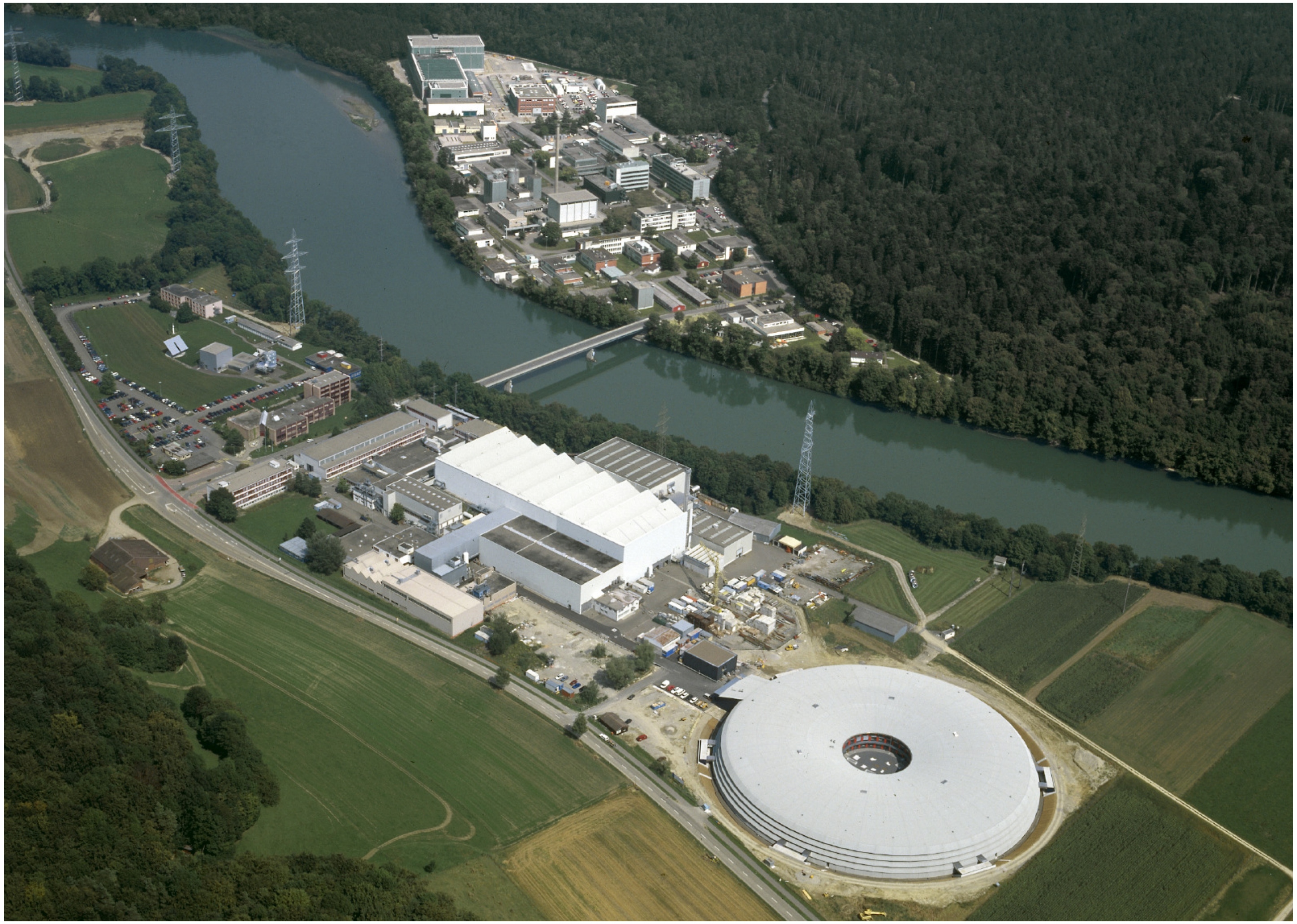
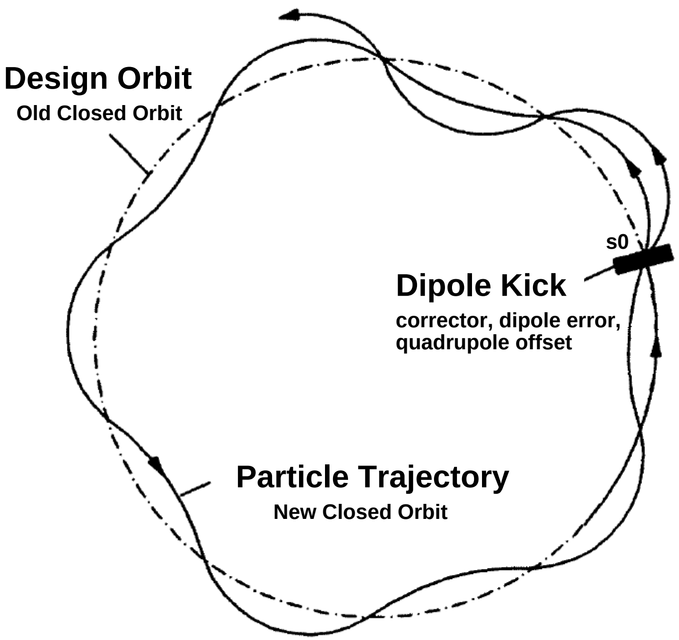
SLS at the Paul Scherrer Institute (PSI), Villigen, Switzerland

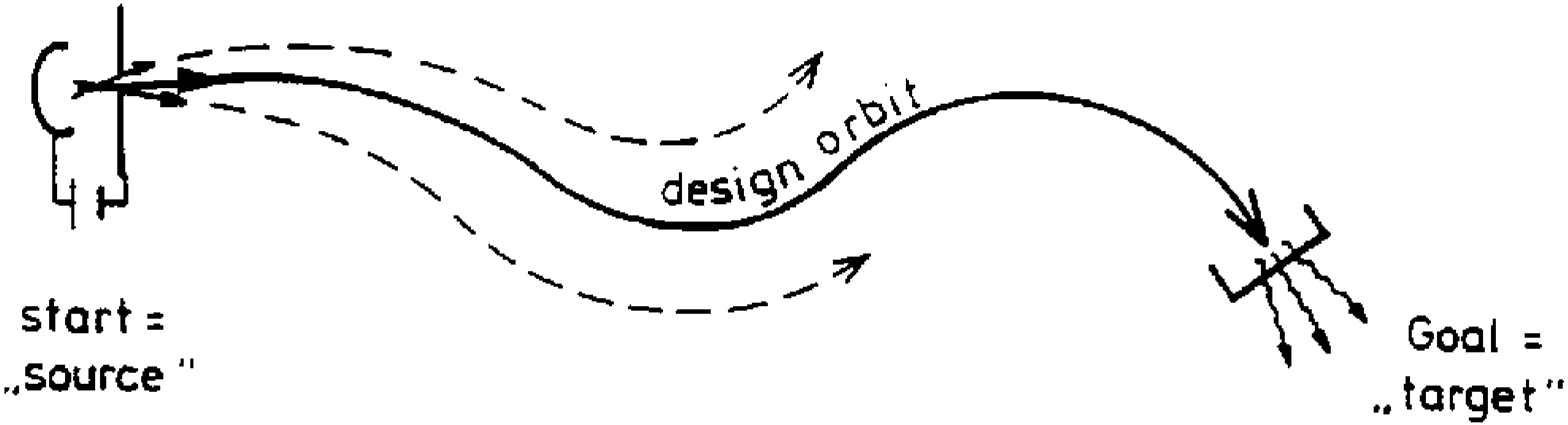


Overview

- What is an Orbit ?
- How is it measured ?
- What is a Closed Orbit ?
- How does the Closed Orbit change with Energy ?
- Motion around the Closed Orbit
- How does the Closed Orbit change with Errors ?
- BPM and Corrector Layout
- Corrector / BPM Response Matrices
- What is a Bare Orbit ?
- Local Orbit Manipulations
- How is a Closed Orbit corrected ?
- What is SVD doing ?
- Inverse Response Matrices, SVD Eigenvalues
- How to correct Off-Energy Orbits ?
- How is the position of the BPMs measured ?

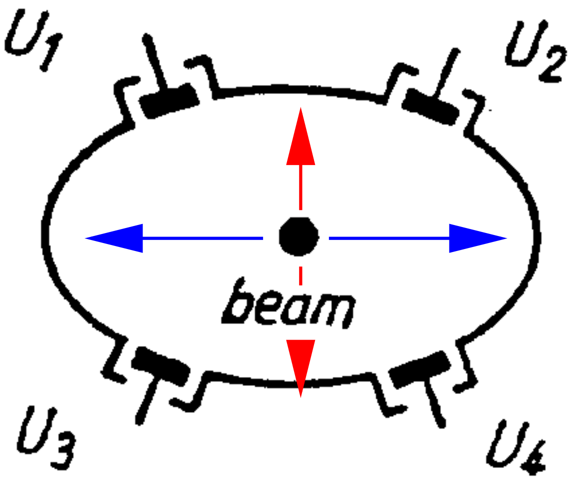


What is an Orbit ?



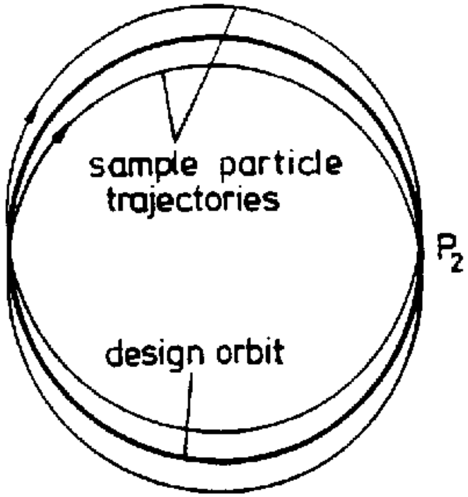
- A certain arrangement of magnets (“Optics”) defines a trajectory (“Orbit”), on which charged particles move from “Start” to “Goal”.
- For the initial design condition and without magnet errors the particles move along the so-called “Design Orbit”.
- Variation of the initial conditions, alignment and magnet errors lead to a deviation from the “Design Orbit”.

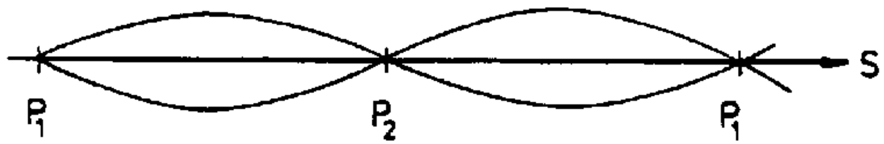
How is it measured ?



- As an example a “Button” Beam Position Monitor (BPM) is shown.
- The particle beam “Beam” in the midlle of the vacuum chamber couples to buttons of the monitor and generates signals ΣU_i, which allow to determine it’s position
- Horizontal Beam Position = $c_M((U2 + U4) - (U1 + U3)/\Sigma U_i$
- Vertical Beam Position = $c_M((U1 + U2) - (U3 + U4))/\Sigma U_i$, c_M = monitor constant.
- At the SLS 73 “button” BPMs are part of a digital BPM System. Orbit deviations are measured to better than 1 μm @ 4 kHz sampling rate.

