
June 17, 2020

# BPM Studies in view of PETRA IV

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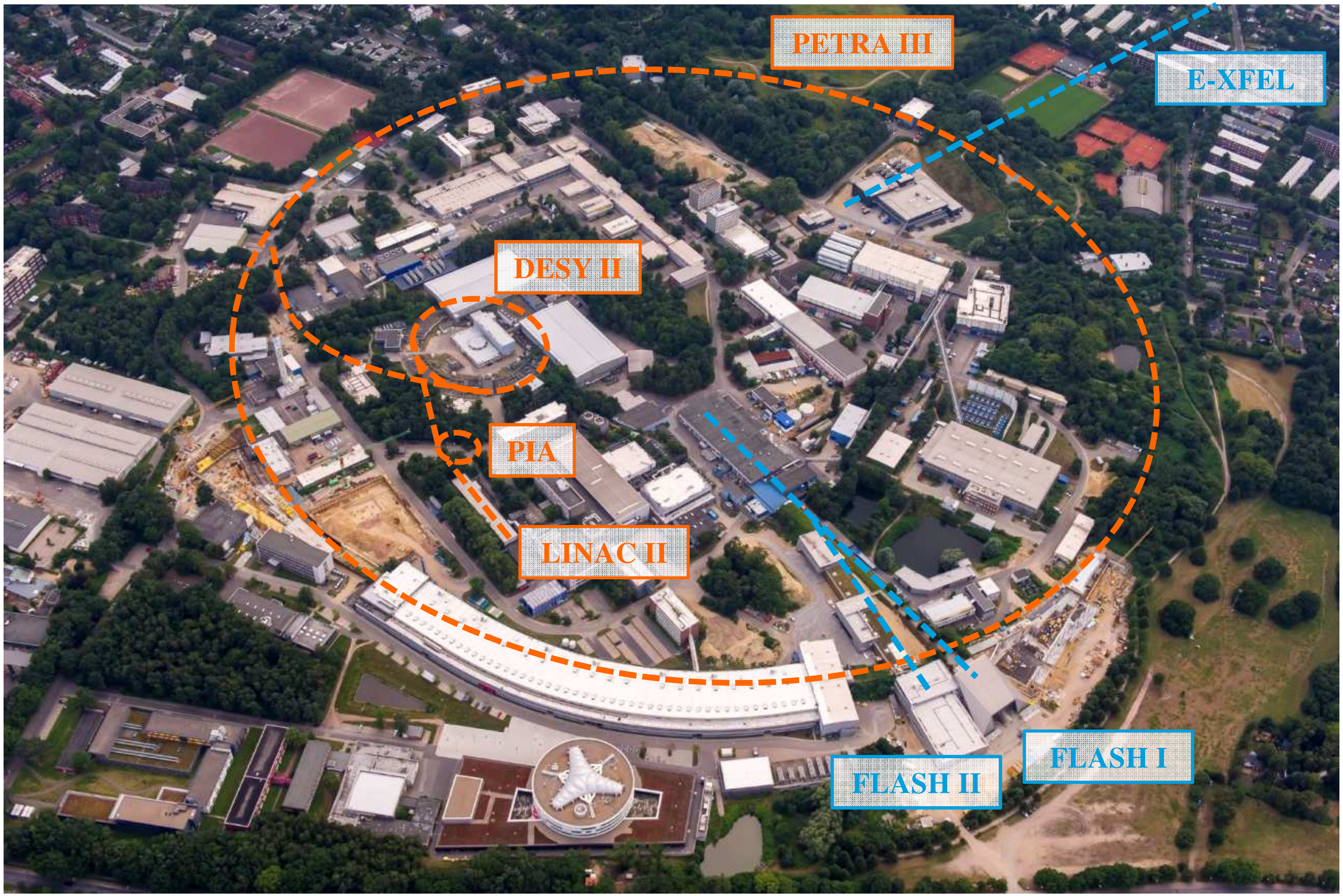
DESY (Hamburg)

- Introduction
- Overview and Particularities of PETRA IV
- Beam Position Monitors
- Test Measurements at PETRA III

