USPAS 2012: Grand Rapids, MSU

Linear Lattice Correction: Coupling

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Outline

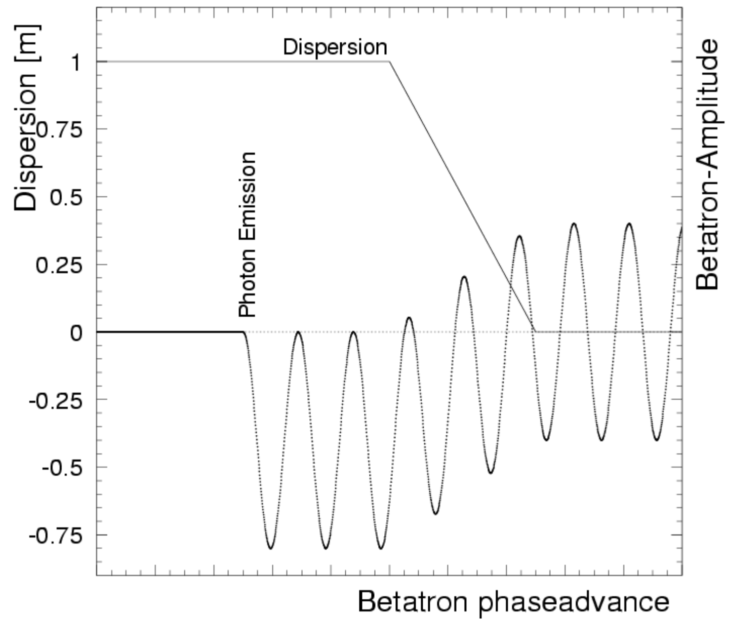
- Introduction/Motivation
- Correction Methods
- Measuring/How to get your model
  - Optimizing the correction algorithm
- Experimental Results
  - Dynamics at very small emittance
- Summary

Motivation: Reducing vertical emittance

- Vertical emittance of ideal, flat accelerator is very small (for ALS of order of 0.5 pm) – correcting coupling errors can help to optimize brightness, luminosity, etc. by substantial amounts
- Simplest errors are tilts of quadrupoles and offsets in sextupoles
- Effects are:
  1. Global coupling
  2. Local coupling
  3. Vertical dispersion
  - To optimize performance, all three effects have to be corrected simultaneously
  - Methods include orbit manipulation, skew quadrupoles, moving of sextupoles, …
  - Most successful strategy at light sources: Do not target the three quantities individually, instead use combined approach

Reminder: Quantum excitation

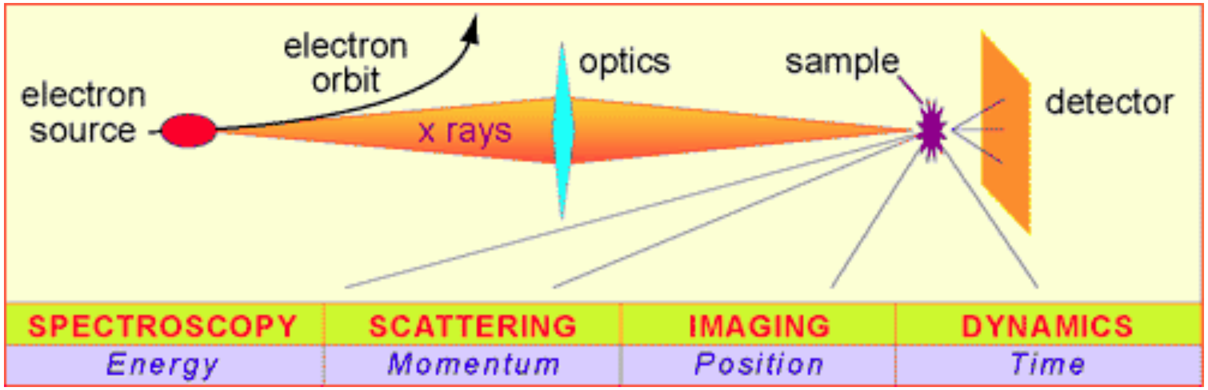
Particles change their energy in a region of dispersion undergoes increase transverse oscillations. This balanced by damping gives the equilibrium emittances.



An ideal, flat accelerator has only horizontal dispersion, i.e. extremely small vertical emittance. In real machine, coupling and spurious vertical dispersion increase vertical emittance.

Experiments requiring small vertical emittance

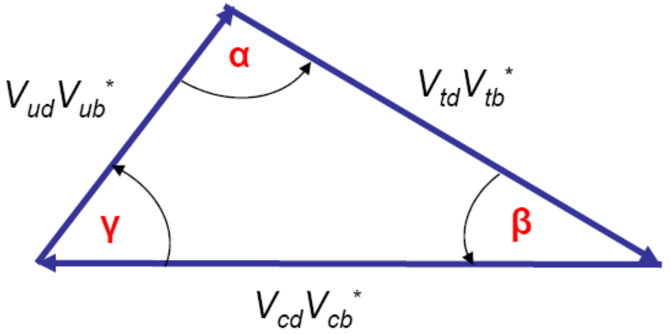
- Synchrotron light sources: High brightness (photon flux/sizes/divergences) enables high resolution experiments and provide partial transverse coherence



- Colliders: Particle physics experiments require high statistics – high luminosity – small vertical beamsize at IP

$$L = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y}$$

$$R = L\sigma_{total}$$



Coupling

Skew quadrupole field errors generate betatron coupling between horizontal and vertical equations of motion.

4x4 transfer matrix for a quadrupole rotated by a small angle φ

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix}_{\text{final}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -k & 1 & -2k\varphi & 0 \\ 0 & 0 & 1 & 0 \\ -2k\varphi & 0 & k & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix}_{\text{initial}}$$

Local/Global Coupling, Vertical Dispersion

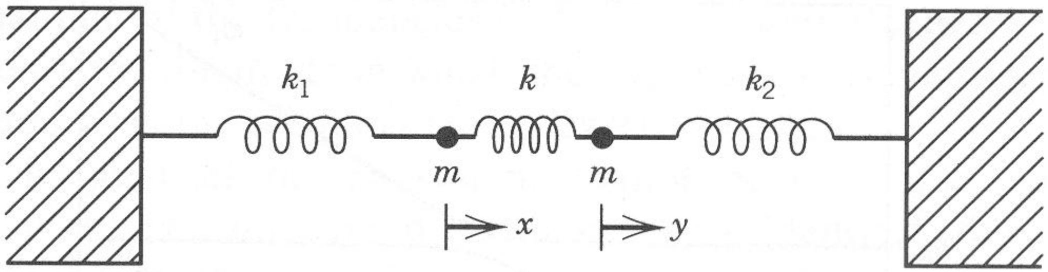
- Coupled (Hills) equations of motion :

$$x'' - Kx = -K_s y \qquad y'' + Ky = -K_s x$$

- With

$$K = \frac{1}{B\rho}\frac{\partial B_y}{\partial x} \qquad K_s = \frac{1}{B\rho}\frac{\partial B_x}{\partial x}$$

- Analogy with mechanical coupled harmonic oscillators (with springs)



$$m\ddot{x} + (k_1 + k)x - ky = 0,$$

$$m\ddot{y} + (k_2 + k)y - kx = 0,$$

Resonance Description of Global Coupling

- Global coupling is typically described using a resonance theory
- Difference coupling resonance

$$\kappa = \frac{1}{4\pi}\int ds\, K_s \sqrt{\beta_x \beta_y}\, e^{i\phi_D}$$

$$\frac{\phi_D}{2\pi} = \mu_x(s) - \mu_y(s) - \frac{s}{C}\Delta_r \qquad \Delta_r = (\nu_x - \nu_y - N)$$

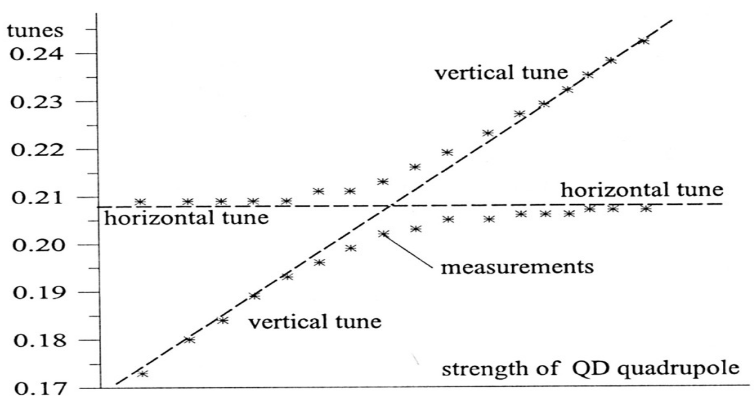
  – Vertical emittance near difference resonance:

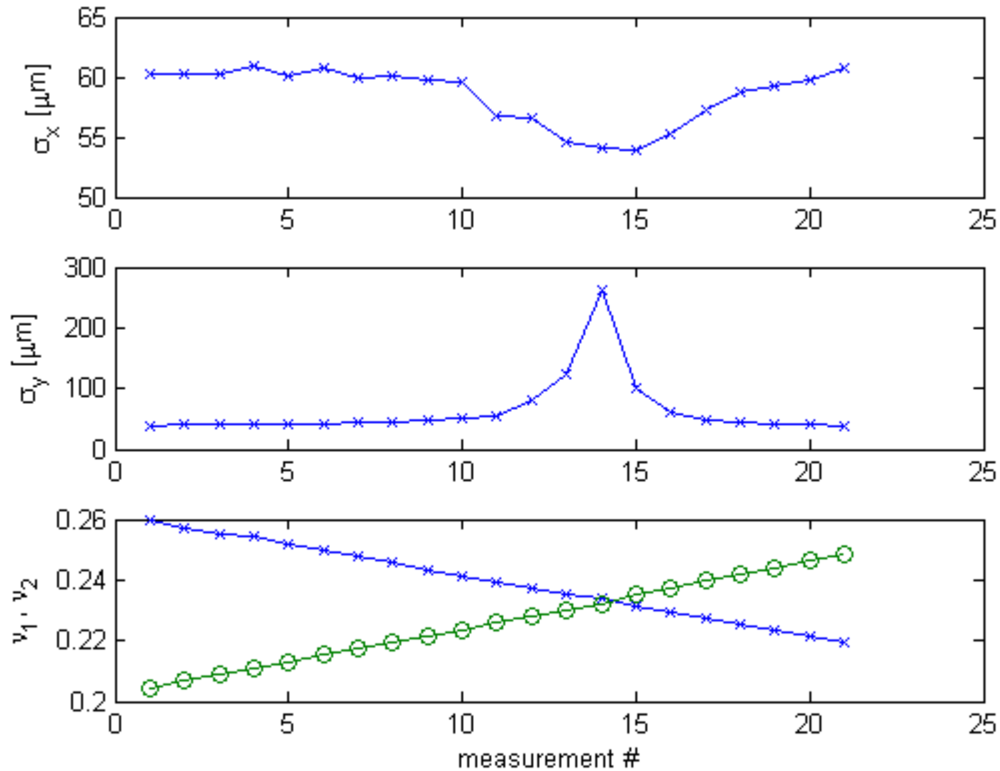
$$\frac{\varepsilon_y}{\varepsilon_x} = \frac{|\kappa|^2}{|\kappa|^2 + \Delta_r^2/2}$$

κ is resonance strength, Δ_r is distance from resonance.

Scan of difference resonance

- ❖ There are sum resonances as well (phase advance proportional to sum of horizontal and vertical phase advance) and of course higher order resonances.
- ❖ One can create orthogonal knobs of skew quadrupoles directly acting on one of those coupling resonances





- ❖ Minimum tune split (on resonance):

$$(\nu_x - \nu_y)_{\min} = 2\,|\,\kappa\,|$$

Normal mode Analysis: C matrix

- On Monday, we only discussed the uncoupled case (and mostly looked at 2x2 matrices). If there are coupling errors, one can do a so-called normal mode analysis (diagonalizing matrix)
- Start with 4x4, one-turn matrix $R_{one\text{-}turn}$, which maps the 4 transverse coordinates **x**=(x,x',y,y'). Normal mode form:

$$\mathbf{R}_{one-turn} = \mathbf{V}\mathbf{U}\mathbf{V}^{-1}, \text{normal mode matrix } \mathbf{U} = \begin{pmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{pmatrix},$$

$$\text{with } \mathbf{A} = \begin{pmatrix} \cos\phi_a + \alpha_a \sin\phi_a & \beta_a \sin\phi_a \\ -\gamma_a \sin\phi_a & \cos\phi_a - \alpha_a \sin\phi_a \end{pmatrix},$$

$\mathbf{V}$ is of the form (Edwards + Teng)

$$\mathbf{V} = \begin{pmatrix} \gamma\mathbf{I} & \mathbf{C} \\ -\mathbf{C}^{+} & \gamma\mathbf{I} \end{pmatrix},$$

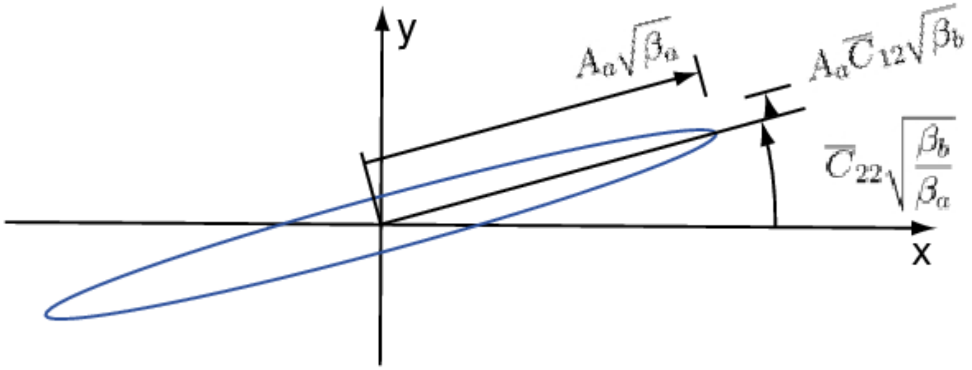
with $\gamma^2 + \left\|\overline{\mathbf{C}}\right\| = 1$. The magnitude of C is a measure of local coupling.