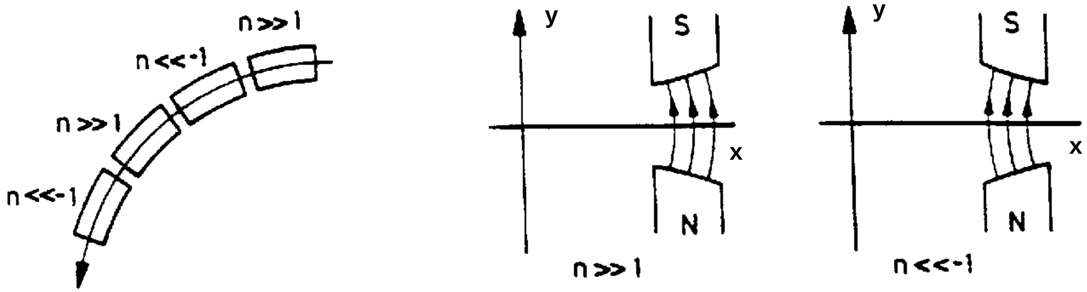
What is a Closed Orbit und what is “weak” focussing ?

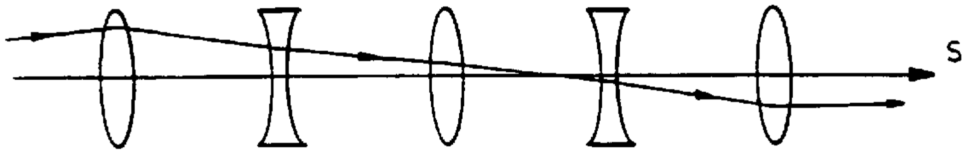




- A periodic closed particle trajectory is called “Closed Orbit”.
- The “Design Closed Orbit” is the closed orbit, which is establised at design energie p_0, if the Optics has no errors. Generally this orbit is centered in the magnets and BPMs.
- Particles with different initial conditions than the closed orbit particle oscillate around the “Closed Orbit”.
- In the case of a homogenous magnetic field there is just “weak” fokussing: particles move on different circles depending on the initial angles at P_1 und P_2 (left). Along the “Design Orbit” these trajectories look like oscillations around this orbit (right).

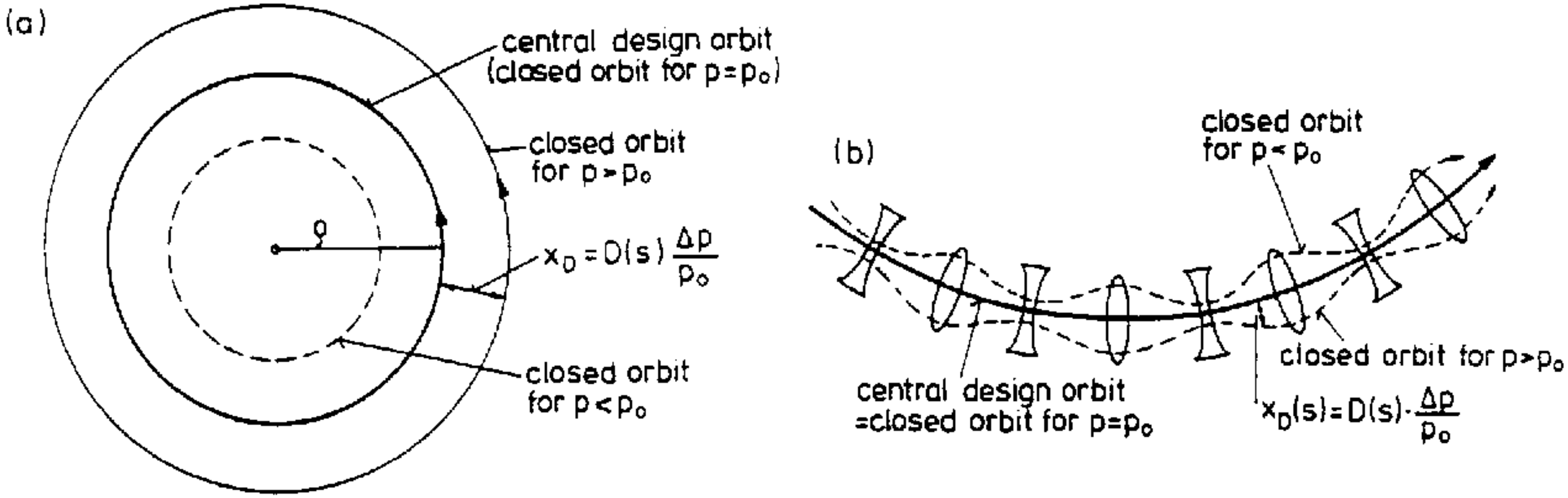
What is “strong” focussing ?





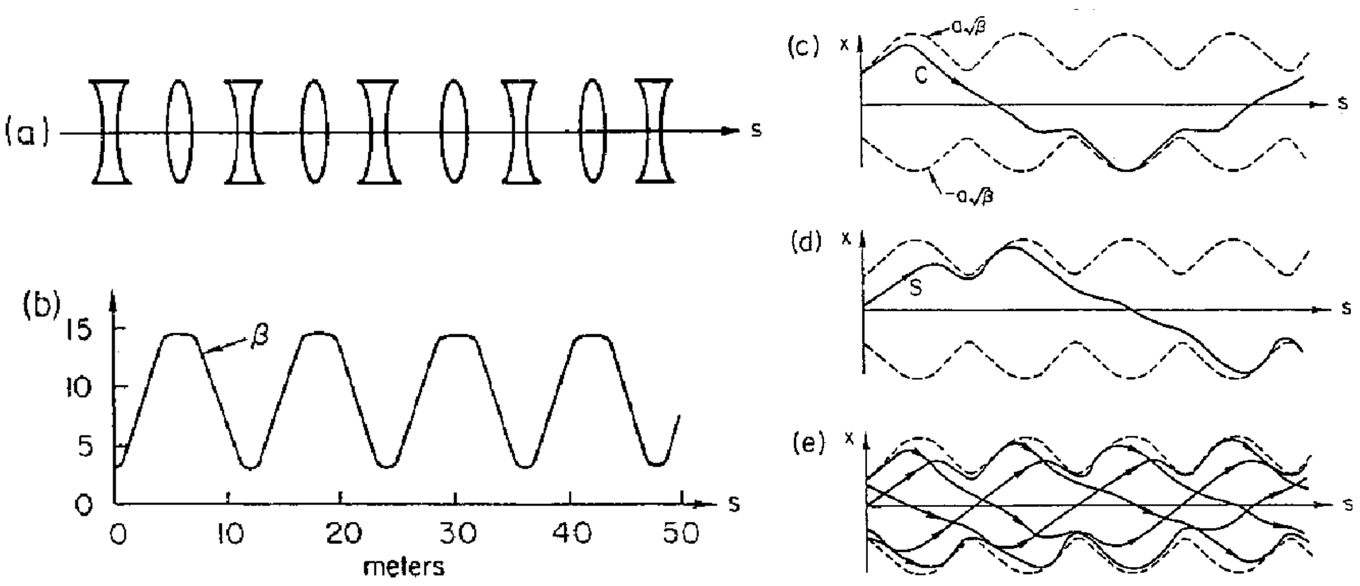
- In the case of “strong” (de)focussing quadrupoles are alternately (de)focussing the particles.
- This allows to have smaller magnet apertures, since the particles with varying initial conditions are kept closer to the “Closed Orbit”.
- In the SLS a total number of 177 quadrupoles is installed.
- The “strong” focussing increases the number of oscillations per turn (“Tune”). In the SLS this leads to $\approx$ 20 horizontal and $\approx$ 8 vertical full oscillations per turn.

How does the Closed Orbit change with Energy ?



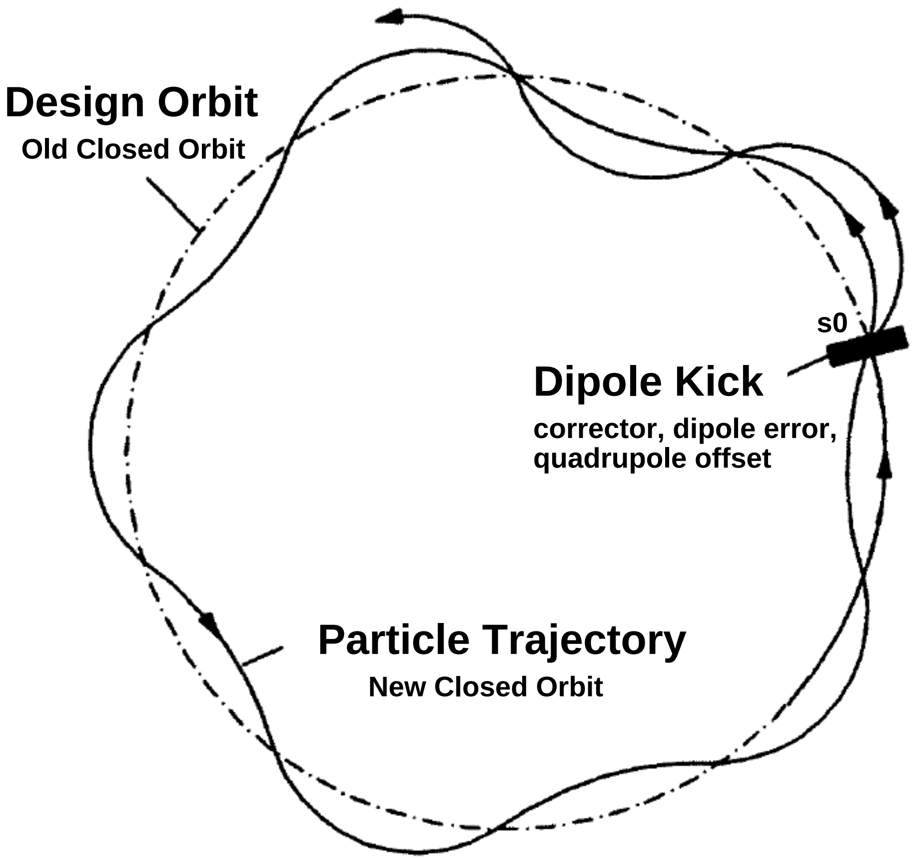
- In a homogenous magnetic field the radius of the "Closed Orbit" is proportional to the energy p (shown are the cases $p < p_0$, $p = p_0$ and $p < p_0$). Thereby the "Closed Orbit" is getting shorter and longer which is also called "Path Length Change" (a).
- The right cartoon (b) visualizes the more complex situation in case of "strong" focussing.
- In general the so-called "Dispersion Function" $D(s)$ describes the change of the particle position x_D at a given longitudinal position s: $x_D = D(s)(p - p_0)/p_0$.

