Adaptive control scheme for the main linac of CLIC

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21th of October 2010

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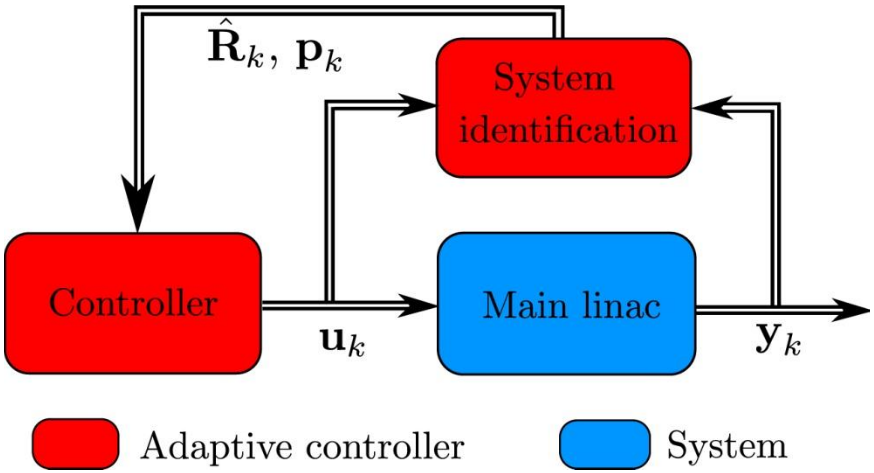

1. Introduction
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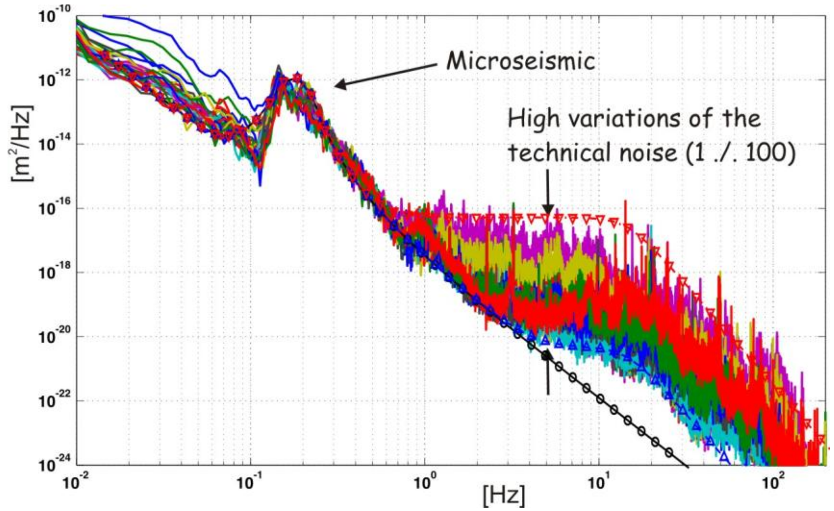
1. Introduction

The problem of ground motion

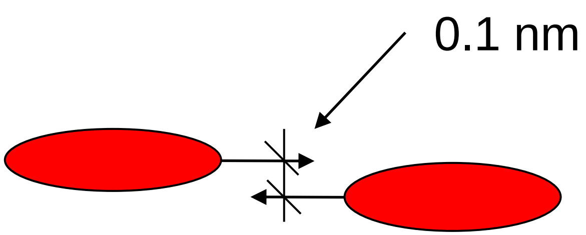
- Main source of emitt. growth and beam offset is **ground motion**
- **Mechanism:**
  - Ground motion misaligns magnets
  - Therefore beam is kicked from its ideal orbit => emitt. increase.



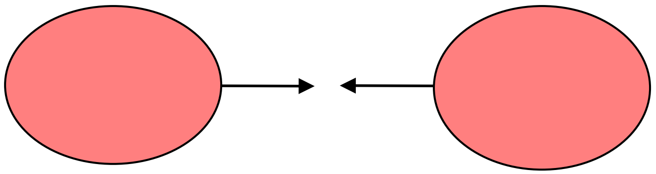
Ground motion PSD (taken from [1])

