BPM Resolution Studies at PETRA III

Gero Kube
DESY (MDI)

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

PETRA III @ DESY

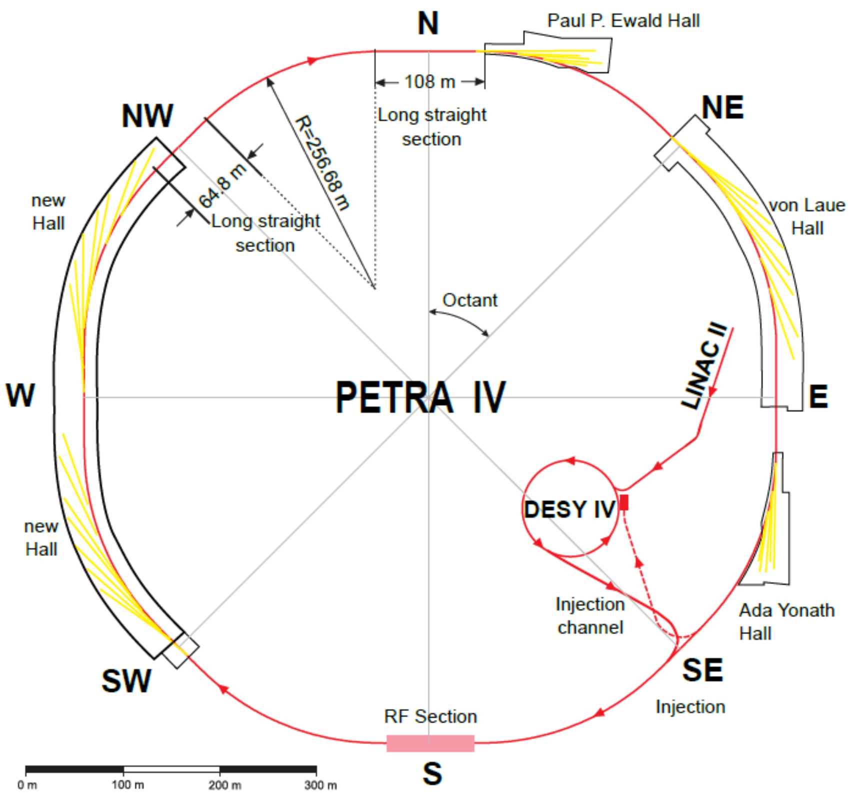
- PETRA history
  - 1978 – 1986: e^+e^- collider (up to 23.3 GeV / beam)
  - 1988 – 2007: pre-accelerator for HERA (p @ 40 GeV, e @12 GeV)
  - since 2007: dedicated 3rd generation light source, commissioned in 2009 TDR: DESY 2004-035

    → ***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

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

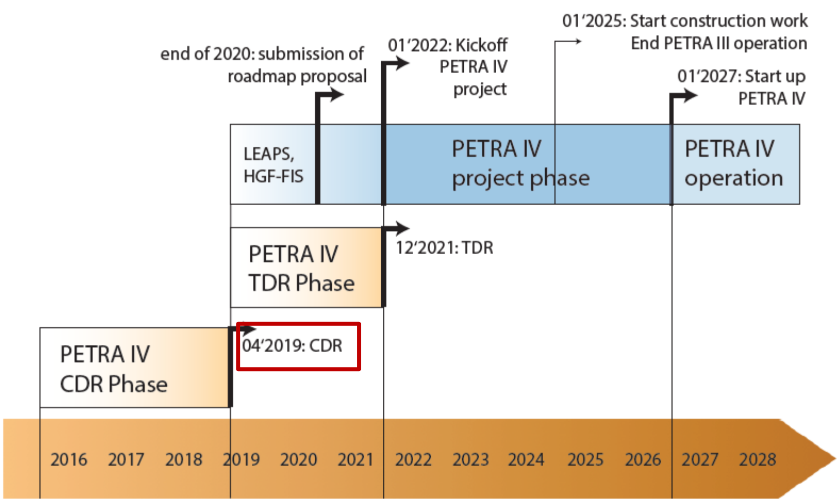
PETRA IV: Overview

- PETRA IV storage ring and pre-accelerators



- use of existing accelerator tunnel
  → asymmetric ring structure
- additional experimental hall
  → 29 straight ID sections