Local Coupling

Often the normalized matrix $\overline{\mathbf{C}}$ is used:

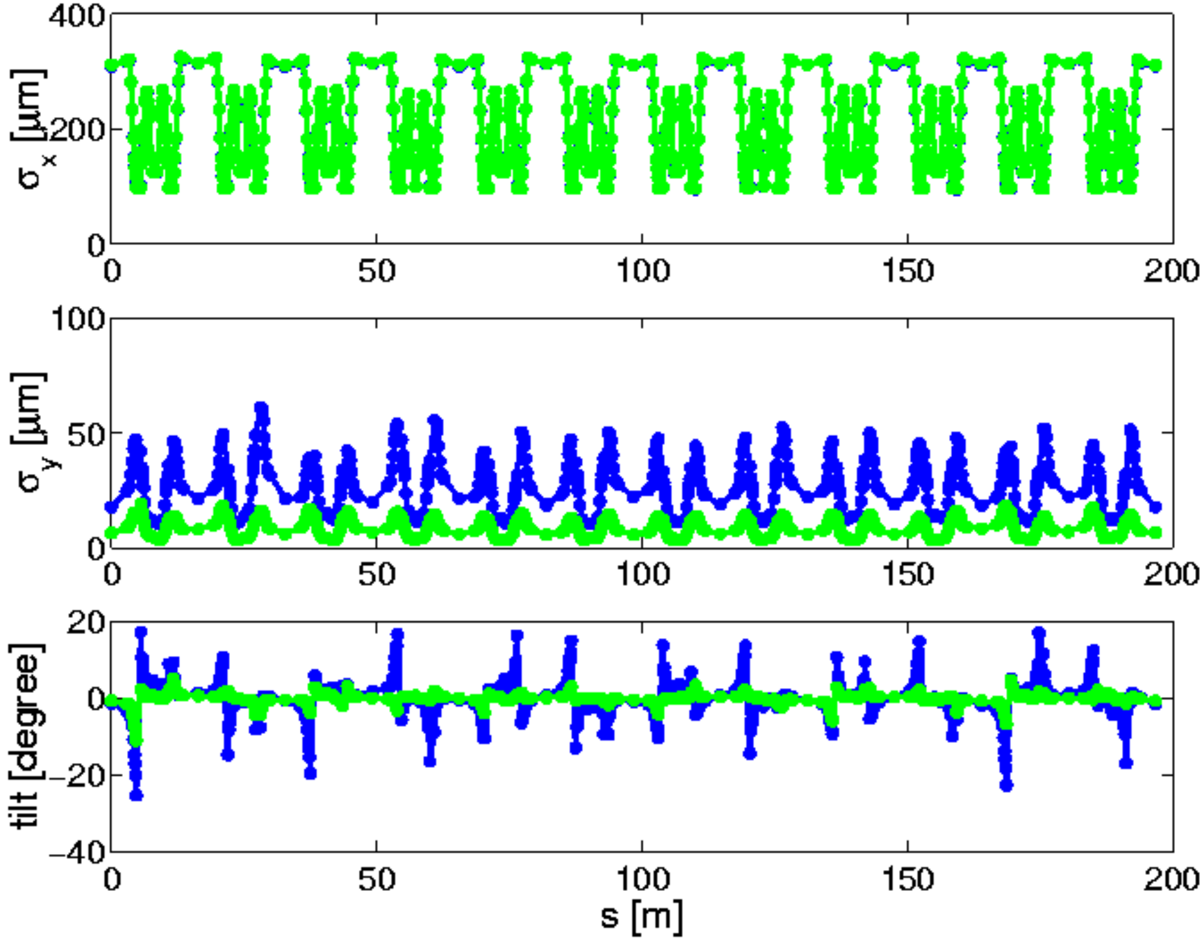
$$\overline{\mathbf{C}} \equiv \mathbf{G}_a \mathbf{C} \mathbf{G}_b^{-1}, \text{where } \mathbf{G}_a = \begin{pmatrix} \frac{1}{\sqrt{\beta_a}} & 0 \\ \frac{\alpha_a}{\sqrt{\beta_a}} & \sqrt{\beta_a} \end{pmatrix}.$$

- Locally there is torsion in addition to the global invariant vertical emittance, resulting in a larger projected emittance:



- Again driving terms scale like the sqrt of the product of the beta functions at the location of the skew errors.

Example: Local Coupling / Tilt Angle



- Even for very well corrected global coupling, local coupling can still be significant (as shown here by local tilt angles).
- Projected emittance can change significantly around ring.

Vertical Dispersion

- There are two main terms that can create vertical dispersion:

$$\eta_y'' + K\eta_y = \frac{1}{\rho_y} - K_s \eta_x$$

  – Dipole errors (steering magnets, misalignments, …) or intentional vertical bending magnets
  – Skew quadrupole fields at the location of horizontal dispersion (due to quadrupole tilts, or vertical offsets in sextupoles)

$$\kappa_{\eta_y} = \int ds\, K_s \eta_x \sqrt{\beta_y}\, e^{i\phi_{\eta_y}}$$

$$\frac{\phi_{\eta_y}}{2\pi} = \mu_y(s) - \frac{s}{C}(\nu_y - 5)$$

- Vertical dispersion directly causes increase of the vertical emittance by quantum excitation (compare my talk on Monday)

Correction Techniques

- One can correct the three coupling effects using skew quadrupoles, vertical offsets (movers or orbit bumps) in sextupoles, steering magnets, …
- The corrections can either target global quantities, local quantities at individual points of the ring, or local quantities everywhere.
  – Coupling correction scales like sqrt of product of beta functions times skew strength.
  – Dispersion correction scales like product of horizontal dispersion times sqrt of vertical beta function time skew quadrupole strength
  – Dispersion' from steering magnets scales like the bending angle.
- Phase advance of coupling (dominant $\mu_x - \mu_y$) and dispersion (μ_y) are different!

Resonance correction of the sum and difference resonance (global)

To correct coupling, tweak orthogonal harmonic knobs for both difference resonance phases. Minimize tune split.

Sum resonance also generates linear coupling.

$$\kappa_{sum} = \frac{1}{4\pi}\int ds\, K_s \sqrt{\beta_x \beta_y}\, e^{i\phi_S}$$

$$\frac{\phi_S}{2\pi} = \mu_x(s) + \mu_y(s) - \frac{s}{C}\Delta_r \qquad \Delta_r = (\nu_x + \nu_y - N)$$

Coupling correction – minimize measured vertical beam size as a function of skew quad strengths:

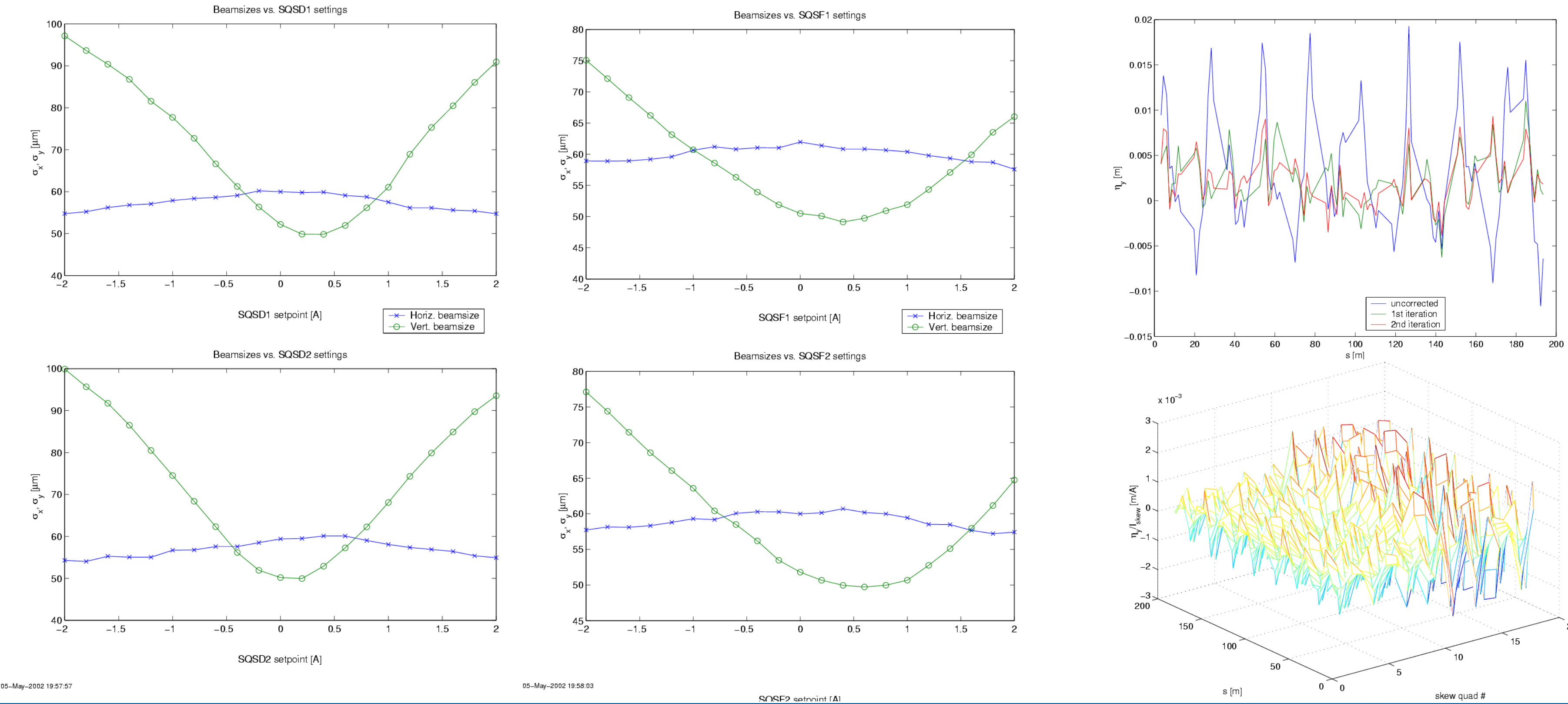
$$\sigma_{y,meas}(K_{s,1}, K_{s,2}, \ldots)$$

One possible method is to use orthogonal harmonic knobs:

$$\sigma_{y,meas}(\kappa_{diff,\cos_N}, \kappa_{diff,\sin_N}, \kappa_{sum,\cos_N}, \kappa_{sum,\sin_N}, \kappa_{\eta_y,\cos_N}, \kappa_{\eta_y,\sin}\ldots)$$

Unsuccessful Correction Attempts … in ALS

- In the past, tried three different approaches:
  1. Coupling correction using chains of skew quadrupoles (single resonance)
  2. Dispersion correction using orbit correctors (TBA, chromaticity)
  3. Dispersion correction using skew quadrupoles without watching the coupling simultaneously



Separated approaches …

- In case you are dealing with a FODO lattice, or you do not have synchrotron radiation users and therefore can use your orbit as a free variable, the separated approach of coupling correction can actually work well (i.e. in colliders).
- FODO lattice is very simple and allows relatively dispersion correction via orbit correction/bumps. In addition/somewhat independently one can often minimize the global coupling with only four orthogonal skew (families). The local coupling is in most colliders only relevant at the interaction point and can be compensated there with few skew quadrupoles.

- In next part of lecture will focus on one very integrated approach (targeting local and global coupling, as well as vertical dispersion simultaneously) – method has proven extremely powerful at light sources.

Skew quadrupole corrector distribution

- Distribute in difference coupling resonance phase

$$\kappa = \frac{1}{4}\pi\int ds K_s \sqrt{\beta_x \beta_y} e^{i\Phi_D} \qquad \frac{\Phi_D(s)}{2\pi} = (\mu_x(s) - \mu_y(s)) - \frac{s}{C}(\nu_x - \nu_y - N)$$

- In sum coupling resonance phase

$$\frac{1}{4}\pi\int ds K_s \sqrt{\beta_x \beta_y} e^{i\Phi_S} \qquad \frac{\Phi_S(s)}{2\pi} = (\mu_x(s) + \mu_y(s)) - \frac{s}{C}(\nu_x + \nu_y - M)$$

- And in η_y phase

$$\eta_x \sqrt{\beta_y} e^{i\Phi_{\eta_y}} \qquad \frac{\Phi_{\eta_y}(s)}{2\pi} = \mu_y(s) - \frac{s}{C}(\nu_y - N)$$

  - Need some skew quadrupoles at non-zero η_x

Simulation of coupling correction

- Use accelerator toolbox (Andrei Terebilo), Matlab and LOCO (James Safranek, Greg Portman) for simulations
- Use random skew error seeds
- Try to find effective skew corrector distributions and to optimize correction technique in simulation
- Used two correction approaches:
  1. Response Matrix fitting – 'deterministic', small number of iterations
  2. Direct minimization (nelder-simplex, …) – easy to do on the model, difficult on real machine

– Surprisingly both approaches gave about the same performance in the model calculations

– For response matrix analysis you have to optimize several parameters of the code as well (weight of dispersion, number of SVs, use of effective model/full model …)

Orbit Response Matrix Analysis: Method

The orbit response matrix is defined as

$$\begin{bmatrix} \vec{x} \\ \vec{y} \end{bmatrix} = M \begin{bmatrix} \vec{\theta}_x \\ \vec{\theta}_y \end{bmatrix}$$

The parameters in a computer model of a storage ring are varied to minimize the χ^2 deviation between the model and measured orbit response matrices (M_{mod} and M_{meas}).

$$\chi^2 = \sum_{i,j} \frac{(M_{ij}^{\mathrm{meas}} - M_{ij}^{\mathrm{model}})^2}{\sigma_i^2} \equiv \sum_{k=i,j} E_k^2$$

The σ_i are the measured noise levels for the BPMs; E is the error vector.

The χ^2 minimization is achieved by iteratively solving the linear equation

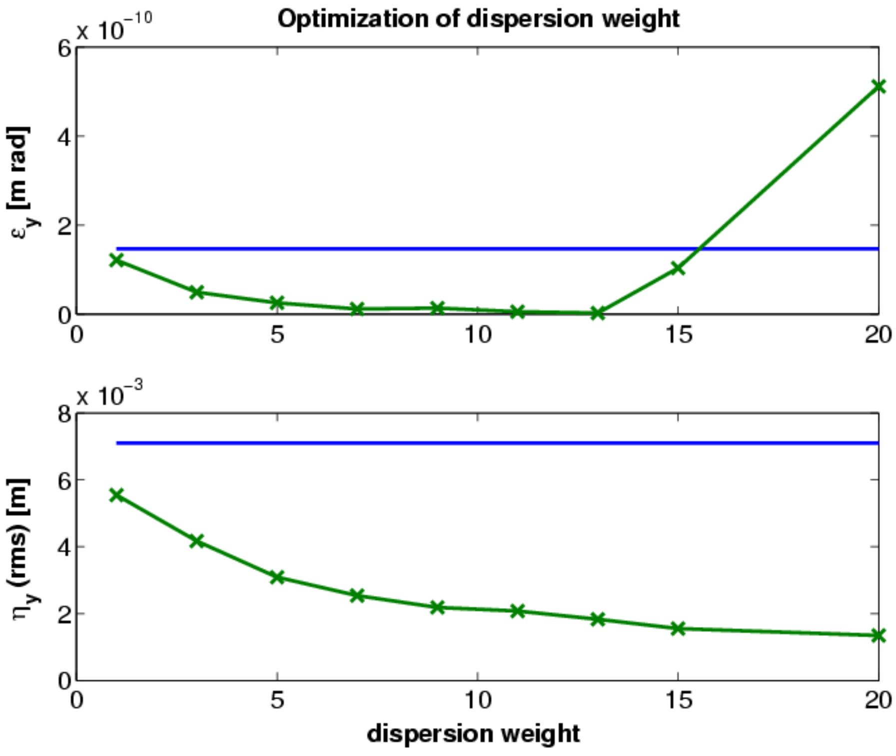
$$E_k^{new} = E_k + \frac{\partial E_k}{\partial K_l} \Delta K_l = 0$$

$$-E_k = \frac{\partial E_k}{\partial K_l} \Delta K_l$$

For the changes in the model parameters, K_l, that minimize $||E||^2=\chi^2$.

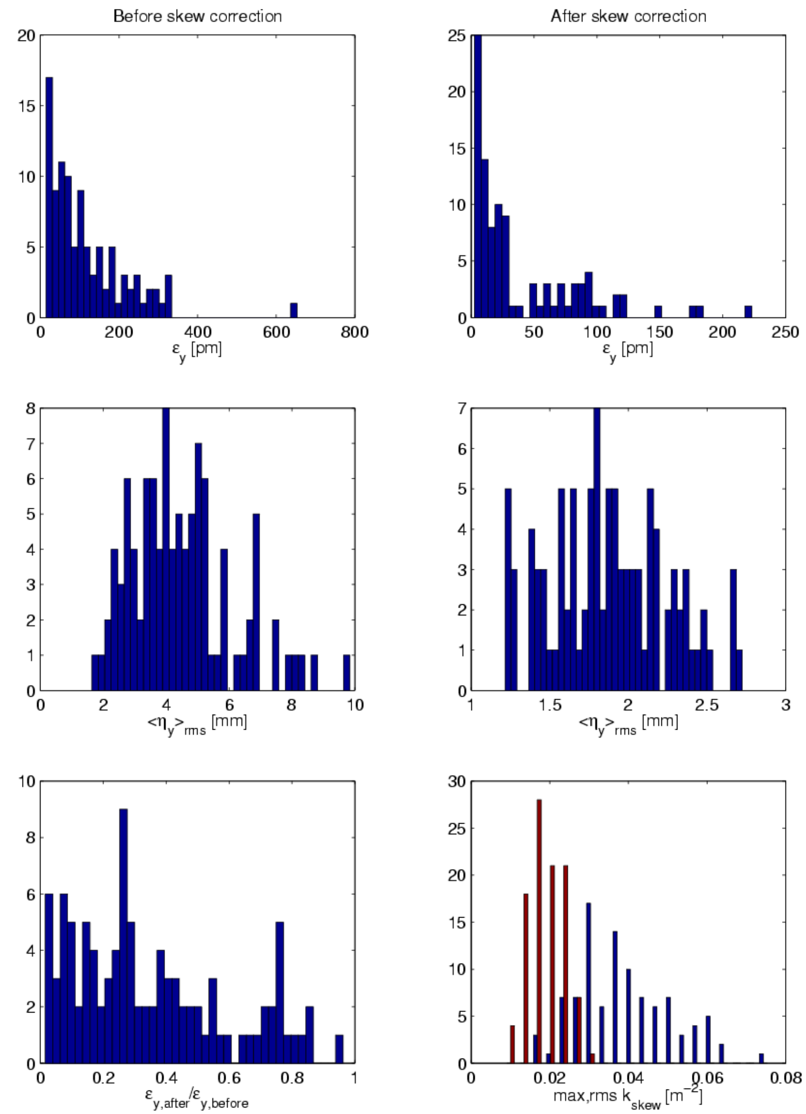
Weight of dispersion in LOCO fit

- The relative contribution of vertical dispersion and coupling to the vertical emittance depends on the particular lattice (and the particular error distribution).
- Therefore the optimum weight for the dispersion in the LOCO fit has to be determined (experimentally or in smulations).
- The larger the weight factor, the better the vertical dispersion gets corrected, but eventually the coupling ‘explodes’.
- Set weight to optimum somewhat below that point.
- Outlier rejection tolerance might be important parameter as well.

