Brazilian Synchrotron Light Laboratory

Performance Optimization for the LNLS Fast Orbit Feedback

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Outline

1. The *Brazilian Synchrotron Light Laboratory* (LNLS)
2. FOFB Hardware Architecture for the LNLS Storage Ring
3. FOFB Systems Overview
4. Correction Algorithms and Orbit Control in Mode Space
5. Actuator Limitations
6. Simulations for performance optimization of the LNLS FOFB
7. Conclusion and Perspectives

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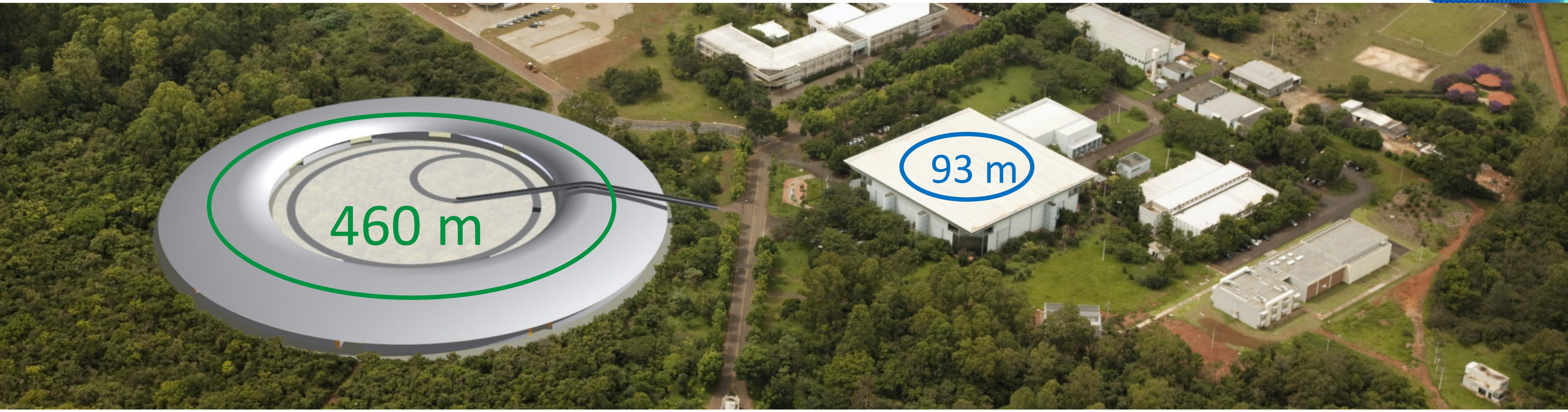


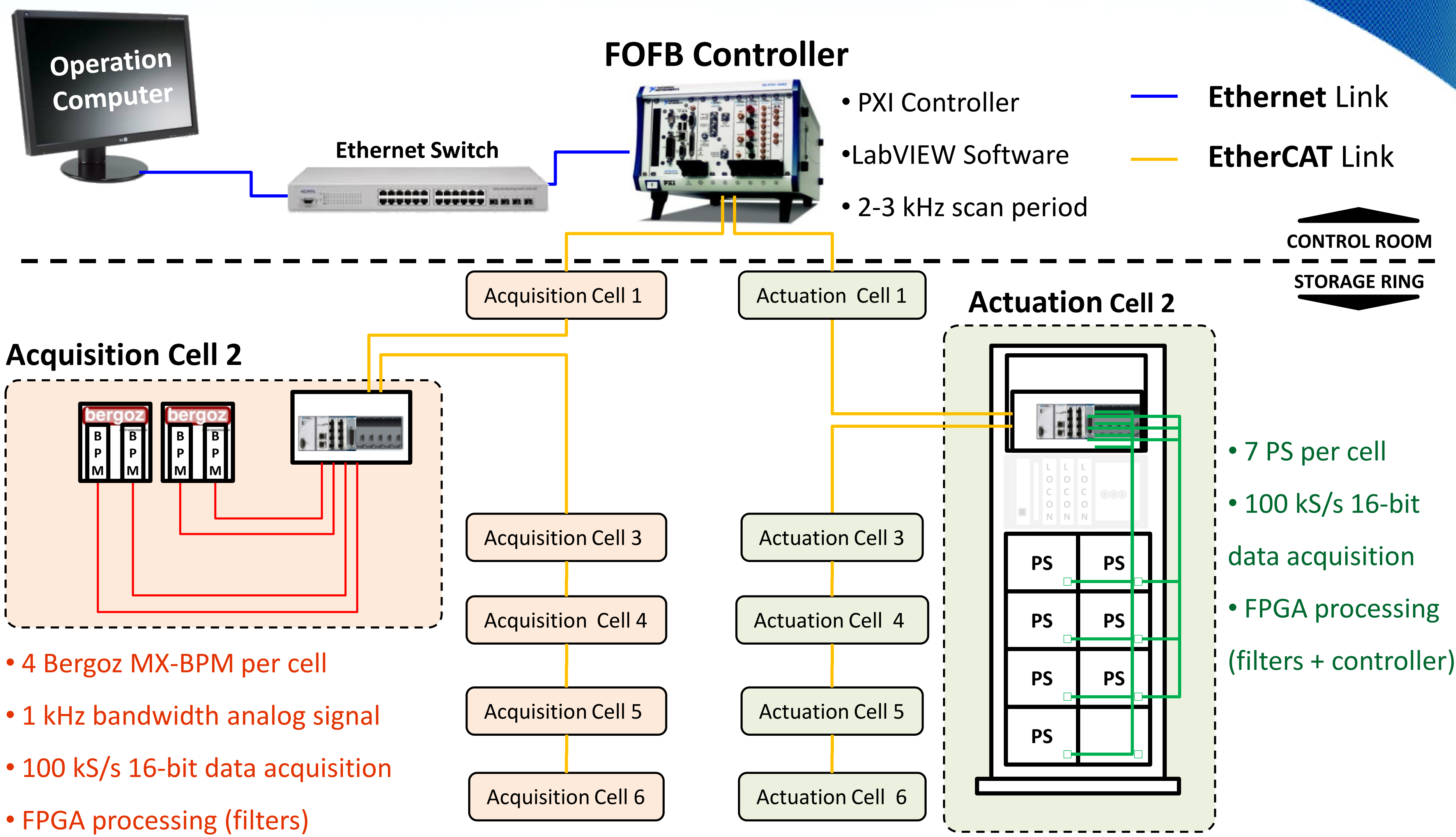
Sirius Project
(in design phase)