- Two tasks

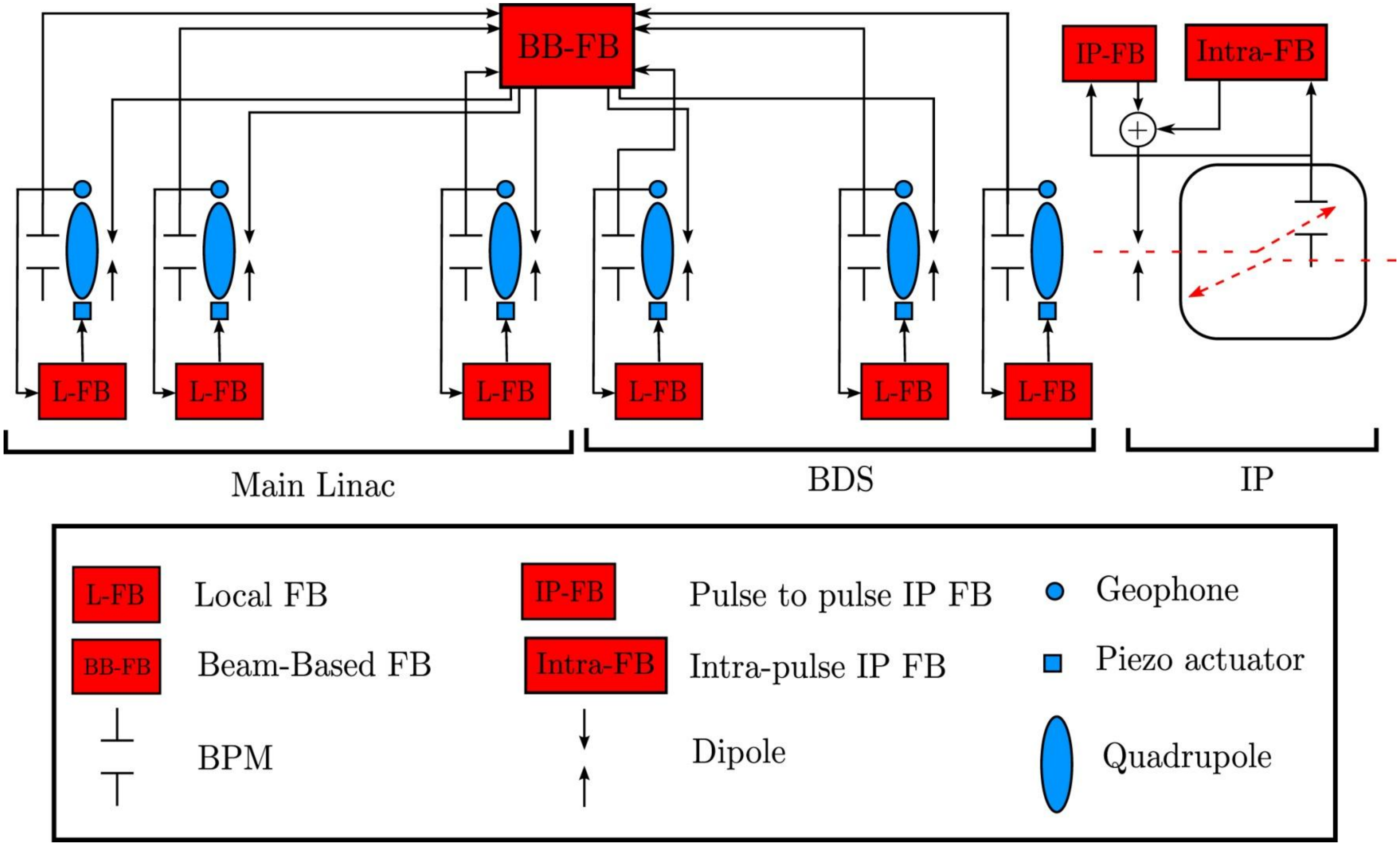
1.) Beam steering



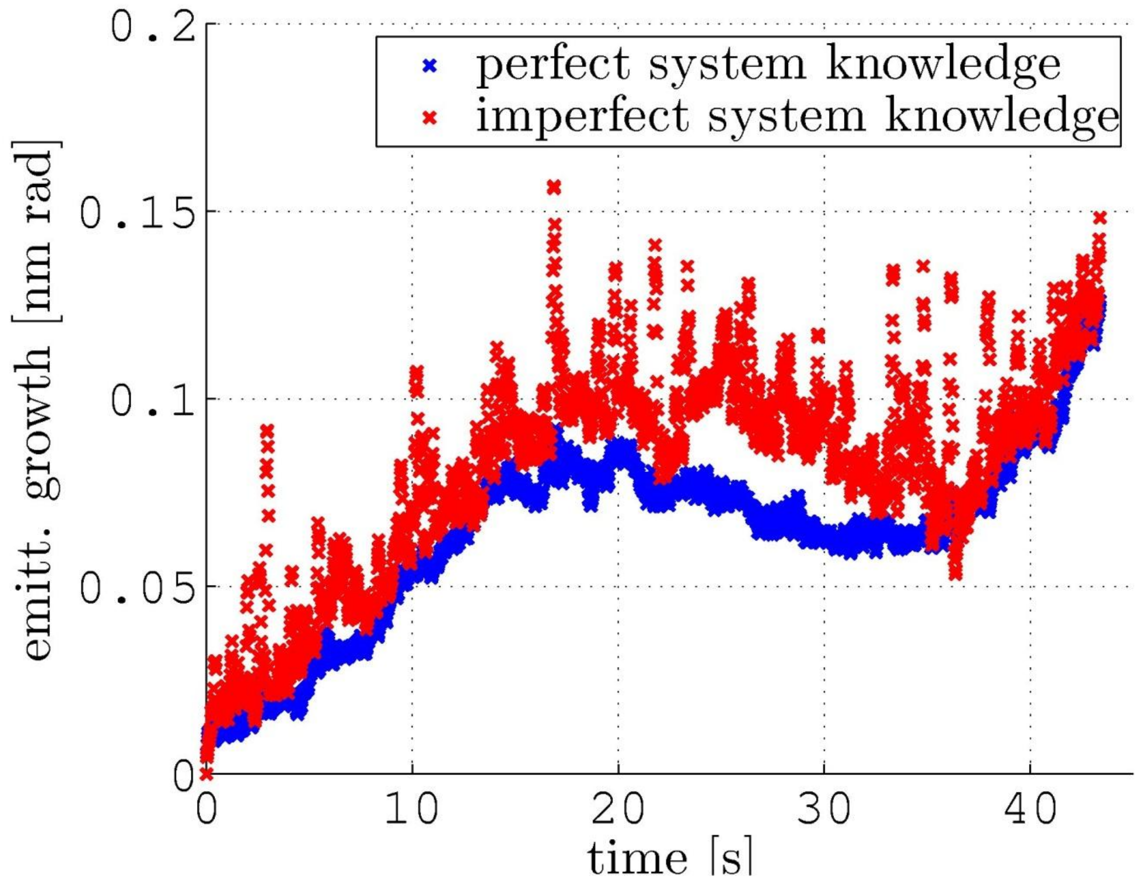
2.) Beam quality preservation



Countermeasures against ground motion



Performance degradation of the BB-FB due to acceleration gradient variations



Adaptive feedback strategy

- Good feedback needs very good system knowledge

- Accelerator behavior can change strongly during operation, due to the large phase advance

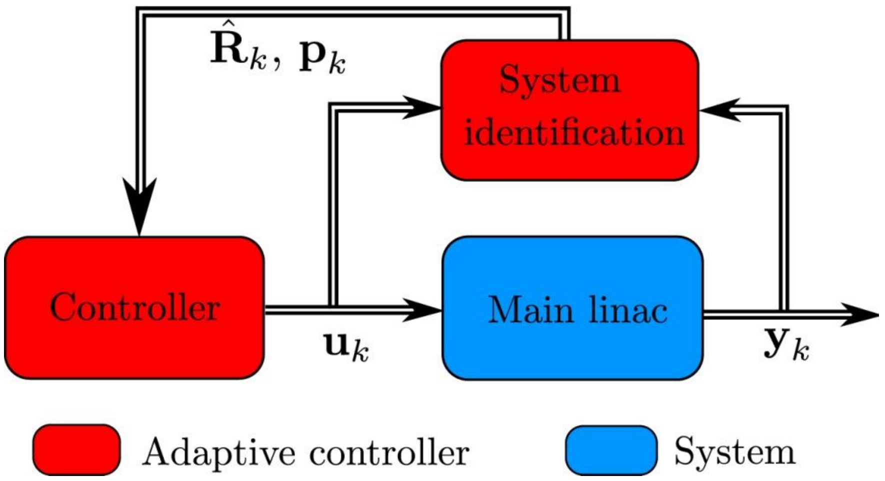
=> Adaptive controller (see [2])

