Fast Orbit Feedback for Diamond-II

12th International Beam Instrumentation Conference

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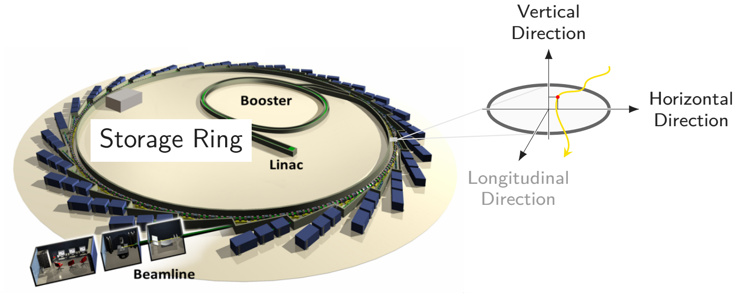
[1]University of Oxford, [2]Diamond Light Source, [3]Helmholtz-Zentrum für Materialien und Energie

Sep. 10-14, 2023, Saskatoon, Canada

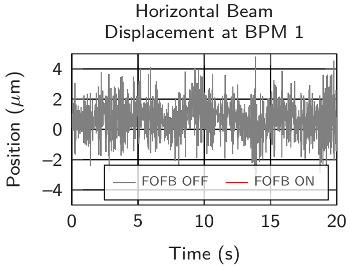
Outline

Fast Orbit Feedback (FOFB) in the Diamond Storage Ring



Short-term disturbances:

- Ground/girder vibrations
- RF/power supply noise
- Water cooling
- ...



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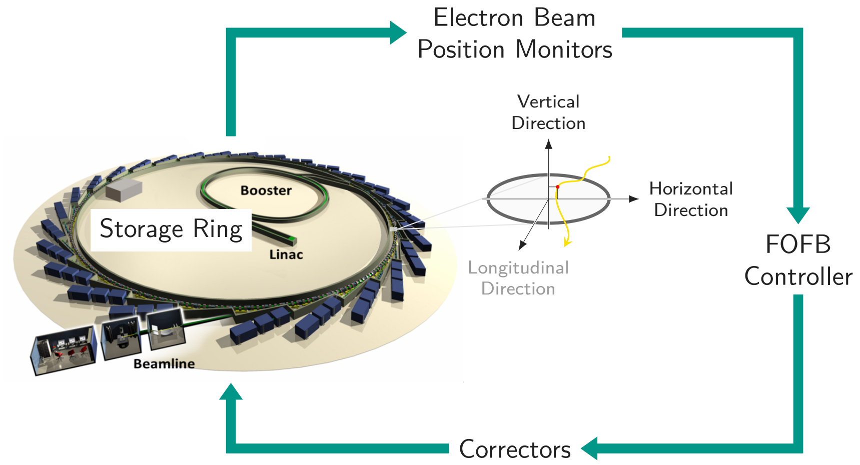

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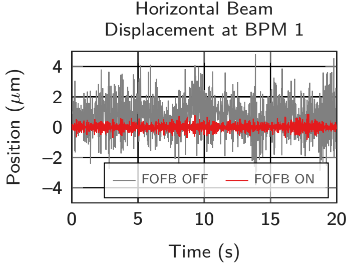

↯ Multi-Input Multi-Output ↯

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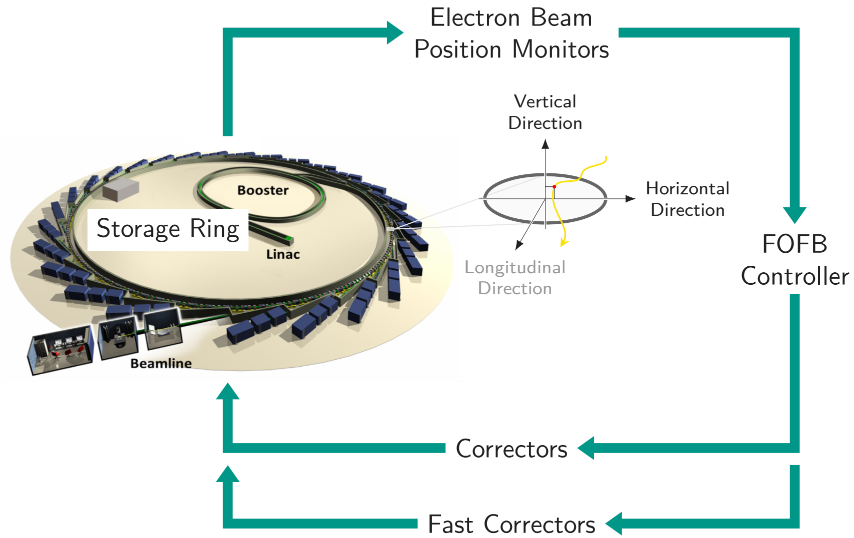

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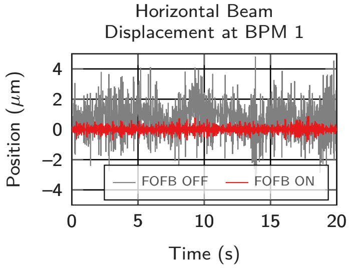

Multi-Input Multi-Output

Diamond-II Upgrade requires Enhanced FOFB Performance

1. Major Changes:

- New MBA lattice → smaller beam
- New beamlines → higher frequency resolution
- New insertion devices with upstream & downstream BPMs

➠ M. G. Abbott *et al.*, "Diamond-II technical design report," Aug. 2022.
➠ L. T. Stant *et al.*, "Diamond-II electron beam position monitor development," IBIC 2022.