Operation energy	3 GeV
Injection energy	3 GeV
Maximum beam current	500 mA
Ring circumference	460 m
Horizontal emittance (no ID)	1.7 nm.rad

LNLS UVX Storage Ring
(in operation since 1997)

Operation energy	1.37 GeV
Injection energy	500 MeV
Maximum beam current	250 mA
Ring circumference	93 m
Horizontal emittance	100 nm.rad

LNLS FOFB – Architecture



More details in MO263 – Fast Orbit Feedback System for the LNLS Storage Ring

LNLS FOFB – Status

- Project started on August 2010
  - Labview training (real-time and FPGA platforms)
  - 1 Engineer + 1 Engineering intern
  - Proof of Concept and Bench Tests

- Installation on the Storage Ring on November/December 2010 Shutdown

- First tests with beam in <u>open-loop</u> on January 2011
  - Fast acquisition at 3 kS/s (500 Hz bw)
  - Hardware OK
  - Software debugging
  - Setbacks (control system, power supplies)

- First tests with beam in <u>closed-loop</u> on February 2011
  - Setbacks (power supplies response)
  - 10 Hz maximum correction rate

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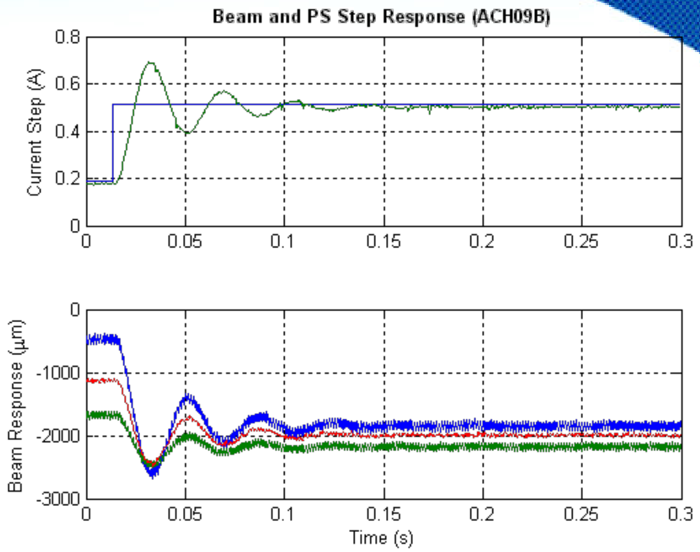
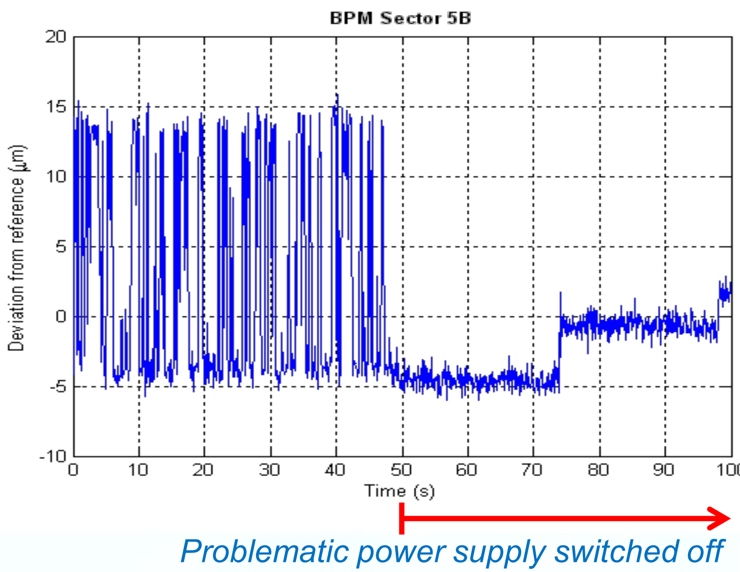




