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LOCO for LHC

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The LOCO principle

$$S\Delta\vec{c} = \vec{V}$$

SVD

$$\vec{c}\,' = \vec{c} + \Delta\vec{c}$$

Set of parameters

Difference vector: $\vec{V}(\vec{c}) = \vec{K}^{\mathrm{meas}} - \vec{K}^{\mathrm{model}}(\vec{c})$

Set of observables

Sensitivity Matrix: (Jacobian) $S^{kl} = -\frac{\partial V_k}{\partial c_l} = \frac{\partial K_k^{\mathrm{model}}}{\partial c_l}$

Orbit response

$$V_k = \frac{R_{ij}^{\mathrm{meas}} - R_{ij}^{\mathrm{model}}}{\sigma_i}$$

Orbit response matrix: $R_{ij}^{\mathrm{meas}} = \frac{\Delta u_i}{\Delta \delta_j}$

Possible parameters:

- Corrector gains, tilts …
- Monitor gains, tilts …
- Arbitrary model parameters.

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Challenges @ LHC

- # Monitors/beam (2 planes): $N_M = 1088$
- # Correctors/beam (2 planes): $N_C = 530$

Different problems/challenges for different applications:

- Size of Sensitivity Matrix:
  - Memory consumption
  - SVD inversion time
- Calculation time for Sensitivity matrix:
  - # twiss runs
- Measurement time. ~ Shifts

Memory Consumption

Size of Sensitivity Matrix:

- #rows $M = N_C \times N_M$,
- #columns N = #parameters.

E.g. Monitor- & Corrector Gains only:

$$N = N_C + N_M$$

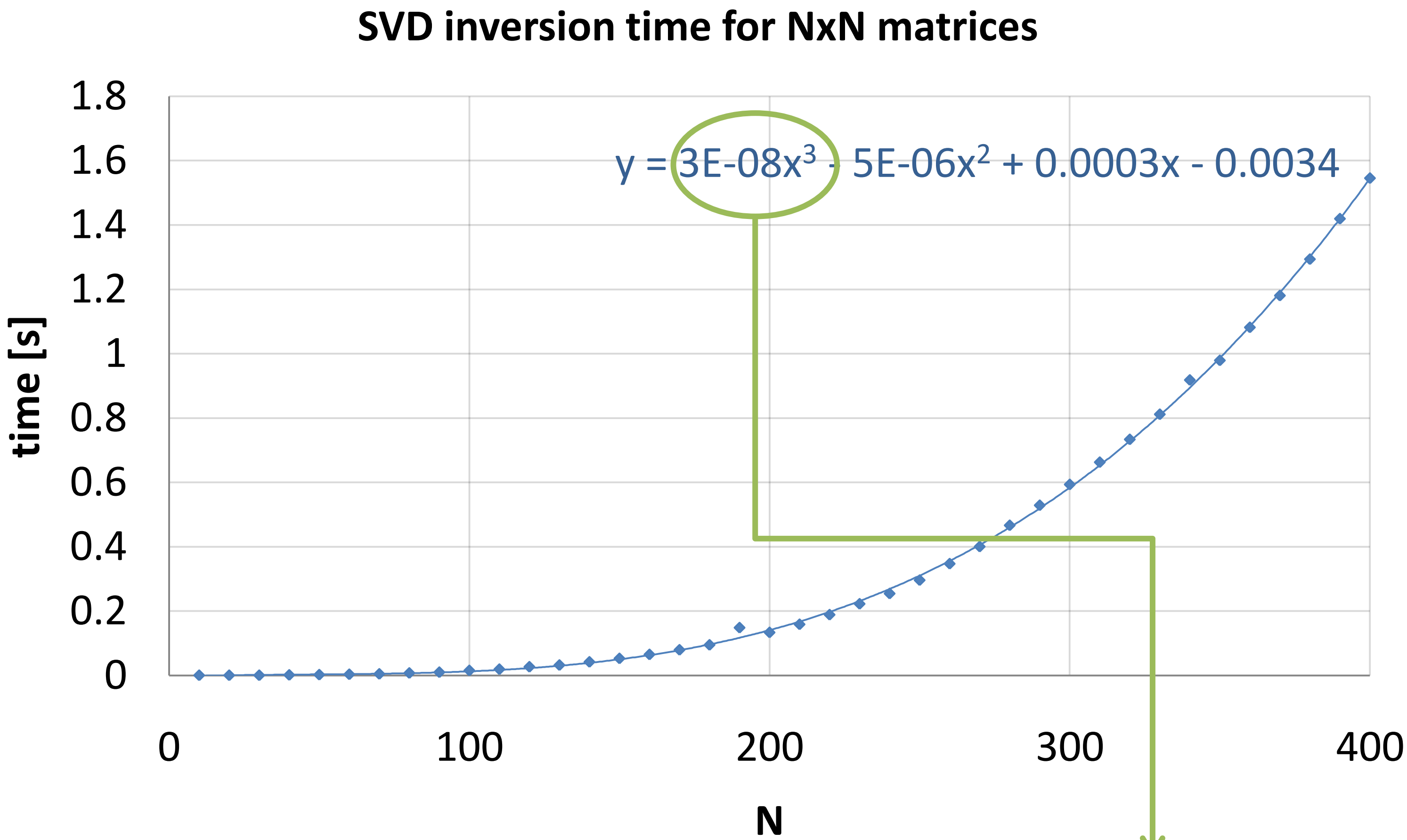
1 beam, 2 planes:

$(1088 \times 530) \times (1088 + 530) \times 8 \sim$ **8 GB**

2 beams, 2 planes: $\sim$**60 GB**

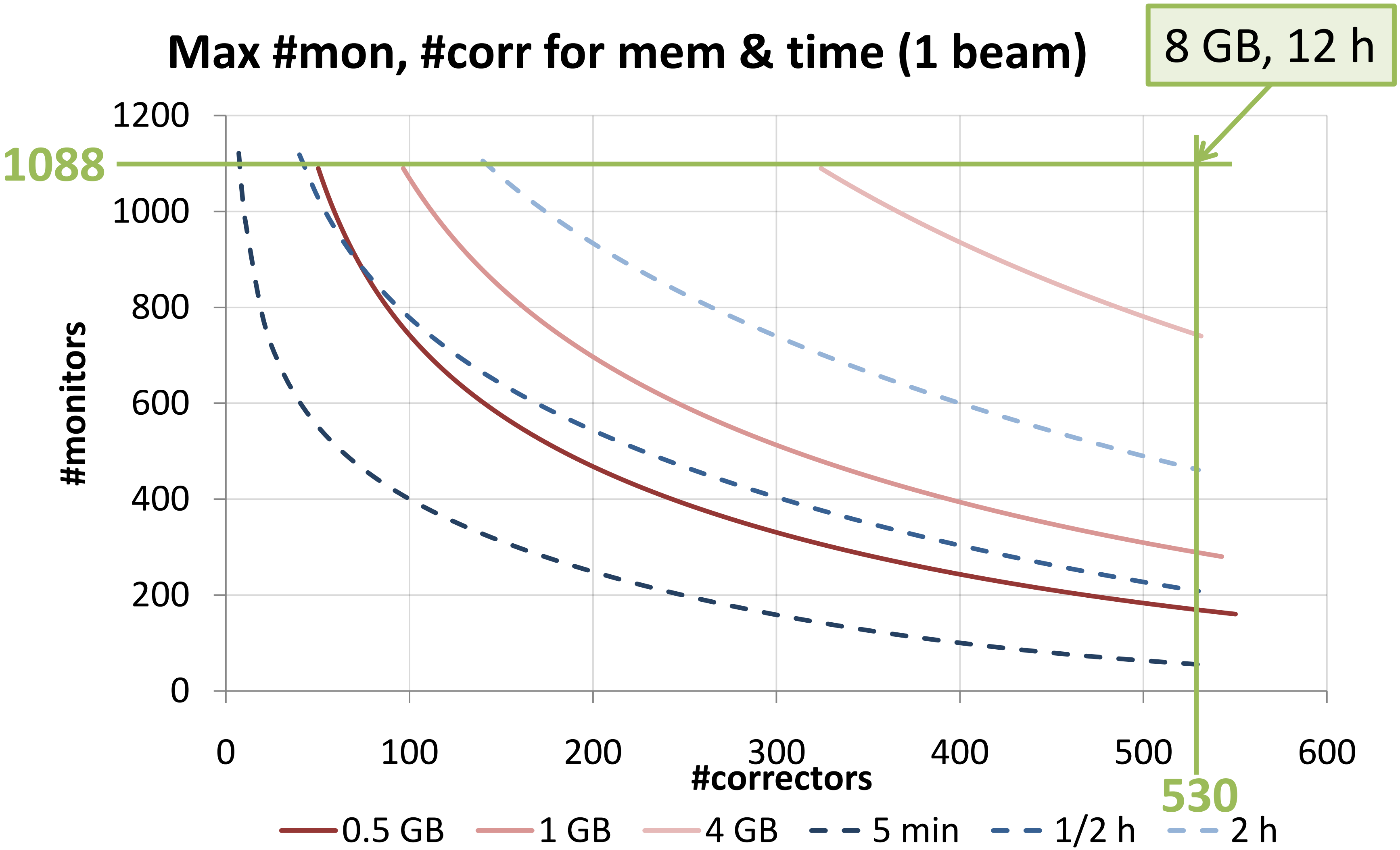
SVD inversion time

Inversion time: $O(MN^2)$ M ... #rows; N... #cols



Est. on Intel Desktop PC (3.17 GHz): $t \sim 3 \times 10^{-8} \times M \times N^2 \ [s]$

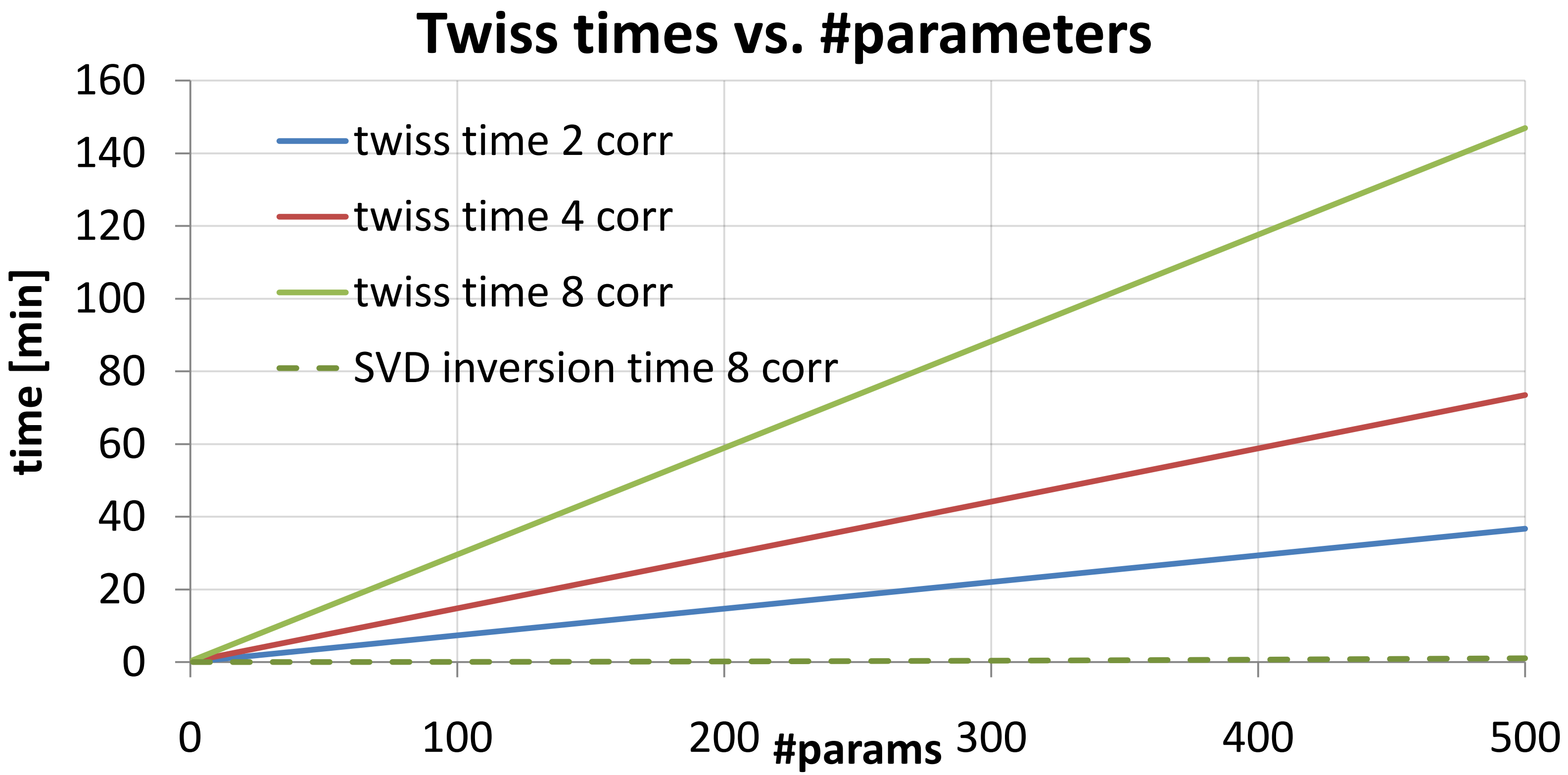
Monitor/COD Gain fits



→ **Possible, but tedious…**

Optics parameter fits

$$S_{kl} = \frac{K_k^{\text{model}}(c_l + \delta c_l) - K_k^{\text{model}}(c_l)}{\delta c_l}$$



Dominated by twiss time; SVD inversion negligible.

