PAUL SCHERRER INSTITUT

SWISS LIGHT SOURCE

Methods for reaching ultra-low vertical emittance: the SLS experience

Masamitsu Aiba, Michael Böge, Natalia Milas, Andreas Streun, PSI

Low-ε-ring workshop, Iraklion, Oct. 3-5, 2011

1. Vertical emittance

1.1 Quantum limit

- direct photon recoil, $1/\gamma$ radiation cone

T. O. Raubenheimer, *Tolerances to limit the vertical emittance in future storage rings*, SLAC-PUB-4937, Aug.1991

$$\epsilon_y = \frac{13}{55} C_q \frac{\oint \beta_y(s) |G^3(s)| ds}{\oint G^2(s) ds}$$

G(s) =curvature, C_q = 0.384 pm

- independent of energy!
- examples:

SLS	**0.20 pm**
MAX-IV	0.05 pm
PETRA-III	0.04 pm

isomagnetic lattice

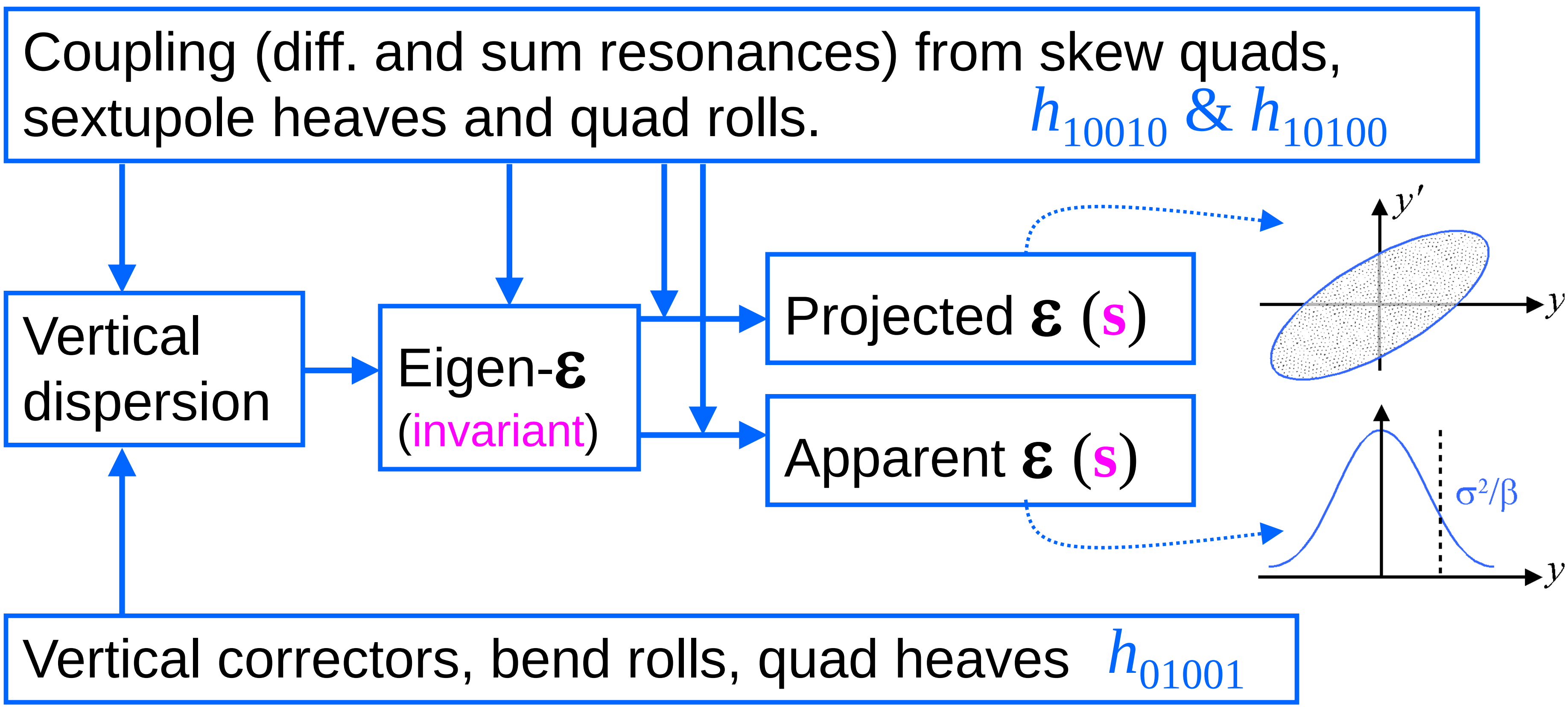
$$\varepsilon_y = 0.09\,\mathrm{pm} \cdot \frac{\langle \beta_y \rangle_{\mathrm{Mag}}}{\rho}$$

⇒ lower limit of vertical emittance

⇒ quantum emittance << coupling

1.2. Vertical emittance with coupling

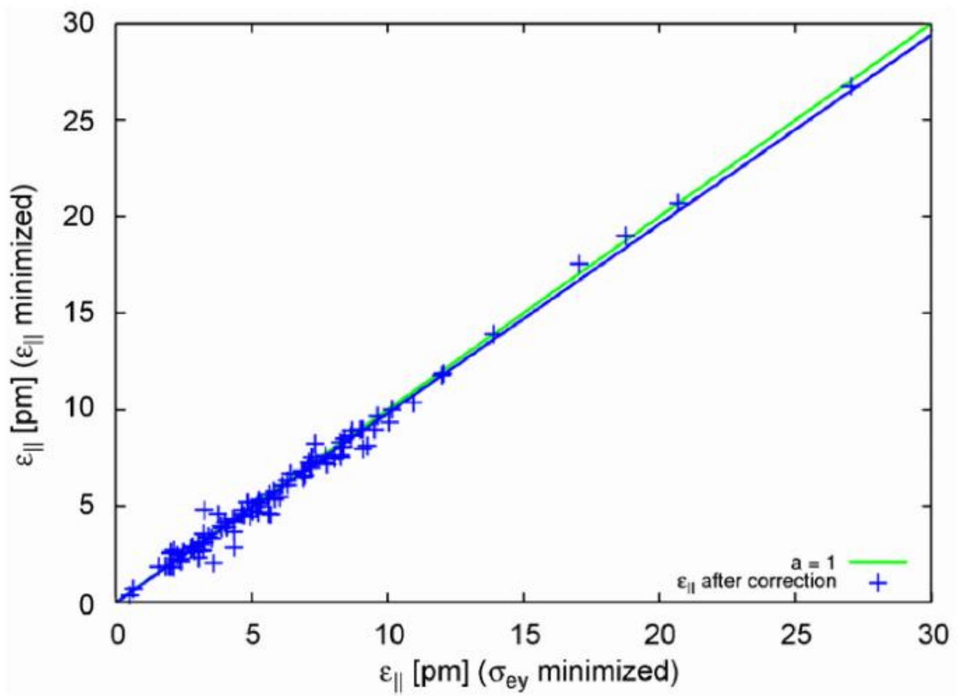
- A. Franchi et al., *Vertical emittance reduction and preservation in electron storage rings via resonance drive terms correction,* PRSTAB 14, 034002 (2011)



Vertical emittance properties

- Apparent-ε oscillates around the lattice.
  - oscillation amplitude is lower for low coupling
- Projected-ε changes at skew quad kicks.
- Eigen-ε is invariant.
- Many monitors average: < App. ε > ≈ Eigen-ε
- Minimization of apparent ε at one location minimizes eigen-ε too:

Simulation (TRACY, 100 seeds, SLS with 6 skew quads):
Eigen-ε results, when optimizing on beam size at monitor (→) vs. optimizing on eigen-ε itself (↑).



