Orbit Feedback at the SLS

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

Swiss Light Source @ PSI

http://sls.web.psi.ch/

Michael Böge

CAS’03
Orbit Feedback at the SLS

Outline

- **Introduction**
  - SLS Layout
  - Storage Ring Design
  - BPM/Corrector Layout
- **Motivation**
  - Stability - Ground Noise
  - Stability - Worst Case Stability Estimate
- **Theory & Simulations (T&S)**
  - Orbit Correction Schemes
  - Response Matrices
  - Path Length Correction
  - Model for a Closed Orbit Feedback
- **Fast Orbit Feedback (FOFB)**
  - Digital BPM System
  - Digital Power Supplies
- **Slow Orbit Feedback (SOFB)**
  - Golden Orbit
  - Schematic View
  - RMS/Mean Orbit, Path Length
  - RF changes vs. Temperature
  - Long Term Stability - BPMS
  - Stability - Top-up
  - Stability - Position Monitoring System (POMS)
- **Fast Orbit Feedback (FOFB)**
  - From Manual Correction to FOFB
  - Power Spectral Densities
  - Vertical Transfer Functions
- **Conclusions**
**Introduction - SLS Layout**

- **Pre-Injector Linac**
  - 100 MeV
- **Booster Synchrotron**
  - 100 MeV to 2.7 GeV @ 3 Hz
  - $\epsilon_x = 9$ nm rad
- **Storage Ring**
  - 2.4 (2.7) GeV, 400 mA
  - $\epsilon_x = 5$ nm rad
- **Initial Four Beamlines:**
  - MS – 4S, PX – 6S,
  - SIS – 9L, SIM – 11M
**Introduction - Storage Ring Design**

- 12 TBA: $8^\circ / 14^\circ / 8^\circ$
- 12 Straight Sections:
  - $3 \times 11 \text{ m (nL)}$
    - Injection, U212
  - $3 \times 7 \text{ m (nM)}$
    - UE56
  - $6 \times 4 \text{ m (nS)}$
    - $2 \times \text{ RF, W61, U24}$
- Energy: 2.4 GeV (2.7 GeV)
- $\epsilon_x$: 5 nm rad
- Current: 400 mA
- Circumference: 288 m
- Tune: 20.42 / 8.17)
- Chromaticity: -66 / -21

**CAS'03**
Introduction - BPM/Corrector Layout

- 12 sectors
- 6 BPMs and 6 Horizontal/Vertical Correctors per sector
- Correctors in Sextupoles, BPMs adjacent to Quadrupoles
Motivation - Stability - Ground Noise

- Stability
- Ground Noise

[Graphs showing time and frequency domain measurements with various noise levels and time durations.]
**Motivation - Stability - Worst Case Estimate**

- $\beta_x = 1.4 \text{ m}$, $\beta_y = 0.9 \text{ m}$ at ID position of section nS →
  - $\sigma_x = 84 \mu\text{m}$, $\sigma_y = 7 \mu\text{m}$ assuming emittance coupling $\epsilon_y/\epsilon_x = 1 \%$

- With stability requirement $\Delta \sigma = 0.1 \times \sigma$ →

**Requirement:** Orbit jitter $< 1 \mu\text{m}$ at insertion devices

<table>
<thead>
<tr>
<th>Worst case Noise estimate</th>
<th>30</th>
<th>60</th>
<th>Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic measurements</td>
<td>300</td>
<td>30</td>
<td>nm</td>
</tr>
<tr>
<td>Damping by hall’s concrete slab</td>
<td>neglected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Girder resonance max amplification</td>
<td>$&lt; 10$</td>
<td>$&lt; 10$</td>
<td></td>
</tr>
<tr>
<td>Closed orbit amplification hor./vert.</td>
<td>8/5</td>
<td>25/5</td>
<td></td>
</tr>
<tr>
<td>→ Maximum Orbit jitter hor./vert</td>
<td>24/15</td>
<td>7.5/1.5</td>
<td>$\mu\text{m}$</td>
</tr>
<tr>
<td>Attenuation by orbit feedback</td>
<td>$-55$</td>
<td>$-35$</td>
<td>dB</td>
</tr>
<tr>
<td>→ Maximum Orbit jitter hor. /vert.</td>
<td>40/30</td>
<td>130/30</td>
<td>$\text{nm}$</td>
</tr>
</tbody>
</table>
**T&S - Orbit Correction Schemes**