Motion around the Closed Orbit



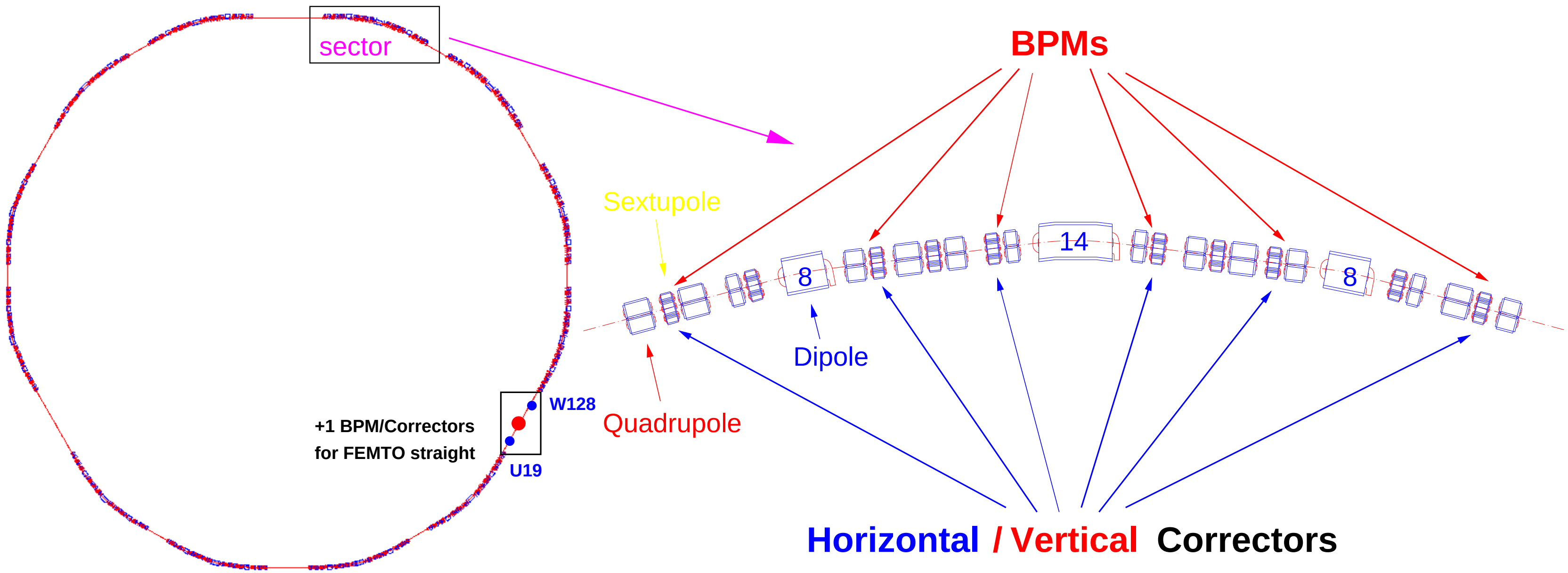
- Particles are performing “Betatron Oscillations” around the “Closed Orbit” (c-e).
- These oscillations are not closed, because otherwise the motion would be resonant !
- The “optics” in cartoon (a) is characterized by an amplitude function “Beta Function” $\beta(s)$ which defines the envelope $a\sqrt{\beta}(s)$ for these oscillations in cartoons (c-e).
- The “Beam Size” at a longitudinal position s is proportional to $\sqrt{\beta}$ and to the constant $a = \sqrt{\epsilon}$ where ϵ is the so-called emittance which appears to be an invariant of motion.

How does the Closed Orbit change with Errors ?



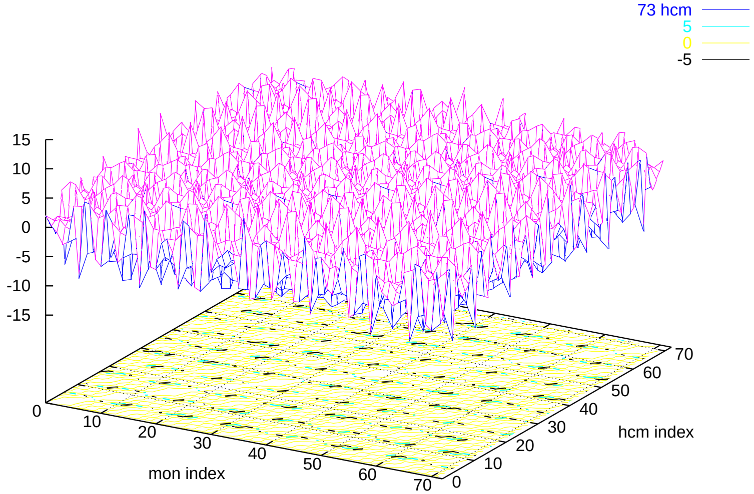
- The “Closed Orbit” is distorted under the influence of a magnet alignemnt/strength error or the deliberate change of a corrector. The RMS deviation from the “Old Closed Orbit” is proportional to $\sqrt{\beta(s)}$ at the location $s0$.

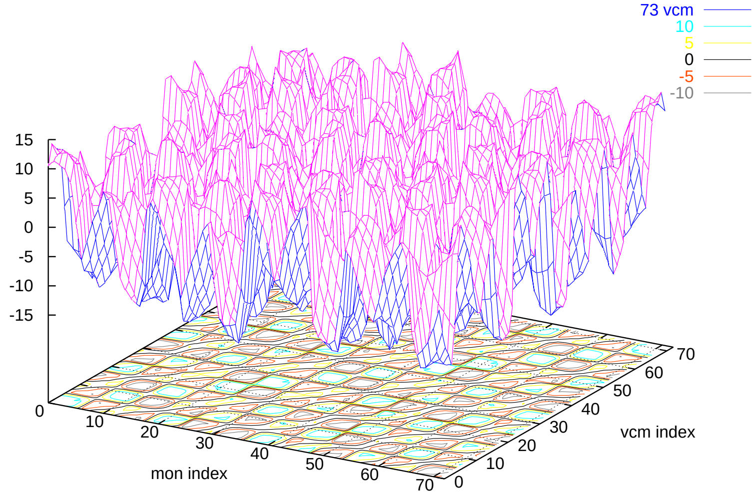
BPM and Corrector Layout (SLS)



- 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).

Corrector / BPM Response Matrices (SLS)

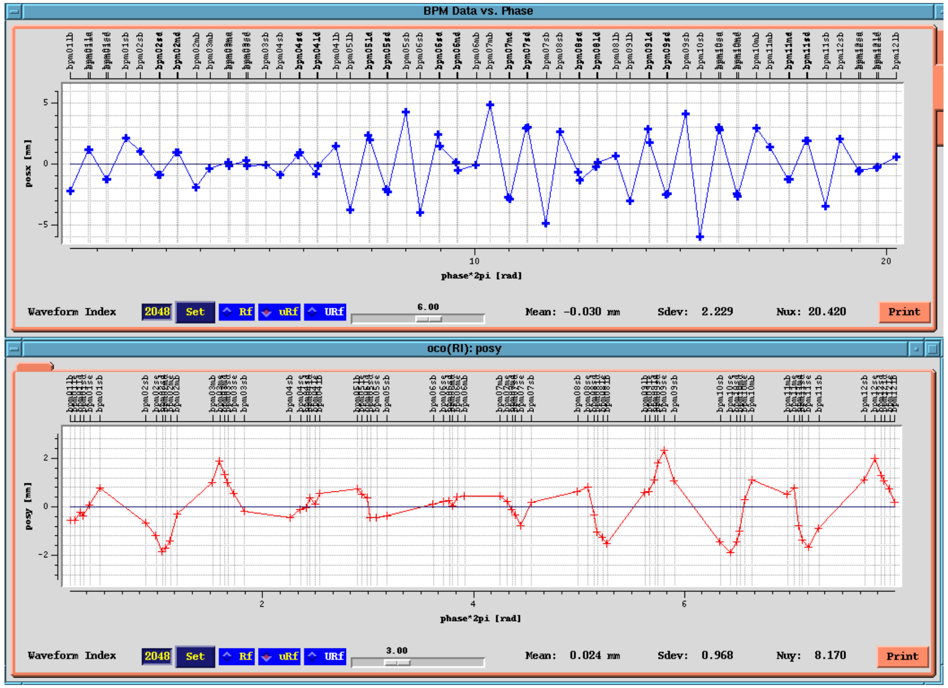




$$A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2\sin \pi\nu} \cos\left[\pi\nu - |\phi_i - \phi_j|\right]$$

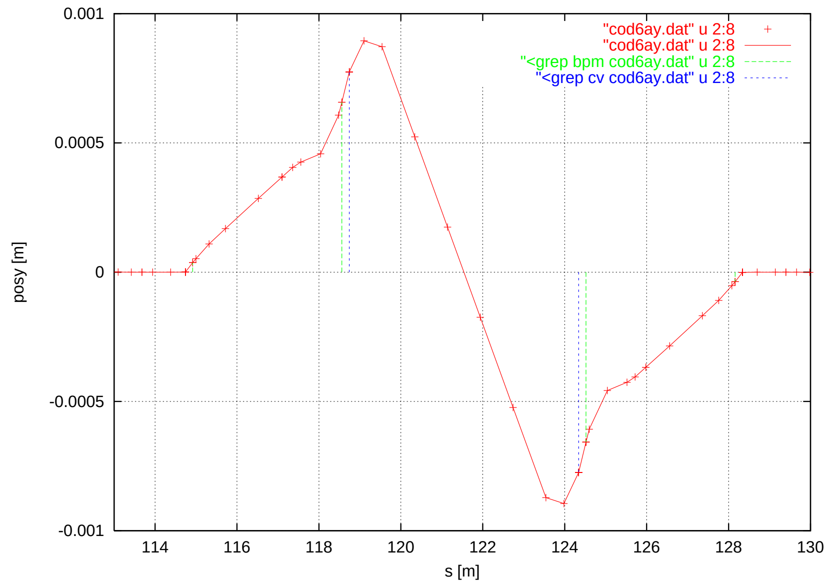
- "Response Matrix": Differences from the "Closed Orbit" ("Difference Orbit") due to a kick of corrector i are recorded at BPM positions $j = 1..73$.
- ν_x = 20.44 (≈3 BPMs/Correctors per unit phase, $\phi = \int_0^s 1/\beta(s)ds$)
- ν_y = 8.74 (≈9 BPMs/correctors per unit phase)

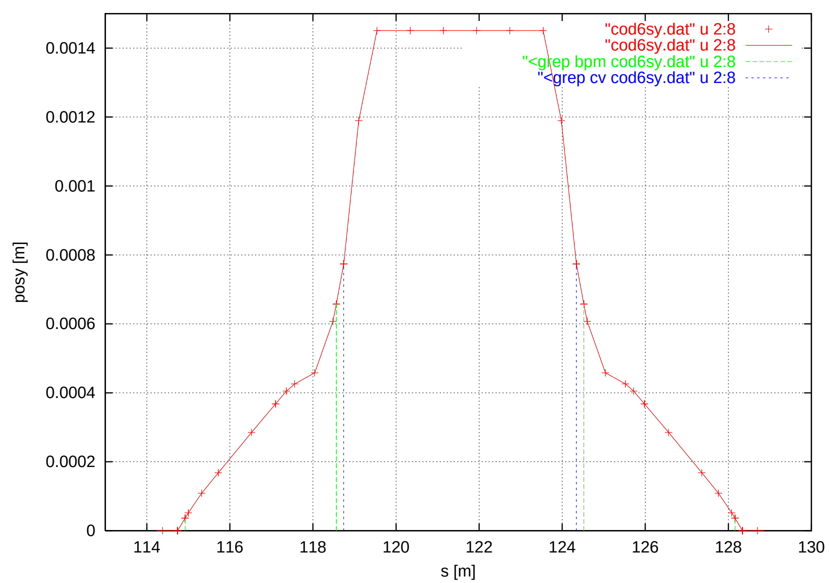
What is a “Bare Orbit” ? (SLS)



- A “Bare Orbit” is a “Closed Orbit” <u>without</u> any corrections applied (ν_x=20.42, ν_y=8.17).
- The “Bare Orbit” is determined by the superposition of all magnet errors.
- x_{rms} = 2.3 mm, y_{rms} = 1 mm gives upper limit for alignment errors of Quadrupoles/Sextupoles $<$ 30 μm.
- The ratio of the RMS of the resulting “Closed Orbit” excitation and the originating RMS magnet distortions is called “Amplification Factor” (A_x=12, A_y=8).

