MODE-BY-MODE ORBIT CONTROL

MOMOC PROJECT

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Diamond Light Source

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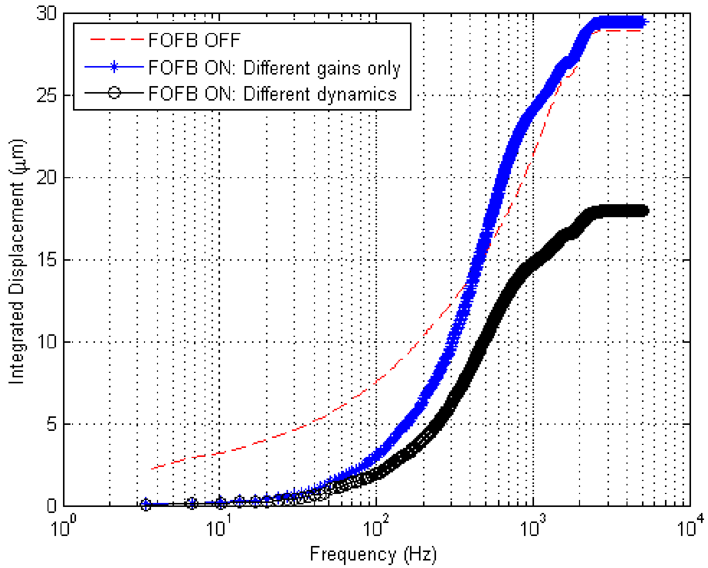
Contents

Introduction & Motivation

- Mode-by-Mode Orbit Control (MOMOC) refers to controller design which exploits knowledge and structure of the spatial modes of the orbit
- Initial demonstrations limited to the Diamond Booster (run as a 100MeV storage ring)
- Propose a project at Diamond to demonstrate advantages of MOMOC on storage ring



1

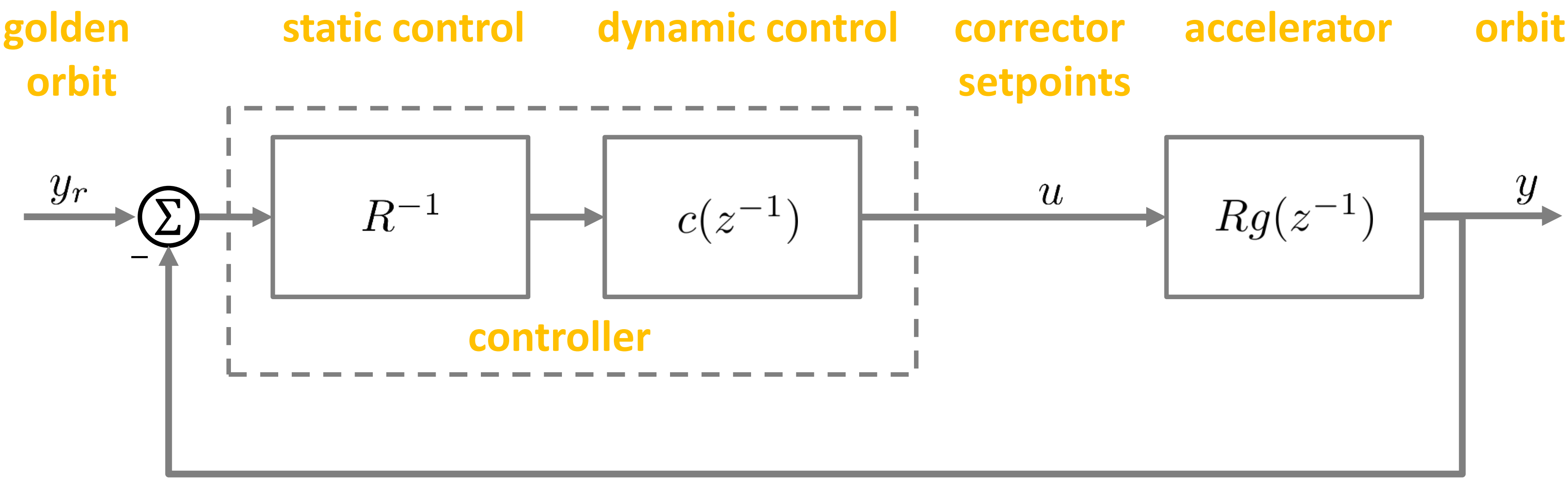
[1] Sandira Gayadeen, "Synchrotron Electron Beam Control", Doctoral Thesis, Oxford University, 2014

1

Orbit Feedback Algorithm

'Traditional Orbit Feedback'

Diamond Orbit Control Algorithm



$$R_{M\times N}\cdot u_{N\times 1}=y_{M\times 1}$$

$$-R^{-1}_{N\times M}\cdot y_{M\times 1}=u_{N\times 1}$$

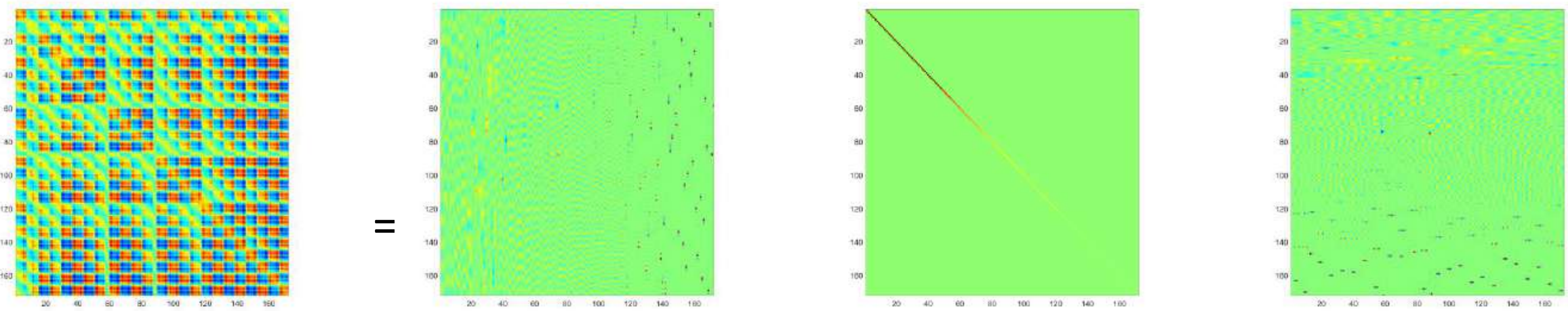
The response matrix: corrector setpoints → beam position

The inverse matrix: beam position → corrector setpoints

Singular Value Decomposition (SVD)

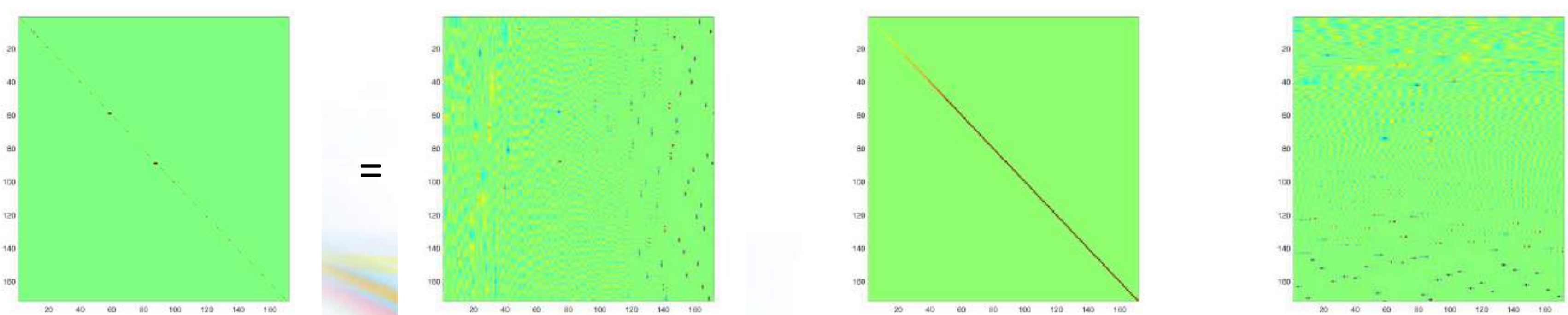
SVD of the Response matrix:

$R \quad U \quad \Sigma \quad V^{\mathrm{T}}$



Inverse response matrix calculation from SVD:

$R^{-1} \quad V \quad \Sigma^{-1} \quad U^{\mathrm{T}}$



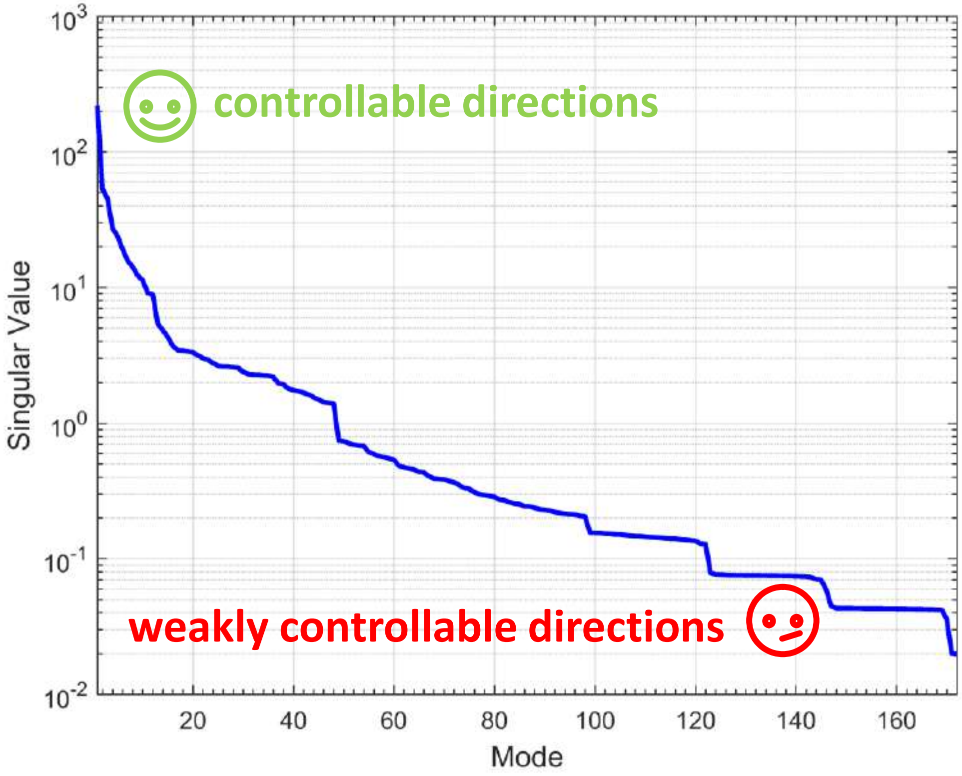
Spatial Modes

- Singular values are associated with a spatial mode

- Modes are ordered from 'most important' i.e. largest singular value to 'least important' i.e. smallest singular value

From a controller design perspective:

- Low order modes i.e. large singular values are well controllable directions
- High order modes i.e. small singular values are weakly controllable directions



The 'Psuedo-Inverse'

Solution: Do not apply the full inverse but the '**pseudo-inverse**'

1) Truncated SVD

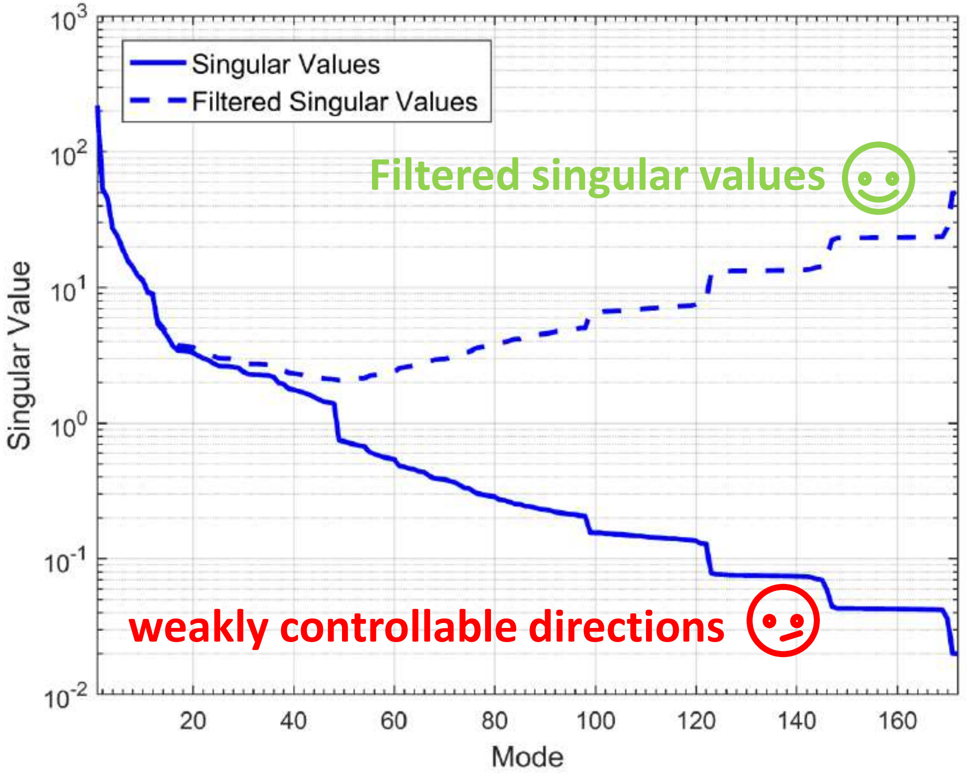
- Set all but the first 'k' largest singular values to 0.
- Use only first 'k' columns of U and V

Information loss; no longer maximum correction

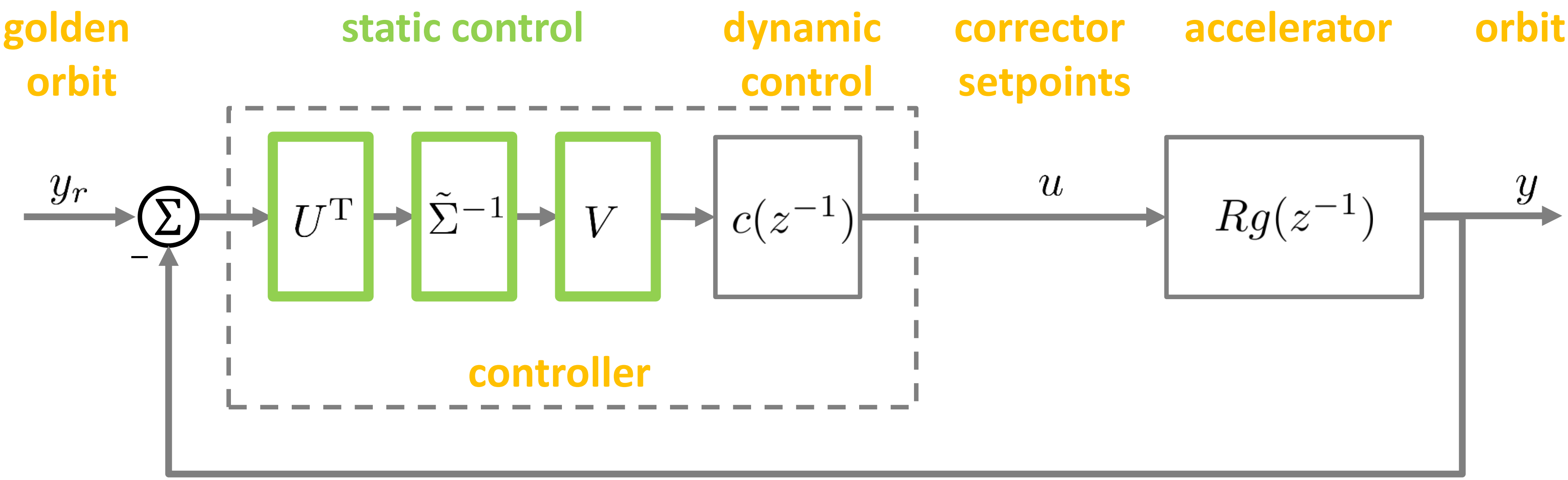
2) Tikhonov Regularisation

- Filter the large inverse singular values

Only one degree of freedom

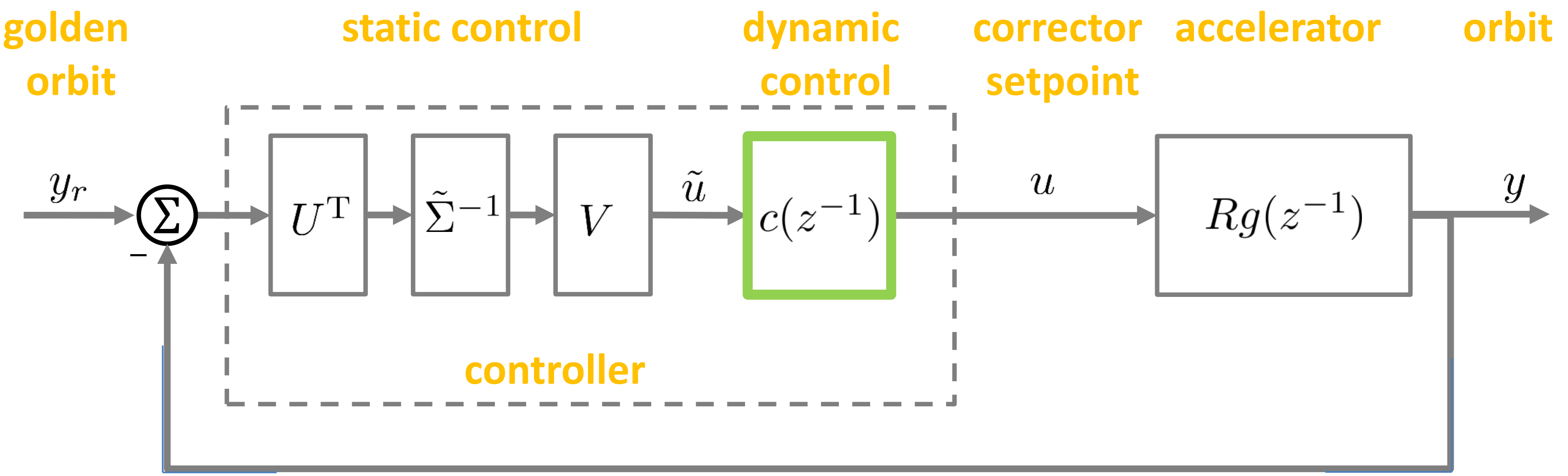


Static Control with Pseudo-Inverse



The inverse matrix is calculated using the Singular Value Decomposition where the singular values are either discarded or filtered.