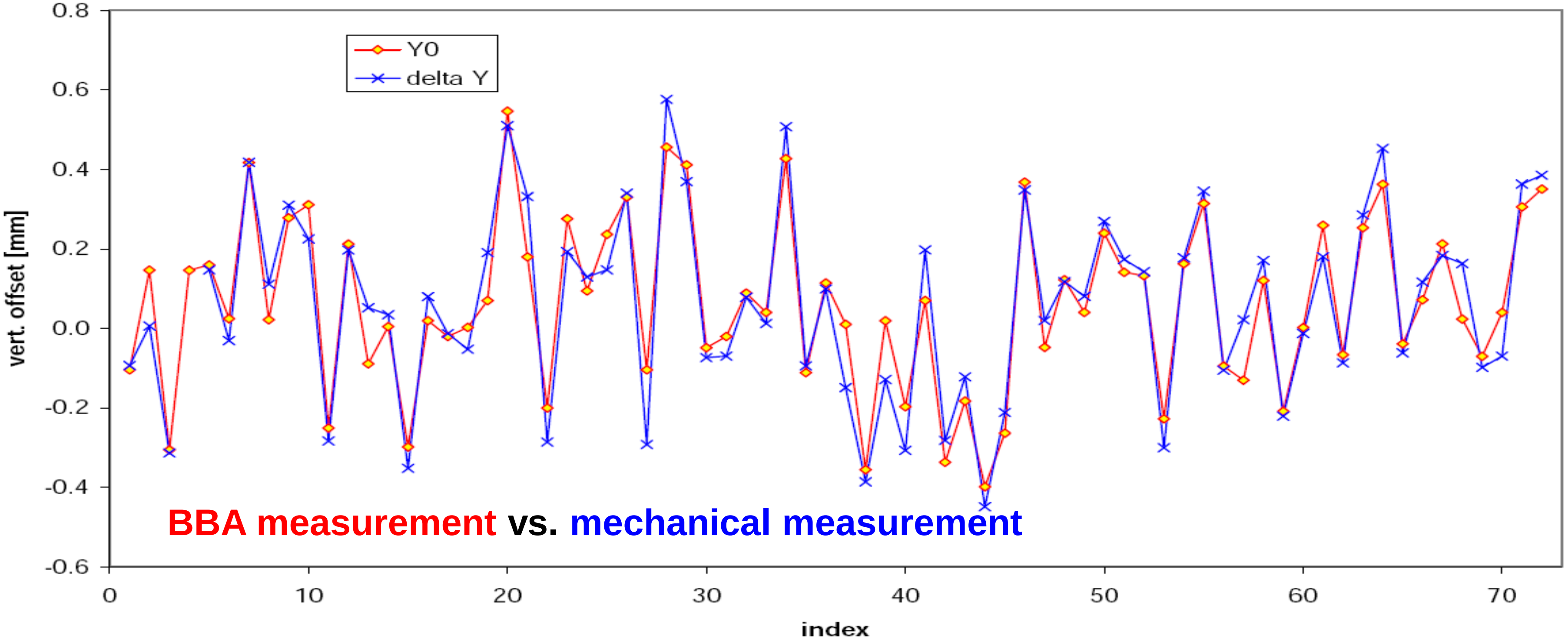
- Å. Andersson et al., NIM A 592 (2008) 437-446

2. Machine preparation

2.1 Orbit correction

Fast orbit feedback (0dB @ 100Hz, 300 nm resolution)

Beam based BPM calibration ("beam based alignment")



2.2 Optics correction

Results on beta beat correction (x / y, RMS)

(Measurement vs. model)

QV (tune shift from quad variation)	4.0% / 3.2%
LOCO (fit to response matrix)	2.0% / 2.0%
TBT (turn by turn data)	1.4% / 3.6%

Required BPM synchronization upgrade and data reconstruction to eliminate turn-to-turn crosstalk.

- M. Aiba, *Comparison of linear optics correction means at the SLS,* Proc. IPAC-2011

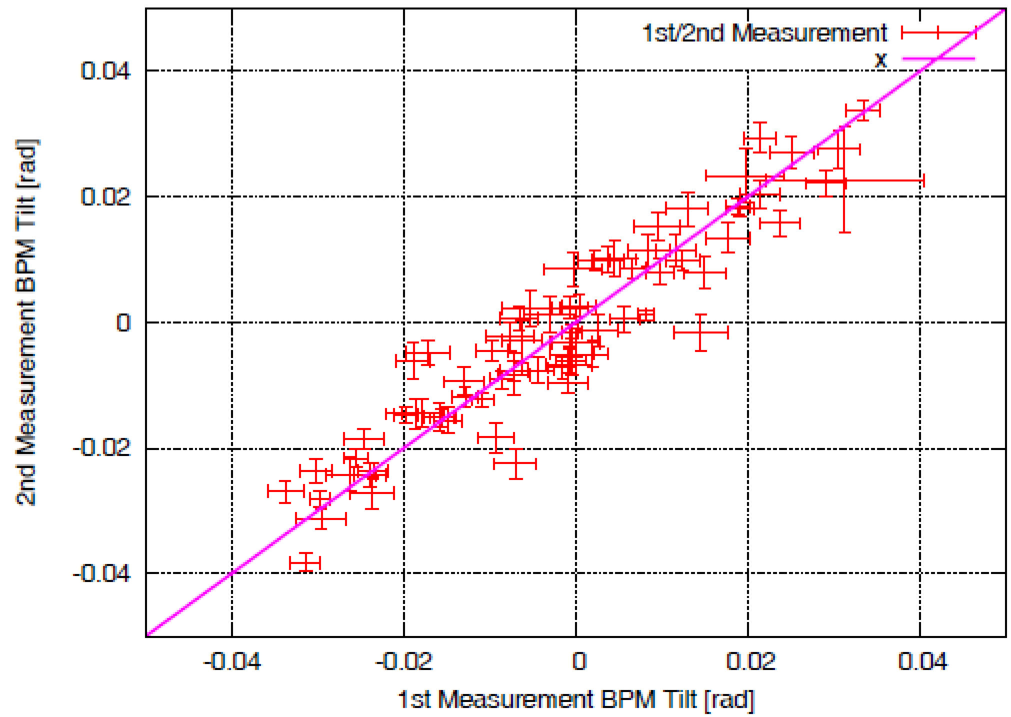
2.3 BPM roll measurements

- Methods:
  - Local bumps ($150\ \mu m$) with fast orbit feedback: get BPM roll from corrector currents.
  - LOCO fit to response matrix.
- Prerequisite: corrector roll << BPM roll ✓
- BPM roll: 17 mrad RMS.
- Origin: electronics.