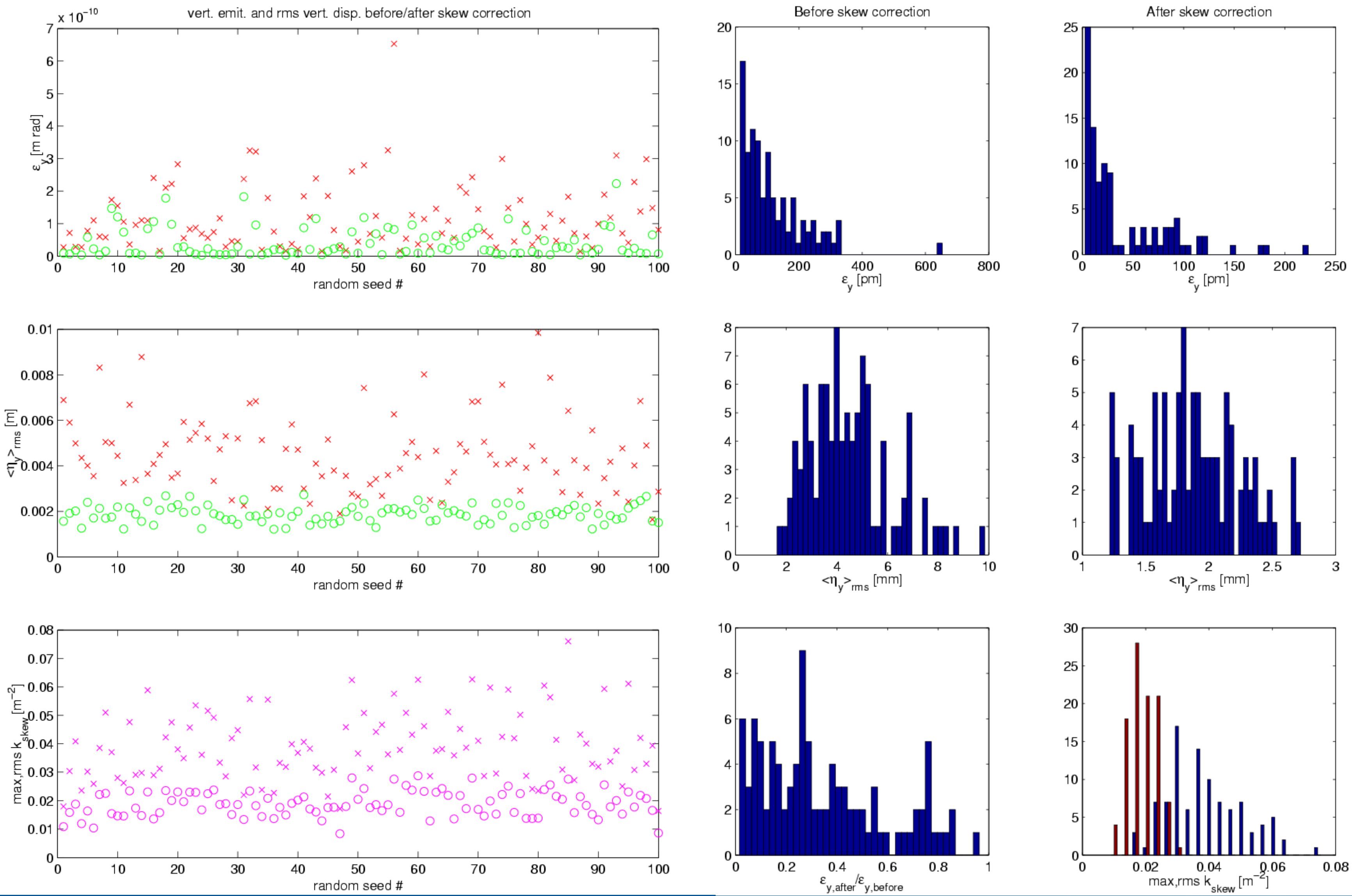


Finding an Effective Skew Quadrupole Set

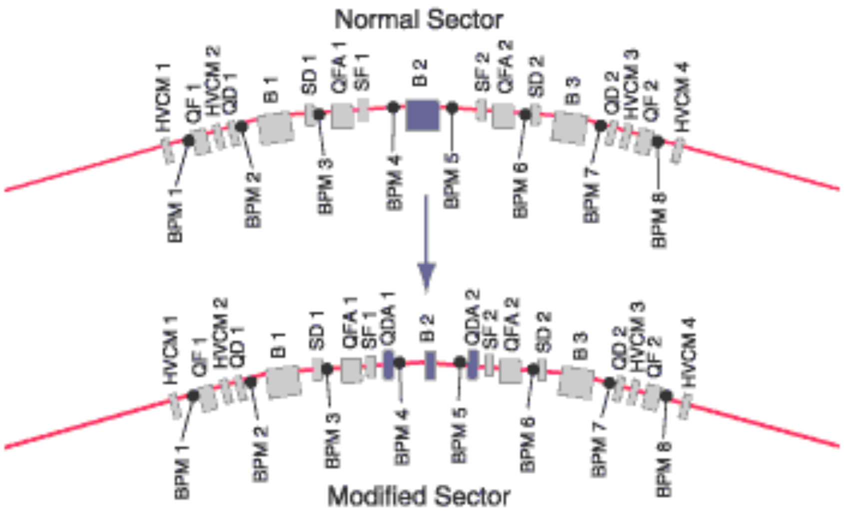
- To find an effective skew quadrupole distribution, we used several correction methods, first in simulations – best method was orbit response matrix fitting (using LOCO)
- Predictive method, can be easily used on real machine
- Issues are:
  - Cover set of phases relative to dominant coupling resonance(s)
  - Magnets should be distributed around the ring in order to avoid excessive local coupling/vertical dispersion
  - Need different values of dispersion/beta function to be effective both for coupling and vertical dispersion correction
- Set of 12 skew quadrupoles was reasonably efficient

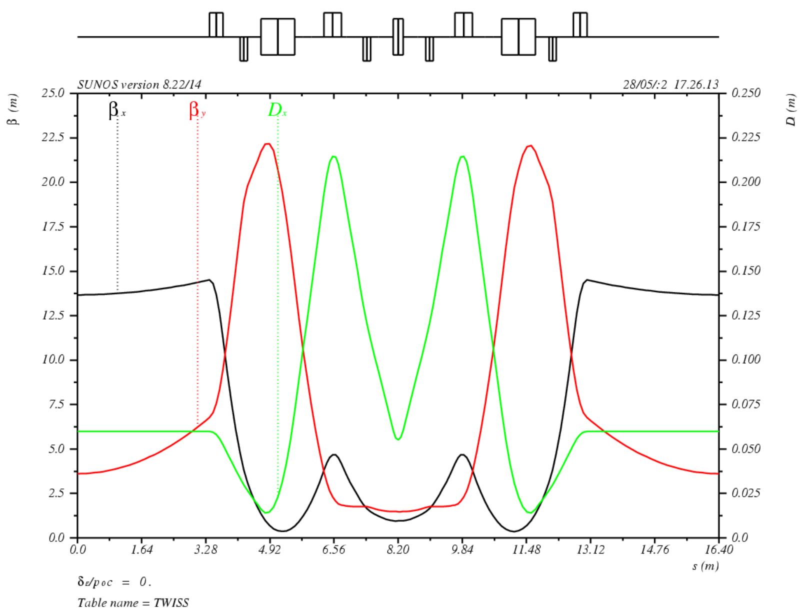


Finding an effective skew set (2)



ALS Lattice – Location of Skew Quadrupoles

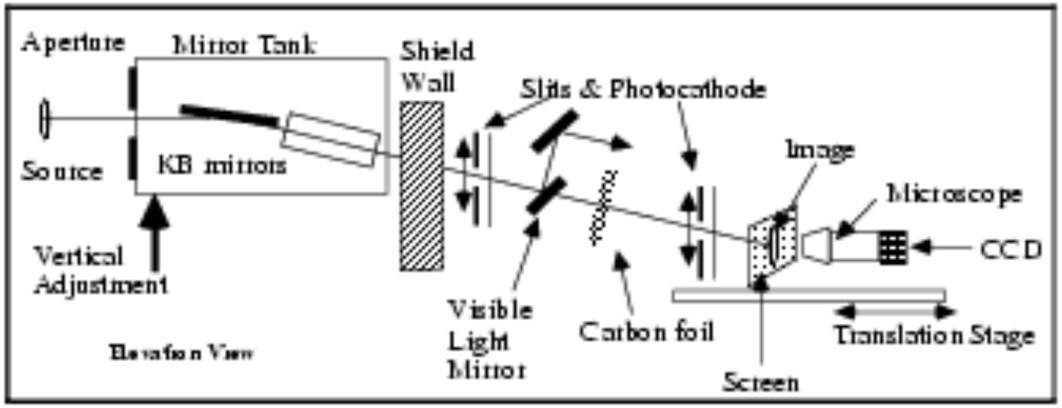




- 24 individual skew quadrupoles (integrated in sextupoles) serve two purposes:
  - global vertical emittance/dispersion control
  - local vertical dispersion bump

Ways to Measure Very Small Emittances

- The single photon emittance (diffraction) is $\lambda/4\pi$, which means that to measure emittances of a few pm, one has to use x-rays.
- Problem even with x-rays is resolution of X-ray beamlines/optics



- Mirror roughness, aberrations, diffraction limit, misalignments, CCD resolution, BGO crystal (glow)
- Fundamental limit (diffraction limit) is a few microns, I.e. sufficient for what we want to measure, but with real optics errors the resolution is often larger.

How to measure very small emittances (2)

- We used three different ways to verify vertical emittances around 4 pm:
  1. Resolution correction (resolution was about 25 μm, measured beamsizes got as small as about 27 μm)
  2. Analysis of orbit response matrix, using a sufficiently large number of skew gradient error fit parameters
  3. RF acceptance-lifetime scan. Quadratic part should scale just with the bunch volume. Therefore one can deduct the small emittance from a beamsize measurement at moderate coupling!

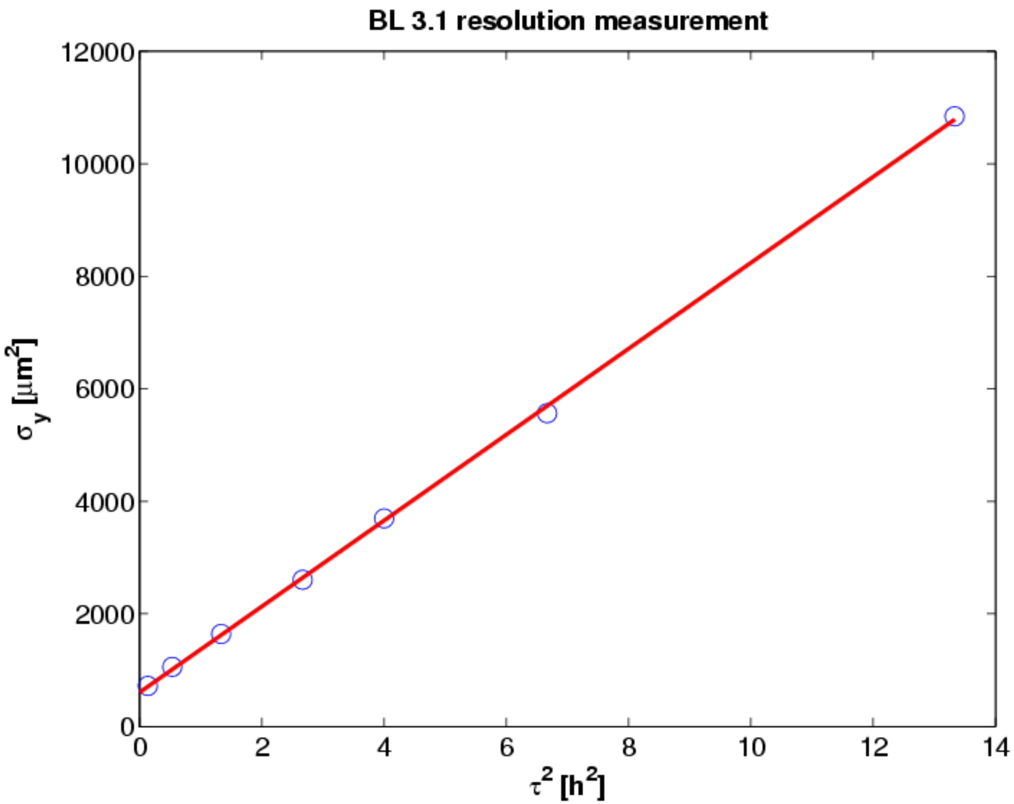
– All measurement methods gave vertical emittances around 4 pm in the best case.

Resolution correction of SLM

- If the rf voltage is significantly reduced, changes in the beam dynamics/dynamic momentum aperture do not impact the total momentum aperture. Therefore the Touschek lifetime is only proportional to the rf-voltage and the bunch volume.

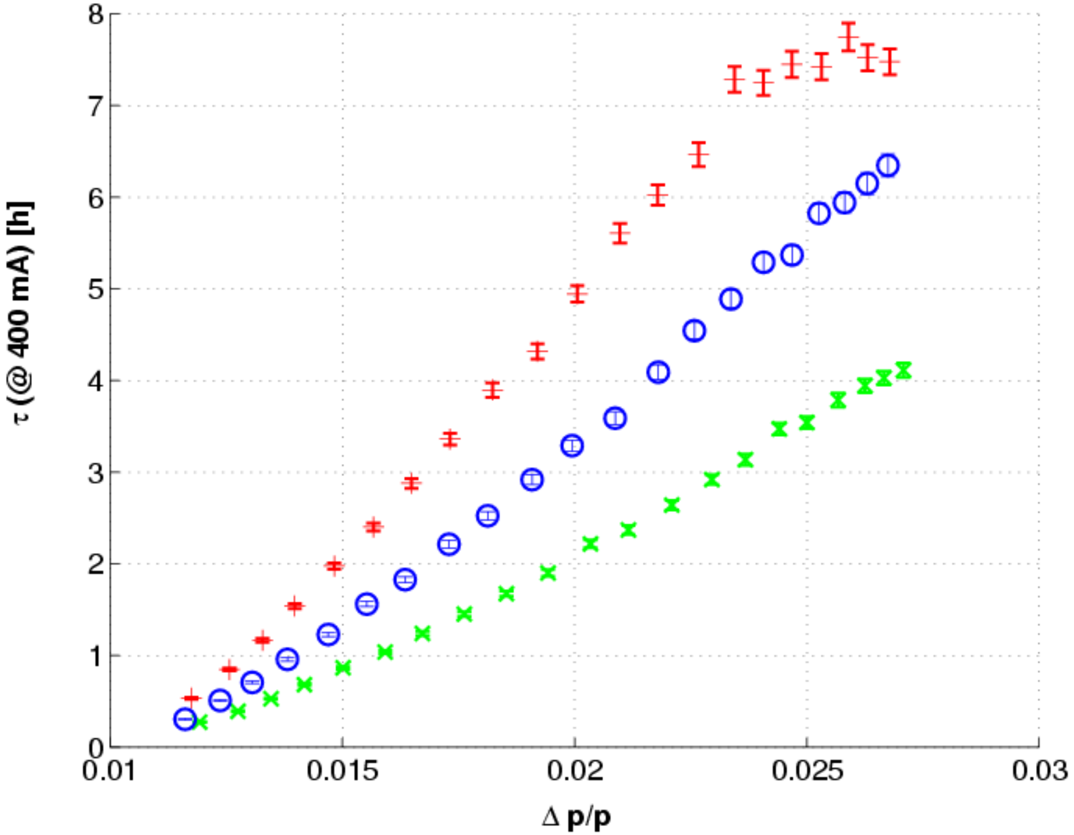
- If one now changes the vertical beamsize and plots the square of the measured beamsize as a function of the square of the measured Touschek lifetime, one can extrapolate the resolution limit of the profile monitor.