Dynamic Control with IIR filter



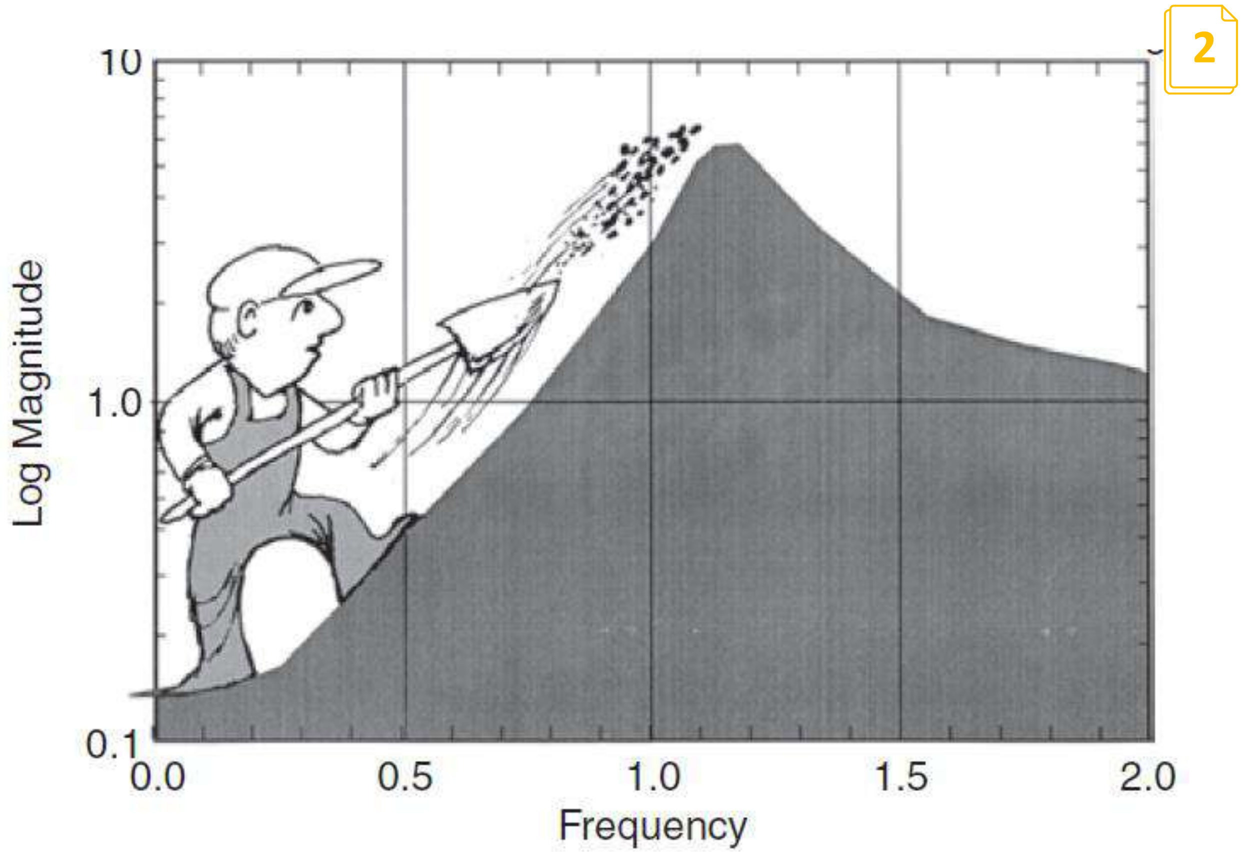
- Dynamic controller is implemented as an IIR filter:

$$u(k) = b_0\tilde{u}(k) + b_1\tilde{u}(k-1) + \cdots + b_p\tilde{u}(k-p) - a_1u(k-1) - \cdots - a_qu(k-q)$$

- The controller is the same for all corrector inputs i.e. the same IIR filter

Closed Loop Sensitivity

- The dynamic controller specifies at which frequencies the control loop suppresses beam disturbances
- The **sensitivity** function describes the ability of the closed loop to attenuate disturbances
- Sensitivity reduction at low frequencies unavoidably leads to sensitivity increase at higher frequencies



[2] Gunter Stein, “Respect the Unstable”, IEEE CDC, 1989

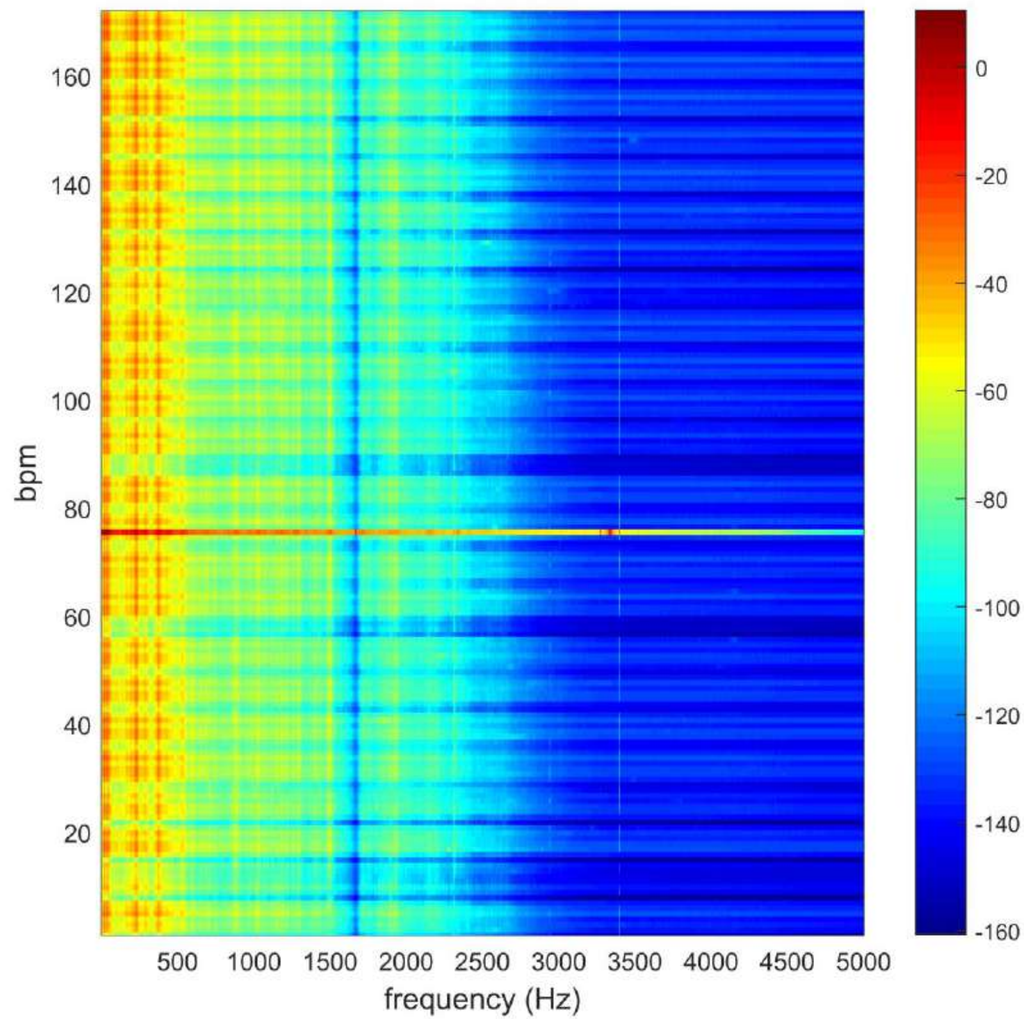
Power Spectrum Density (PSD) at each BPM

Power spectrum density at each BPM over 10s (in dB)

- Power density distributed across all BPMs
- Power concentrated at lower frequencies

For control design:

- Controller must suppress disturbances at all BPM locations and low frequencies



Sensitivity Bandwidth

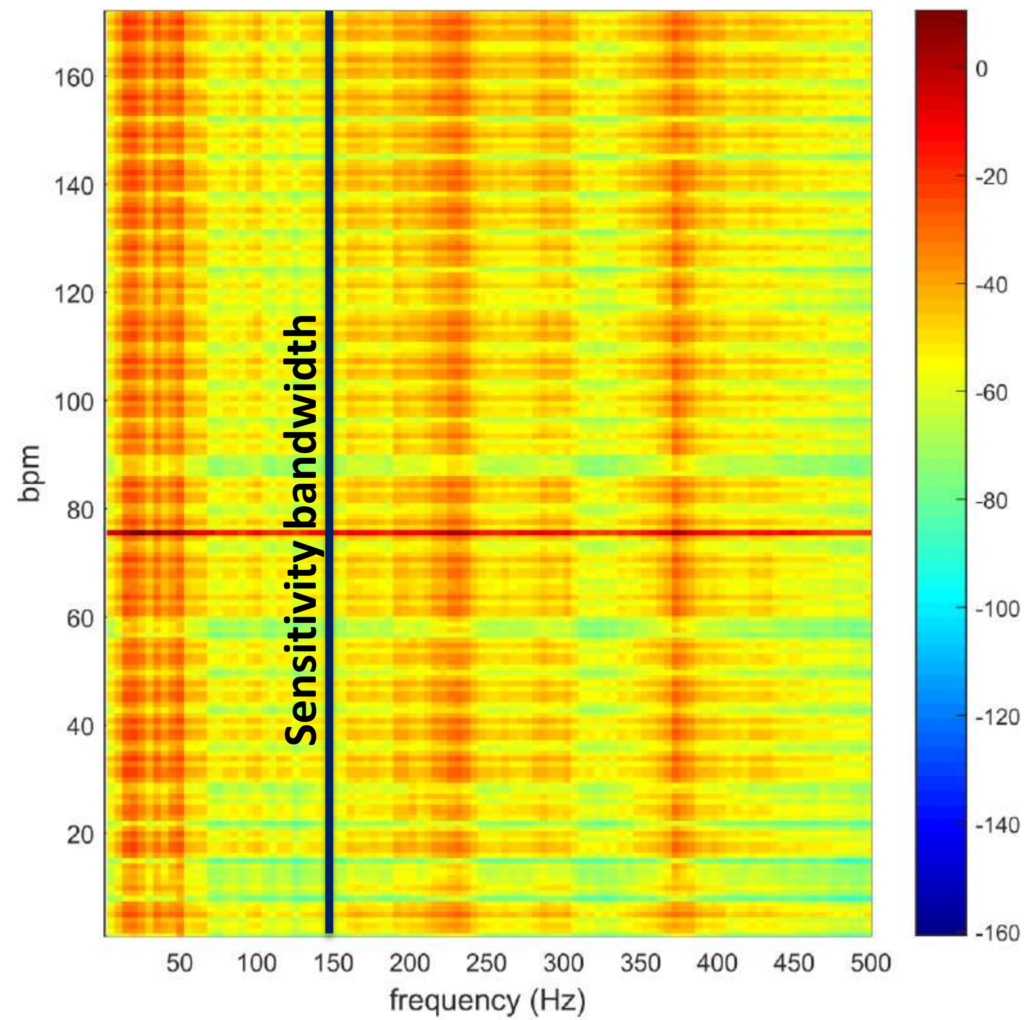
Sensitivity has the same bandwidth at all BPMs

Sensitivity bandwidth limited by

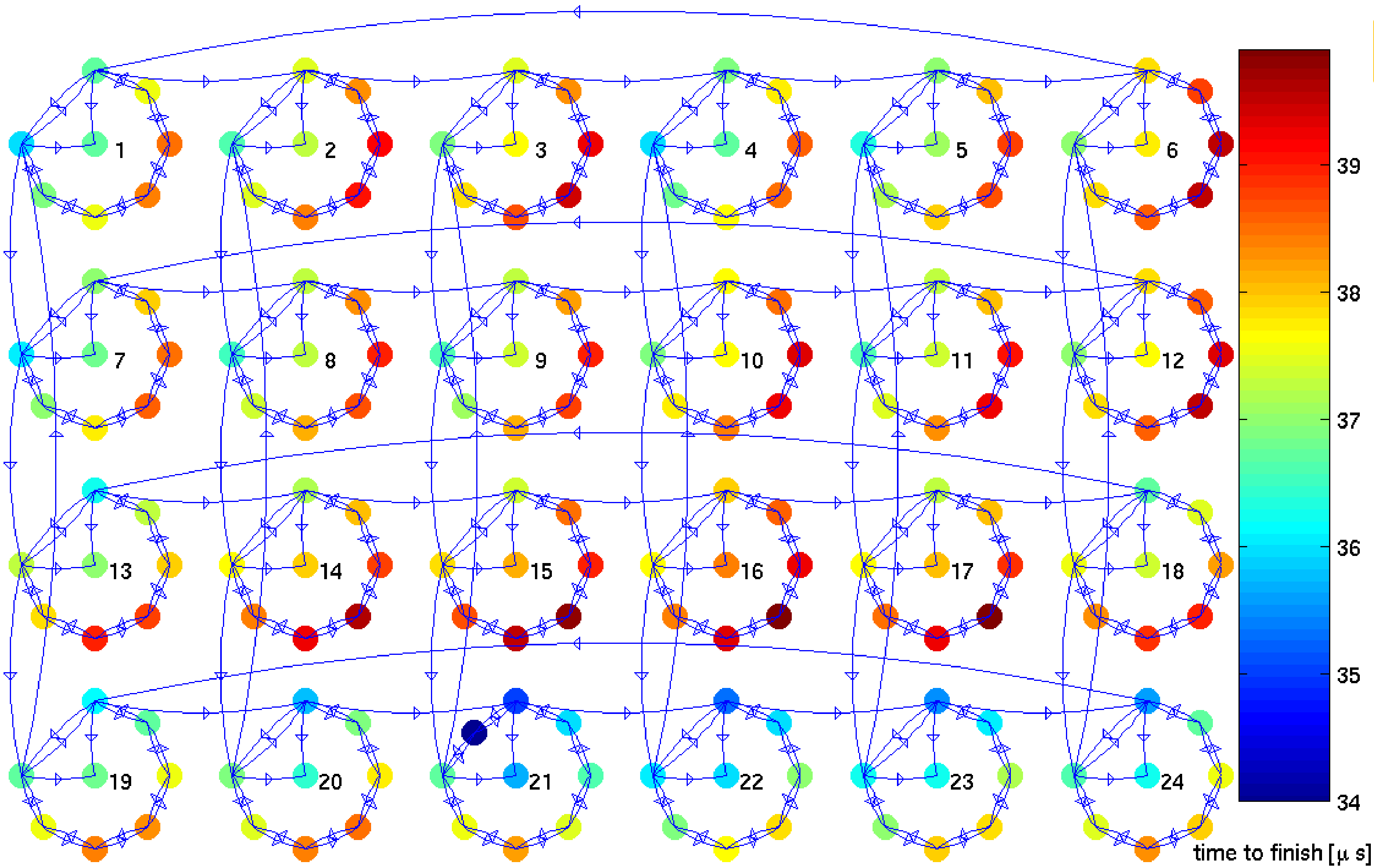
- Bandwidth of correctors
- Delays

For sensitivity bandwidth of 150Hz:

- Disturbances beyond 150Hz cannot be attenuated
- and may even be amplified!



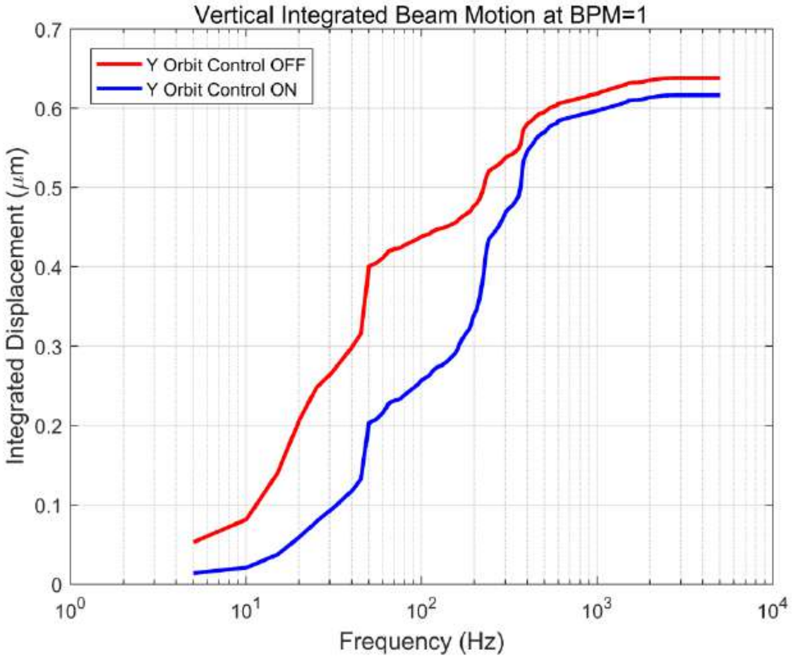
Diamond Controller Communication Network

