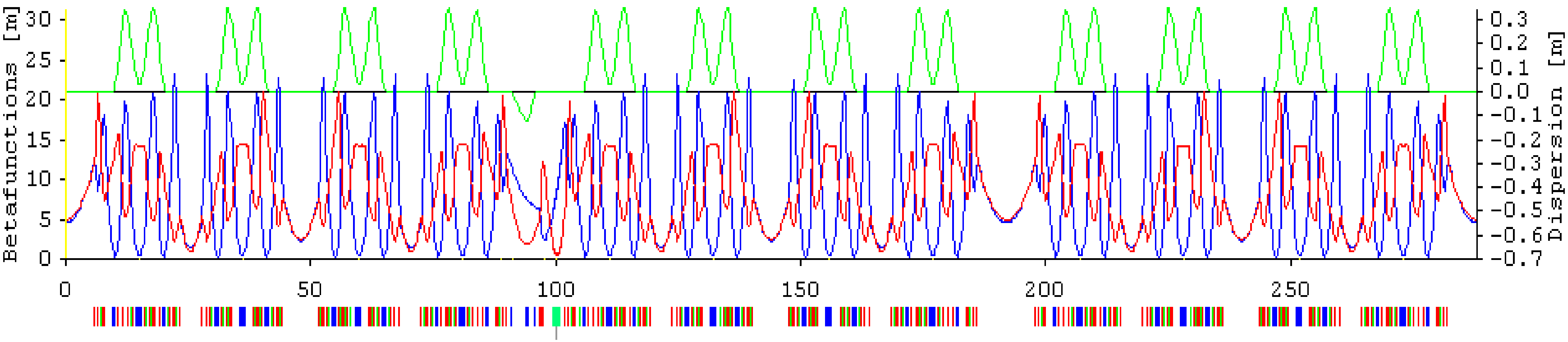
The Swiss Light Source SLS



- 12×TBA lattice, 288 m circumference, 2.4 GeV
- 5.0...6.8 nm emittance (dep. on ID status)
- 400 ±1 mA top up operation
- User operation since 10 years; 18 beam lines
- Upgrades: laser slicing & 3 super-bends
- 1 micron photon beam stability at front ends
- 3 pm rad vertical emittance (0.05% coupling)

Vertical emittance limit

- 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
  - independent of energy!
  - examples:

SLS	**0.20 pm**
SOLEIL	0.26 pm
MAX-IV	0.05 pm
PETRA-III	0.04 pm

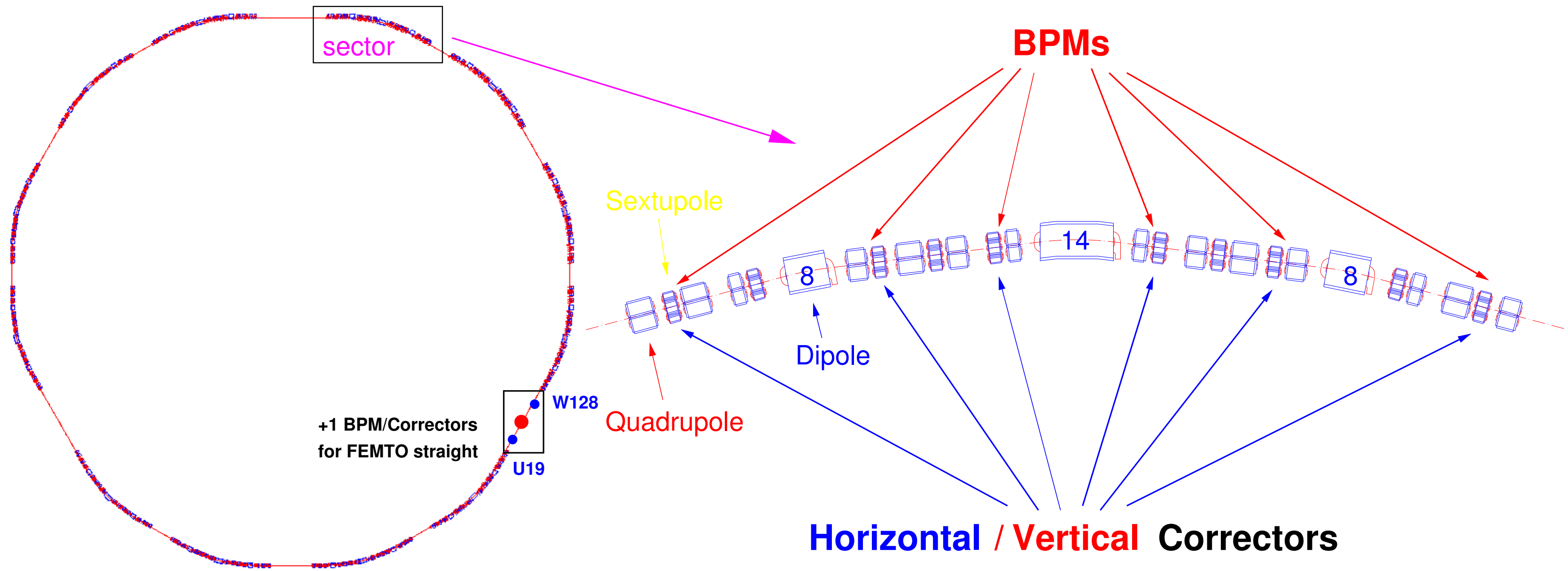
$$\epsilon_y = \frac{13}{55} C_q \frac{\oint \beta_y(s) |G^3(s)| ds}{\oint G^2(s) ds}$$

$G(s)$ =curvature, C_q = 0.384 pm

isomagnetic lattice

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

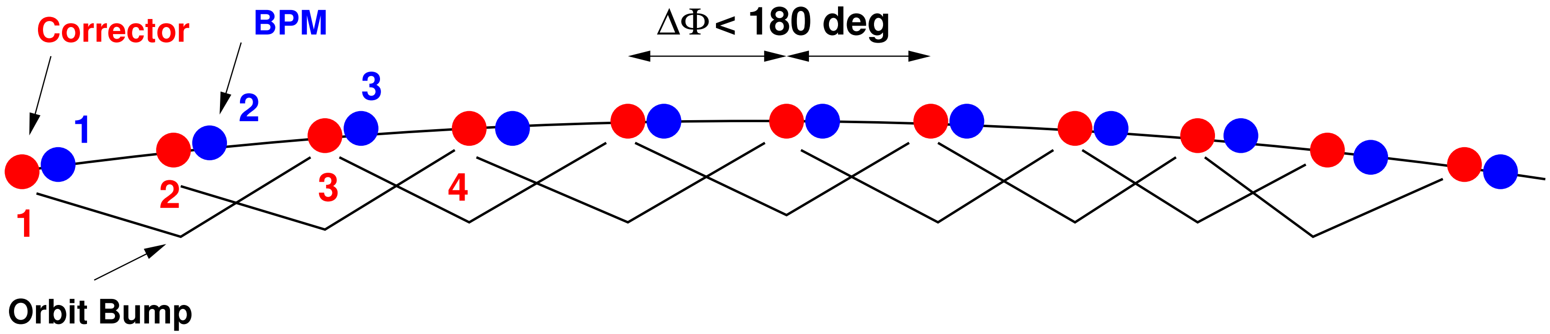
BPM/Corrector Layout



- The SLS Storage Ring is divided into 12 sectors.
- Pairs of 6 BPMs and 6 horizontal/vertical Dipole Corrector Magnets are distributed over one Sector (+1 BPM/Correctors set for FEMTO straight).
- The Corrector Magnets are implemented as extra windings on the Sextupoles, the BPMs are adjacent to the Quadrupols (nonzero orbit in a quadrupole field leads to a dipole kick).

How is the Closed Orbit corrected ?

- **Sliding Bump** - Phase advances between Correctors $0^\circ < \Delta\phi < 180^\circ$, Correctors 1,2,3 allow to zero the orbit in BPM 2 near Corrector 2. 1 opens "Orbit Bump", 2 provides kick for 3 to close it again. Continue ("Slide") with 2,3,4 to zero orbit in BPM 3 ... iterate until orbit is minimized in all BPMs !

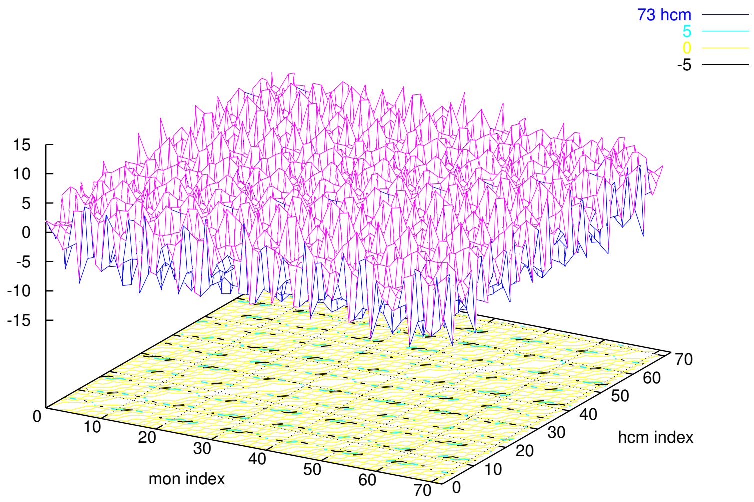


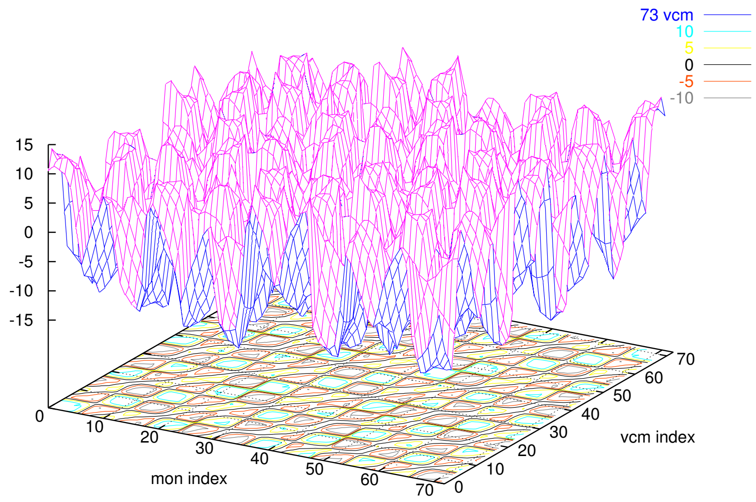
- **MICADO** - Finds a set of "Most Effective Correctors", which minimize the RMS orbit in all BPMs at a minimum ("most effective") RMS Corrector kick by means of the SIMPLEX algorithm. The number of Correctors (= iterations) is selectable.

- **Singular Value Decomposition (SVD)** - Decomposes the "Response Matrix"

  $A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \cos\left[\pi\nu - |\phi_i - \phi_j|\right]$ containing the orbit "response" in BPM i to a change of Corrector j into matrices U,W,V with $A = U * W * V^T$. W is a diagonal matrix containing the sorted Eigenvalues of A. The "inverse" correction matrix is given by $A^{-1} = V * 1/W * U^T$.
  SVD makes the other presented schemes obsolete !-)

Corrector/BPM Response Matrices

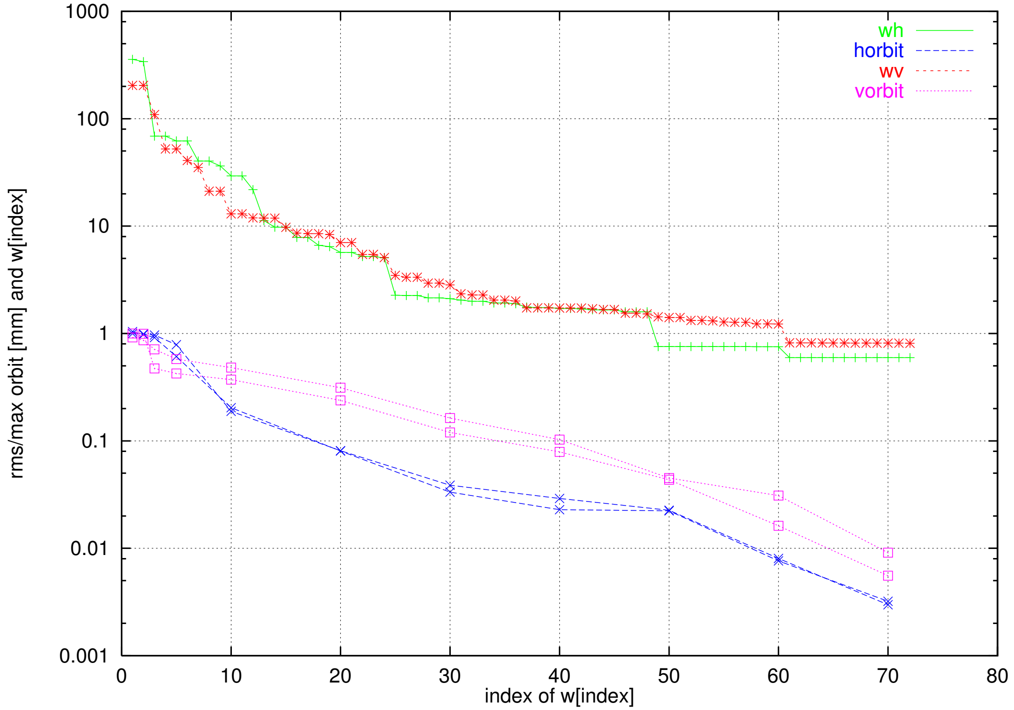




$$A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi\nu} \cos\left[\pi\nu - |\phi_i - \phi_j|\right]$$

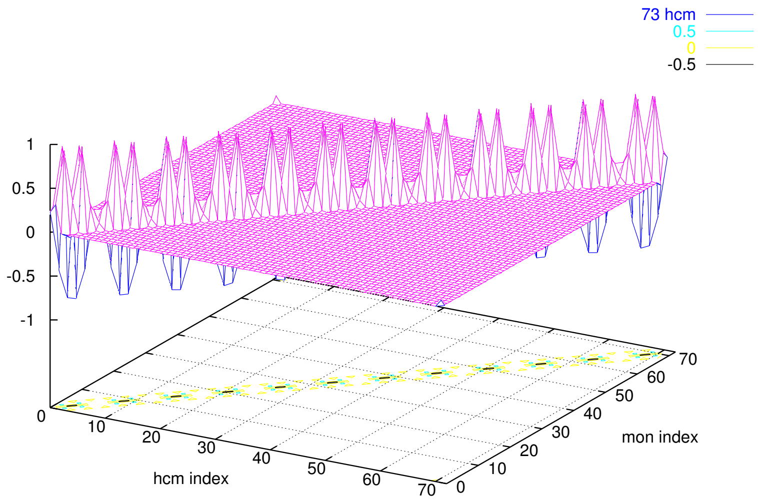
- "Response Matrix": Differences from the "Closed Orbit" ("Difference Orbit") due to a kick of corrector i are recorded at BPM positions $j = 1..73$.
- ν_x = 20.44 (≈3 BPMs/Correctors per unit phase, $\phi = \int_0^s 1/\beta(s)ds$)
- ν_y = 8.74 (≈9 BPMs/correctors per unit phase)

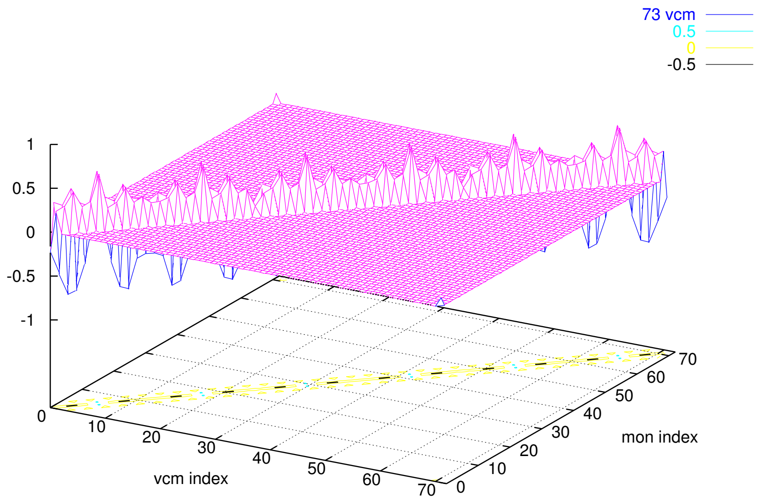
SVD Eigenvalues



- Range of Eigenvalues $0.5 < W < 500$
- Eigenvalue Cutoff @ i_0 ($W_i = 0$ for $i > i_0$) determines the minimum achievable RMS Orbit and Corrector Strength after Correction $\rightarrow$ "MICADO" like: the largest Eigenvalues correspond to the "Most Effective Corrector" patterns
- No Cutoff corresponds to "Matrix Inversion". The RMS Orbit after Correction is Zero !

Inverse Corrector/BPM Response Matrices

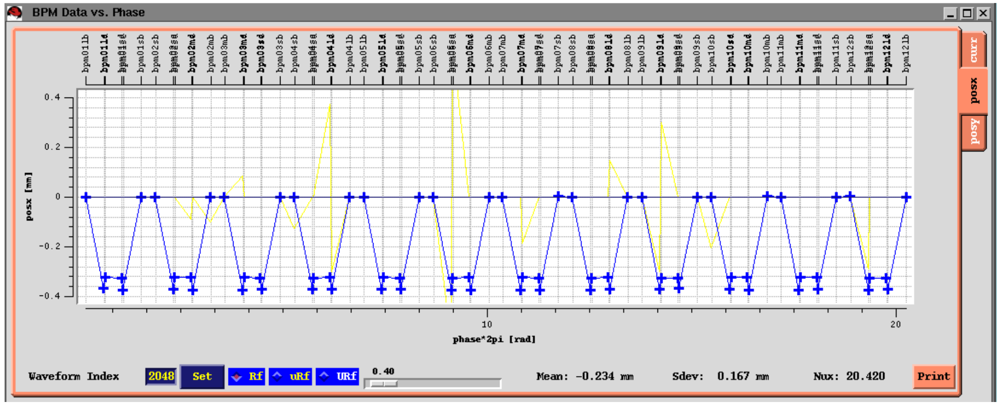


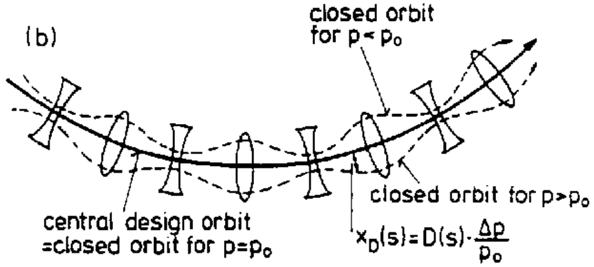


$$A^{-1}_{ij} = (V * 1/W * U^T)_{ij}$$

- A^{-1}_{ij} is a sparse "*tridiagonal*" matrix (3 large (+1 small) adjacent coefficients are nonzero since BPM and Corrector positions are slightly different)
  $\rightarrow$"Sliding Bump Scheme" iteratively inverts A
- A^{-1}_{ij} contains *global* information although it is a "*tridiagonal*" matrix !
  $\rightarrow$ Implementation of a Fast Orbit Feedback (FOFB)

How to correct Off-Energy Orbits ?

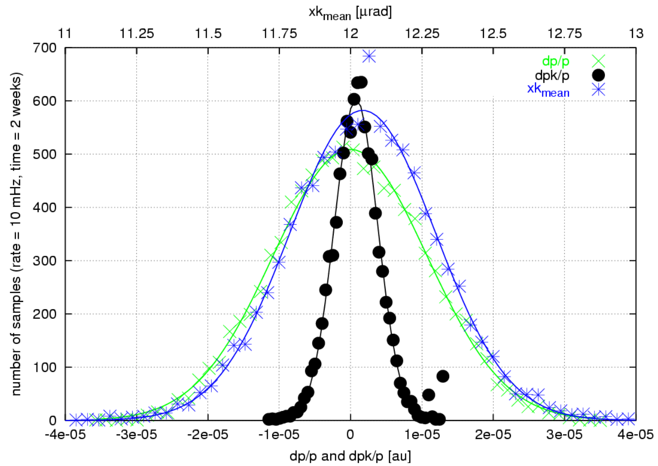


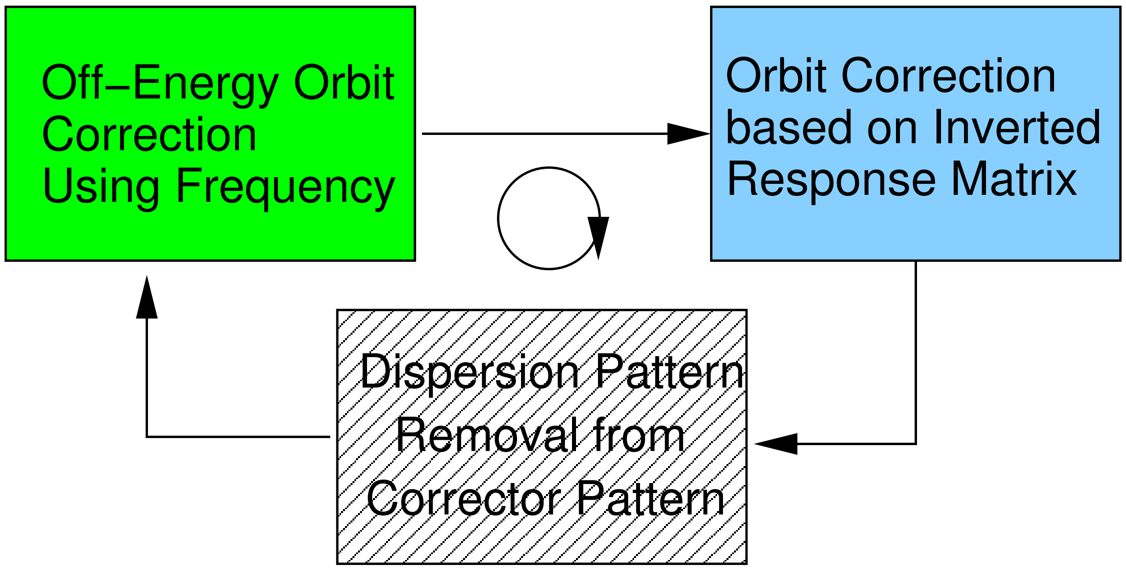


- In the case of "strong focussing" (b) the Orbit Deviation @ a location s is given by $x_0(s) = D(s)\Delta p/p_0$ with $\Delta p = p - p_0$, $D(s)$ denotes the Dispersion. $\Delta L/L_0 = \alpha_c \Delta p/p_0$ with the so-called "Momentum Compaction Factor" $\alpha_c = 1/L_0 \int_0^{L_0} D(s)/\rho(s) ds$ ($\approx\ 6 \cdot 10^{-4}$ at the SLS)
- p variations due to "Path Length" $\Delta L/L_0$ (thermal or modelling effects) changes have to be corrected by means of the RF Frequency f with $\Delta f/f = -\alpha_c \Delta p/p_0$ and NOT by the Orbit Correctors !

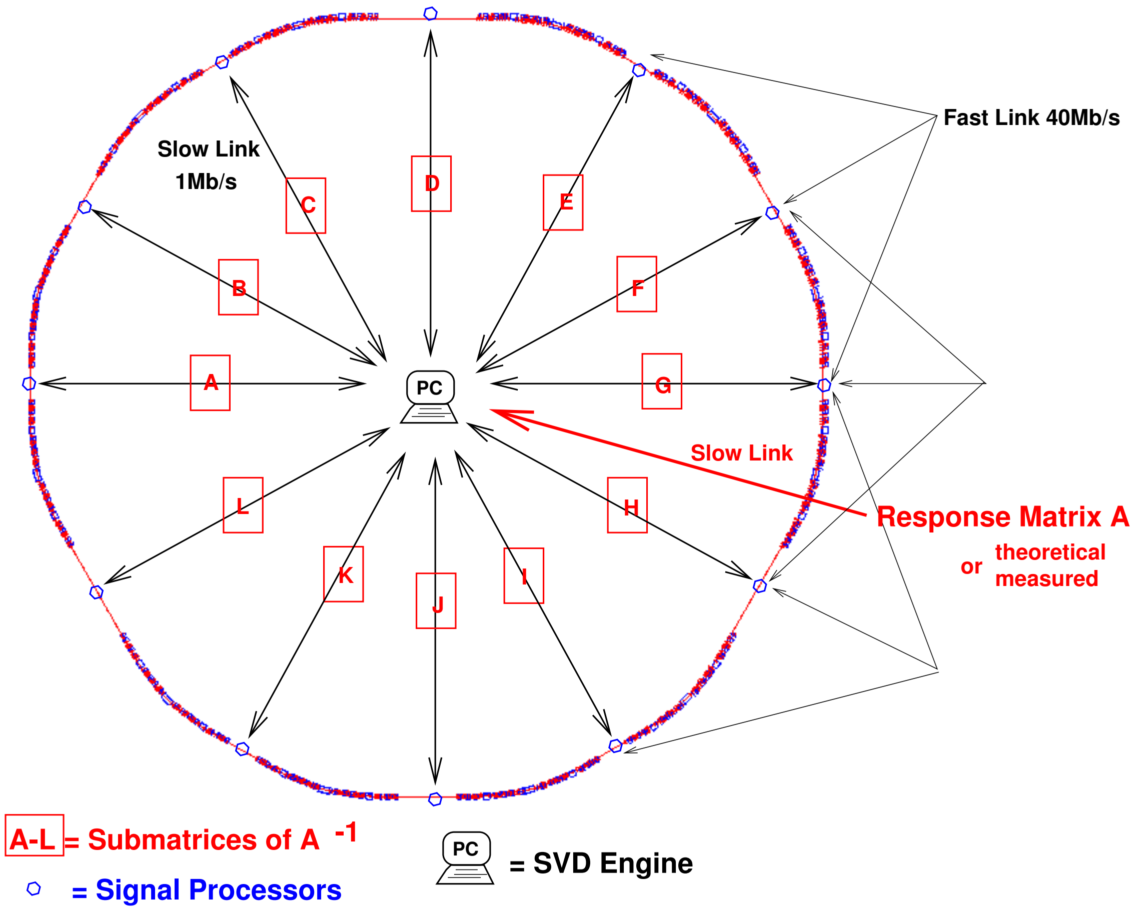
$\longrightarrow$ Fit $\Delta p/p_0$ part of the Orbit using SVD on a 1 column response matrix containing dispersion values D_{i0} @ the BPMs and change the RF frequency by $-\Delta f$ to correct for $\Delta p/p_0$!

