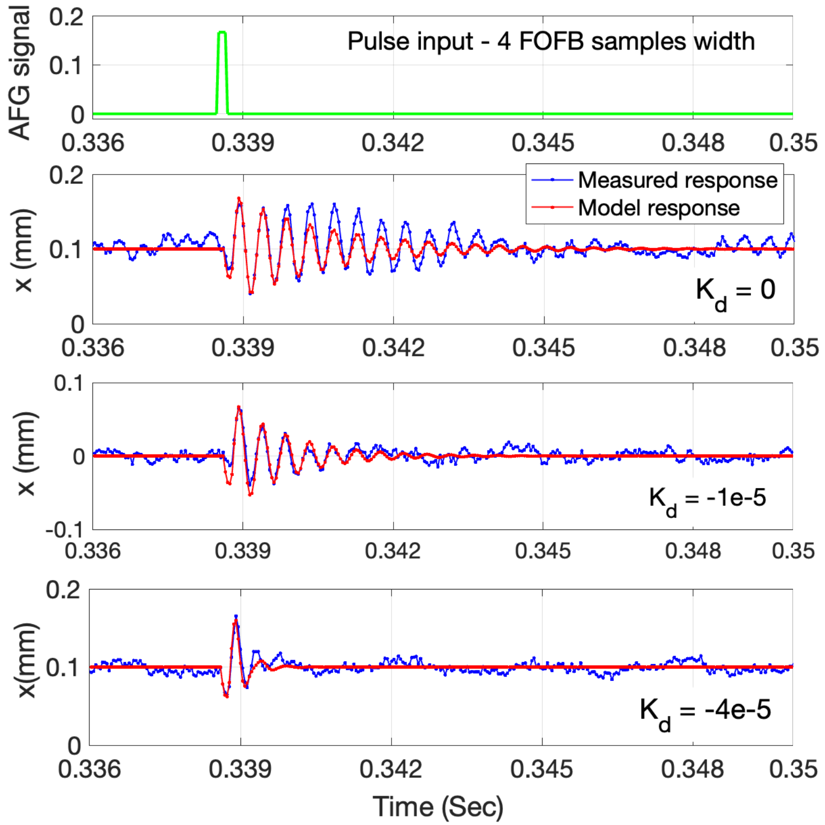
- Developed a MATLAB/simulink model for prototype FOFB+CBM0 correction setup using theoretical knowledge and measurement-based system identification.
- Open loop and closed loop simulation models are validated by comparing model responses against measurements.

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

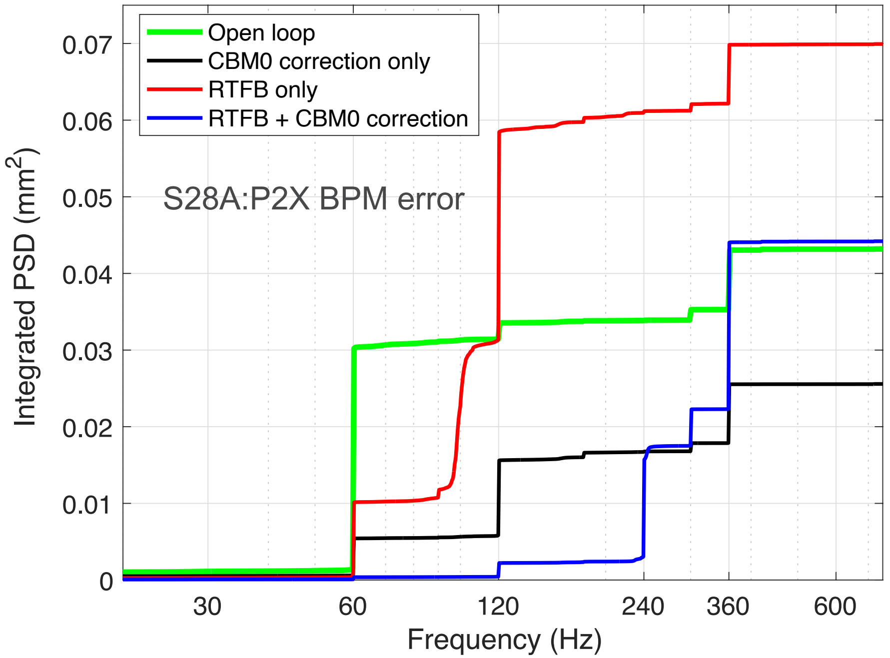
Argonne NATIONAL LABORATORY

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

Coupled bunch mode zero correction within orbit feedback bandwidth

Experimental study with low-alpha lattice

- 6 GeV low-alpha lattice: Synchrotron frequency (60 Hz) is within the orbit feedback bandwidth (90 Hz).
  - Large RF system noise at 60 Hz harmonics.
- Real time feedback system (RTFB) is used - orbit feedback system for APS operations
  - 38 fast correctors and 154 BPMs to deal with large noise.
  - Limited functionality compared to prototype controller with 1.5 kHz sampling rate.