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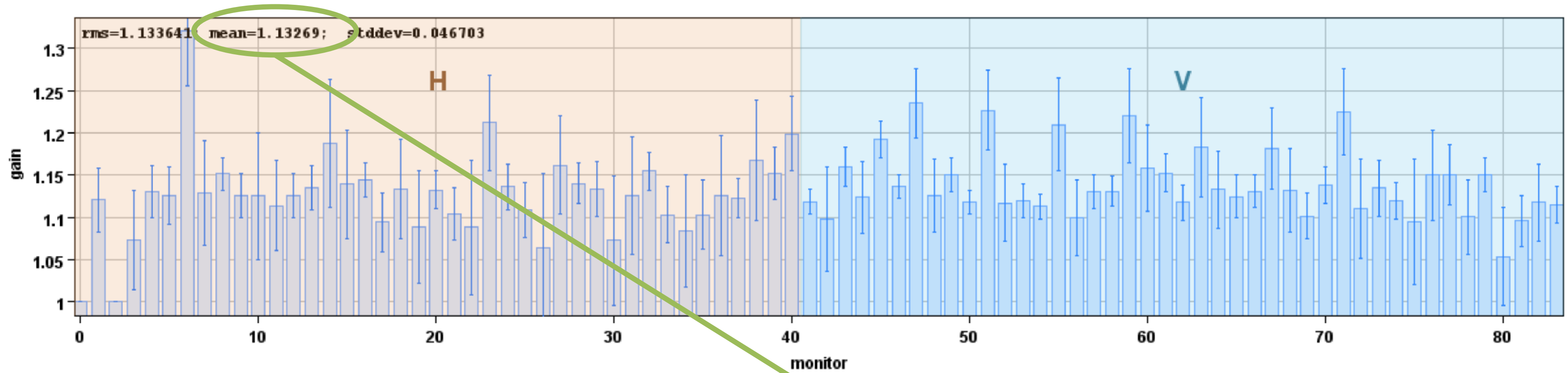
Ex. I

Monitor Gains in Transfer lines and LHC

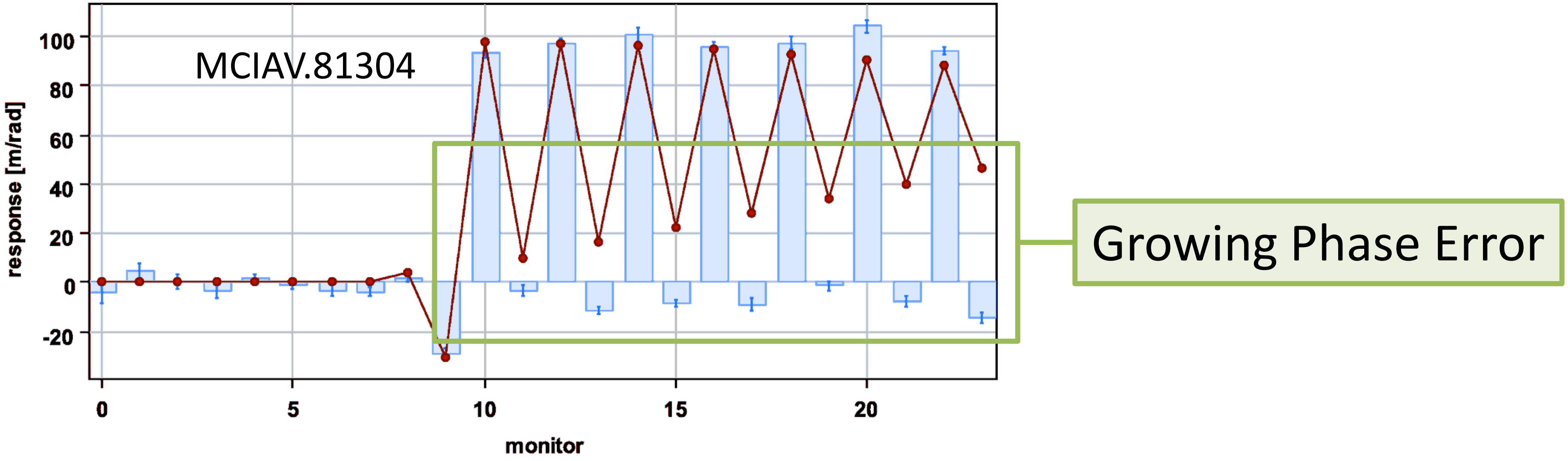


Average gain of 1.13:
→ Resulting from uncorrected electronics (Correction was later on applied in frontends)

- Fits done with corrector gains fixed
- At least 2 additional parameters (quad chains) to take care of phase advance

Ex. II – a

Phase advance error in Transfer line TI 8



Suspicion: Higher order field components in the main bends:

- b_2, b_3: quadrupolar and sextupolar field error, respectively.

Ex. II - b

Off-momentum Kick response

Combined sensitivity matrix:

$$S = \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ \ldots \\ S_7 \end{pmatrix}$$

7 measurements with different values for $\frac{\delta p}{p}$ (-2 … +2 permill)

Momentum offset:

$$\frac{\Delta p}{p} = \frac{\delta p}{p} + \frac{\Delta p_0}{p}$$

Trimmed value

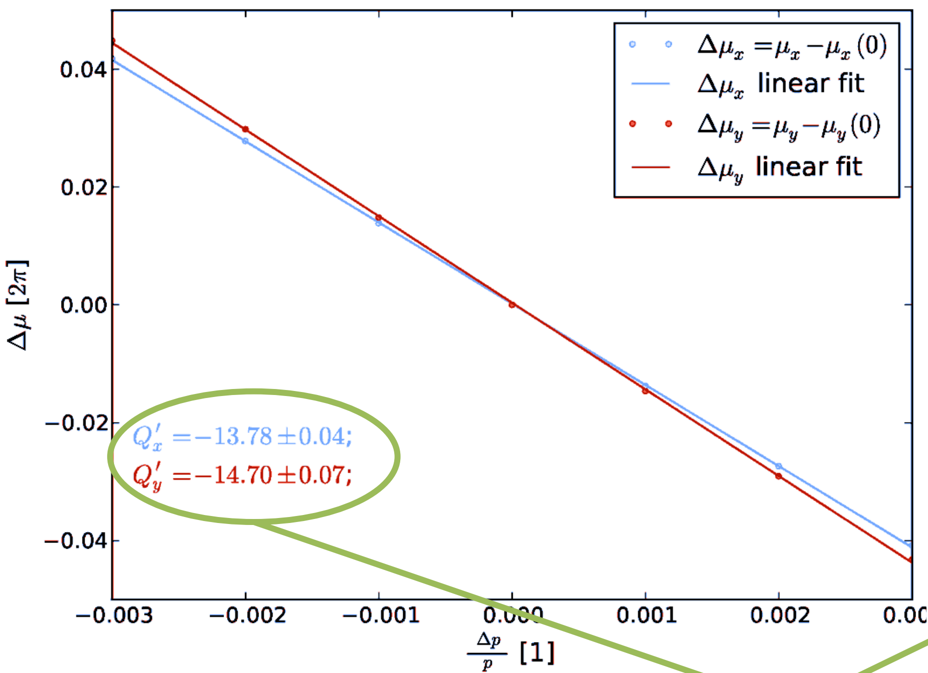
Unknown offset

- 4 correctors / measurement / plane
- Fits with 4 parameters: $\frac{\Delta p_0}{p}$, $\frac{\Delta K}{K}$, b_2 and b_3