Orbit Correction Loop



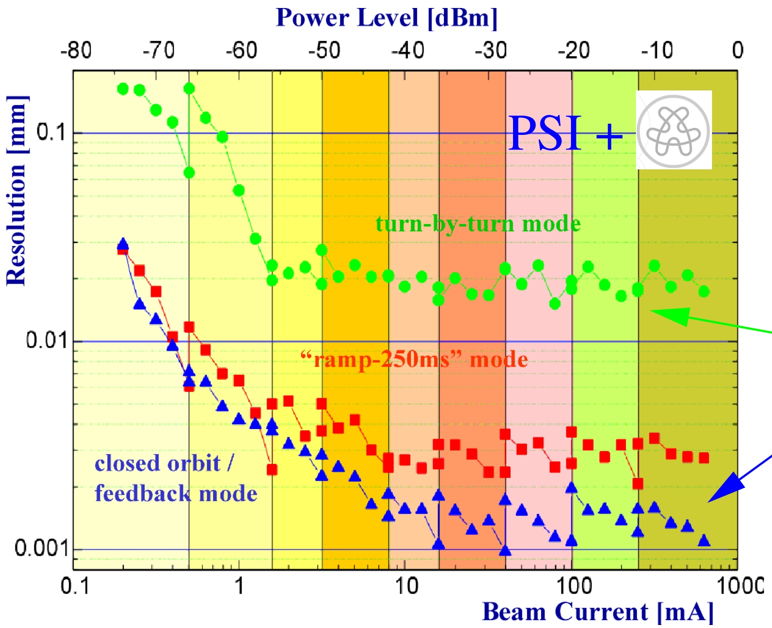


Fast Orbit Feedback - Schematic View



- Dedicated Signal Processors perform Matrix Multiplications in parallel !

Fast Orbit Feedback - Digital BPM System



Only One BPM System in Different Operation Mode for All Machines

Turn–by–Turn:

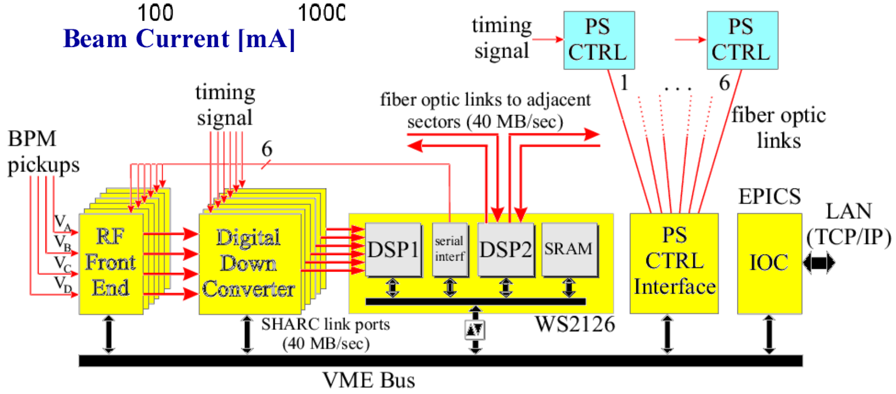
1 MSample/s, <20 μm

Closed Orbit:

4 KSample/s, <0.8 μm

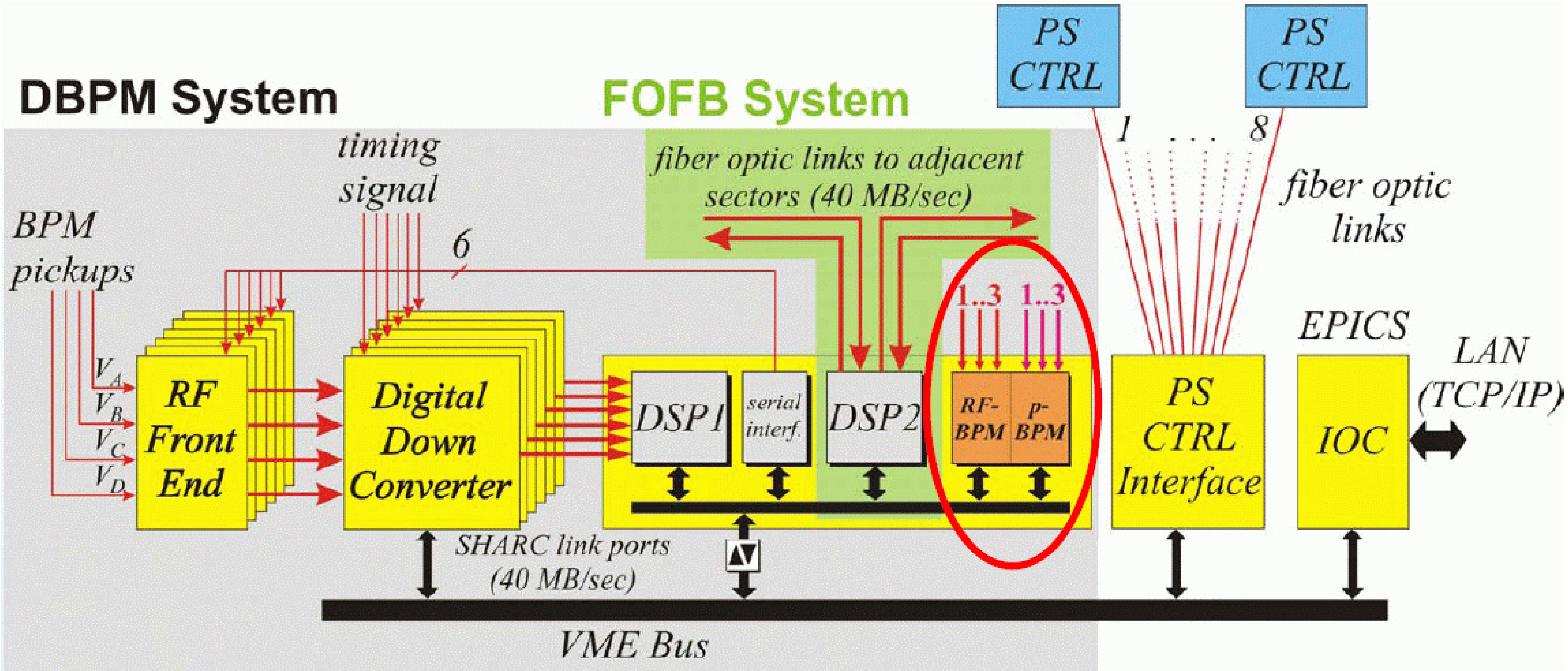
~300 nm <100 Hz

Turn–by–Turn: Vital for Commissioning



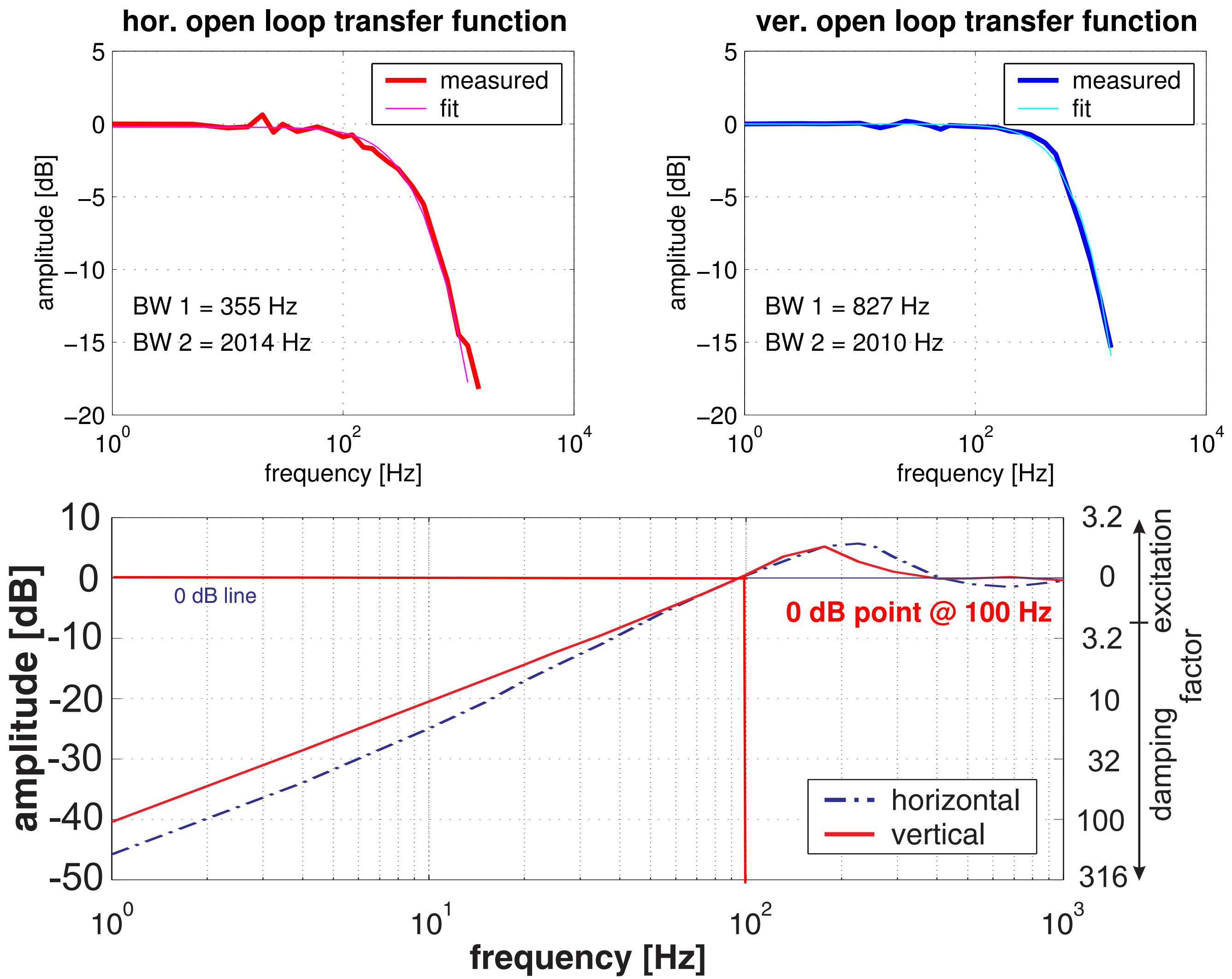
Closed Orbit Mode –> Fast Orbit Feedback

Fast Orbit Feedback - Detail

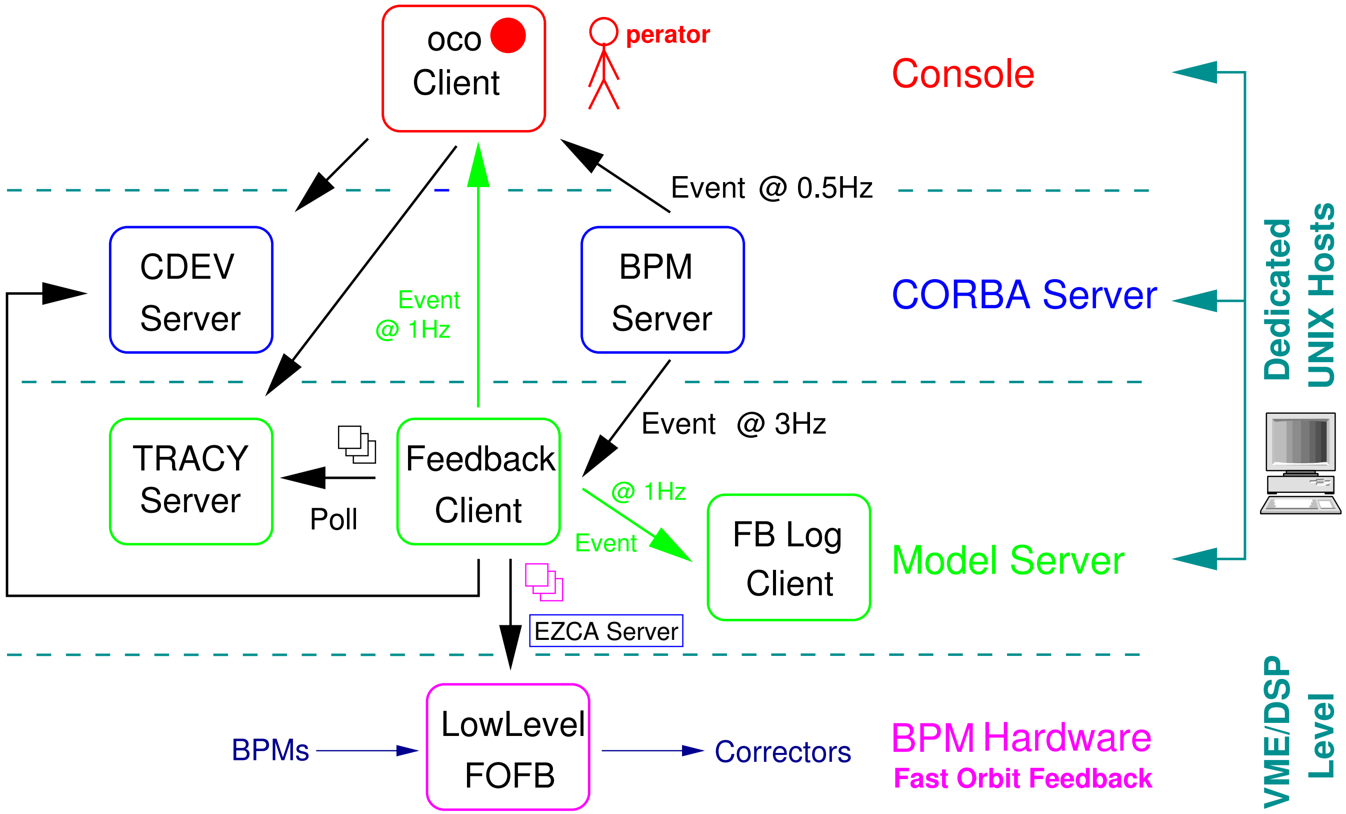


- integration of photon BPMs into FOFB (→IR beamlines)
- DSP processor: ADSP2106x (on the market since Sep. 1994)
- DDC: Intersil HSP50214 (on the market since ~1997)

Fast Orbit Feedback - Performance

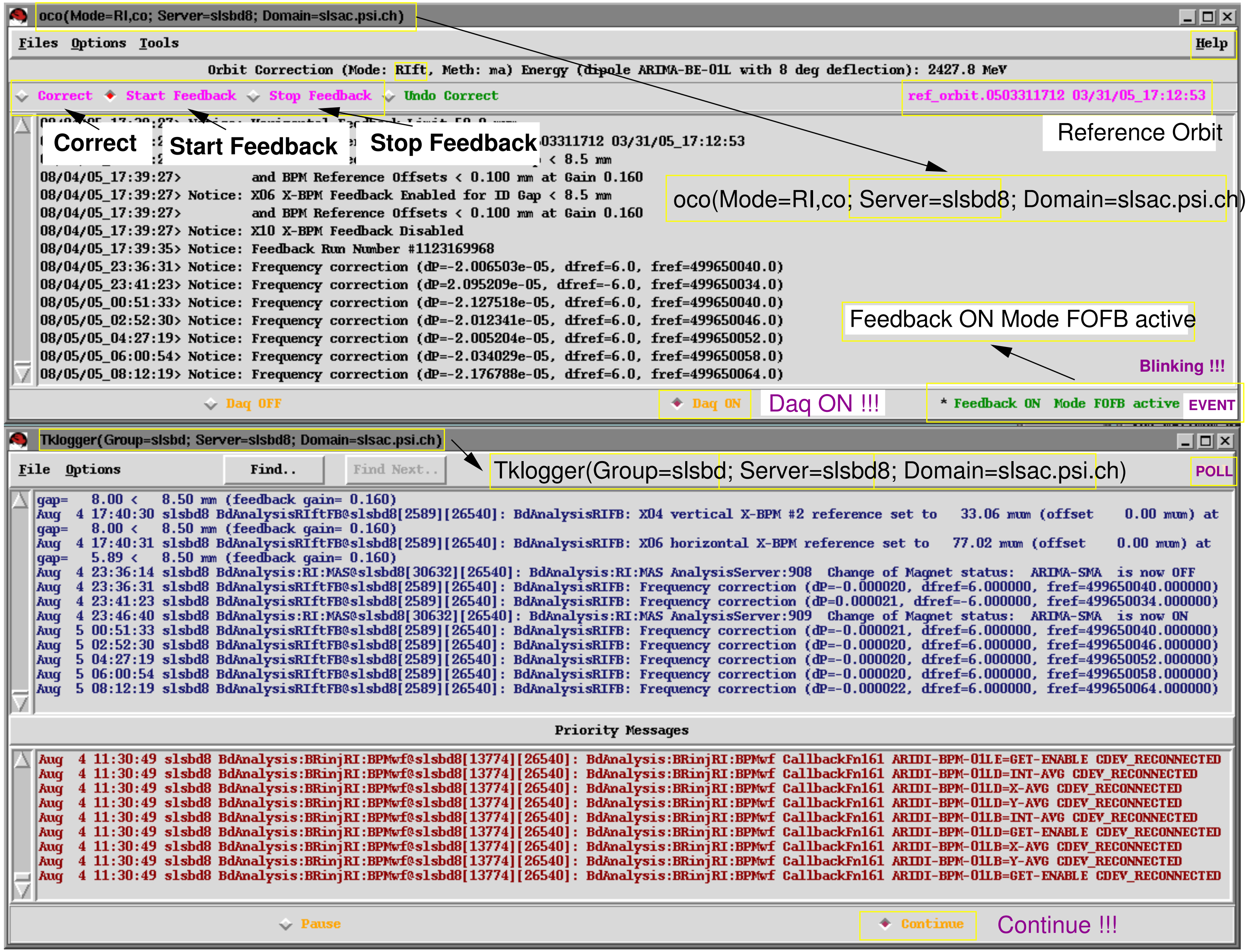


Slow/Fast Orbit Feedback - System Integration

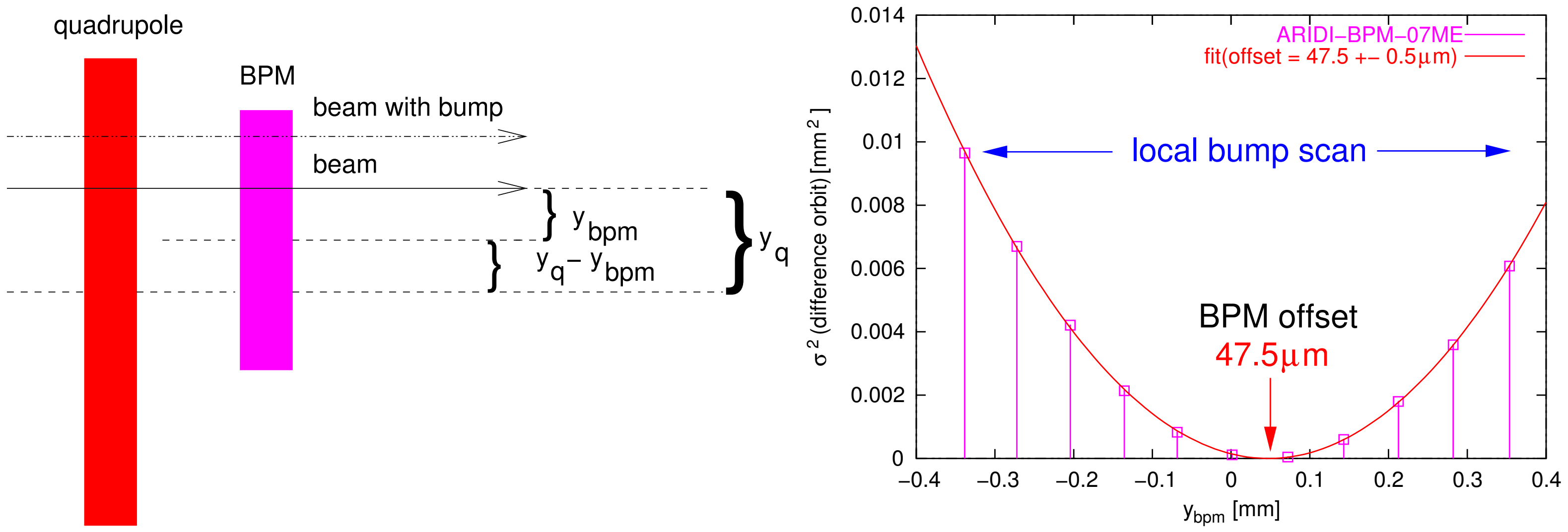


- Development within a Client-Server (Common Object Request Broker CORBA) environment
- Hard Correction ("Matrix Inversion" on the Model based Response Matrix using SVD)
- BPM Datasets @ 3 Hz, average over 3 successive Datasets => ≈ 1 Hz correction rate (toggle between x/y plane => 2 s for full cycle)

Slow/Fast Orbit Feedback - Operator Interface

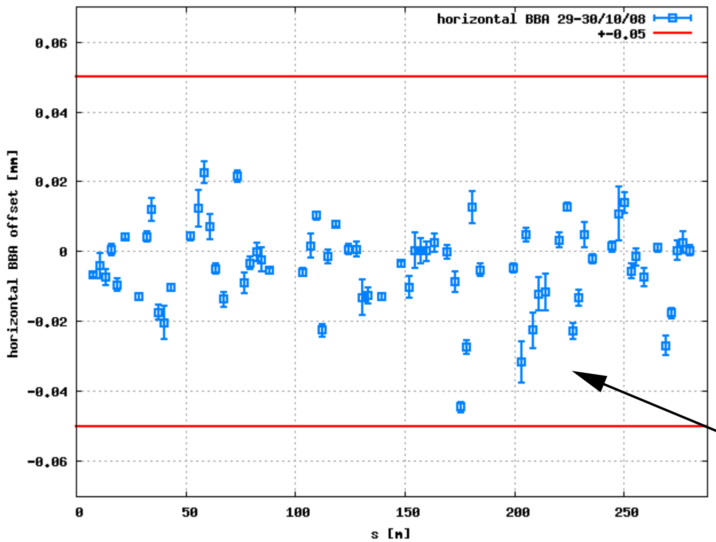


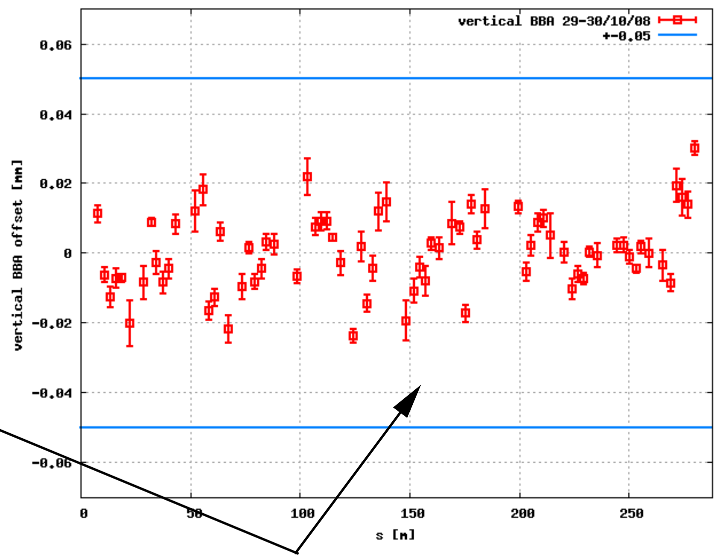
Beam-Based Alignment - Principle

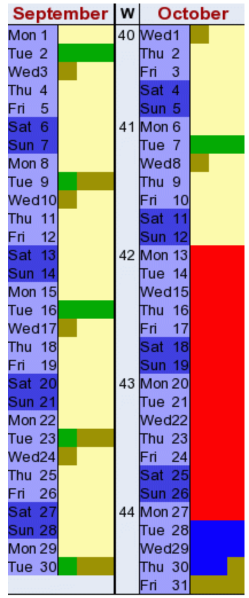


The so-called "Beam-Based Alignment" (BBA) (with respect to quadrupoles) technique is based on the fact that if the strength of a single quadrupole q in the ring is changed, the resulting difference in the closed orbit $\Delta y(s)$ is proportional to the original offset y_q of the beam at q:
$\Delta y''(s) - (k(s) + \Delta k(s))\Delta y(s) = \Delta k(s) y_q(s)$.
The difference orbit is thus given by the closed orbit formula for a single kick, but calculated with the perturbed optics including $\Delta k(s)$. From the measured difference orbit the kick and thus y_q can be easily determined and compared to the nominal orbit y_{bpm} in the BPM adjacent to the quadrupole, yielding the offset between BPM and quadrupole axis. The error of the position y_{bpm} is given by the resolution of the BPM system (Method can also be applied to sextupoles).