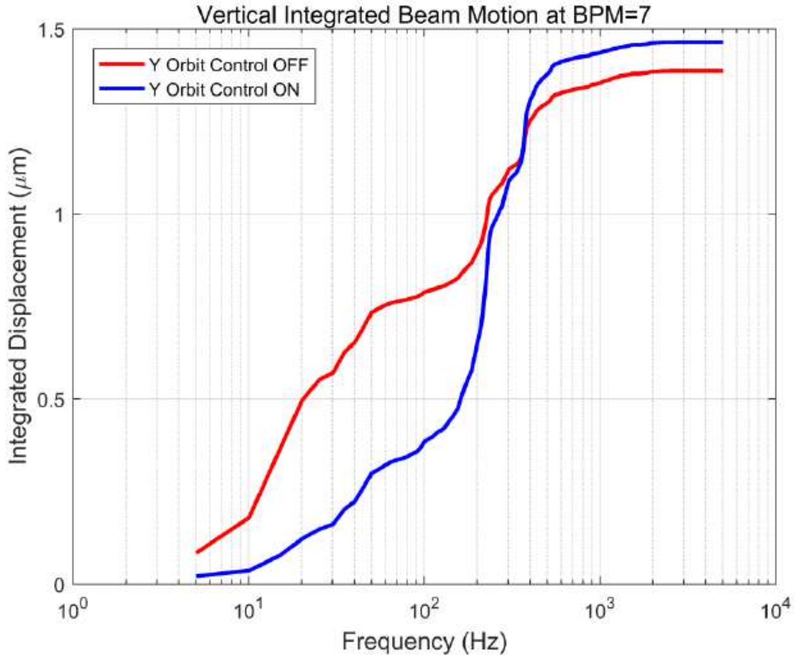


3

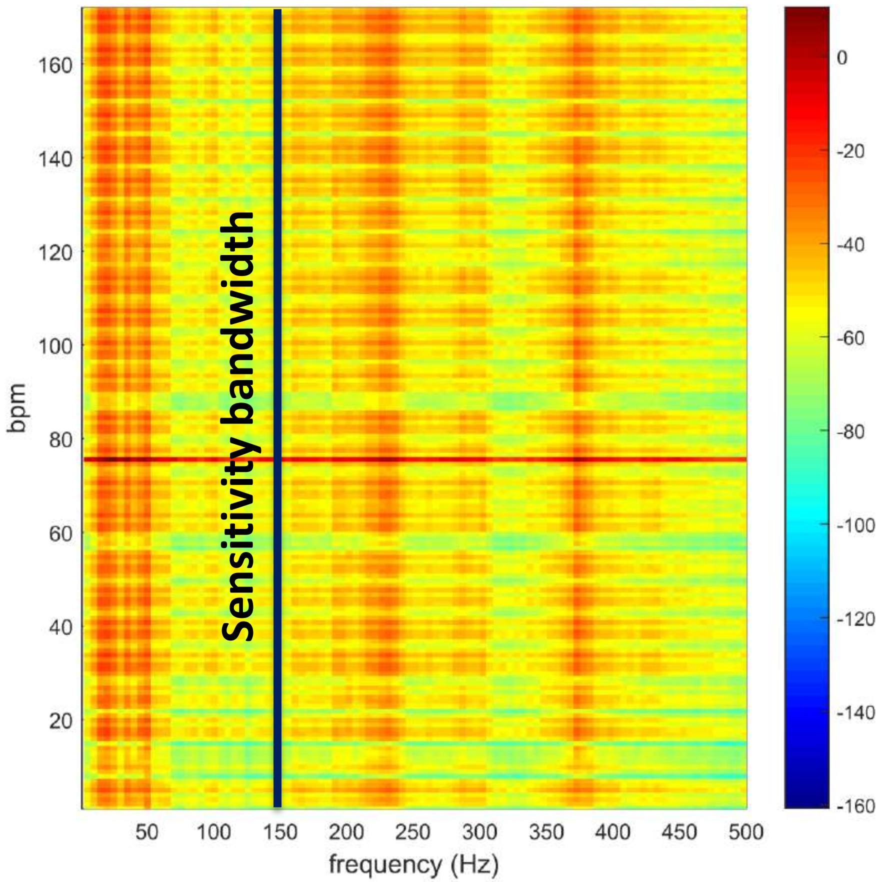
[3] Mark Heron et al, “Diamond Light Source Electron Beam Position Feedback”, ICALEPCS, 2009

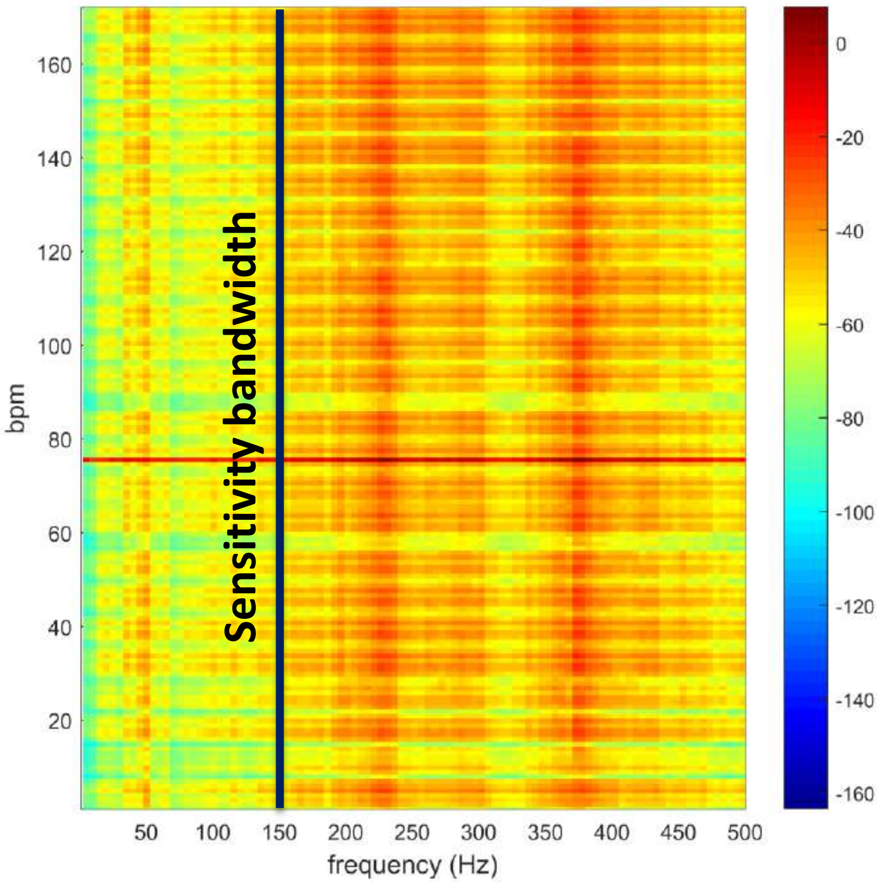
Orbit Control Performance: Integrated Motion





Orbit Control Performance: PSD





2

Mode-by-Mode Orbit Control

MOMOC

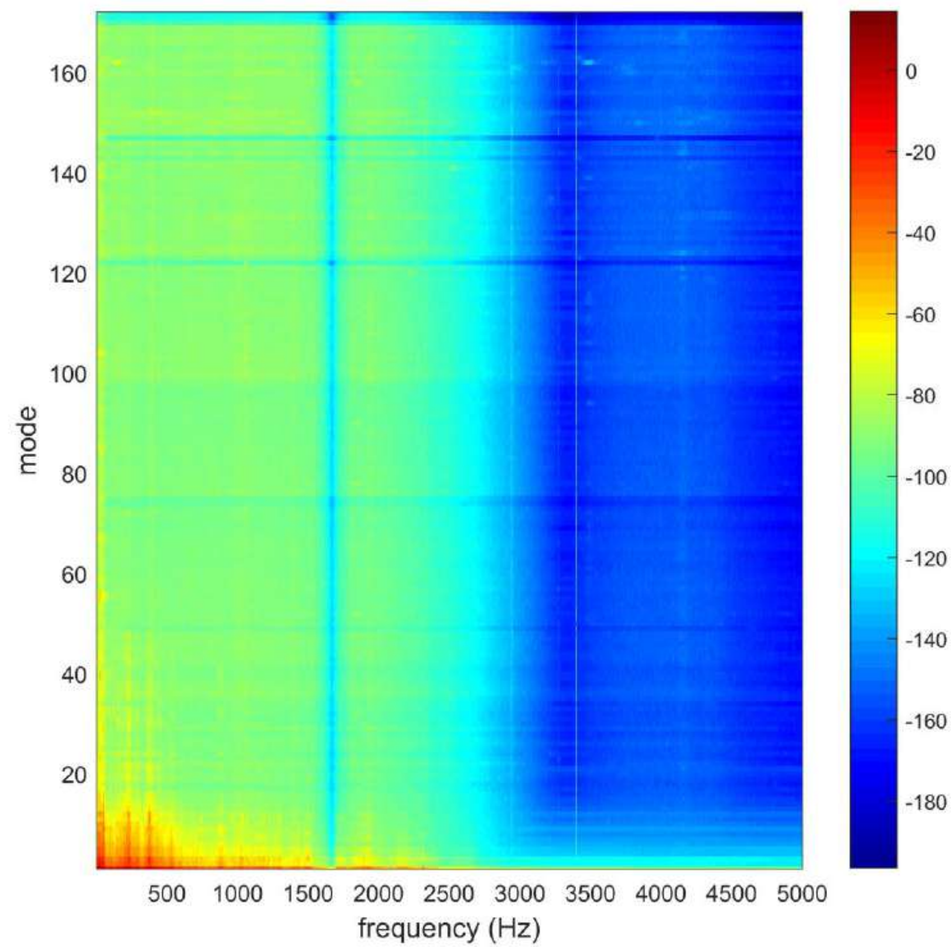
Power Spectrum Density at each MODE

Power spectrum density at each BPM over 1s (in dB) **transformed into mode space**