- time line



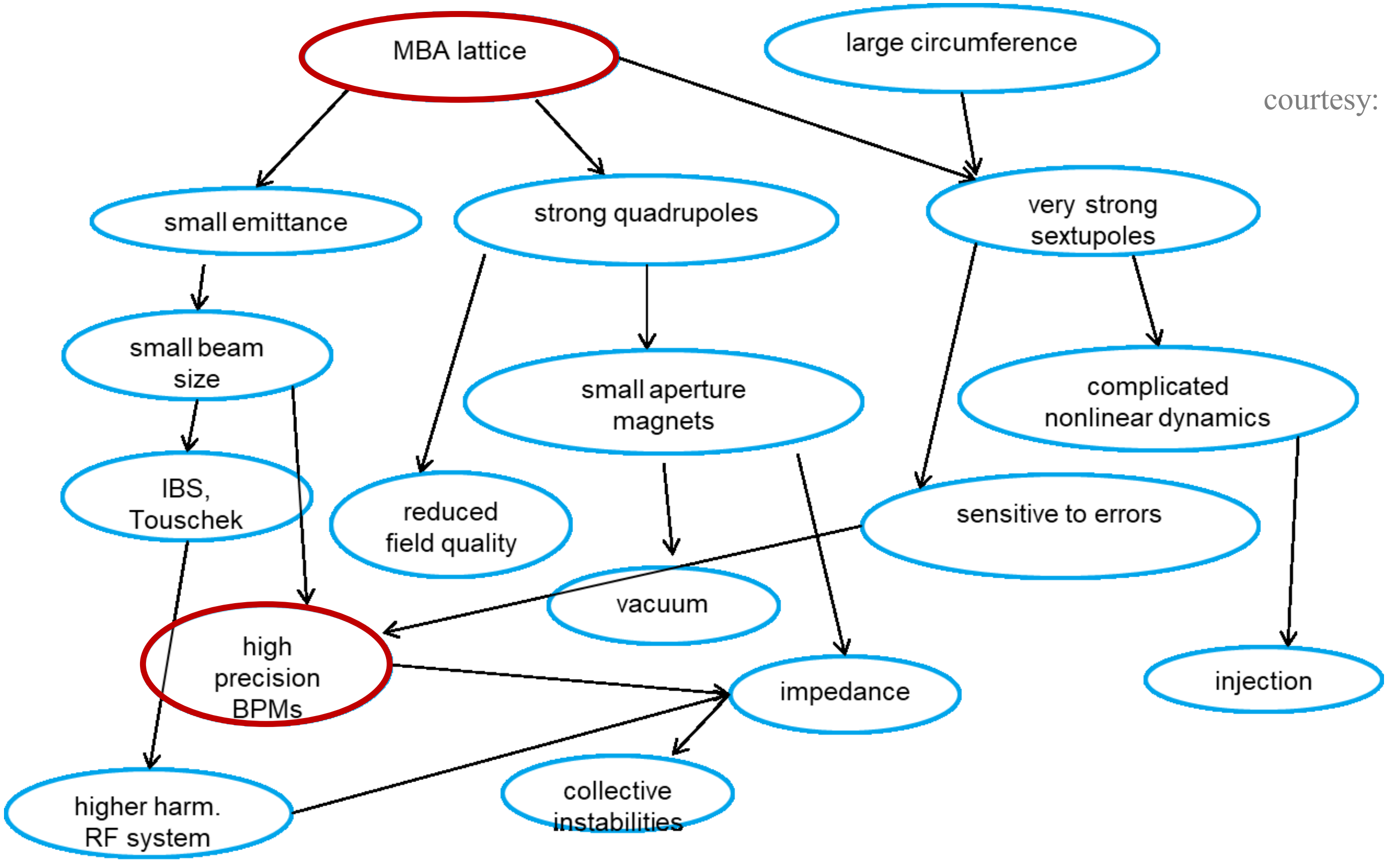
Design parameter	PETRA III		PETRA IV	
Energy / GeV	6		6	
Circumference / m	2304		2304	
Operation mode	Continuous	Timing	Brightness	Timing
Emittance (horz. / vert.) / pm rad	1300 / 10		< 20 / 4	< 50 / 10

- presently
  → preparation of *Conceptual Design Report*

PETRA IV: Diffraction Limited Light Source

- DLS design

courtesy: I. Agapov (DESY)

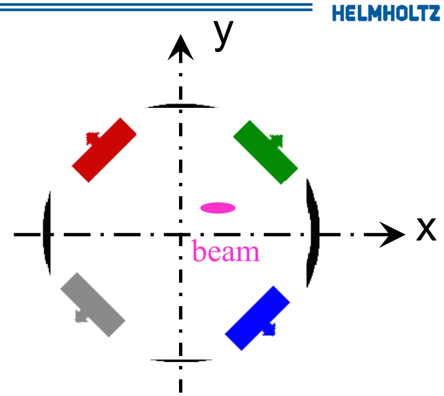


- BPM resolution requirements
  - single bunch / single turn **< 20 µm** (assuming 0.5 mA in single bunch → 2.5×10^{10} particles bunch)
  - closed orbit **< 100 nm** (rms, 200 mA in 1600 bunches) at 300 Hz BW

BPM Resolution

- position determination in circular accelerator

$$x = K_x \frac{(P_1+P_4) - (P_2+P_3)}{P_1+P_2+P_3+P_4} \qquad y = K_y \frac{(P_1+P_2) - (P_3+P_4)}{P_1+P_2+P_3+P_4}$$



- position resolution (small displacements from center)

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

$K_{x,y}$: monitor constant

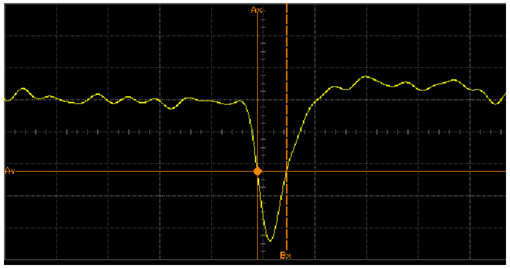
SNR : signal-to-noise ratio

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

➡ main focus: read-out electronics

- goal
  - performance test → 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

    → quantitiy to be measured

    → **no correlation** between adjacent BPM readings

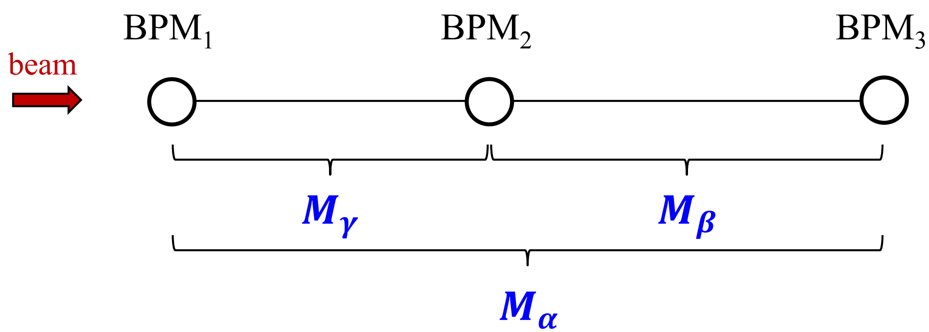
  ➡ correlation analysis in order to disentangle both jitter sources