✘ Spoils measurements of vertical dispersion.

⇒ Low level implementation as “3rd BBA constant”: BPM sway, heave & roll

M. Böge et al., *The Swiss Light Source – a test-bed for damping ring optimization,* Proc. IPAC-2010



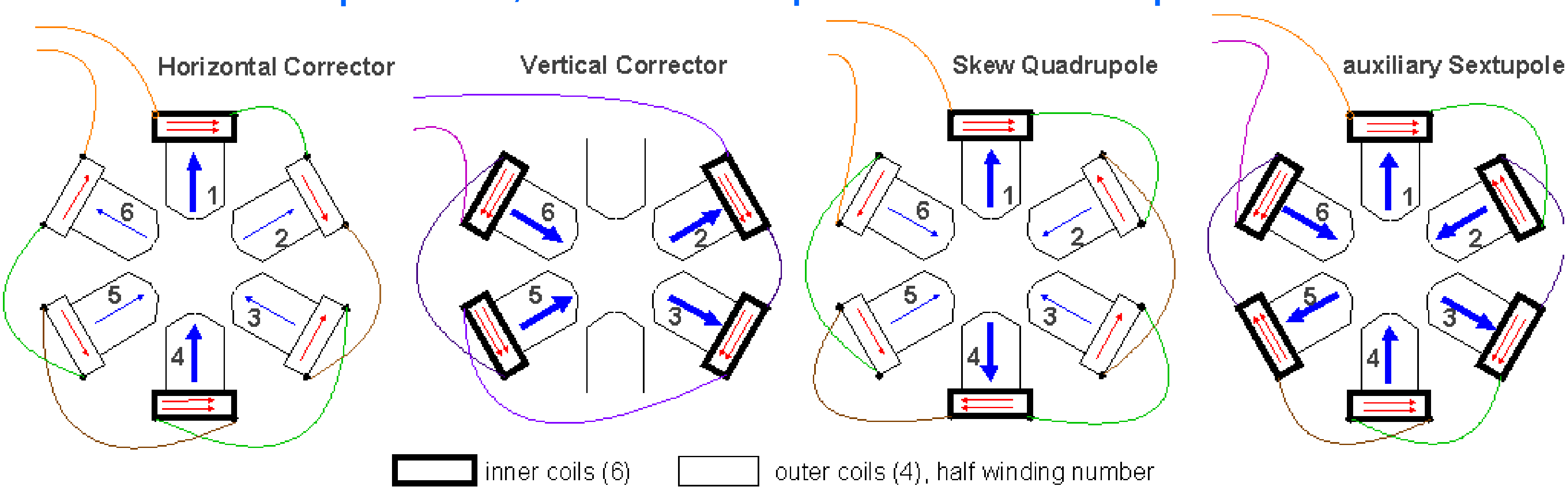
Correlation of two BPM roll measurements

2.4 Knobs for coupling control

- 120 sextupoles (9 families) with additional coils:
  - 72 wired as horizontal/vertical orbit correctors.
  - 12 wired as auxiliary sextupoles for sextupole resonance suppression (empirical).
  - 36 wired as skew quadrupoles:
    12 dispersive, 24 non-dispersive.

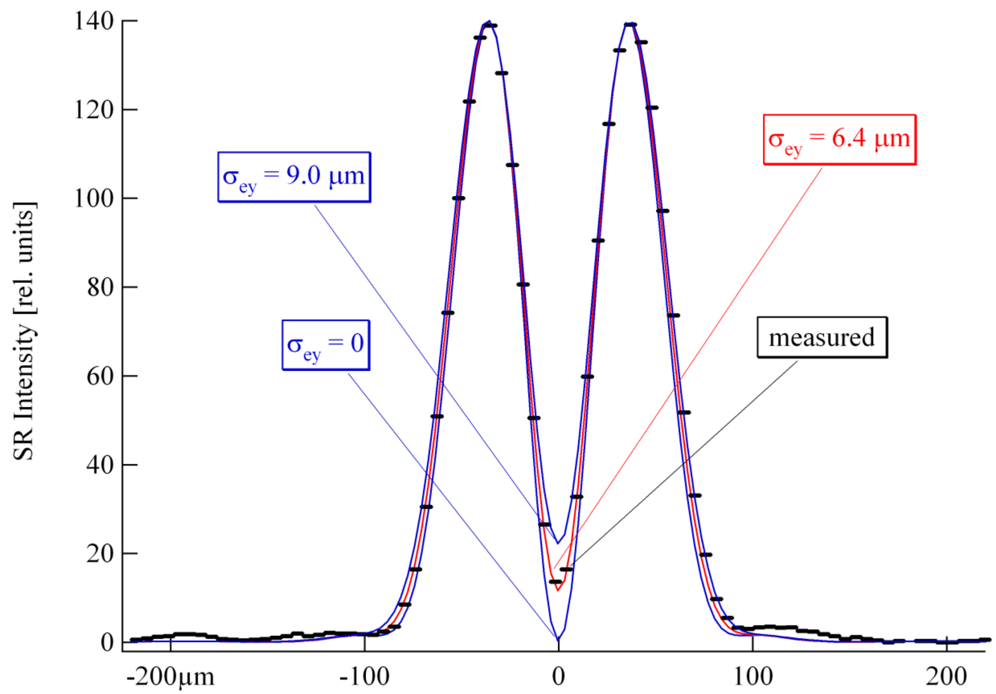
$$a_2 = 2b_3\, y_o$$

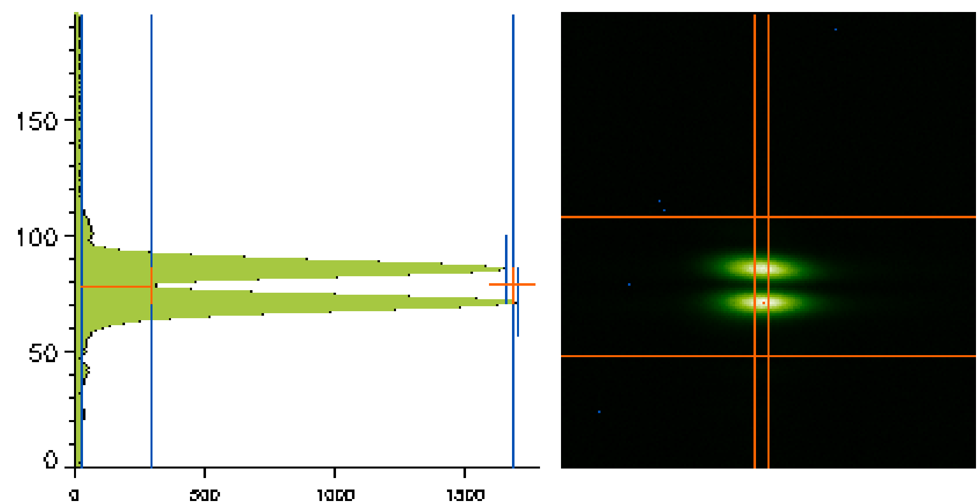
- Skew quads from orbit bumps in 120 sextupoles:
  72 dispersive, 48 non-dispersive "skew quads"