Local Orbit Manipulations (SLS)

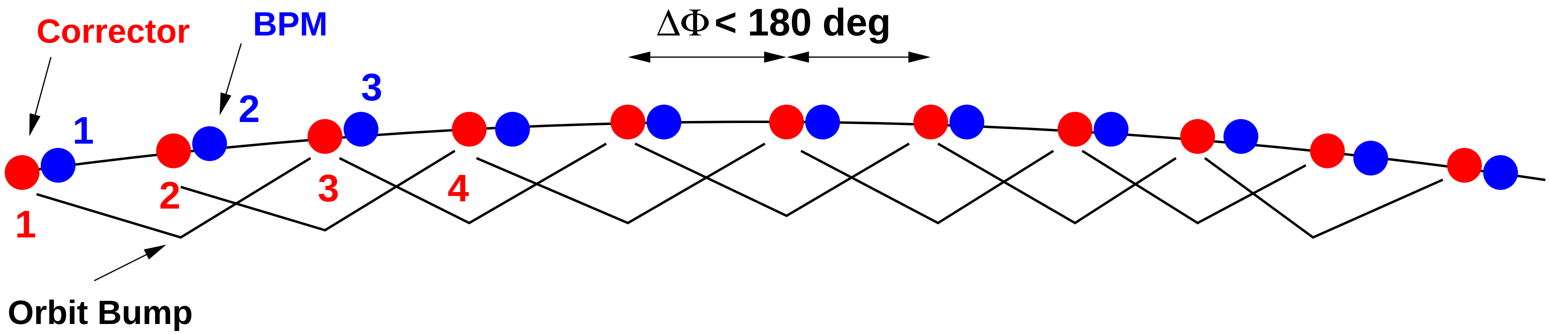




- The example depicts so-called vertical asymmetrical (left) and symmetrical (right) "4-Bumps" for an undulator beamline at SLS (well definied corrections involving 4 corrector magnets in order to independently vary position and angle at the location of the insertion device (ID) (angle and position steering by $\approx$ -400 μrad and $\approx$ 1.4 mm is shown).
- "3-Bumps" consist of 3 magnets and are used to change position or angle at a given location.
- The corrector magnets in a bump have fixed phase- and beta function dependent kick ratios, in order to close the bump (no residual oscillation outside of the bump).

How is a Closed Orbit corrected ?

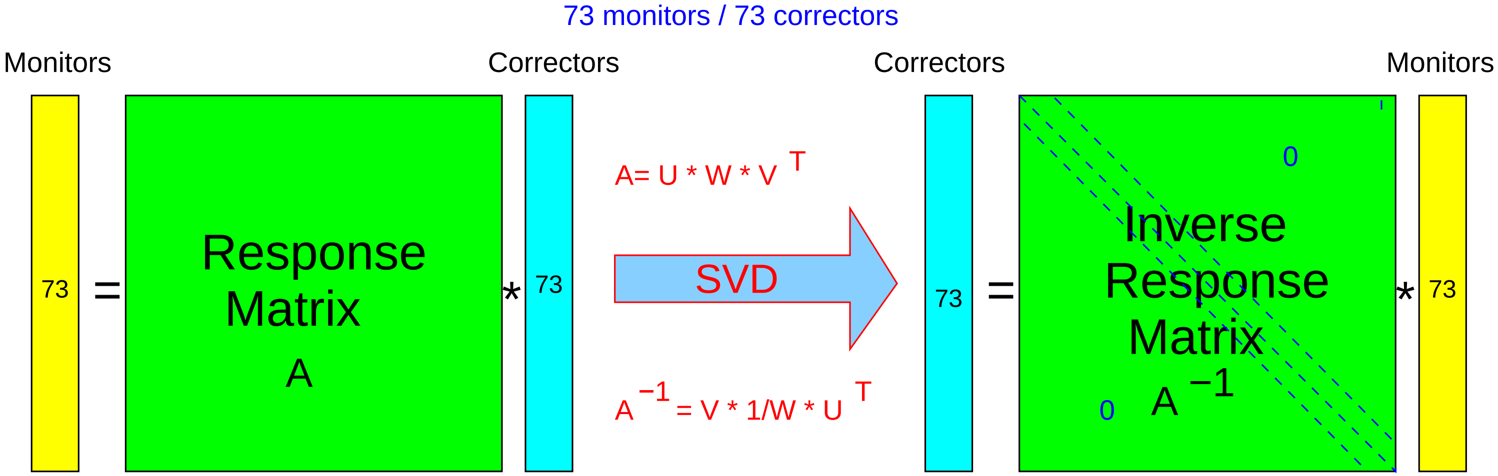
- **Sliding Bump** - Phase advances between Correctors $0° < \Delta\phi < 180°$, Correctors 1,2,3 allow to zero the orbit in BPM 2 near Corrector 2. 1 opens "Orbit Bump", 2 provides kick for 3 to close it again. Continue ("Slide") with 2,3,4 to zero orbit in BPM 3 ... iterate until orbit is minimized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



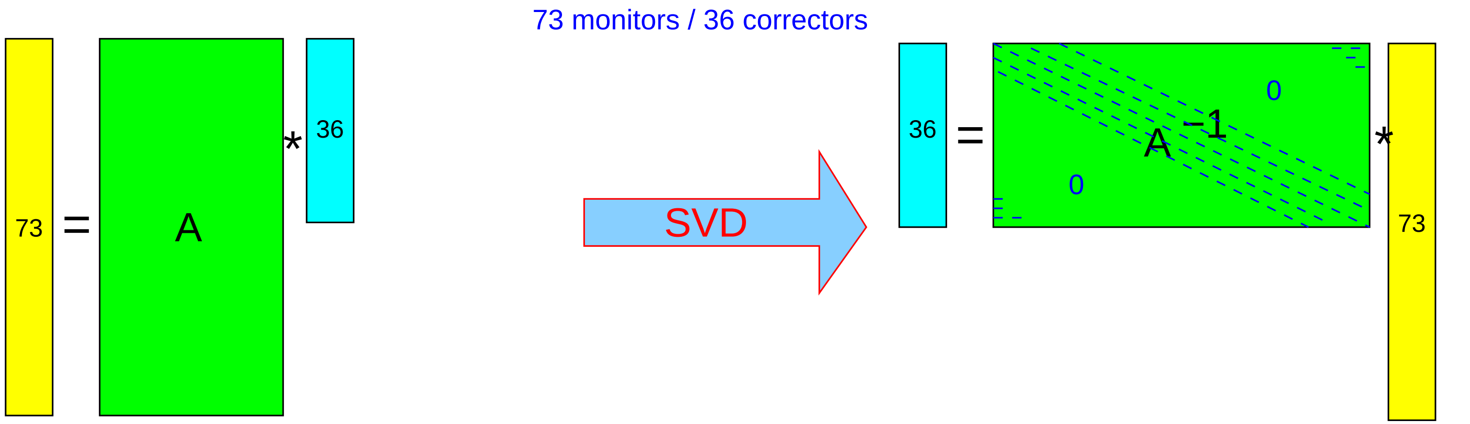
- **MICADO** - Finds a set of "Most Effective Correctors", which minimize the RMS orbit in all BPMs at a minimum ("most effective") RMS Corrector kick by means of the SIMPLEX algorithm. The number of Correctors (= iterations) is selectable.

- **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 !-)

What is SVD doing ?

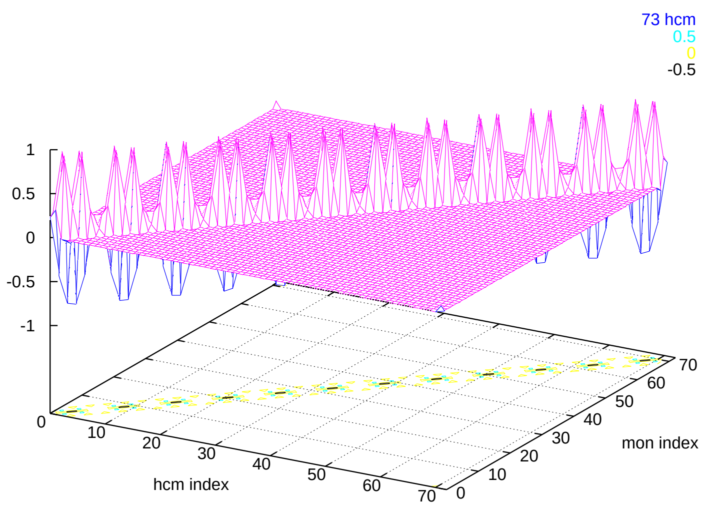


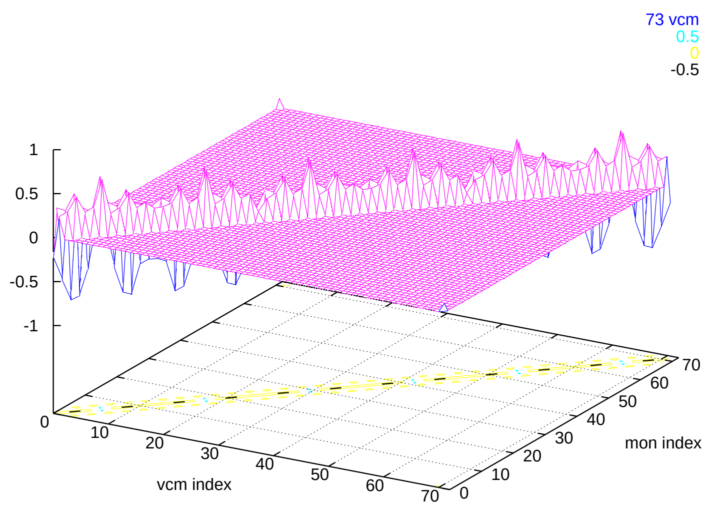
=> Minimization of the RMS orbit (=0 in case of "Matrix Inversion" using all Eigenvalues)



=> Minimization of the RMS orbit (monitor averaging)

Inverse Corrector / BPM Response Matrices (SLS)