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

  ➡ brief review

„Three BPM“ Correlation Method

- principle setup: 3 adjacent BPMs



- connection via transport matrices
  - no non-linear elements between BPMs

$$\begin{pmatrix} y_3 \\ y'_3 \end{pmatrix} = \begin{pmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{pmatrix} \begin{pmatrix} y_1 \\ y'_1 \end{pmatrix} = \begin{pmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{pmatrix} \begin{pmatrix} y_2 \\ y'_2 \end{pmatrix}$$

$$\begin{pmatrix} y_2 \\ y'_2 \end{pmatrix} = \begin{pmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{pmatrix} \begin{pmatrix} y_1 \\ y'_1 \end{pmatrix}$$

- BPM reads position information

$$\left.\begin{aligned} y_2 &= \gamma_{11} y_1 + \gamma_{12} y'_1 \\ y_3 &= \alpha_{11} y_1 + \alpha_{12} y'_1 \end{aligned}\right\} \quad y_2 = \left(\gamma_{11} - \frac{\alpha_{11}\gamma_{12}}{\alpha_{12}}\right) y_1 + \frac{\gamma_{12}}{\alpha_{12}} y_3 \quad \Rightarrow \quad y_2 = X_{21} y_1 + X_{23} y_3$$

- difference: measured position vs. expectation

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

- calculate variance (error propagation)

$$\sigma_\Delta^2 = \sigma_{y_2}^2 + X_{21}^2 \sigma_{y_1}^2 + X_{23}^2 \sigma_{y_3}^2$$

- all BPM readings with same error

$$\sigma_{y_1} \sim \sigma_{y_2} \sim \sigma_{y_3} = \sigma_{BPM}$$

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

- σ_Δ → N consecutive position measurements

$$\sigma_{BPM} = \sqrt{\frac{1}{N-1} \frac{\sum_{i=1}^{N} \left\{y_{2,i} - \left(X_{21} y_{1,i} + X_{23} y_{3,i}\right)\right\}^2}{1 + X_{21}^2 + X_{23}^2}}$$

„Three BPM“ Correlation Method (2)

- procedure
  - N consecutive position measurements with 3 adjacent BPMs
  - determination of transfer matrix elements $\boldsymbol{X_{21}}, \boldsymbol{X_{23}}$

    → <u>straight forward:</u> calculation according to beam optics

    → <u>model independent:</u> ***Moore-Penrose*** pseudo inverse (least-square estimate for $\boldsymbol{X}$)

constant offset ≈ 0

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

  - BPM resolution

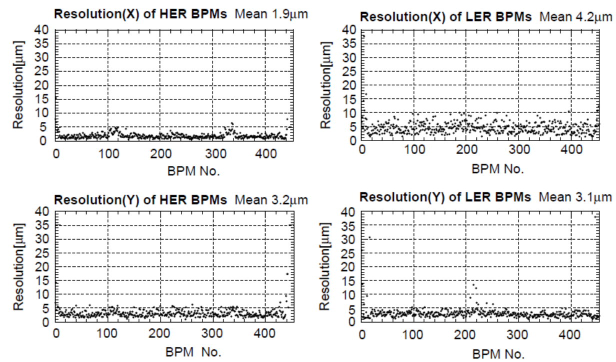
    → evaluate formula

$$\sigma_{BPM} = \sqrt{\frac{1}{N-1} \frac{\sum_{i=1}^{N} \{y_{2,i} - (X_{21} y_{1,i} + X_{23} y_{3,i})\}^2}{1 + X_{21}^2 + X_{23}^2}}$$

  - 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)

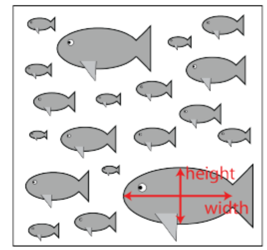
phase advance $\neq n/2\ \pi$
$n = \pm 1, 3, 5, \ldots$

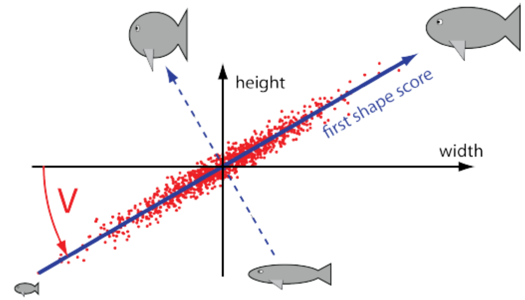
Principal Components Analysis (PCA)

- 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, …





- prinicipal axis determination
  - orientation of first principal axis

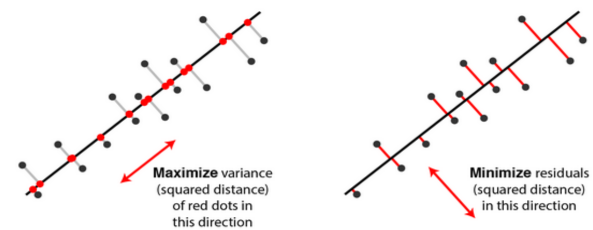
    → axis rotation such that overall data variance is maximized (requires centering of data)

    → alternative: minimize projections (hint: χ^2)
  - orientation of second (third, …) principal axis

    → remove contribution of 1^{st} PC from data

    → repeat rotation and variance maximization

    <u>condition:</u> uncorrelated with (i.e., perpendicular to) first principal component



- mathematics behind
  - form covariance matrix $\boldsymbol{C}$ → real & symmetric matrix
  - diagonalization of $\boldsymbol{C}$ → $C = V \Lambda V^T$

    V : formed by orthonormal eigen vectors
  - eigen vectors → principal components

    eigen values (Λ) → 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*

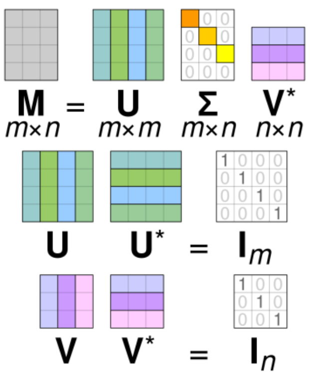
    → *SVD* of *data matrix* ***M***

$$M = U \cdot \Sigma \cdot V^T$$

(M real: $V^* \rightarrow V^T$)