- Result with current optimization of BL 3.1 is about 25 μm



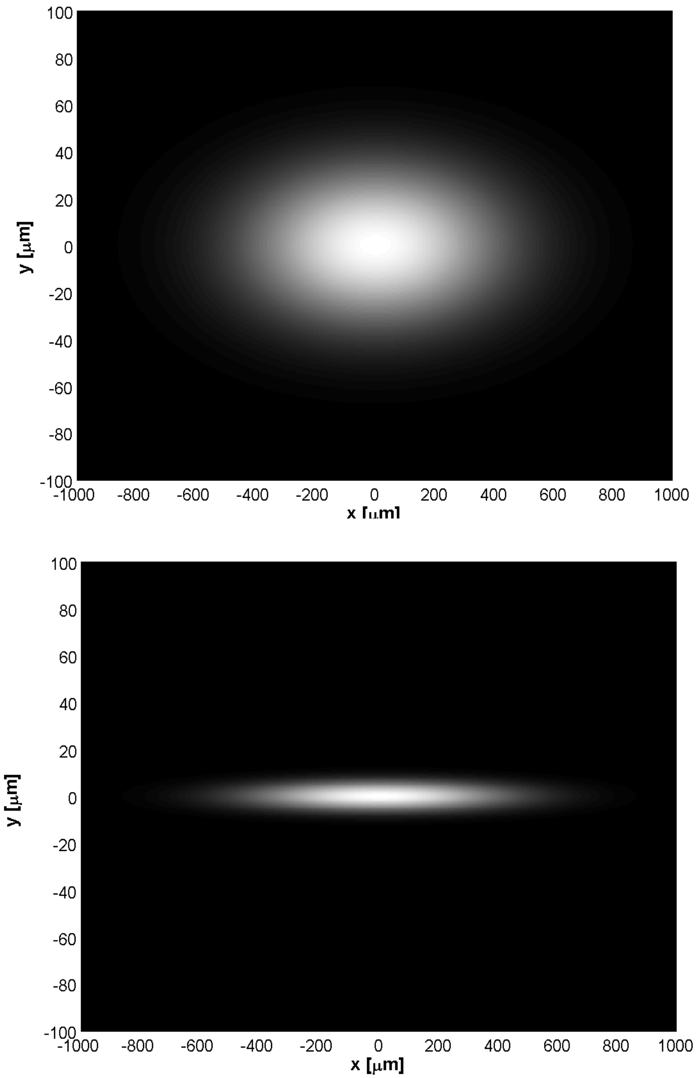
RF-acceptance/lifetime scan

- ‘Quadratic’ part of lifetime curve does not depend on single particle dynamics.
- Relative scaling of curves is determined by bunch volume only.
- Comparison gives an emittance scaling which combined with a direct emittance measurement at the ‘high’ emittance case allows a determination of the emittance in the small emittance case.

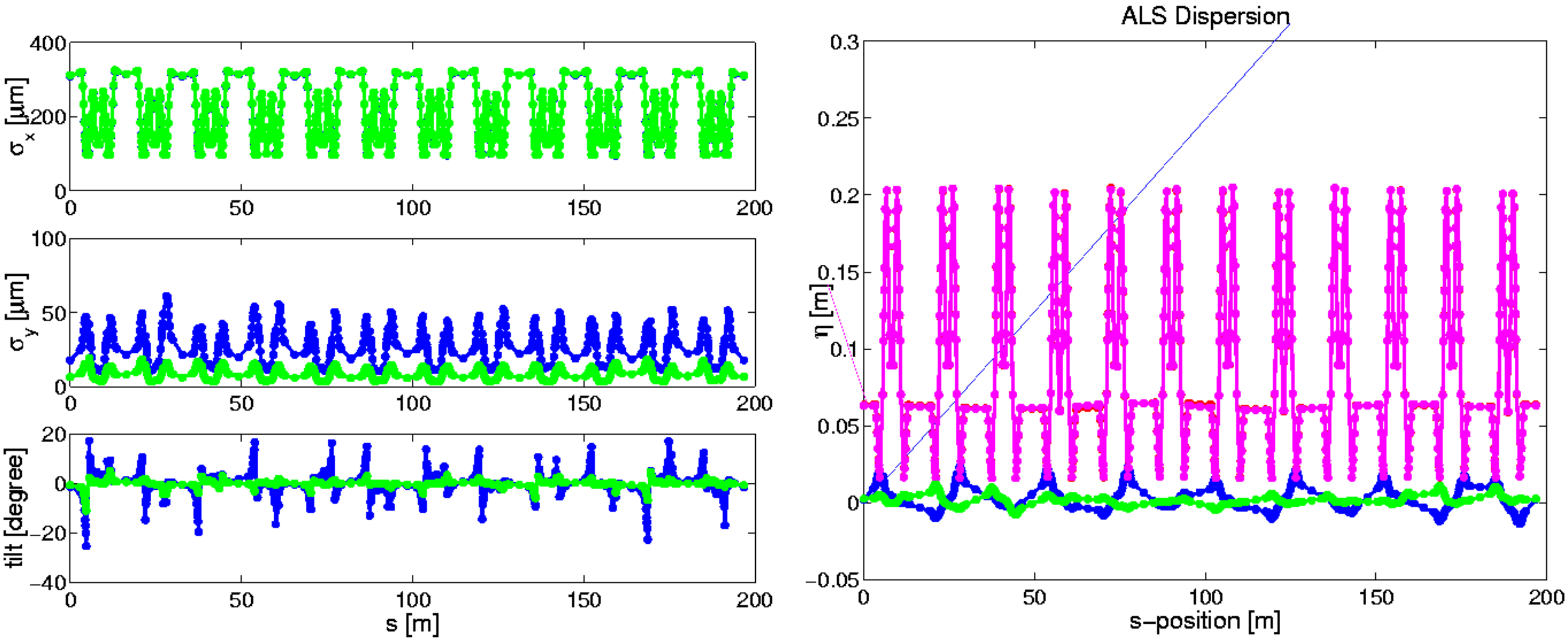


Achieved Emittance Reduction

- Achieved an emittance reduction from 150 pm (routine ALS operation) to about 4 pm (pictures on the right illustrate size reduction for insertion device straights).
- Touschek lifetime requires to not make full use of the possibility: Nowadays in topoff we operate at about 30-40 pm.
- This was a world record in 2003 and about the NLC damping ring design value
- Correspondingly the brightness would increase by factor 30 (for hard x-rays – because of diffraction limit less for soft x-rays)



Example of Emittance and Dispersion Correction



- In this example vertical beamsize was reduced by factor of more than 4 (emittance by factor 20)
- Spurious vertical dispersion reduced from 7 mm rms to below 3 mm rms
- Tilt of phase space reduced significantly everywhere

Reminder: Phase Advance Measurement

- Use digitized position signal, then

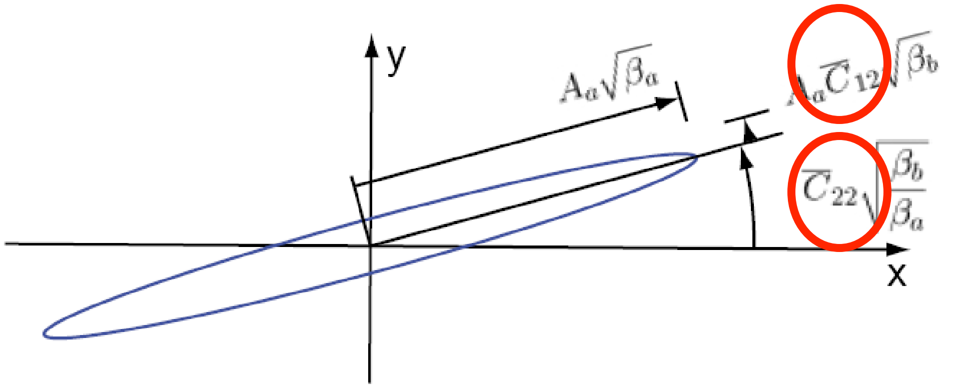
  The phase of the reference signal at turn n is used to construct sine cosine references

$$R_{\sin}(n) = \sin\phi_{ref}(n)$$
$$R_{\cos}(n) = \cos\phi_{ref}(n)$$

- Convolute the beam signal with these (digital lock-in) and integrate

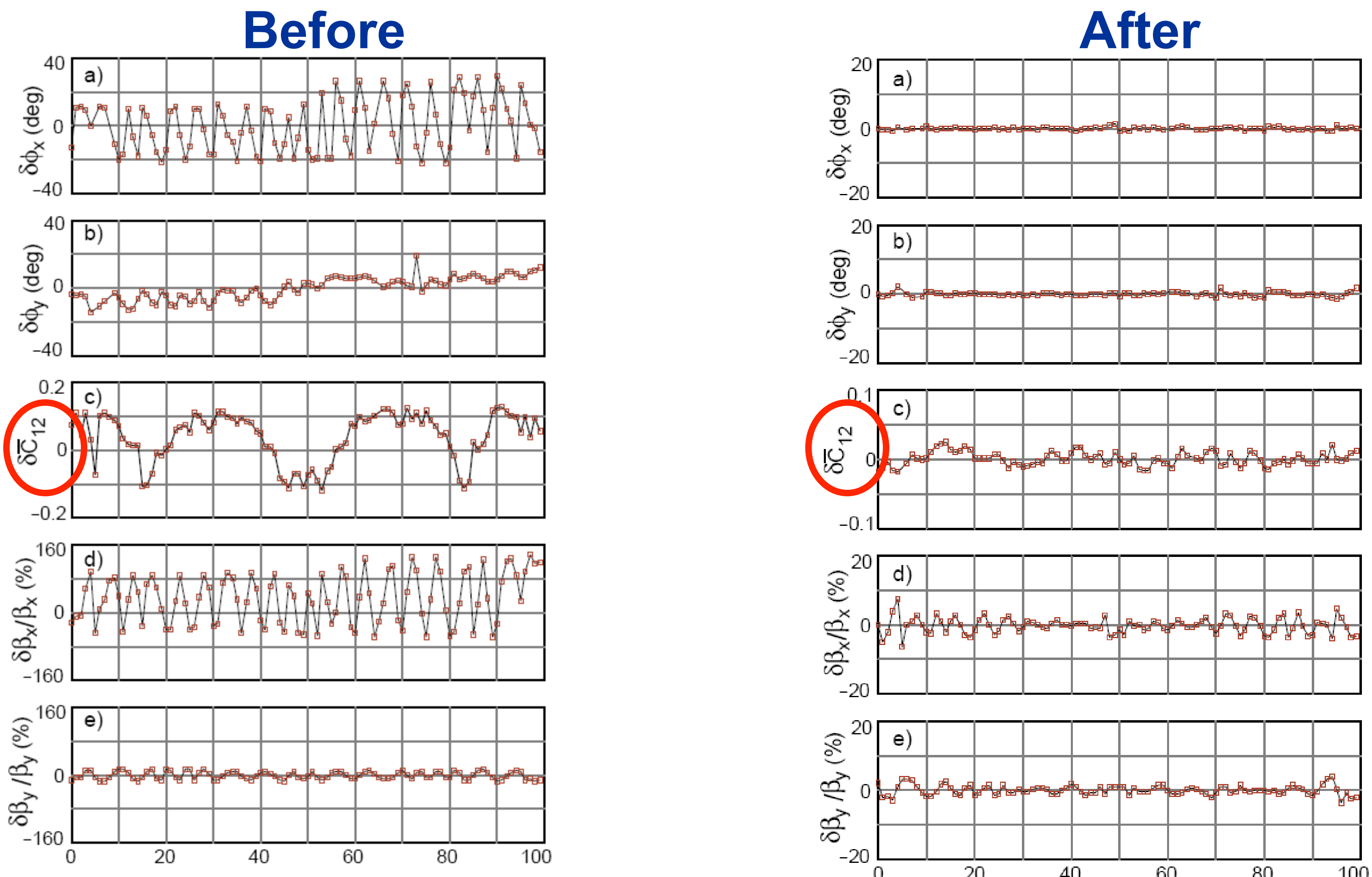
Results are used to solve for the lattice functions

$$\begin{aligned} x &= A_a\sqrt{\beta_a}\cos(n\omega_a + \phi_a), \\ y &= -A_a\sqrt{\beta_b}(\overline{C}_{22}\cos(n\omega_a + \phi_a) + \overline{C}_{12}\sin(n\omega_a + \phi_a)). \end{aligned}$$



In practice assume $\beta = \beta(\text{design})$ and solve for ϕ and $\overline{C}_{ij}$.