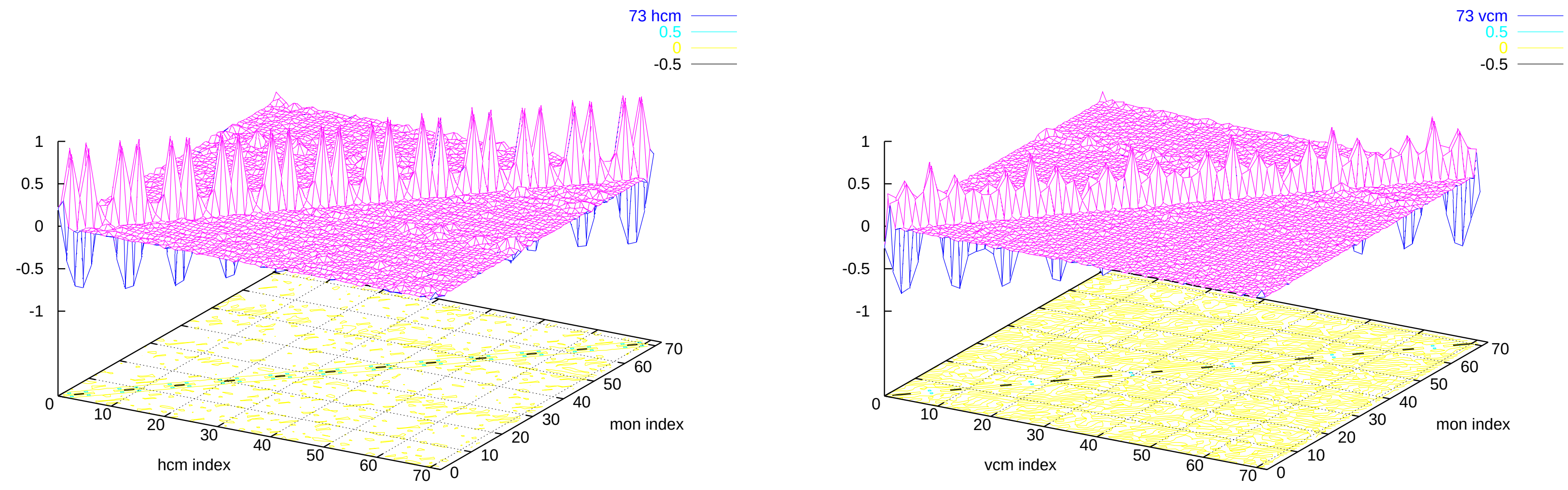




$$A_{ij}^{-1} = (V * 1/W * U^T)_{ij}$$

- A_{ij}^{-1} 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_{ij}^{-1} contains *global* information although it is a "*tridiagonal*" matrix !
  $\rightarrow$ Implementation of a Fast Orbit Feedback (FOFB)

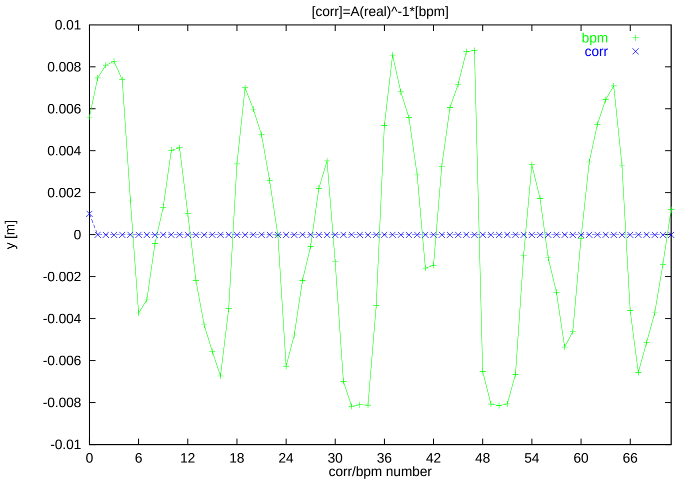
Inverse Measured Corrector / BPM Response Matrices (SLS)

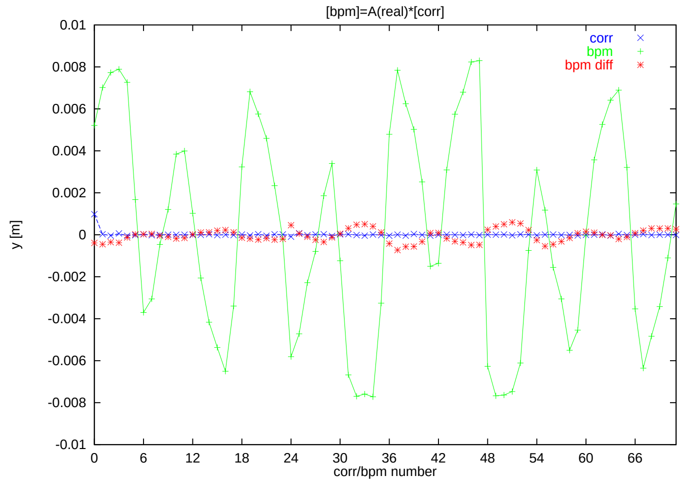


- Horizontal β Beat: $\approx$ 4 % (RMS $\Delta(\beta - \beta_0)/\beta_0$)
- Vertical β Beat: $\approx$ 3 %

$\rightarrow$ $A(real)^{-1}_{ij}$ is still a sparse "*tridiagonal*" matrix plus some noise

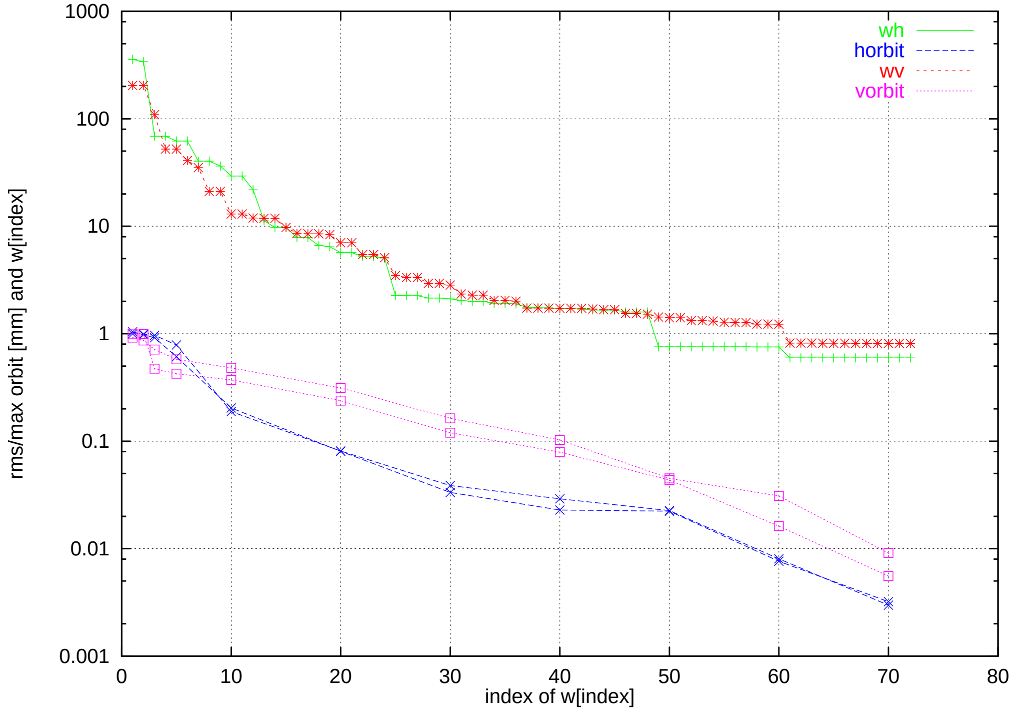
Single Corrector Example





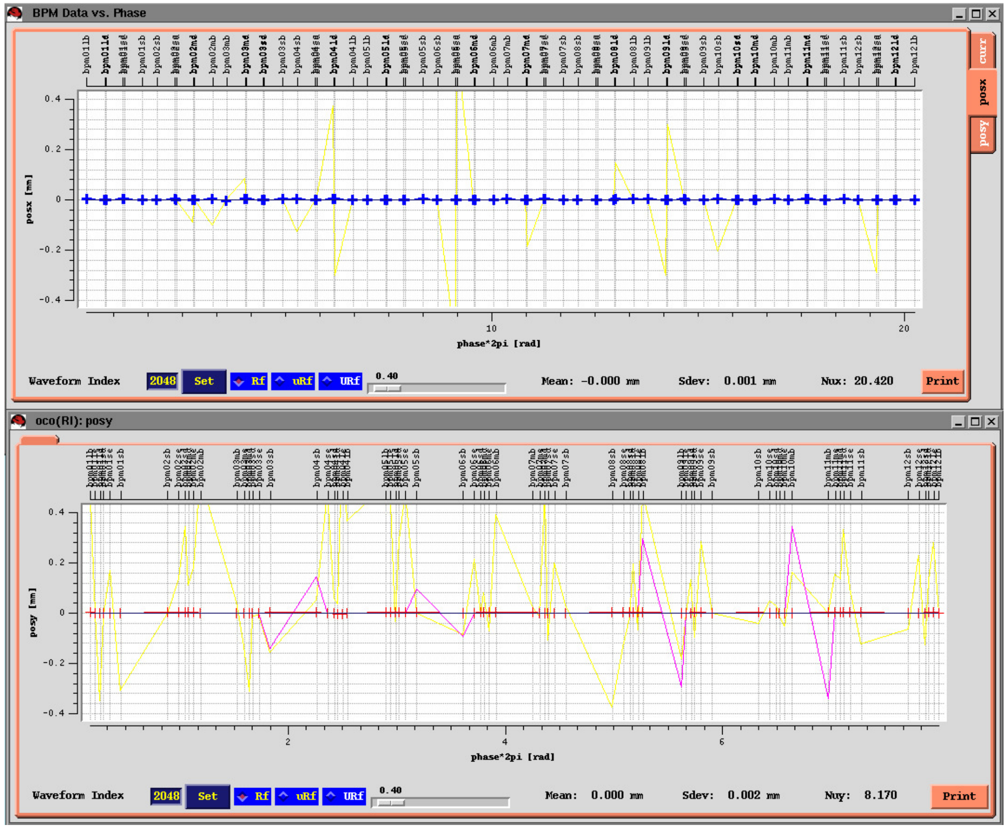
- Vertical βtron oscillation in a machine with distortions
- The measured $A(real)^{-1}_{ij}$ would predict *one* corrector
- $A(ideal)^{-1}_{ij}$ for the ideal machine predicts *one* corrector plus some noise on the other correctors
- Residual βtron oscillation after the correction (removed by iteration)