  - relation between ***singular*** and ***eigen values***:

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



courtesy: Wikipedia

  - 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: $\propto \dfrac{1}{\sqrt{n\,m}}$

*orbit (**space** coordinate)* →

$$M = \begin{pmatrix} BPM_1(turn\#1) & \cdots & BPM_n(turn\#1) \\ \vdots & \ddots & \vdots \\ BPM_1(turn\#m) & \cdots & BPM_n(turn\#m) \end{pmatrix}$$

↓ *turns (**time** coordinate)*

C.X. Wang, SLAC-R-547 (2003)

  - exploration of SVD matrix properties

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

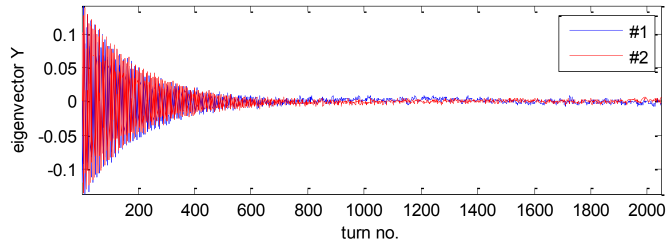
    → ***V:*** column vectors contain information about ***spatial*** pattern (orbit / β function, …)

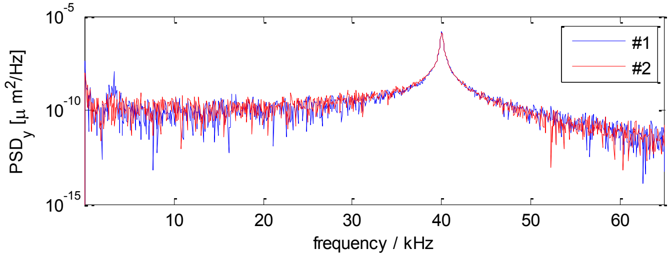
    <u>comment</u>: *U*/*V* as temporal/spatial vectors → depends on orientation of matrix *M*

PCA Example

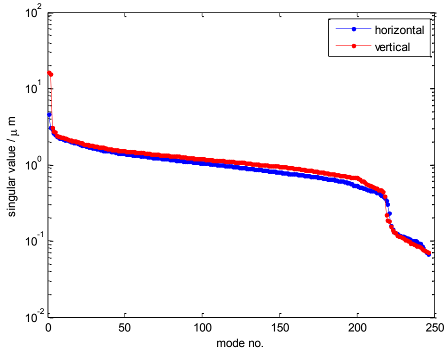
- test measurement @ PETRA III
  - fill pattern: 960 bunches @ 5.6 mA
  - single vertical kick with excitation kicker
  - 2048 turns recorded
- temporal modes
  - information about tune

    → FFT of u_1, u_2

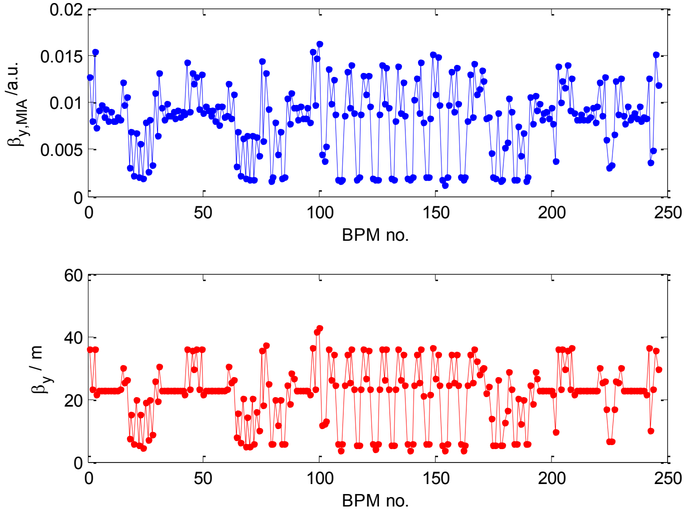




- BPM resolution
  - singular values $\sigma_1, \sigma_2, \ldots = 0$ → calculate cleaned orbit data
- SVD analysis
  - dominant modes (singular values) → mode 1 & 2

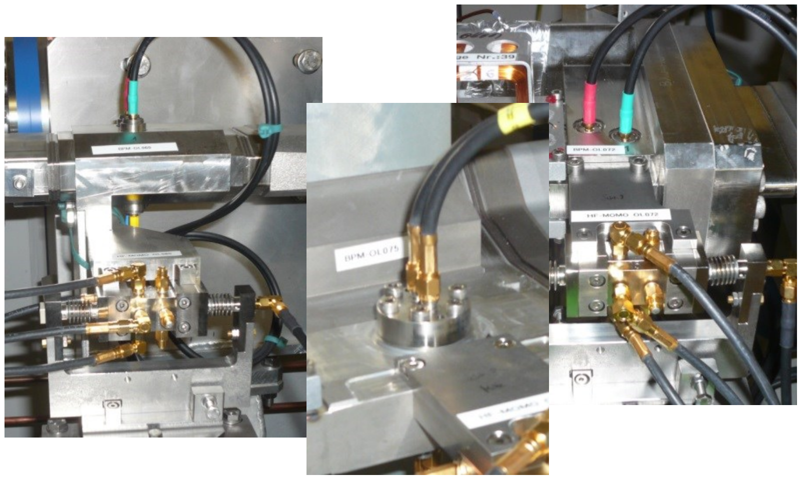


- spatial modes
  - information about beam optics → $\beta \propto (v_1^2 + v_2^2)$



PETRA III BPM System

- 11 different pickup types:
  - Max von Laue hall



  - standard octants:

I. Krouptchenkov et al., Proc. DIPAC 2009, Basel, TUPD03, p. 291

- 3 different cable types

RFA ½″, ⅜″, ⅞″ – 50 Ω

⇩

cable lengths: 10m … 200m

⬇

246 individual settings

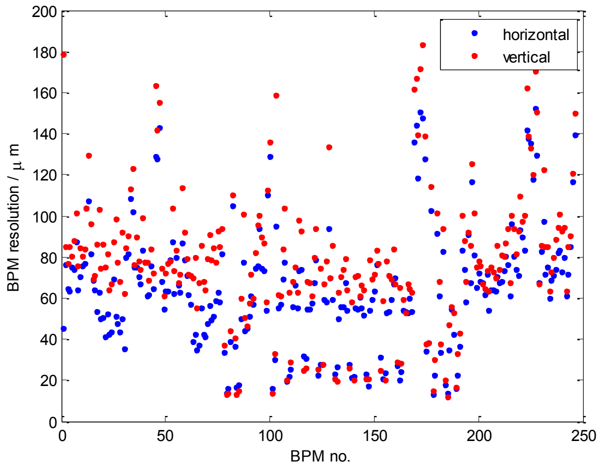
⬇

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

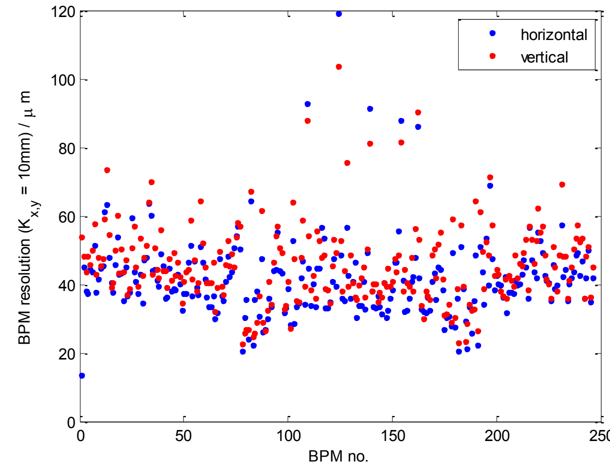
BPM Resolution Studies

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

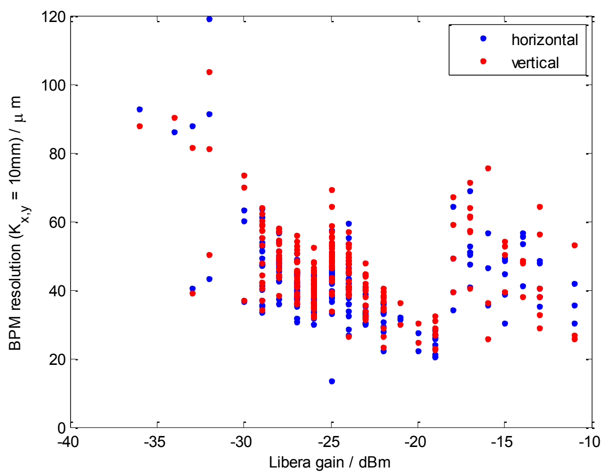
PCA for beam jitter removement



$K_{x,y}$ normalization



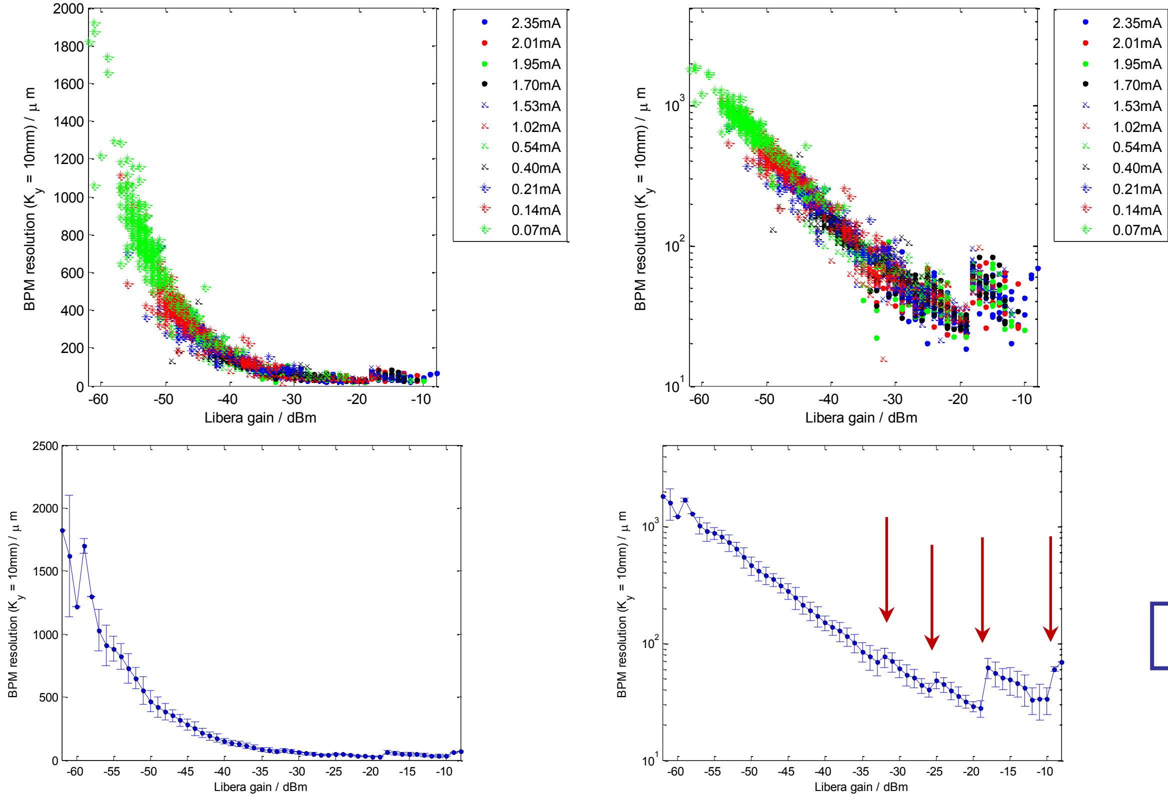
plot as function of signal power



combination of measurements for various Q_b

TbT Single Bunch Resolution

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



Default Gain Scheme for 500 MHz Libera Brilliance

P[dBm]	A1	A2	h	t	X[nm]	Y[nm]
0	31	00	0.5	10	0	0
-1	31	00	0.5	10	0	0
-2	31	00	0.5	10	0	0
-3	31	00	0.5	10	0	0
-4	31	00	0.5	10	0	0
-5	31	00	0.5	10	0	0
-6	31	00	0.5	10	0	0
-7	31	00	0.5	10	0	0
-8	31	00	0.5	10	0	0
-9	31	00	0.5	10	0	0
-10	21	00	0.5	10	0	0
-11	21	00	0.5	10	0	0
-12	21	00	0.5	10	0	0
-13	21	00	0.5	10	0	0
-14	21	00	0.5	10	0	0
-15	21	00	0.5	10	0	0
-16	21	00	0.5	10	0	0
-17	21	00	0.5	10	0	0
-18	21	00	0.5	10	0	0
-19	11	00	0.5	10	0	0
-20	11	00	0.5	10	0	0
-21	11	00	0.5	10	0	0
-22	11	00	0.5	10	0	0
-23	11	00	0.5	10	0	0
-24	11	00	0.5	10	0	0
-25	11	00	0.5	10	0	0
-26	7	00	0.5	10	0	0
-27	7	00	0.5	10	0	0
-28	7	00	0.5	10	0	0
-29	7	00	0.5	10	0	0
-30	7	00	0.5	10	0	0
-31	7	00	0.5	10	0	0
-32	7	00	0.5	10	0	0
-33	0	00	0.5	10	0	0
-34	0	00	0.5	10	0	0