1.) System Identification

- Establishes and updates on-line a model of the accelerator behavior

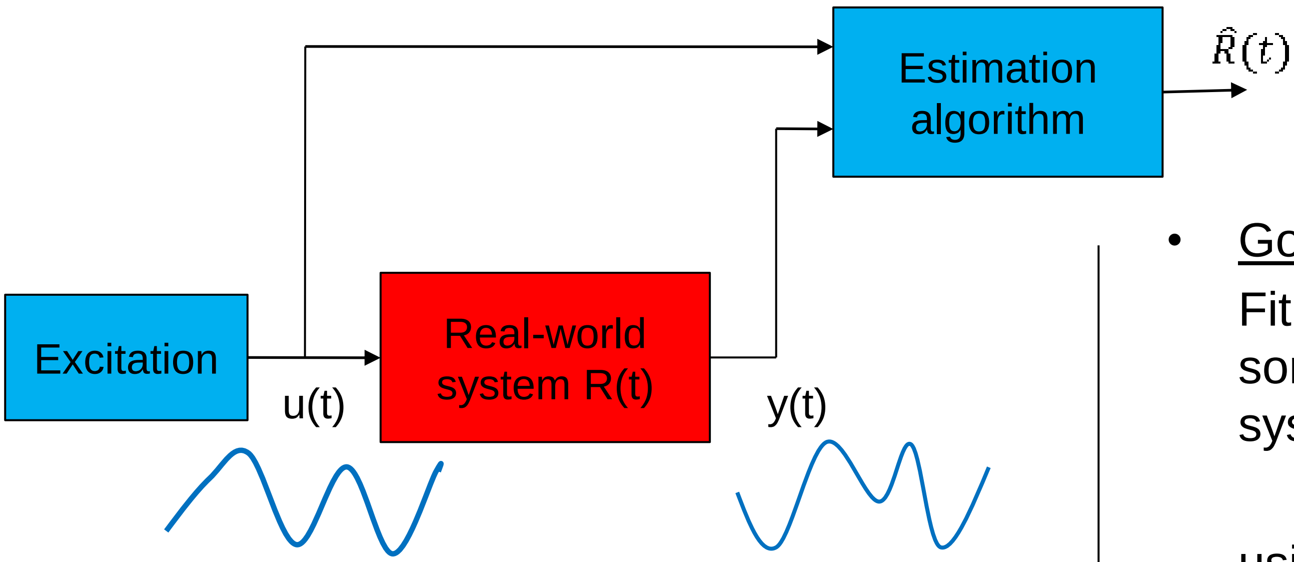
2.) Controller

- Uses the estimated system model, to optimally mitigate ground motion effects



2. System Identification

What is system identification ?



$u(t)$ ... Input data

$y(t)$ … Output data

$R(t)$ … real-world system (e.g. accelerator)

$\hat{R}(t)$ … estimated system

- Goal:

  Fit the model system in some sense to the real system,

  $$\hat{R}(t) \approx R(t)$$

  using u(t) and y(t)

- Ingredients
  - Model assumption
  - Estimation algorithm
  - System excitation

RLS algorithm and derivative [2]

- $M \approx \hat{M}$ can e.g. be formalized as

$$min\{(y_i - \hat{y}_i)^T (y_i - \hat{y}_i)\}$$

- **Off-line solution** to this Least Square problem by pseudo inverse (Gauss):

$$\hat{\theta} = (\Phi^T \Phi)^{-1} \Phi^T Y$$

$\hat{\theta}$ ... Estimated parameter

Φ … Input data

Y … Output data

- LS calculation can be modified for recursive calculation (RLS):

$$\hat{\theta}_i = \hat{\theta}_{i-1} + K_i (y_i - \varphi_i^T \hat{\theta}_i)$$
$$K_i = P_i \varphi_i = P_{i-1} \varphi_i (\lambda + \varphi_i^T P_{i-1} \varphi_i)^{-1}$$
$$P_i = (I - K_i \varphi_i^T) P_{i-1} / \lambda$$

- α is a **forgetting factor** for time varying systems
- Derivatives (easier to calculate)

  - Projection algorithm (PA)

  - Stochastic approximation (SA)

  - Least Mean Square (LMS)

Problems with the basic approach

Problem 1: **Excitation**

- Particles with different energies move differently
- If beam is excited, these different movements lead to **filamentation** in the phase space (**Landau Damping**)
- This increases the emittance

=> Excitation cannot be arbitrary

Problem 2: **Learning speed**

- To fully identify the R, all columns have to be excited

  => 1005 linear independent inputs

  => one full cycle:

  0.02s x 1005 = 20.1s

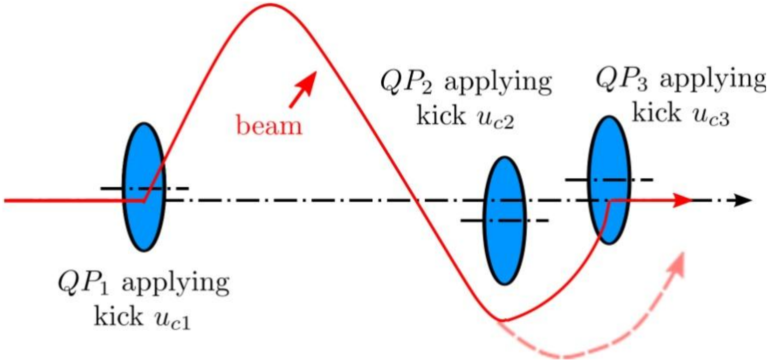
- For identification some drifts have to be used

  => time constants in the order of some minutes.