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2. Increased Stability Requirements:

Parameter	Diamond	Diamond-II
Beam size H/V	123 µm 3.5 µm	30 µm 4 µm
Rel. stability	10 % up to 100 Hz	3 % up to 1 kHz
Abs. stability H/V	12 µm 0.35 µm	0.9 µm 0.12 µm

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3. Enhanced FOFB Specs:

Parameter	Diamond	Diamond-II
Closed-loop BW	140 Hz	$\geq$ 1 kHz
Latency	700 μs	$\leq$ 100 μs
Number of BPMs	173	252
Number of correctors	172	252 slow 144 fast
Sample frequency	10 kHz	100 kHz

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+ Centralised computing node (White Rabbit v4)
+ New communication network
+ New BPMs

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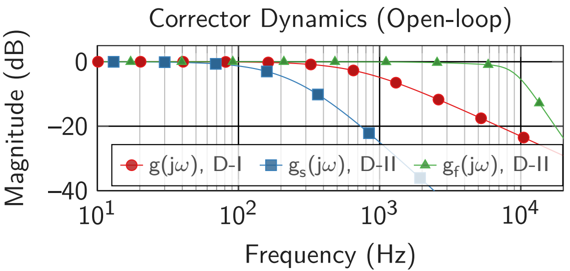
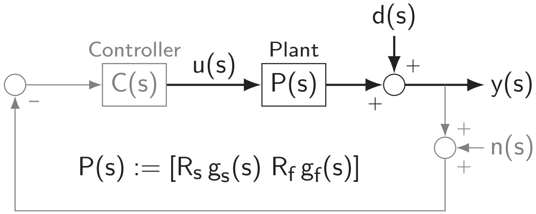
➠ L. T. Stant *et al.*, "Diamond-II electron beam position monitor development," IBIC 2022.

Orbit Feedback Dynamics for Diamond-II: Slow and Fast Correctors

$$y(s) = R_s\, g_s(s)\, u_s(s) + R_f\, g_f(s)\, u_f(s) + d(s)$$

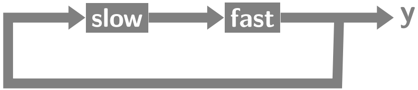
Beam displacement | Contribution from slow correctors | Contribution from fast correctors | Disturbance





More on n(s) ➟ S. Banerjee *et al.*, "Modified FOFB controller for disturbance attenuation in long straights for D-II," IBIC 2023.

Existing Solutions for Slow & Fast Correctors



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  ✓ Separate loops for slow ($f_{slow} \approx 1\,\text{Hz}$) & fast ($f_{fast} = 10\,\text{kHz}$) correctors
  ✓ Exchange data between slow & fast loops → no frequency deadband

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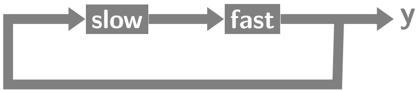

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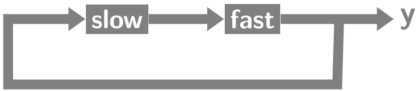

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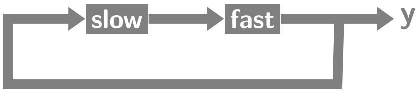

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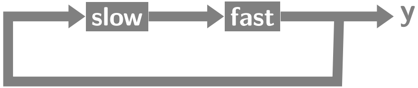

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  - ✓ Applicable to ≥ 2 corrector arrays

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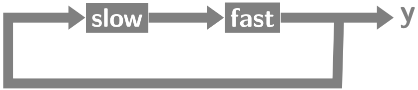

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\+ Other controllers: linear quadratic regulator, model predictive control,...

\+ Literature: cross-directional/spatio-temporal systems, paper making, steel rolling, process control,...

Decoupling Systems with One Corrector Type in Modal Space

1. System with one corrector type:
$$y(s) = R\,g(s)\,u(s) + d(s)$$
2. Substitute SVD:
$$y(s) = U\Sigma V^T\,g(s)\,u(s) + d(s)$$
3. Define modal variables:
$$\hat{y}(s) := U^T y(s), \qquad \hat{u}(s) := V^T u(s), \qquad \hat{d}(s) := U^T d(s)$$

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$n_y \times$ single-input single-output

Large condition number $\sigma_{max}/\sigma_{min}$

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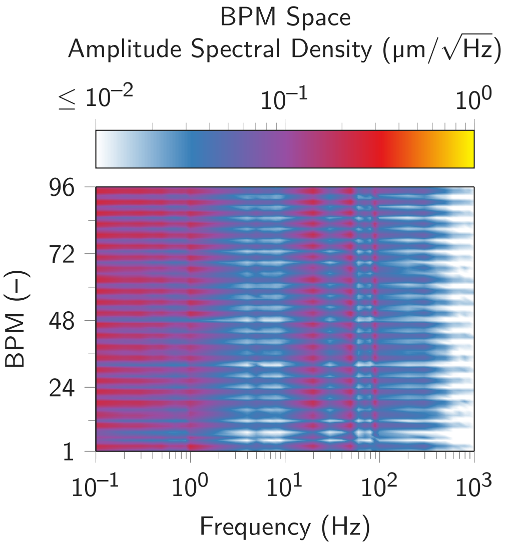
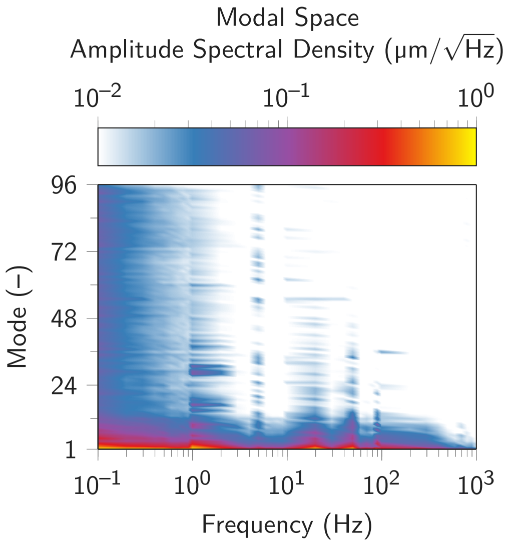
Measured Vertical Disturbance at Diamond