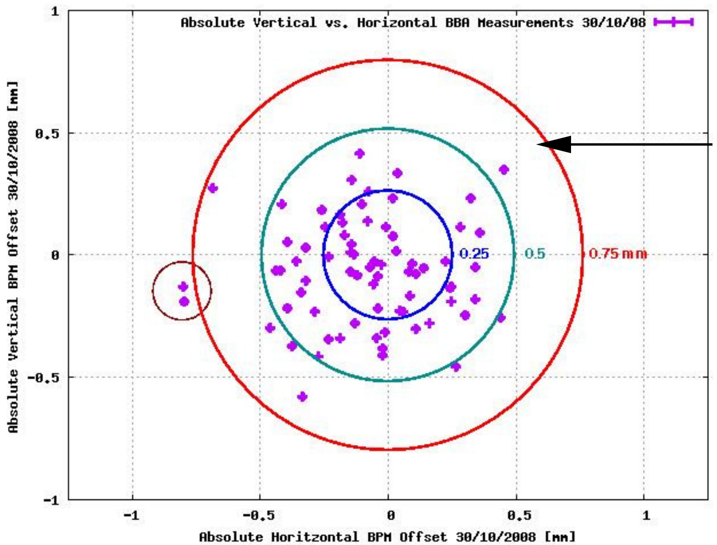
Beam-Based Alignment - Measurements







Changes of BBA constants after 2 months of operation and 2 weeks of shutdown (changes stay within a +-50 um band)



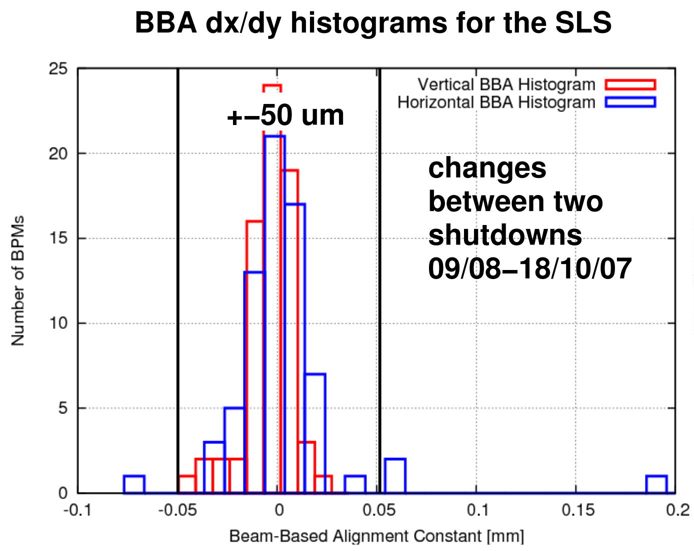
Absolute BBA constants which feature offsets of more than

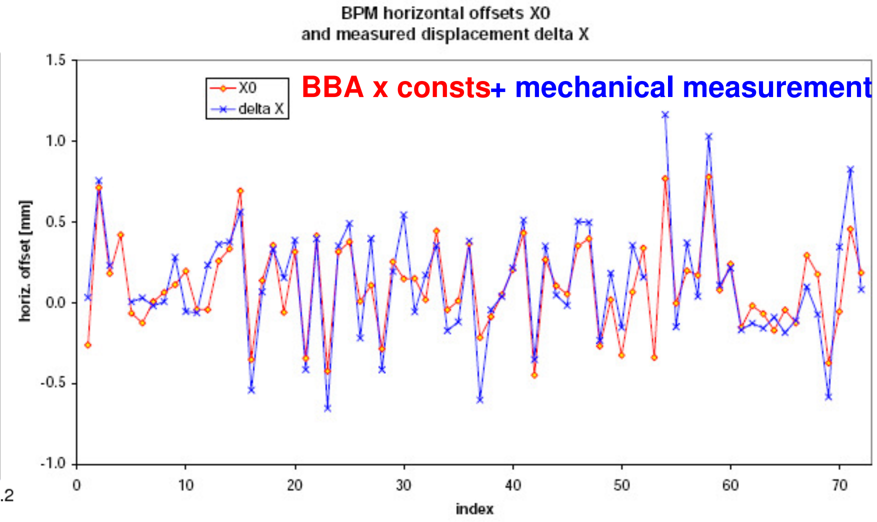
750 um !

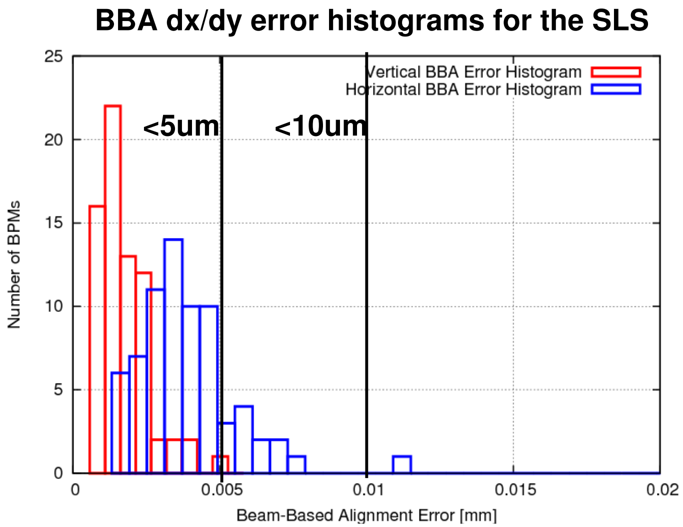
These large offsets are of electronical origin and mechanical origin (vacuum chambers are floating with respect to the quadrupole centers).

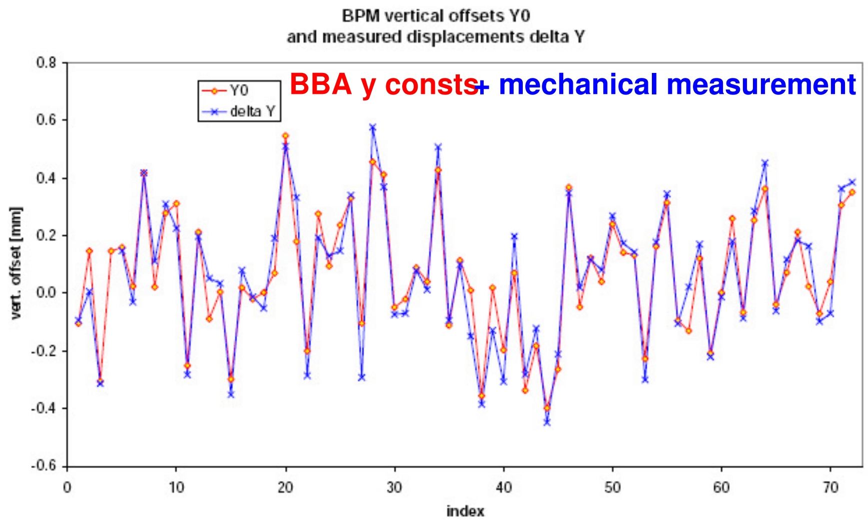
How to destinguish between the two contribution ?

Comparing BBA with Mechanical Measurements

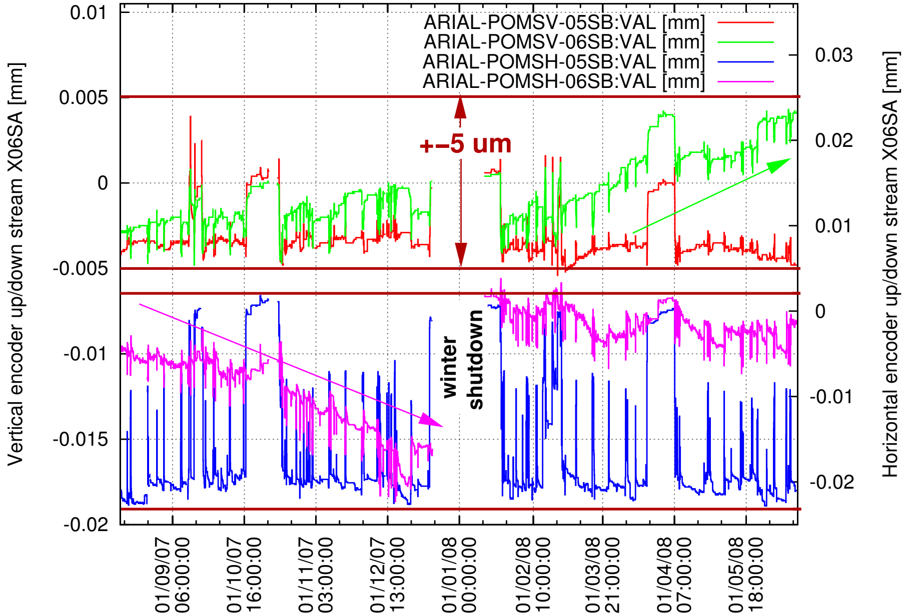


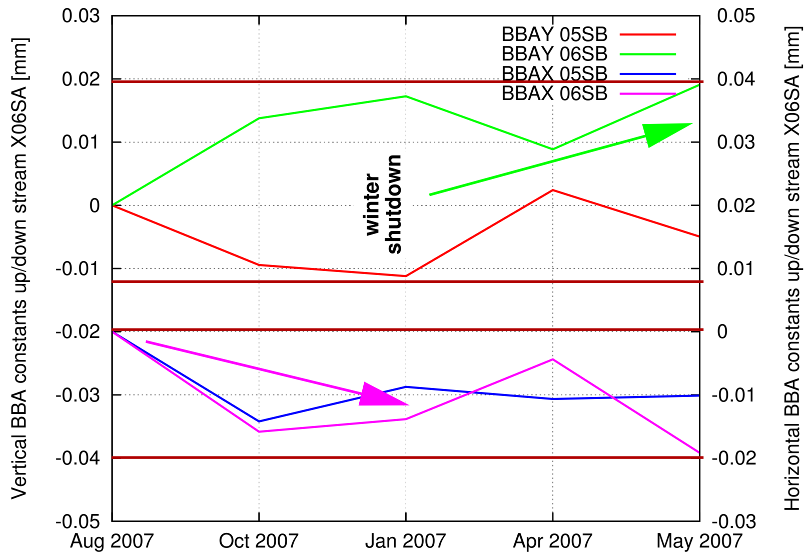






Comparing BBA with Linear Encoders





- Readings of the linear encoders (100 nm resolution) at an undulator beamline readings over ≈10 months stay within a band of ±5/10 μm in the x/y plane (Please note: SLS linear encoders don't have a calibrated zero position).
- The corresponding BBA constants are only roughly following these changes since they are also accounting for drifts of the electronics.

Dynamic alignment system

5 mover motors and encoders:

⇒ set and read **u v χ η σ**

Hydrostatic levelling (HLS)

⇒ read **v χ σ** (*slow...!*)

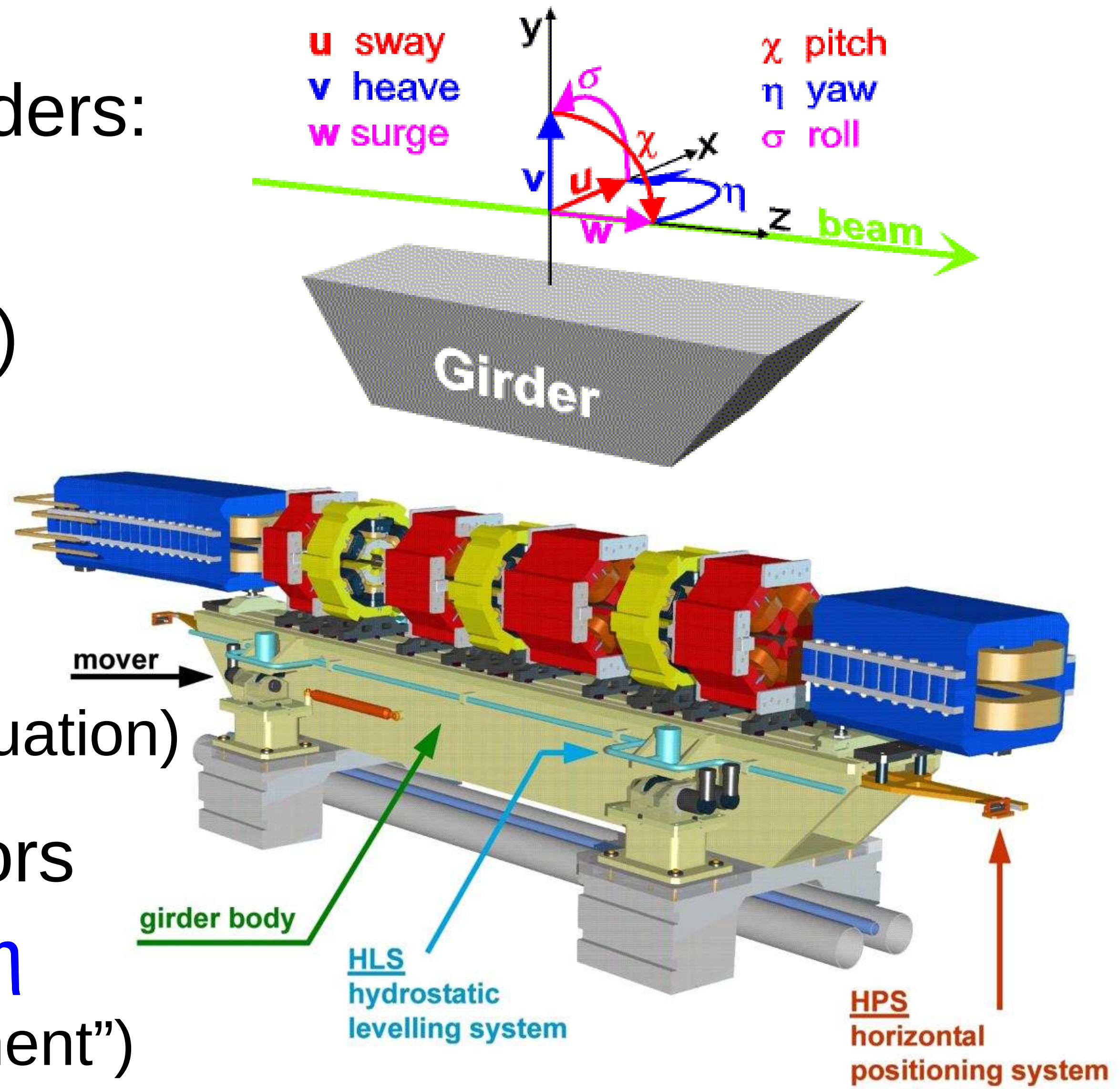
Horizontal sensors (HPS)

⇒ read **u η**
(requires HLS data for evaluation)

BPMs with position monitors

⇒ reconstruction of **u v χ η**
(“beam based girder alignment”)

no control: **w**

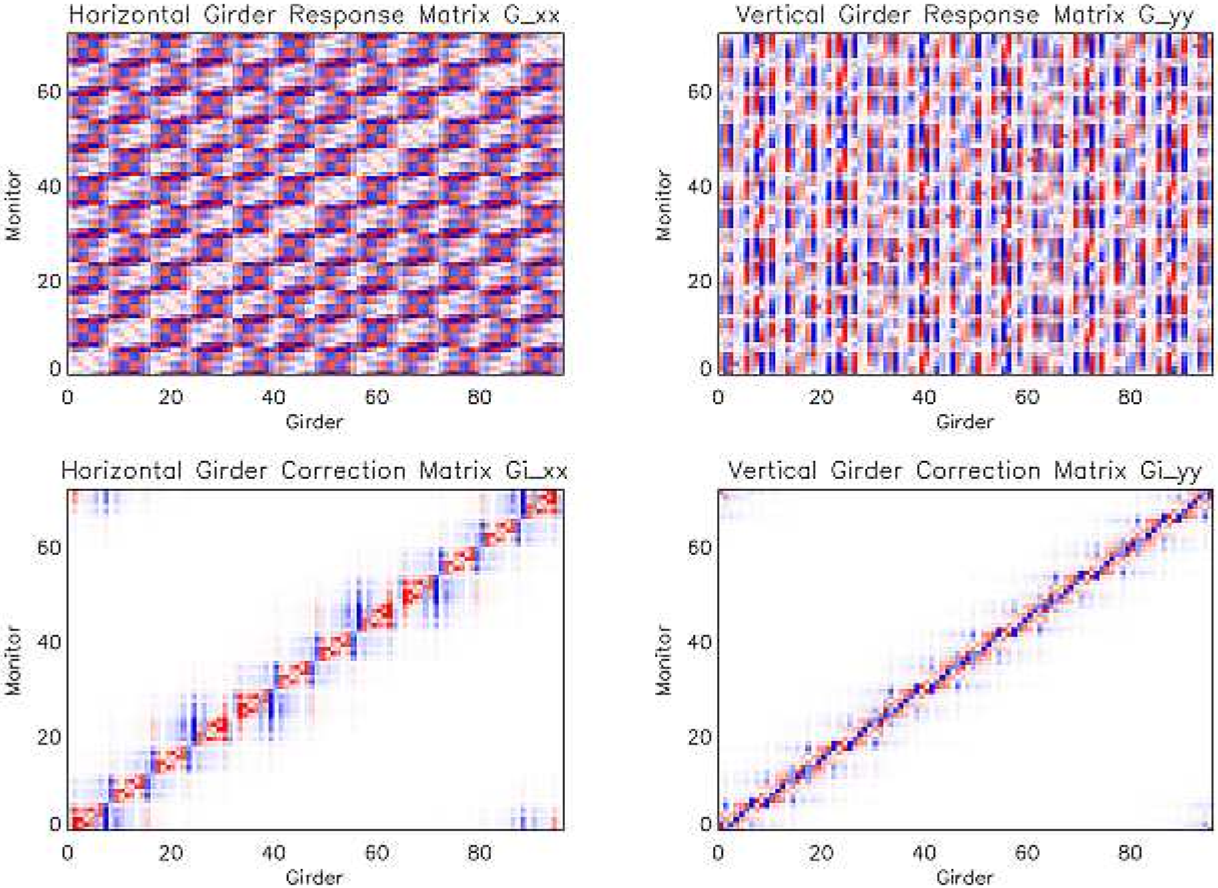


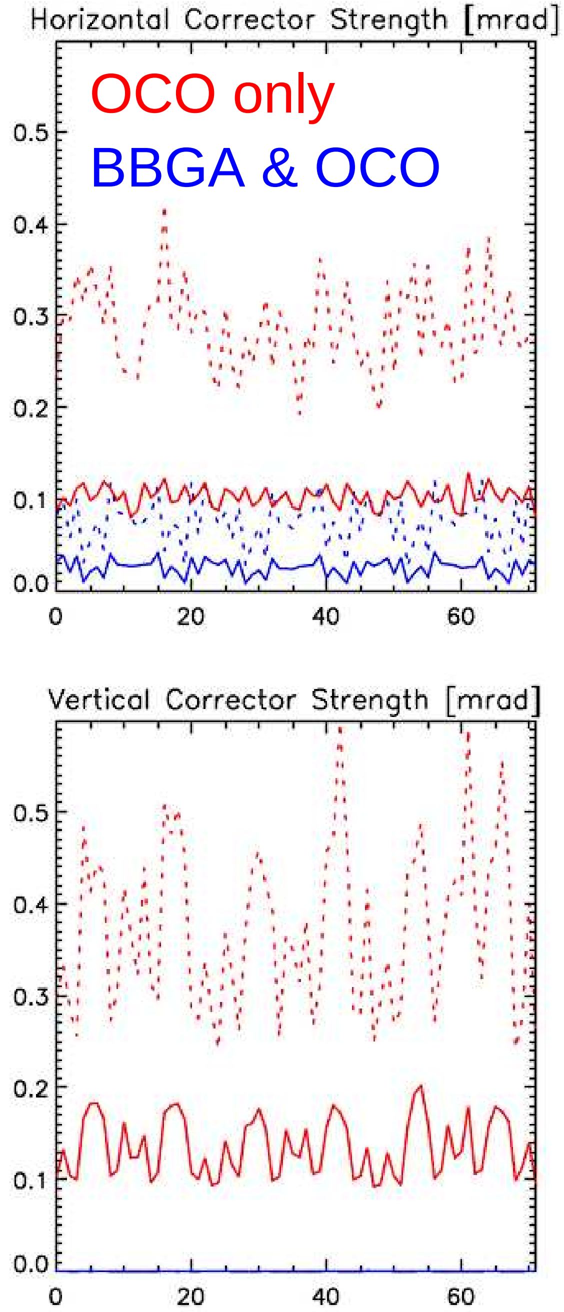
+ coupling correction !

Beam based girder alignment

48 girders = 96 horizontal and vertical “correctors”:
orbit kicks from displaced girder ends

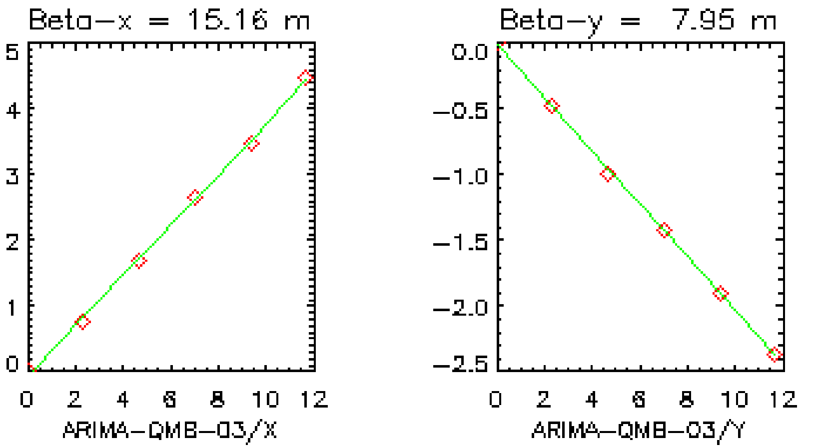
Orbit response and correction matrices



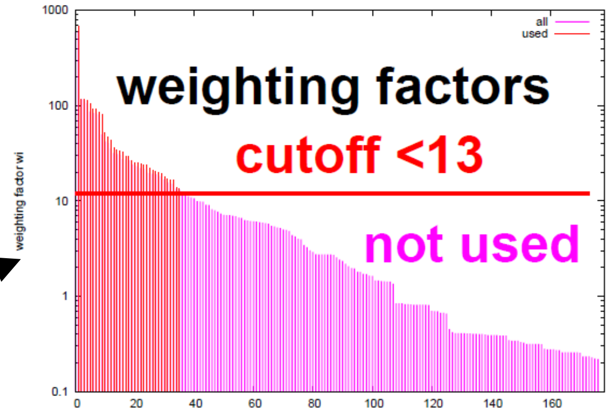


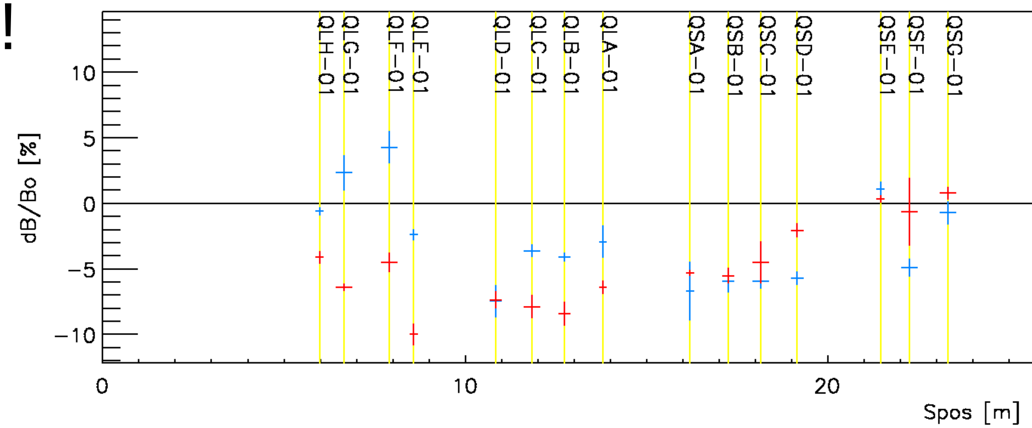
Simulation:	horizontal	vertical
SVD: used/all weighting factors	60/96	96/96
saved magnetic corr. strength	**75%**	**100%**

Beta function measurement and correction at quadrupoles



- Measurement of $\langle\beta_{x,y}\rangle_L$ from tune & single quad variation: Gradient distortion: $\Delta b_2 L \rightarrow \Delta\mu$
  $\cos\mu - \tfrac{1}{2}\langle\beta\rangle_L \Delta b_2 L \sin\mu = \cos(\mu + \Delta\mu) \neq \cos\mu - \Delta\mu \sin\mu \quad (\mu = 2\pi\nu)$
- Precision: 0.5% (rms)
- Beta function response matrix M from model:
  $\{\langle\beta_x\rangle_L ; \langle\beta_y\rangle_L\} = M \bullet \{\Delta b_2 L\}$.
  M is a 354×177 matrix for SLS.
- Solve by SVD with rigorous filtering!
- Apply gradient corrections.
- Beta beat after correction:
  3...4 % in x and y (rms)

