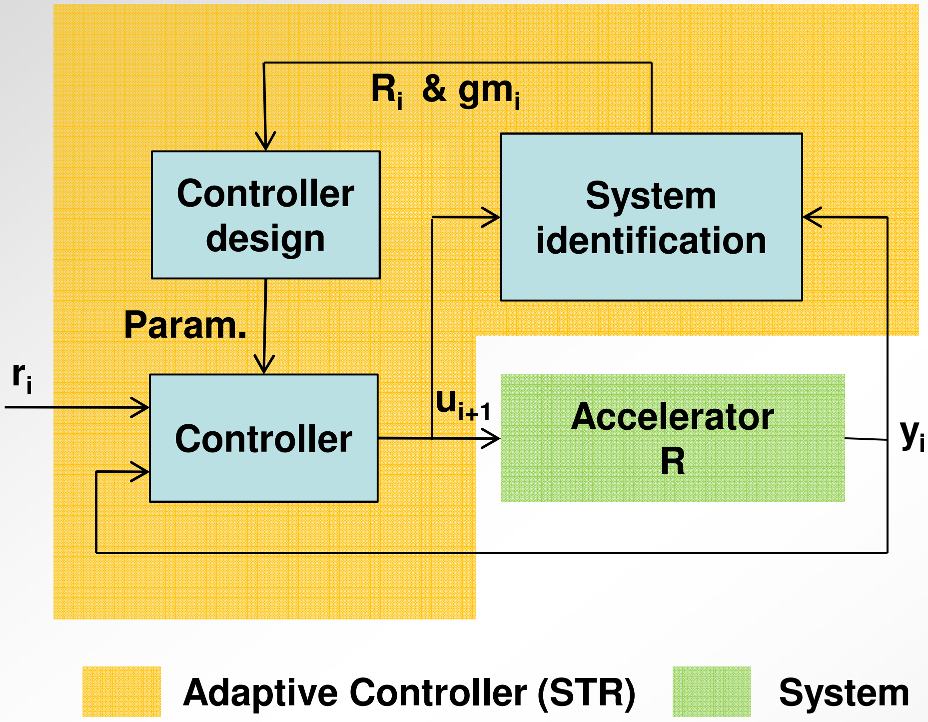
Status of the Beam-Based Feedback for the CLIC main linac

Jürgen Pfingstner

14th of October 2009

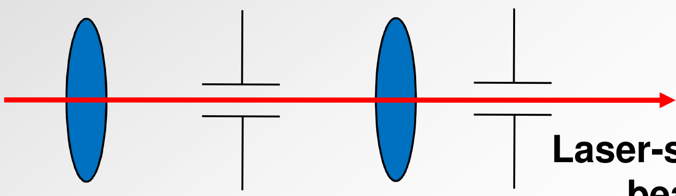
Content



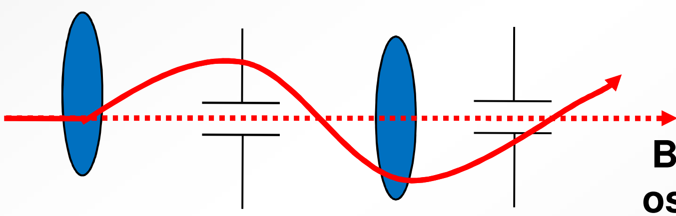
1. Review of the work on the BBF
2. Idea of an adaptive controller
3. Problems with an adaptive scheme and possible solutions

The model of the main linac

1.) Perfect aligned beam line



2.) One misaligned QP



a.) 2 times x_i -> 2 times amplitude
-> 2 times y_j
b.) x_i and x_j are independent

$\Rightarrow$ Linear system without 'memory'

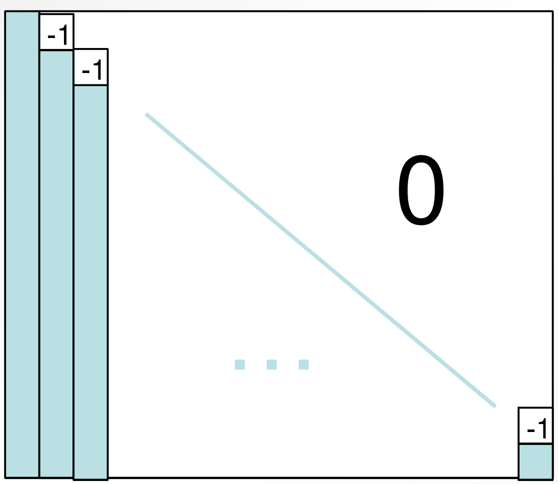
$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \cdots \\ r_{21} & r_{22} & \\ \vdots & & \ddots \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \end{pmatrix}$$