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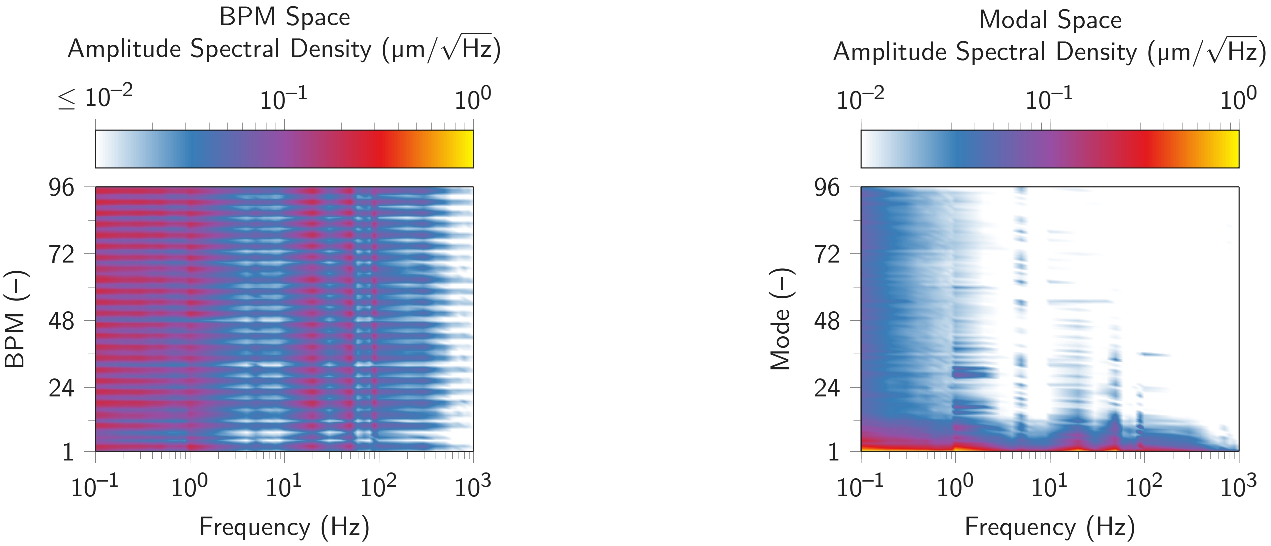

ϟ Disturbance concentrated in low-order modes ϟ

Generalised Singular Value Decomposition (GSVD) for two Matrices

$$y(s) = R_s\, g_s(s)\, u_s(s) + R_f\, g_f(s)\, u_f(s) + d(s)$$

$$R_s = X \begin{bmatrix} \Sigma_s & \\ & I \end{bmatrix} U_s^T \qquad R_f = X \begin{bmatrix} \Sigma_f \\ 0 \end{bmatrix} U_f^T$$

➠ G. H. Golub and C. F. Van Loan, *Matrix Computations*, 3^{rd} ed., 2013.

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- $X \in \mathbb{R}^{n_y \times n_y}$ is invertible
- $\Sigma_{(\cdot)} = \mathrm{diag}(\sigma_{(\cdot),1}, \ldots, \sigma_{(\cdot),n_f})$ are the generalised singular values ($\neq$ singular values)
- $U_{(\cdot)} \in \mathbb{R}^{n_{(\cdot)} \times n_y}$ are orthonormal

➠ G. H. Golub and C. F. Van Loan, *Matrix Computations*, 3rd ed., 2013.

Diagonalising the System with Slow and Fast Correctors

1. System with slow and fast actuators:

$$y(s) = R_s\, g_s(s)\, u_s(s) + R_f\, g_f(s)\, u_f(s) + d(s)$$

2. Substitute GSVD:

$$y(s) = \dots$$

3. Define generalised modes:

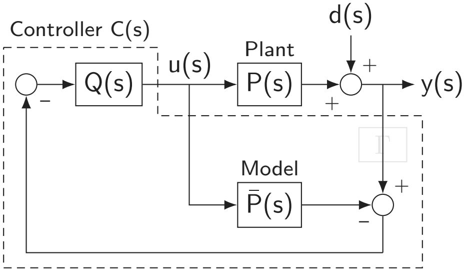
$$\hat{y}(s) := X^{-1} y(s), \qquad \hat{u}_s(s) := U_s^T u_s(s), \qquad \hat{u}_f(s) := U_f^T u_f(s), \qquad \hat{d}(s) := X^{-1} d(s)$$

$$\hat{y}(s) = \begin{bmatrix} \Sigma_s & \\ & I \end{bmatrix} g_s(s)\, \hat{u}_s(s) + \begin{bmatrix} \Sigma_f \\ 0 \end{bmatrix} g_f(s)\, \hat{u}_f(s) + \hat{d}(s)$$

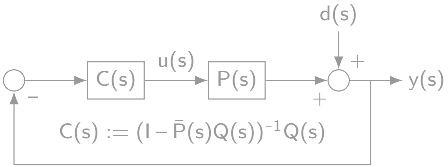
$n_f \times$ two-input single-output $\qquad$ $n_s - n_f \times$ single-input single-output

➠ I. Kempf, P. Goulart, and S. Duncan, “A higher-order GSVD for rank-deficient matrices,” SIAM J. Matrix Anal. Appl., Sep. 2023.

