BPM Resolution Studies at PETRA III

Gero Kube
DESY (MDI)

- Introduction
- Comments on BPM Resolution
- „Three BPM“ Correlation & Principal Components Analysis
- Resolution Studies at PETRA III
- Conclusion
PETRA III @ DESY

**PETRA history**

- **1978 – 1986:** $e^+e^-$ collider (up to 23.3 GeV / beam)
- **1988 – 2007:** pre-accelerator for HERA (p @ 40 GeV, e @12 GeV)
- **since 2007:** dedicated 3rd generation light source, commissioned in 2009
  
  → **14 beamlines** (15 experimental stations) operating in parallel

- **from 2014:** staged extension project
  
  W. Drube et al., 2016 [https://doi.org/10.1063/1.4952814](https://doi.org/10.1063/1.4952814)

  → **up to 12 additional beamlines** (presently not all of them in operation)
PETRA IV: Overview

- PETRA IV storage ring and pre-accelerators
  - use of existing accelerator tunnel
    - asymmetric ring structure
  - additional experimental hall
    - 29 straight ID sections

**Timeline**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>PETRA IV CDR Phase</td>
</tr>
<tr>
<td>2021</td>
<td>PETRA IV project phase</td>
</tr>
<tr>
<td>2022</td>
<td>PETRA IV operation</td>
</tr>
<tr>
<td>2025</td>
<td>Start construction work</td>
</tr>
<tr>
<td>2027</td>
<td>Start up PETRA IV</td>
</tr>
</tbody>
</table>

**Design Parameters**

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>PETRA III</th>
<th>PETRA IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy / GeV</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Circumference / m</td>
<td>2304</td>
<td>2304</td>
</tr>
<tr>
<td>Operation mode</td>
<td>Continuous</td>
<td>Timing</td>
</tr>
<tr>
<td>Emittance (horz. / vert.) / pm rad</td>
<td>1300 / 10</td>
<td>&lt; 20 / 4</td>
</tr>
</tbody>
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DEELS 2019 Workshop @ ESRF, 4.6.2019
PETRA IV: Diffraction Limited Light Source

- **DLS design**
  - MBA lattice
  - large circumference
  - small emittance
  - strong quadrupoles
  - very strong sextupoles
  - small beam size
  - IBS, Touschek
  - reduced field quality
  - complicated nonlinear dynamics
  - high precision BPMs
  - vacuum
  - impedance
  - injection
  - higher harm. RF system
  - collective instabilities
  - sensitive to errors

- **BPM resolution requirements**
  - single bunch / single turn \(<20 \, \mu m\) (assuming 0.5 mA in single bunch \(\rightarrow 2.5 \times 10^{10}\) particles bunch)
  - closed orbit \(<100 \, \text{nm}\) (rms, 200 mA in 1600 bunches) at 300 Hz BW

courtesy: I. Agapov (DESY)
BPM Resolution

position determination in circular accelerator

\[
x = K_x \frac{(P_1+P_4) - (P_2+P_3)}{P_1+P_2+P_3+P_4} \quad \quad y = K_y \frac{(P_1+P_2) - (P_3+P_4)}{P_1+P_2+P_3+P_4}
\]

position resolution (small displacements from center)

\[
\sigma_{x,y} \propto K_{x,y} \frac{1}{\sqrt{SNR}}
\]

\begin{align*}
K_{x,y} : & \quad \text{monitor constant} \quad & SNR : & \quad \text{signal-to-noise ratio} \\
\end{align*}

depends on

- pickup geometry \rightarrow beam pipe diameter
- geometry (button size) \rightarrow signal strength
- button size \rightarrow small correction
- infrastructure \rightarrow cable length & attenuation
- read-out electronics

main focus: read-out electronics

goal

- performance test \rightarrow existing *Libera Brilliance* readout electronics @ PETRA III
BPM Resolution Measurements

- modern ADCs optimized for cw signals
  - signal from BPM button → far away from cw signal
  - BPM resolution with beam generated signals

- BPM signal measurement with beam → 2 kinds of jitter
  - beam jitter
    → real change of beam angle and position caused by fluctuations in accelerator
    - (ground motion, energy fluctuation, kicks, …)
    → seen by several / all BPMs simultaneously
      - (correlation via beam optics)
  - noise of BPM electronics
    → quantity to be measured
    → no correlation between adjacent BPM readings

- common methods for correlation analysis
  - „three BPM“ correlation method
  - Principal Components Analysis (PCA)

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Three BPM Correlation Method

**BPM principle setup:** 3 adjacent BPMs

BEAM

\[ y_2 = y_{11}y_1 + y_{12}y'_1 \]

\[ y_3 = \alpha_{11}y_1 + \alpha_{12}y'_1 \]

**BPM reads position information**

\[ y_2 = \left( y_{11} - \frac{\alpha_{11}y_{12}}{\alpha_{12}} \right)y_1 + \frac{y_{12}}{\alpha_{12}}y_3 \]

\[ \Rightarrow y_2 = X_{21}y_1 + X_{23}y_3 \]