# DESY Accelerator Complex  (User Facilities)

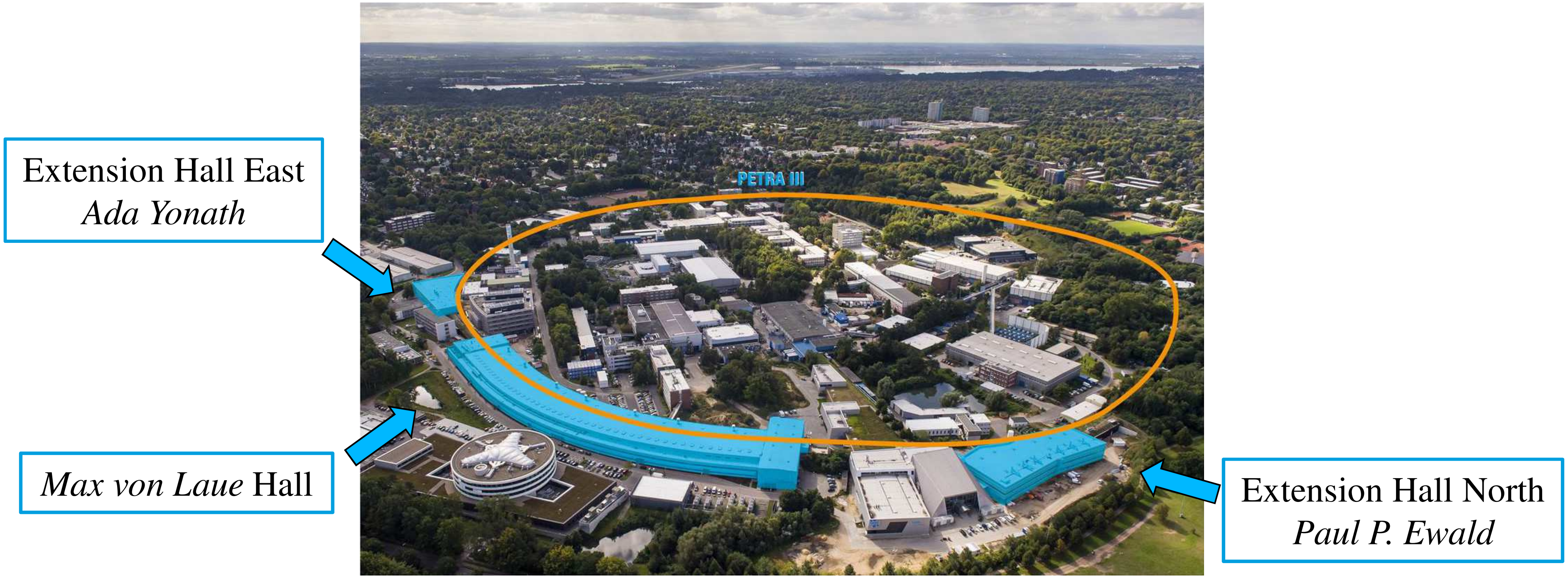


# PETRA III @ DESY

- 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

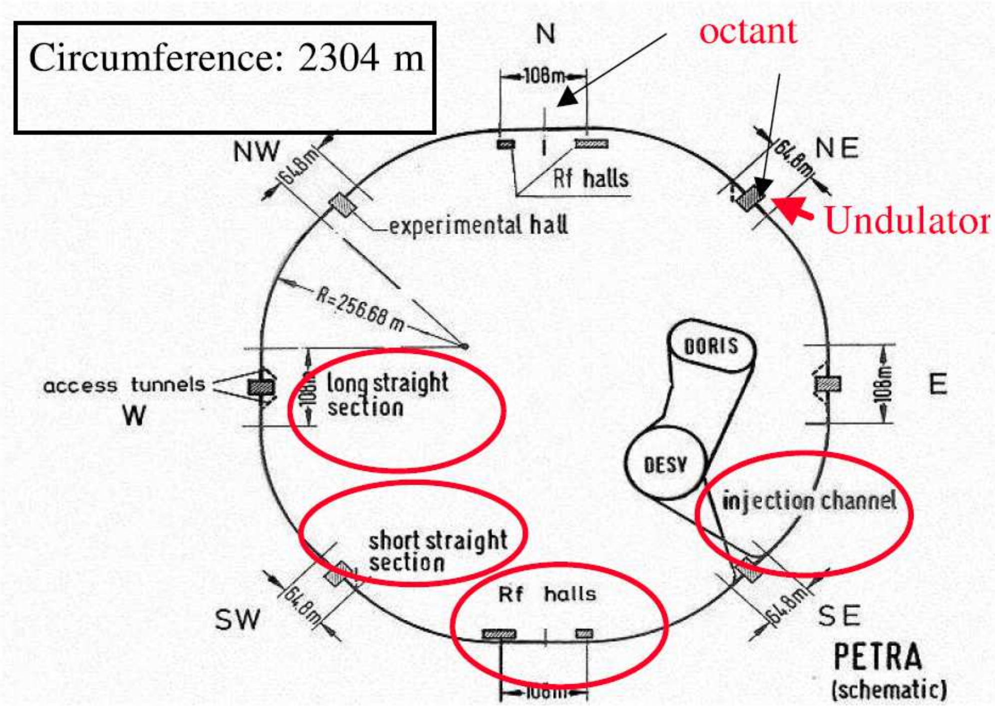
    → ***14 beamlines*** (15 experimental stations) operating in parallel
  - from 2014: staged extension project W. Drube et al., 2016 https://doi.org/10.1063/1.4952814

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



# PETRA III @ DESY

- consequence of re-using HEP structure
  - large circumference
    - → beamlines not all around the machine
    - → small natural emittance
    - ( + space for damping wigglers)
  - different machine sectors
    - → 8 arcs: $L_{arc} = 201.6$ m
    - → 4 long straight sections: $L_{lss} = 108$ m
    - → 4 short straight sections: $L_{sss} = 64.8$ m




- PETRA III concept
  - one octant with DBA lattice
    - → 9 cells / arc, $L_{DBA}$=23 m
    - (P3X: 2 additional DBA cells in 2 octants)
  - canted undulator beamlines: (14 out of possible 26)
    - → canting angles 5 / 20 mrad
  - remaining part: FODO lattice + dispersion suppressors

**asymmetric ring structure**

| Parameter | | | |
|---|---|---|---|
| Energy | 6 | | GeV |
| Circumference | 2304 | | m |
| Emittance (hor. / vert.) | 1.2 / 0.012 | | nm rad |
| Total current | 100 | | mA |
| Number of bunches | 960 | 40 | |
| Bunch population | 0.5 | 12 | $10^{10}$ $e^-$ |
| Bunch separation | 8 | 192 | ns |