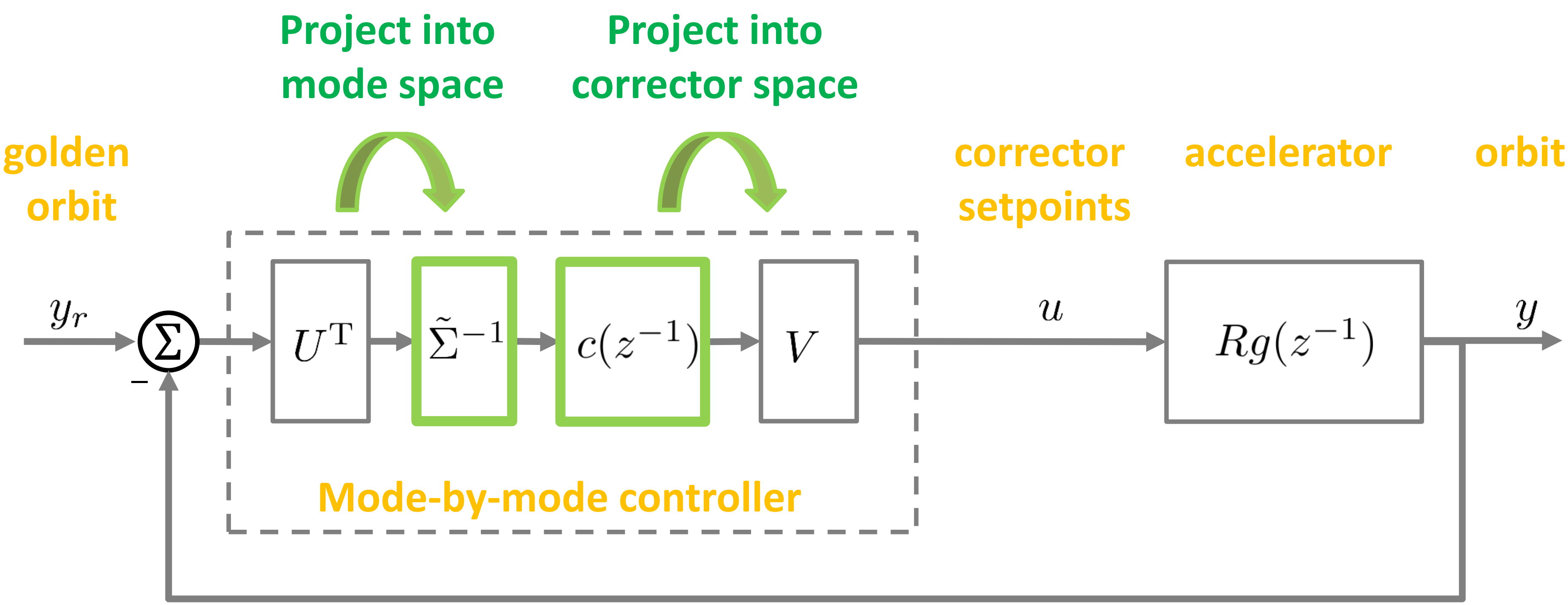
- Power concentrated at low order modes
- Power concentrated at lower frequencies

For control design:

- Controller must suppress disturbances
- Low frequencies
- Low order modes



Mode-by-Mode Orbit Control

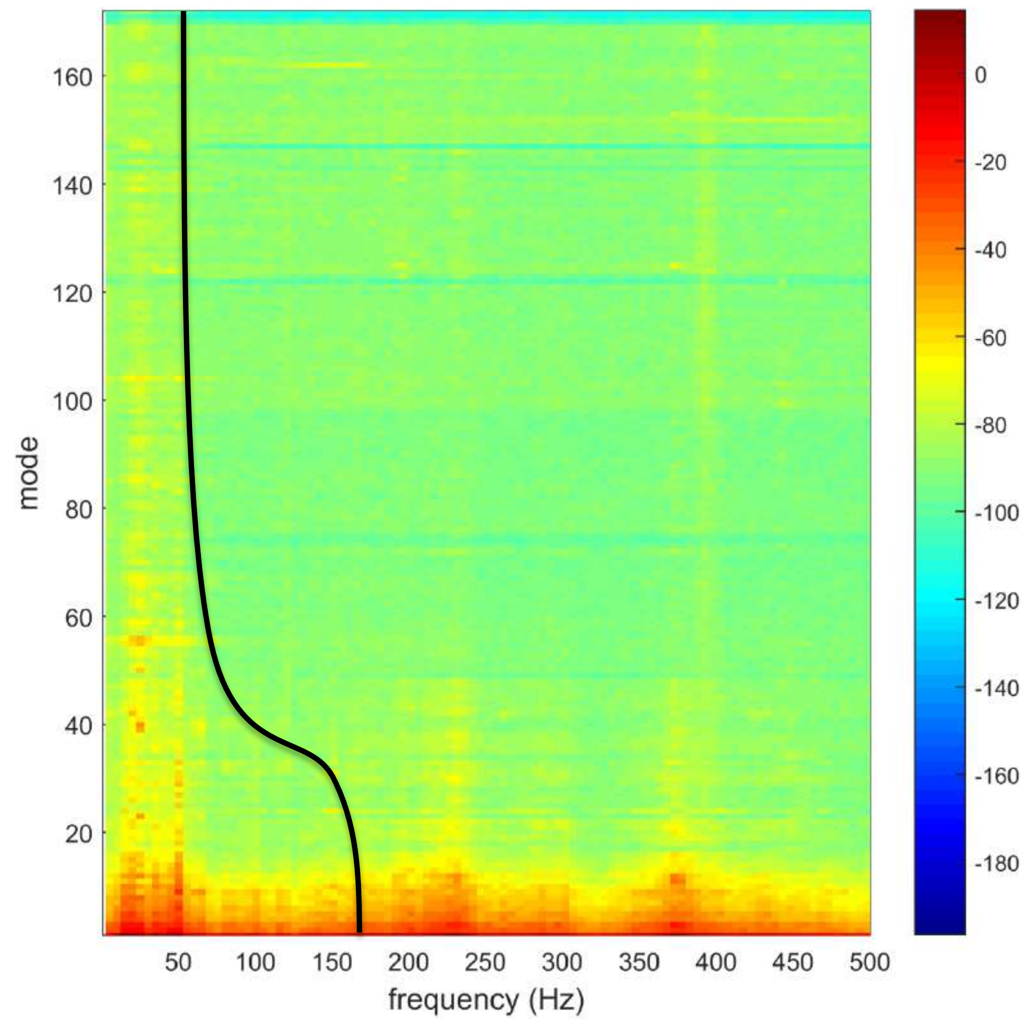


1. Project beam positions into mode space
2. Apply spatial correction ('tuned' inverse singular values for individual modes)
3. Apply dynamic correction ('tuned' IIR for individual modes)
4. Project correction out of mode space (i.e. map back to correctors)

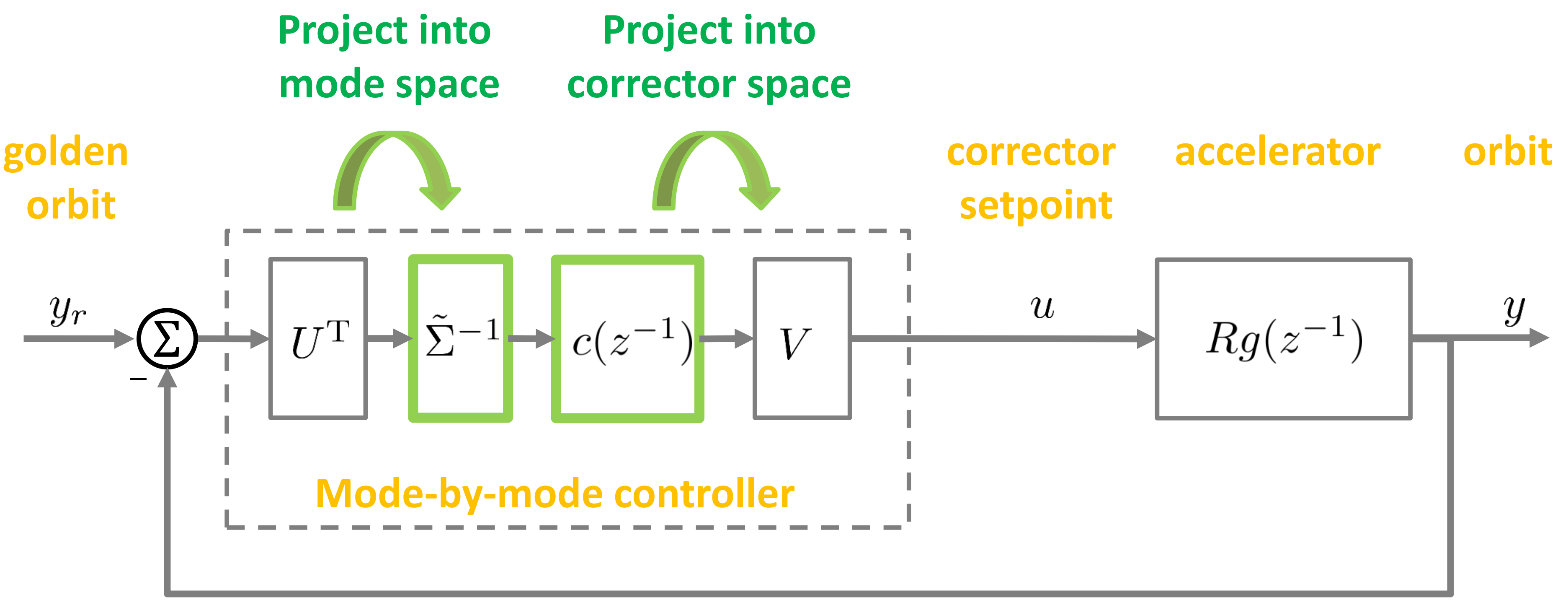
Sensitivity Shaping in Mode Space

How to select dynamics for each mode?