SVD Eigenvalues



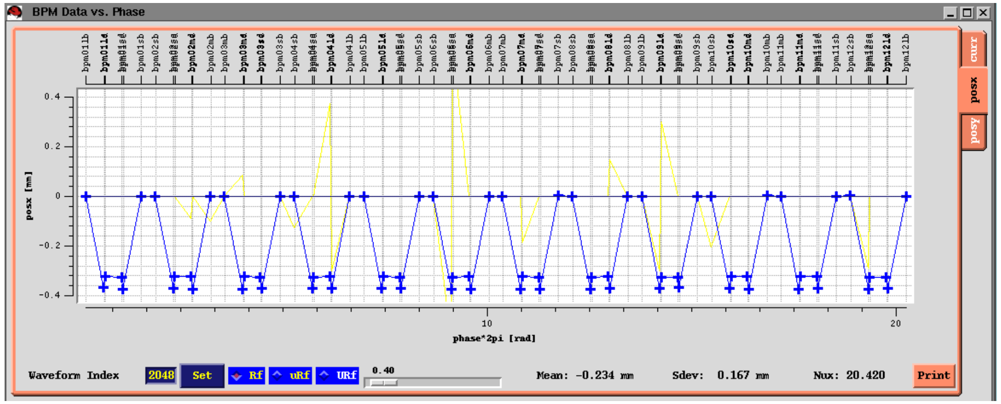
- Range of Eigenvalues $0.5 < W < 500$
- Eigenvalue Cutoff @ i_0 ($W_i = 0$ for $i > i_0$) determines the minimum achievable RMS Orbit and Corrector Strength after Correction $\longrightarrow$ “MICADO” like: the largest Eigenvalues correspond to the “Most Effective Corrector” patterns
- No Cutoff corresponds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

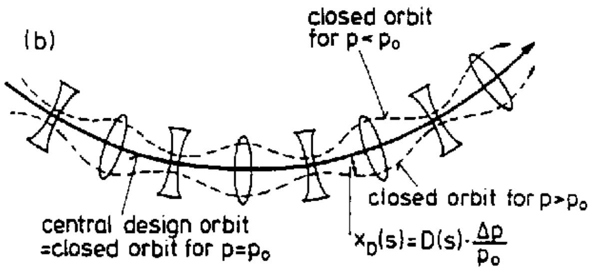
Closed Orbit after Correction - Golden Orbit



- Closed Orbit after correction deviates by $x_{rms} \approx y_{rms} \approx 1\ \mu m$ from the so-called "Golden Orbit", which contains some extra steering for the IDs (→No Cutoff).
- At SLS corrector values are at RMS values of ≈ 140 μrad (1.3 A) and ≈ 130 μrad (1.2 A).

How to correct Off-Energy Orbits ?

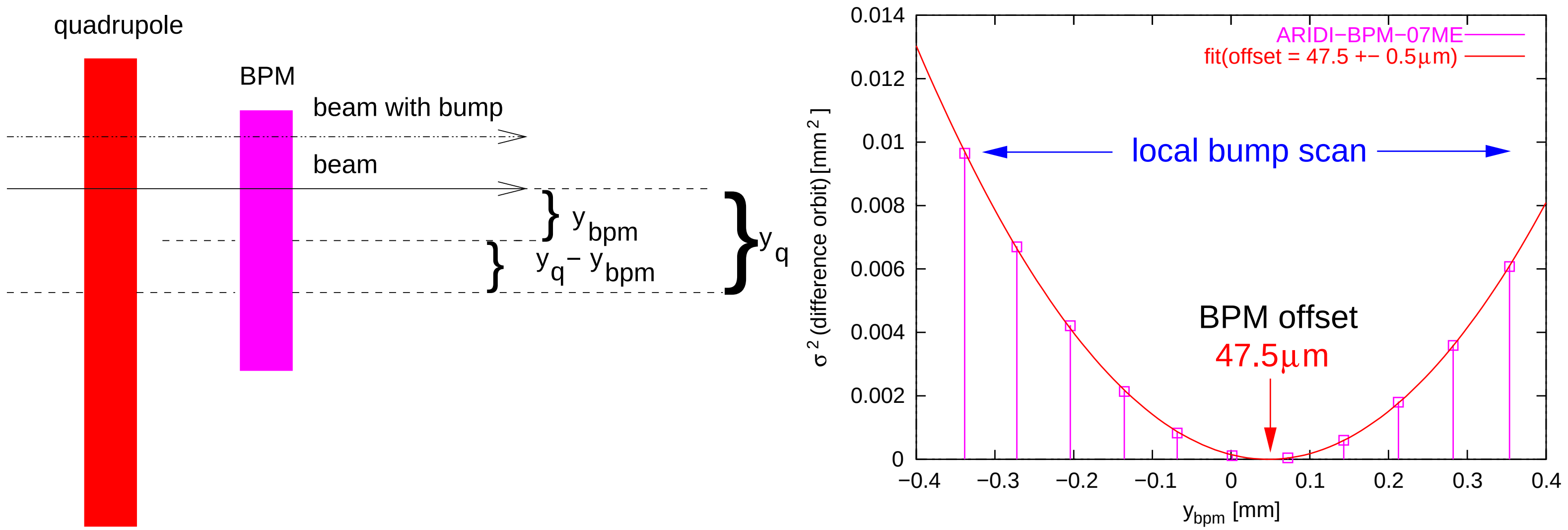




- In the case of "strong focussing" (b) the Orbit Deviation @ a location s is given by $x_0(s) = D(s)\Delta p/p_0$ with $\Delta p = p - p_0$, $D(s)$ denotes the Dispersion. $\Delta L/L_0 = \alpha_c \Delta p/p_0$ with the so-called "Momentum Compaction Factor" $\alpha_c = 1/L_0 \int_0^{L_0} D(s)/\rho(s)ds$ ($\approx\ 6 \cdot 10^{-4}$ 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 $\Delta p/p_0$!

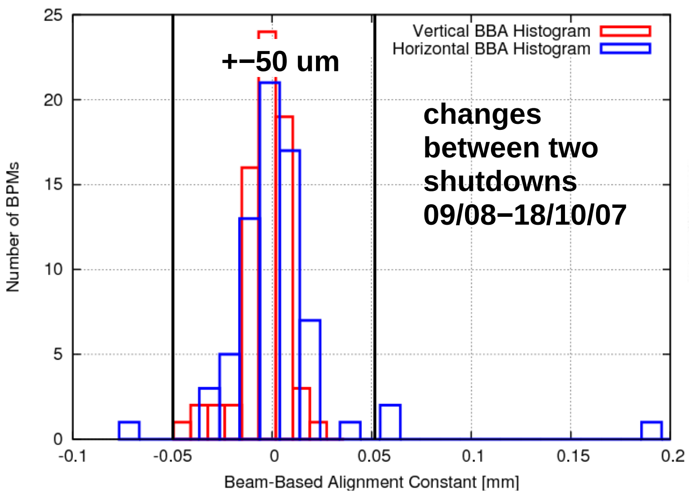
How is the position of BPMs measured ?

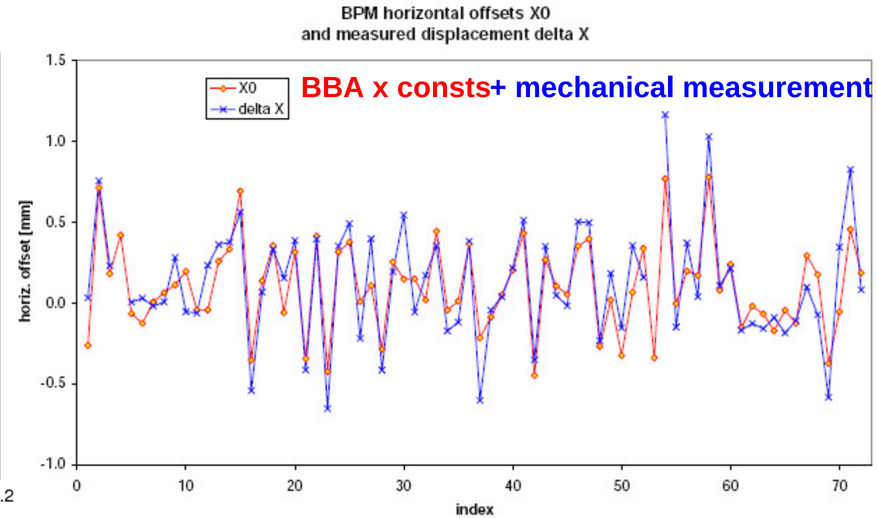


The so-called "Beam-Based Alignment" (BBA) (with respect to quadrupoles) technique is based on the fact that if the strength of a single quadrupole q in the ring is changed, the resulting difference in the closed orbit $\Delta y(s)$ is proportional to the original offset y_q of the beam at q:
$\Delta y''(s) - (k(s) + \Delta k(s))\Delta y(s) = \Delta k(s) y_q(s)$.
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).

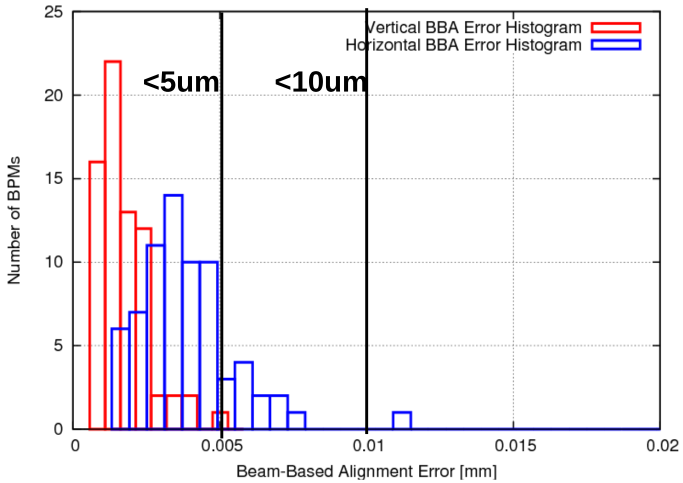
Comparing BBA with Mechanical Measurements

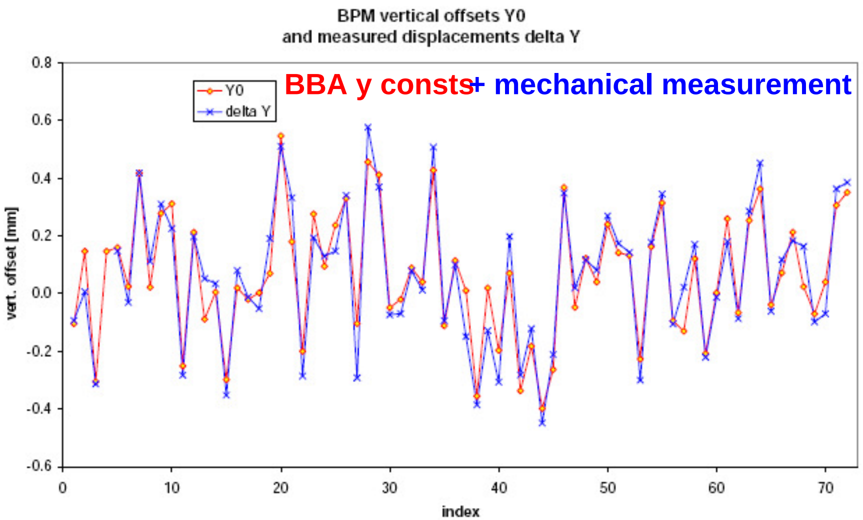
BBA dx/dy histograms for the SLS





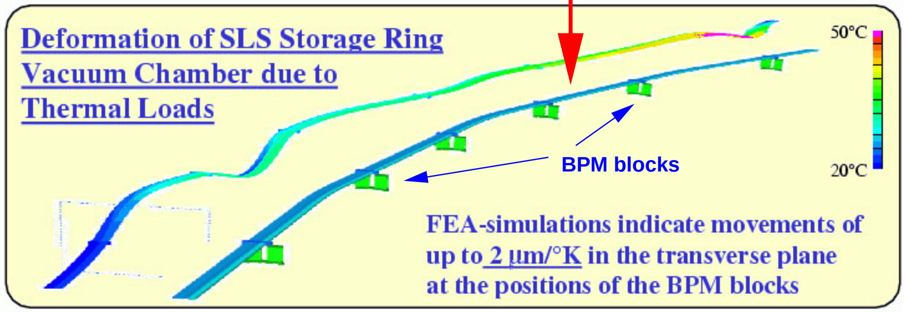
BBA dx/dy error histograms for the SLS





Measuring BPM Positions with Linear Encoders (SLS)