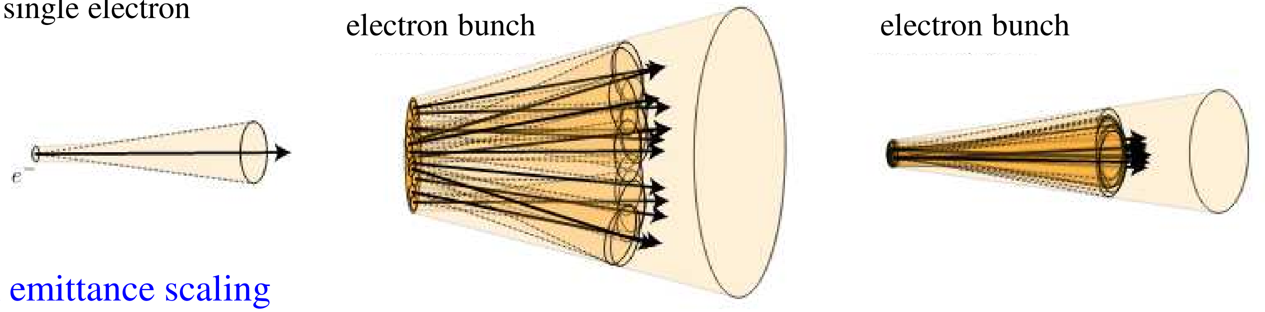
# Diffraction Limited Storage Ring

- „diffraction“ limited

single electron

PETRA III
electron bunch

PETRA IV
electron bunch



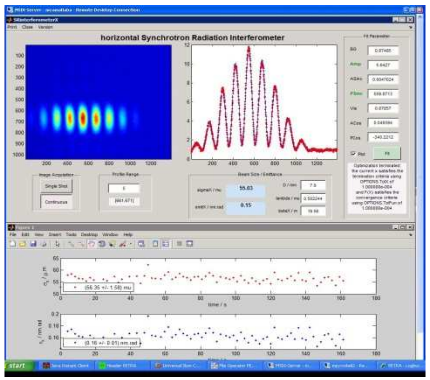
- natural emittance scaling

$$\varepsilon_x \propto \gamma^2 \theta^3 \Gamma$$

| | |
|---|---|
| $\gamma = {}^{E}/_{m_0 c^2}$ | Lorentz factor |
| $\theta$: | bending magnet angular deflection |
| $\Gamma$: | magn. lattice design of storage ring |

- emittance reduction

  - reduction of beam energy




PETRA III operated @ 3 GeV

→ $\varepsilon_x \approx 150$ pm.rad

**but:** E defines radiation spectrum

$$\hbar\omega_c \approx 0.665 E^2 B$$

  - reduce deflection angle θ per bending

→ from ***double*** bend achromat (2)

to ***multi*** bend achromat (5, 7, 9, …)

→ MAX IV paved the way

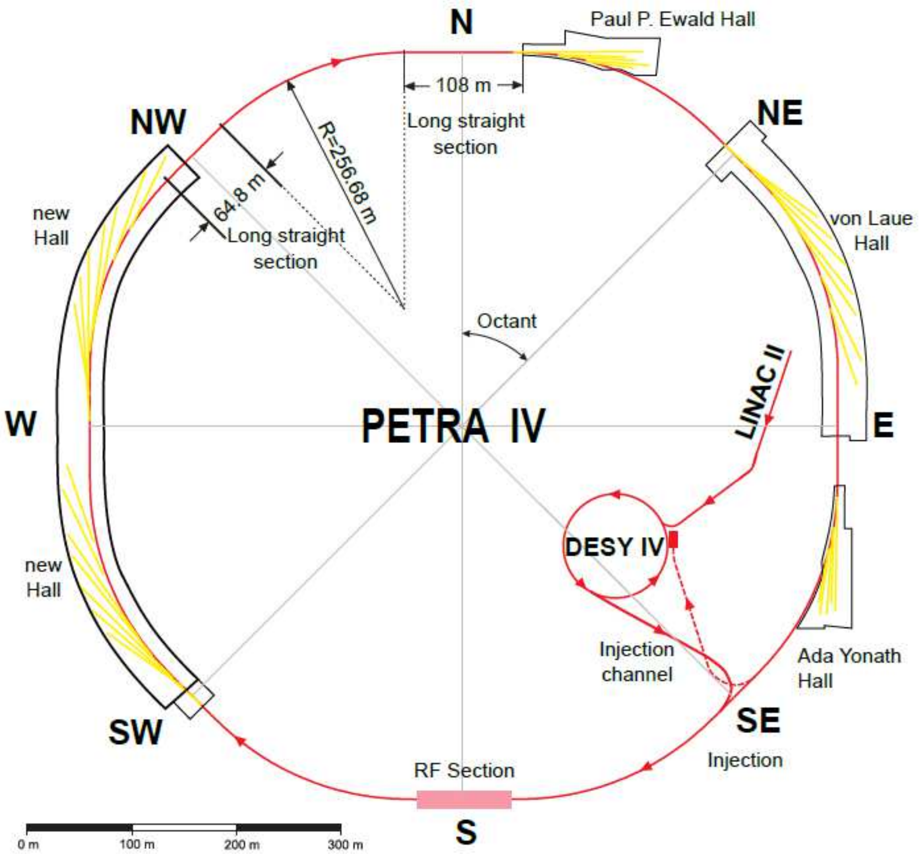
→ others followed / will follow soon

(SIRIUS, ESRF-EBS, …)