**Difference: measured position vs. expectation**

\[ \Delta = y_2 - X_{21}y_1 - X_{23}y_3 \]

**All BPM readings with same error**

\[ \sigma_{y_1} \sim \sigma_{y_2} \sim \sigma_{y_3} = \sigma_{BPM} \]

\[ \Rightarrow \sigma_{BPM} = \frac{\sigma_\Delta}{\sqrt{1 + X_{21}^2 + X_{23}^2}} \]

**Calculate variance (error propagation)**

\[ \sigma^2_\Delta = \sigma^2_{y_2} + X_{21}^2 \sigma^2_{y_1} + X_{23}^2 \sigma^2_{y_3} \]

\[ \sigma_\Delta \rightarrow N \text{ consecutive position measurements} \]

\[ \sigma_{BPM} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( y_{2,i} - (X_{21}y_{1,i} + X_{23}y_{3,i}) \right)^2} \]
„Three BPM“ Correlation Method (2)

procedure

- N consecutive position measurements with 3 adjacent BPMs
- determination of transfer matrix elements $X_{2p}, X_{23}$
  - straight forward: calculation according to beam optics
  - model independent: Moore-Penrose pseudo inverse
    (least-square estimate for $X$)

- BPM resolution
  - evaluate formula
    $$
    \sigma_{BPM} = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left( y_{2,i} - (X_{21}y_{1,i} + X_{23}y_{3,i}) \right)^2} \left/ \left( 1 + X_{21}^2 + X_{23}^2 \right) \right.
    $$
- successive application to all BPMs
  - grouping three adjacent BPMs
  - example: KEK-B M. Arinaga et al., NIM A499 (2003) 100

restrictions

- no non-linear elements  →  difficult at DLS
- same error of BPM readings  →  not possible at PETRA III
- sometimes weak correlations with neighbour BPMs
  - large uncertainty in BPM resolution (especially with Moore-Penrose)

constant offset $\approx 0$

$$
\begin{pmatrix}
  y_{2,1} \\
  \vdots \\
  y_{2,N}
\end{pmatrix} =
\begin{pmatrix}
  1 & y_{1,1} & y_{3,1} \\
  \vdots & \vdots & \vdots \\
  1 & y_{1,N} & y_{3,N}
\end{pmatrix}
\begin{pmatrix}
  X_0 \\
  X_{21} \\
  X_{23}
\end{pmatrix}
$$

phase advance $\neq n/2 \pi$

$n = \pm 1, 3, 5, \ldots$
**Principal Components Analysis (PCA)**

- **method of multivariate statistics**
  - conversion of set of correlated variables into set of linearly uncorrelated ones
    - → principal components (PC)
  - cleansing of correlations in data sets
    - → structuring of large data sets, compression, …

- **principal axis determination**
  - orientation of first principal axis
    - → axis rotation such that overall data variance is maximized  (requires centering of data)
      - → alternative: minimize projections  (hint: $\chi^2$)
  - orientation of second (third, …) principal axis
    - → remove contribution of 1st PC from data
      - → repeat rotation and variance maximization
        - condition: uncorrelated with (i.e., perpendicular to) first principal component

- **mathematics behind**
  - form covariance matrix $C$ → real & symmetric matrix
    - diagonalization of $C$ → $C = V \Lambda V^T$
      - $V$: formed by orthonormal eigen vectors
  - eigen vectors → principal components
    - eigen values ($\Lambda$) → amount of variance for PC
    - sort eigen vectors according to eigen values
Principal Components Analysis (2)

alternative numerical method → Singular Value Decomposition (SVD)

› instead of diagonalization of covariance matrix

→ SVD of data matrix $M$

› relation between singular and eigen values:

$$\Lambda = \frac{\Sigma^2}{n-1}$$

› advantage

→ SVD numerically more stable (formation of $MM^T$ can cause loss of precision → Läuchli matrix)

→ benefit: SVD provides additional information (accelerator physics)

application to BPM data

› construction of BPM matrix $M$

→ BPM data centered

→ normalization: $\propto \frac{1}{\sqrt{nm}}$


› exploration of SVD matrix properties

→ $U$: column vectors contain information about temporal pattern (tune, …)

→ $V$: column vectors contain information about spatial pattern (orbit / $\beta$ function, …)

comment: $U/V$ as temporal/spatial vectors → depends on orientation of matrix $M$
PCA Example

- test measurement @ PETRA III
  - fill pattern: 960 bunches @ 5.6 mA
  - single vertical kick with excitation kicker
  - 2048 turns recorded

- temporal modes
  - information about tune
    - FFT of $u_1, u_2$

- spatial modes
  - information about beam optics
    - $\beta \propto (v_1^2 + v_2^2)$

- BPM resolution
  - singular values $\sigma_1, \sigma_2, \ldots = 0$ → calculate cleaned orbit data