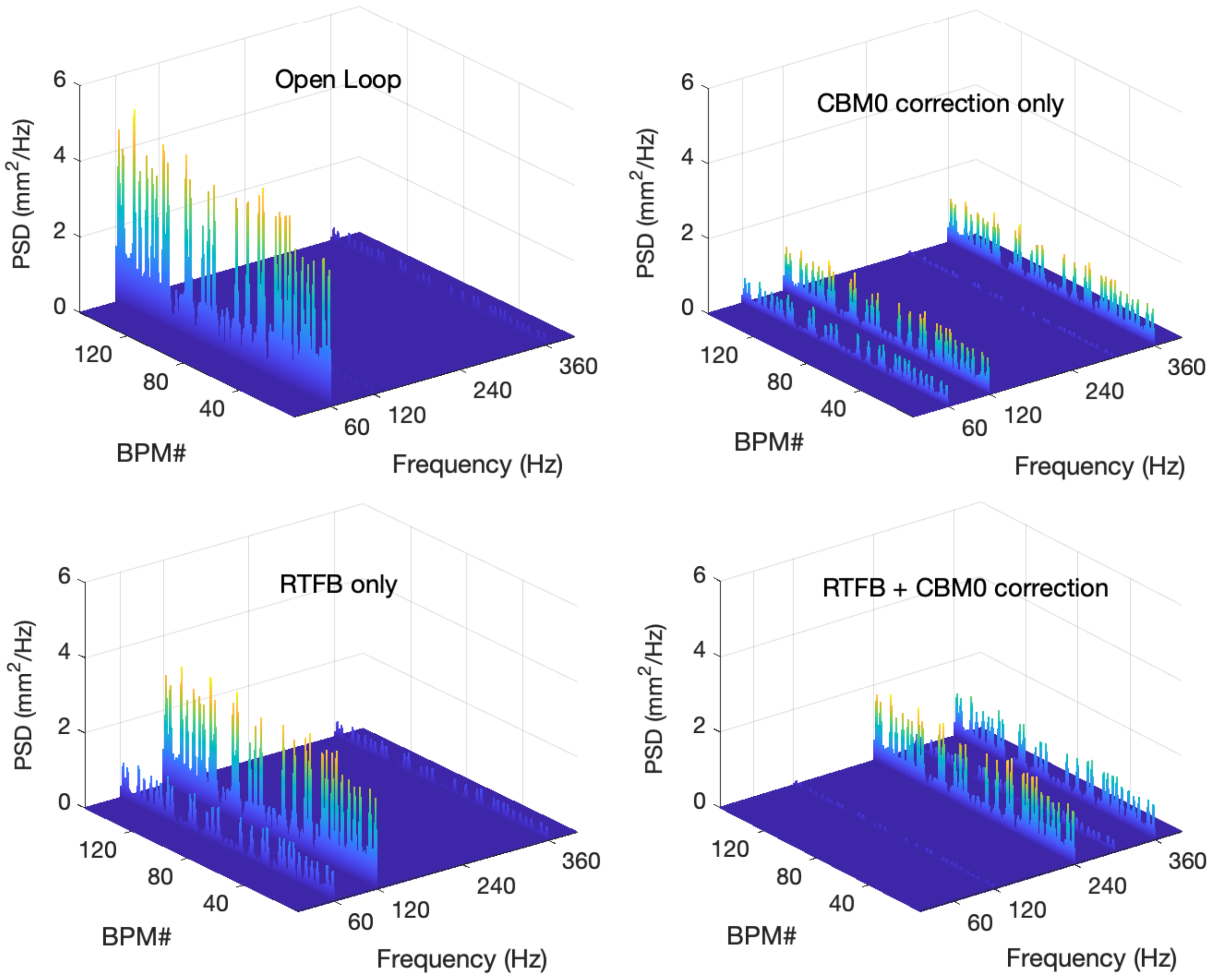


Cumulative mean square orbit motion with different feedback configurations

- Stable combined operation of RTFB + CBM0 correction.
- Partial suppression at synchrotron frequency when feedbacks are operated individually.
- More suppression at 60 Hz with both feedbacks running together.