- **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”

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

  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! -)
### T&S - What SVD does

**Response Matrix**

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

**Inverse Response Matrix**

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

- **Monitors Correctors**
  - 72 monitors / 72 correctors
  - Minimization of the RMS orbit (monitor averaging)

- **Monitors Correctors**
  - 72 monitors / 36 correctors
  - Minimization of the RMS orbit (=0 in case of "Matrix Inversion" using all Eigenvalues)
T&S - Response Matrices

\[ A_{ij} = \frac{\sqrt{\beta_i \beta_j}}{2 \sin \pi \nu} \cos \left[ \pi \nu - |\phi_i - \phi_j| \right] = (U \ast W \ast V^T)_{ij} \]

- \( \nu_x = 20.42 \) (\( \approx 3 \) BPMs/Correctors per unit phase, \( \phi = 360^\circ \))
- \( \nu_y = 8.17 \) (\( \approx 9 \) BPMs/correctors per unit phase)
\[ A_{ij}^{-1} = \left( V \ast \frac{1}{W} \ast U^T \right)_{ij} \]

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

- \( A_{ij}^{-1} \) contains global information although it is a "tridiagonal" matrix!
  → Implementation of a Fast Orbit Feedback (FOFB)
T&S - Inverse Measured Response Matrices

- Horizontal $\beta$ Beat: $\approx 4\%$
- Vertical $\beta$ Beat: $\approx 3\%$

$\rightarrow A(real)_{ij}^{-1}$ is still a sparse “tridiagonal” matrix plus some noise
- Vertical $\beta$tron 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 $\beta$tron oscillation after the correction
- 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!
In a homogeneous magnetic field (a) the radius of the Closed Orbit is proportional to the Energy $p$ (shown are $p < p_0$, $p = p_0$ and $p < p_0$). The Orbit gets shorter or longer ("Path Length" change $\Delta L/L_0$).

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 momentum compaction factor $\alpha_c = 1/L_0 \int_0^{L_0} D(s)/\rho(s) ds (\approx 6 \cdot 10^{-4})$.

$p$ variations due to "Path Length" (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 $\Delta p/p_0$!
T&S - Model for a Closed Orbit Feedback

- **Corrector Settings**
- **Eddy Currents in Magnet Yoke Beam Chamber**
- **Corrector Fields**
- **Machine Optics**
- **Digital PID Feedback**
- **SVD Algorithm**
- **Beam Position Readings**
- **BPM Readout**
- **Orbit Offsets**
- **Electron Beam Jitter**

CAS'03

Michael Böge
T&S - Calculated Corrector Transfer Functions $|B|$

- MAFIA estimated Eddy Current Effects induced by the Vacuum Chamber (3 mm Stainless Steel) and the Laminated Iron of the Sextupoles:

**Horizontal Polarization**

- Only vacuum chamber
- Including lamination, $d=1\text{mm}$

**Vertical Polarization**

- w/o magnet losses
- with magnet losses
4 KHz Sampling Rate needed in order to have a gain $\approx 20 \text{ dB} @ 90 \text{ Hz}$
TRACY estimated Residual Vertical RMS Orbit after Orbit Correction as seen by the BPMs (histograms for 200 seeds introducing RMS girder misalignment of 1µm):

- 1 ppm in amplitude corresponds to a resolution of $10^{-6}$ at a maximum Current of 7 A ($\approx 860 \, \mu rad$ in the vertical plane)
- 60 ppm: $y_{rms} = 0.75 \mu m$, 30 ppm: $y_{rms} = 0.5 \mu m$, 15 ppm: $y_{rms} = 0.25 \mu m$

$\rightarrow$ 15 ppm ($\approx 10 \, \text{nrad or } 100 \, \mu A$) sufficient
**T&S - Power Supply Resolution and RMS Position/Angle @ IDs**