FOFB Systems - Overview

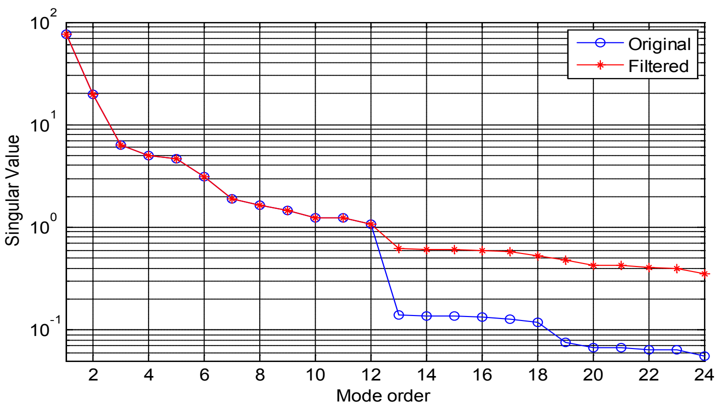
- FOFB Goal
  - Mitigation of "fast" disturbances, caused mainly by:
    - Magnets vibration (mainly quadrupoles)
    - Power supplies ripple
    - Booster cycles
    - ID gap-phase reconfiguration
    - "Cultural noise" (facility specific)
- History
  - APS pioneer work, 1993: the "real-time orbit feedback" (1 kHz correction rate, 30 Hz effective correction bandwidth)
  - Hardware platform: from control-system-workstation-based to dedicated embedded systems (DSP processor, FPGA) linked by high throughput synchronized network
  - Recently commissioned systems: 4-10 kHz correction rate (global correction), up to 100-250 Hz effective correction bandwidth

FOFB Systems - Overview

- Local vs. Global
  - First systems: multiple local feedbacks in closed-bumps
  - Not desirable in recent 3rd-generation machines → tenths of IDs moving simultaneously
- FOFB vs. SOFB
  - First systems: low- and high-pass filtering to avoid “loop fighting” → generates deadband
  - ALS and SOLEIL had good results downloading SOFB setpoints to FOFB
- Photon BPMs in the loop
  - APS Local Loops
  - SLS local corrections integrated to global feedback
  - SOLEIL’s experience, etc.
- Orbit Control in Mode Space
  - Singular Values Filtering
  - Tikhonov regularization
  - One dynamic controller for each mode? (not yet tried!)
- Actuator Limitations
  - Power supplies (smaller the setpoint step, greater the bandwidth)
  - Vacuum chamber roll-off (most critical for copper and aluminum chambers, not an issue for LNLS stainless steel chamber)
  - Time delay (BPM data filtering group delay, data distribution, correction algorithm processing)

Singular Value Decomposition (SVD)

- The SVD method for matrix "inversion" has replaced MICADO and Harmonic algorithms without performance losses



- Mathematical formulation:

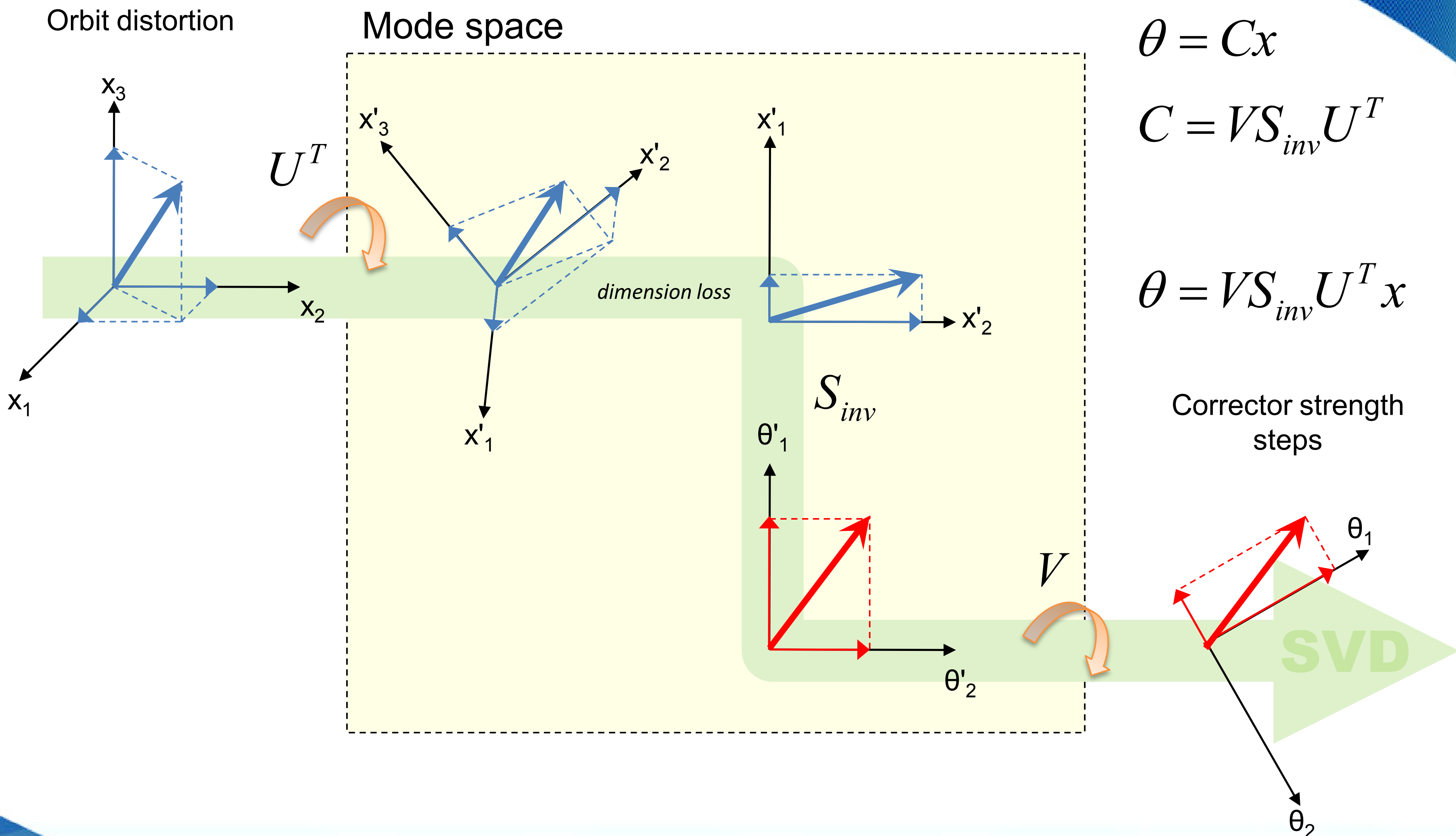
$$R = USV^T \rightarrow C = VS_{inv}U^T$$