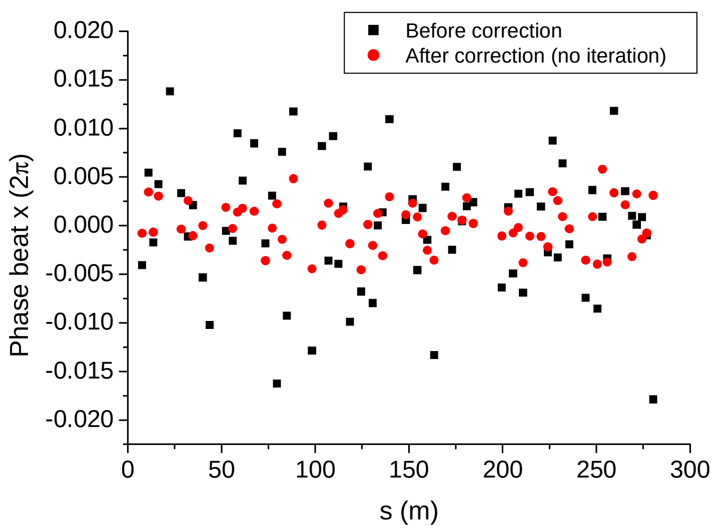


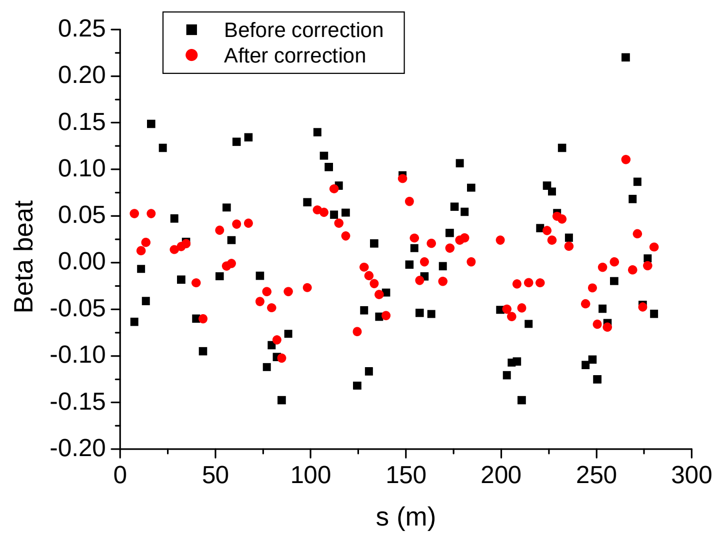


Optics measurement and correction turn by turn BPM data

- Betatron phase advance between BPMs
  - Calibration and model independent measurement
  - Phase-beating correction is equivalent to beta-beating correction
  - Not very successful in vertical plane - under investigation

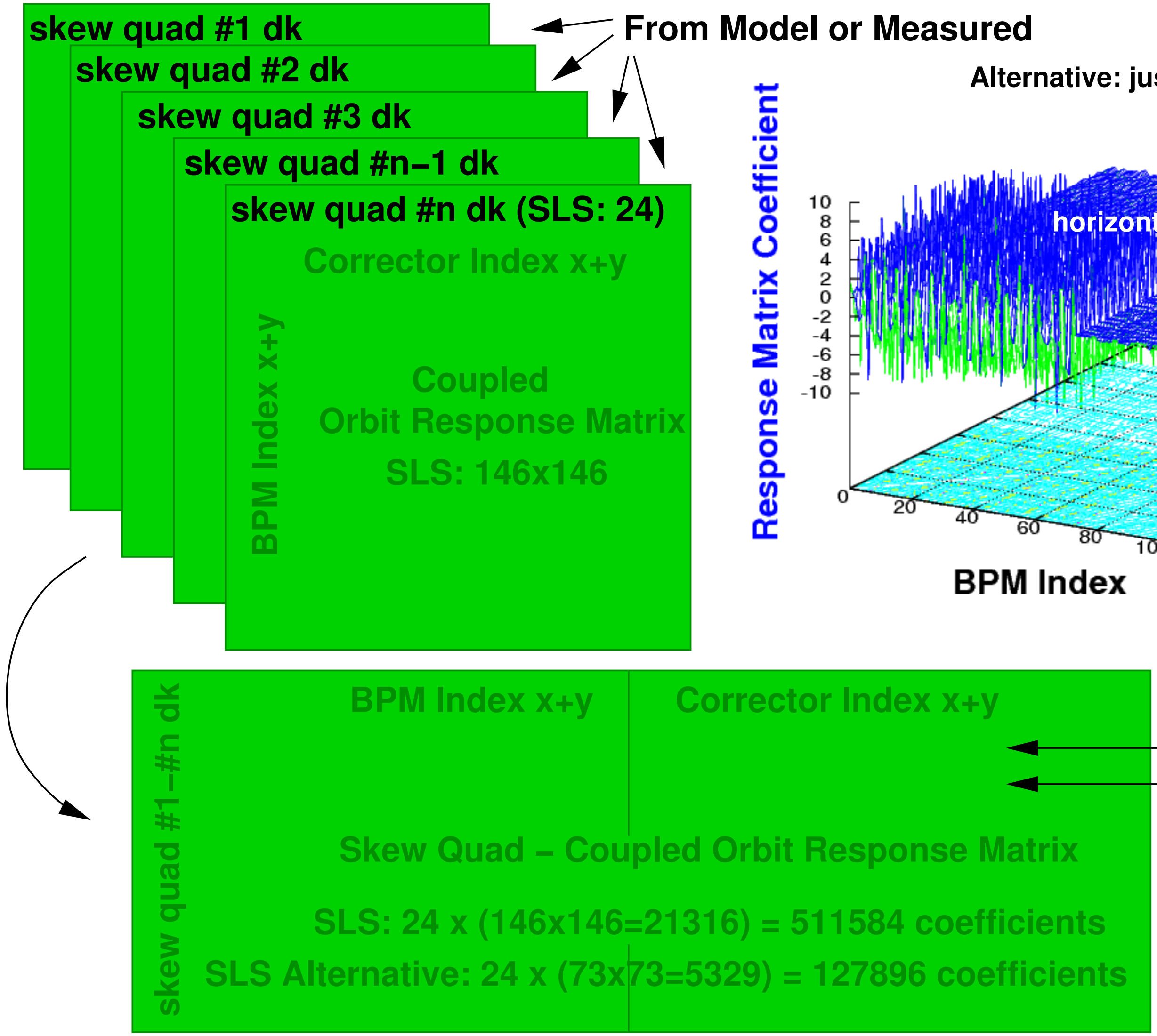
Correction based on phase advance (test on 31.01.11)

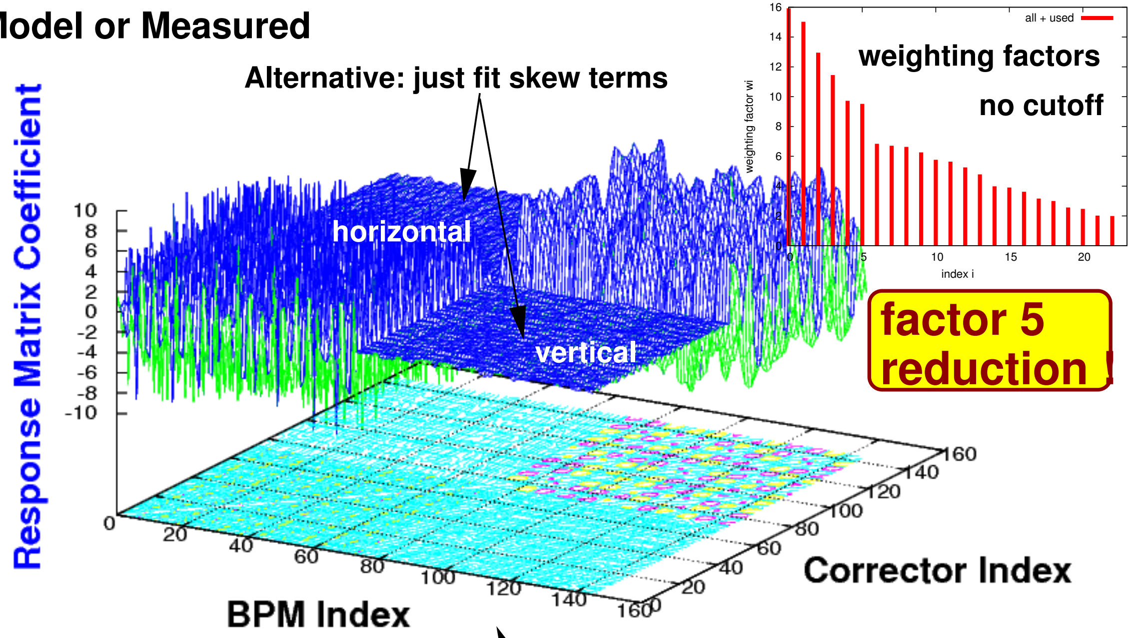




* Beta-beat contains unknown BPM calibration error

Betatron Coupling Correction





- measure the Orbit Response Matrix
- invert 24 x 21316 Matrix using SVD
- plug ORP into the "inverted" Matrix
- calculate quadrupole variations dk_i which fit the model best to the Orbit Response Matrix
- *iterate within model for large errors*
- apply –dk_i to the machine in order to correct the betatron coupling.

Vertical Dispersion/Betatron Coupling Correction - Summary

1. Suppression of η_y by 12 $\eta_x > 0$ skew quads:
   η_y from off-momentum orbit measurement and SVD fit
2. Suppression of $Q_x \pm Q_y$ by 24 $\eta_x = 0$ skew quads.
   response matrix measurement and SVD fit using model RM
3. + some empirical tuning of skew-quad Hamiltonian modes
   h_{00101}, h_{10100} and h_{10010}
   for best ratio $T/\sqrt{\varepsilon_y}$

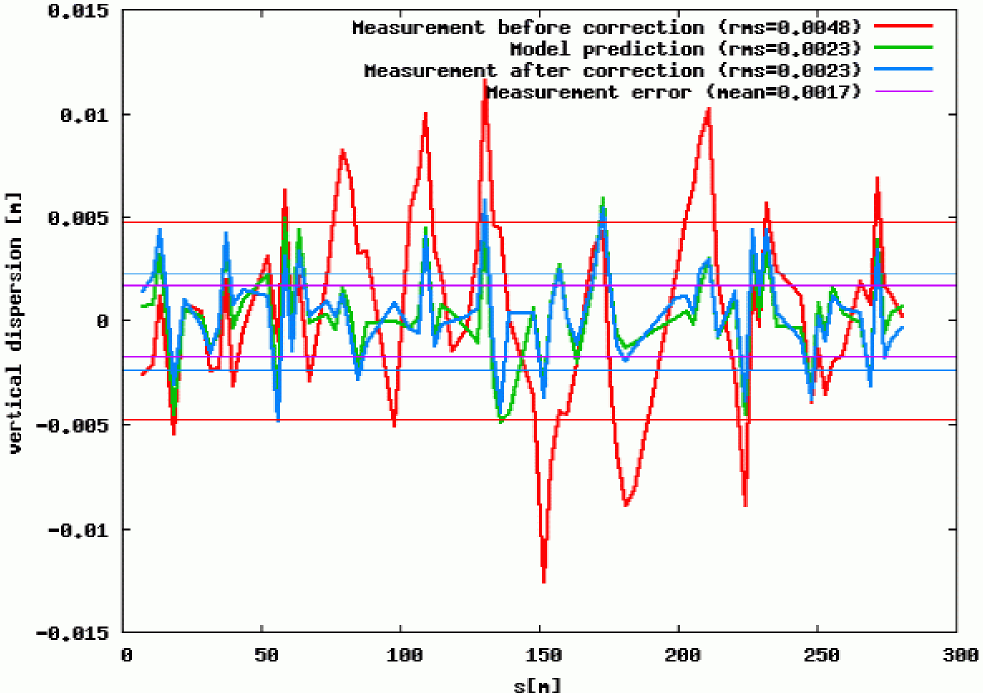
➔ lowest V-emittance:

$\varepsilon_y = 2.8\ (\pm 0.4)$ pm rad

$= 5 \times \varepsilon_{yo}$ from $1/\gamma$

$= 0.05\%$ of ε_x

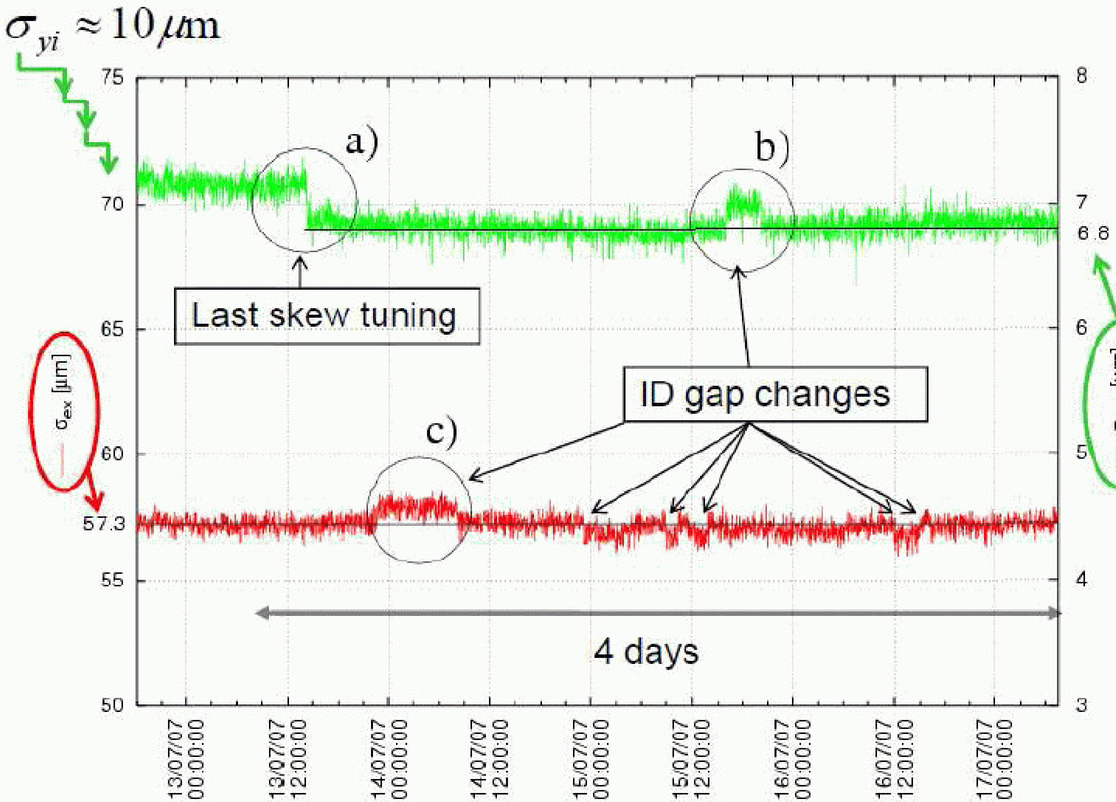
➔ option: η_y-wave to adjust $\varepsilon_y \leftrightarrow T$ on $T \propto \sqrt{\varepsilon_y}$ scaling curve



Sigma and Emittance - Operation

Åke Andersson, CLIC workshop, Oct.16, 2008:

ε_y reduction in user top-up operation, I=400mA



$\beta_y = (13.55 \pm 0.14)\,\mathrm{m}$

$\eta_y = (2.3 \pm 0.55)\,\mathrm{mm}$

$\varepsilon_y = (3.2 \pm 0.7)\,\mathrm{pm}$

$$\frac{\varepsilon_y}{\varepsilon_x} = (0.05 \pm 0.02)\,\%$$

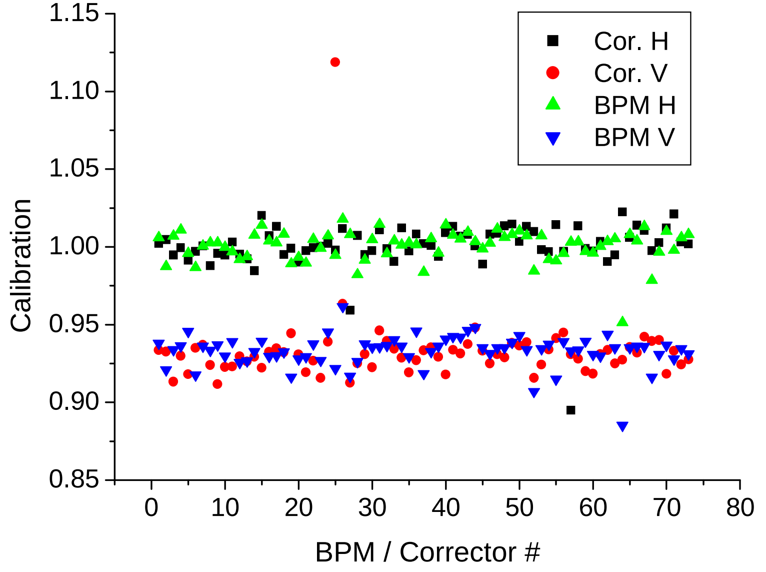
$\beta_x = (0.431 \pm 0.009)\,\mathrm{m}$

$\eta_x = (27.3 \pm 1.0)\,\mathrm{mm}$

$\varepsilon_x = (6.3 + 0.7 - 0.9)\,\mathrm{nm}$

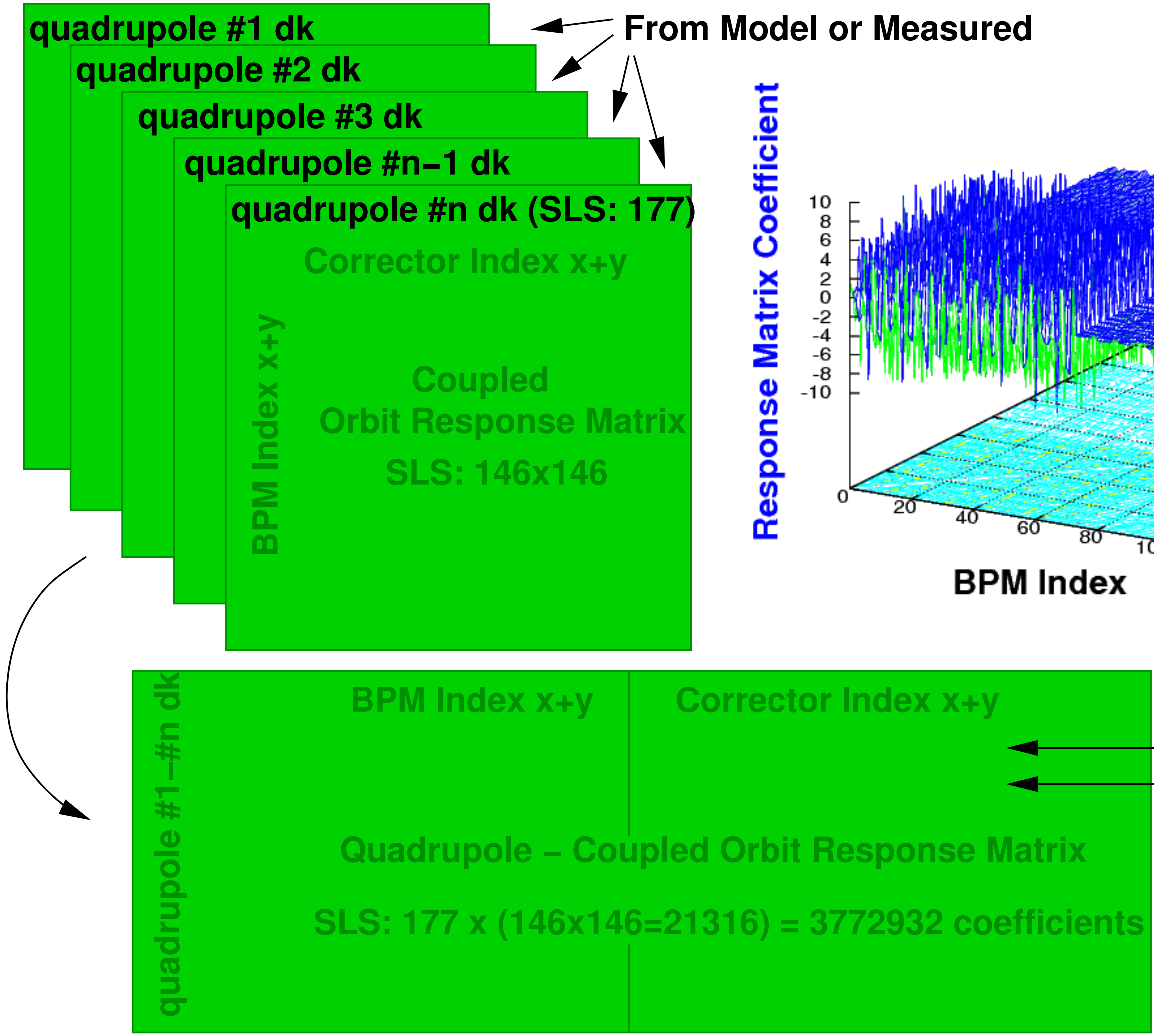
Optics measurement and correction LOCO

- Linear orbit correction based on orbit response
  - Great success at DIAMOND
  - Already done at SLS for the coupling. Extend to correct the linear optics at the same time
  - Infer not only the optics but also corrector/BPM calibration/rotation
    - First test revealed wrong calibration in vertical corrector and/or BPM…



* Systematic offset in vertical plane indicates wrong calibration in corrector and/or BPM

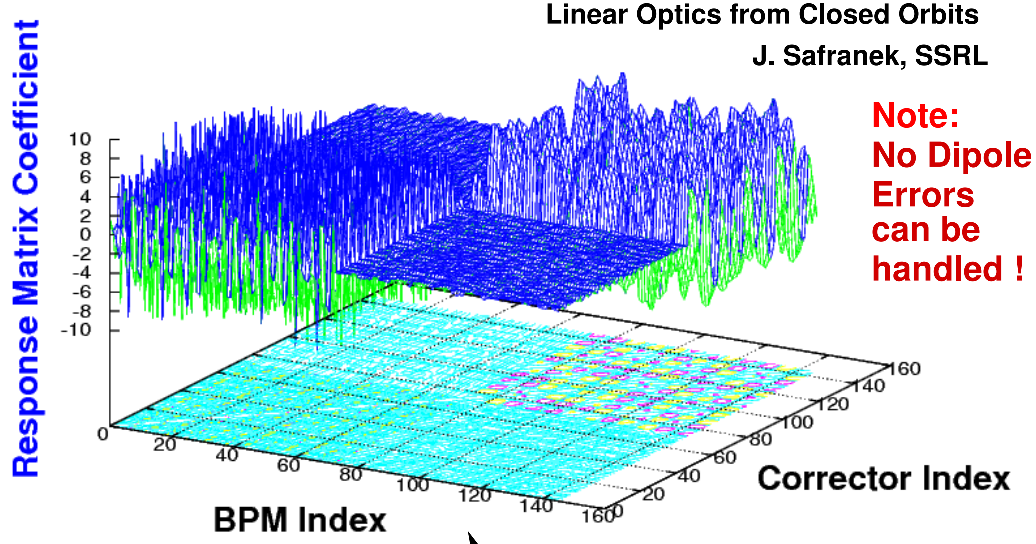
Response Matrix Measurements - LOCO Principle



Doing it the LOCO way

Linear Optics from Closed Orbits

J. Safranek, SSRL



Note: No Dipole Errors can be handled !

- measure the Orbit Response Matrix
- invert 177 x 21316 Matrix using SVD
- plug ORP into the "inverted" Matrix
- calculate quadrupole variations dk_i which fit the model best to the Orbit Response Matrix (cut weight. facs)
- *iterate within model for large errors*
- apply −dk_i to the machine in order to correct the beta beat.