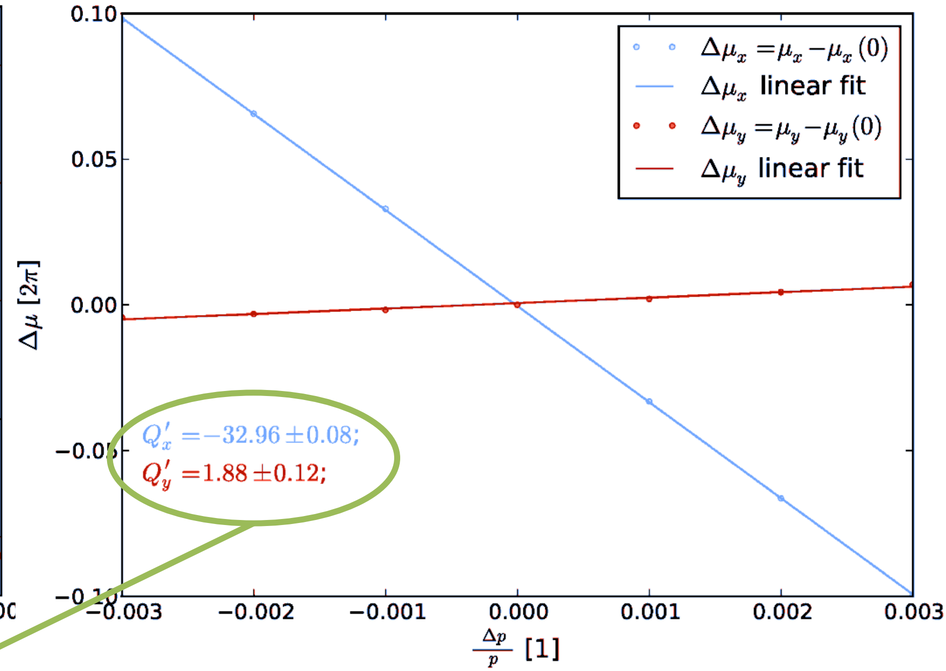
Measured Chromaticity (TI 8)

$$\Delta\mu_u = Q'^{\,\mathrm{tl}}_u \frac{\Delta p}{p}$$

Nominal model



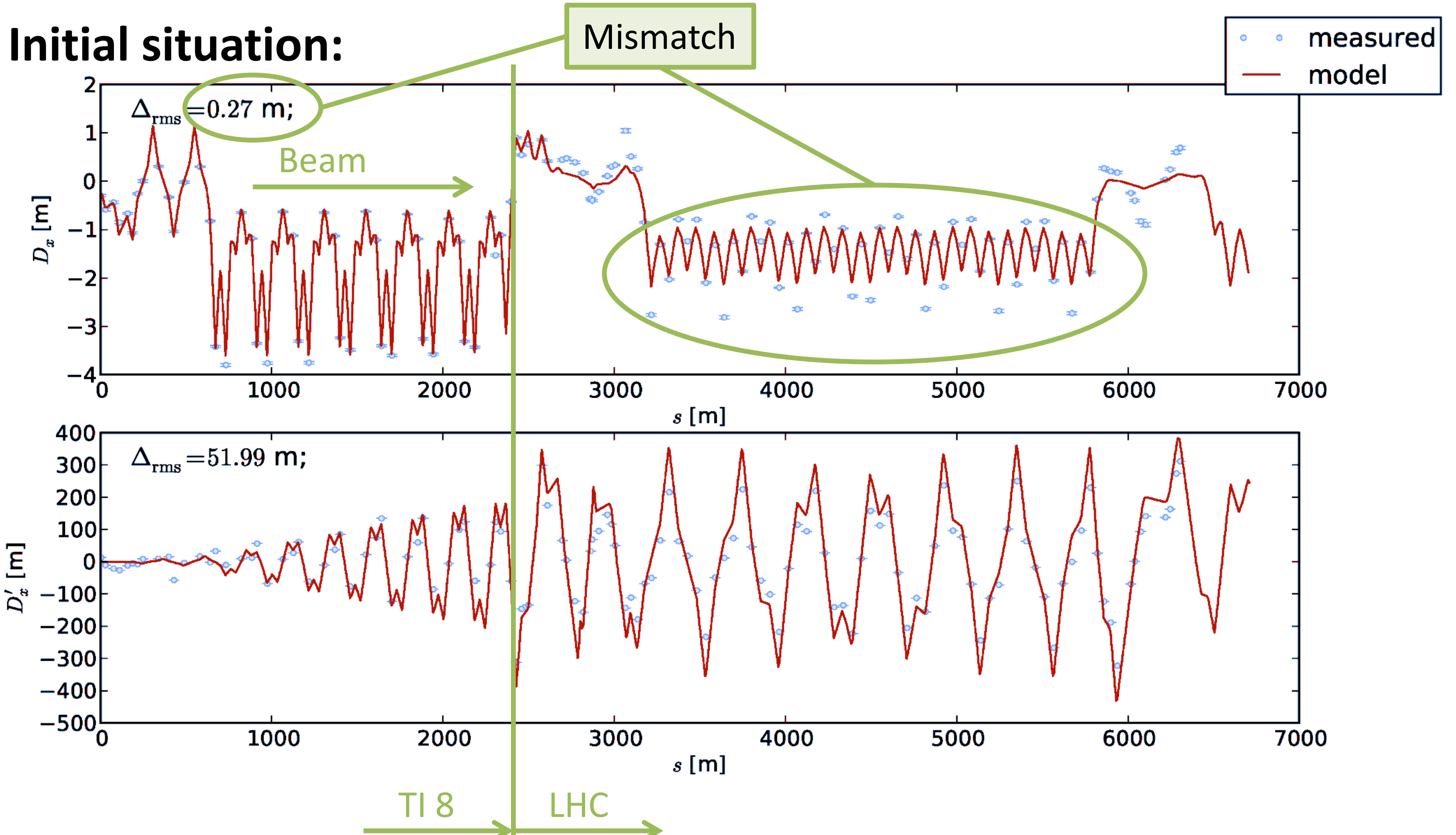
Fitted model



Q'_x about doubled, $Q_y{}'$ vanishes.