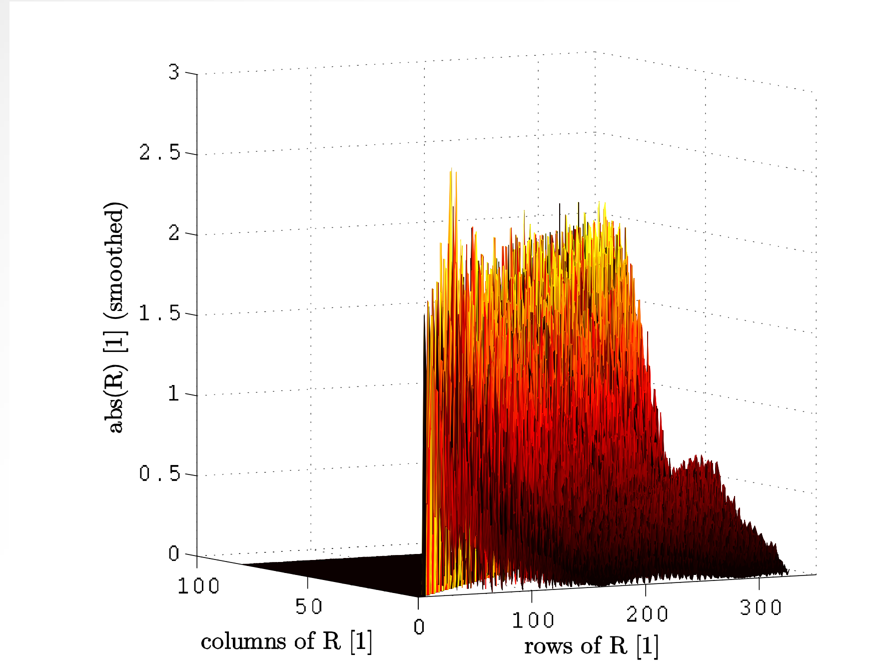
$$\Rightarrow y = Rx$$

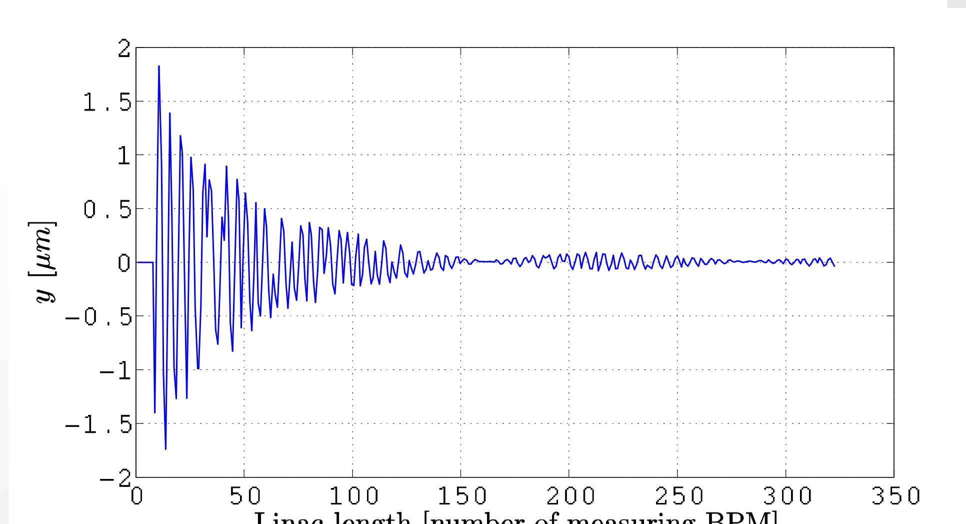
y … vector of BPM readings
x … vector of the QP displacements
R … response matrix

The matrix R

- N's Columns correspond to the measured beam motion in the linac, created by the N's QP
- Motion is characterized by phase advance $\phi(s)$, beta function and Landau damping
- R is 'nearly' triangular and the elemets close to the diagonal are most important.