Response Matrix Correction Matrix

- Interpretation
  - Low-order modes demands little effort of corrector magnets to correct large distortions
  - High-order modes demands large excursions of corrector magnets for correction small disturbances
  - **We must consider the "direction" (making an analogy to the BPM readings as a vector in space) of the disturbance vector**

- Filtering the singular values allow to avoid correcting high order modes aggressively
  - Possible approaches:
    - Discard small singular values → information loss → no exact (or maximum) correction anymore
    - Apply Tikhonov regularization (only one degree of freedom; is it the best we can get?)
    - **Why not free weighting the singular values, is there any drawback?**

SVD Graphical Interpretation



$$\theta = Cx$$

$$C = VS_{inv}U^T$$

$$\theta = VS_{inv}U^T x$$

Eigenvector with Constraints (EVC)

- *Nakamura et al.* proposes a novel method based on Lagrange multipliers to set constraints of zero error for some BPM readings when "inverting" the response matrix.

- Mathematical formulation:

$$A = R^T R$$

"Squared" Response Matrix

$$C = DZ - (DB^T - I_n)A^{-1}R^T$$

Correction Matrix

$$A = V\lambda V^T$$

Eigen decomposition

Auxiliary matrices:

$$Z = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

$$B = (ZR)^T$$

$$D = A^{-1}B\left(B^T A^{-1} B\right)^{-1}$$

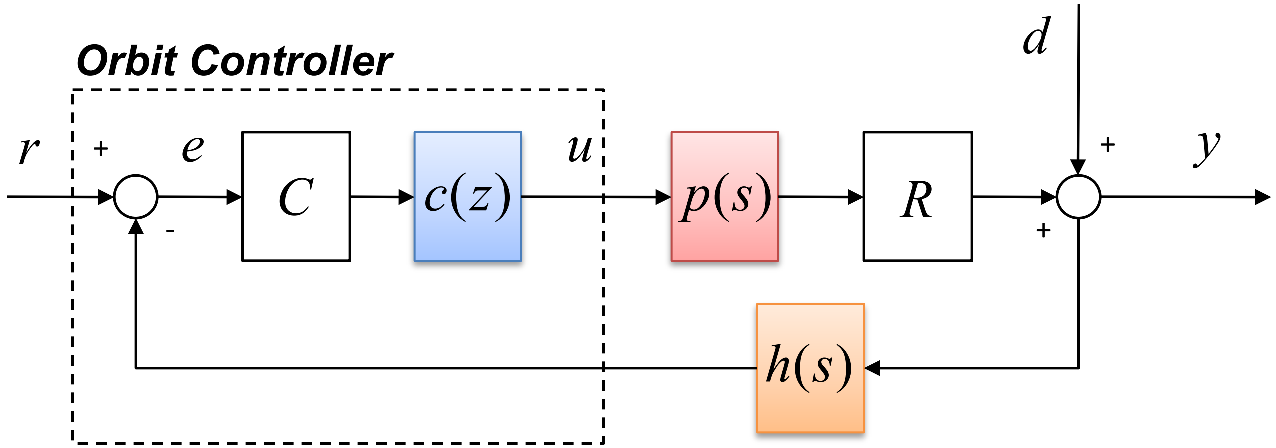
- Equivalent to SVD (minimization of least squares) when calculating the correction matrix without constraints.