TI8-LHC dispersion matching

Initial situation:



Ex. III - b

Combined sensitivity matrix:

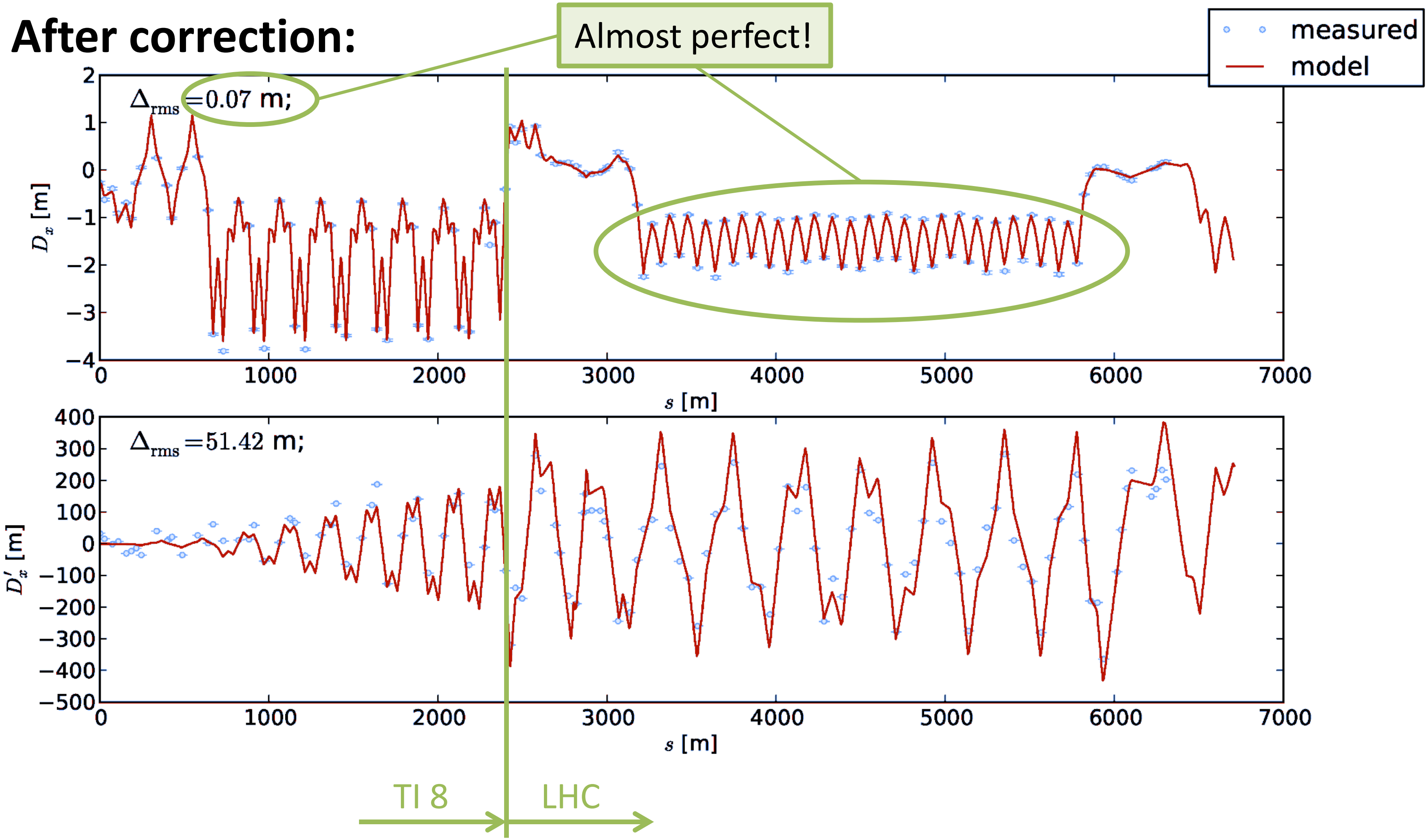
$$S = \begin{pmatrix} S_K \\ S_D \\ S_C \end{pmatrix}$$

- S_K: Kick response
- S_D: Dispersion
- S_C: Additional Constraints

- MD: Letting MICADO select 2 most effective out of 10 individually powered quads.
- Later: SVD together with additional constraints to ensure phase advance at collimators (3 per plane)

Ex. III - c

After correction:



Constrained by Kick-Response!

Ex. IV

Systematic b_2 in LHC arcs

Fit:

- Circulating beam
- 60 correctors (distribute)
- All BPMS
- No monitor/corrector gains fitted
- 9 Parameters:
  - 1 Systematic b_2 per sector
  - Systematic detuning of quads

$$\frac{\Delta K}{K} = 2.31 \cdot 10^{-4}$$

Result:

	b_2 model	b_2 fitted
Sector 12	-1.49	-1.68
Sector 23	1.46	1.40
Sector 34	1.35	1.67
Sector 45	1.31	1.44
Sector 56	-1.05	-1.75
Sector 67	-1.23	-1.57
Sector 78	-1.06	-1.20
Sector 81	1.30	1.30

Model prediction (WISE) well reproduced.

Other Observations

- Fitting **corr+monitor gains** → mostly **doubtable result** (Errors distributed between corr and monitor gains). Works well, if one is fixed.
- Check of **COD polarity** was done ‚**visually**'.
- LHC BPMs can have many different problems:
  - Polarity flip
  - Plane flip
  - Beam flip
  - Wrong rotation (e.g. BPMS, rotated by 45 deg)
  - + Any combination of these.

  → **Not easily covered by automatic fit**.

