Digital BPMs and Orbit Feedback Systems

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Outline

• stability requirements at SLS storage ring
• digital beam position monitors (DBPM)
• SLS global fast orbit feedback system
• SLS multi bunch feedback system
• beam stabilization plans at European XFEL
Stability Requirements at SLS

- Angular stability: $\Delta \Theta_{\text{beam}} < 1 \mu\text{rad}$
  * typical $< 10 \mu\text{m}$ at the experiment

- Position stability: $\sigma/10$ at Insertion Devices (ID)
  → low beta ID: vertical beam size $\sim 10 \mu\text{m}$ (1% coupling)
  → 1 $\mu\text{m}$ RMS in vertical plane

- suppression of orbit distortion up to 100 Hz by factor of $>5$

- fast compensation of orbit distortions due to **ID gap changes**
Beam Stability Strategy at the SLS

• reduce drifts and vibrations as much as possible
  (air and water temperature regulation, proper girder design, top-up operation,...)

• reduce well-known noise sources by feed forward  (ID gap changes,...)

• suppress remaining noise on e⁻ beam by fast orbit feedback

• use all available correctors for fast orbit feedback
  (no distinction between slow and fast orbit feedback)
  → lock beam to center of BPMs
  → monitor mechanical movement of BPMs with respect to adjacent quads by encoder system
  → good feedback systems:
    beam stability ≈ BPM stability & resolution
Why digital BPMs?

- **digitize beam position as early as possible to**
  - simplify RF front end
  - minimize non-linearities of analog components (mixers, etc.)
  - minimize temperature dependencies & drifts in electronics
  - minimize beam current dependence, guarantee high stability and reproducibility of beam position

- **reduce number of analog components in processing chain**
  - potential to reduce noise sources

- **high flexibility in output bandwidth of digital BPM due to programmable filters (+decimation)**
  - single pulse, turn-by-turn capability (broadband BPM)
  - closed orbit capability (narrow band BPM)
  - choose operating mode for required application (machine studies, orbit feedbacks, ...)

Digital Beam Position Monitor (DBPM)

principle:

- e⁻ bunches
- band-pass
- transfer function of pick-up
- direct sampling of RF

• provide enough oscillations to be sampled
• bunch-by-bunch resolution: distinction between pulses
• omitting RF mixer → reduce non-linearities
• multi bandwidth BPM (simultaneously)

(f_{rep} \ll f_{band-pass})
# SLS DBPM Specifications and Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification for SLS</th>
<th>SLS DBPM Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF carrier freq.</td>
<td>500 MHz</td>
<td></td>
</tr>
<tr>
<td>IF carrier freq</td>
<td>36 MHz</td>
<td></td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>1-400 mA</td>
<td>1-400 mA</td>
</tr>
<tr>
<td>Beam Current Dependence</td>
<td>&lt; 100 µm</td>
<td>&lt; 100 µm</td>
</tr>
<tr>
<td>1-400 mA</td>
<td>&lt; 5 µm</td>
<td>&lt; 30 µm</td>
</tr>
<tr>
<td>relative 1 to 5 range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>position measuring radius</td>
<td>5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>resolution*) / BW</td>
<td>&lt; 1 µm @ 2 kHz</td>
<td>0.8 µm @ 2 kHz</td>
</tr>
<tr>
<td></td>
<td>&lt; 20 µm @ 0.5 MHz</td>
<td>17 µm @ 0.5 MHz</td>
</tr>
</tbody>
</table>

*) with SLS ring vacuum chamber geometry

**recent developments: DBPM**

(Instrumentation Technology)

(scaled to SLS ring vacuum chamber geometry)

resolution:  < 1 µm @ 0.5 MHz BW
beam current dep.:  < 2 µm (1:5 range)
SLS Fast Orbit Feedback Layout

- only one feedback (no separation between slow and fast feedback)
- 72 BPMs / 72 corrector magnets in each plane, 12 sectors
- sampling and correction rate: 4 kHz
- inverted response matrix: sparse matrix

\[
A^T = \begin{bmatrix}
1 & \text{bpm} & 72 \\
72 & \text{corr} & 1
\end{bmatrix}_{72 \times 72}
\]