Multipole Correctors

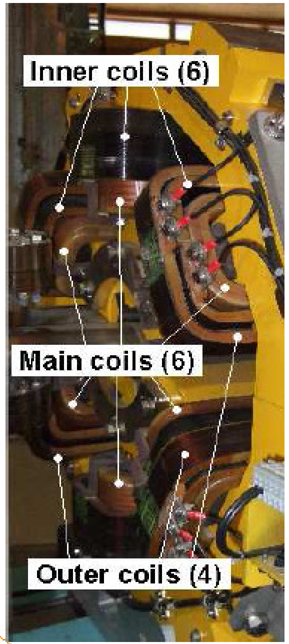
Versatile Sextupoles

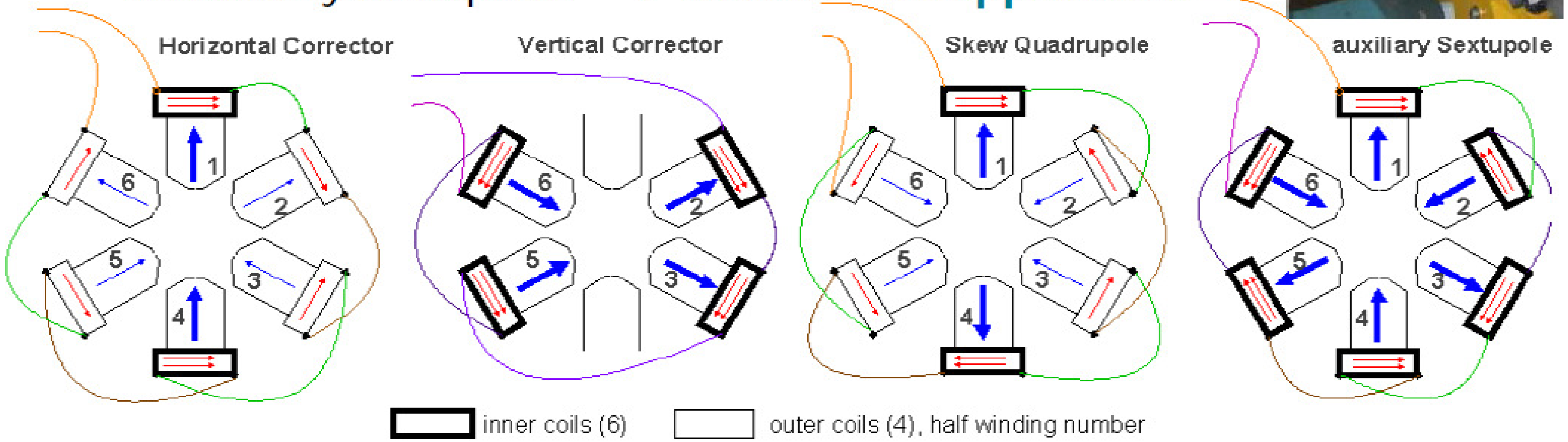
all 120 sextupoles were delivered with H&V corrector coils
⇨ make skew quadrupoles and auxiliary sextupoles

120 sextupoles in 9 families:

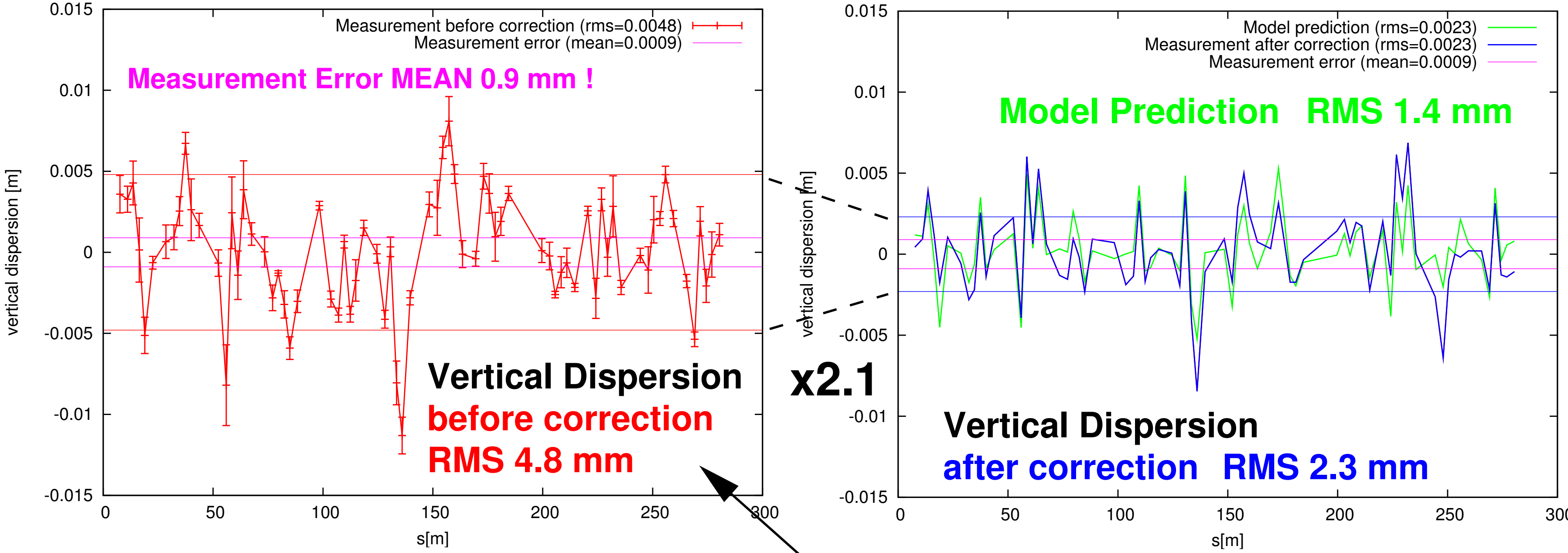
SF(24), SD(24), SE(24) → **chromaticities**
SSA(12), SSB(12), SMA(6), SMB(6), SLA(6), SLB(6) → **D.A.**
SD, SE, S∗B: **72** H&V correctors → **orbit correction**

S∗A: **24** skew quads (η=0) → **betatron coupling**
SF: **12** skew quads (η>0) → **vertical dispersion**
12 auxiliary sextupoles → **resonance suppression**





Vertical Dispersion Correction



Disp Skew Quads

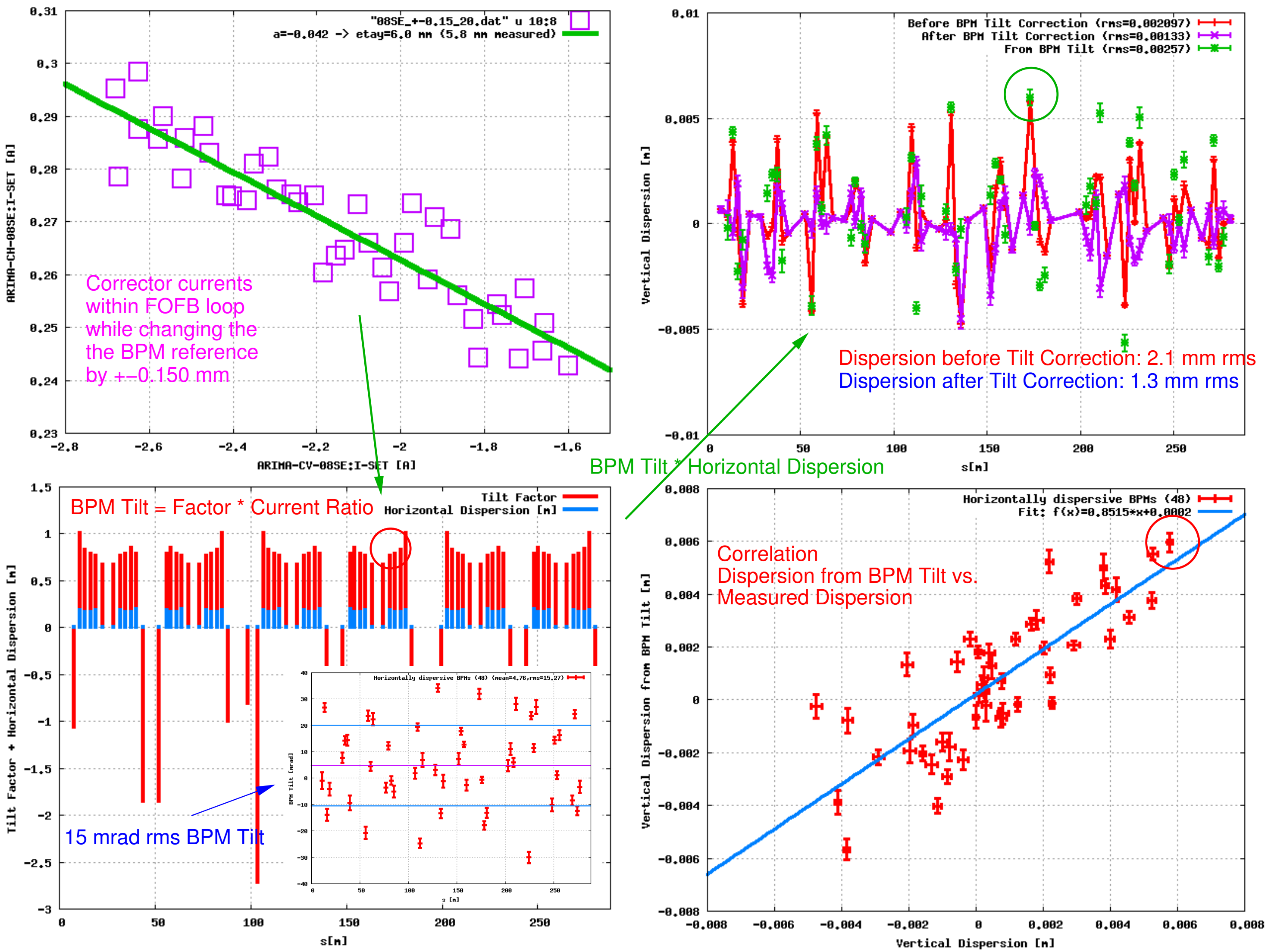
Vertical Dispersion @ BPMs

Skew Quad – Dispersion Response Matrix

SLS: 12 x 73 coefficients

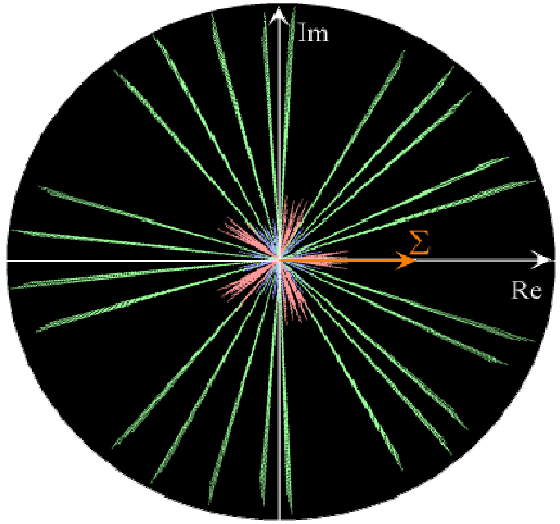
- measure difference orbits for various dp/p
- determine vertical dispersion knowing dp/p
- invert Skew Quad – Dispersion Response Matrix
- feed measured dispersion into it to determine Dispersive Skew Quads values for correction
- Get a Model Prediction
- Apply correction and remeasure

Vertical Dispersion Correction - BPM Tilts



Sextupole symmetrization

$$h_{jklmp} \propto \sum_n^{N_{sext}} (b_3 L)_n \beta_{xn}^{\frac{j+k}{2}} \beta_{yn}^{\frac{l+m}{2}} D_n^p e^{i\{(j-k)\phi_{xn}+(l-m)\phi_{yn}\}}$$



Sextupoles in symmetric *families*:

- Im $(h) = 0$ by lattice symmetry
- design: optimized for Re $(h) \to 0 \ \forall \ h$.

⇨ Auxiliary sextupoles breaking the symmetry

- compensate parasitic Re,Im $(h) \neq 0$.
- first step: do *empirical* optimization
- ≥9 knobs required for Re and Im of h_{21000}, h_{30000}, h_{10200} and h_{10020} and $\Delta\xi_x = 0$
- $h_{10110} \propto h_{21000}$ and $\Delta\xi_y \propto \Delta\xi_x$ (SLS: all aux. sext. at same $\beta_x\, \beta_y\, \eta$)
- 12 auxiliary sextupoles installed

⇨ energy acceptance 2% → **3%**

- auxiliary sextupole strength ~ 3% of SF strength

Multi-purpose coils in sextupoles

all 120 sextupoles were delivered with H&V corrector coils
⇨ make skew quadrupoles and auxiliary sextupoles

120 sextupoles in 9 families:

SF(24), SD(24), SE(24) → **chromaticities**

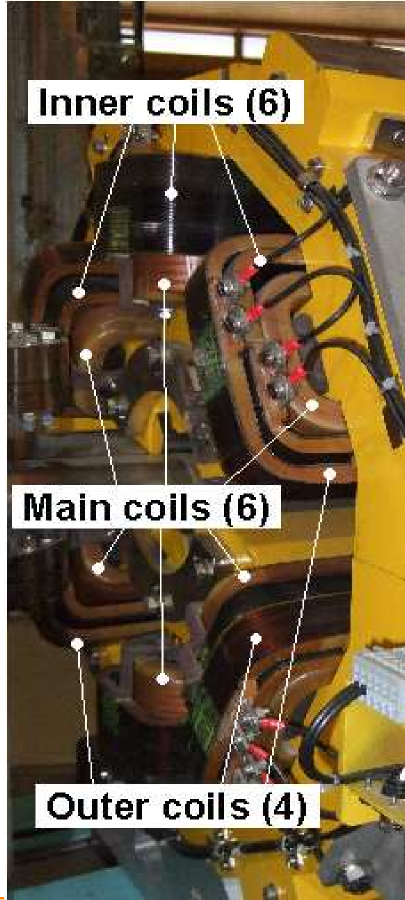
SSA(12), SSB(12), SMA(6), SMB(6), SLA(6), SLB(6) → **D.A.**

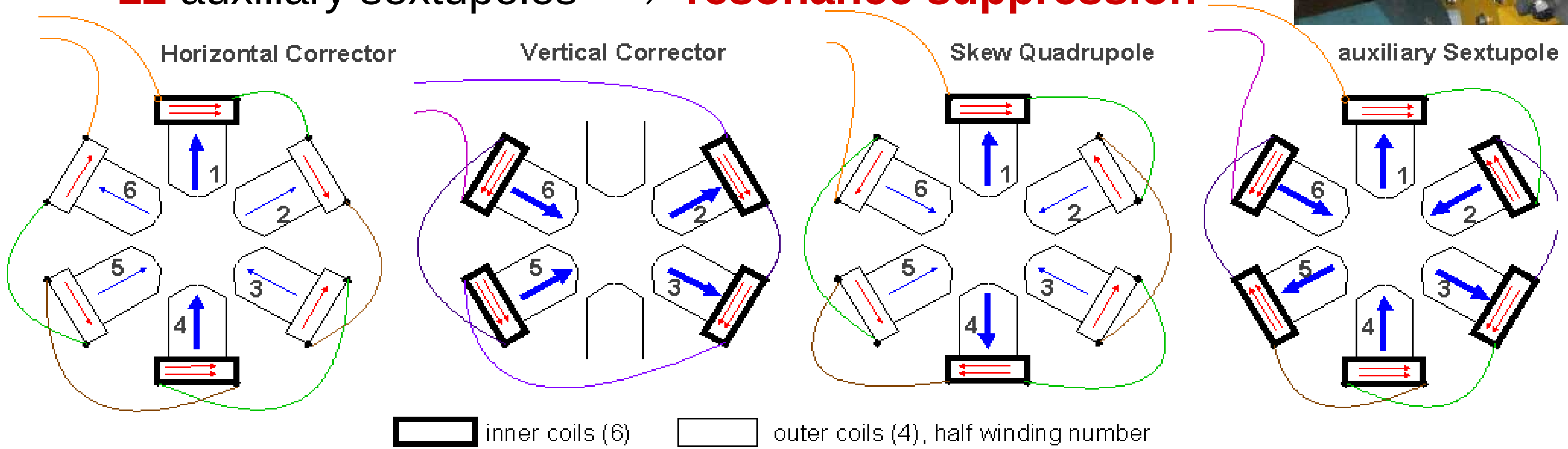
SD, SE, S∗B: **72** H&V correctors → **orbit correction**

S∗A: **24** skew quads ($\eta=0$) → **betatron coupling**

SF: **12** skew quads ($\eta>0$) → **vertical dispersion**

12 auxiliary sextupoles → **resonance suppression**





Touschek (IBS) lifetime measurement

Particle losses due to **T**ouschek and **C**oulomb scattering:

$$\dot{N} = -r_C N - r_T N^2 \Rightarrow N(t) = N_o \frac{e^{-t/T_C}}{1+(1-e^{-t/T_C})\frac{T_C}{T_T}} \approx N_o \cdot \left[1 - t\cdot\left(\frac{1}{T_C}+\frac{1}{T_T}\right)\right] \quad \text{for } t \ll T_C, T_T$$

$r = 1/T$

Touschek life time

RF acceptance

Lattice energy acceptance

Horizontal dynamic aperture

Vertical physical aperture

Betatron coupling

36 skew quadrupoles

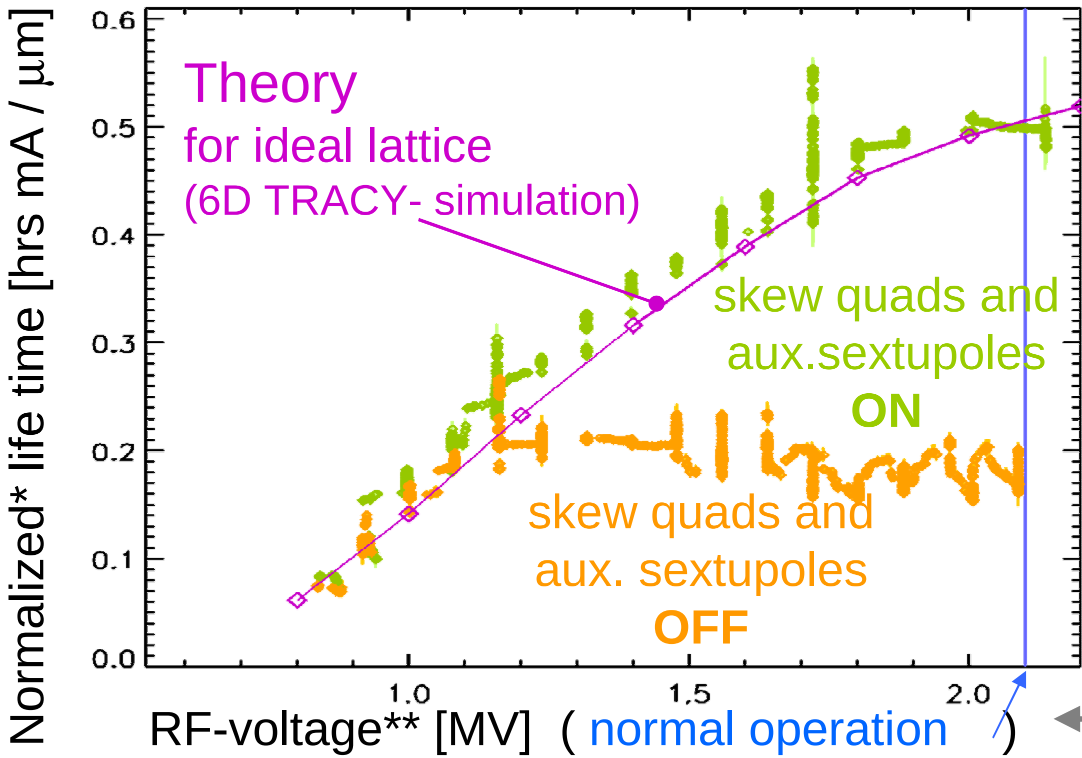
12 auxiliary sextupoles

➔ **Agreement of energy acceptance with design:**

Normalized* life time as function of RF voltage**

* normalized to bunch current and vertical beam size

** without 3rd harmonic cavity



SWISS LIGHT SOURCE

Chao's Sigma Matrices

Evaluation of beam distribution parameters in an electron storage ring – Alexander W. Chao
J.Appl.Phys. 50(2), 1979 p.595–598

V. BEAM SIZES AND SHAPES

Our method can be used to determine quantities like the horizontal and vertical beam sizes, the tilt angle in the x-y plane, the natural bunch length and energy spread, etc. To do this, let us consider a photon being emitted at position s_0 with energy deviating from the mean value by a random amoung δE. Let $T(s_0)$ be the coupled 6×6 transformation matrix for one revolution obtained in Sec. IV without radiation damping. The eigenvalues, λ_k, and eigenvectors, $E_k(s_0)$, of $T(s_0)$ with $K = \pm\mathrm{I}, \pm\mathrm{II}, \pm\mathrm{III}$ are defined by

$$T(s_0)E_k(s_0) = \lambda_k E_k(s_0),$$
$$E_k^*(s_0) = E_{-k}(s_0), \qquad (13)$$
$$\lambda_{\pm k} = \exp(\pm i2\pi\nu_k).$$

Following the photon emission, the subsequent motion of the electron is described by

$$X(s) = \sum_k A_k E_k(s), \qquad s \geqslant s_0, \qquad (14)$$

where $E_k(s)$ is the eigenvector of $T(s)$ obtained from $E_k(s_0)$ by the matrix transformation from s_0 to s. Equation (14) satisfies the initial condition

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -\delta E/E_0 \end{bmatrix} = \sum_k A_k E_k(s_0) \qquad (15)$$

Excitation

and

where the left-hand side is the impulse perturbation to electron state due to the photon emission event. It should be pointed out that the transverse dimensions of the electron are not excited at the instance of photon emission and consequently no knowledge of the energy dispersion functions is needed.

From the symplecticity condition[9] of $T(s)$, i.e.,

$$\tilde{T}ST = S, \qquad (16)$$

where a tilde means taking the transpose of a matrix and

$$S = \begin{bmatrix} 0 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix},$$

one can prove that

2nd moment of eq. 14

$$\tilde{E}_j S E_i = 0 \quad \text{unless } j = -i. \qquad (17)$$

We will normalize the eigenvectors so that

$$\tilde{E}_k^* S E_k = i, \quad k = \mathrm{I}, \mathrm{II}, \mathrm{III}. \qquad (18)$$

This normalization condition is preserved as a function of s due to the symplecticity of $T(s)$. Using Eqs. (17) and (18), Eq. (15) yields

$$A_k = -i(\delta E/E_0)E_{k5}^*(s_0), \qquad (19)$$

where E_{ki} means the i^{th} component of the vector E_k. Assuming all photon emission events are uncorrelated, one obtains the quantum diffusion rate of $|A_k|^2$ by averaging Eq. (19) around the storage ring:

$$\frac{d}{dt}\langle |A_k|^2\rangle = \frac{1}{2\pi R}\oint ds \left\langle \dot{N}\frac{\delta E^2}{E_0^2}\right\rangle |E_{k5}(s)|^2. \qquad (20)$$

In Eq. (20), $\dot{N}$ is the number of photons emitted per unit time and[2,3]

$$\left\langle \dot{N}\frac{\delta E^2}{E_0^2}\right\rangle = \frac{2C_L\gamma^5}{|\rho(s)|^3}, \qquad (21)$$

where $C_L = (55/48\sqrt{3})r_e\hbar/m_e$ with $\hbar$ the reduced Planck's constant, γ is the relativistic factor, and $\rho(s)$ is the bending radius.

So far we have ignored the radiation damping which, when taken into account, gives an additional contribution

$$\frac{d}{dt}\langle |A_k|^2\rangle = -\frac{2\alpha_k}{T_0}\langle |A_k|^2\rangle, \qquad (22)$$

Damping

with T_0 the revolution time and α_k the radiation damping constants found in Sec. IV. The equilibrium values of $\langle |A_k|^2\rangle$ is given by a balance between quantum diffusion and radiation damping, which gives

$$\langle |A_k|^2\rangle = \langle |A_{-k}|^2\rangle$$
$$= C_L\frac{\gamma^5}{c\alpha_k}\oint ds \frac{|E_{k5}(s)|^2}{|\rho(s)|^3}. \qquad (23)$$

generalized emittances Mode I,II,III

Excitation = Damping

It follows from Eq. (14) that the particle distribution parameters at postion s are given by

$$\langle x_i x_j\rangle(s) = 2\sum_{k=\mathrm{I,II,III}} \langle |A_k|^2\rangle \mathrm{Re}[E_{ki}(s)E_{kj}^*(s)]. \qquad (24)$$

Equations (23) and (24) are our final expressions. The tilt angle θ of the x-y beam profile relative to the horizontal axis can be found from

Undamped Eigenvectors transformed from s0 to s using 6x6 Matrix T(s)

Tilt

$$\tan 2\theta = \frac{2\langle xy\rangle}{\langle x^2\rangle - \langle y^2\rangle} \qquad (25)$$

and the transverse beam area (for luminosity calculation) is given by

$$A = \pi(\langle x^2\rangle\langle y^2\rangle - \langle xy\rangle^2)^{1/2}. \qquad (26)$$

ACKNOWLEDGMENTS

The author would like to thank Professor G.-A. Voss and his colleagues at DESY, where most of this work was done, for the hospitality extended to him during his visit there.