Internal Model Control for Systems with One Corrector Type (Diamond)



$P(s) := Rg(s), \quad \bar{P}(s) := \bar{R}\bar{g}(s)$



➠ M. Morari and E. Zafiriou, *Robust Process Control*, 1989.

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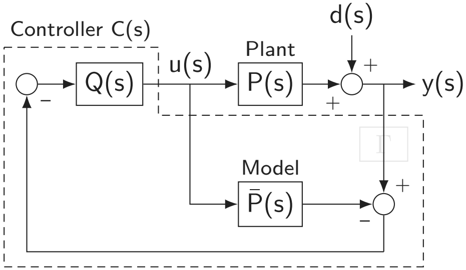

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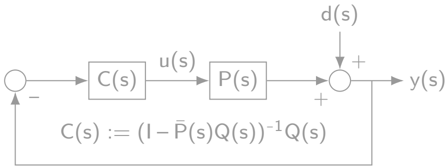

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1. Choose $T(s)$ and invert plant:

$$Q(s) = \bar{P}^{\dagger}(s)\,T(s)$$

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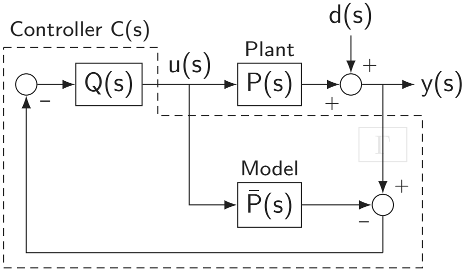

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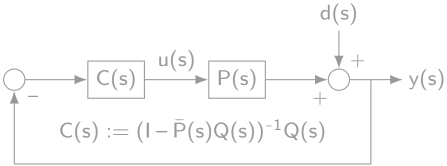

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$$Q(s) = \bar{P}^{\dagger}(s)\, T(s)$$

2. Closed loop for perfect model ($\bar{P}(s) = P(s)$):

$$y(s) = \left(1 - T(s)\right) d(s)$$

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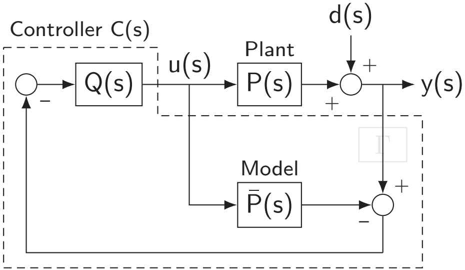

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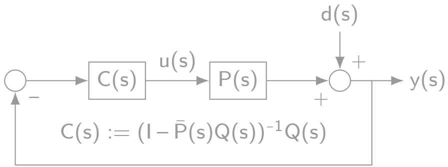

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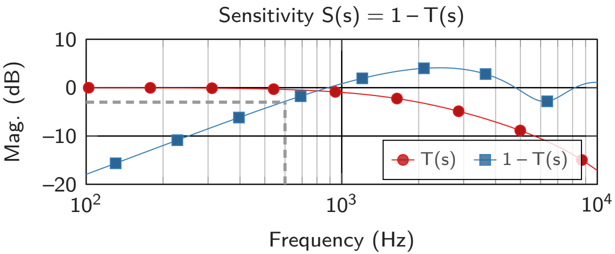

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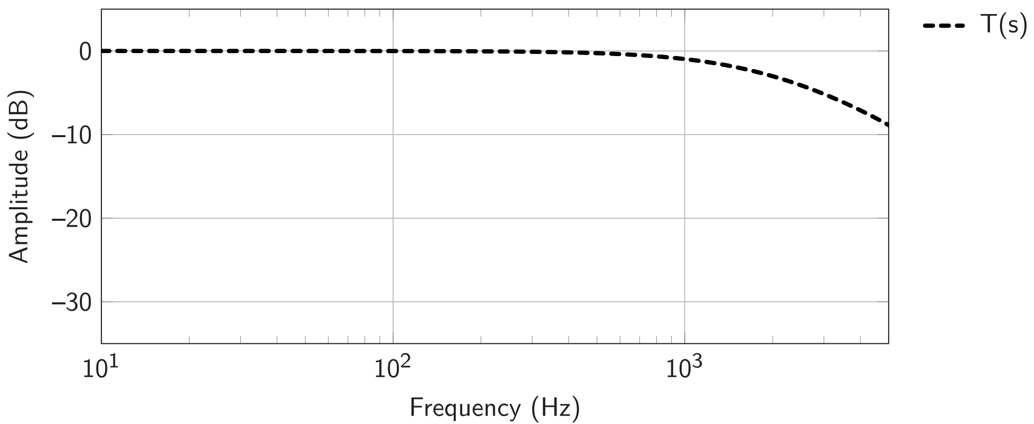
Mid-Ranging Control: Split Control Effort T(s) between Slow and Fast Correctors