- Shape sensitivity depending on the disturbance distribution across modes
- Low order modes with most disturbance concentration → larger bandwidth
- High order modes with least disturbance concentration → lower bandwidth



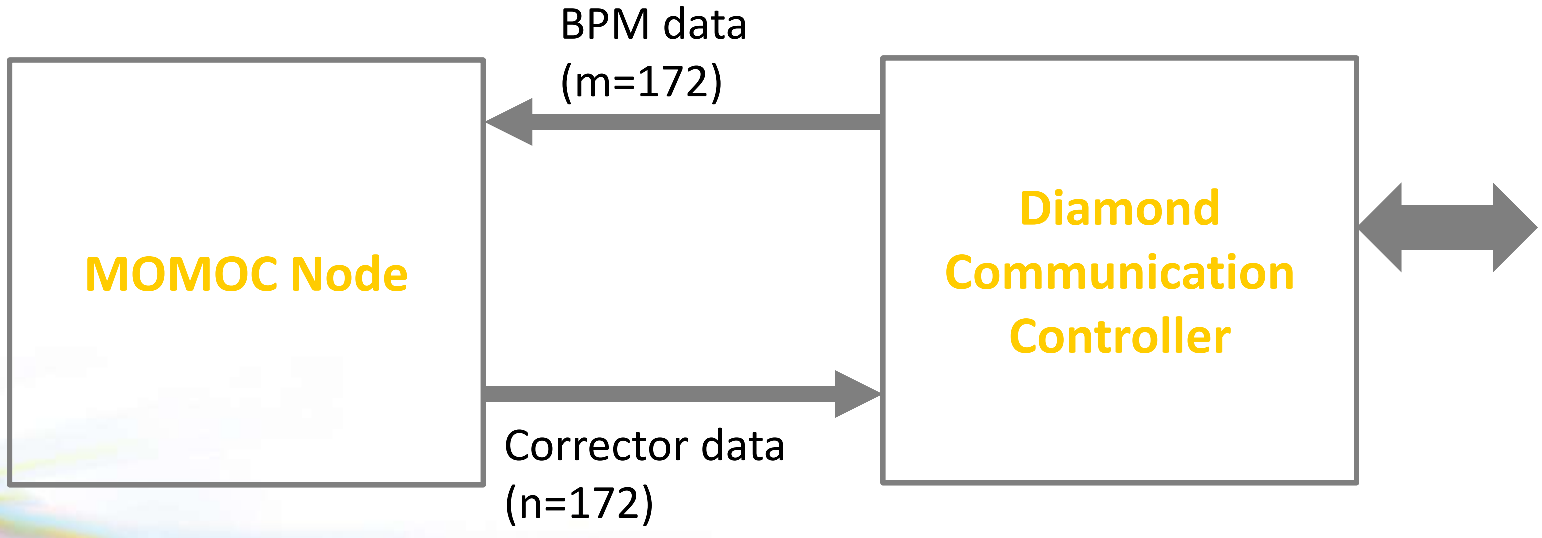
Mode-by-Mode Orbit Control



- The mode-by-mode controller has **spatial and dynamic** adjustment of individual modes
- ‘Traditional’ approach only provides spatial tuning for individual modes

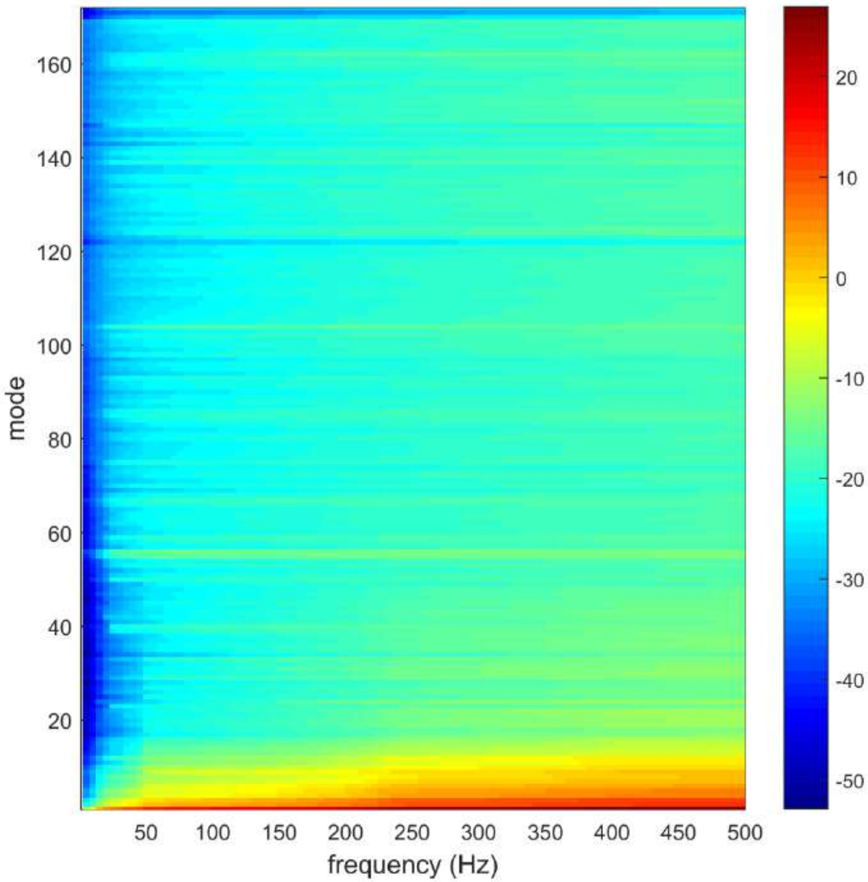
Changes to Orbit Control Communication

- Insert MOMOC node into fast communication network
- Reconfigure existing computation nodes for straight through delivery of corrector values
- Reversible implementation
- Higher latency expected with 2, 172x172 matrix multiplications

