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 middle of the vacuum chamber couples to buttons of the monitor and generates signals $\sum U_i$, which allow to determine its position.
- **Horizontal Beam Position** = $c_M ((U_2 + U_4) - (U_1 + U_3))/\sum U_i$
- **Vertical Beam Position** = $c_M ((U_1 + U_2) - (U_3 + U_4))/\sum U_i$, $c_M = \text{monitor constant}$.
- At the SLS 73 “button” BPMs are part of a digital BPM System. Orbit deviations are measured to better than 1 $\mu m$ @ 4 kHz sampling rate.

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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 established at design energy $p_0$, 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 homogeneous magnetic field there is just “weak” focussing: particles move on different circles depending on the initial angles at $P_1$ and $P_2$ (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 $s$: $x_D = D(s)(p - p_0)/p_0$. 
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 $\epsilon$ is the so-called emittance which appears to be an invariant of motion.
The “Closed Orbit” is distorted under the influence of a magnet alignment/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 $s0$. 
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)

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

- “Response Matrix”: Differences from the “Closed Orbit” (“Difference Orbit”) due to a kick of corrector $i$ are recorded at BPM positions $j = 1..73$.
- $\nu_x = 20.44$ ($\approx$3 BPMs/Correctors per unit phase, $\phi = \int_0^s 1/\beta(s)ds$)
- $\nu_y = 8.74$ ($\approx$9 BPMs/correctors per unit phase)
What is a “Bare Orbit” ? (SLS)

- A “Bare Orbit” is a “Closed Orbit” without any corrections applied ($\nu_x = 20.42$, $\nu_y = 8.17$).
- 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 $\mu$m.
- The ratio of the RMS of the resulting “Closed Orbit” excitation and the originating RMS magnet distortions is called “Amplification Factor” ($A_x = 12$, $A_y = 8$).
The example depicts so-called vertical asymmetrical (left) and symmetrical (right) “4-Bumps” for an undulator beamline at SLS (well defined 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 $\approx -400 \, \mu\text{rad}$ and $\approx 1.4 \, \text{mm}$ 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 $0^\circ < \Delta \phi < 180^\circ$, 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”

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

Matrix Response

\[ A^{-1} = V \times \frac{1}{W} \times U^T \]

Matrix Inversion

\[ A = U \times W \times V^T \]

\[ A^{-1} = V \times \frac{1}{W} \times U^T \]

Minimization of the RMS orbit (monitor averaging)

73 monitors / 73 correctors

Monitors Correctors Correctors Monitors

Monitors Correctors

Monitors

Minimization of the RMS orbit (monitor averaging)

73 monitors / 36 correctors

Monitors Correctors

Monitors

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CAS’08
Inverse Corrector / BPM Response Matrices (SLS)

\[ A^{-1}_{ij} = (V \ast 1/W \ast U^T)_{ij} \]

- \( A^{-1}_{ij} \) is a sparse “tridiagonal” matrix (3 large (+1 small) adjacent coefficients are nonzero since BPM and Corrector positions are slightly different)
  → “Sliding Bump Scheme” iteratively inverts \( A \)

- \( A^{-1}_{ij} \) contains global information although it is a “tridiagonal” matrix!
  → Implementation of a Fast Orbit Feedback (FOFB)
Closed Orbit (Correction)

Inverse Measured Corrector / BPM Response Matrices (SLS)

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

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

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CAS’08
• Vertical $\beta$tron oscillation in a machine with distortions

• The measured $A(real)^{-1}$ would predict one corrector

• $A(ideal)^{-1}$ for the ideal machine predicts one corrector plus some noise on the other correctors

• Residual $\beta$tron oscillation after the correction (removed by iteration)
• 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 → “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 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 $\approx 140 \mu rad \ (1.3 \ A)$ and $\approx 130 \mu rad \ (1.2 \ A)$.
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”
  \[ \alpha_c = 1/L_0 \int_0^{L_0} D(s)/\rho(s) ds \approx 6 \cdot 10^{-4} \text{ at the SLS} \]

- $p$ 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!

→ 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 $\Delta p/p_0$!
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

Changes between two shutdowns 09/08–18/10/07

BBA dx/dy error histograms for the SLS

BBA x const. vs mechanical measurement

BBA y const. vs mechanical measurement
Measuring BPM Positions with Linear Encoders (SLS)

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

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)

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• 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.
What is Beam-Based Girder Alignment?

Reshuffle Machine Errors $\rightarrow$ Minimize Distortions
SVD weighting factor filter $\omega / \omega_0 >$
SVD weighting factors used (from 96)
saved magnetic corrector strength (rms)

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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.

Decker distortions at APS
- Stray radiation from upstream dipole, quadrupoles, sextupoles and correctors
- ID photons
- Blade sum vs. ID gap

Upstream X-ray BPM
- Unmodified Sector 1-ID
- Modified Sector 34-ID
- Stray radiation reduction

Blade sum vs. ID gap
- 77 mrad
- 1 mrad

G. Decker
L. Farvacque
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

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.