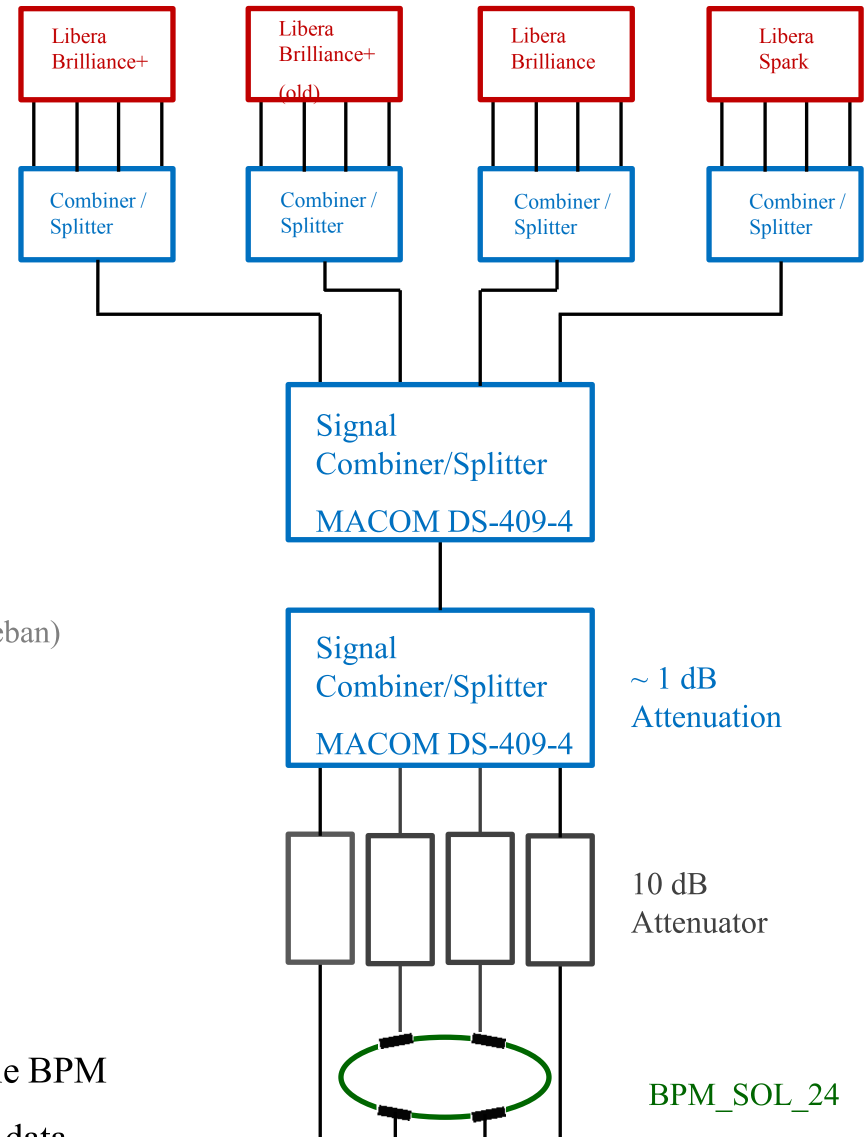
$\min(RMS_{x,y}) \approx 30\ \mu m$

⇒ Libera Brilliance resolution not sufficient for PETRA IV

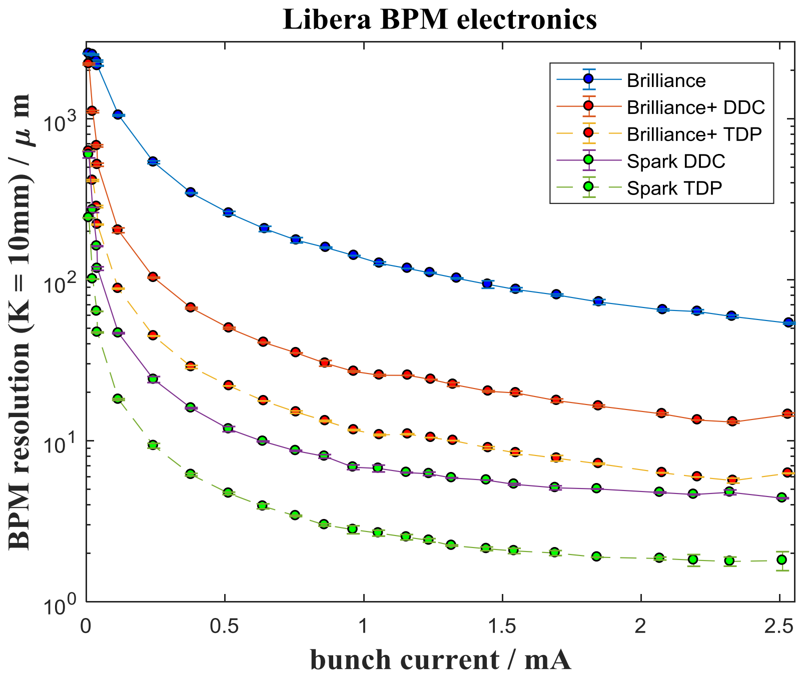
- PETRA IV CDR: rely on successor model → Libera Brilliance+

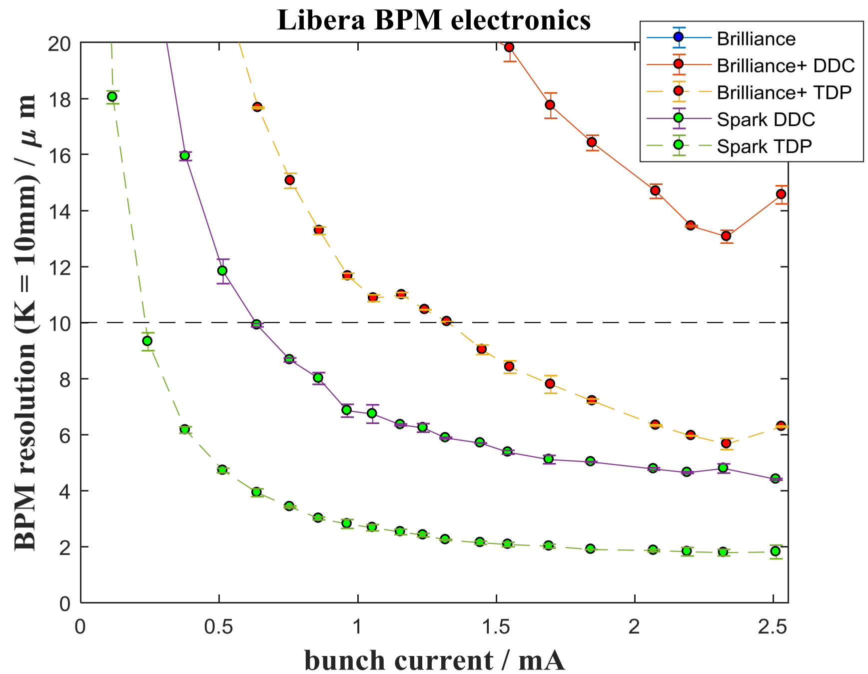
Test of Read-out Electronics

- 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



Resolution Comparison





- Libera Brilliance+
  - digital down conversion (DDC)

    σ < 10 μm never achieved

    σ = 19.8 μm @ I_B = 1.549 mA (-29 dB)

    → correct for attenuation: I_B = 0.38 mA (≈ -42 dB)