SVD analysis

- dominant modes (singular values) → mode 1 & 2
11 different pickup types:
- Max von Laue hall

3 different cable types:
- RFA $\frac{1}{2''}$, $\frac{3}{8''}$, $\frac{7}{8''}$ – 50 Ω

Cable lengths: 10m … 200m

246 individual settings

- Normalize to $K_{x,y} = 10$ mm
- $RMS_{x,y} = f(signal\ power)$

BPM Resolution Studies

- resolution studies @ PETRA III
  - single bunch with $Q_b$ varying
  - single vertical kick with excitation kicker
  - 2048 turns

PCA for beam jitter removement

Plot as function of signal power

$K_{x,y}$ normalization

Combination of measurements for various $Q_b$
**TbT Single Bunch Resolution**

- machine studies at PETRA III with existing BPM system
  - Libera Brilliance (Instrumentation Technologies)

Libera Brilliance resolution not sufficient for PETRA IV

PETRA IV CDR: rely on successor model → Libera Brilliance+

\[ \text{min}(RMS_{x,y}) \approx 30 \, \mu \text{m} \]
Test of Read-out Electronics

- beam test @ PETRA III: december 2018
  - Libera Brilliance
    → BPM_SOL_24, in use at PETRA III
  - Libera Brilliance+
    → CDR: PETRA IV system
    → one system bought for DORIS / Olympus
    → one system recently bought
  - Libera Spark
    → new platform, no long-term stabilization
    → borrowed from I-Tech (thanks to Peter Leban)

- BPM TbT resolution determination
  - orbit data contain contributions due to
    → correlated beam jitter
    → noise of BPM electronics

- disentangle contributions
  - correlation analysis → does not work for single BPM
  - eliminate correlated jitter → sum & split orbit data

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Resolution Comparison

Libera Brilliance+

- digital down conversion (DDC)
  \[ \sigma < 10 \mu m \text{ never achieved} \]
  \[ \sigma = 19.8 \mu m \quad @ \quad I_B = 1.549 mA \quad (-29 dB) \]
  \[ \rightarrow \text{correct for attenuation:} \quad I_B = 0.38 mA \quad (\approx -42 dB) \]

- time domain processing (TDP)
  \[ \sigma = 10.3 \mu m \quad @ \quad I_B = 1.323 mA \quad (-30 dB) \]
  \[ \rightarrow \text{correct for attenuation:} \quad I_B = 0.38 mA \]
  Would fulfil requirements

DDC mode \( < 20 \mu m \text{ (rms)} \) \( \rightarrow \) \( I_B \approx 0.4 mA \)

TDP mode \( \approx 10 \mu m \text{ (rms)} \) \( \rightarrow \) \( I_B \approx 0.4 mA \)

\[ \rightarrow \text{but Libera Spark is better…} \]
Closed Orbit & Stability

- long term stability
  - user operation: 480 bunches in 100 mA, top-up
  - all Liberas in closed orbit (SA) mode → drift compensation (digital signal conditioning, DSC) on Spark:
    - no DSC available

Brilliance+ without DSC

- good climatization (hutches, racks) mandatory
Closed Orbit Resolution

**specification:** \(<100\text{nm (rms)}\) in brightness mode (200mA in 1600 bunches) \(@\) BW 300 Hz

- horizontal orbit
  - first 12 hours (before beam dump):
    \[
    \sigma_{\text{rms}} = 20.76 \text{ nm} \quad \text{in SA mode (BW 4Hz, } K_{x,y} = 10\text{mm; BW 4Hz → see Brilliance+ User Manual, p.34)}
    \]
    
    \[
    \rightarrow \text{scaling with band width:} \\
    \times \sqrt{300/4} = 8.66
    \]
    
    \[
    \rightarrow \sigma_{\text{rms}} = 180 \text{ nm} \quad (\text{@ BW 300Hz})
    \]
**Conclusion**

- BPM resolution studies
  - require correlation analysis in order to disentangle noise and beam generated jitter
  - → „three BPM“ correlation method & PCA

- correlation analysis
  - „three BPM“ correlation method → not suitable for PETRA III BPM system
  - PCA → powerful tool, not only for resolution studies (e.g. BPM performance evaluation @ SSRF, …)
  - → model independent, but limited by mode mixing
  - next step: Independent Component Analysis (ICA)

- Libera Brilliance
  - single bunch resolution → specs not fulfilled for PETRA IV

- Libera Brilliance+
  - single bunch resolution → specs fulfilled @ bunch current $I_B \approx 0.4$ mA and monitor constant $K_{x,y} = 10$ mm
  - DDC mode $< 20$ µm (rms), TDP mode $\approx 10$ µm (rms)
  - closed orbit → specs not fulfilled ($< 100$ nm @ 300 Hz bandwidth)
  - $\sigma_{y,\text{rms}} \approx 180$ nm @ 300 Hz bandwidth and $K_{x,y} = 10$ mm

- Libera Spark
  - single bunch resolution much better → closed orbit: needs stabilization