Easily implemented in codes with 6x6 formalism (with radiation and damping) –> TRACY–2

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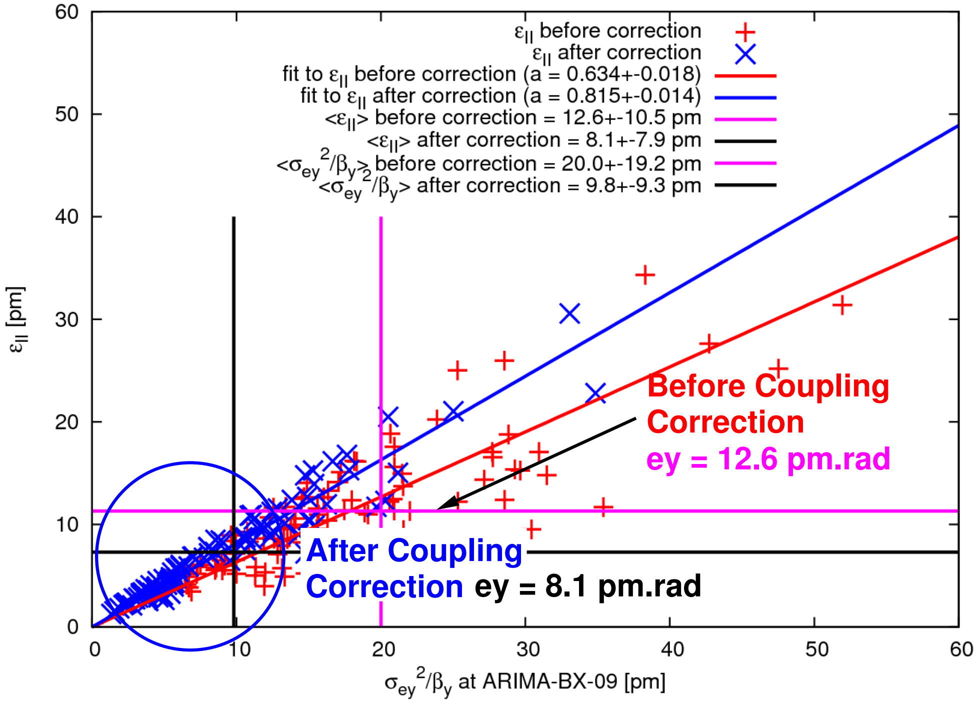
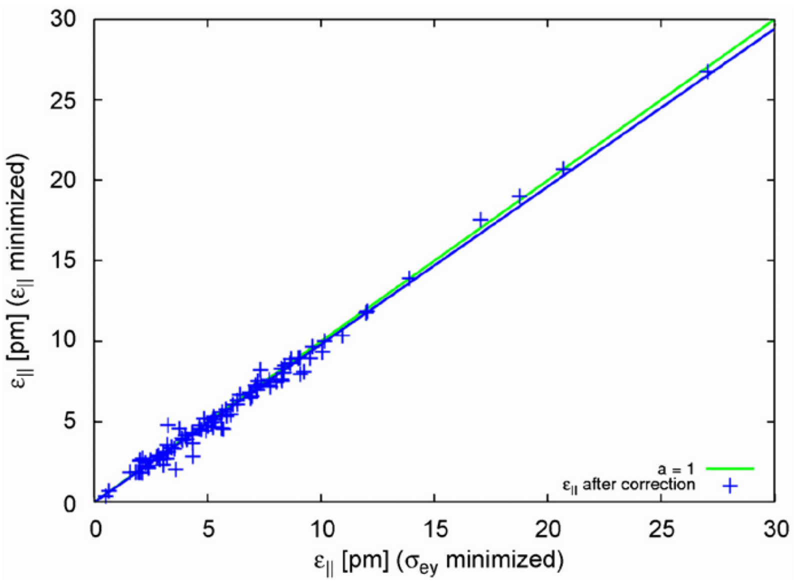
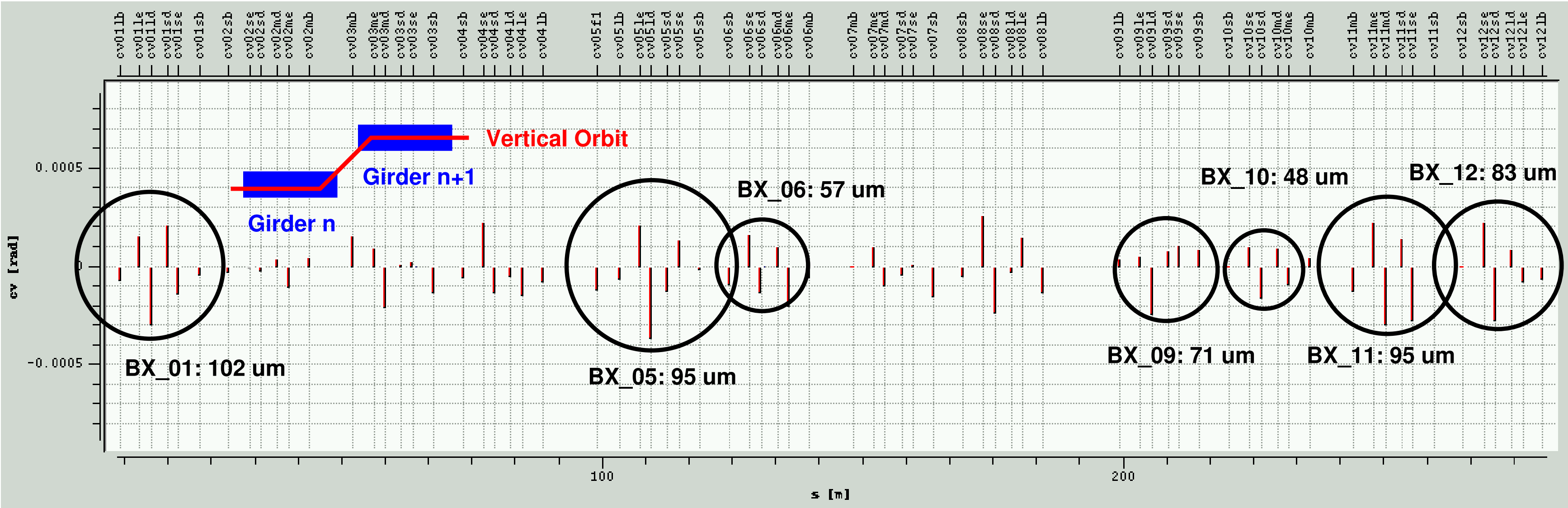
Sigma and Emittance





- Does the minimization of the beam size σ_y @ one dipole imply the minimization of the emittance ϵ_y ?
  Yes, at least for a small number of skew quadrupoles (22 skew quads, simulation for 100 seeds) → left plot !
- Is it equivalent to minimize the beam size σ_y instead of the emittance ϵ_y ?
  Yes, it nearly is (22 skew quads, simulation for 100 seeds) → right plot !

Girder Re-alignment



- Corrector Pattern can be used to determine alignment errors (→No Cutoff).
- Prominent girder-girder alignment errors related to local corrector patterns (circles).
- Girder-girder errors introduce mechanical steps driving the adjacent correctors.
- Leads to saturation of correctors in machines with large alignment errors (→Eigenvalue Cutoff = "Long Range Correction").
- →Beam-based girder alignment (magnets on girders as super-correctors).

Sources of Vertical Emittance

For randomly distributed alignment errors, the vertical dispersion makes a contribution to the vertical emittance, given by:

$$\varepsilon_y = 2J_\varepsilon \frac{\langle \eta_y^2 \rangle}{\langle \beta_y \rangle} \sigma_\delta^2 \qquad 1)$$

Vertical dispersion, in turn, is generated entirely by COD and skew quads:

$$\eta_y(s) = \frac{\sqrt{\beta_y(s)}}{2\sin(\pi\nu_y)} \int_s^{s+C} F(s')\sqrt{\beta_y(s')} \cos\left[\phi(s') - \phi(s) - \pi\nu\right] ds' \qquad 2)$$

with

$$F(s) = (K + S\eta_x)\, y_c - K_{sq}\eta_x + G_y$$

where K, S, K_{sq} and G_y are the normal quad, sextupole skew quad strengths and vertical steering respectively and y_c is the closed orbit displacement

- Term $K + S\eta_x$ related to local chromaticity ξ ($\approx$0 for corrected local ξ).
- Term $G_y \approx 0$ for well (to centers of quadrupoles) corrected y_c.
- Term $K_{sq}\eta_x$ is small since the quadrupole roll errors are small.
- Local ξ ONLY $\approx$0 if y_c is corrected in quadrupoles and sextupoles simultaneously !

Sextupole Beam-Based Alignment I

- With stable orbit, measure beam position with BPMs where individual magnet strength changes has a null effect
- Gradient error from sextupoles is source of DA reduction, so ideal would be to align to sextupole magnetic centers
- First order effect is a tune shift due to gradient

$$\Delta Q_x \approx \frac{1}{4\pi}\beta_x(s)(K_2L)x = \frac{1}{2\pi}\beta_x(s)(b_3L)x$$

$$\Delta Q_y \approx \frac{1}{4\pi}\beta_y(s)(K_2L)x = \frac{1}{2\pi}\beta_y(s)(b_3L)x$$

Courtesy: S.L. Kramer, NSLS–II

No tune shift with y coordinate except through coupling

Resolution of tune shift dependent on energy spread and chromaticity, at best <30μm

Synchro-betatron coupling could easily increase resolution to ~100μm

M. Kikuchi, et.al. (KEK), introduced gradient coils to shift orbit rather than tunes

Sextupole Beam-Based Alignment II

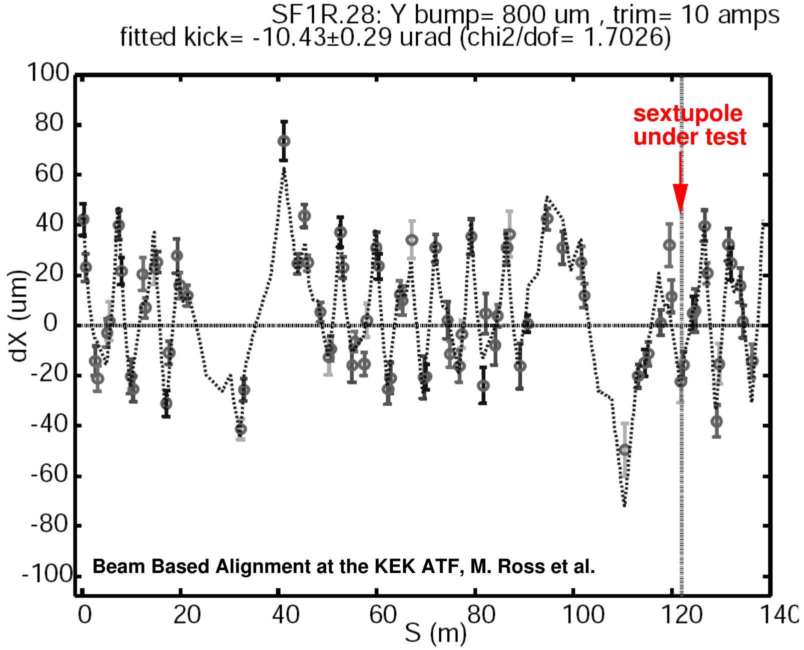


Figure 3. Example orbit with the superimposed fit. The dashed line shows the location of the sextupole under test.

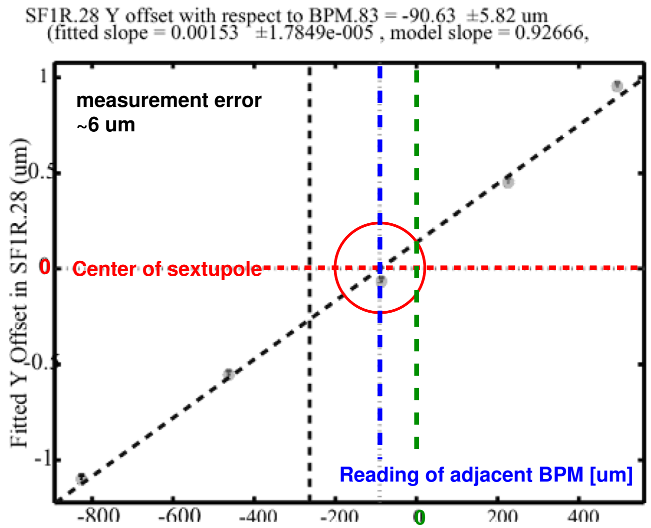


Figure 4: Fitted offsets, derived from trim kicks, as a function of the reading in the nearby BPM. The reported error in the intercept is 6 microns.

- At KEK ATF skew quadrupole trims (K=0.01 m^{-1}) on the sextupoles were used (sextupole center = skew quad center). The kick induced by the offset of the beam in the skew quad is determined from the difference orbit using the machine model. This fit is done for several closed orbit bump amplitudes at the location of the sextupole under test. At the SLS 36 out of 120 sextupoles are equipped with auxiliary skew quadrupoles (K=0.03 m^{-1}) for betatron coupling and dispersion correction.

Plan: RDT based coupling correction at SLS

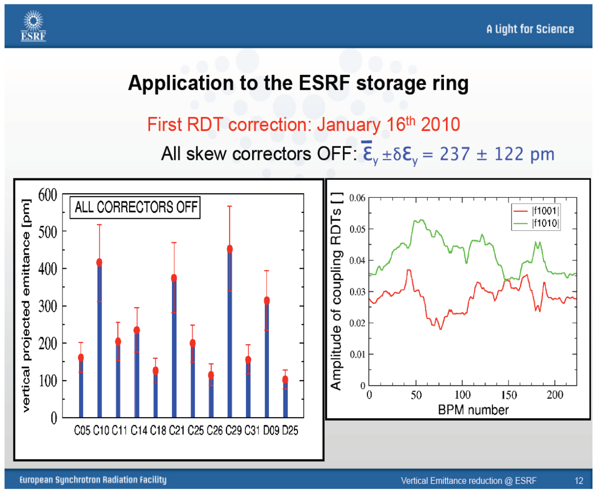
- Similar work to ESRF
  - Construct RDTs with
    - Orbit response
    - TBT BPM data – maybe difficult for the nicely corrected coupling (signal/noise)
  - Correction with skew quads (and orbit bumps)
  - Confirm the correction globally and locally with orbit response, TBT BPM data, emittance monitor and lifetime

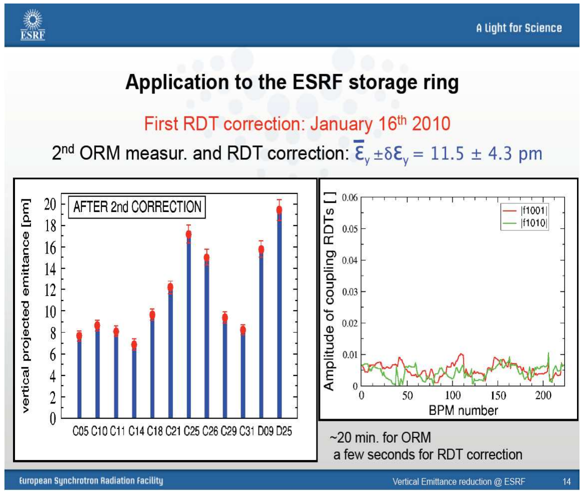
Summary of recent coupling correction at ESRF

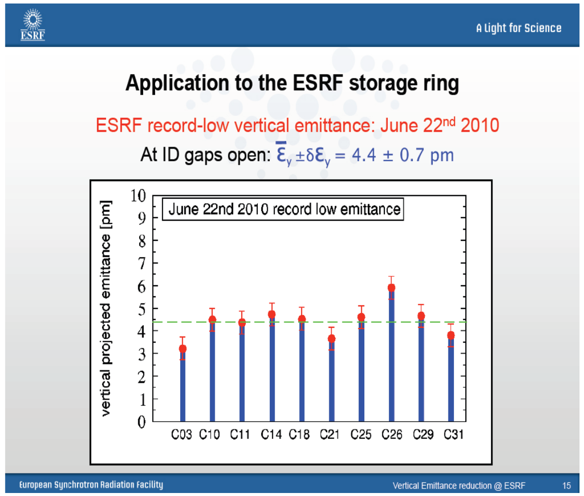
- Coupling correction based on resonance driving terms
  - Resonance driving terms are the direct figures of merit of the coupling resonances
  - Great success at ESRF (18th ESLS workshop, A. Franchi/ESRF)

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

J: Skew quad component







The SLS beam size monitor

Åke Andersson (MaxLab) and Natalia Milas (PSI)

- **Principle, Set-up and Performance**
- **Operation and Maintenance**
- **Possible Improvements**

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Nuclear Instruments and Methods in Physics Research A 591 (2008) 437–446

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Determination of a small vertical electron beam profile and emittance at the Swiss Light Source

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Principle

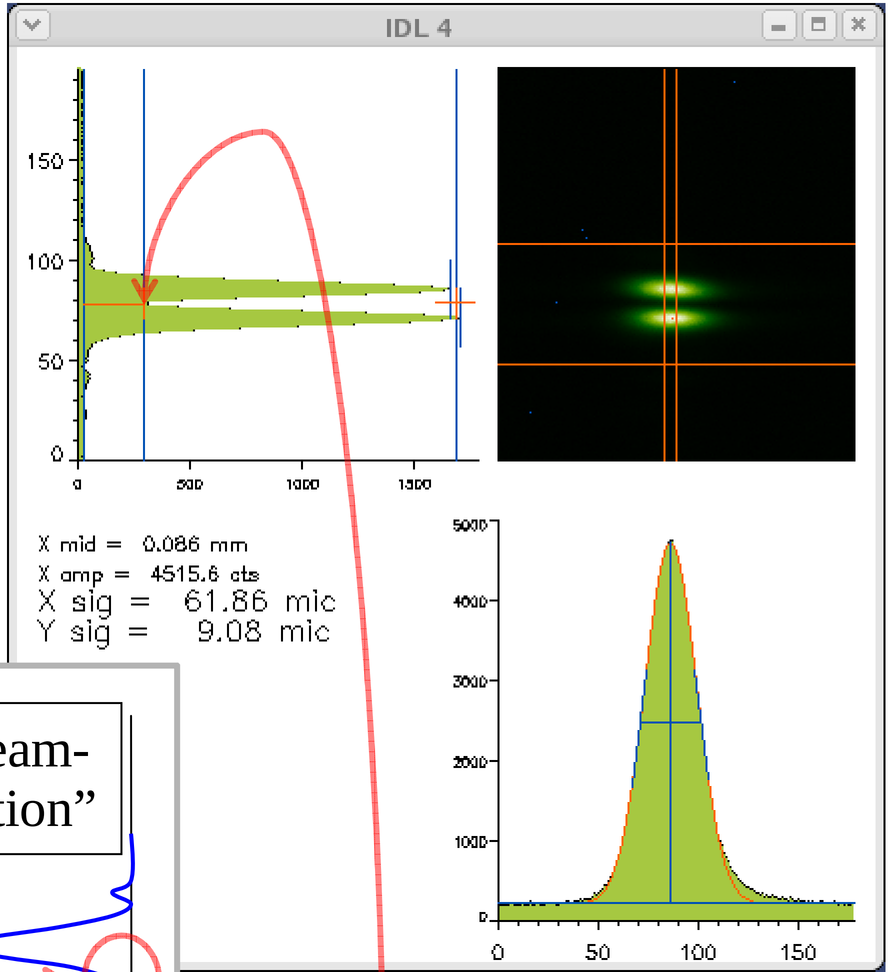
The π -polarization method*):

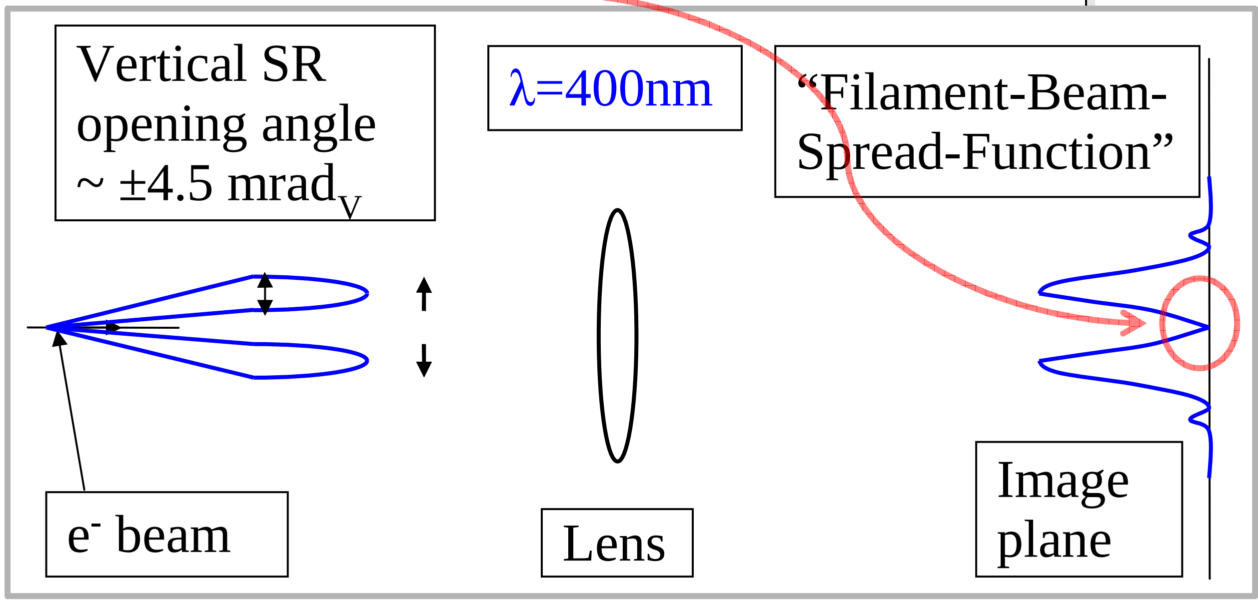
An image of the beam is formed from vertically polarized visible-UV synchrotron radiation.

A π phase shift between the two radiation lobes ==> $I_{y=0}=0$ in "FBSF"

(FBSF =filament beam spread function)