System identification principle

Excitation Strategy:

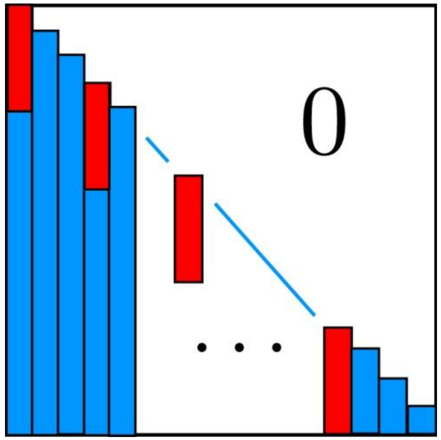
- **Necessary excitation can not be arbitrary**, due to emittance increase
- **Strategy:** beam is just excited over short distance and caught again.



- **Orbit Bump** with min. 3 kickers is necessary

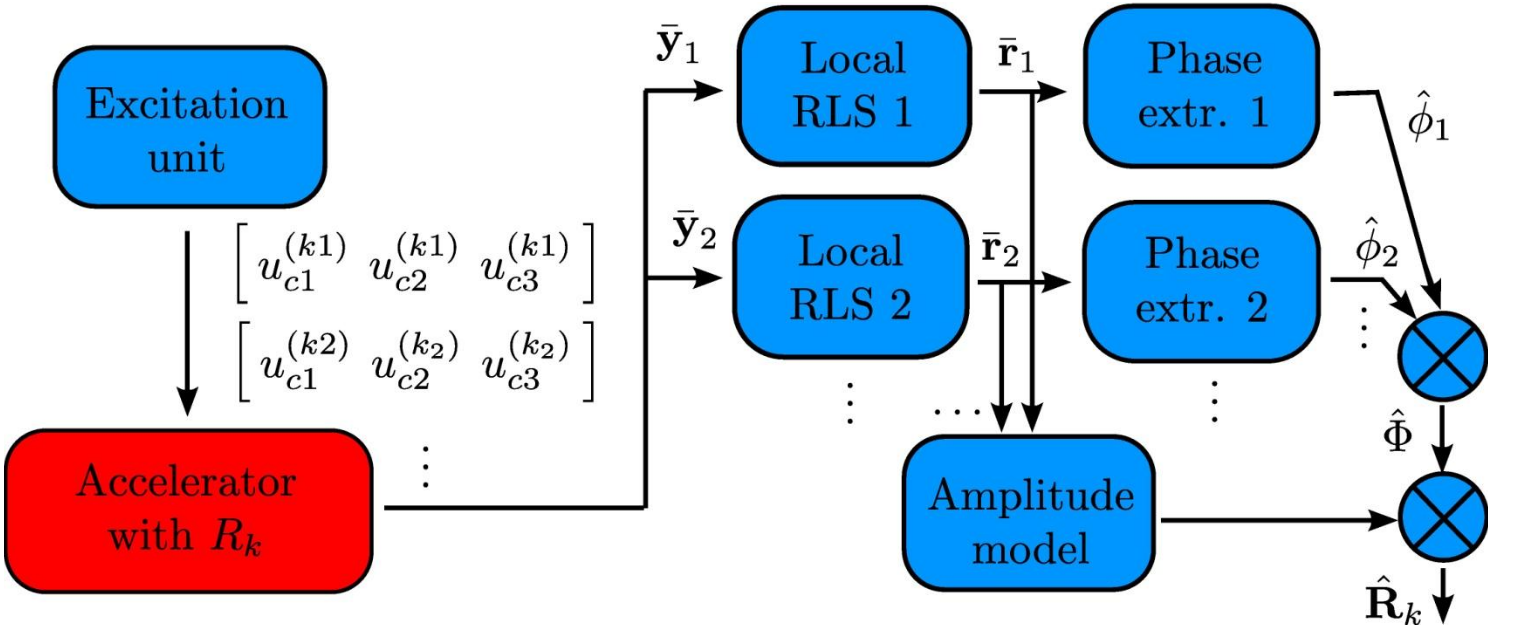
Interleaved orbit bumps:

- Just parts of R can be identified



- **Rest** has to be **interpolated**
  - Algorithm to calculate phase advance from BPM data (see [3])
  - Amplitude model (see [4])

Allover identification algorithm



u_c^k … Input values

$\bar{y}_i$ … BPM measur.