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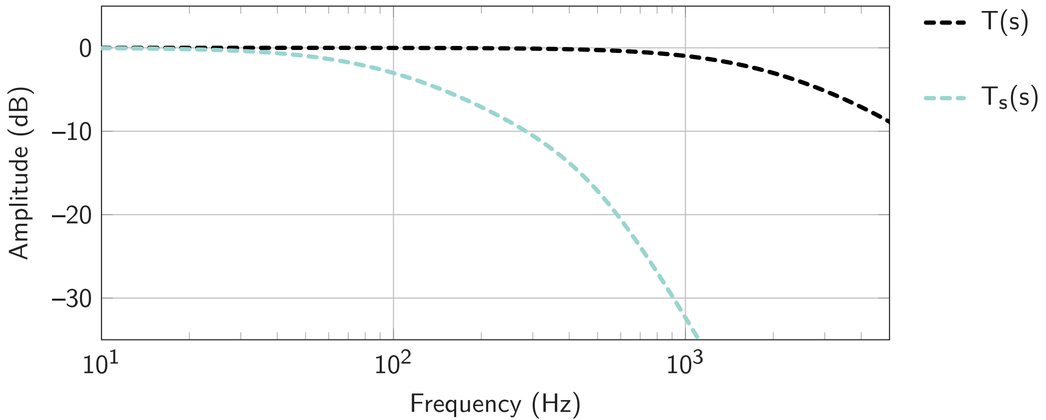

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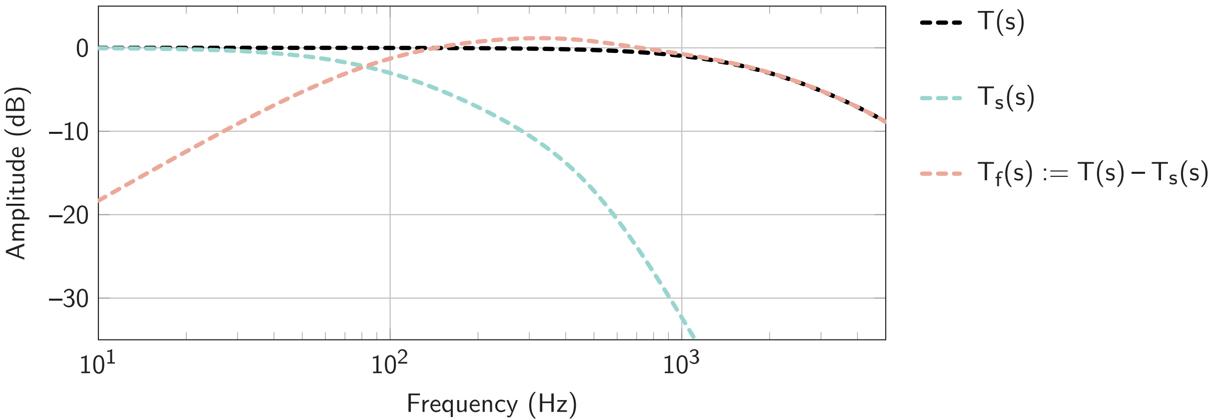

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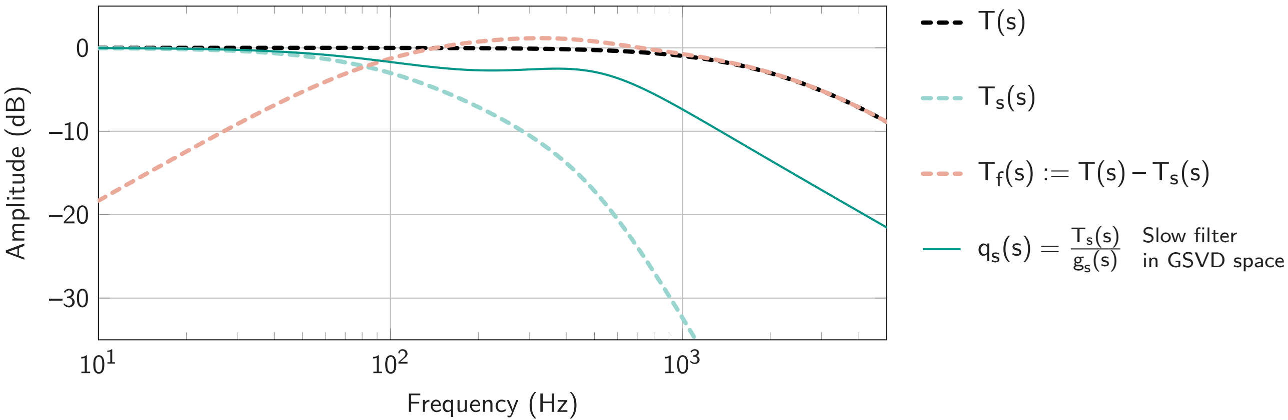

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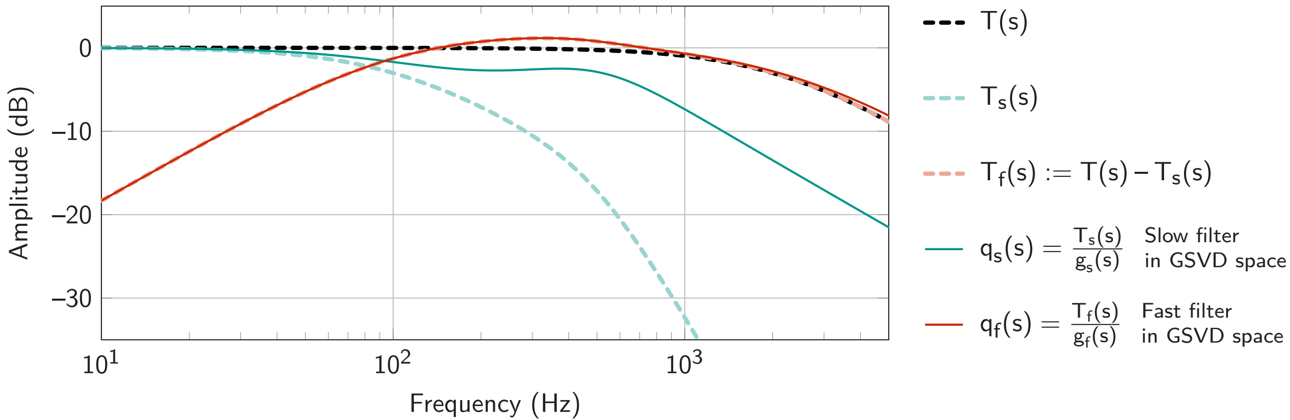