2.5 Emittance (beam size) monitor

- π-polarization method: image of vertically polarized visible-UV synchrotron radiation.
- Get beam height from "valley"- intensity: lookup-table of SRW simulations.
- Resolution:
  Beam height ±0.5 μm
  Emittance ±0.7 pm
  (incl. dispersion subtraction)

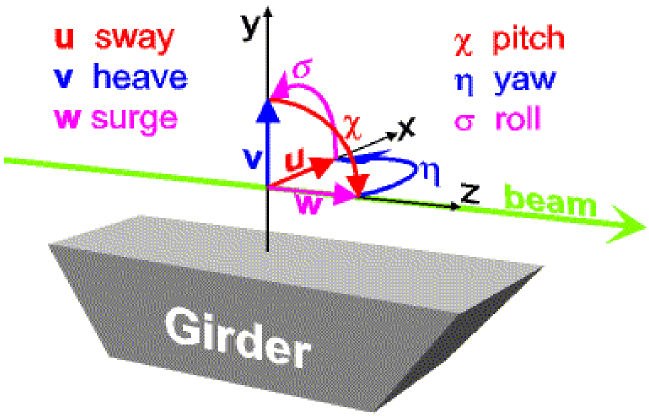




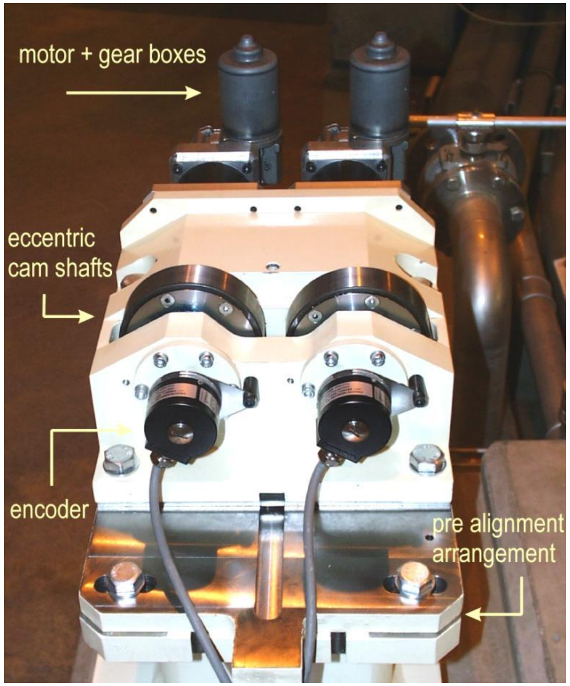
→ *Åke Andersson's talk*

3. Girder realignment

3.1 The SLS dynamic girder alignment system



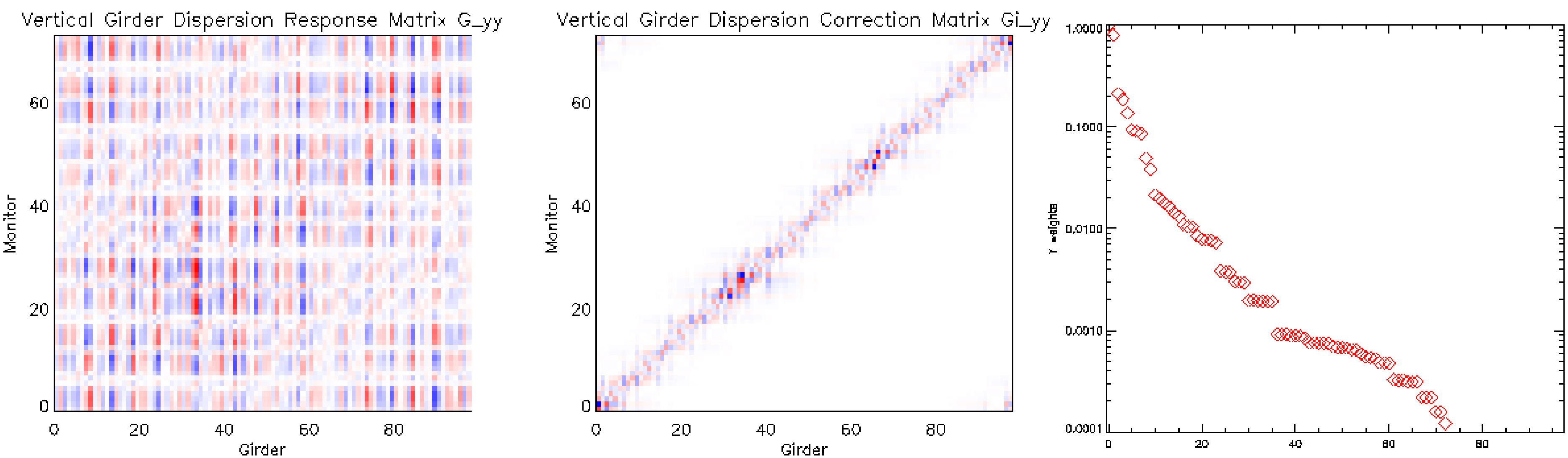
- Remote positioning of the 48 girders in 5 DOF (**u**, **v**, **χ**, **η**, **σ**) by eccentric cam shaft drives.
- 36 dipoles (no gradients) supported by adjacent girders.
  - except 3 super-bends: extra supports
  - except laser slicing insertion FEMTO
- Magnet to girder alignment < **50 μm**
  - girder rail 15 μm, magnet axis 30 μm