Coupling Correction using turn-by-turn data

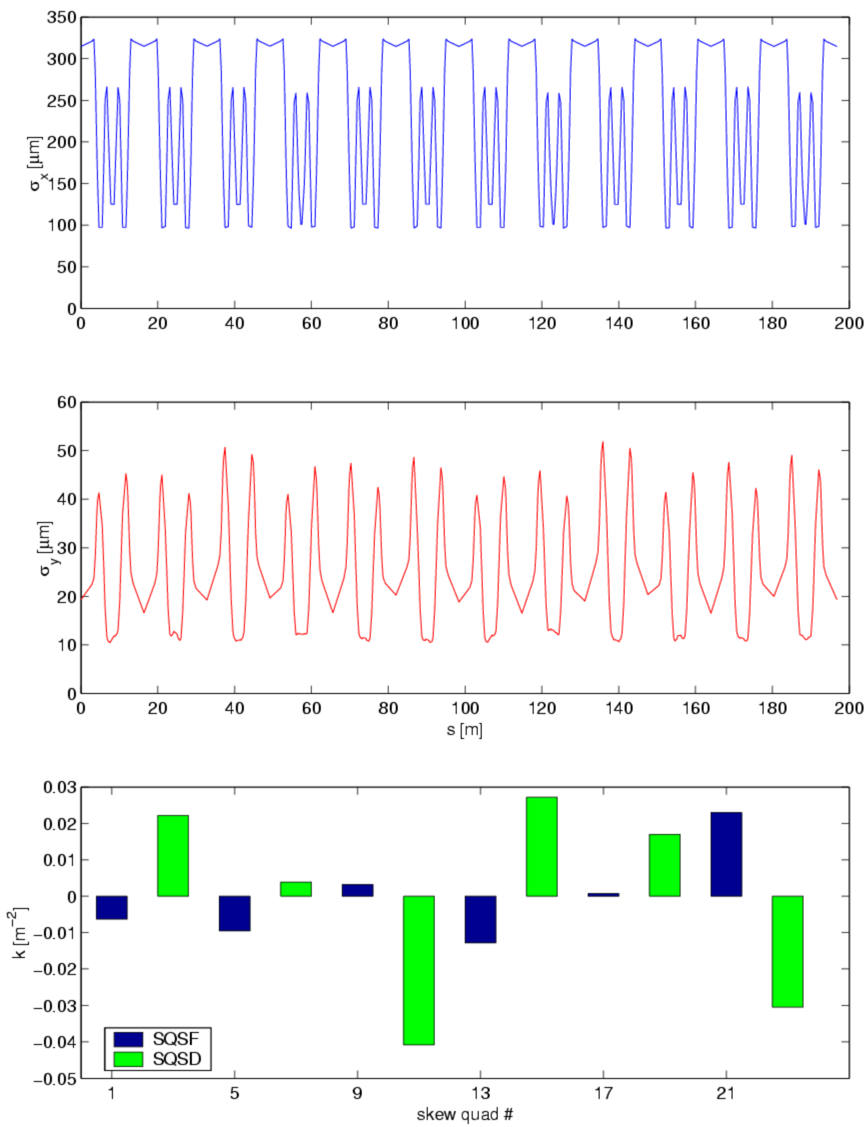


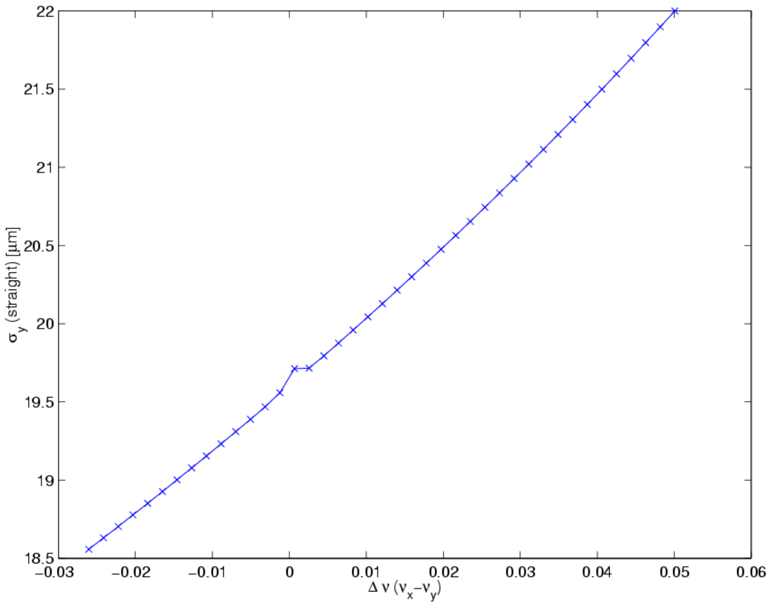
Note the change in scale

Ways to Increase the Vertical Emittance …

- Low energy third generation light sources usually increase the vertical emittance intentionally to achieve acceptable lifetime.
- Historically at the ALS we used a family of skew quadrupoles to excite linear coupling resonance.
- Recently switched to a mode where we correct the coupling and dispersion as well as possible and then blow up the vertical emittance using a global vertical dispersion wave.
- Method has many advantages (beamsize stability, dynamic momentum aperture, …)

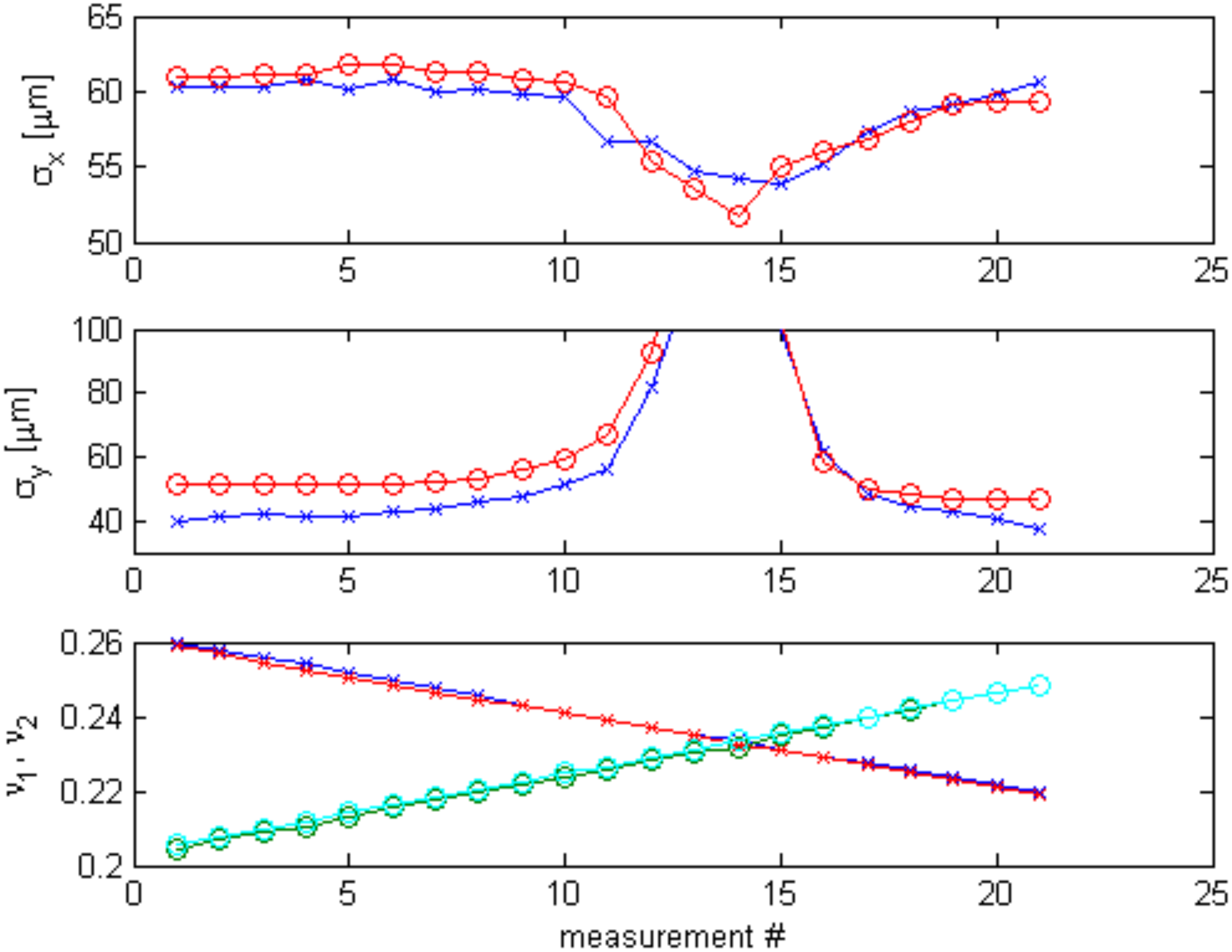
Vertical Dispersion Wave





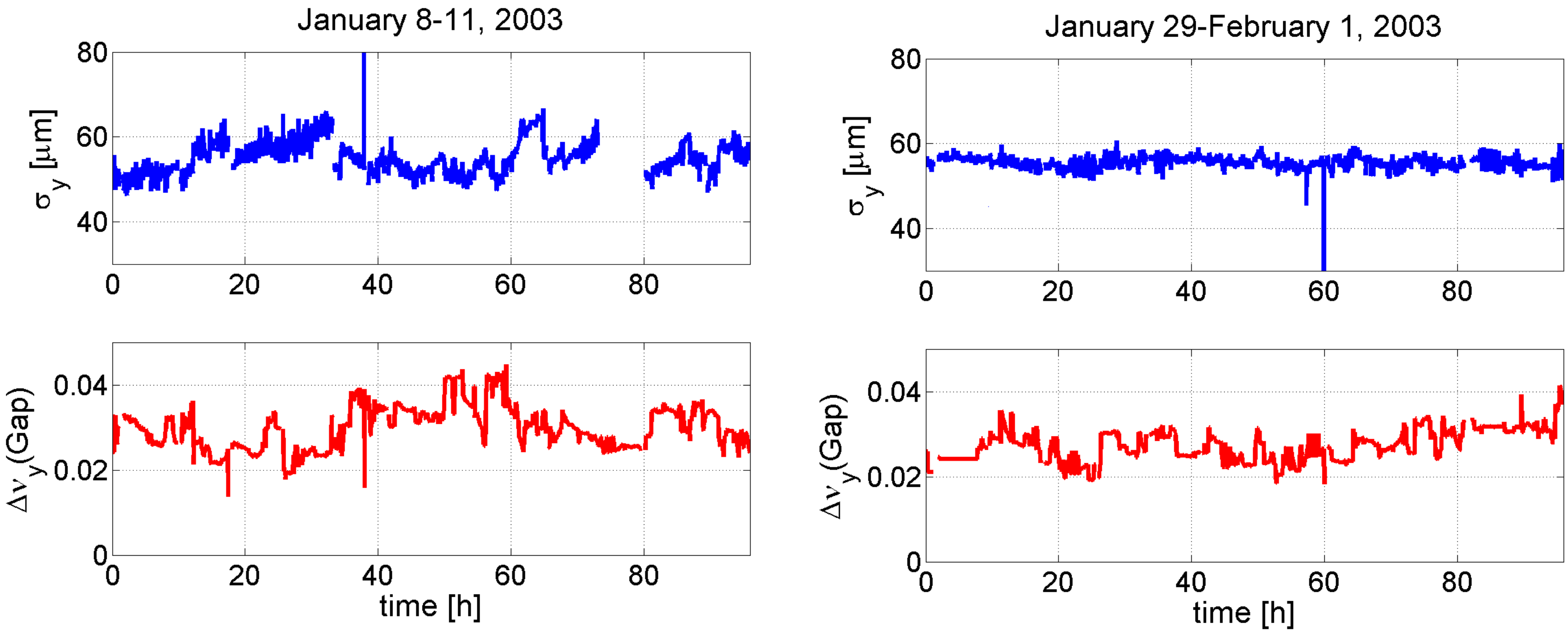
- 12-20 skew quadrupoles are used such, as to generate a global vertical dispersion wave, without exciting nearby coupling resonances
- Vertical emittance is directly generated by quantum excitation
- Local emittance ratio around the ring is fairly constant, local tilt angles are small

Vertical Dispersion Wave II



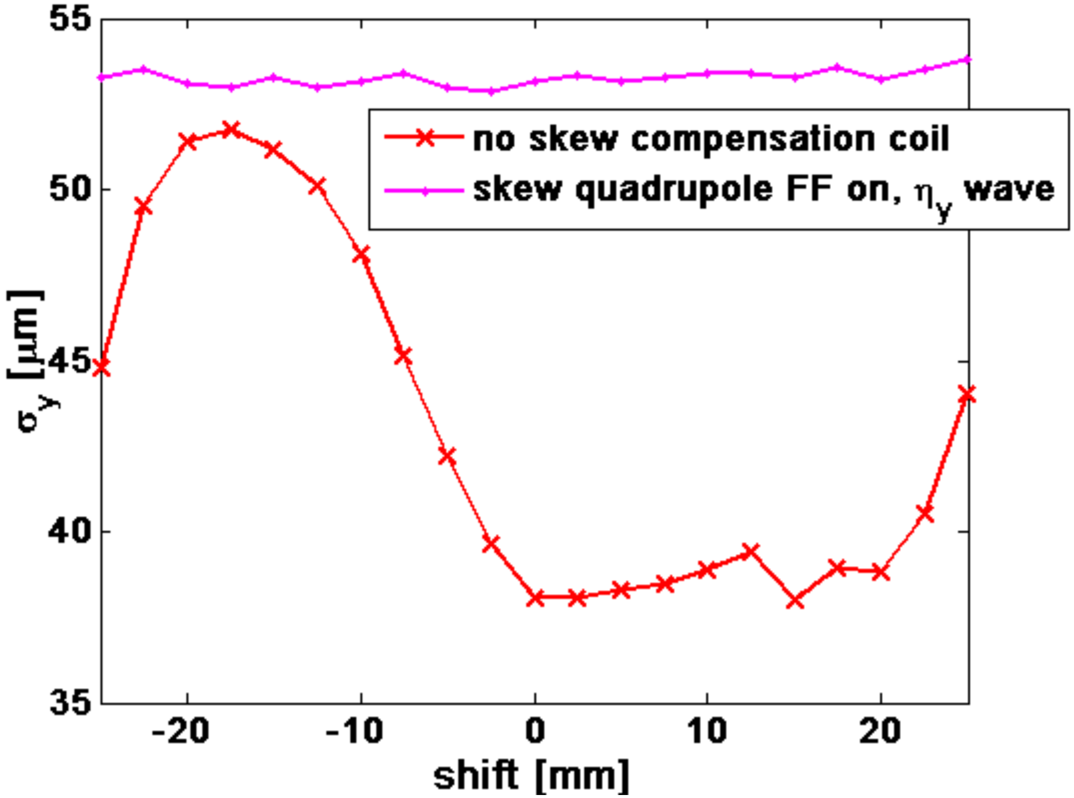
Vertical Beamsize Stability

- The stability of the (vertical) beamsize is important for users (not all effects of varying beamsize can be normalized out)
  - Main issues affecting the beamsize are residual tuneshifts (after feedforward compensation) when scanning undulators or skew errors inside those undulators (especially EPUs)
- Using dispersion wave instead of coupling resonance to increase vertical emittance improves beamsize stability



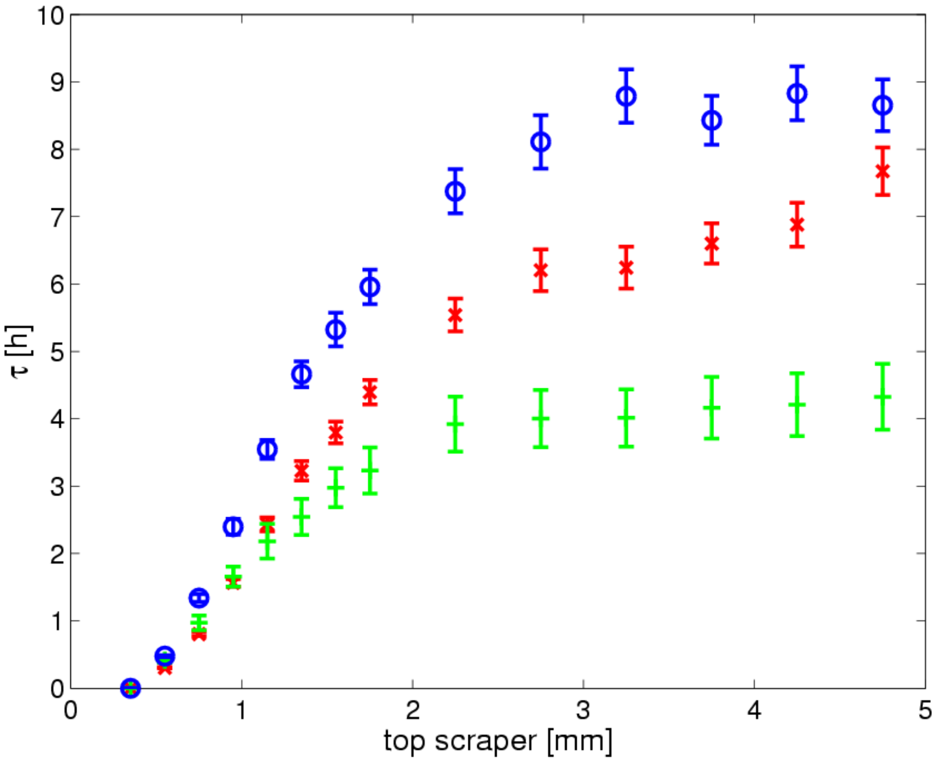
Skew quadrupole compensation for EPUs

- Beamsize variation was solved in 2004: Installed correction coils for feedforward based compensation
- Feed-forward tables were generated analyzing multiple orbit response matrix measurements (and fits). Result is an excellent compensation.
- Early 2005 we identified the root cause: 2-3 micron correlated motion of magnet modules due to magnetic forces. Newer devices have modified design to reduce effect.