  - time domain processing (TDP)

    σ = 10.3 μm @ I_B = 1.323 mA (-30 dB)

    → correct for attenuation: I_B = 0.38 mA

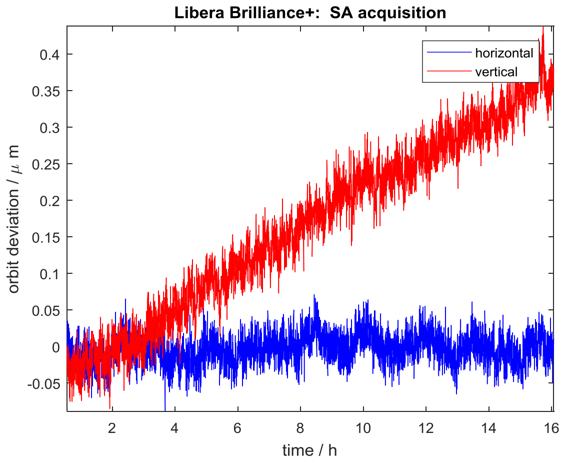
DDC mode	< 20 μm (rms)	→	I_B ≈ 0.4 mA
TDP mode	≈ 10 μm (rms)	→	I_B ≈ 0.4 mA

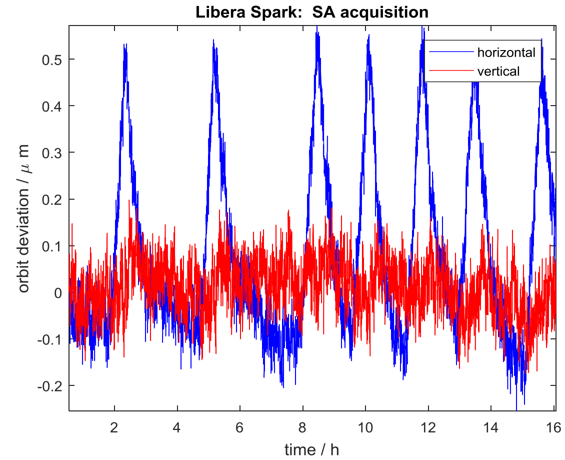
would fulfil requirements

→ but Libera Spark is better…

Closed Orbit & Stability

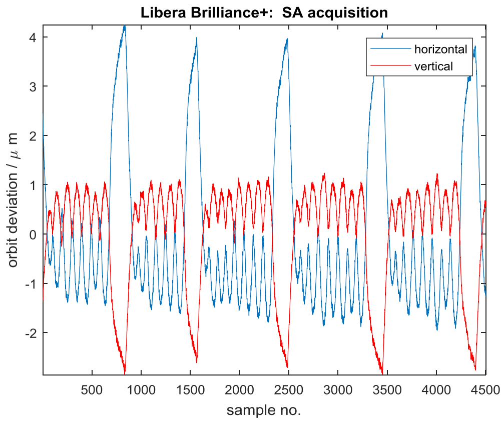
- long term stability
  - user operation: 480 bunches in 100 mA, top-up
  - all Liberas in closed orbit (SA) mode → drift compensation (digital signal conditioning, DSC) on