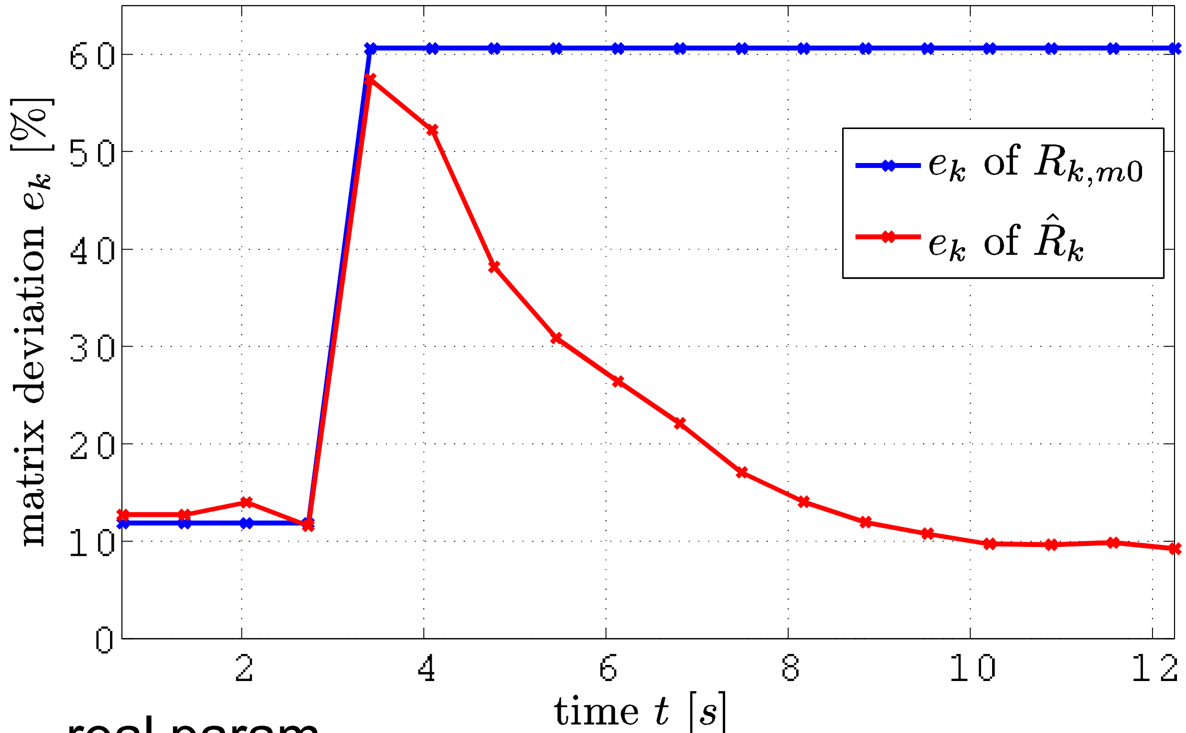
$\bar{r}_i$ … RLS results

ϕ_i … local phase

Φ … global phase

$\hat{R}_k$ … estim. R

Results: Error in the response matrices due to an RF step change



R_k … real param.

$R_{k,m0}$ … initially measured param.

$\hat{R}_k$ … estim. Param.

$$e_k = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|r_{ij} - \hat{r}_{ij}\right|}{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|r_{ij}\right|}$$ … error