*) Old idea springing from MAX-lab, see EPAC'96 Andersson, Eriksson, Chubar

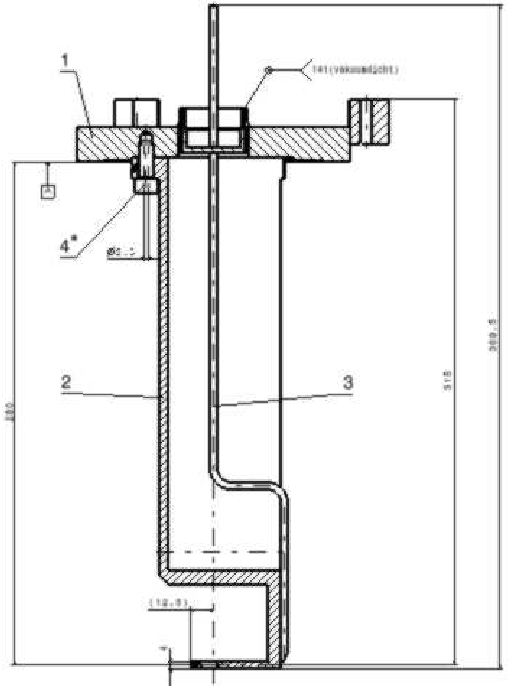


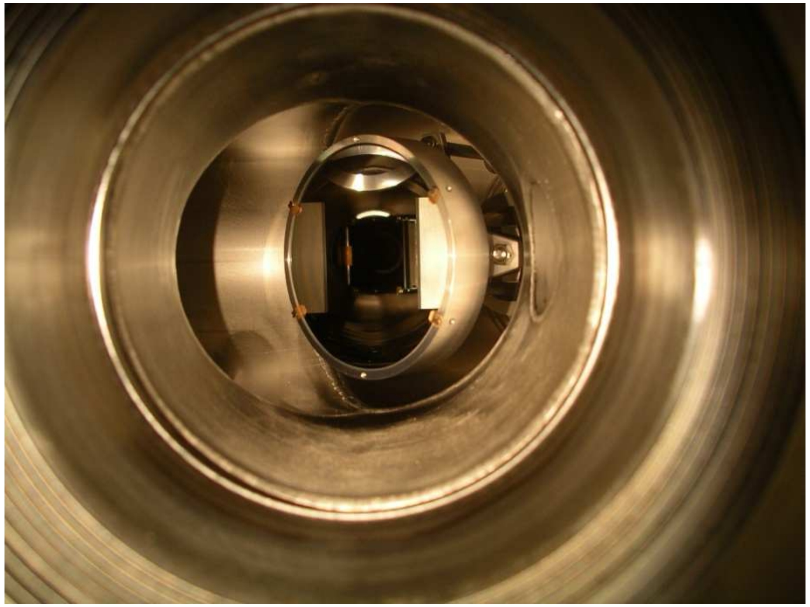


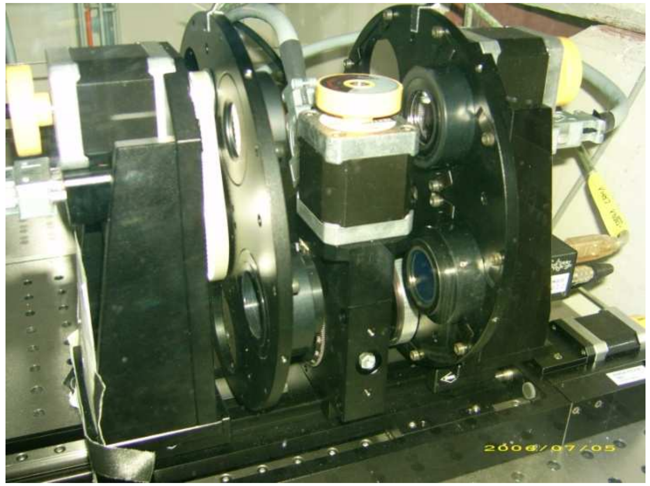
Finite vert. beam size ==>

Non-zero central intensity

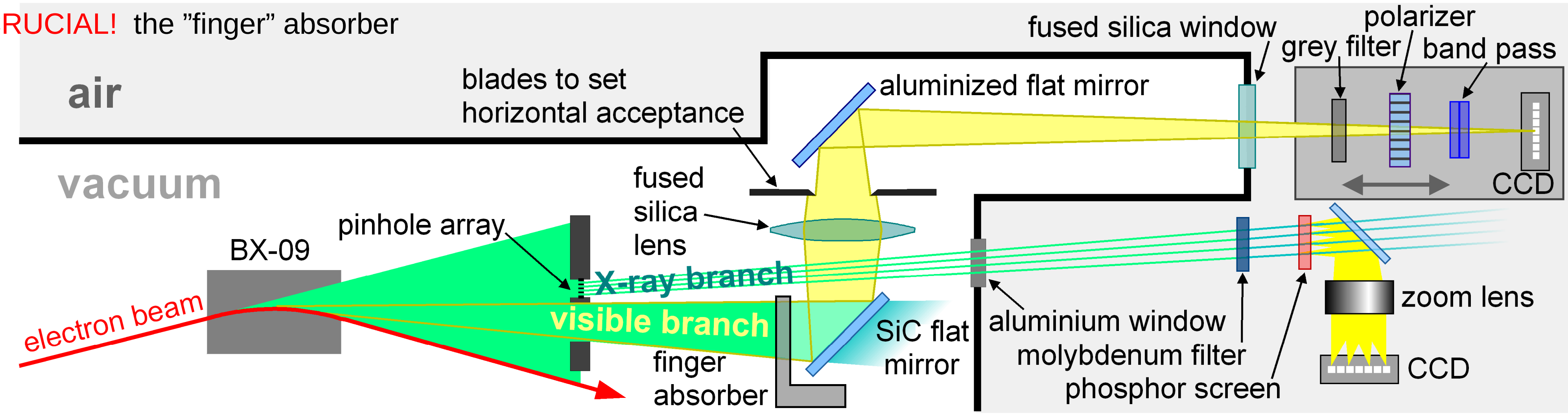
Beamline components



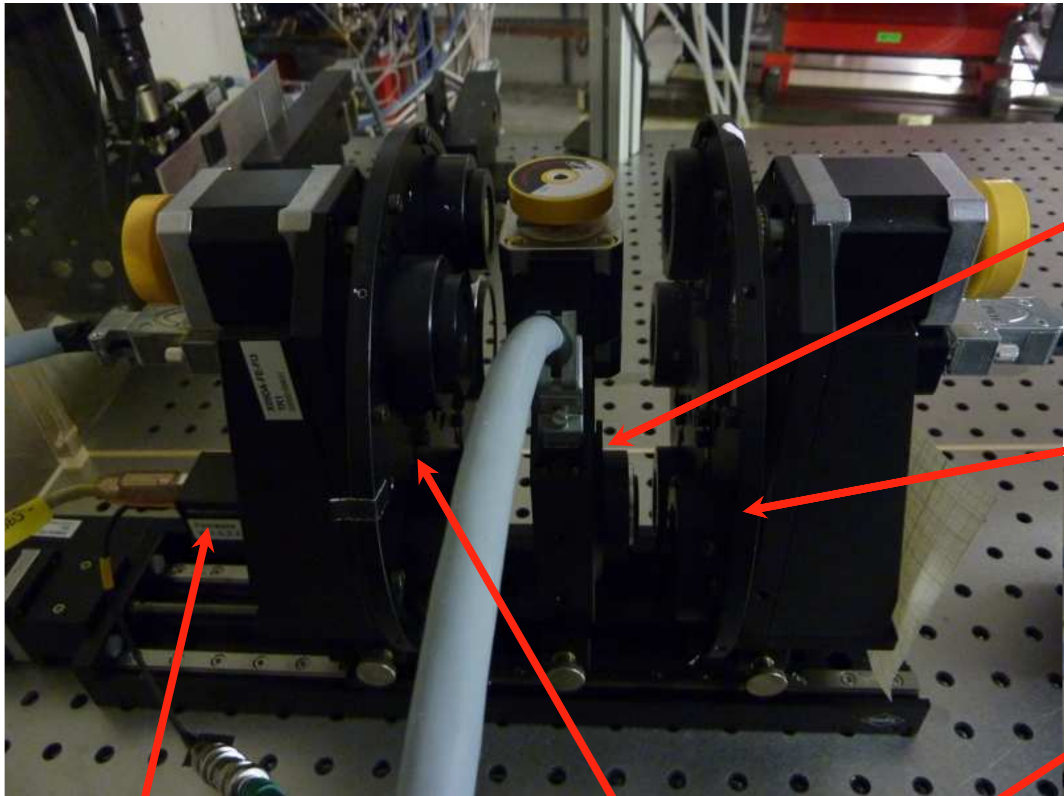


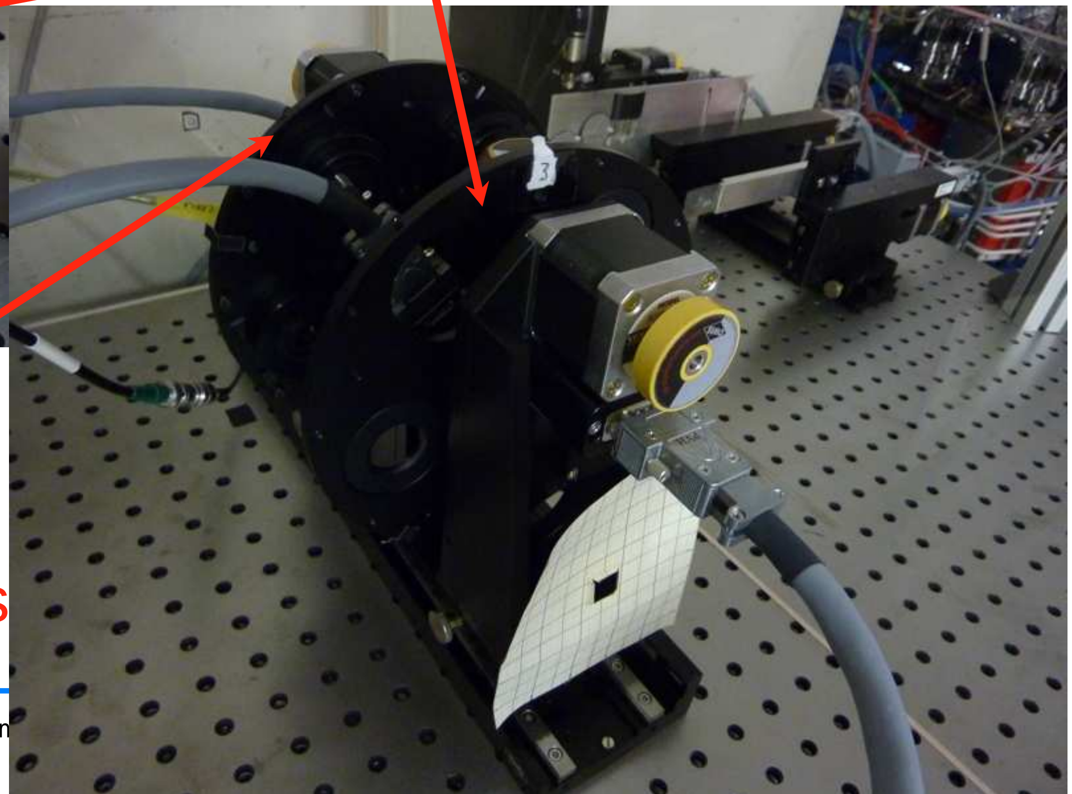


CRUCIAL! the ”finger” absorber



The actual setup in SLS





Polarizer

Neutral density filter

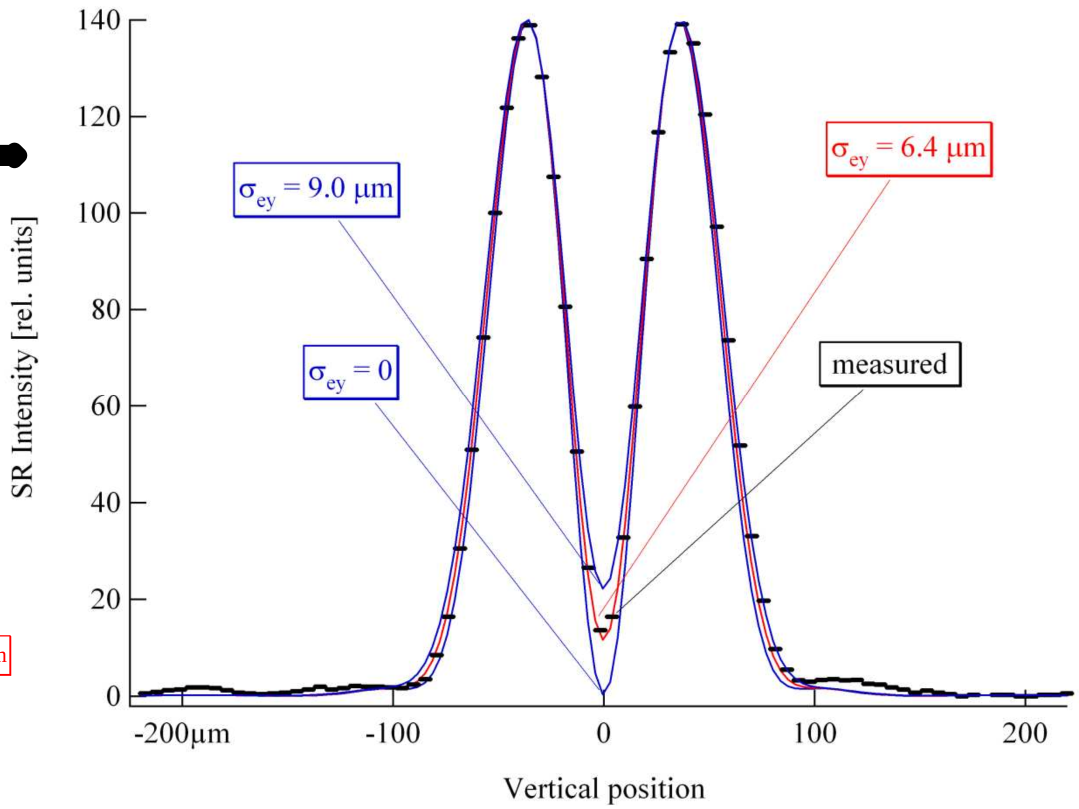
CCD camera

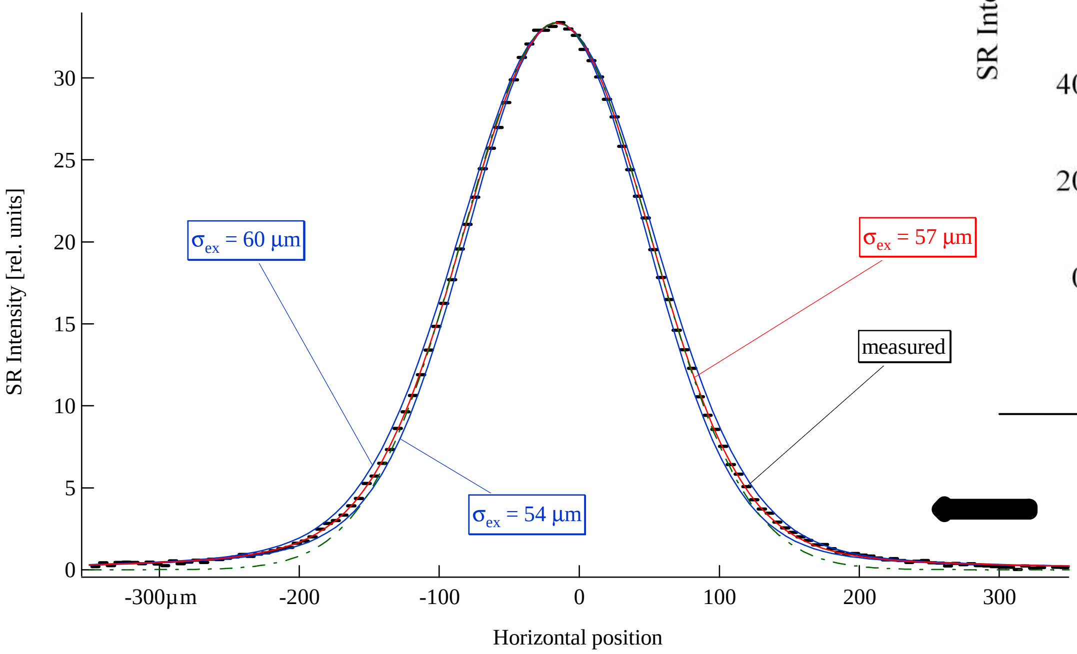
Band Pass + Line Filters

Precision

Vertical: Predicted profiles (SRW*) for beam height values 0, 6.4, 9.0 µm, and measured.
Statistical rms error = 0.1µm

*) Synchrotron Radiation Workshop, see EPAC'98 Chubar, Ellaume





Horizontal: Predicted profiles (SRW) for beam width values 54, 57, 60 µm, and measured.
Statistical rms error = 0.3µm

Error analysis

Nominal (no IDs) and measured parameter values at the observation point, together with derived emittances and emittance ratio

Parameter	Nominal value	Measured value	Max. error margin
σ_δ (%)	0.086	–	$+0.009/-0.000$
β_x (m)	0.452	0.431	± 0.009
η_x (mm)	29	27.3	± 1.0
σ_{ex} (µm)	56	57.3	± 1.5
ε_x (nmrad)	5.6	6.3	$+0.7/-0.9$
β_y (m)	14.3	13.55	± 0.14
η_y (mm)	0	2.3	± 0.55
σ_{ey0} (µm)	–	6.8	± 0.5
ε_y (pmrad)	–	3.2	± 0.7
g (%)	–	0.05	± 0.02

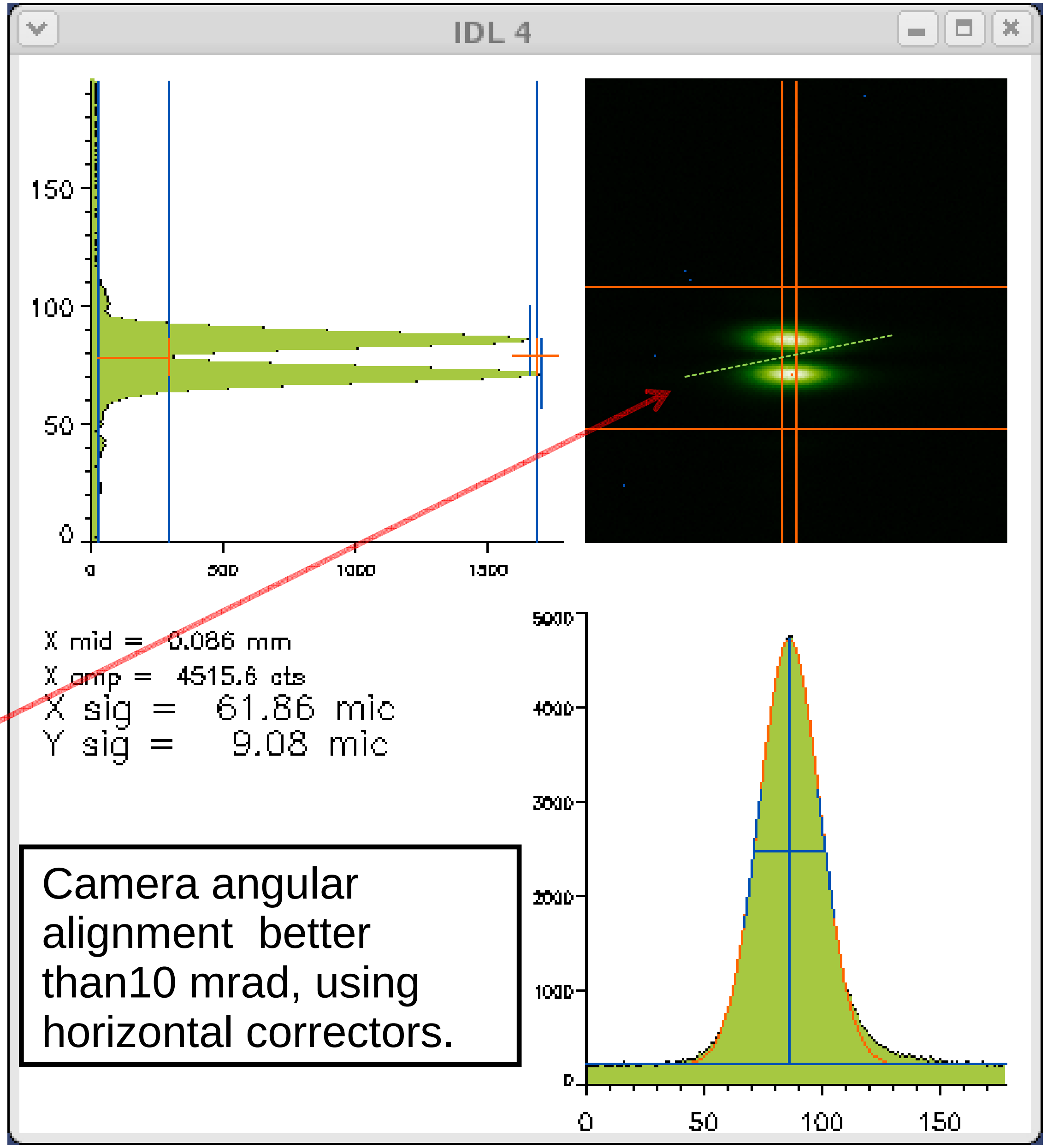
Systematic errors

- The smallest rms beam height values so far measured at SLS are around 5 µm. In this region it is difficult to exclude systematic error contributions to the measured value from various non-perfect optical elements. The valley-to peak ratio is only ~ 5 %, and this number we should consider as a lower limit.
- However, for a rms beam height of 3 µm, we can keep the (intrinsic) valley-to-peak ratio to 6% with almost the same experimental set-up. In this case we have to introduce an extra finger absorber with larger height.
- The π-polarization method then very much resembles an interference method. The advantage will be to be able to swap between the modes in order to crosscheck the influence from non-perfect optical elements.
- This method seems more advantageous than moving to shorter wavelength.

Dispersion measurements

- Dispersions are measured *in the same source point*, by tracking the image ”centre of gravity”-movement for small RF changes.
- ±500 Hz ⇔ (α known) ΔE/E=±0.165% ==> Δx~±40μm ; Δy~±4μm
- Rms precision = 0.4 μm

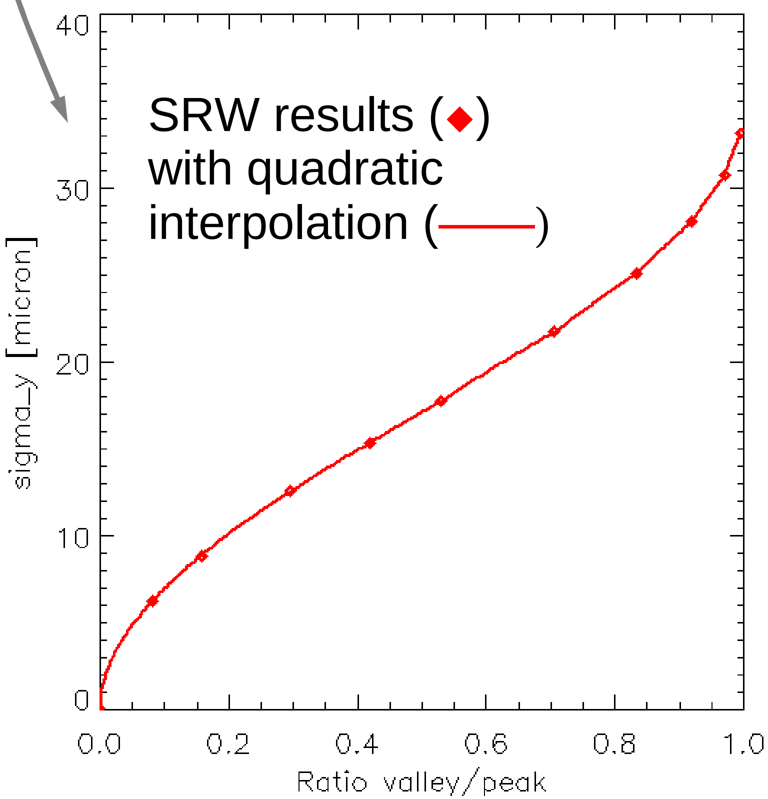
Rms precision in dispersion determination ~ 0.25 mm

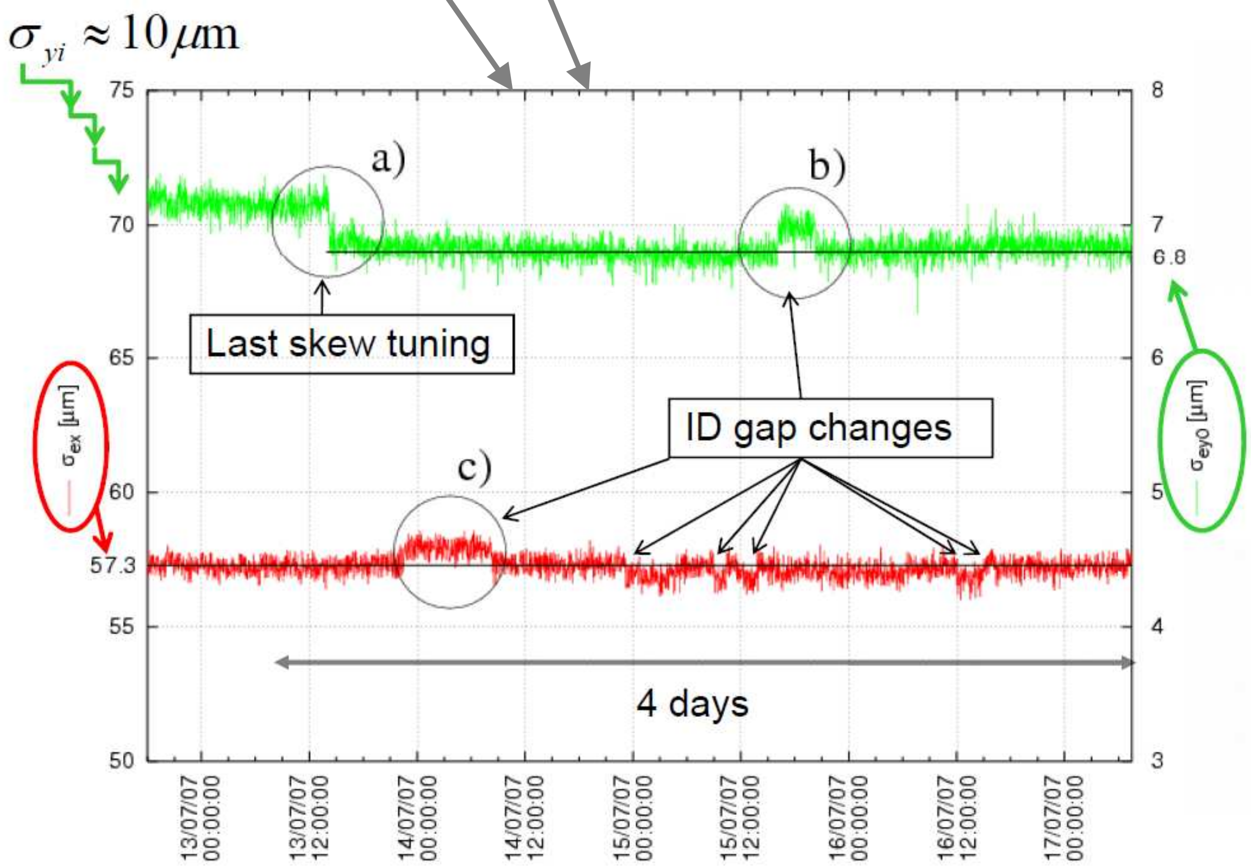


Camera angular alignment better than10 mrad, using horizontal correctors.

Operation

- The images of the camera are analyzed by a software which has a lookup table that gives the the beam size correspondent to the depth of the valley between the two peaks;
- The whole system works 24/7 (nonstop) and is reliable, and
- The beam size values are archived.



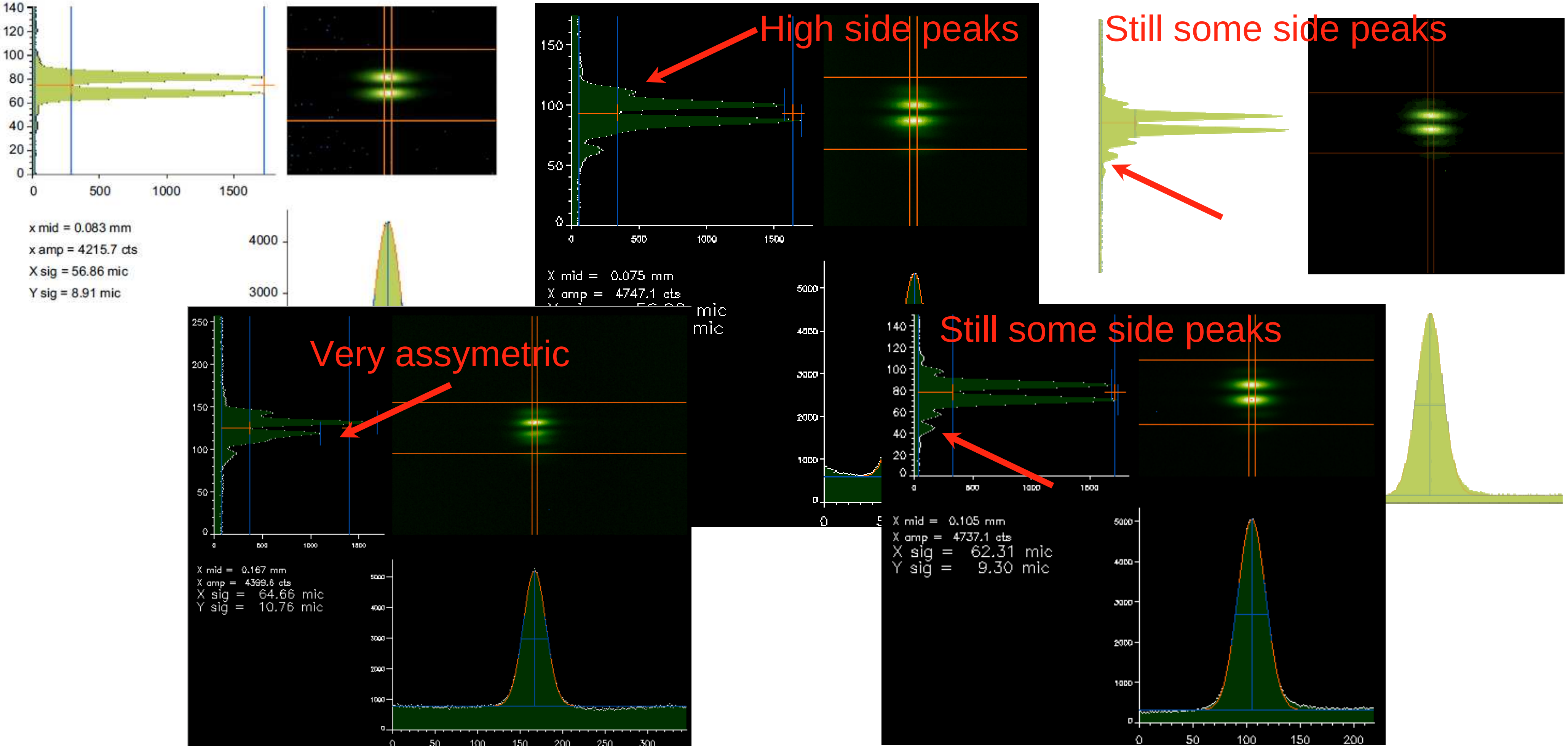


Maintenance

- We perform a simple maintenance about twice a year which includes:
  - cleaning the vacuum window;
  - cleaning the filters;
  - replacing the older band-pass (BP) filter when markings are already visible.
  - re-check filter positions + position optimization and
  - re-check camera sensitivity.