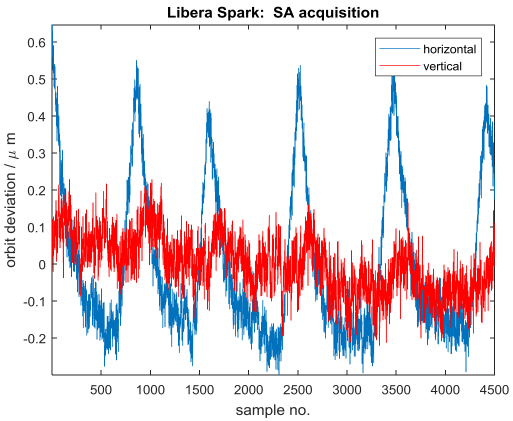




Spark:
no DSC available

- Brilliance+ without DSC

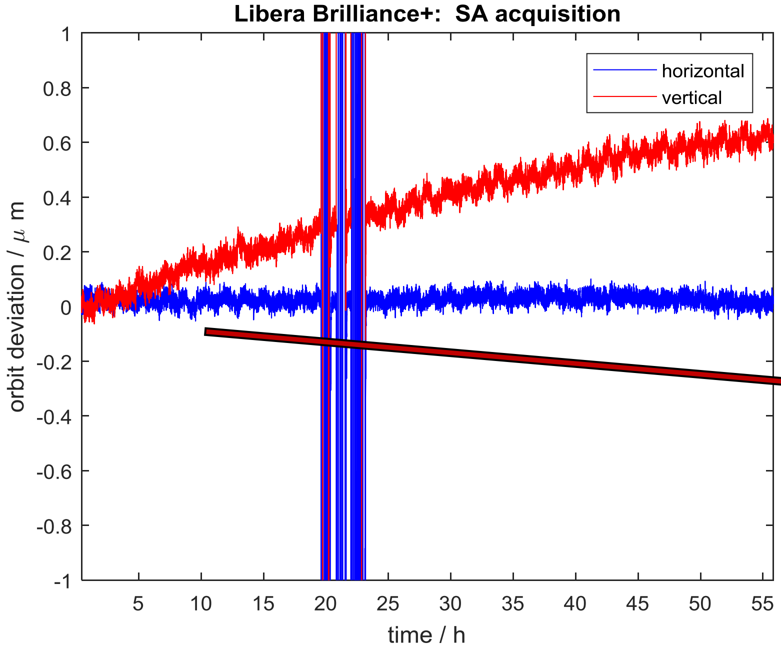


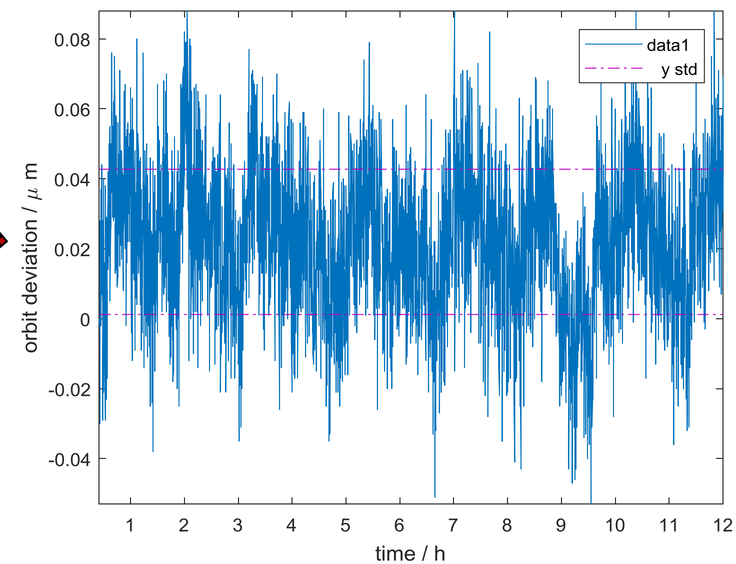


➡ good climatization (hutches, racks) mandatory

Closed Orbit Resolution

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





- horizontal orbit

first 12 hours (before beam dump):

σ_{rms} = ***20.76 nm*** in SA mode (BW 4Hz, $K_{x,y}$ = 10mm; BW 4Hz → see Brilliance+ User Manual, p.34)

→ scaling with band width:
× sqrt(300/4) = 8.66

→ σ_{rms} = ***180 nm (@ BW 300Hz)***

Name of the data flow	Type	Buffer size*	Rate	Bandwidth
ADC rate data	on demand	1 M atoms (8 MB)	ADC freq.	~20 MHz
Turn-by-Turn (DDC)	on demand	2 M atoms (64 MB)	rev.freq	0.35*rev.freq
Turn-by-Turn (TDP)	on demand	2 M atoms (64 MB)	rev.freq	
Fast Acquisition data	stream		10 kS/s	2 kHz
Slow Acquisition data	stream		10 S/s	4 Hz

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

    Z.-C. Chen et al., Chinese Physics **38** (2014) 077004

    Nucl. Sci and Tech. **25** (2014) 020102

    ➡ 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 curent $I_B \approx 0.4$ mA and monitor constant $K_{x,y} = 10$ mm

    DDC mode < 20 µm (rms), TDP mode ≈ 10 µm (rms)
  - closed orbit → specs not fulfilled (< 100 nm @ 300 Hz bandwidth)

    $\sigma_{y,rms} \approx$ 180 nm @ 300 Hz bandwidth and $K_{x,y} = 10$ mm
- Libera Spark
  - single bunch resolution much better → closed orbit: needs stabilization