RMS Position at Insertion Devices with $\beta_x \approx 1.4\text{m}, \beta_y \approx 0.9\text{m}$ ($x/y_{rms} = 0.5\mu\text{m}$ for 15 ppm):

RMS Angle at the Insertion Devices ($\alpha_{x/y_{rms}} = 0.08\mu\text{rad}$ for 15 ppm):
Orbit Feedback at the SLS

FOFB - 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, <1.2 µm

Turn–by–Turn: Vital for Commissioning
Closed Orbit Mode -> Fast Orbit Feedback

CAS’03
Michael Böge
FOFB - Digital Power Supplies

One Digital Control Unit for ~600 power supplies of the SLS

Precision of the AD converter card

- Long-term stability (1000h) better than 30ppm
- Reproducibility better than 30ppm
- Resolution up to 1ppm
- Short-term stability (<60s) better than 10ppm

Short/Long-term: <10/30 ppm
FOFB - Inverse Response Matrix

- 12 sectors
- 6 BPMs and 6 Horizontal/Vertical Correctors per sector
**FOFB - Schematic View**

- **A-L** = Submatrices of $A^{-1}$
- **PC** = SVD Engine
- **Response Matrix A** or theoretical measured
- **Fast Link 40Mb/s**
- **Slow Link 1Mb/s**

- Dedicated **Signal Processors** perform **Matrix Multiplications in parallel**!
FOFB - Hardware Layout

DBPM System
- BPM pickups
  - $V_A$
  - $V_B$
  - $V_C$
  - $V_D$
- RF Front End
- Digital Down Converter
- Timing signal
- SHARC link ports (40 MB/sec)

FOFB System
- Fiber optic links to adjacent sectors (40 MB/sec)
- DSP1
- DSP2
- Serial interf.
- PS CTRL Interface
- PS CTRL
- EPICS
- LAN (TCP/IP)
- IOC

VME Bus

CAS’03
**SOFB - Stability - Girder Response**

- **20 nm!**
- **27.7 Hz**
- **15.5 Hz**
- **35.2 Hz**
- **21.6 Hz**
- **50.5 Hz!**
- **61.4 Hz**

- **Measurement 1999**
- **vertical tunnel slab/girder motion**
- **tunnel slab**
- **girder response**

CAS’03

Michael Böge
SOFB - Stability - Power Spectral Densities

Boosters: 3.1 Hz
Girders: 21.6, 27.7 Hz
Mains: 50 Hz

$\beta_x = 11 \text{m} < \beta_x \geq 10 \text{m}$
$\beta_y = 18 \text{m} < \beta_y \geq 11 \text{m}$
SOFB - Golden Orbit

0.5 mm horizontal difference orbit

~1 µm \( v_x = 20.42 \)

0.5 Hz (3 Hz) refresh rate

~0.3 µm precision of BPMs

0.5 mm vertical difference orbit

~1 µm \( v_y = 8.17 \)

72 BPMs
72 corrs

/ plane

Michael Böge

CAS’03
- 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 @ 2 Hz, average over 3 successive Datasets $\Rightarrow \approx 0.4$ Hz correction rate (toggle between x/y plane $\Rightarrow 5$ s for full cycle)
Orbit Feedback at the SLS

SOFB - RMS/Mean Orbit, Path Length

- Sample run Aug, 13-16 2002: $x_{rms}$, $y_{rms} \approx 1 \mu m$ (see histograms)
- Off energy $dp/p$ orbits fitted through SVD and subtracted before correction
- RF frequency changed by $df$ whenever $|df|$ exceeds 5 Hz ($dp/p \approx 2 \cdot 10^{-5}$) \rightarrow correction every $\approx 45$ min (see “saw tooth”)
SOFB - RF changes vs. T, X-BPM Readings

- Outside air temperature and RF frequency changes –>
- X-BPM @ PX
  ≈ 8.6 m from ID U24:
  \( \sigma_x = 2.7 \, \mu m \) (drift: 2.3 \( \mu m \))
  \( \sigma_y = 1.5 \, \mu m \)  (drift: 1.7 \( \mu m \))
  \( \sigma_{x'} < 0.31 \, \mu \text{rad} @ \text{source point} ! 
  \( \sigma_{y'} < 0.18 \, \mu \text{rad} @ \text{source point} ! 