- **The eigenvalues of *A* are the squared singular values of *R*.**

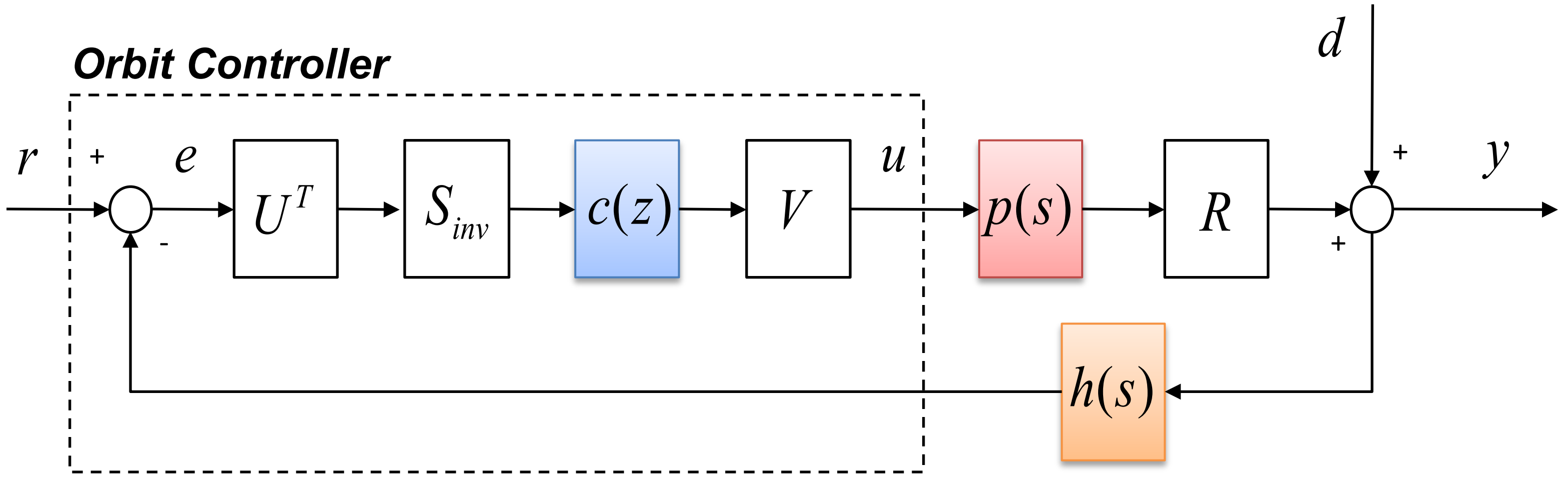
- **Successful experiences with beam in KEK, ALS and LNLS**

Dynamic Orbit Control

- Traditional Approach

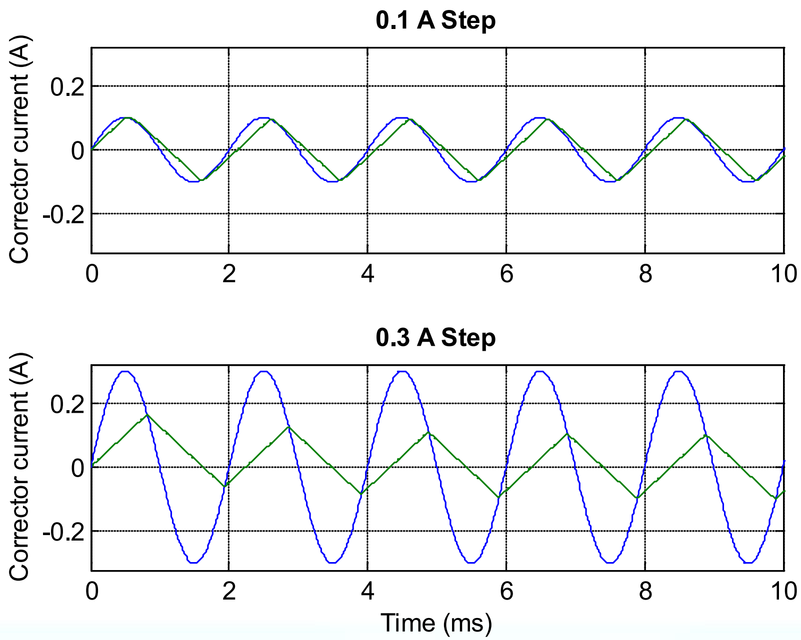


- Dynamic Control in Mode Space

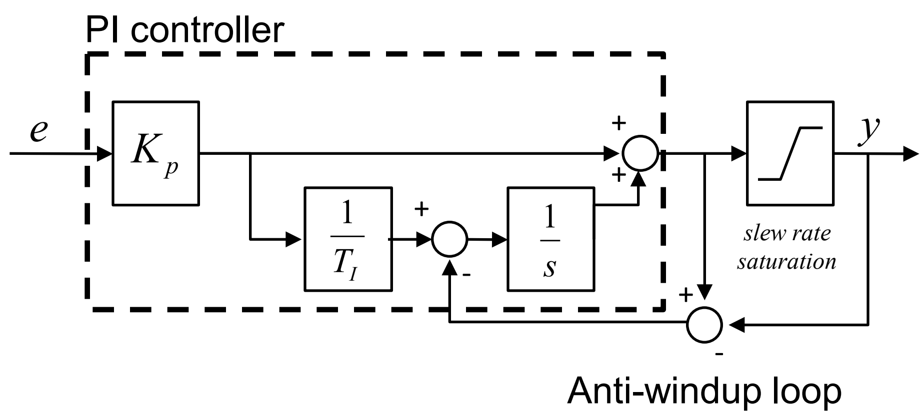


Actuator limitation and some ideas…

- The power supplies are always limited in amplitude and slew rate – increasing the **step amplitude** reduces **bandwidth (and linearity)**



- **Classical approach → anti-windup**



  – It works well for single-input-single-output systems (SISO), but **not for multivariable systems (MIMO)**

  – More sophisticated schemes must be investigated.