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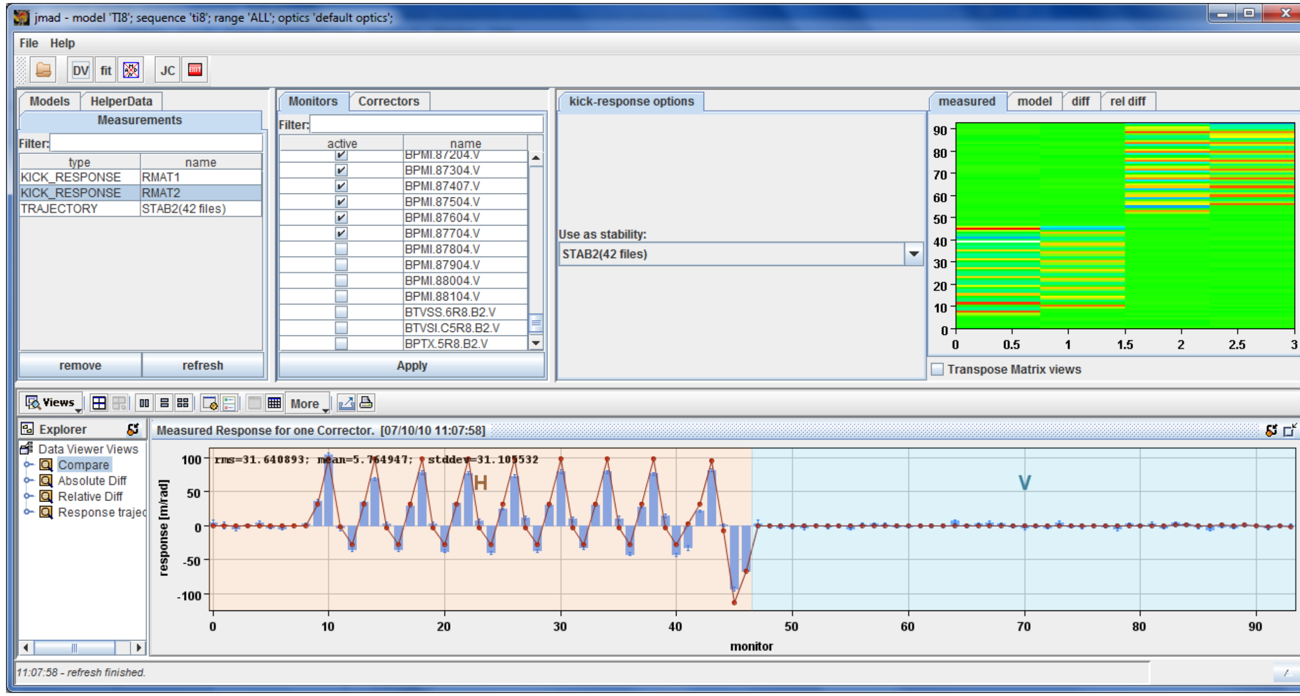
Aloha - "Another Linear Optics Helper Application"

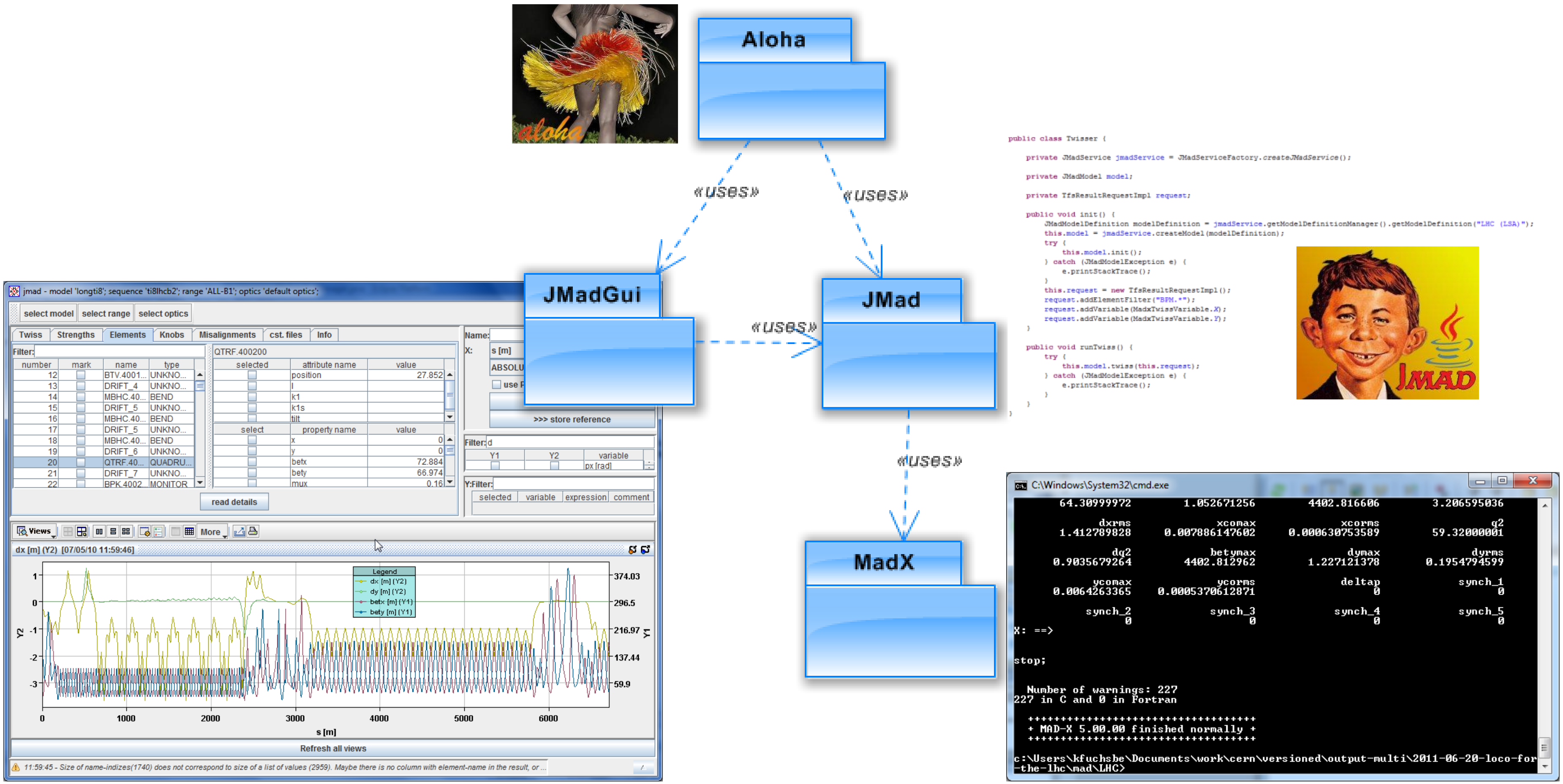


- **Input Data:** Kick-Response, Dispersion, Beta-Beat (from TBT)
- **Algorithms:** SVD, MICADO
- **Works for every** accelerator with existing **MadX model**
- **Plug-In system:** Easy to add e.g. new input formats, algorithms….

JMad

Tight coupling to model → All MadX parameters can be used

→ JMad: Java API for MadX

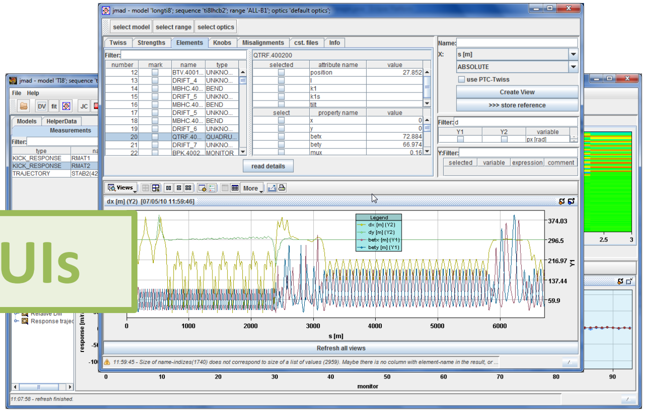


General Remark

Optics analysis is an interactive process.