- **Just for reference: Whenever an undulator moves, about 120-150 magnets are changed to compensate for the effect (slow+fast feed-forward, slow+fast feedback)**

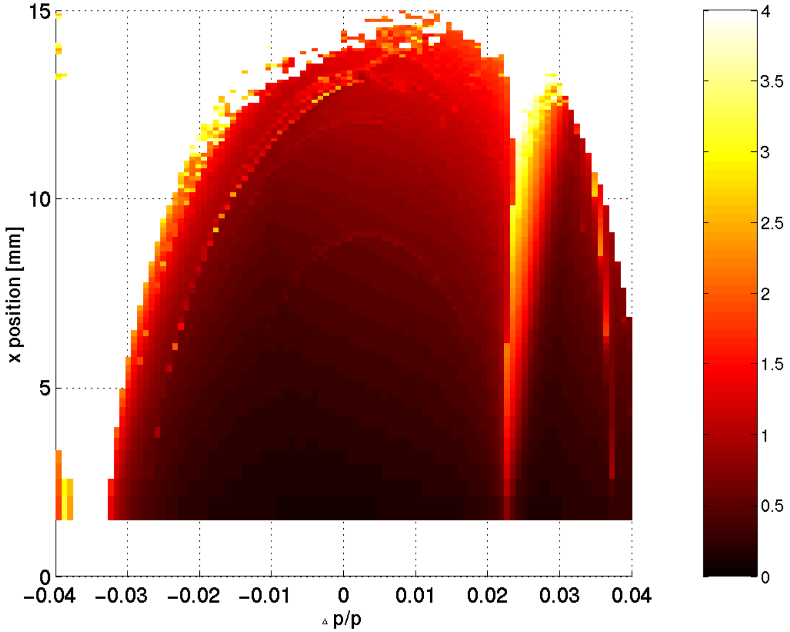
Lifetime vs. Vertical Physical

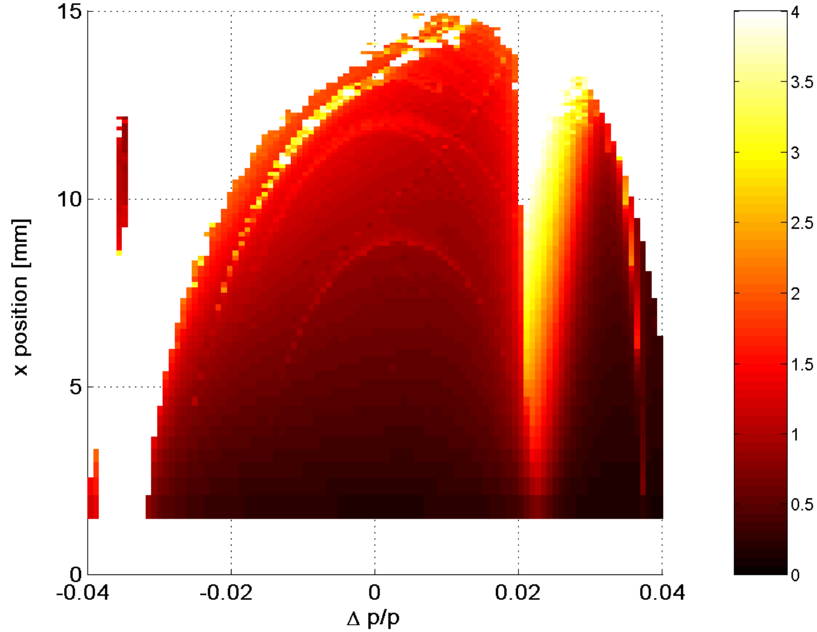


- Performance (Brightness) of undulators/wigglers (both permanent magnet and SC) depends on magnetic gap
- Strong incentive to push physical aperture as low as possible
- The vertical physical aperture at which the lifetime starts to get smaller depends strongly on how well global and local coupling is corrected!

Simulation Results (Momentum Aperture – Gap)

Emittance increased using vertical dispersion wave … using excitation of coupling resonance

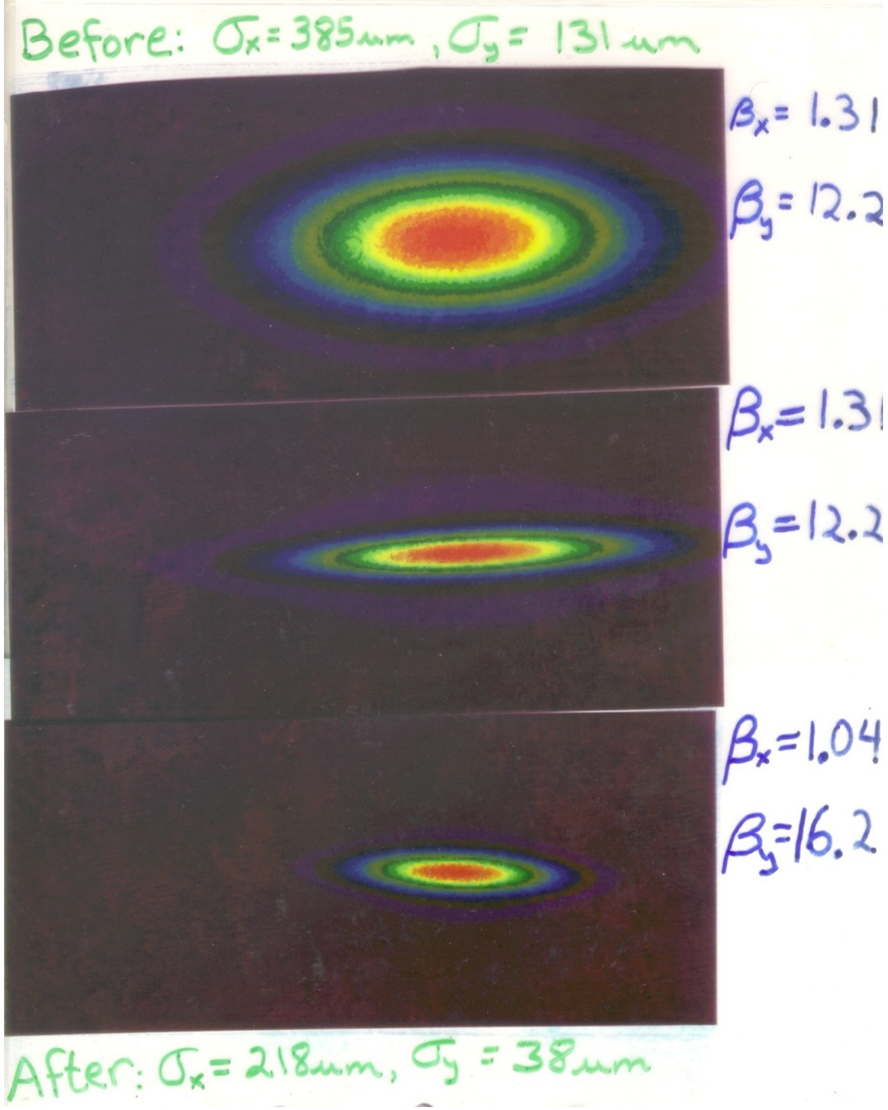




- Tracking results are in good agreement with measured effects, i.e. case with dispersion wave has less yellow and orange areas than the one with excited coupling resonance, indicating less sensitivity to reduced vertical aperture

Other Examples: NSLS

- James was (to my knowledge) the first to use response matrix based fitting to correct coupling (20? Years ago).
- Applied it very successful at the NSLS, achieving less than 0.1% emittance ratio. Still about the best emittance ratio reached anywhere, though the absolute vertical emittance was somewhat larger than in ALS, because of much larger natural emittance of X-ray ring.
- (Data from James Safranek)

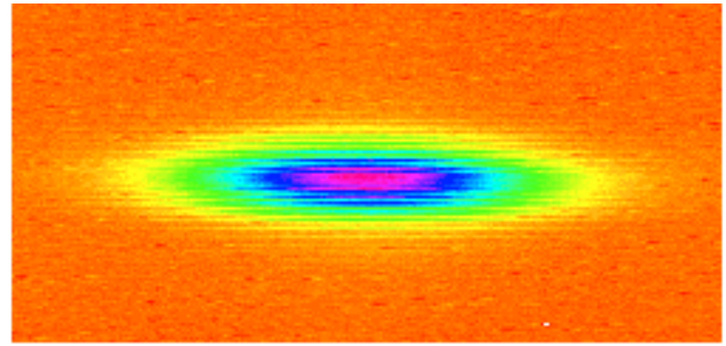


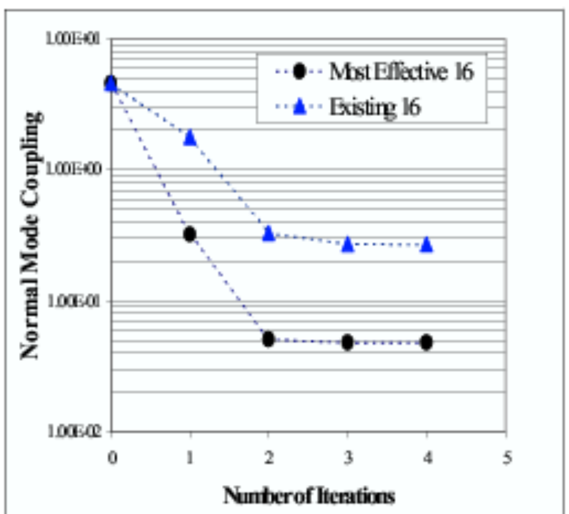
Other Examples: ESRF

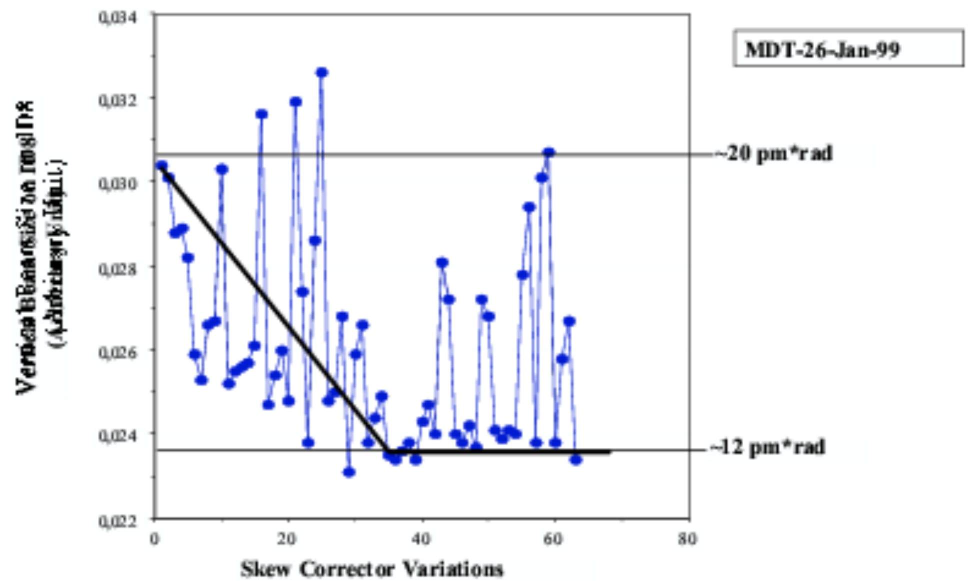
- Phi Nghiem, R. Nagaoka and Tordeux carried out very nice work at ESRF using a method similar to LOCO (back in 1999).
- Problem was the large number of elements in ESRF, order of magnitude is 400 correctors and 400 BPMs and similar number of quadrupoles, sextupoles.
- Back then, could only use partial response matrix in analysis. Averaged over several of those matrices.
- Did not fit tilt errors of individual magnets, but effective skew distribution (enough to describe the local coupling structure, but few enough to not get strong degeneracies)
- It was important to study precisely what singular values to keep in inversion and which ones to neglect.
- Had to iterate with empirical correction on top of the LOCO predicted correction – reason seems to be relatively small number of skew quadrupoles (16).

Other Examples: ESRF

- Reached about 10 pm emittance.
- Predictions from model (tune scan, …) agree very well with independent measurements.
- (All plots courtesy of R. Nagaoka ESRF/Soleil)

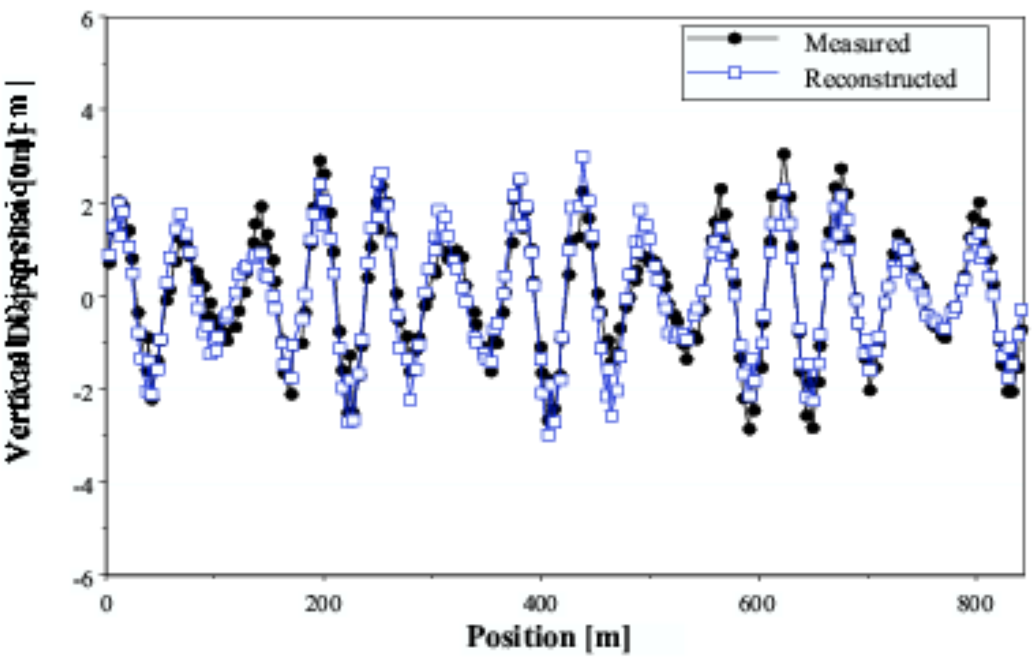


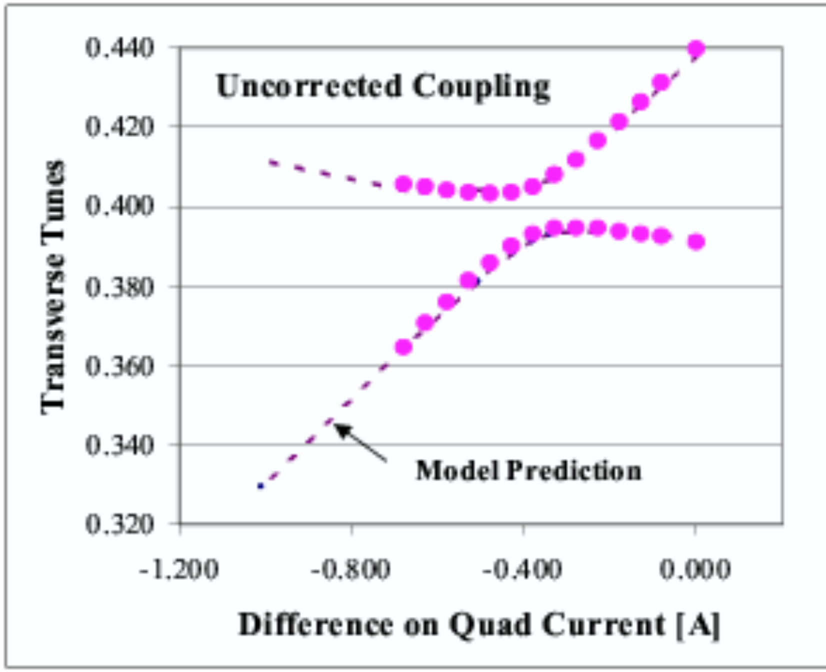




Other Examples: ESRF

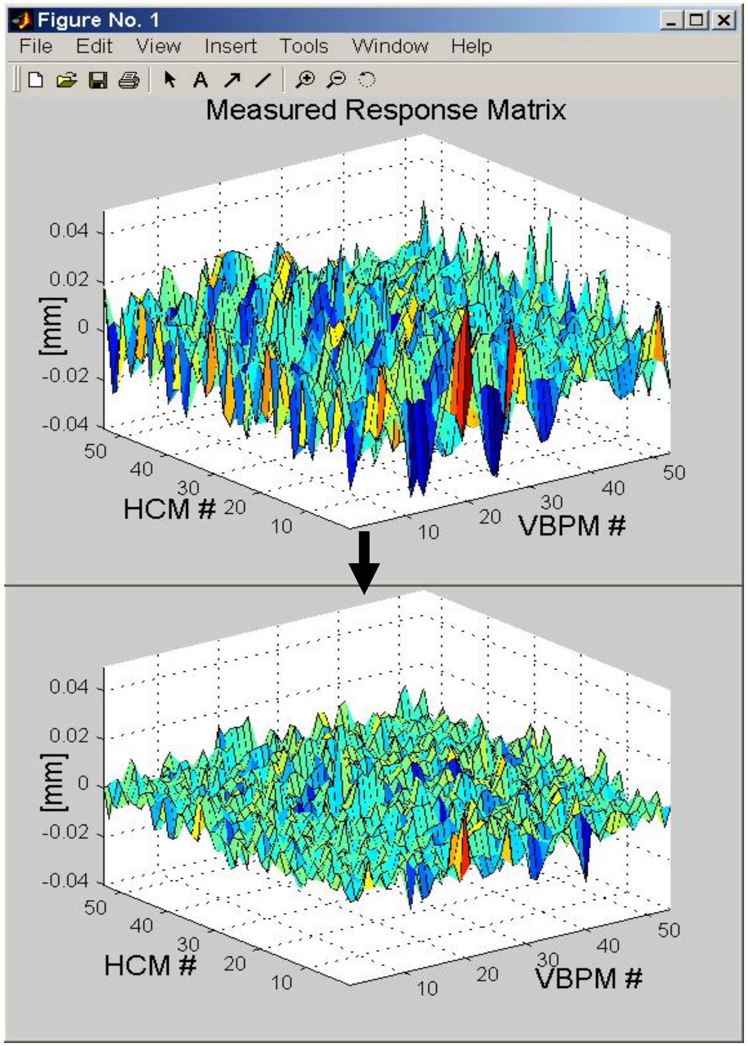
- (Plots courtesy of R. Nagaoka)