Preliminary Results

- Plant Model

$$p(s) = \frac{K_{PS}\, e^{-\theta s}}{\tau_{PS} s + 1}$$

$$K_{PS} = 1$$
$$\tau_{PS} = 0.5 \quad \text{ms}$$
$$\theta = 1 \quad \text{ms}$$
$$\left.\frac{di}{dt}\right|_{\max} = \pm 0.2 \quad \text{A/ms}$$

Vacuum chamber and corrector magnet core ignored → high cutoff on 1.25 kHz (stainless steel vacuum chamber)

It is assumed that the power supply is regulated by an internal control loop which adjusts the gain according to the setpoint step

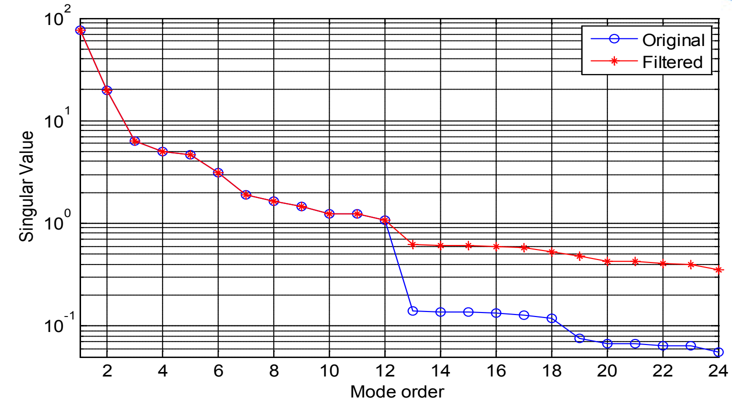
- PI control with anti-windup
  - Tuning rule (Skogestad):

$$T_i = \min(\tau_{PS}, 4 \cdot (\tau_{CL} + \theta)) \qquad K_P = \frac{1}{K_{PS}} \frac{\tau_{PS}}{\tau_{CL} + \theta}$$

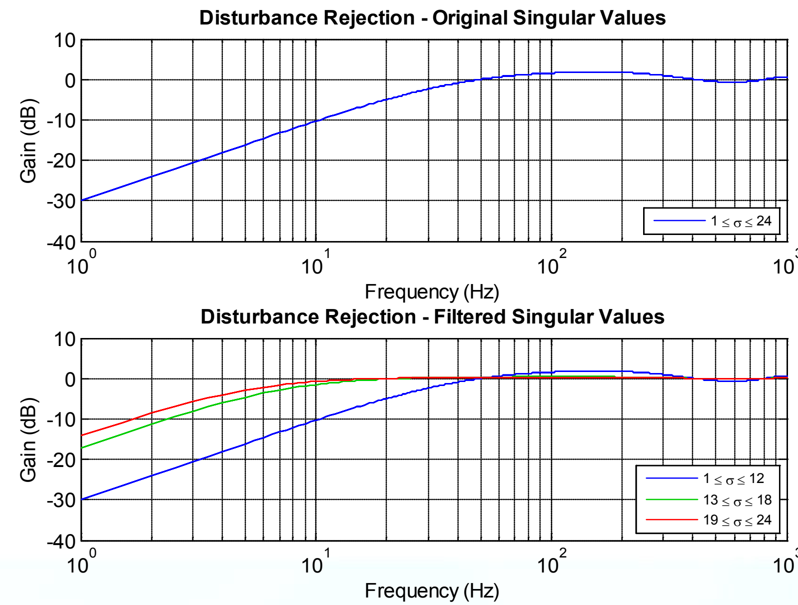
τ_{CL} *is the desired closed-loop time constant*

- Correction algorithm
  - EVC with 2 constraints (undulator sector)
  - Singular Value Filtering
    - Identification of 3 singular value levels
    - Multiplication by constant factors for each level

Singular Values Filtering



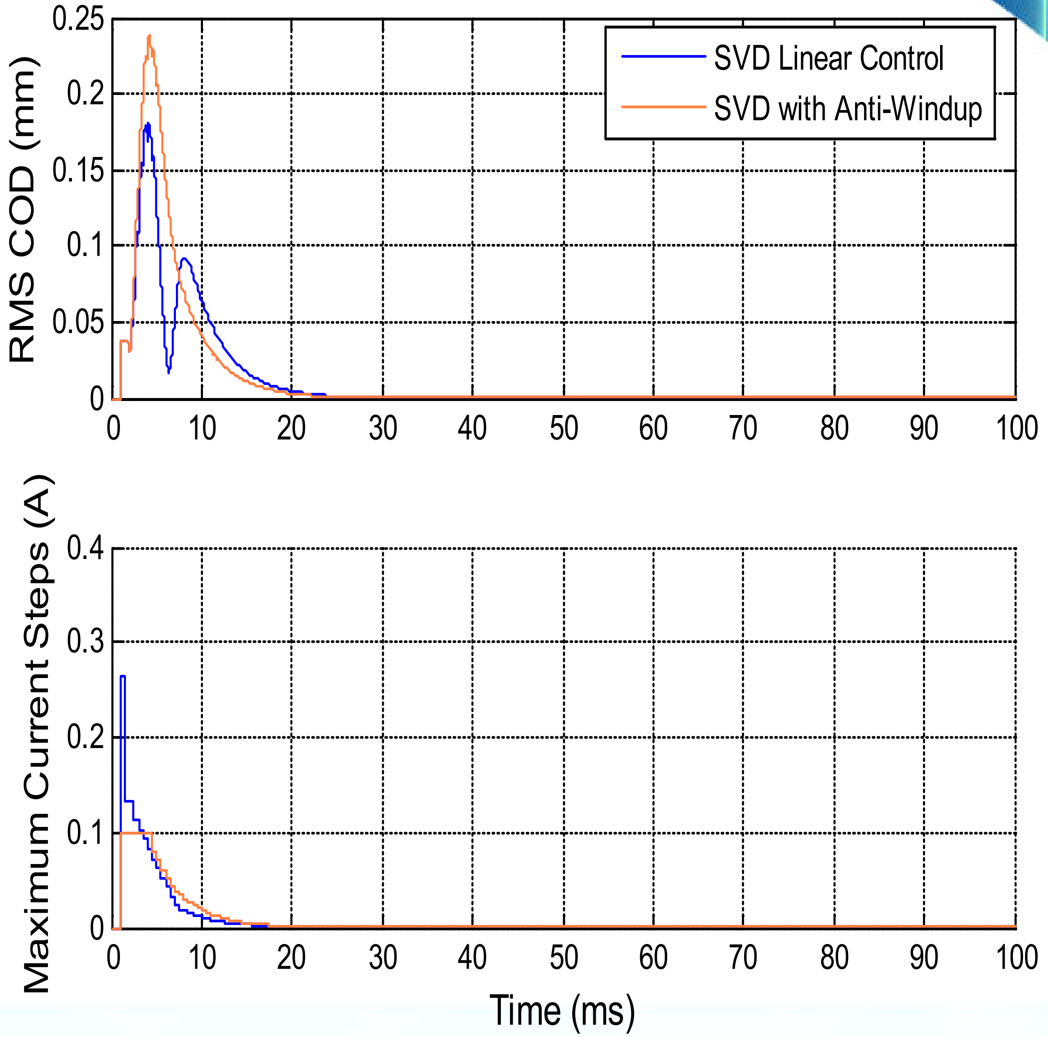
Disturbance Rejection Bandwidth for each singular value group