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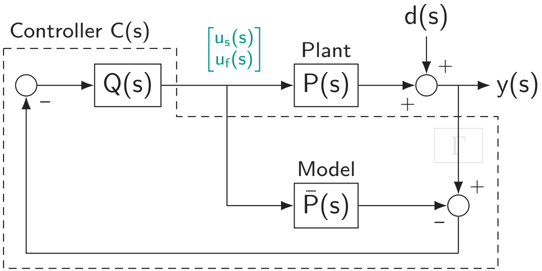
Internal Model Control for Systems with Slow and Fast Correctors



$P(s) := [R_s g_s(s)\ R_f g_f(s)] := [P_s(s)\ P_f(s)], \quad \bar{P}(s) := \dots$

$Q(s) := \begin{bmatrix} Q_s(s) \\ Q_f(s) \end{bmatrix}$

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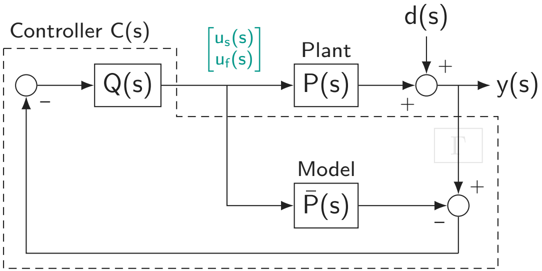

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$$Q(s) := \begin{bmatrix} Q_s(s) \\ Q_f(s) \end{bmatrix}$$

1. Choose $T_s(s)$, $T_f(s)$, and "invert" plant:

$$Q_s(s) = \bar{P}_s^{\dagger}(s)\, T_s(s)$$
$$Q_f(s) = \bar{P}_f^{\dagger}(s)\, T_f(s)\, \Upsilon_f$$

2. Closed loop for perfect model ($\bar{P}(s) = P(s)$):

$$y(s) = \left(I - IT_s(s) - X \begin{bmatrix} IT_f(s) & \\ & 0 \end{bmatrix} X^{-1} \Upsilon_f \right) d(s)$$

3. Add Υ_f if $n_f < n_s$

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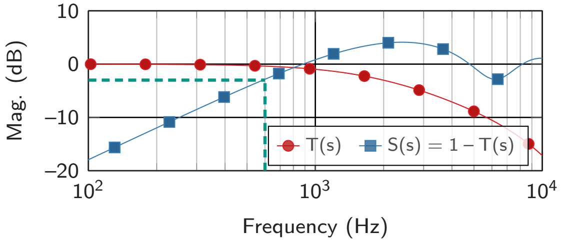
Choosing the Closed-Loop Bandwidth for Diamond-II

Bandwidth ↑ ⇒ Peak of S(s) ↑ ⇒ Instability, disturbance amplification



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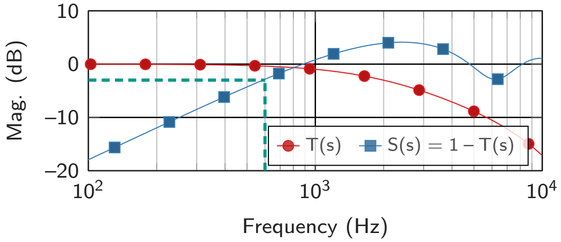

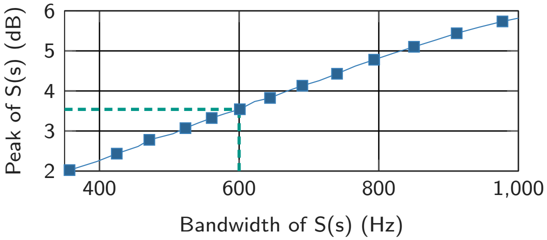

Limiting factors for Diamond-II:

- Time delay
- Complexity of $g_{(\cdot)}(s)$
- Slow corrector bandwidth

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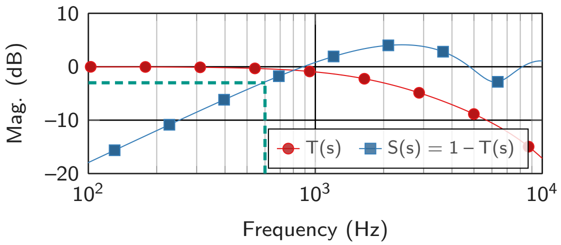

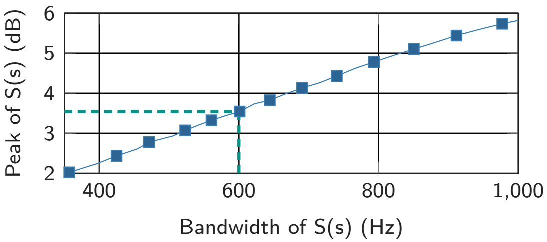

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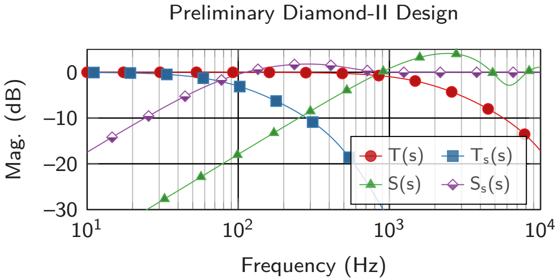
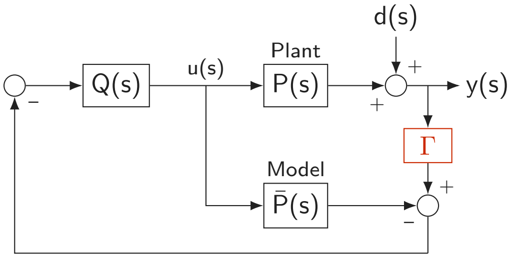