3. Feedback design

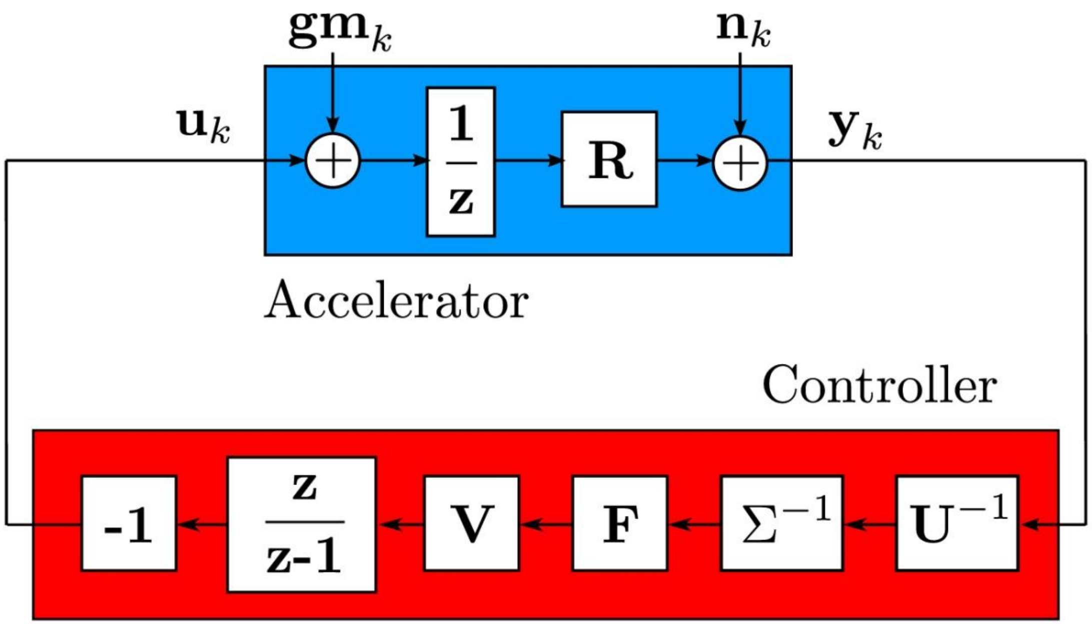
Design principles used

1. Decoupling of the inputs and outputs [5]

2. Spatial filtering to reduce the influence of noise

3. Frequency filtering is based on ATL motion assumption. This will be improved in future designs [6]

Weighted SVD controller

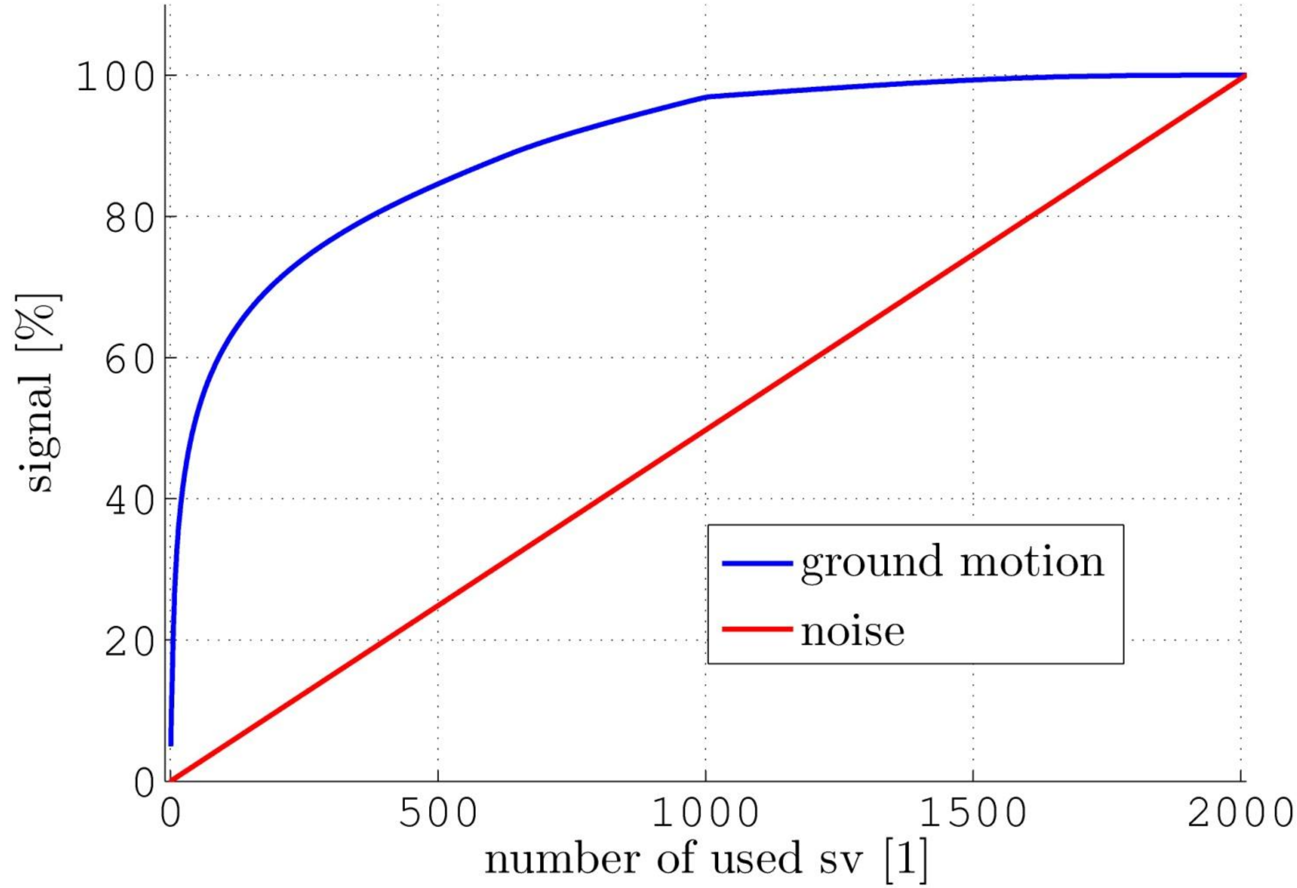


$\mathbf{gm}_k \ldots$ ground motion
$\mathbf{n}_k \ldots$ BPM noise
$\mathbf{y}_k \ldots$ BPM measur.

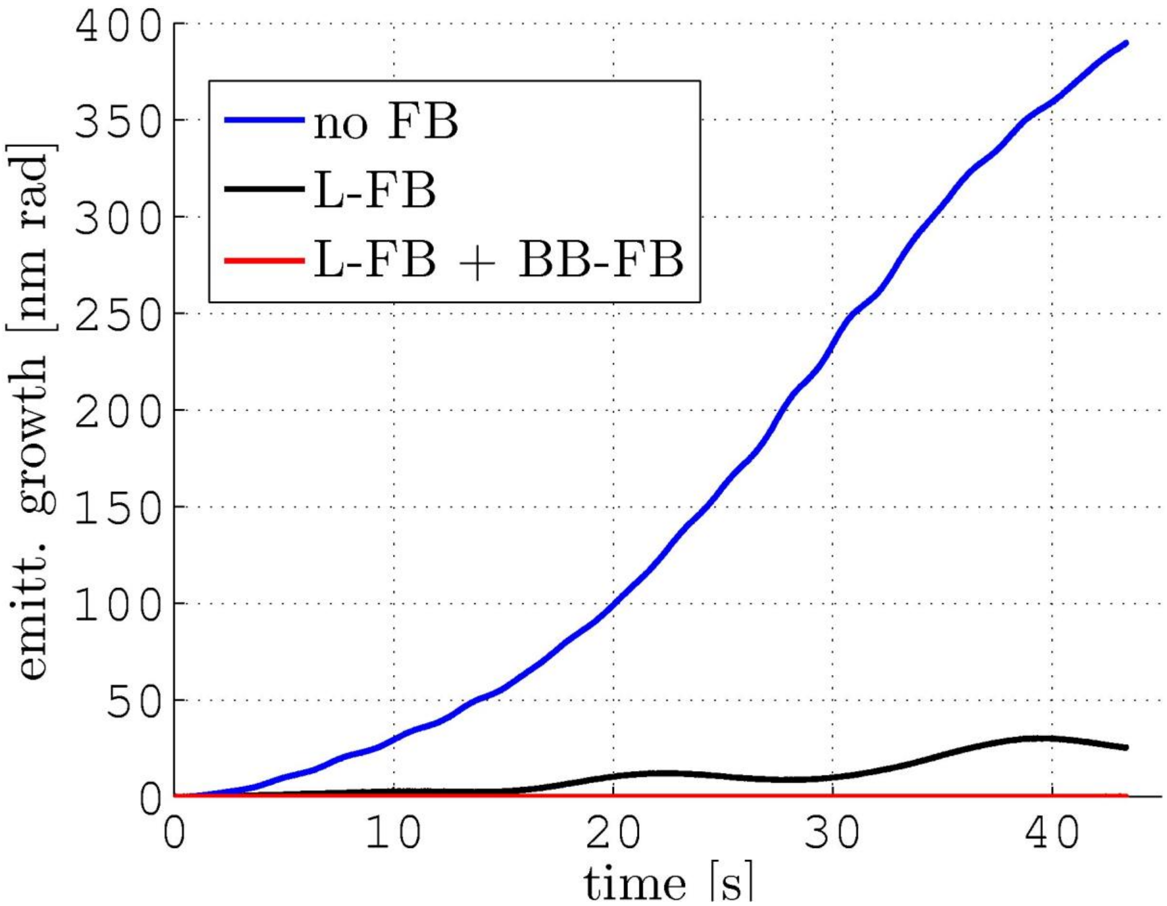
$\mathbf{R} \ldots$ response matr.
$\mathbf{R} = \mathbf{U}\Sigma\mathbf{V}^T$
$\mathbf{R}^{-1} = \mathbf{V}\Sigma^{-1}\mathbf{U}^T$

$$\mathbf{F} = \begin{bmatrix} \mathbf{I}_{n\times n} & \mathbf{0} \\ \mathbf{0} & a\mathbf{I}_{m\times m} \end{bmatrix}$$