Robustness study and properties of the system

Robustness study [1]:

- Feedback with nominal R applied to not-nominal accelerator
- **Simulations** of the feedback performance **in PLACET** [2]
- Feedback was the dead-beat controller (see next slide)

Results:

- Outcome was a table of still valid accelerator parameters
- **Message:**
  - System is by itself very robust against imperfect system knowledge
  - Stability is not an big issue

System properties summarized:

- Main linac is a **discrete memoryless FIFO system** (simple), but **MIMO**

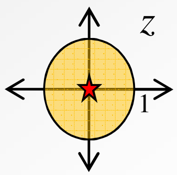
$$y_i = z^{-1}R(x_i + v_i) + n_i$$

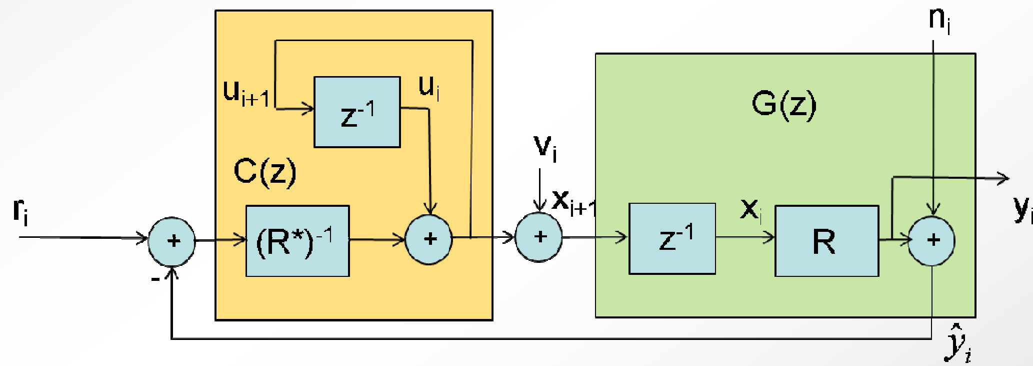
- The system in in principal **easy to control**, since there is no inner dynamic (dynamic just by feedback).

Character of the control problem:

- Classical feedback design objectives as stability and set point following are **not important** issues,
- Minimal steady state error, due to noise and disturbances and very good system knowledge **matters**.
- **Focus is more on precision and not on robustness**

State controller

- **Idea:** Calculate the QP positions of the last step and correct them [3].
- Corresponds to a **state controller** [4], that puts all poles to zero (**deadbeat contr.**)
- 



- Set point **transfer function**:

$$R(z) \equiv \frac{y(z)}{r(z)} = R(R^*)^{-1} \frac{1}{z-(1-R(R^*)^{-1})}$$

- **Deadbeat controller [5]:**
  - Very fast ground motion rejection and set point following
  - but introduces a lot of noise from the BPMs in the system

Alternative state controller:

- Apply not full correction

$$corr_i = -(R^*)^{-1}(r_i - \hat{y}_i)$$

  but

$$g\ corr_i \quad with\ 0 < g < 1$$

- Factor **g balances between speed and noise**, by moving to poles further away from zero

Emittance based controller [6]

- **Idea:** Emittance as a function of normalized beam macro particle coordinates at the end of the linac