Tikhonov Regularisation: Avoid Large Control Inputs for Slow and Fast Correctors



✗ Controller gains $\sim 1/\sigma_i$

✗ Large corrector inputs u(s)

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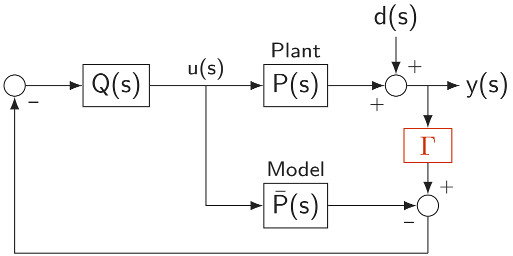
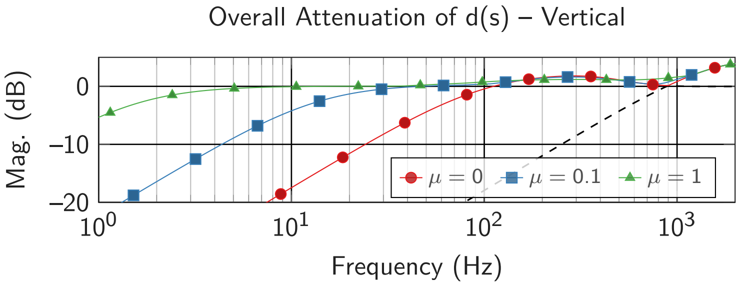


- ✗ Controller gains $\sim 1/\sigma_i$
- ✗ Large corrector inputs u(s)
- ✓ Attenuate gains for $\sigma_i^2 \ll \mu$:

$$\Gamma = U \operatorname{diag}\left(\frac{\sigma_1^2}{\sigma_1^2 + \mu}, \ldots, \frac{\sigma_{n_y}^2}{\sigma_{n_y}^2 + \mu}\right) U^T$$

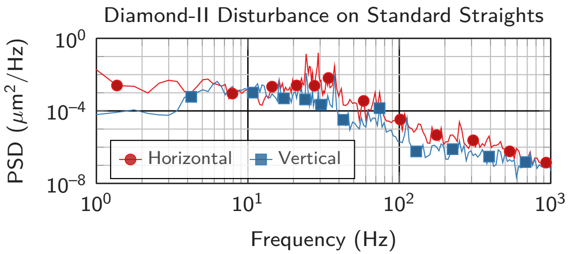


- ✓ Mainly affects higher-order modes
- ✓ Disturbance concentrated in low-order modes

Predicting the Performance for Diamond-II using Estimated Disturbance

Given disturbance PSD, predict performance via...

- Conservative upper bound
- Simulations using sampled disturbance



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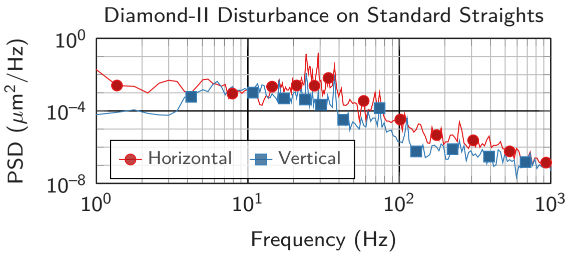

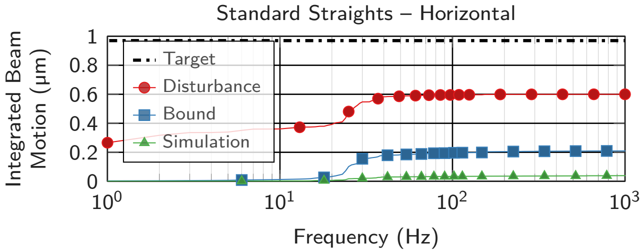

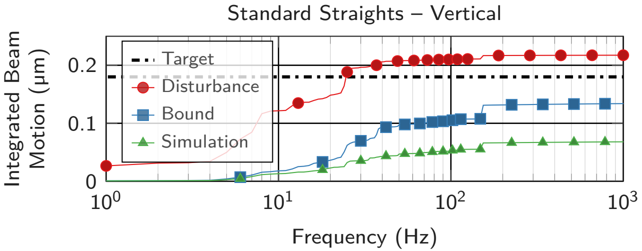

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Stability Targets for Diamond-II Met Except for Long Straights

Integrated Beam Motion at 1 kHz (in μm)

	Horizontal			Vertical		
	LS	MS	SS	LS	MS	SS
Disturbance	0.68	0.47	0.6	0.25	0.21	0.22
Target	1.20	0.90	0.97	0.23	0.14	0.18
Upper Bound	0.47	0.23	0.34	0.26	0.09	0.12
Simulation	0.17	0.07	0.08	0.18	0.05	0.07

LS: Long Straight, MS: Mid Straights, SS: Short Straights

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↯ PSD not suited for regularisation or TISO/SISO split ↯