FEA−simulations indicate:
chamber moves ~2 µm/K @ BPM blocks

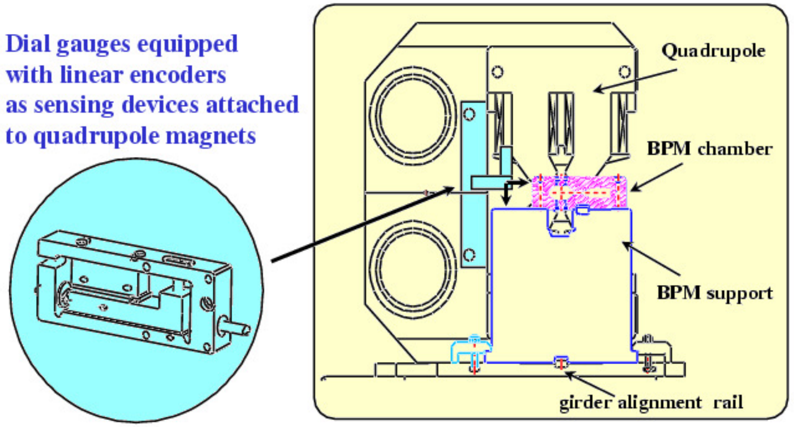


POMS System

- Dial gauges sense transverse movements of BPM block in reference to adjacent quadrupole magnets.
- Linear encoders of type Renishaw RGH24Z50A00A with 0.5 µm resolution are used as sensing devices.
- Complete integration into EPICS control system through serial SSI-interface and 32 channel VME-SSI card.

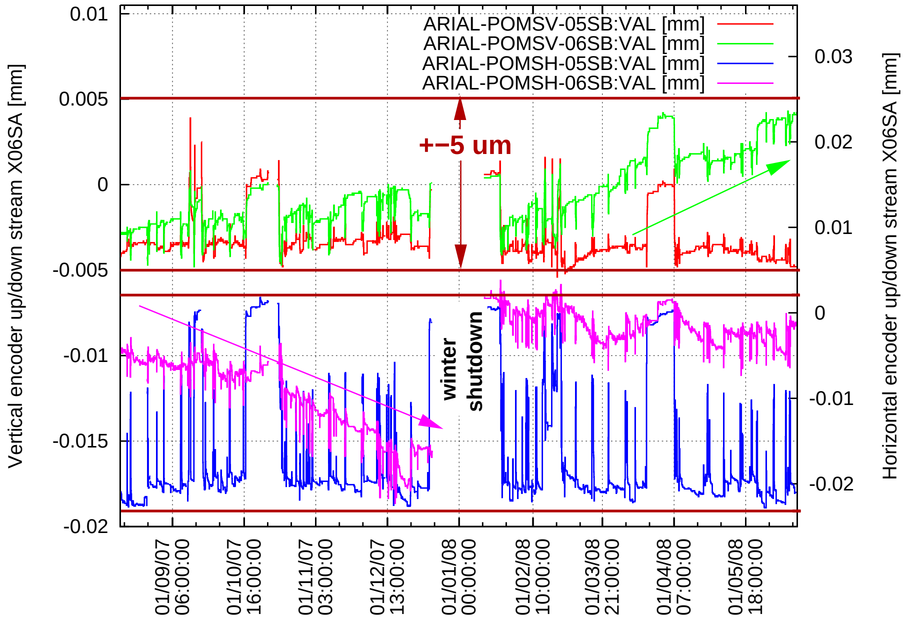
Measure BPM/Quadrupole offsets with
0.5 µm resolution in x and y !

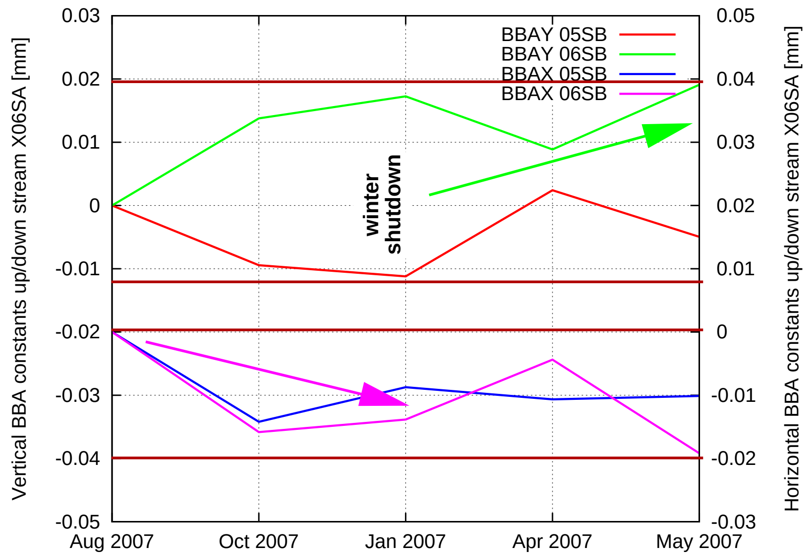
100 nm @ one undulator beamline



- 6 BPMs per sector (+1 BPM in 5L / FEMTO)
- BPMs rigidly attached to girders (BPM support mounted on girder alignment rail)
- BPM supports serve as supports for the vacuum system (→ BPM chamber)
- Initially planned to be used within the FOFB loop (NOT necessary →Top-Up)

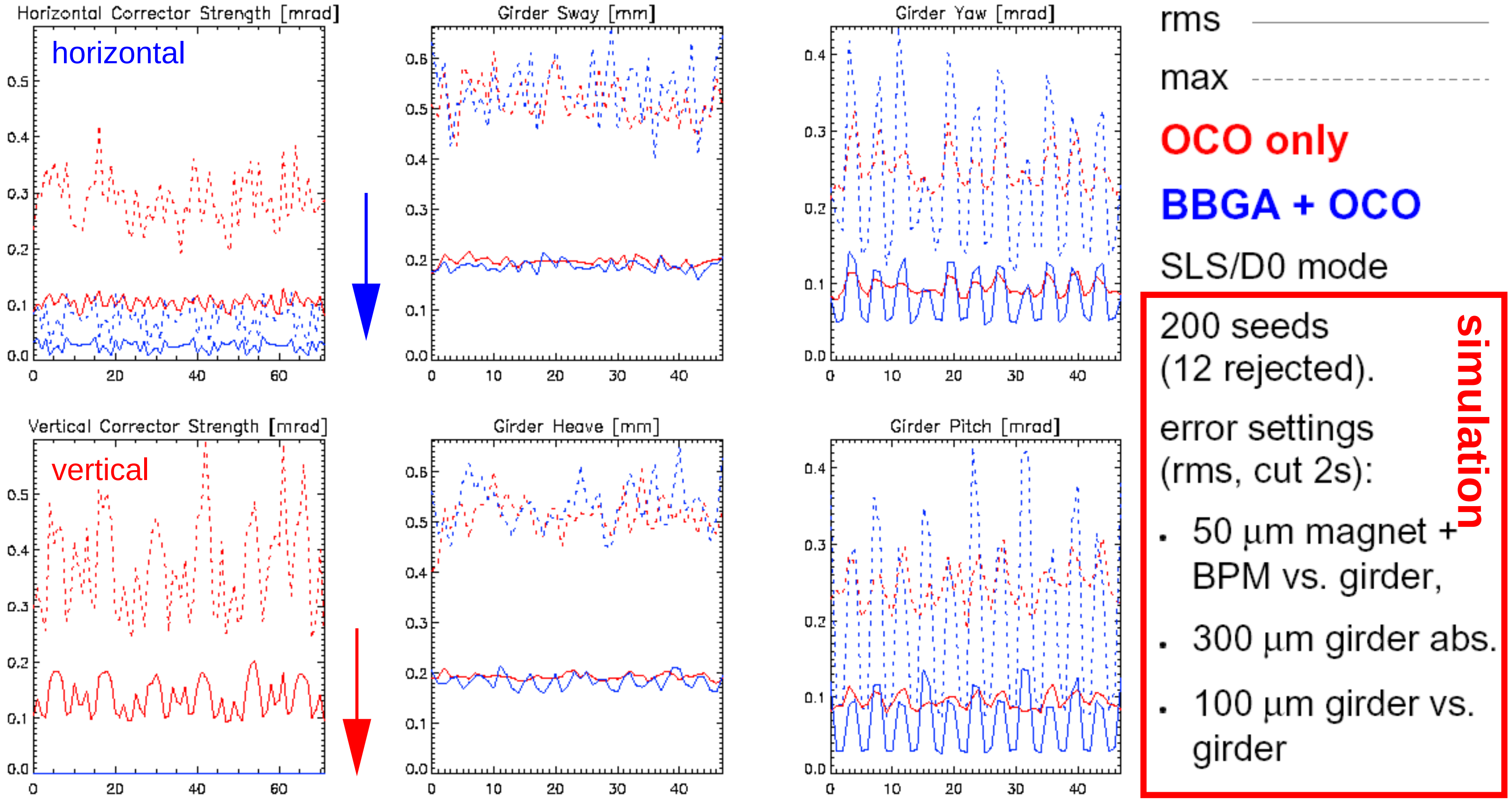
Comparing BBA with Linear Encoders (SLS)





- Readings of the linear encoders (100 nm resolution) at an undulator beamline readings over $\approx$10 months stay within a band of $\pm 5/10$ 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.

What is Beam-Based Girder Alignment ?