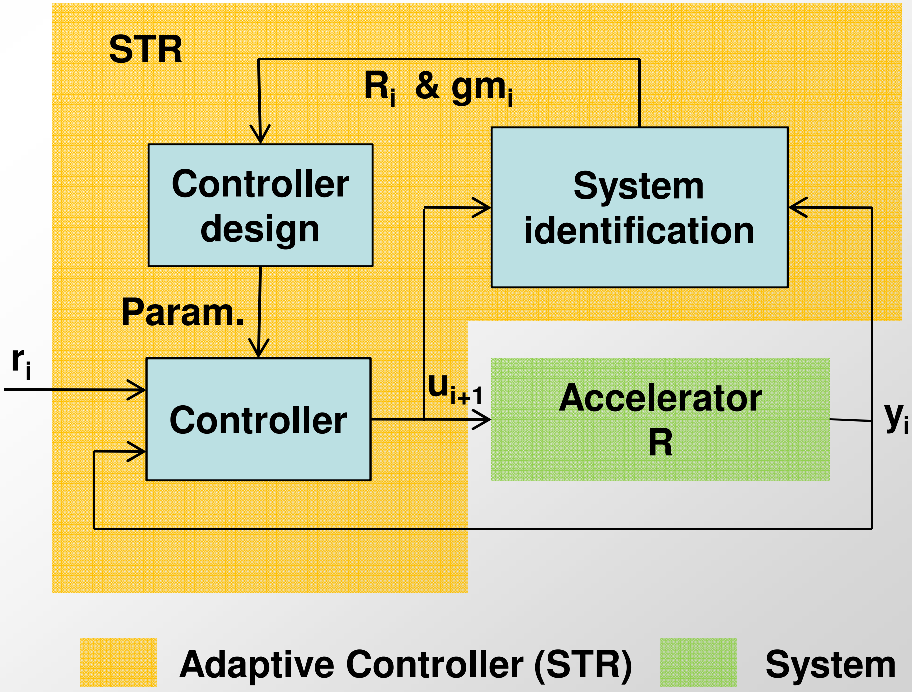
$$\epsilon_N \approx \tilde{y}^T M^T M \tilde{y} = y^T y$$

- Optimizing feedback for min. emittance growth and min. BPM offset (quadratic sense)
- Result is a 10 times smaller growth rate.
- Design uses SVD decomposition but is not a SVD controller (no diagonalization).

- **Problem:** Controller design uses macro particle coordinates that cannot be measured in reality.
- **Controller has to rely on simulated data.**
- Practical usefulness is questionable and has to be verified, by robust performance evaluation.

Idea of an adaptive controller

- Previous designs do not take into account system changes.
- **Idea:** Tackle problem of system changes by an online system identification
- Lear about the system by:
  - Input data
  - Output data
  - Guess about the system structure
- **Usage:**
  - For system diagnostics and input for different feedbacks (keep R as it was)
  - Input for an online controller design
- **3 adaptive control schema [7]:**
  - Model-Reference Adapt. Sys. (MRAS)
  - Self-tuning Regulators (STR)
  - Dual Control



System identification

- Real system: M

  $y_i = g(u_i)$

- Model system: $\hat{M}$

  $y_i = \hat{R}_i u_i + \hat{R}_i gm_i + n_i$

- <u>Goal:</u>

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

  $M \approx \hat{M}$

  using u_i and y_i

u_i ... Input data
y_i … Output data
gm_i … Ground motion
n_i … white and gaussian noise (always here)

RLS algorithm and derivative

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

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

- **Offline 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)

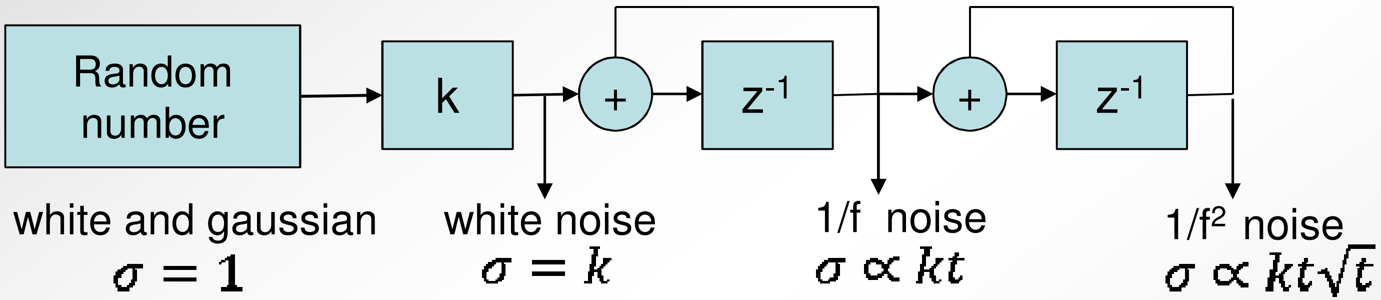
Computational effort

- Normally the **computational effort for RLS is very high**.
- For most general form of linac problem size:
  - Matrix inversion (1005x1005)
  - Storage of matrix P (1 TByte)
- Therefore often just simplifications as PA, SA and LMS are used.