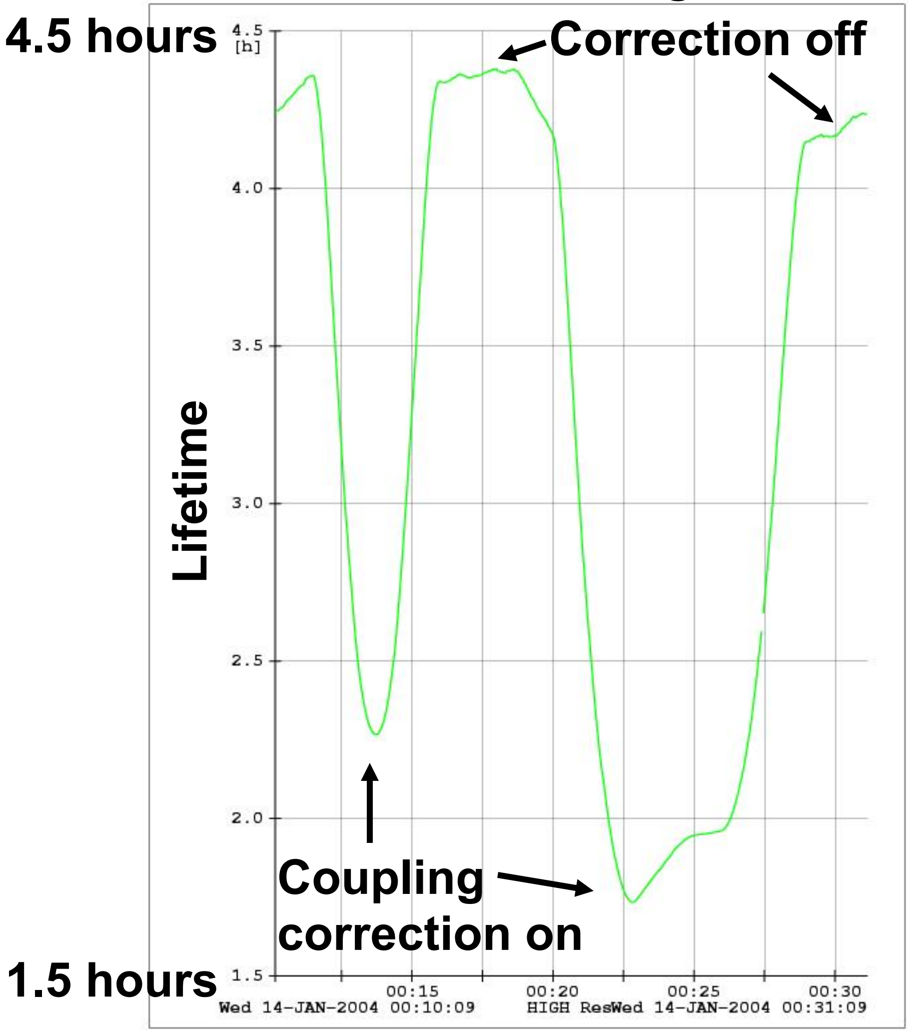


Other Examples: Spear 3

Minimize η_y and off-diagonal response matrix:



Lifetime, 19 mA, single bunch

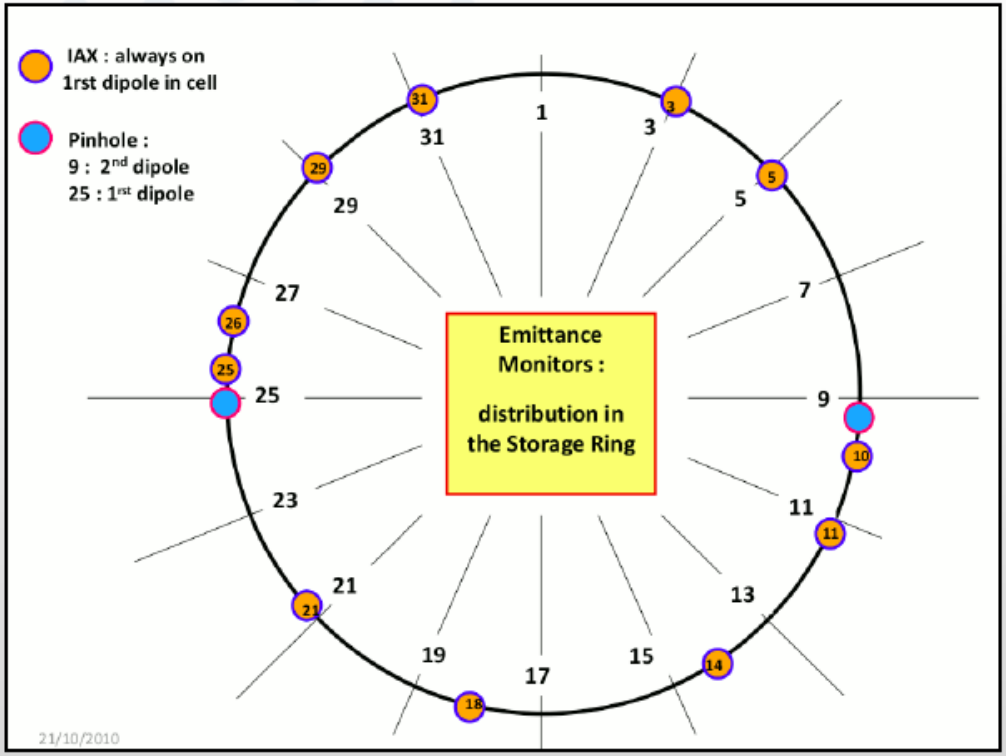


Other Examples: ESRF (new)

Meas. vertical emittance Ey from RMS beam size

ESRF SR equipment:

- 11 dipole radiation projection monitors (IAX)
- 2 pinhole cameras



(Plots courtesy of A. Franchi)

Other Examples: ESRF (new)

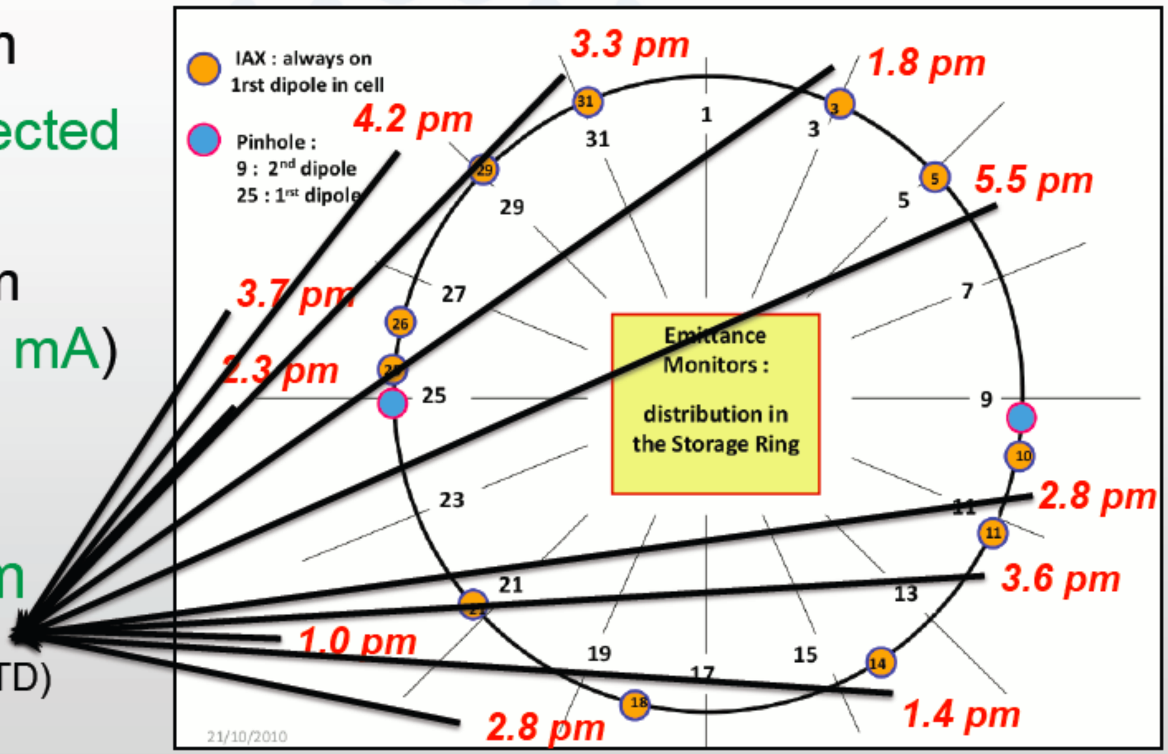
Meas. vertical emittance Ey from RMS beam size

Ex=4.2 nm

- Well corrected coupling
- Low beam current (20 mA)

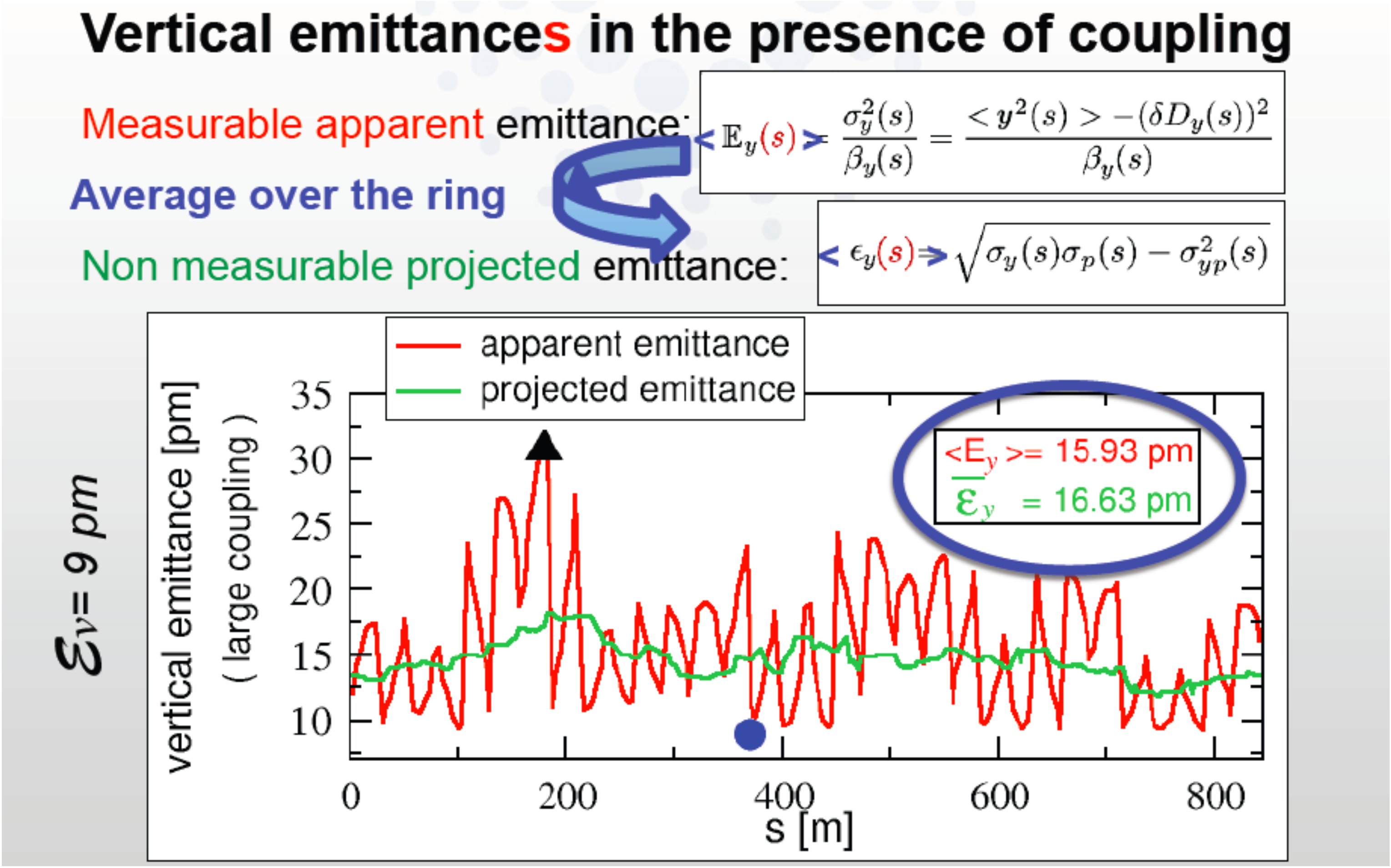
$\overline{E}$y=3.0 pm

±1.3 (STD)



(Plots courtesy of A. Franchi)

Other Examples: ESRF (new)



(Plots courtesy of A. Franchi)

Other Examples: ESRF (new)

Coupling correction via Resonance Driving Terms

$$f_{\substack{1001\\1010}} = \frac{\sum_{w}^{W} J_{w,1}\sqrt{\beta_x^w \beta_y^w}\, e^{i(\Delta\phi_{w,x} \mp \Delta\phi_{w,y})}}{4(1 - e^{2\pi i(Q_u \mp Q_v)})}$$

1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) => RDTs and Dy

$$\vec{F} = (a_1 {*} f_{1001},\ a_1 {*} f_{1010},\ a_2 {*} Dy)\ ,\quad a_1 + a_2 = 1$$

1. Evaluate response matrix of the available skew correctors **M**
2. Find via SVD a corrector setting $\vec{J}$ that minimizes both RDTs and Dy

$\vec{J} = -M\,\vec{F}$ **to be pseudo-inverted**

(Plots courtesy of A. Franchi)

Other Examples: ESRF (new)

Coupling correction via Resonance Driving Terms

$$\begin{pmatrix} a_1\vec{f}_{1001} \\ a_1\vec{f}_{1010} \\ a_2\vec{D}_y \end{pmatrix}_{\text{meas}} = -\mathbf{M}\vec{J}_c,$$

a_2=0.7 (2010) , 0.4 (2011)

$a_1+a_2=1$

Different weights on f_{1001} and f_{1010} tried, best if equal.