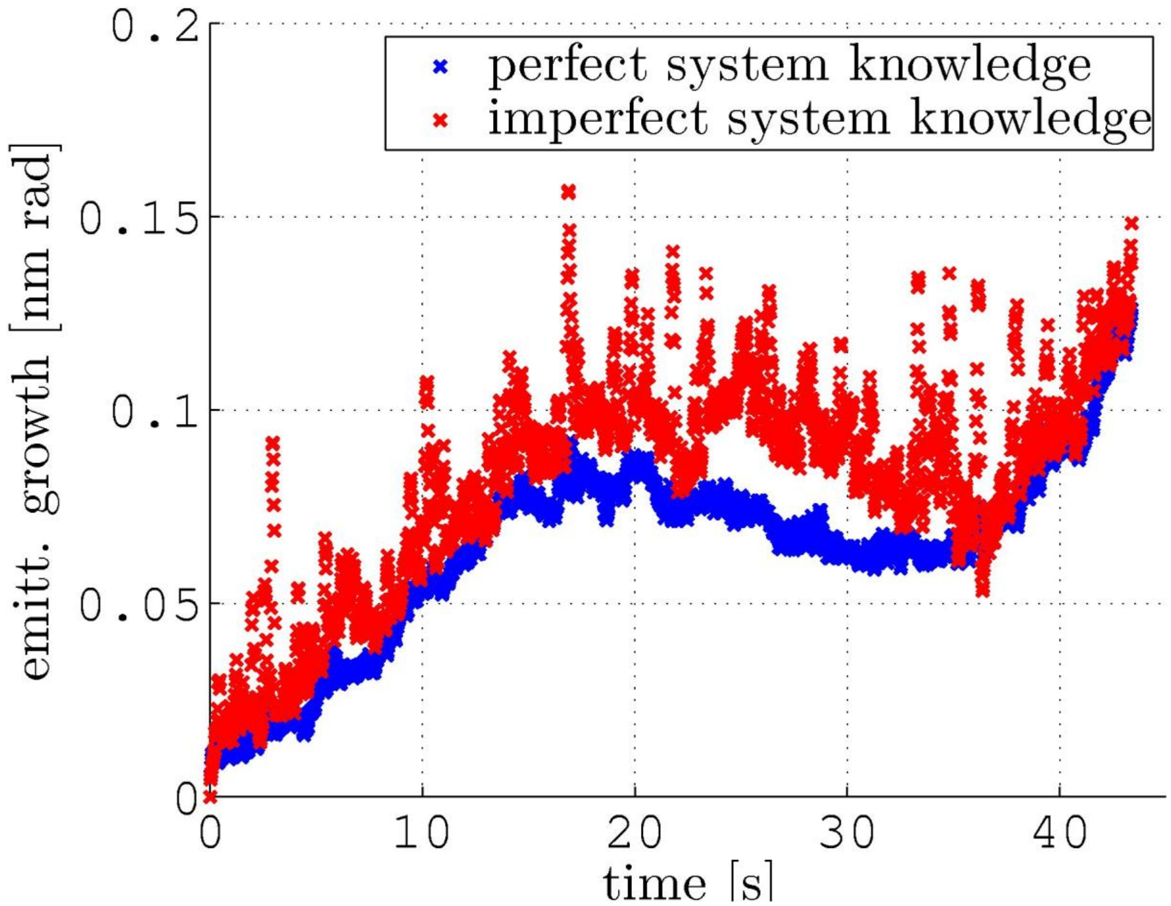
Reason for the choice of matrix F



Results: Ground motion mitigation of the control algorithm (sim. in Placet [7])