- For the linac system φ_i and $\hat{\theta}_i$ have a simple diagonal form.
- The computational effort can be reduced strongly
  - Matrix inversion becomes scalar inversion
  - P (few kByte)
  - Parallelization is possible
- **Full RLS can be calculated easily**

Modeling of the system change

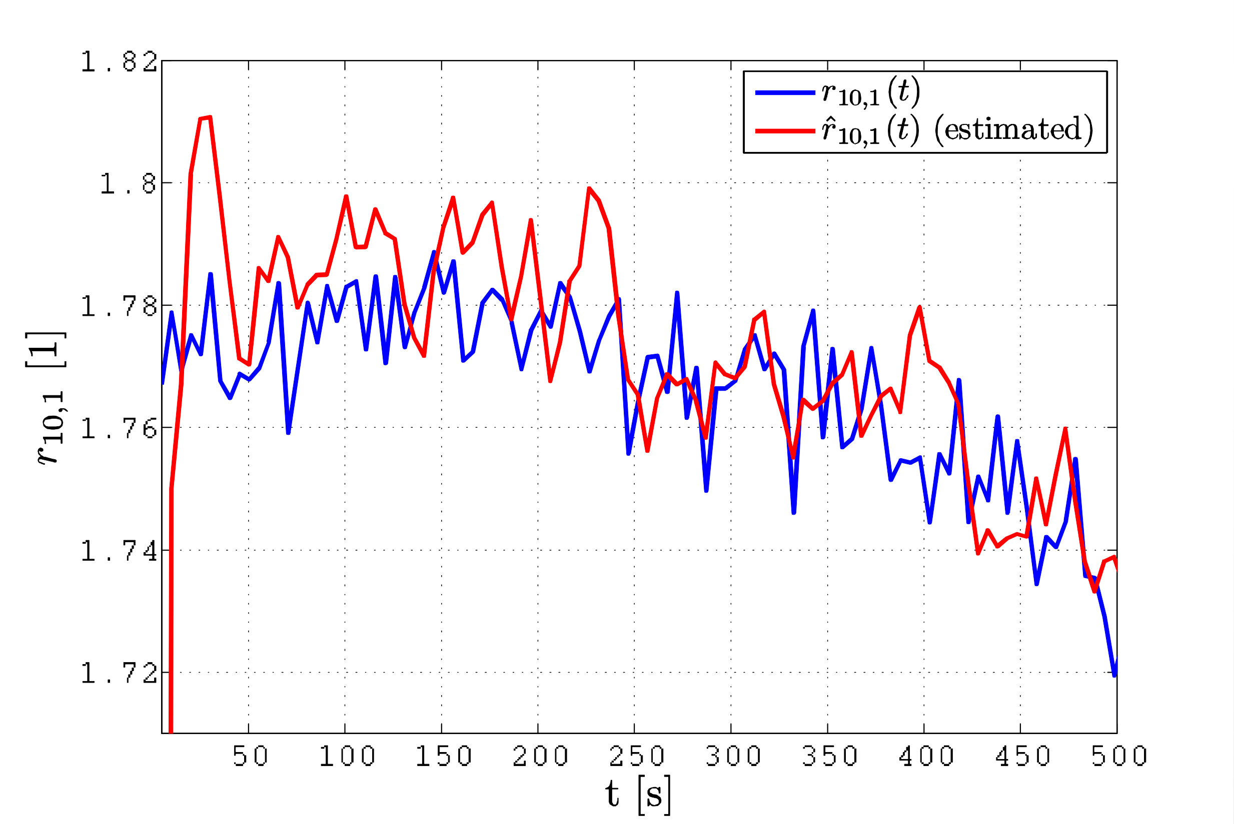
- **Noise/Drift generation**



- Parameter of noise (for similar emittance growth; $\Delta T = 5$s):
  - **BPM noise**: white noise ($k = 5 \times 10^{-8}$)
  - **RF disturbance**: $1/f^2$ drift ($k = 7 \times 10^{-4}$) + white noise ($k = 1.5 \times 10^{-2}$)
  - **QP gradient errors**: $1/f^2$ drift ($k = 4 \times 10^{-6}$) + white noise ($k = 3 \times 10^{-4}$)
  - **Ground motion**: According to Model A of A. Sery [8]