1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) => RDTs and Dy

$$\vec{F} = (a_1{*}f_{1001},\ a_1{*}f_{1010},\ a_2{*}Dy)\ ,\quad a_1+a_2=1$$

1. Evaluate response matrix of the available skew correctors **M**
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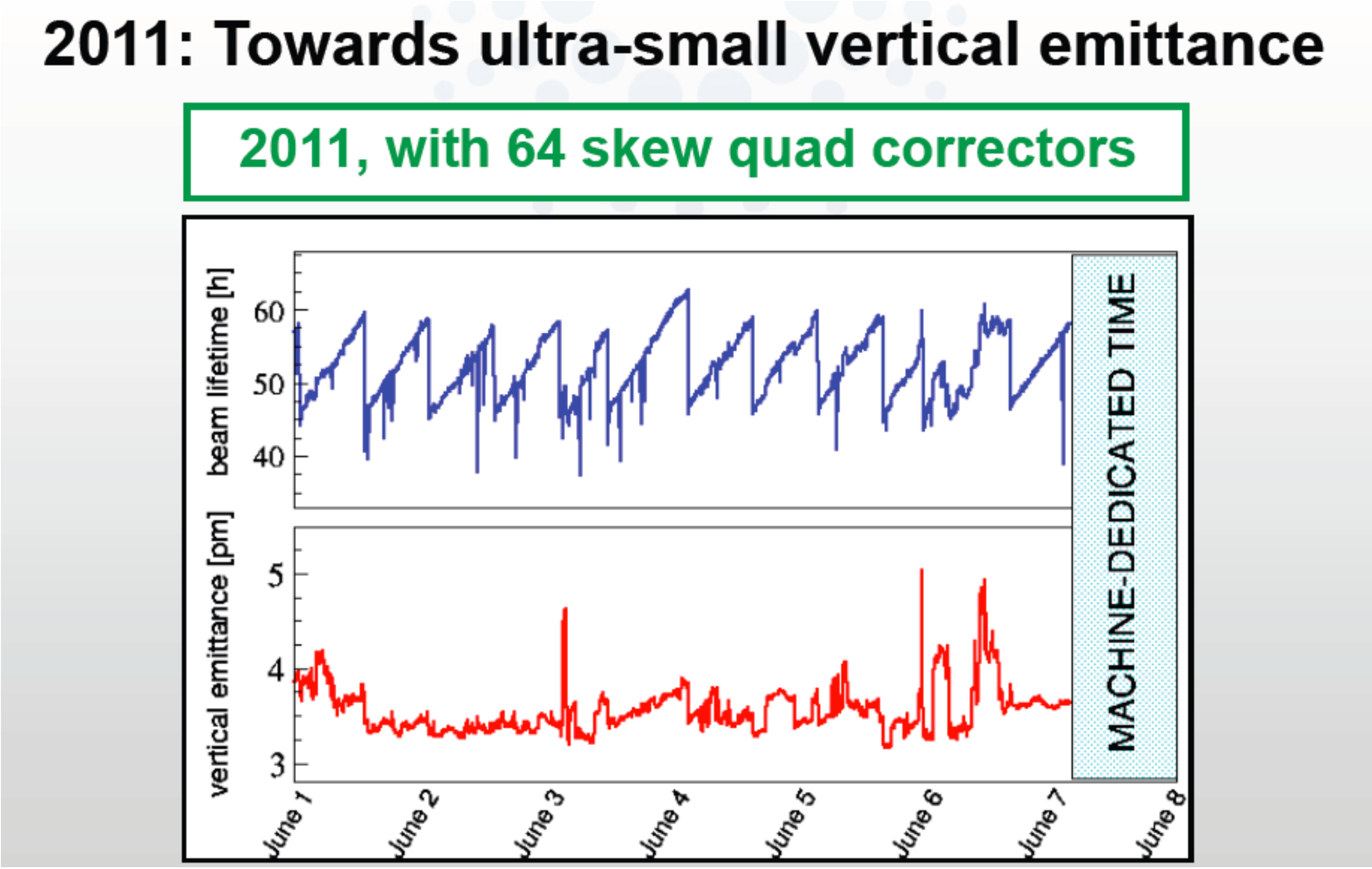
(Plots courtesy of A. Franchi)

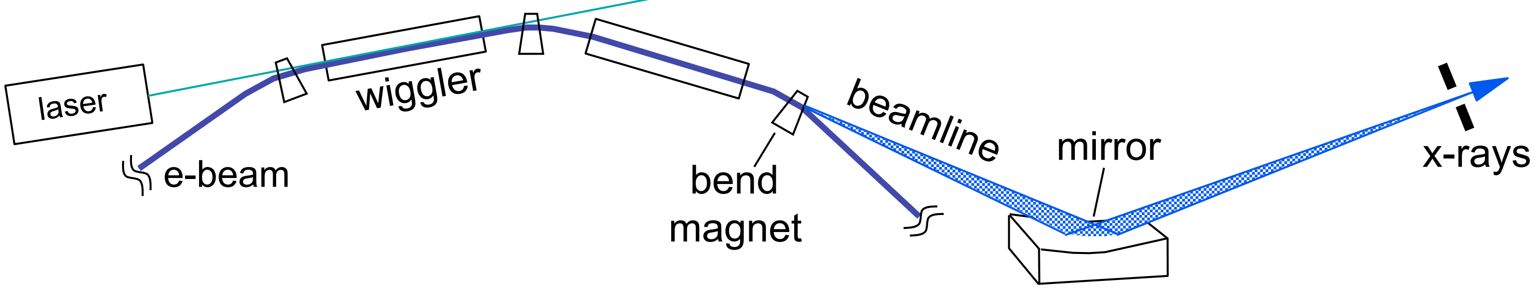
Other Examples: ESRF (new)

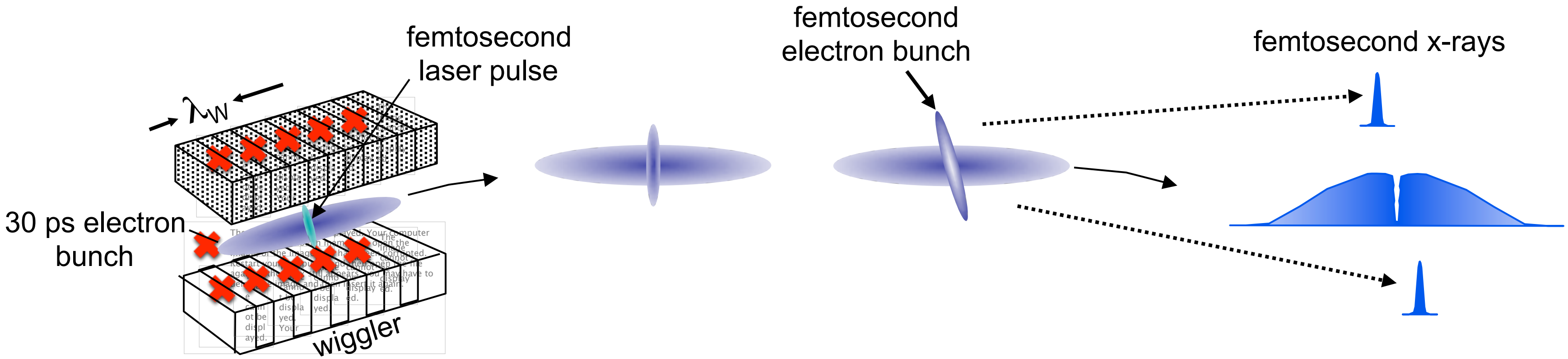


(Plots courtesy of A. Franchi)

Final Example: Dispersion/Coupling Insertion

- Inverse FEL interaction in Wiggler/Undulator used to impose big energy spread on small slice of bunch
- Subsequent arc provides horizontal dispersion
- Lattice Insertion transforms this into vertical separation at radiator





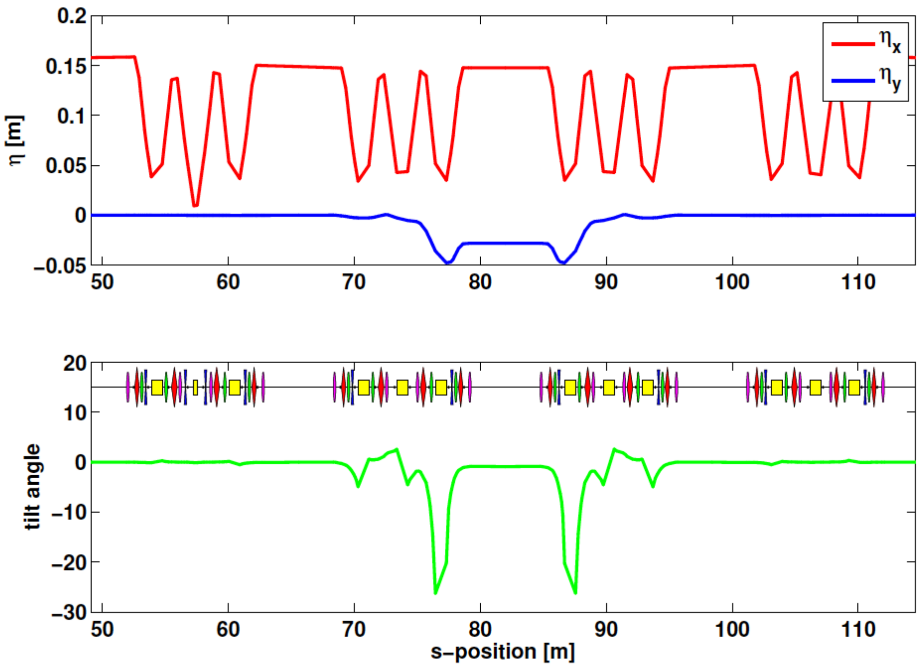
electron-photon interaction in wiggler

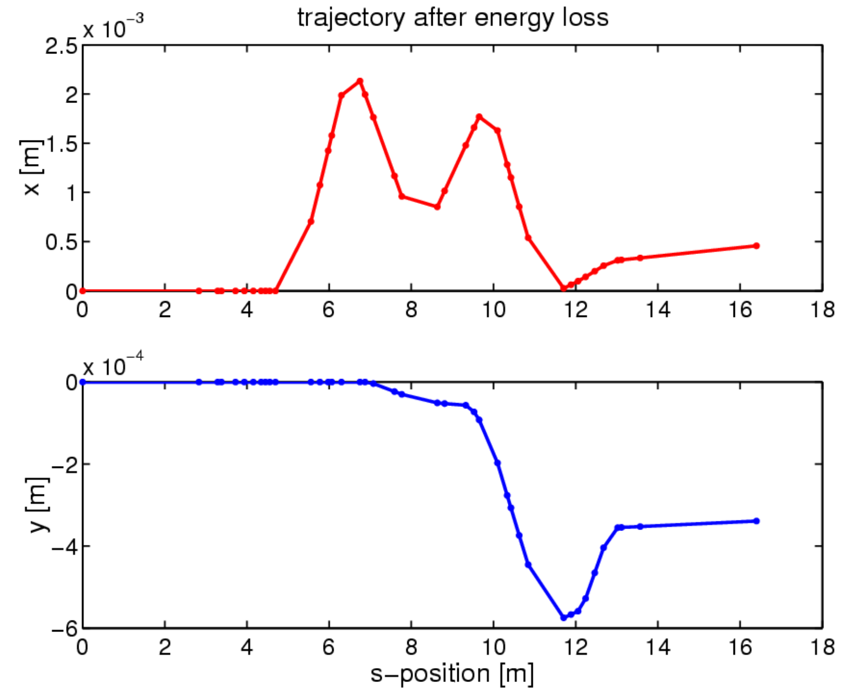
spatial separation dispersive bend

bend magnet beamline

Zholents and Zolotorev, *Phys. Rev. Lett.*, **76**, 916,1996.

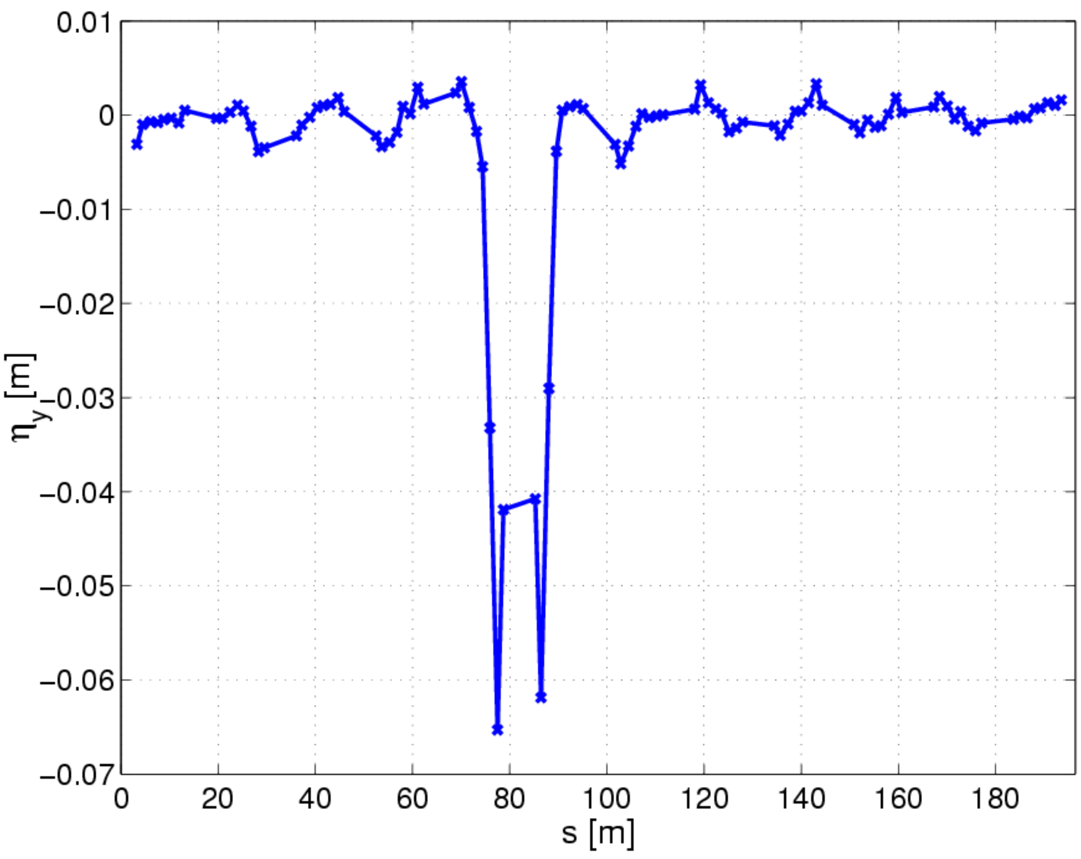
Dispersion/Coupling Insertion





- Design uses 12 skew quadrupoles to generate closed vertical dispersion bump with negligible global coupling and small local coupling at radiation
- Some sextupoles are already operated deep in saturation – sextupole field gets suppressed by reasonably strong skew quadrupole (>1% effect) → nonlinear dynamics could be important! → No problem.
- Horizontal dispersion in straights automatically generates horizontal separation in addition to vertical separation of dispersion bump
- Separation shown on the right is for 4 cm η_y, 6 cm η_x and 9 σ energy kick

Measurement of Vertical Dispersion Bump



- Measured η_y>4 cm in straight
- Vertical emittance increase was as predicted

•Non-closure of bump (caused by differences in saturation because of different corector magnet settings in the combined sextupoles/skew quadrupoles/corrector magnets) was small and is routinely corrected by orbit response matrix analysis

Summary

- Coupling correction is important to optimize the performance of an accelerator. Direct benefits are increased brightness or increased luminosity. More indirect improvements are dynamic (momentum) aperture and therefore injection efficiency and lifetime.
- There are several correction methods. At light sources a combined approach targeting local coupling, global coupling and vertical dispersion simultaneously has been most successful.
- Using orbit response matrix analysis (LOCO), emittance ratios below 0.1% have been achieved. For the ALS that corresponds to a vertical emittance of about 4 pm rad, which is within a factor of ten of the theoretical limit due to the finite opening angle ($1/\gamma$) of the synchrotron radiation!

Further Reading

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- P. Nghiem, and Tordeux, Coupling correction for the ESRF, 1999.
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- K. Kubo, et al., Phys. Rev. Lett. 88:194891 (2002)
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- A. Streun, 'Low Emittance in SLS', ESLS XIX, 2011
- A. Franchi, 'Coupling Correction in ESRF', FLS 2012