S. Zelenika et al., *The SLS storage ring support and alignment systems, NIM A 467 (2001) 99*

3.2 Beam based girder alignment

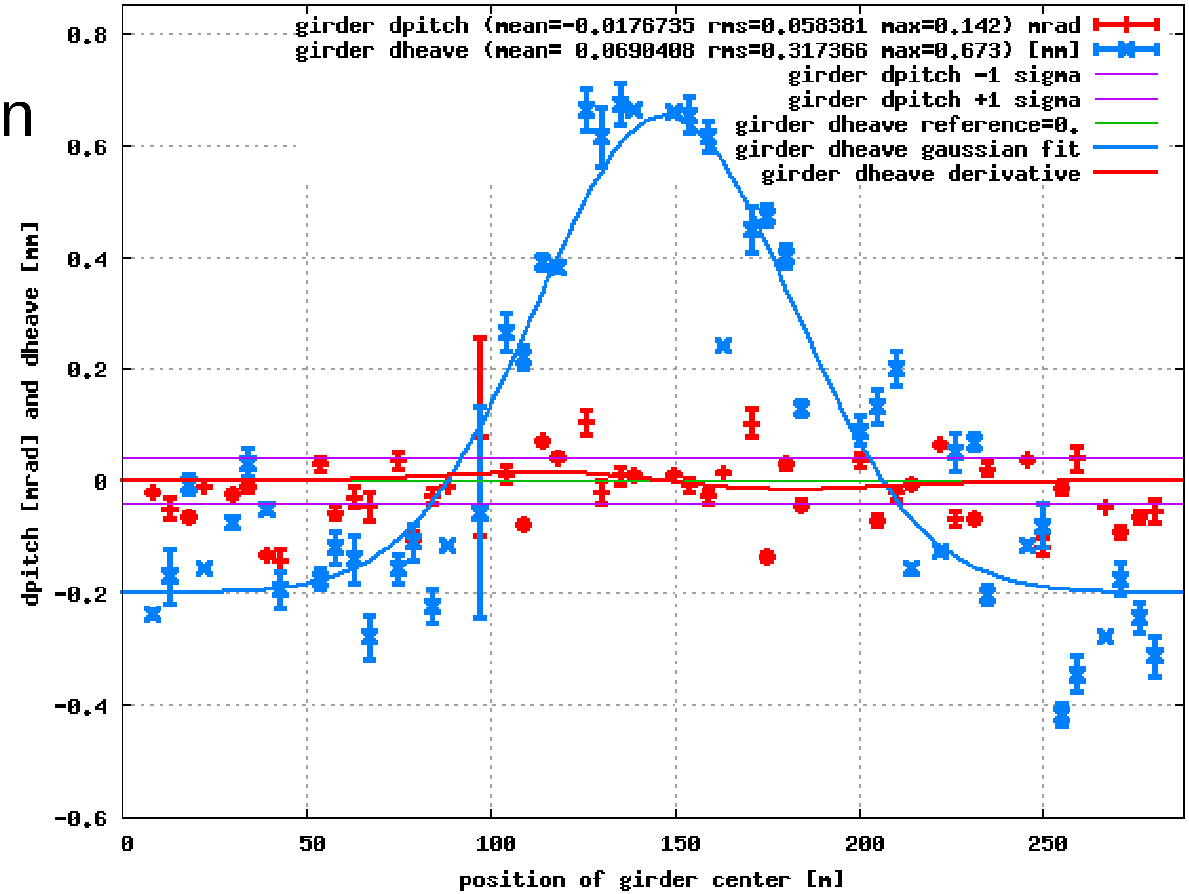
- 48 girders (shift & angle) = 96 “correctors”
- Response & correction matrices for
  - orbit correction (saves 75% CH, 100% CV strength !),
  - or, vertical dispersion suppression.
- ✘ Orbit based remote girder alignment rejected:
  - Mistrust in girder moving procedures.
  - Possible negative impact on user operation.



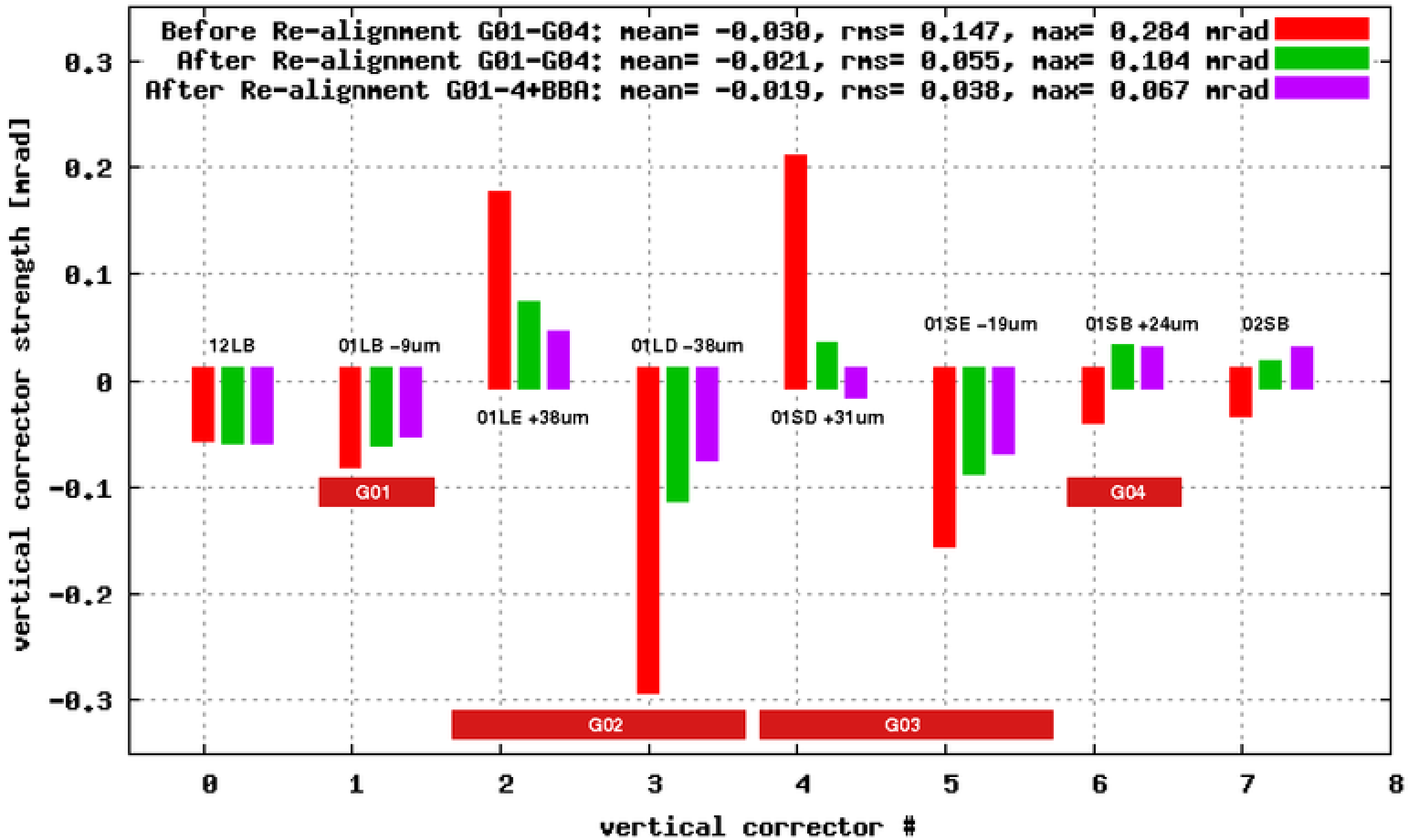
Vertical dispersion girder response and correction matrices and SVD weights

3.3 Survey based girder realignment

- Girder heave and pitch from survey
- Align girders to medium line
  (long wavelength machine deformation is not a problem)
- Fast orbit feedback active
  ↓
  correctors confirm girder move.