Michael Böge
**SOFB - Long Term Stability - BPMS**

- $x_{rms}$ and $y_{rms}$ over 28 weeks $\uparrow$

- Outside air temperature and $\Delta$ circumference in 2002 $\rightarrow$

- $\Delta$ circumference vs. outside air temperature in 2002 $\rightarrow$
  - $\Delta$ circumference $\approx 1.2$ mm!
  - $\Delta$ RF frequency $\approx 2000$ Hz!
SOFB - Stability - Top-up

Electron beam current
from 8. October 15:00 to 10. October 15:00

- 2 days run @ 250 mA with a deadband of 1 mA in October
- $\tau = 12 \text{ h} @ I = 250 \text{ mA} (I \times \tau = 3 \text{ Ah})$
- time between injections $dt = 3 \text{ min} (\approx 960 \text{ injections in 48 h})$
- SR in thermal equilibrium!

CAS’03

Michael Böge
SOFB - Stability - POMS

- Top-up: Current is stabilized @ 200 mA ($\tau=12$ h) with a deadband of 0.5 mA (injection every $\approx 2$ min)

- PPosition Monitoring System: linear encoders on all BPM stations measuring BPM/adjacent Quadrupole offsets (0.5 $\mu$m resolution) $\rightarrow$ no movement during Top-up!
SOFB - Long Term Stability - POMS

- POMS Readings for ARIDI-BPM-05SB upstream of U24
FOFB - From Manual Correction to FOFB

Stepwise Implementation of the Orbit Feedback:

1. Manual Orbit Correction, 0.5 Hz – **Operator** corrects Orbit using **oco Client**

2. Slow Orbit Feedback (SOFB), 2 Hz – **Operator** is replaced by **Feedback Client**

3. Fast Orbit Feedback (FOFB), 4 KHz – **Feedback Client**:
   - Corrects Orbit to < 5 µm with respect to “Golden Orbit” using **SOFB**
   - Initializes **FOFB** (“Golden Orbit”, “Inverted” Response Matrices)
   - Starts/Stops **FOFB**
   - Runs in “Watchdog” like passive Mode **supervising** **FOFB**
   - Monitors BPM, Corrector Values (Faults, Saturation), Restarts **FOFB** with adapted settings
- Snapshots of the horizontal and vertical power spectral densities measured with the digital BPM system at the location of the tune BPM ($\beta_x \simeq 11$ m, $\beta_y \simeq 18$ m):

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>horizontal FOFB</th>
<th>horizontal FOFB</th>
<th>vertical FOFB</th>
<th>vertical FOFB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-100 Hz</td>
<td>1.7 $\mu$m</td>
<td>1.4 $\mu$m</td>
<td>1.5 $\mu$m</td>
<td>0.9 $\mu$m</td>
</tr>
<tr>
<td>100-400 Hz</td>
<td>0.95 $\mu$m</td>
<td>1.1 $\mu$m</td>
<td>0.95 $\mu$m</td>
<td>1.2 $\mu$m</td>
</tr>
</tbody>
</table>
FOFB - Vertical Transfer Functions

Openloop Transfer Functions + Low Pass Filter Fit + Time Delay Fit

Closed Loop Transfer Function with Moderate PI Parameters
Conclusions

- For Frequencies >0.2 Hz: residual orbit noise $\approx 1 \, \mu m$ level
- For Frequencies <0.2 Hz: SOFB for “Long Term” Drifts:

  ![Graphs showing orbit feedback performance](image)

  - **ID** Operation induced Distortions ($\approx 10 \, \mu m$) corrected by SOFB
  - Path Length changes corrected by means of the RF Frequency
  - “Golden Orbit” established by SOFB
  - Top-up Operation is vital for $\mu m$ level stability!
  - FOFB performs according to Design and will replace SOFB