BPM responses measured at 154 BPMs around the storage-ring

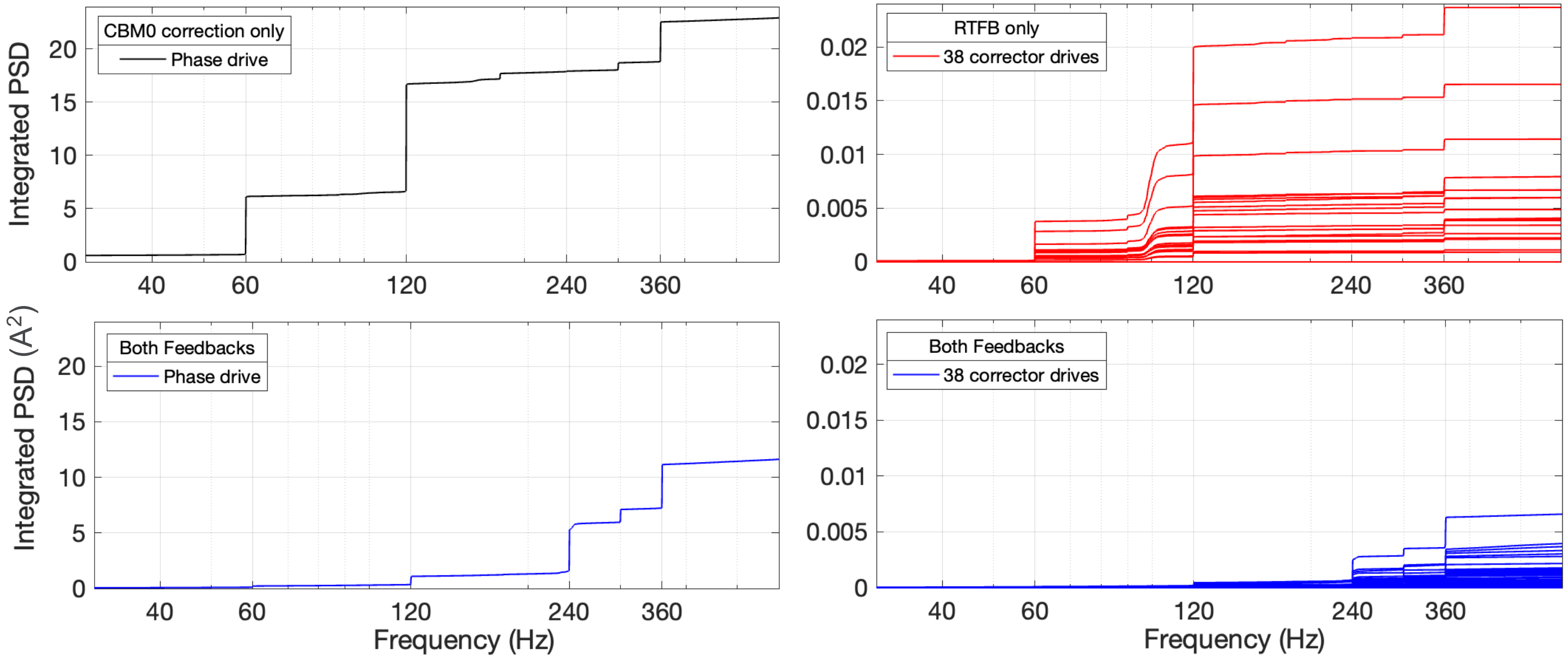
- BPMs in the high dispersion area has larger magnitudes compared to others.
- Individual operation of RTFB or CBM0 correction partially suppressed 60 Hz
  - Frequencies beyond 90 Hz are amplified.
- Narrow resonant increase of RF noise at 60 Hz harmonics when high frequency motion is amplified.
- RTFB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

Conclusions

- Successfully demonstrated CBM0 correction within the orbit feedback bandwidth via experiments with low-alpha lattice setup.
- CBM0 oscillations are damped using orbit to RF phase feedback method.
  - Energy-induced component is extracted from measured orbit and RF phase control signal is generated as if it were another corrector drive in the orbit feedback algorithm.
- Individual operation of RTFB and CBM0 correction resulted in partial suppression at synchrotron frequency.
- The combination of CBM0 correction and RTFB was significantly more effective in suppressing synchrotron frequency.
  - Achieved better orbit motion suppression and reduction in feedback drive efforts.