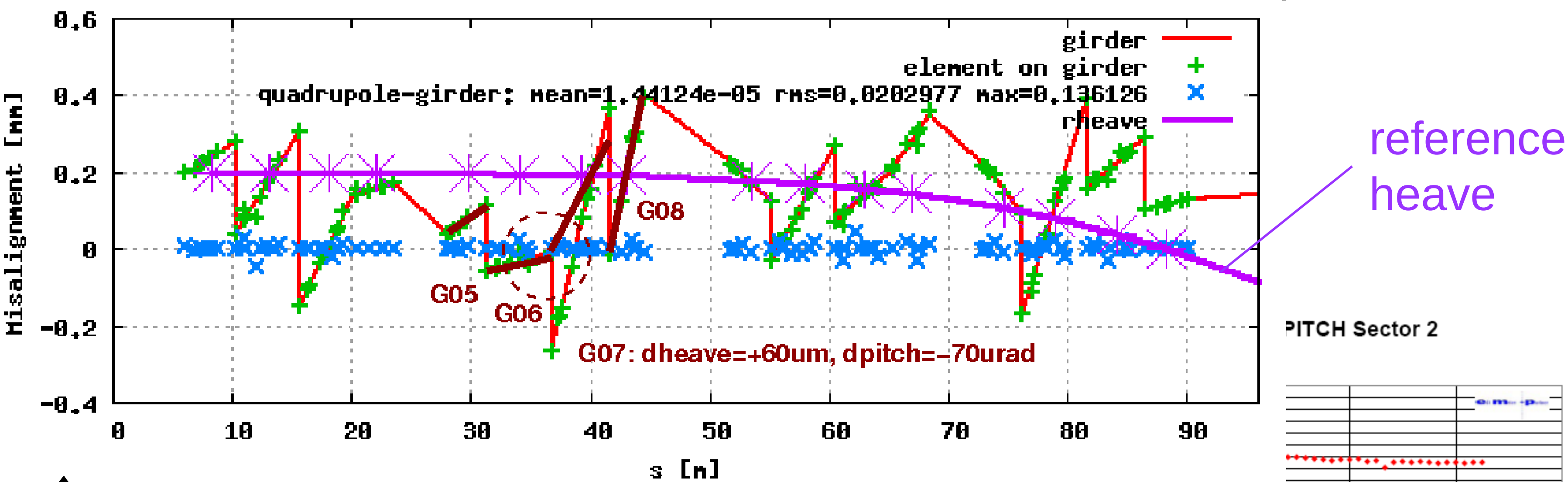
M. Böge et al., *SLS vertical emittance tuning, Proc. IPAC-2011*



Corrector strengths before and after girder realignment, and after beam based BPM calibration* (sector 1)

(*girder move causes vacuum chamber deformation)

⇒ Factor ≈4 reduction of rms CV kick in sector (= 4 girders)

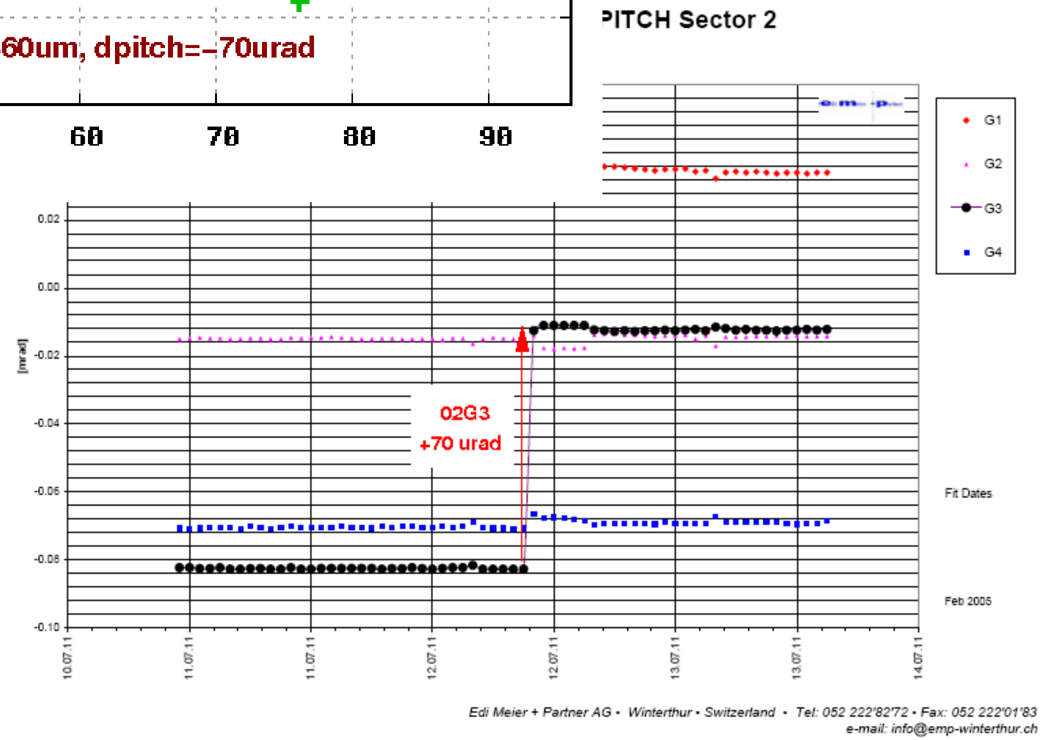


↑ Re-establishment of "train link" between G06 and G07

G07 pitch 70 μm, confirmed by hydrostatic leveling system →

Manual alignment of super-bend between G06/G07

⇒ Improvement for beam line too.



Status (Sep.2011) : done, partially done, malfunction

Sector 1 2 3 4 5 6 7 8 9 10 11 12

Vertical corrector kick (all CV) 140 ⇒ 81 μrad rms

(expect ≈60 μrad rms after repair of sectors 4,9,11)

4. Emittance minimization

4.1 Vertical dispersion measurement

- Vertical orbit as function of energy
- Upgrade of RF oscillator for fast frequency shift
- Prerequisite: determination of BPM roll errors.