A. Streun

simulation

200 seeds (12 rejected).

error settings (rms, cut 2s):

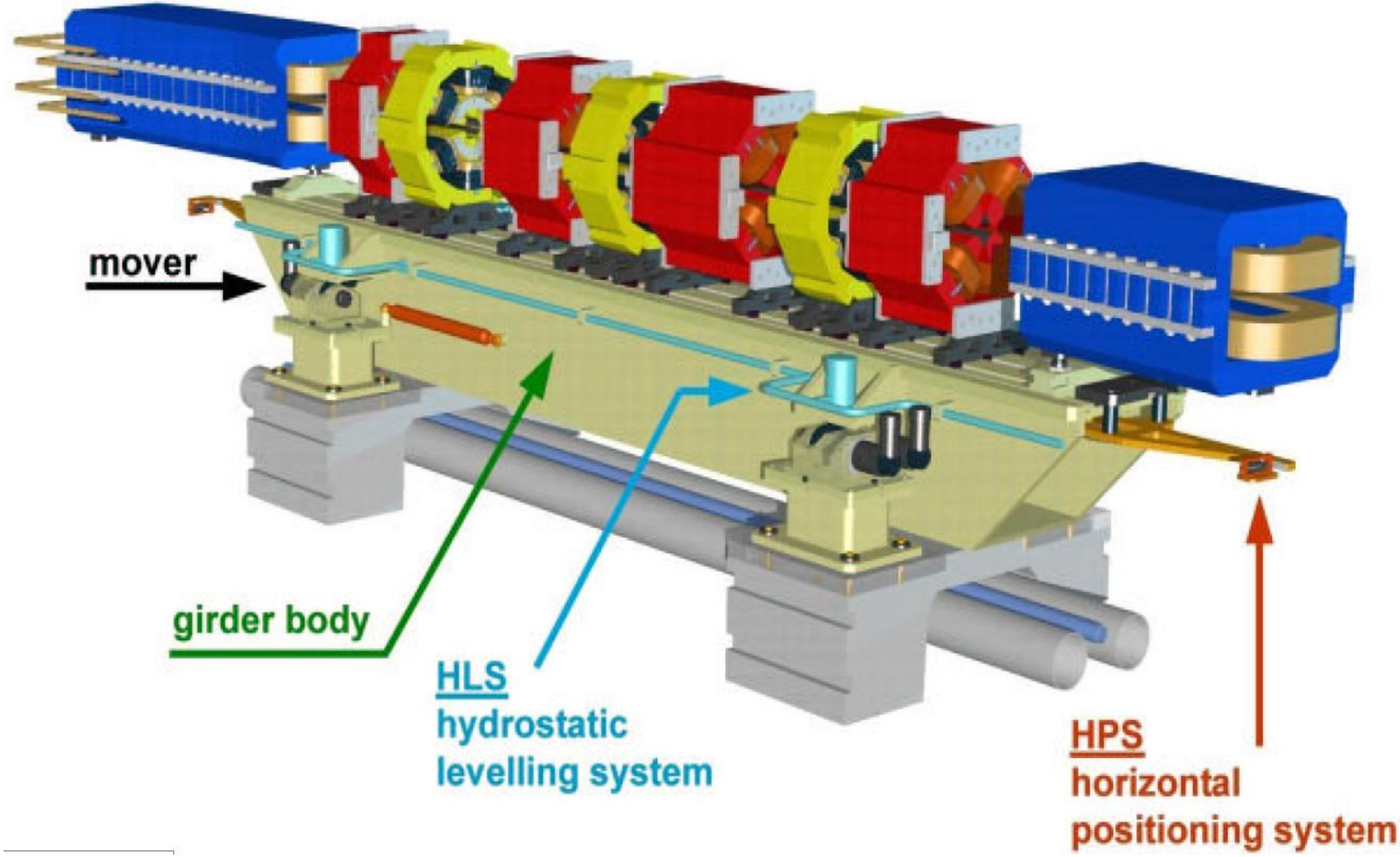
- 50 µm magnet + BPM vs. girder,
- 300 µm girder abs.
- 100 µm girder vs. girder

Reshuffle Machine Errors –> Minimize Distortions

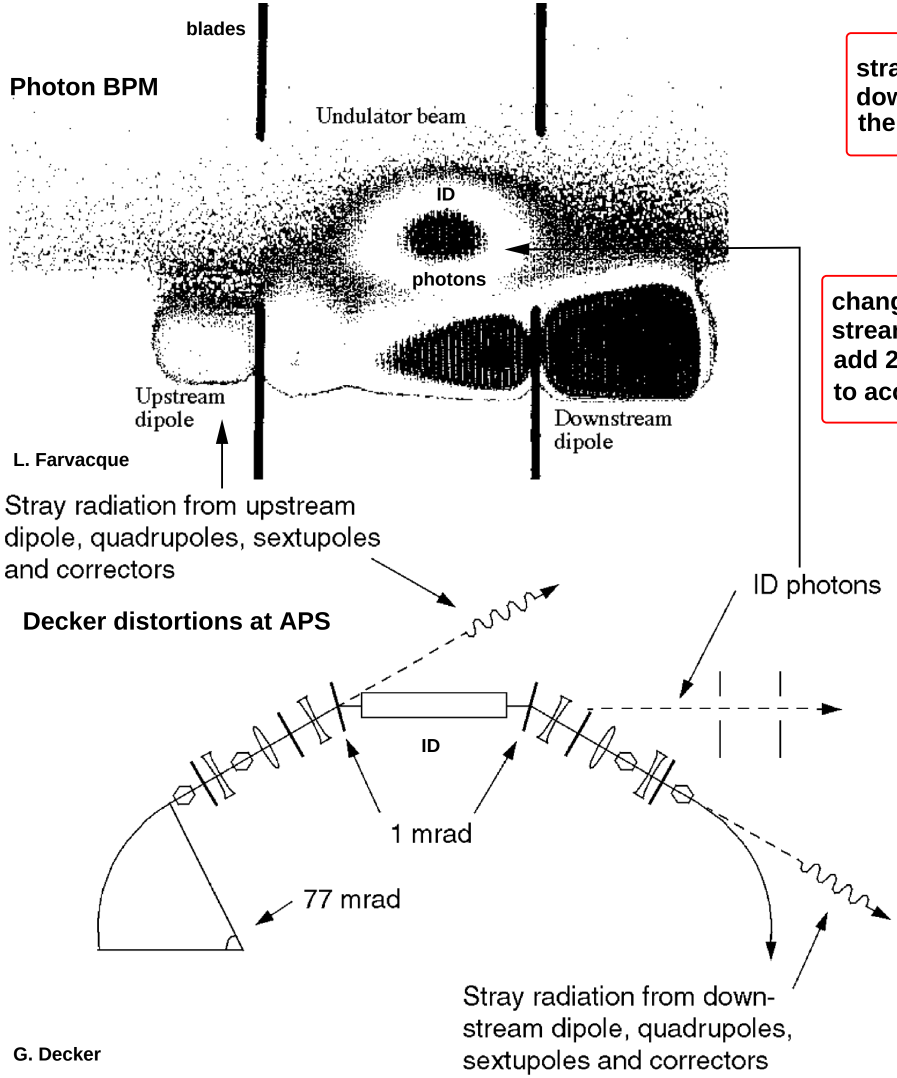
	horizontal	vertical
SVD weighting factor filter ω_i/ω_o >	0.001	0
SVD weighting factors used (from 96)	60	96
saved magnetic corrector strength (rms)	**75 %**	**100 %**

girder remote control

Girder Design (SLS)



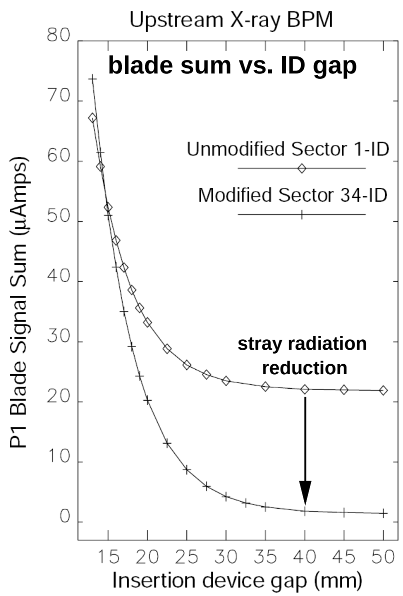
BPMs Using the Photon Beam (X-BPMs)



stray radiation from up− and down−stream magnets bias the reading of a Photon BPM

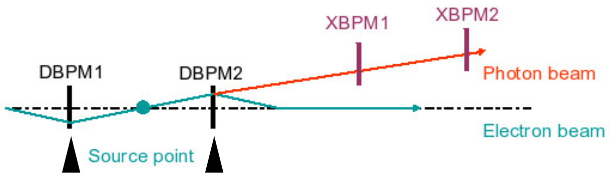
Solution

change strength of up− and down−stream dipoles (APS: 78−>77 mrad) add 2 extra magnets (APS: 1 mrad) to account for the difference.

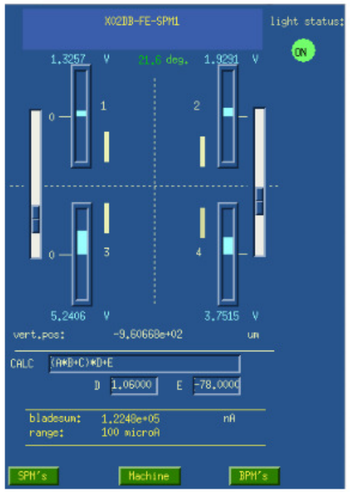


Calibration of X-BPMs

Calibration using machine bumps [1]:

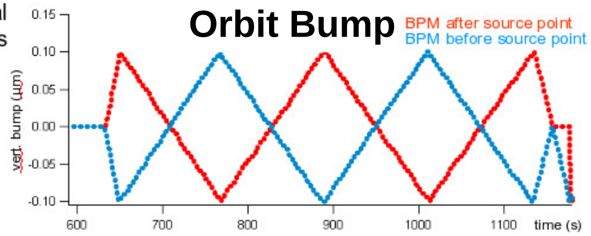


While the FOFB is running the reference positions of DBPM1 and 2 are varied.



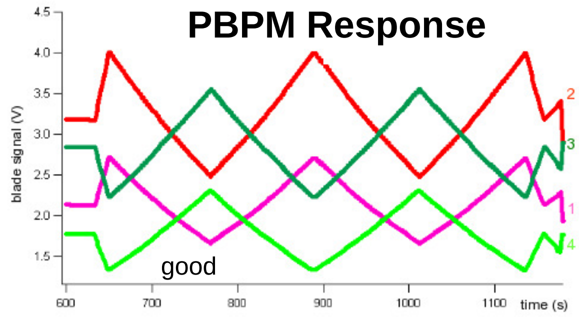
Synoptic view of the PBPM in the control system

Vertical asymmetrical bumps

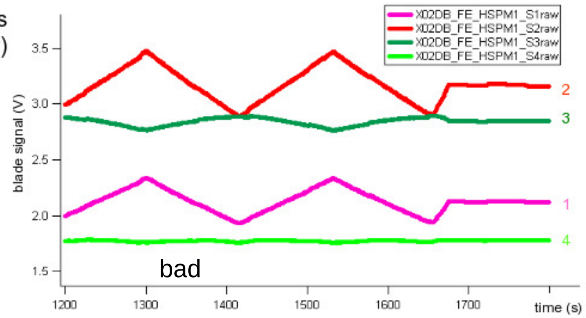


+−100 um bump amplitude

Response of the blades (well aligned monitor)



Response of the blades (badly aligned monitor)



E. van Garderen (please visit her poster :−)

Calibration using machine bumps is preferred to calibration using motors as it is a tool to detect *alignments*.