- decentralized data processing possible
- point-to-point fiber optic ring structure for global data exchange
SLS DBPM / Fast Orbit Feedback Hardware Layout (sector view)

DBPM System

FOFB System

technology choice: 1998
Performance: Stability Frequency Ranges

- **short term stability**: ~ 6 ms – 1 s (1 Hz – 150 Hz)
  - mainly limited by
    - BPM resolution
    - corrector magnet resolution
    - system latency
    - eddy currents in vacuum chambers

- **long term stability**: 1 s – days (run period)
  - mainly limited by
    - reliability of hardware components
    - systematic errors of BPMs
    - thermal equilibrium of the machine (→ top-up)
Performance: Short Term Stability

SLS transfer function measurement

Present sensitivity range of the experiments

0 dB point: ~ 95 Hz (in both planes)
SLS FOFB: spectral power density (1–400 Hz)

Fast Orbit Feedback *off/on*
(without any ID gap change)

(measured at tune BPM, outside of the feedback loop, $\beta_x = 11$ m, $\beta_y = 18$ m)
### SLS FOFB: Cumulated Power Spectral Density

<table>
<thead>
<tr>
<th></th>
<th>horizontal</th>
<th>vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOFB</td>
<td>off</td>
<td>on</td>
</tr>
<tr>
<td>1-100 Hz</td>
<td>$0.73 , \mu m \cdot \sqrt{\beta_x}$</td>
<td>$0.46 , \mu m \cdot \sqrt{\beta_x}$</td>
</tr>
<tr>
<td>100-150 Hz</td>
<td>$0.07 , \mu m \cdot \sqrt{\beta_x}$</td>
<td>$0.18 , \mu m \cdot \sqrt{\beta_x}$</td>
</tr>
<tr>
<td>1-150 Hz</td>
<td>$0.73 , \mu m \cdot \sqrt{\beta_x}$</td>
<td>$0.49 , \mu m \cdot \sqrt{\beta_x}$</td>
</tr>
</tbody>
</table>

RMS values to be scaled with $\sqrt{\beta}$ at desired location

**Examples (with FOFB):**

- **Tune BPM ($\beta_y=18$ m):**  
  $\sigma_y = \sqrt{18} \cdot 0.30 \, \mu m = 1.3 \, \mu m \quad (1 – 100 \, Hz)$

- **Source point at ID 6S ($\beta_y=0.9$ m):**  
  $\sigma_y = \sqrt{0.9} \cdot 0.30 \, \mu m = 0.28 \, \mu m \quad (1 – 100 \, Hz)$
Performance: Short Term Stability at Photon BPM

external reference:
Photon BPM at beam line 6S (protein crystallography)

⇒ successful suppression of noise sources originating from the electron beam

vertical power spectral density

preliminary results (March 2005)

J. Krempasky

closed loop transfer function

T. Schlücher

ERL 2005, Jefferson Laboratory, March 21, 2005
Performance: Long Term Stability

Strategy @ SLS:

- if photon BPMs are reliable enough
  ⇒ used to minimize systematic effects of RF BPMs, girder drifts, temperature drifts, etc.
  ⇒ slow PBPM feedback which changes reference orbit of FOFB (cascaded feedback scheme)
  ⇒ keep photon beam position constant at first PBPM
- so far: only one PBPM at ID beam-line 4S and 6S is reliable enough and understood to be integrated in PBPM feedback
SLS Multi Bunch Feedback System

Parameters & Layout

• bunch spacing: 2 ns

• 1 µrad maximum kick angle
  @ 2.4 GeV
  (15 kHz – 250 MHz)

• overall latency time ~ 3 µs
  (3 turns of SLS storage ring)

• fast real time ADC and DAC
  mezzanine boards with 8 bit,
  up to 1 GS/s and 750 MHz analog band width for low latency
  data processing

• clock generator for synchronization on picosecond time scale

• MBF has been developed in close collaboration with ELETTRA
SLS Multi Bunch Feedback System

First Results

vertical mode pattern in SLS storage ring
(revolution frequency $f_0 = 1.04 \text{ MHz}$)

corresponding pinhole camera images

MBF off

MBF on
Requirements for Beam Stabilization along the European XFEL

**beam energy**
- **510 MeV**
  - RF-gun / injector 1
  - SC booster
  - bunch compression 1 / 2
  - main SC LINAC
- **20 GeV**
  - undulator sections
  - collimation diagnostics
  - switchyard, beam distribution
  - beam dumps towards beam lines