→It is not sufficient to have good algorithms, we also need **good tools** (preferable online):

- Well integrated → Java
- Interactive and Intuitive → **GUIs**



- Good Software → **well designed, tested, documented, reusable…**

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Conclusions & Outlook

- LOCO for LHC? **Yes, we can!** (And we did!)
- LOCO principle was intensively used during LHC commissioning, especially for single-pass applications (**Transfer lines**, **injection tests**).
- Full BPM+COD gain fit for ring should be **possible but** is **problematic** (8GB ram, 12 h). The effort is questionable.
- Optics fit in ring works fine, but better covered by multiturn measurements. (faster, no influence of gains)
- It would be useful to join efforts to better integrate/merge different optics measurement methods/tools → e.g. **„Optics Analysis Workbench"?** (Aloha could serve as starting point; Plug-In System)

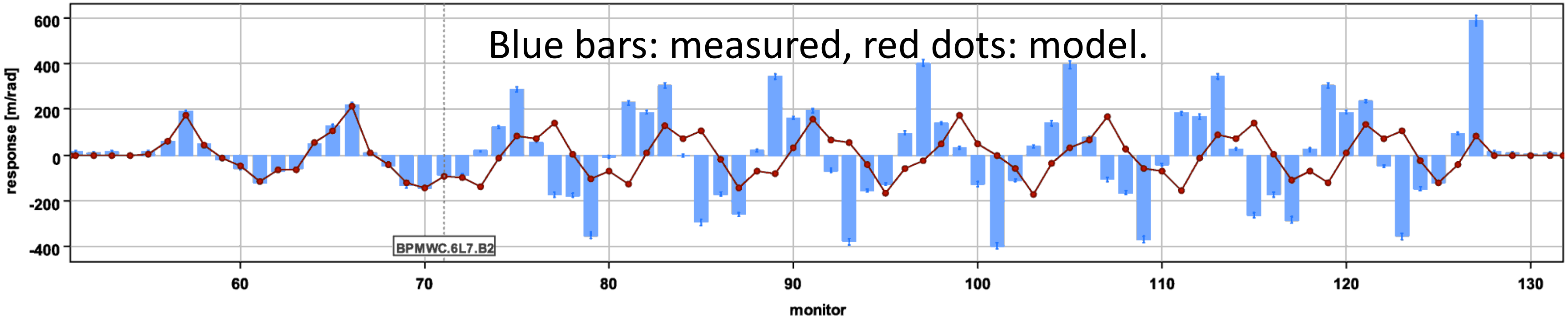
The end

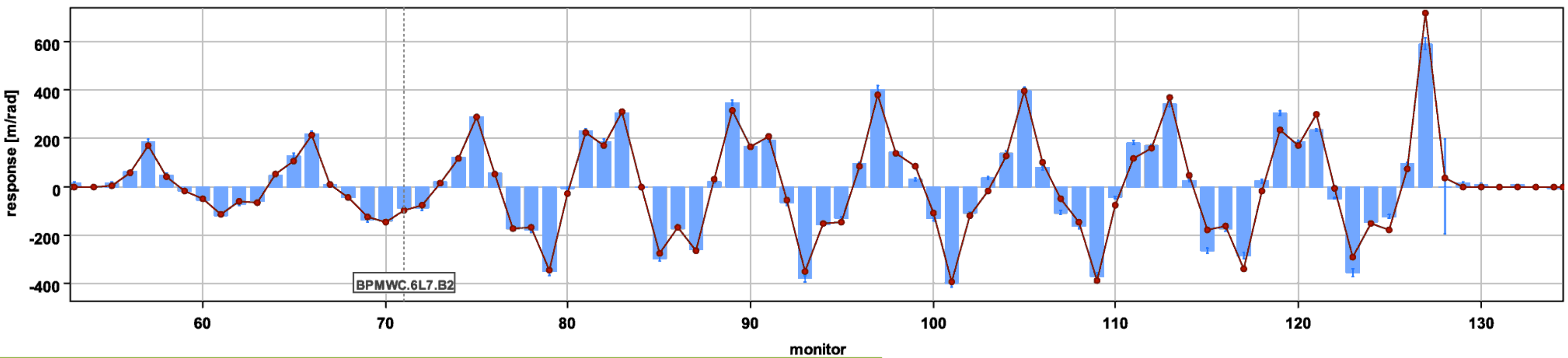
Thank you for your attention!

Additional Material

September 2008, first injection B2 to point 7:

Example: MCBH.14R7.B2





→ Clear result: Inversion of Q6.L7.B2

Influence on response matrix

$$\Delta R_{ij} = A_{ij}\left(\frac{\Delta K}{K} - \frac{\Delta p}{p}\right) + B_{ij}b_2 + C_{ij}b_3\frac{\Delta p}{p}$$

Full Sensitivity matrix

$$S = \begin{pmatrix} \omega_1^{\mathrm{man}}\,\omega_1^{\mathrm{auto}} & \dots & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & \omega_k^{\mathrm{man}}\,\omega_k^{\mathrm{auto}} & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & \dots & \omega_{N_K}^{\mathrm{man}}\,\omega_{N_K}^{\mathrm{auto}} \end{pmatrix} \cdot$$

$$\cdot \begin{pmatrix} \tilde{S}_1^M & \tilde{S}_1^C & S_1^{P_1} & \dots & S_1^{P_{N_P}} \\ \dots & \dots & \dots & \dots & \dots \\ \tilde{S}_k^M & \tilde{S}_k^C & S_k^{P_1} & \dots & S_k^{P_{N_P}} \\ \dots & \dots & \dots & \dots & \dots \\ \tilde{S}_{N_K}^M & \tilde{S}_{N_K}^C & S_{N_K}^{P_1} & \dots & S_{N_K}^{P_{N_P}} \end{pmatrix} \cdot$$

$$\cdot \begin{pmatrix} 1 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & \omega_{P_1}^{\mathrm{auto}} & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & \omega_{P_{N_P}}^{\mathrm{auto}} \end{pmatrix}$$

Column factors

$$S = \begin{pmatrix} \omega_1^{\text{man}}\,\omega_1^{\text{auto}} & \dots & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & \omega_k^{\text{man}}\,\omega_k^{\text{auto}} & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & \dots & \omega_{N_K}^{\text{man}}\,\omega_{N_K}^{\text{auto}} \end{pmatrix} \begin{pmatrix} S_1 \\ \dots \\ S_k \\ \dots \\ S_{N_K} \end{pmatrix}$$

$$\omega_1^{\text{auto}} = 1$$

$$\omega_k^{\text{auto}} = \frac{\|S_1\|_F}{\|S_k\|_F}$$

LOCO principle

$$\left\|\vec{V}\right\| = \sqrt{\sum_k |V_k|^2} \qquad \vec{V} = \vec{K}^{\mathrm{meas}} - \vec{K}^{\mathrm{model}}$$

$$\vec{V} = \vec{K}^{\mathrm{diff}} = \vec{K}^{\mathrm{meas}} - \vec{K}^{\mathrm{model}} \qquad S^{kl} = -\frac{\partial V_k}{\partial c_l}$$

$$S^{kl} = -J_{kl} = -\frac{\partial V_k}{\partial c_l} \qquad S^{kl} = -\frac{\partial V_k}{\partial c_l} = -\left(-\frac{\partial K_k^{\mathrm{model}}}{\partial c_l}\right) = \frac{\partial K_k^{\mathrm{model}}}{\partial c_l}.$$