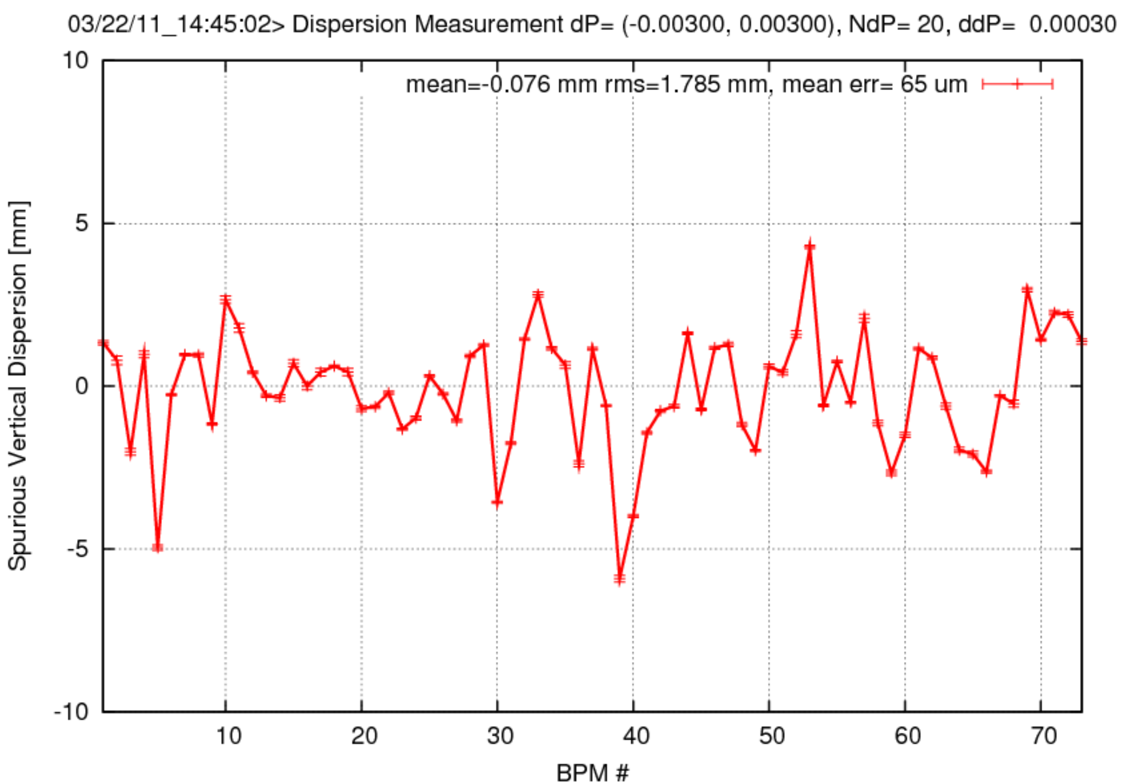
Vertical dispersion measurement

Energy range ± 0.3%
(–Δf = ± 920 Hz)

20 points

10 minutes

65 μm resolution



4.2 Vertical dispersion suppression

- 12 dispersive skew quadrupoles ($D_x \approx 33$ cm)
- 73 BPMs $\Rightarrow$ 73 × 12 dispersion response matrix
- Feed in measured $D_y \Rightarrow$ apply $\Rightarrow$ measure again.
- Best results up to now: $D_y \approx 1$ mm RMS.

$$D_y(s) = \frac{\sqrt{\beta_y(s)}}{2\sin \pi Q_y} \oint_C F(s')\sqrt{\beta_y(s')}\cos\left(\left|\mu(s)-\mu(s')\right| - \pi Q_y\right) ds'$$

$$F(s) = b_2 y_{co} + 2b_3 D_x y_{co} - \boxed{a_2 D_x} + a_1$$

orbit bump in quadrupole

orbit bump in dispersive sextupole

dispersive skew quadrupole

vertical dipole

4.3 Betatron coupling correction

- 24 non-dispersive skew quads.
- from model: coupled response matrix as function of skew quad strength: Jacobian $\{\partial \mathrm{RM} / \partial a_{2k}\}$.
- 73 BPMs and CH/CV: $\Rightarrow$ 146 × 146 × 24 tensor.
- Rearrange: 21316 × 24 matrix $\Rightarrow$ SVD-inversion.
  - Alternative: use only coupled RM-quadrants: 73 × 73 × 24 tensor $\Rightarrow$ 5329 × 24 matrix.
- Feed in measured orbit response matrix.
- Fit 24-vector $\{\Delta a_2\}$ of skew quad strengths.
- Apply inverse to machine: $-\{\Delta a_2\}$.
- Iterate within model for large errors.
- Compensates also betatron coupling increase from previous vertical dispersion suppression.

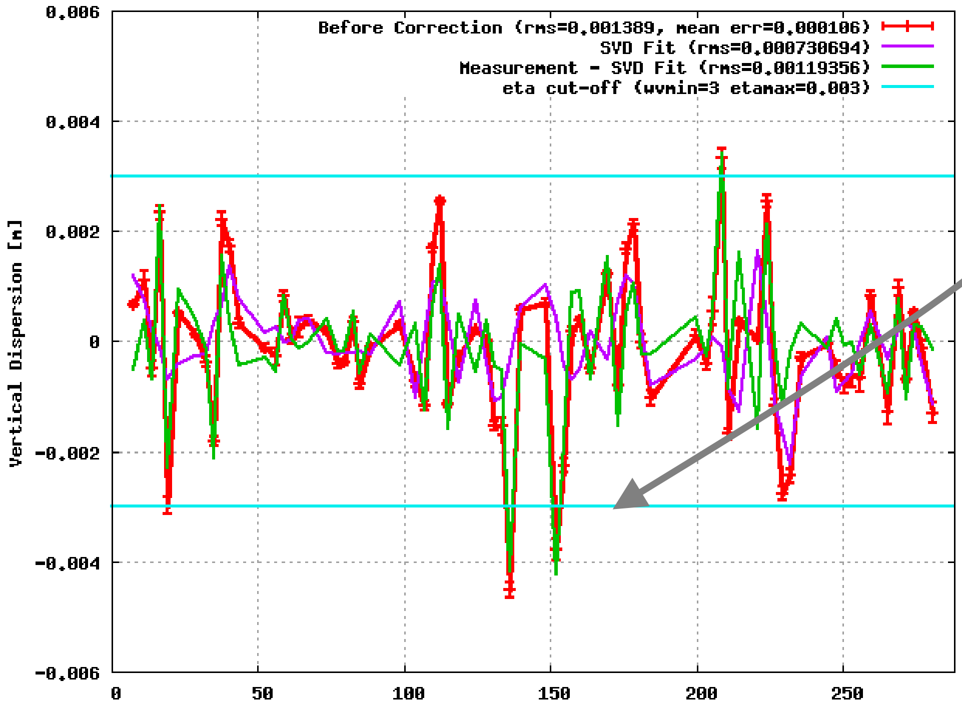
4.4 Orbit manipulation

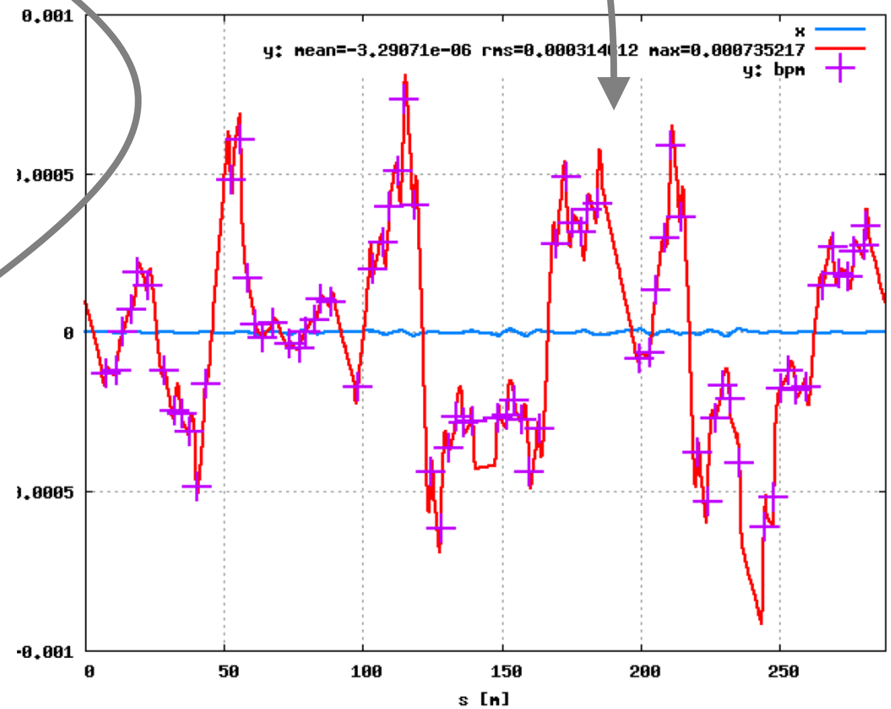
“dispersion free steering”

- Orbit bumps:
  - get skew quads from sextupoles
  - get vertical dipoles from quadrupoles
- Simultaneous suppression of vertical dispersion and betatron coupling.
- Individual corrector method: use all correctors with additional constraints on orbit and optics
  $\rightarrow$ *Simone Liuzzo’s talk*
- 3-bump method: closed orbit bumps for compatibility with user operation.