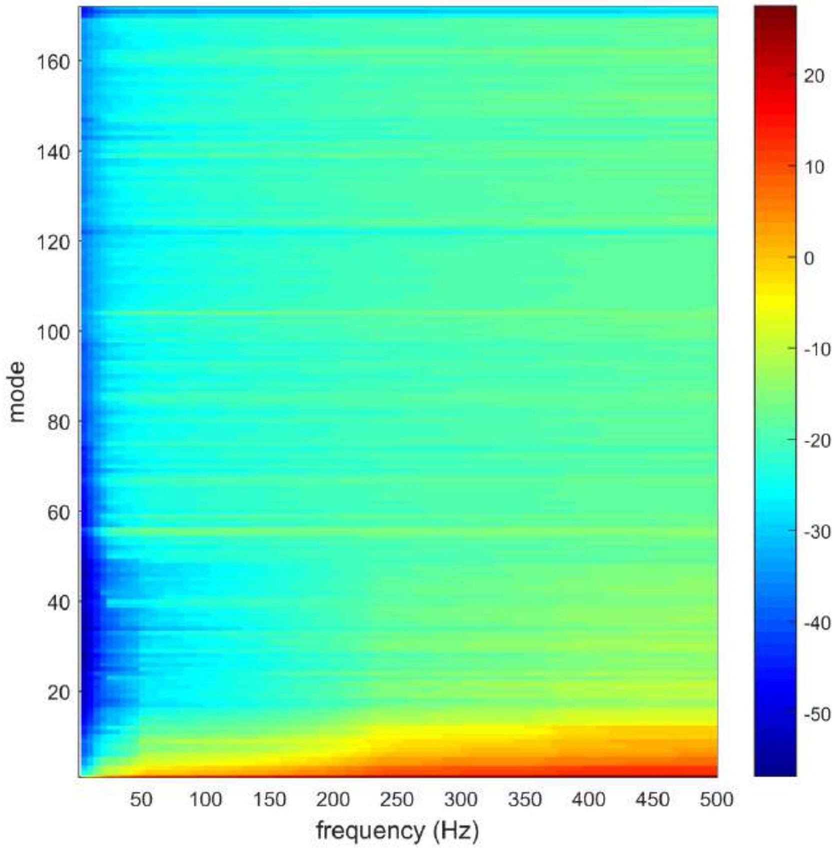


Simulation of MOMOC Performance

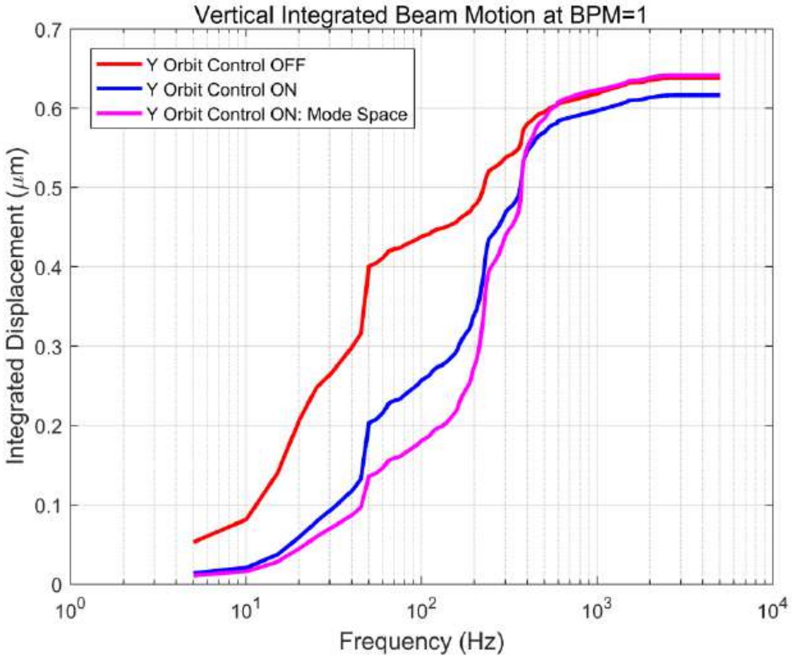
Traditional Orbit Control

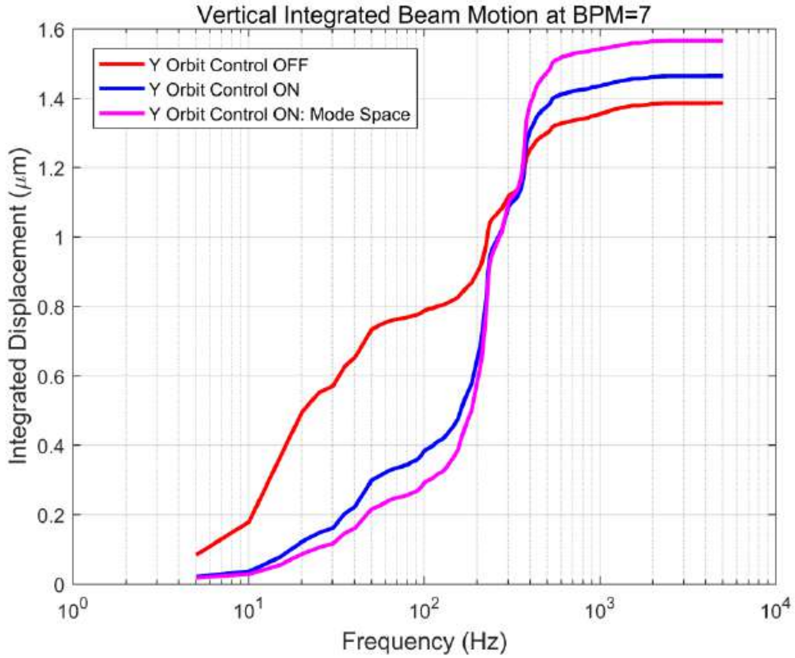


Mode-by-mode Orbit Control

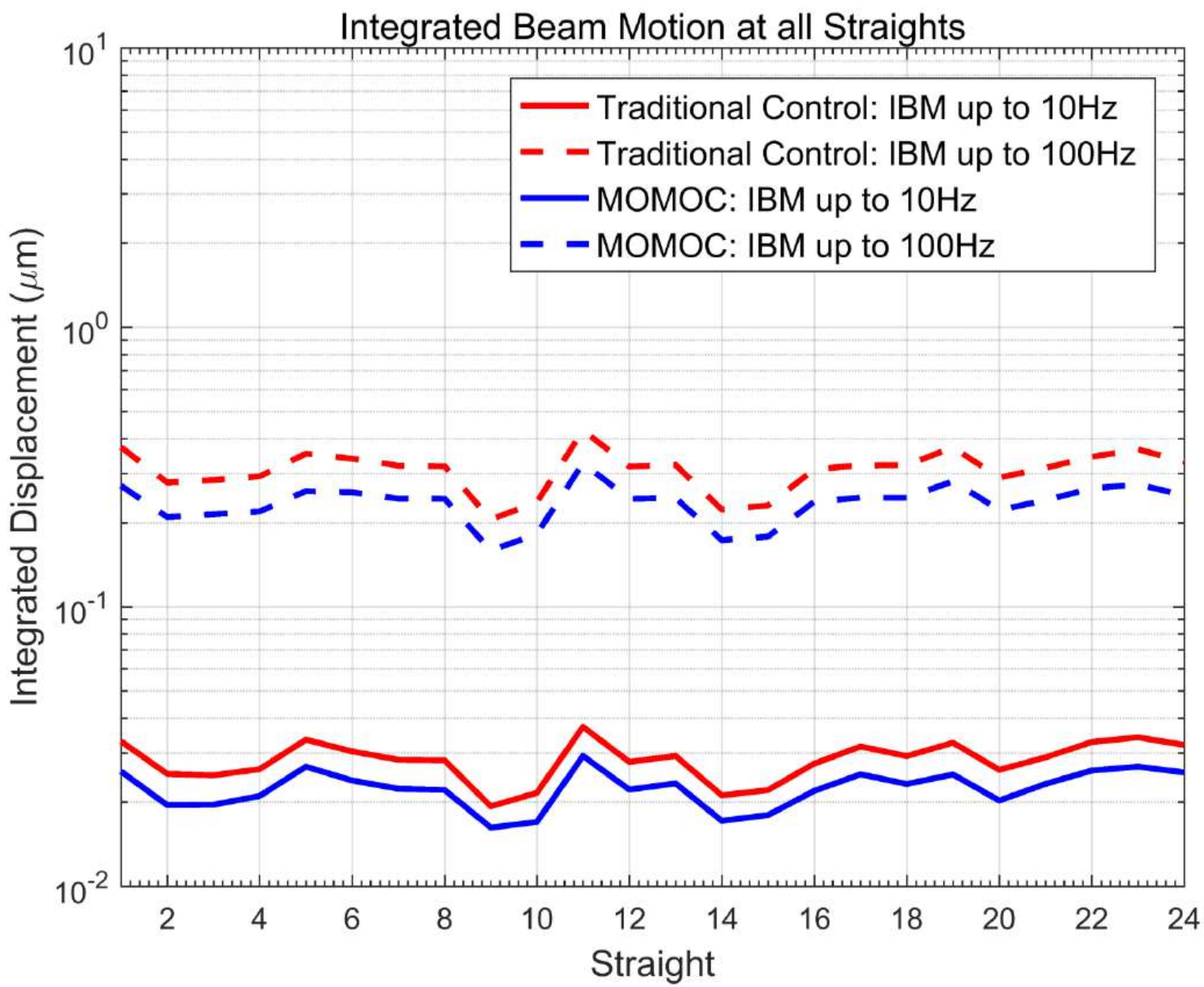


Simulation of MOMOC Performance





Simulation of MOMOC Performance

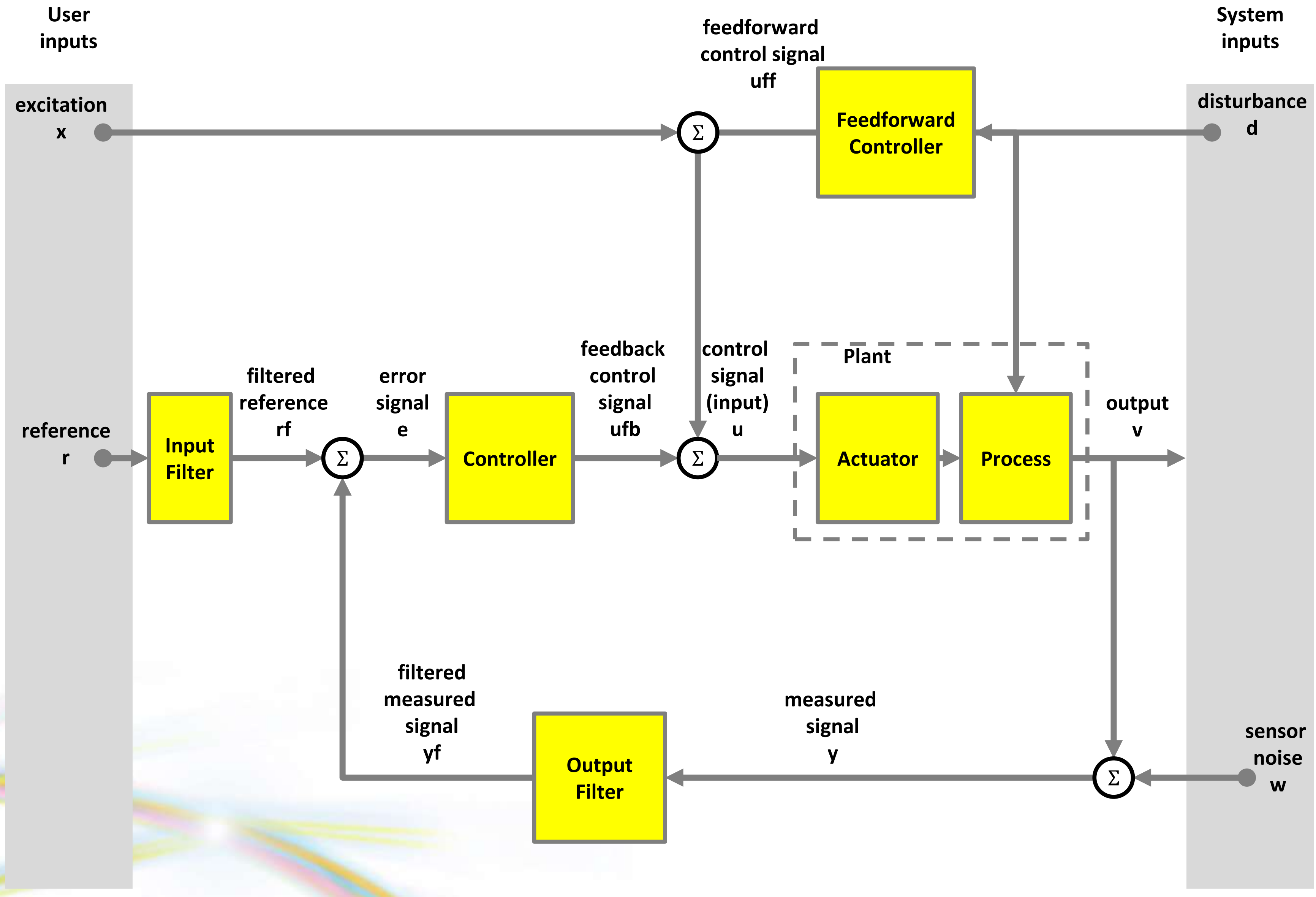


3

Further Control Design

Enhanced control structure

Control System Architecture



4

Summary

Conclusions

- Mode-by-Mode Orbit control can give improved performance
- Better suppression achieved by tuning the dynamic control to each mode (in addition to tuning the spatial control for each mode)
- Analogous to applying different filtered singular values to individual modes
- MOMOC Project aims to make minimal changes to existing infrastructure to demonstrate mode-by-mode control

Acknowledgments

DLS: Diagnostics Groups and Controls Group

Oxford University: Stephen Duncan