**Injector / Bunch Compressor**
- transverse and longitudinal phase space can be deteriorated through beam fluctuations caused by:
  - ⇨ current variations and timing jitter at RF photo gun
  - ⇨ RF transients and wake fields

**Beam Distribution / Undulator Sections**
- transverse beam stabilization behind main LINAC needed for:
  - stable SASE operation
  - stable user operation

**beam size** $\sigma_{x,y} \approx 70 \, \mu m$
**bunch length** $\sigma_z \approx 1.8 \, - \, 0.02 \, mm$

**stability requirement**:
- transverse: $\sigma/10 \rightarrow \Delta x/y < 7 \, \mu m \, (rms)$
- longitudinal: $0.015^\circ \, @ \, 1.3 \, GHz \rightarrow \Delta z < 10 \, \mu m / 30 \, fs \, (rms)$

**transv. beam size** $\sigma_{x,y} \approx 30 \, \mu m$
**bunch length** $\sigma_z \approx 20 \, \mu m$

**stability requirement**:
- transverse: $\sigma/10 < 3 \, \mu m \, (rms)$

* stability requirements for stable SASE operation at bunch-by-bunch distances of 200 ns
Noise Sources (TTF1)

Fast motions
- switching magnets, power supply jitter
- RF transient, RF jitter
- photocathode laser jitter
- beam current variations
- long range wake fields

Slow and medium term motions
- ground settlement, temperature drifts
- girder / magnet excitation by
ground motion, cooling water, He flow…

Leads to:
- beam centroid motions
- beam arrival time jitter

→ requires intra bunch feedback
→ bunch train to bunch train feedback
Parameters for Intra Bunch Train FB Systems (IBFB) for the European XFEL:

### Stability Requirements behind SC Booster
- **beam energy:** 510 MeV
- **bunch spacing \( \tau_b \):** 200 ns
- **transv. stability:** \( \sigma/10 \Rightarrow < 7 \) \( \mu \)m (rms)
- **long. stability:** 0.015° @ 1.3 GHz
  - \( \Rightarrow < 10 \) \( \mu \)m (rms)
  - \( \Rightarrow 30 \) fs (rms)

### IBFB Parameters
- **system resolution:** ~ 1 \( \mu \)m
- **system latency:** < 200 ns
- **ADC / DAC resolution:** ~ 12-14 bit @ 1 GS/s
- **FPGA / DSP data rate:** ~ 1 Gbyte/s
- **FPGA clock rate:** > 200 MHz

### Stability Requirements behind main LINAC
- **beam energy:** 20 GeV
- **bunch spacing \( \tau_b \):** 200 ns
- **transv. stability:** \( \sigma/10 \Rightarrow < 3 \) \( \mu \)m (rms)

### RF amplifier (x,y,z) Parameters

#### behind SC Booster
- **power:** \( \leq 4 \) kW
- **BW:** \( \leq 100 \) MHz
- **transv. kick strength:** \( \leq 5 \) \( \mu \)rad

#### behind main LINAC
- **power:** \( \leq 10 \) kW
- **BW:** \( \leq 100 \) MHz
- **transv. kick strength:** \( \leq 0.5 \) \( \mu \)rad
Orbit “Feedback” at ERLs

- orbit correction is more feed forward than feedback
- where is orbit stability required? To which level?
- orbit correction necessary along the accelerator? (different energy)
- frequency range of noise sources?
Summary

• digital BPMs already provide few μm resolution in the ~MHz bandwidth
  → potential to go to μm resolution with several MHz BW in the near future

• sub-μm orbit stability achievable in 3rd generation light sources up to several 100 Hz BW
  (good mechanical design of girders, fast orbit feedback system(s))

• photon BPMs → sub-μm resolution of e⁻ beam due to long lever arm
  → valuable devices to be integrated in orbit feedback systems

• multi bunch feedback system (SLS) under commissioning,
  design of orbit stabilization system for European XFEL has just started

• orbit feedback: certainly some common grounds of storage rings and ERLs...