Preliminary Results

- Time Response for Step Disturbance
  - SVD linear control
  - SVD with anti-windup
  - SVD with singular value filtering
  - SVD with singular value filtering and anti-windup
  - EVC with 2 constraints, singular value filtering and anti-windup
- Disturbance direction combines higher and lower order modes ("easiest" and "best" direction) with 100 µm of most distorted BPM

Before Filtering Singular Values



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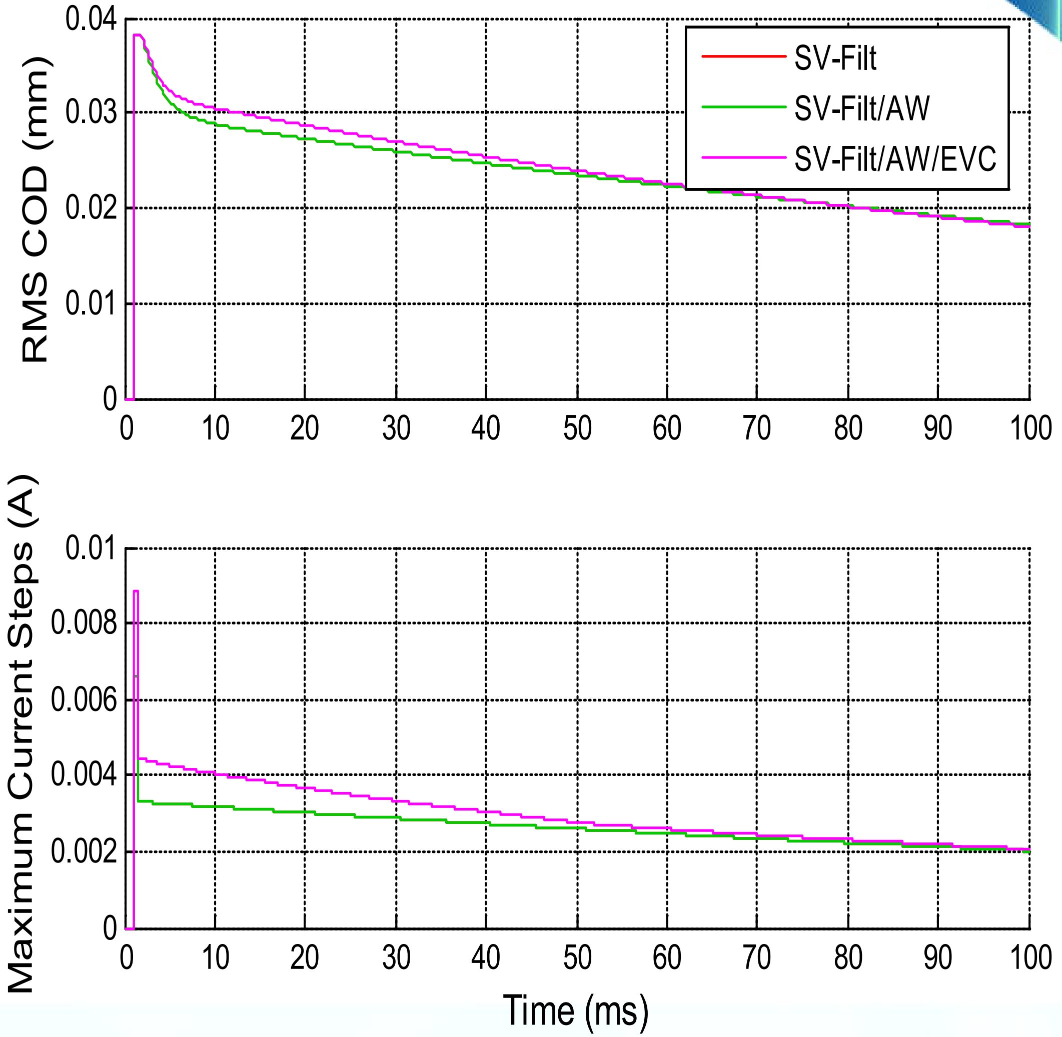