Effects of equipment deterioration on the image

Beginning (2007/08) | Moved vacuum window (2010) | New BP filter (2011)



Marked vacuum window (2010) | Re-focused system (2010)

Deterioriation Examples

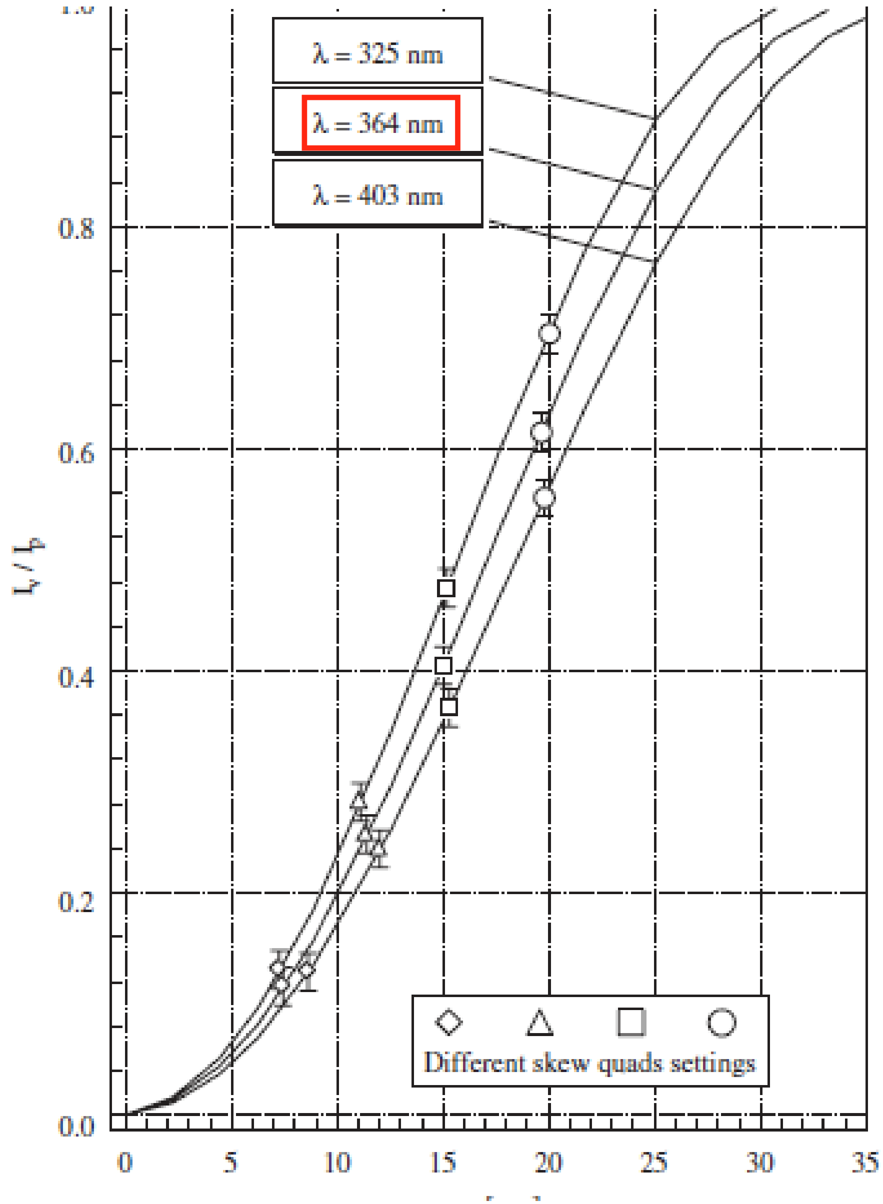
Vacuum Window:

BP filter:

Possible Improvements

Improvements on performance

- Shorter wavelengths to increase sensitivity and resolution (SLS: 364 nm)
- Use thicker finger absorber and rather interferometric method. (also better protection of first mirror to hard radiation)
- Better CCD camera (more and smaller pixels)



Possible Improvements

Improvements on reliability

Refining the optics:

- Exit window should be made of a λ/20 optical flat piece.
  Tests OK at MAX-lab.
- The exit window can be cleaned in situ if a valve is introduced in front. It is a possible method for mirror cleaning (removing Carbon), to leak in oxygen and expose it to UV-radiation.
  We should be able to do likewise.
- The lens can be made with better surface accuracy, λ/20, than the present. It should also have a longer focal length.
- Check optical components outside vacuum...

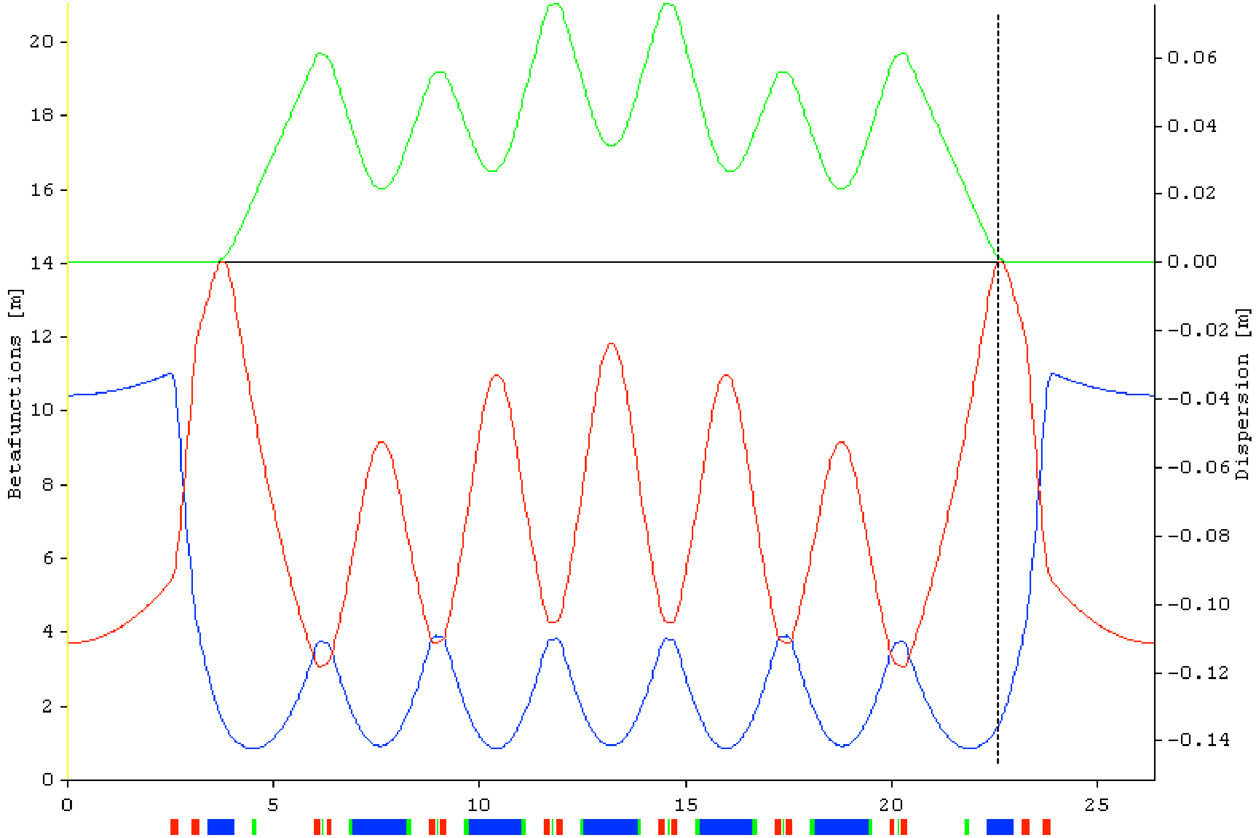
Outlook

MAX-IV 3 GeV ring: π-polariz. method

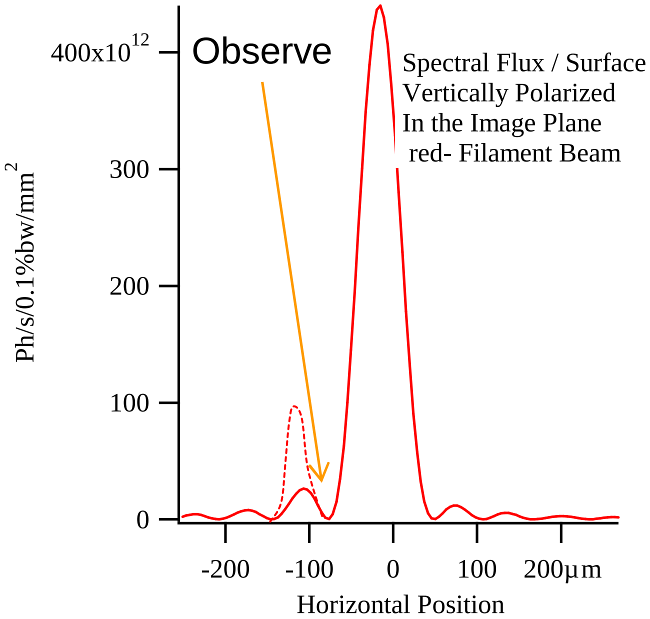
Light source **MAX IV**

E = 3 GeV
C = 528 m
I = 500mA
ε_x = 250 pmrad
ε_y = 1 pmrad

MAX-lab



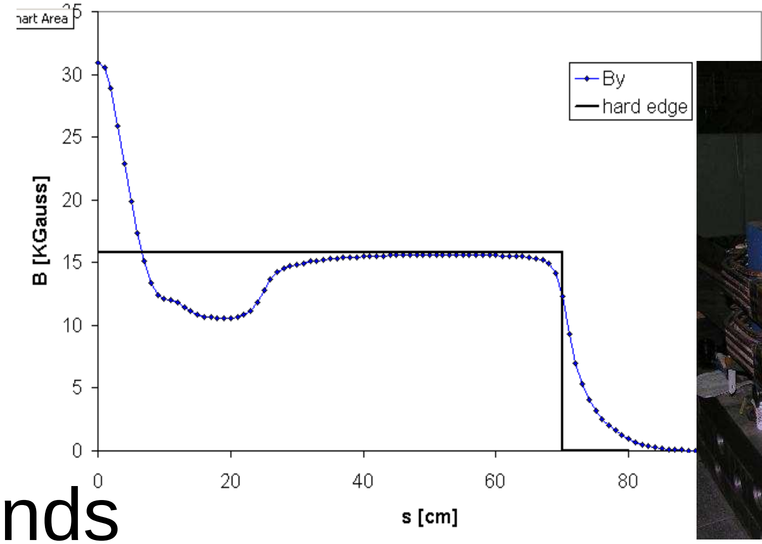
β_y = 14 m ==> σ_y=3.7μm OK!
β_x = 1.8 m ==> σ_x=21μm
Large hor. acc. angle ==> OK!

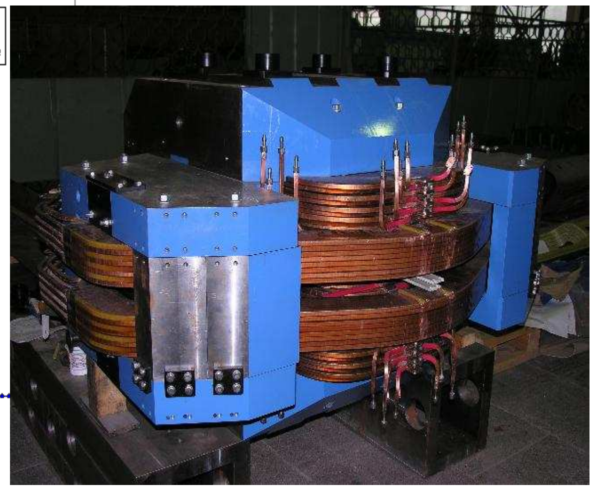


Storage ring energy scaling

- Beam Optics
- Magnet Kalibration
- Beam energy
  $(B\rho)$ [Tm] $= 3.3356 \times$ E [GeV]
- Magnet currents

$$B^{(n)} = (B\rho)\cdot\left(b_{\mathrm{res}} + |I|\cdot t_{\mathrm{lin}}\cdot\left(1+\left(\frac{|I|}{I_{\mathrm{sat}}}\right)^{A}\right)^{N}\right)\cdot \mathrm{sign}(I)$$





- SLS: nominal energy
  2.411 GeV (400mA)

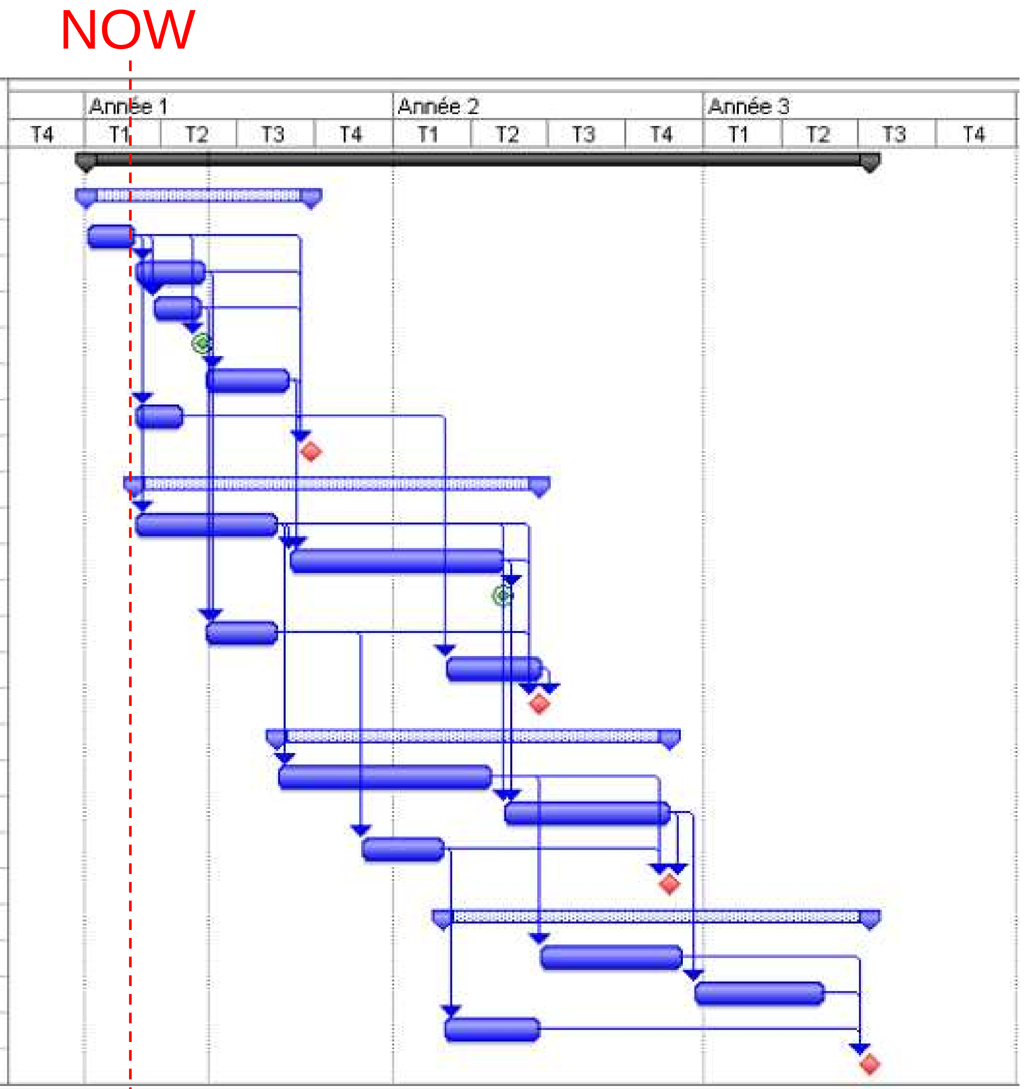
- Saturation in superbends
  (3 Tesla, normal conducting !): **E < 2.5 GeV**
  before superbend installation: **E = 2.7 GeV (250 mA)** (2005)

- 2010: operation at **1.57 GeV**, max. **300 mA**
  Problem: cavity HOMs $\rightarrow$ w.i.p.
  No problems with superbends
  center pole: **500 A @ 2.41 GeV $\Rightarrow$ 120 A @ 1.57 GeV !**

Time schedule

Gantt Chart 1.3.a6 for Work Package WP6

N°	WBS	Task Name
1	**WP6**	**WP6 Upgrade of SLS vertical emittance tuning system**
2	**6.1**	**6.1 SLS_NOW: Experimental tests at SLS with existing systems**
3	6.1.1	6.1.1 EPS_Limit: emittance limit
4	6.1.2	6.1.2 EPS_Sens: emittance sensitivity
5	6.1.3	6.1.3 MON-RES: profile monitor resolution
6	**M6.1**	**M6.1 M_INSTR: Interim report on existing beam instrumentation**
7	6.1.4	6.1.4 COUPLING: coupling theory
8	6.1.5	6.1.5 MAG_Scale: magnet scaling
9	**D6.1**	**D6.1 D_SLS_NOW: Report on existing hardware situation and limitations**
10	**6.2**	**6.2 SPEC: Specification of necessary upgrades**
11	6.2.1	6.2.1 ORB_C_SPEC: Orbit Control Specifications
12	6.2.2	6.2.2 KNOB_SPEC: emittance knobs
13	**M6.2**	**M6.2 M_KNOBS: Specification of emittance knobs ready**
14	6.2.3	6.2.3 MON_SPEC: Monitor specification
15	6.2.4	6.2.4 ENERGY: Specification of knob for energy scaling
16	**D6.2**	**D6.2 D_SPEC: Specifications ready**
17	**6.3**	**6.3 IMPL: Implementation of the specified upgrade**
18	6.3.1	6.3.1 ORB_C_IMPL: Orbit Control upgrade
19	6.3.2	6.3.2 COUPL_IMPL: Coupling automation
20	6.3.3	6.3.3 MON_IMPL: Monitor installation
21	**D6.3**	**D6.3 D_IMPL: Hardware ready and installed**
22	**6.4**	**6.4: COMM**
23	6.4.1	6.4.1 ORB_C_COMM: Orbit Control Commissioning
24	6.4.2	6.4.2 COUPL_COMM: Coupling control
25	6.4.3	6.4.3 MON_COMM: Monitor commissioning
26	**D6.4**	**D6.4 FINAL_R: Commissioning report**



Next dates: M_INSTR mile stone: report on existing instrumentation 31.5.2011
New post doc (hopefully) starting mid 2011

Post Doc recruitment

The Paul Scherrer Institut, in collaboration with CERN, INFN-LNF Frascati and MaxLab/Lund University, will undertake a program of R&D to upgrade the SLS storage ring and allow it to be used as a test-bed for research on ultra-low vertical emittance, in order to support the design of damping rings for linear colliders, particle factories and light sources. The R&D program at SLS will involve the following theoretical and experimental activities:

a) control and suppression of betatron coupling and vertical dispersion by means of skew quadrupoles,
b) measurement of small beam size and further developments of high resolution emittance monitors,
c) measurements of intra-beam scatting (IBS) contributions to vertical emittance and of the particle distribution in the halo.

In this context PSI offers a **2-year** (renewable 1 year) position for a

Postdoctoral Fellow.

Your tasks

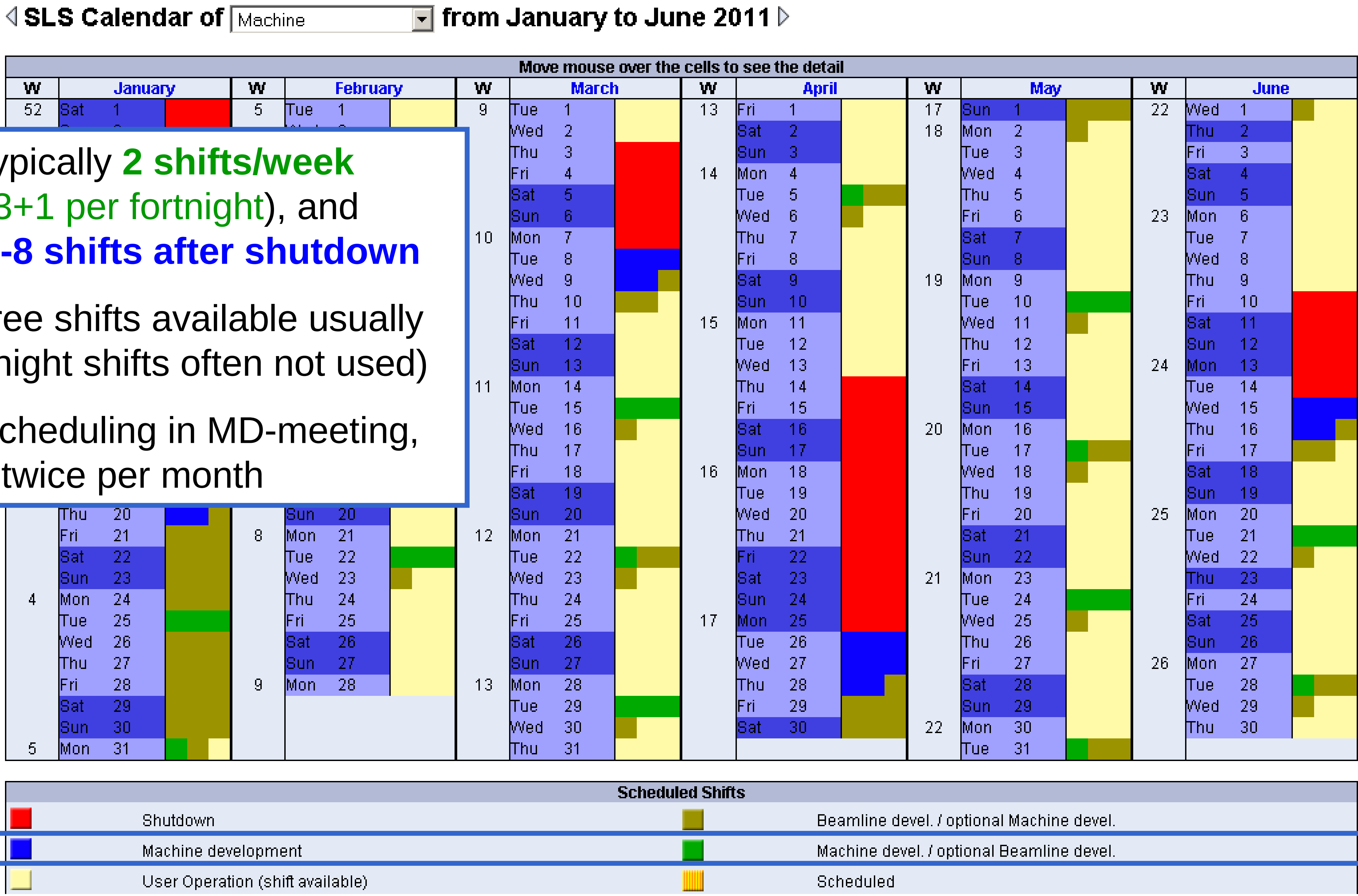
In the **three fields of activities** outlined above, you will characterize the current SLS status and its limitations. Based on these findings you will elaborate theories, extend codes and specify new diagnostic devices. As a new beam size monitor is planned, your work may focus on the specification, construction and commissioning of this device as well as calculations and simulations which kind of information it is able to provide. Using this and existing devices you will perform measurements on the issues mentioned and characterize the total performance of the upgraded storage ring with respect to research on ultra-low emittance.

Your profile

You have completed a PhD in physics, electrical engineering, mathematics or related areas, and the subject of your thesis was related to accelerators and beam dynamics. Ideally you have both a thorough knowledge of theoretical beam dynamics, in particular the formalism of coupled betatron motion, and sound practical experience in accelerator diagnostics including controls and data acquisition. Since this position involves a collaboration of four institutes you should enjoy work in a dynamic and internationally oriented environment and to communicate actively and in fluent English.

➔ approved by PSI management, Feb.21. To be published within the next days.

Machine development shifts



typically **2 shifts/week** (3+1 per fortnight), and **5-8 shifts after shutdown**

free shifts available usually (night shifts often not used)

scheduling in MD-meeting, ~twice per month