- RF drift much more visible in parameter changes than QP errors

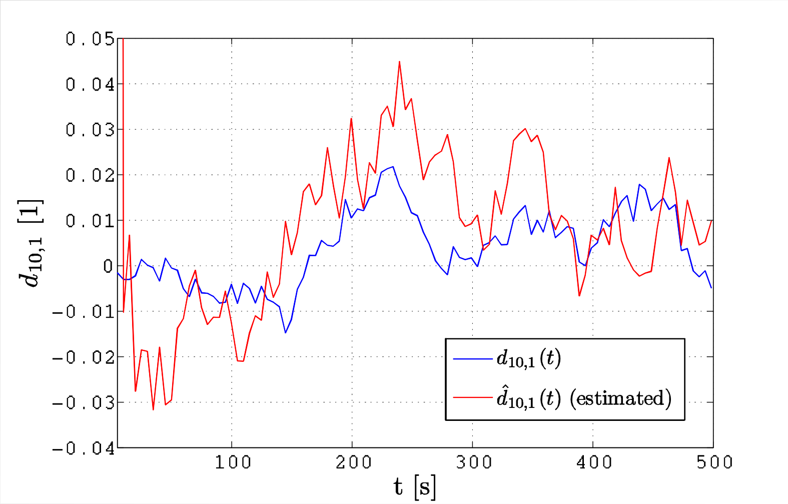
First simulation results

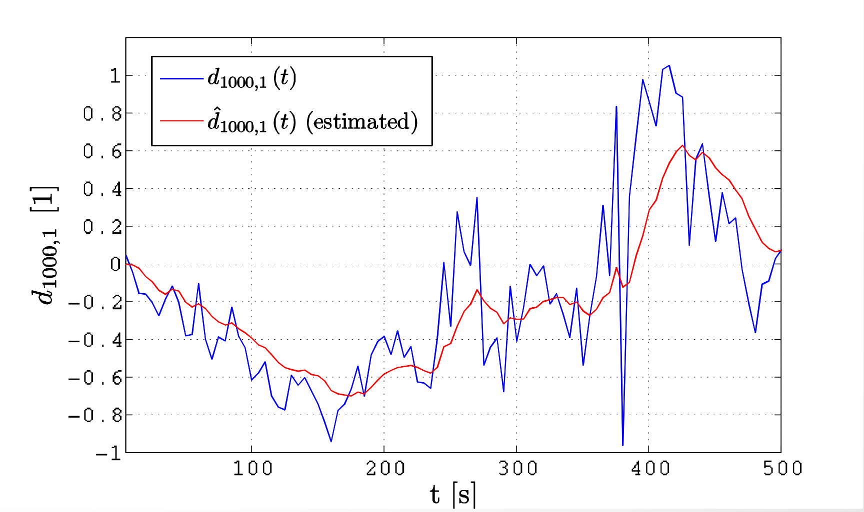


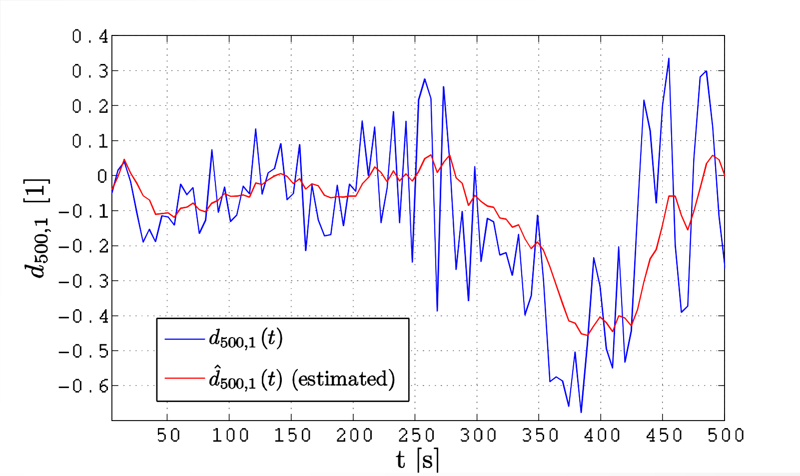
- ΔT = 5s
- λ = 0.85
- R changes according to last slide
- Ground motion as by A. Seri (model A [8])

- Identification of one line of R and the gm-vector d
- Simulation data from PLACET

Forgetting factor λ







d_{10}: λ to big (overreacting)

d_{500}: λ fits

d_{1000}: λ is to small

=> Different positions in the linac should use a different λ (work)