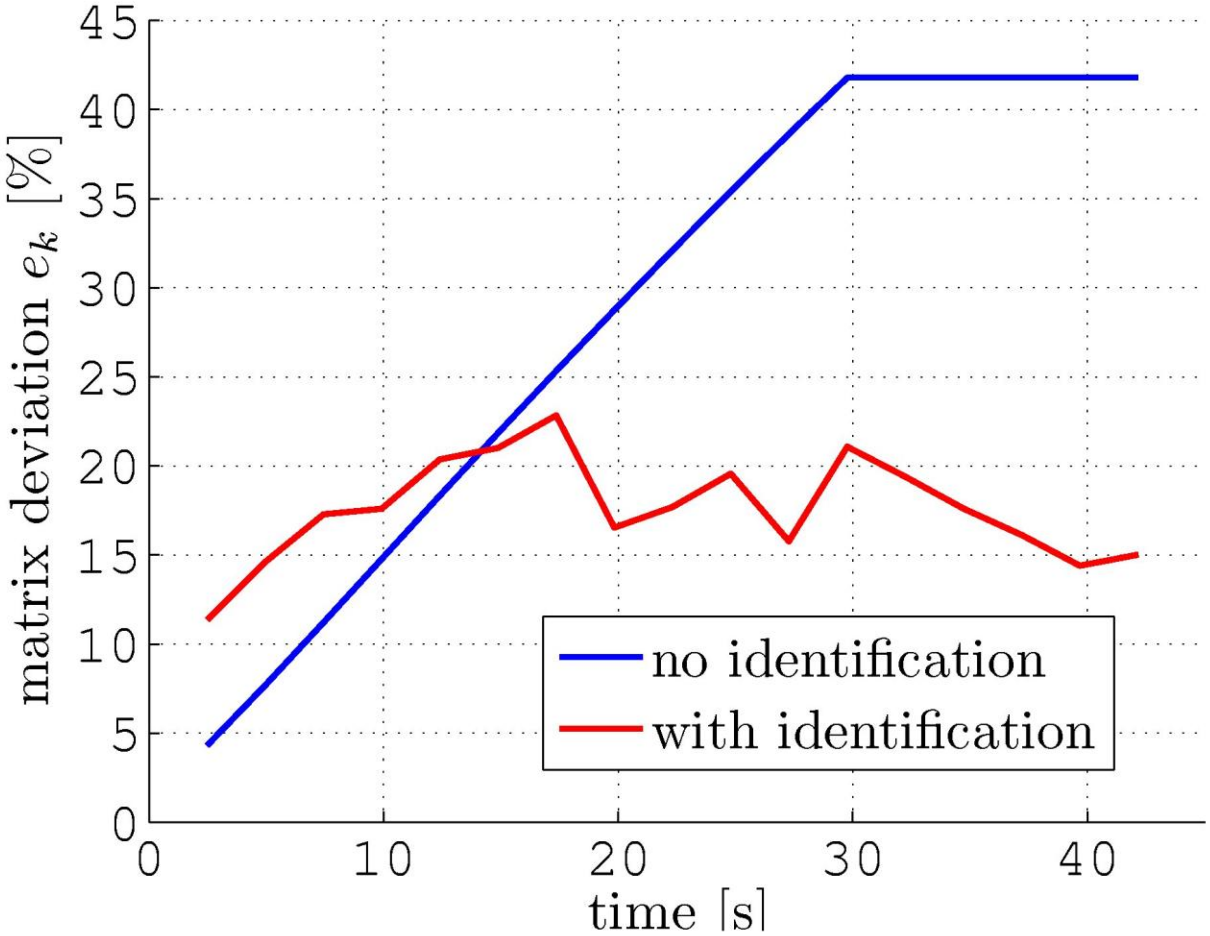


Control algorithm with imperfect system knowledge

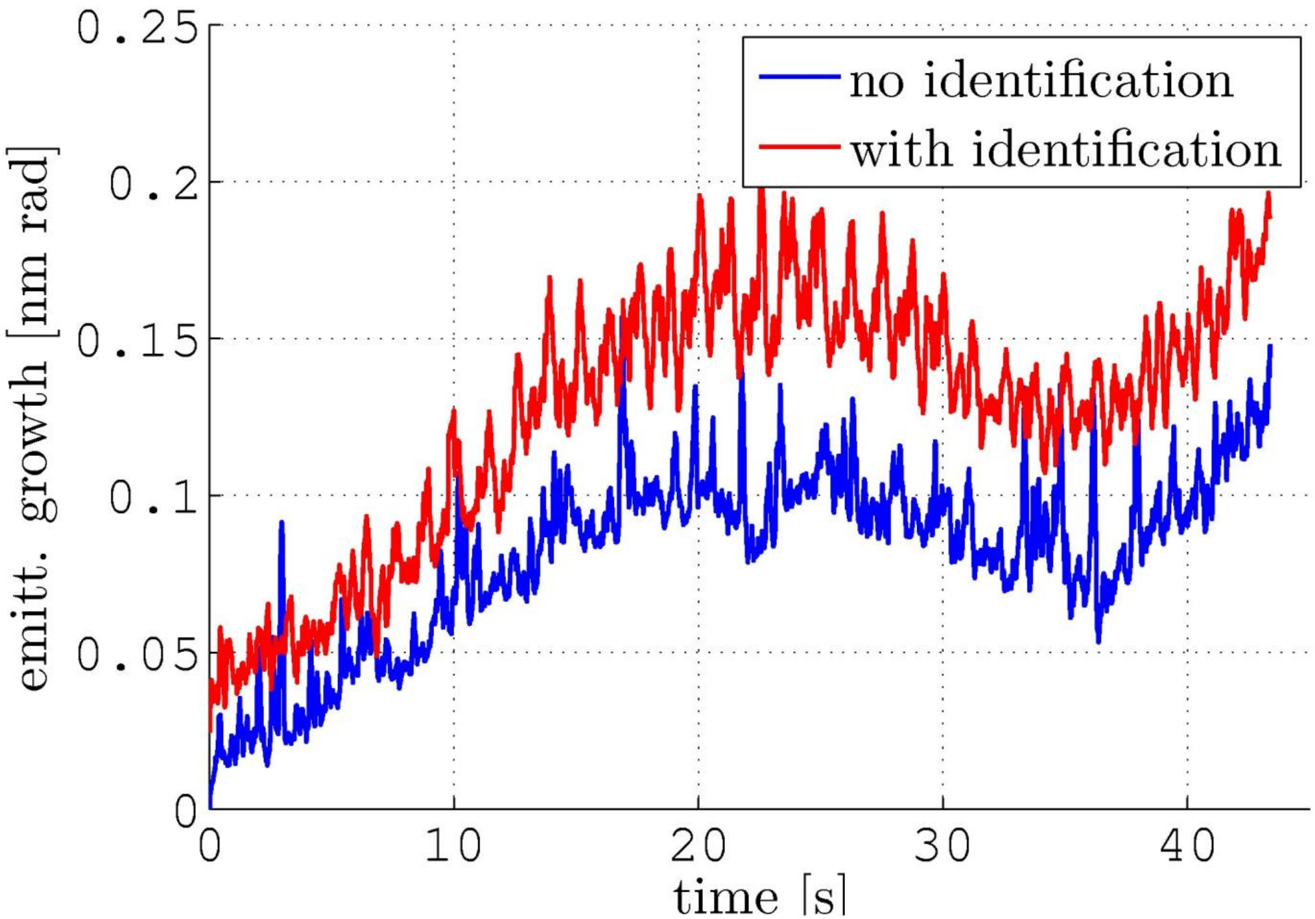


4. Simulation results for the allover algorithm

Identification results



Emittance growth with accelerator change



Summary

- Adaptive feedback strategy chosen to mitigate ground motion effects
- Algorithm consists out of a system identification unit and an control algorithm
- The complete system works and the results are very appealing.

Further work

- Optimization of the control algorithm
- Robustness analysis of the adaptive controller
- Experimental verification of the system identification
- System identification for the BDS !?

Further information and references

[1] C. Collette, K. Artoos, M. Guinchard and C. Hauviller, Seismic response of linear accelerators, Physical reviews special topics - accelerators and beams.

[2] K. J. Åström and B. Wittenmark. Adaptive Control. Dover Publications, Inc., 2008. ISBN: 0-486-46278-1.

[3] J. Pfingstner, et al, An interleaved, model-supported system identification scheme for the particle accelerator CLIC, Proceedings of the CDC10, 2010.

[4] J. Pfingstner, et al, Amplitude model for beam oscillations in the main linac of CLIC, CERN CLIC-Note, to be published 2010.

[5] S. Skogestad and I. Postlethwaite, Multivariable Feedback Control: Analysis and Design, Wiley-Interscience, 2005, ISBN: 0-470-01168-8

[6] H. Kwakernaak and Raphael Sivan, Linear Optimal Control Systems, Wiley-Interscience, 1972, ISBN: 0-471-51110-2

[7] D. Schulte et al, The Tracking code PLACET. https://savannah.cern.ch/projects/placet

Thank you for your attention!