Tests on the Existing Diamond Storage Ring

1. **Implementation:**
   - VadaTech AMC540
   - FPGA for signal routing
   - DSPs for H/V controllers

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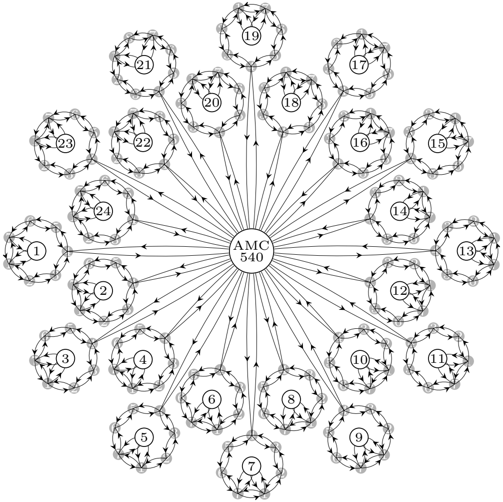

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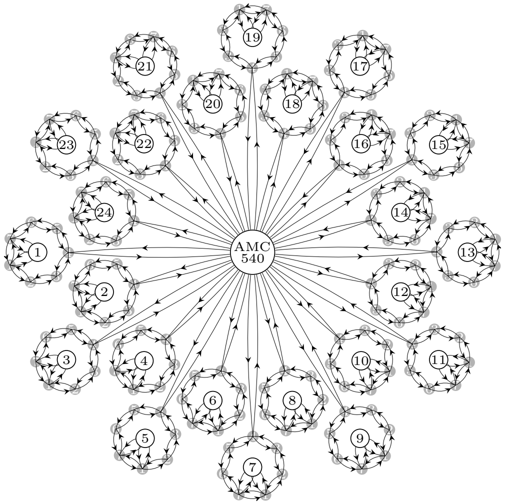
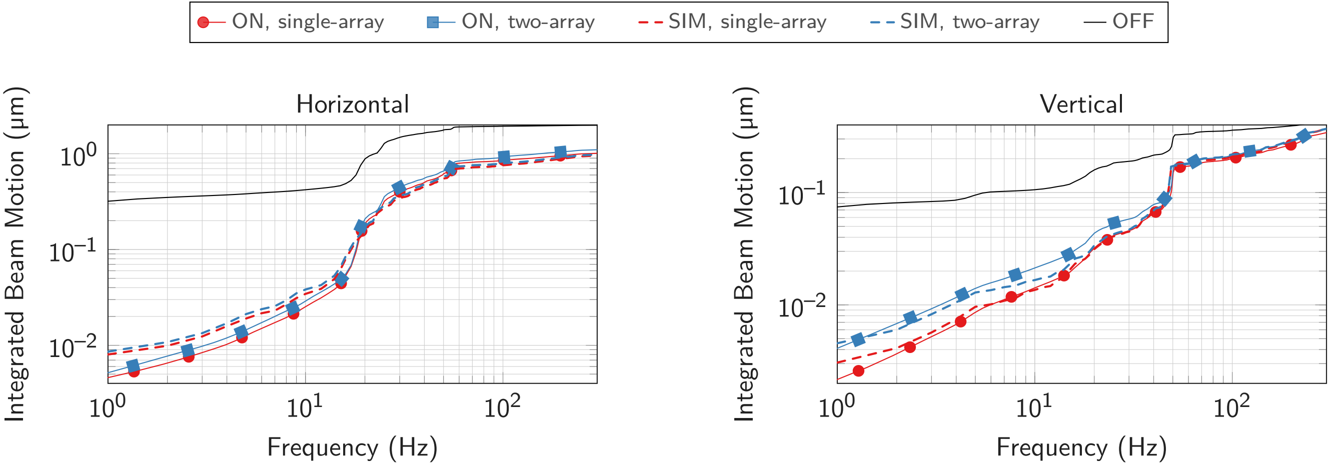


3. Adapt Diamond-II controller:

- Choose $n_y = 96$ BPMs
- Choose $n_s = 96$ “slow” and $n_f = 64$ “fast“ correctors
- Split 140 Hz bandwidth using mid-ranging:
  - Fast (TISO) bandwidth at 140 Hz
  - Slow (SISO) bandwidth at 50 Hz

Comparing Results from the Storage Ring with Simulations



- ✓ Practice matches simulation results
- ✓ Single-array and two-array controllers show similar performance

➠ I. Kempf, “Advanced control systems for fast orbit feedback of synchrotron electron beams,” PhD thesis, Nov. 2023.

Conclusions

- Joint design method for slow & fast correctors
  - ✓ Predict performance for Diamond-II
  - ✓ Analyse split between slow and fast *modes*
  - ✓ Standard regularisation
- Mid-ranging approach
  - ✓ Seamless split between slow and fast *correctors*
  - ✓ Bandwidths can be tuned easily
- Successful tests on the existing storage ring:
  - ✓ Diamond-II controller works in practice
  - ✓ Performance in-line with theoretical expectations
  - ✓ Performance comparable to controller with one corrector type

On-Going Work at Diamond

- Impact of noise & signal-to-noise ratio
- Models for slow & fast correctors:
  - AC power supply for fast correctors $\Rightarrow$ modify mid-ranging approach
  - Vacuum vessel geometries may produce > 1 fast corrector type $\Rightarrow$ use *higher-order* GSVD
  - Identify more accurate models when prototypes are available
- Integrate front-end XBPMs in FOFB
  - Increased fault tolerance
  - Controller allows electron BPMs to be substituted for X-ray BPMs
- Additional research
  - Closed-loop sensitivity identification
  - Alternative algorithms (e.g. model predictive control and linear quadratic regulator)

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