- S. Liuzzo et al., *Low emittance studies for Super-B, Proc. IPAC-2010*.
- M. Aiba et al., *Coupling and vertical dispersion correction in the SPS, Proc. IPAC-2010*

- Application of the individual corrector method:
- Reduction $D_y = 1.4 \rightarrow 1.1$ mm RMS.
- Orbit 310 μm RMS.
- Dispersion spikes resistant to correction
  ⇒ steps between girders





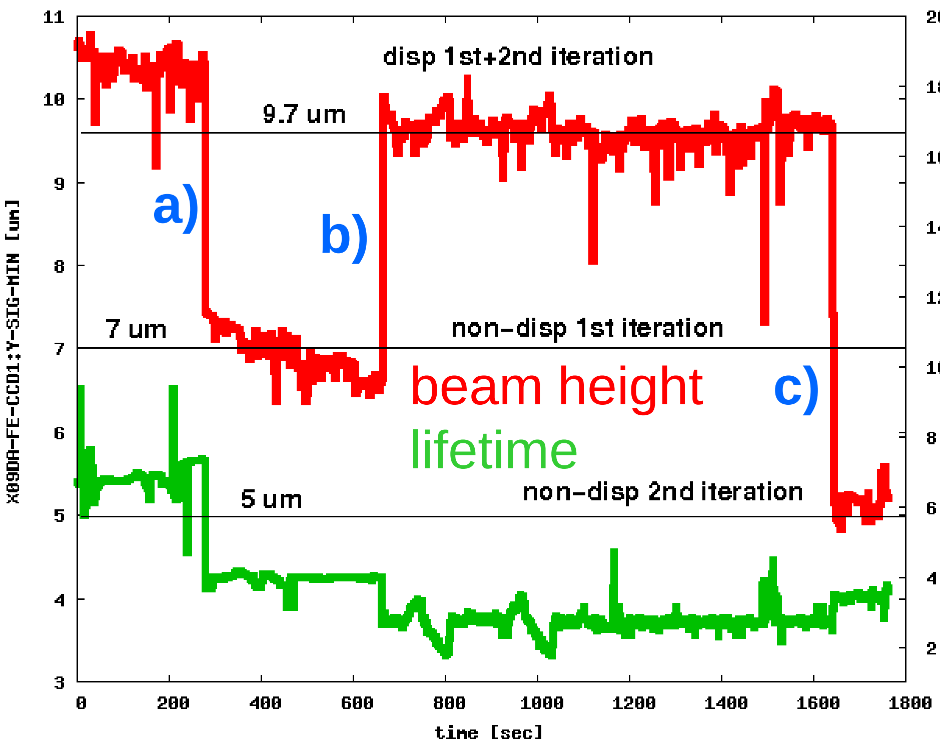
- Recent (Aug. 30) MD-shift (*S. Liuzzo, M. Aiba, M.Böge*):
  ⇒ vertical emittance **3.6 pm** with all skew quads **off**.

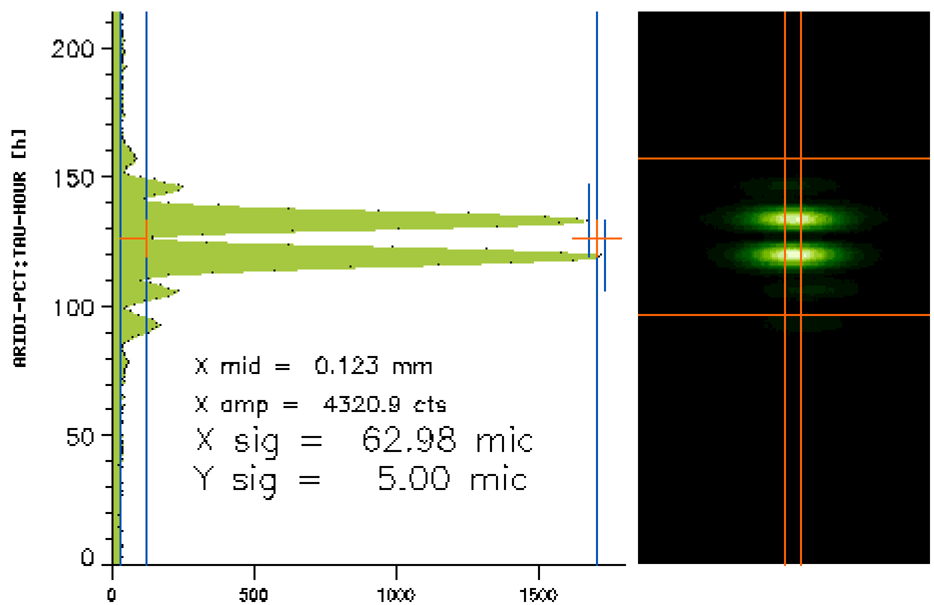
4.5 Emittance achievements

- Best result up to now (March 16, 2011):
  - a) coupling correction
  - b) vertical dispersion suppression $\rightarrow$ 1.4 mm RMS
  - c) 2 iterations of coupling correction
  - ! no orbit manipulations

$\Rightarrow$ Beam height $5 \pm 0.5\ \mu\text{m RMS}$ $\Rightarrow$ $\boldsymbol{\varepsilon_y = 1.9 \pm 0.4\ \text{pm}}$

(dispersion not subtracted)





Conclusion

- The SLS storage ring is well equipped for ultra-low vertical emittance tuning
  - orbit feedback, BPM calibration and optics correction
  - high resolution emittance monitor
  - remote girder alignment system
- Methods have been established to control/suppress vertical dispersion and betatron coupling
  - solving the linear system for 12+24 skew quadrupoles
  - 2 methods of orbit manipulation
- Vertical emittance < 2 pm has been reached
  - only factor 10 × quantum limit

Outlook

- Next steps
  - repair malfunctioning girder movers and realign
  - iterate further dispersion and coupling correction
  - orbit manipulation on top of skew quad correction
- Emittance monitor upgrades
  - operate existing monitor at lower wavelength for higher resolution (Dec. 2011)
  - design, construction and commissioning of a new monitor with even higher resolution * (2012).
- Recruitment of 2 year post-doc* (Oct. 2011)

* partially funded by the European Commission under the FP7-INFRASTRUCTURES-2010-1/INFRA-2010-2.2.11 project TIARA (CNI-PP). Grant agreement no 261905.