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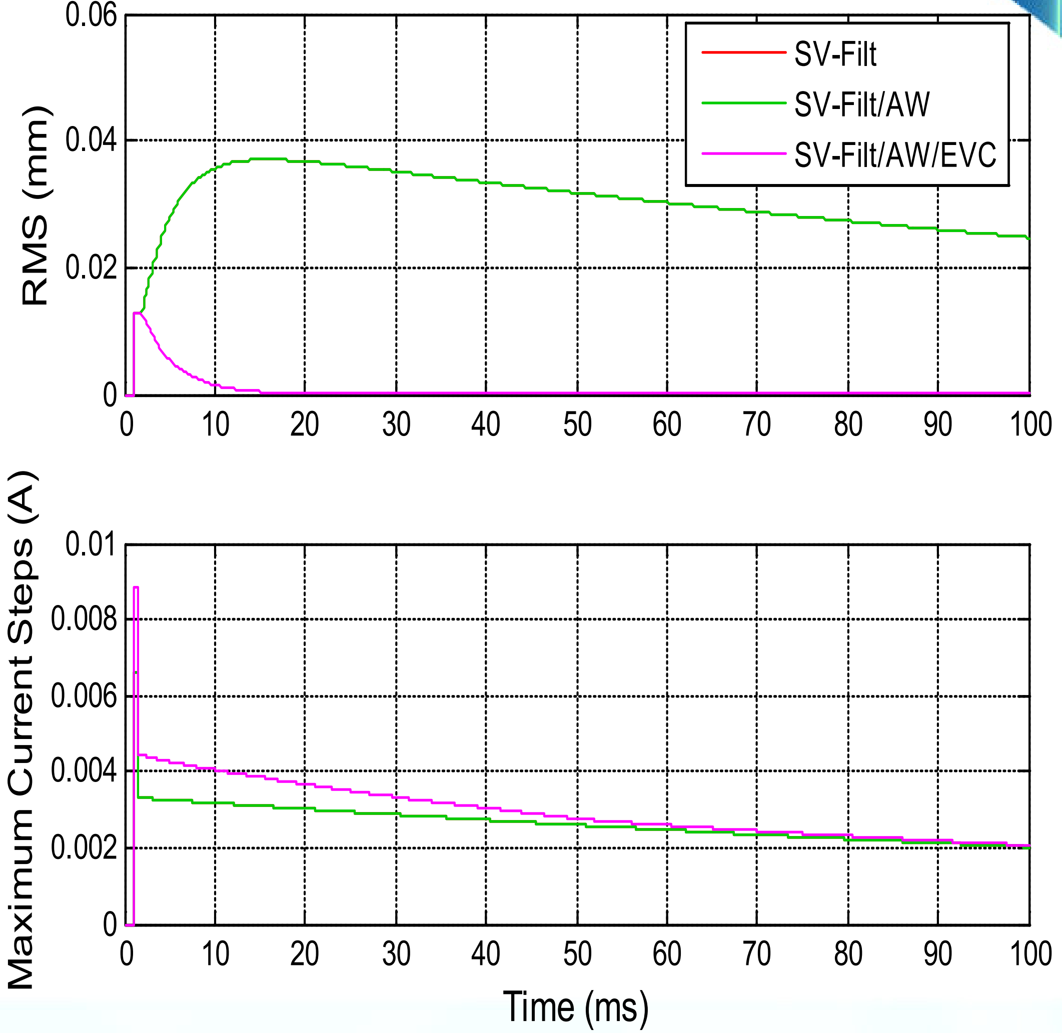
- Disturbance direction combines higher and lower order modes (“easiest” and “best” direction) with 100 µm of most distorted BPM

- **EVC does not significantly disturb the remaining COD, while guarantying fast disturbance mitigating in the constrained BPMs**

After Filtering Singular Values

Plotting only the selected BPMs for zero error



Conclusions and Perspectives

PERFOMANCE OPTIMIZATION

- The **"Eigenvector with constraints (EVC)"** method can provide excellent results, comparable to the SVD, with the additional benefit of providing zero error for the selected BPMs.
- The **singular values filtering** is essential to increase performance and **can also be done inside the EVC framework**.
- The **control in mode space** treats each **"disturbance direction" with a different dynamics.**
- Simple **anti-windup** technique is **not effective for multivariable systems**.

SYSTEM IMPLEMENTATION

- The **current LNLS machine will be used as a "test bench"** for orbit correction schemes for Sirius.
- The use of commercial hardware allowed quick development → **few months with reduced manpower to put the hands on the beam!**
- The **bottleneck today is the corrector power supplies response** (should be replaced until the end of 2011)

FUTURE STEPS (while power supplies were not replaced)

1. Identify the disturbance spectrum
2. Develop new diagnostic tools with the new hardware capabilities
3. Continue to optimize the dynamic control in mode space (simulations)
4. Investigate more deeply constrained control techniques for multivariable systems