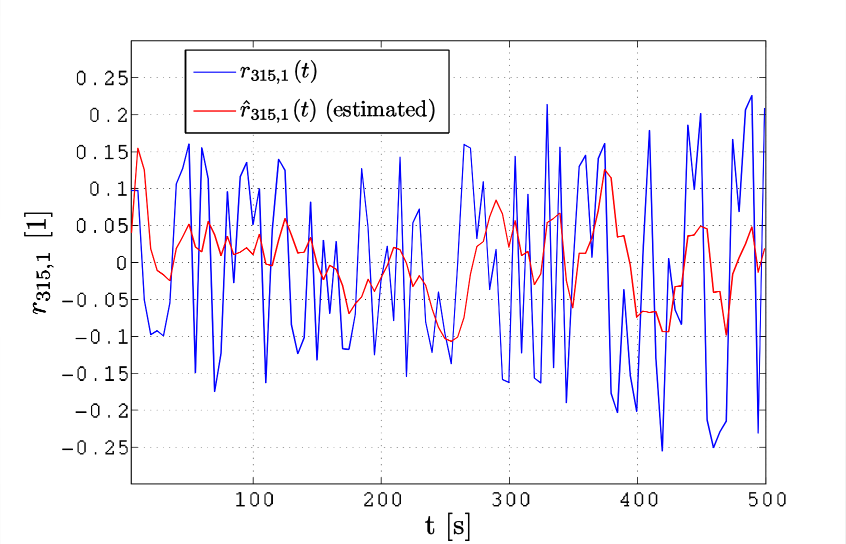
Problems with the basic approach

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: **Nature of changes**

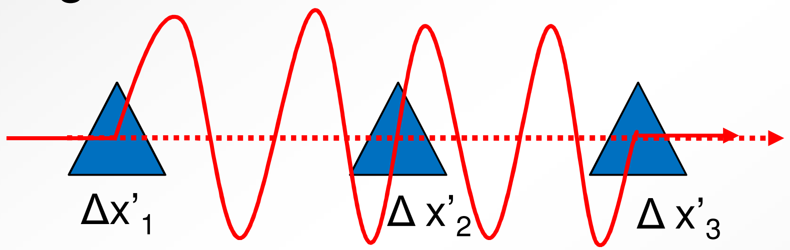


- No systematic in system change
- Adding up of many indep. Changes
- Occurs after long excitation

Semi-analytic identification scheme

<u>Excitation Strategy:</u>

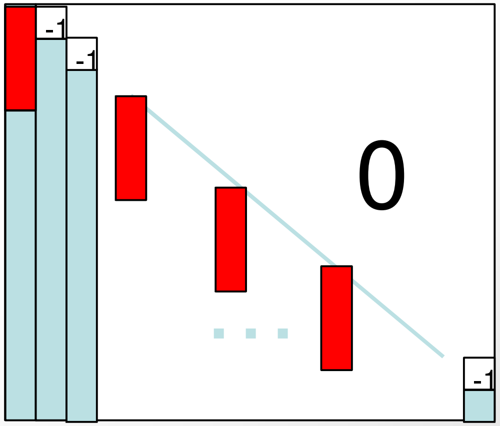
- **Necessary excitation can not be arbitrary**, due to emittance increase
- **Strategy:** beam is just excited over short distance and caught again.



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

<u>Practical system identification:</u>

- Just parts of R can be identified



- **Rest** has to be **interpolated**
  - Transient landau damping model
  - Algorithm to calculate phase advance from BPM/R data

Model of the transient Landau Damping

- **Approach** [9]:

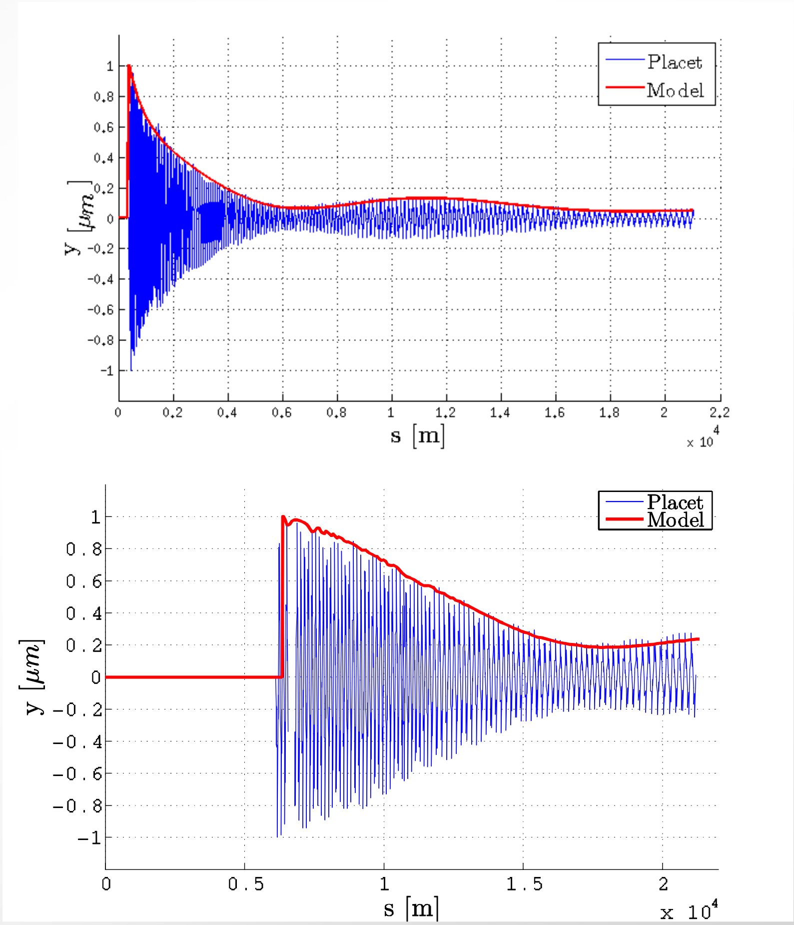
$$< x(t) >= \int_{-\infty}^{+\infty} x(t,\delta)\, pdf(\delta)\, d\delta$$

- Envelope by **peak detection algorithm**
- **Limitation:** Works just for time independent energy distribution

$$pdf(\delta,t) = pdf(t)$$

- Not the case at injection into linac => fit to data

Result: (Kick at 390 and 6350m)



Open questions

- Strategy of determine α in an way, that the knowledge about the disturbance signals is best possible used.
- Gaining knowledge of the best possible excitation of the beam without loosing to much beam quality.
- Getting more detailed information about the nature of many disturbances to tailor the algorithm accordingly (not only RLS is possible).

Resume

- The approach of an adaptive controller is in principle good, but
- There are many accumulating inaccuracies as:
  - Landau Model
  - Phase advance reconstruction
  - Remaining Jitter in the estimated model
  - Undeterministic propagation of disturbances
- Hopefully these inaccuracies do not destroy the practical usability!!!

References

[1] J. Pfingstner, W. http://indico.cern.ch/conferenceDisplay.py?confId=54934. Beam-based feedback for the main linac, CLIC Stabilisation Meeting 5, 30th March 2009.

[2] E. T. dAmico, G. Guignard, N. Leros, and D. Schulte. Simulation Package based on PLACET. In Proceedings of the 2001 Particle Accelerator Converence (PAC01), volume 1, pages 3033–3035, 2001.

[3] A. Latina and R. Tomas G. Rumolo, D. Schulte. Feedback studies. Technical report, EUROTeV, 2007. EUROTeV Report 2007 065.

[4] Otto Föllinger. Einführung in die Methoden und ihre Anwendung. Hüthig Buch Verlag Heidelberg, 1994. ISBN: 3-7785-2915-3.

[5] Nicolaos Dourdoumas and Martin Horn. Regelungstechnik. Pearson Studium, 2003. ISBN: 3-8273-7059-0.

[6] Peder Eliasson. Dynamic imperfections and optimized feedback design in the compact linear collider main linac. Phys. Rev. Spec. Top. Accel. Beams, 11:51003, 2008.

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

[8] Andrey Sery and Olivier Napoly. Influence of ground motion on the time evolution of beams in linear colliders. Phys. Rev. E, 53:5323, 1996.

[9] Alexander W. Chao. Physics of Collective Beam Instabilities in High Energy Accelerators. John Wiley & Sons, Inc., 1993. ISBN: 0-471-55184-8.

Thank you for your attention!