Kick-Response

$$R_{ij}^{\text{diff}} = \frac{R_{ij}^{\text{meas}} - R_{ij}^{\text{model}}}{\sigma_i} \qquad K_k^{\text{model}} = \frac{R_{ij}^{\text{model}}}{\sigma_i}$$

$$R_{ij}^{\text{model}} = \frac{\sqrt{\beta_i \beta_j}\cos\left(|\mu_i - \mu_j| - \pi Q\right)}{2\sin\left(\pi Q\right)}$$

$$R_{ij}^{\text{model}} = \begin{cases} \sqrt{\beta_i \beta_j}\sin\left(\mu_i - \mu_j\right) & \text{for } \mu_i > \mu_j, \\ 0 & \text{otherwise.} \end{cases}$$

$$V_k = R_{ij}^{\text{diff}}$$

The LOCO principle

Observables $\vec{K} = \begin{pmatrix} K_1 \\ K_2 \\ \ldots \\ K_{N_K} \end{pmatrix}$, Parameters $\vec{c} = \begin{pmatrix} c_1 \\ c_2 \\ \ldots \\ c_{N_f} \end{pmatrix}$

Difference vector $\vec{V}(\vec{c}) = \vec{K}^{\mathrm{meas}} - \vec{K}^{\mathrm{model}}(\vec{c})$

Fit minimizes $\left|\left|\vec{V}\right|\right|^2$ by solving $S\Delta\vec{c} = \vec{V}$

Sensitivity matrix S: $S^{kl} = -\frac{\partial V_k}{\partial c_l} = \frac{\partial K_k^{\mathrm{model}}}{\partial c_l}$

SVD

$$\vec{c}\,' = \vec{c} + \Delta\vec{c}$$

Kick response

Positions $\vec{u} = \begin{pmatrix} u_1 \\ u_2 \\ \dots \\ u_{N_M} \end{pmatrix}$, COD kicks $\vec{\delta} = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \dots \\ \delta_{N_C} \end{pmatrix}$,

$$\vec{u} = R\vec{\delta}$$

Response matrix

$$V_k = \frac{R_{ij}^{\text{meas}} - R_{ij}^{\text{model}}}{\sigma_i}, \quad k = i(N_C - 1) + j$$

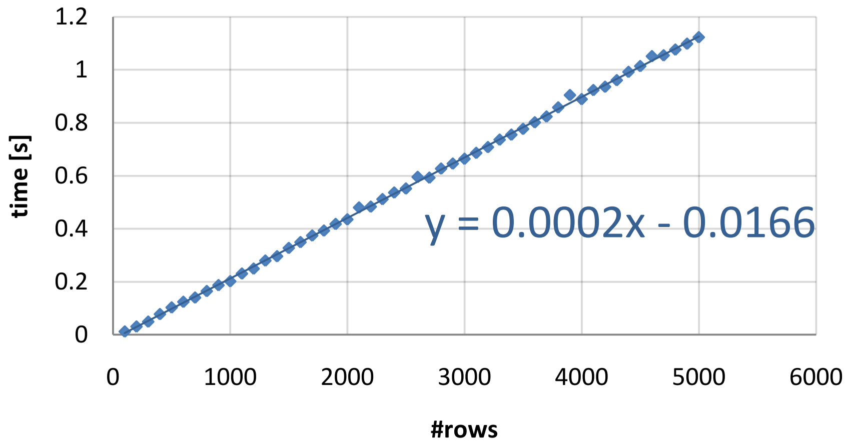
Possible parameters:

- Corrector Gains
- Monitor Gains
- Arbitrary model parameters

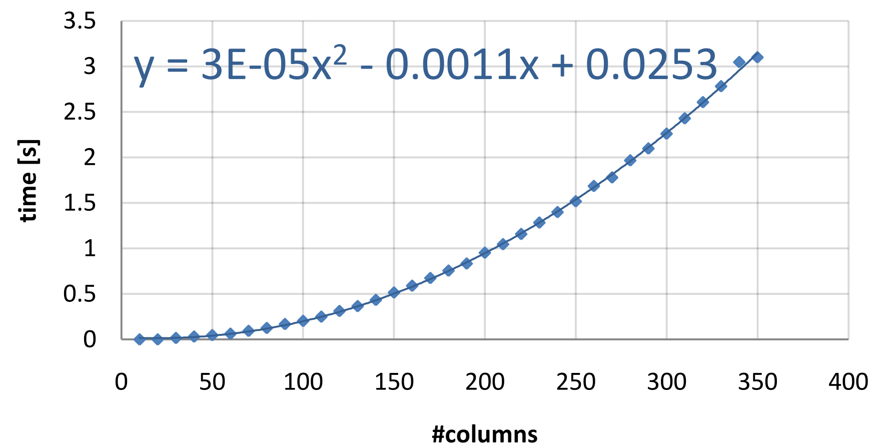
SVD inversion time

Inversion time: $O(MN^2)$ M ... #rows; N ... #cols

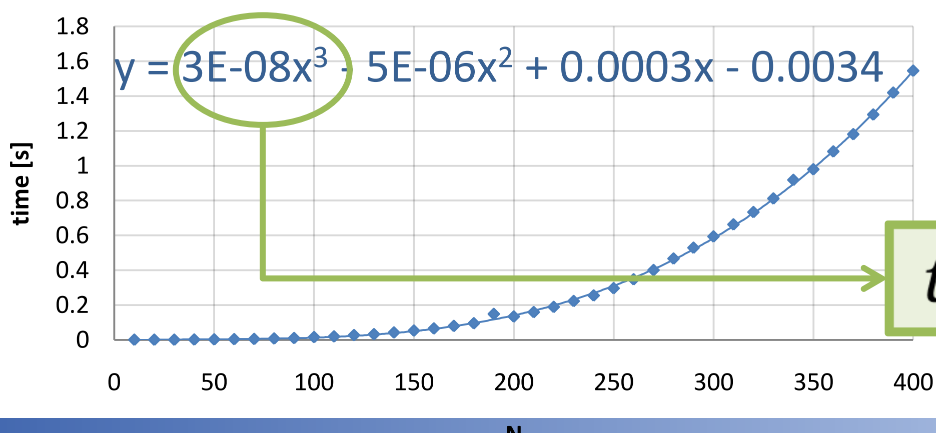
time vs #rows (100 cols)



time vs #cols (1000 rows)



SVD inversion time for NxN matrices



Estimation on Intel Desktop PC (3.17 GHz):

$$t \sim 3 \times 10^{-8} \times M \times N^2 \; [s]$$

Monitor/COD Gain fits II