➡ PETRA IV

# PETRA IV: Overview

- PETRA IV storage ring and pre-accelerators

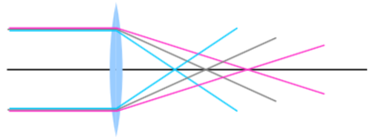


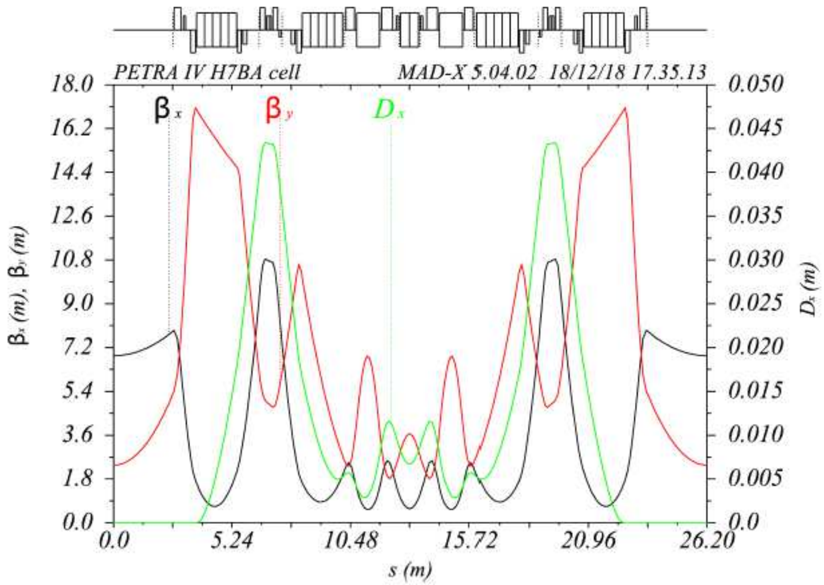

| Design parameter | PETRA III | | PETRA IV | |
|---|---|---|---|---|
| Energy / GeV | 6 | | 6 | |
| Circumference / m | 2304 | | 2304 | |
| Operation mode | Continuous | Timing | Brightness | Timing |
| Emittance (horz. / vert.) / pm rad | 1300 / 10 | | < 20 / 4 | < 50 / 10 |

- use of old accelerator tunnel
  - → HEP structure remains
- asymmetric ring structure
  - → reduced momentum / dynamic acceptance (estimated: factor 1.5 – 2)
  - → beam dynamics safely under control
- no canted undulator beamlines forseen
  - → strong emittance increase
  - → additional experimental hall (30 straight ID sections)

# PETRA IV Lattice

- Extremely low emittances → strong focusing required
  - consequence
    - → large negative chromaticity has to be compensated
  - needs strong sextupoles
    - → negative impact on nonlinear beam dynamics
    - → strong decrease of dynamic / momentum aperture






- Hybrid-Multibend Achromat (HMBA)
  - based on 7-bend achromat
    - → ESRF-EBS  J. Biasci et al., Sync. Rad. News **27** (2014) 8
  - creation of two dispersion bumps
    - → inside bumps: three sextupole families installed
    - → helps to significantly reduce sextupole strength
  - cell length $L_{HMBA} = 26.2$ m  (PETRA III: $L_{DBA} = 23$ m)
    - → beamline configuration of PETRA III cannot be preserved
    - → 8 HMBA cells / arc ➡ 64 HMBA cells
  - further emittance reduction via reverse bends → in discussion

- straight sections
  - 4 with space for 10m-IDs
  - remaining straights
    - → based on FODO structure

# PETRA IV: Operation Modes

- from PETRA III to PETRA IV

| Design Parameter | PETRA III | | PETRA IV | |
|---|---|---|---|---|
| Energy / GeV | 6 | | 6 | |
| Circumference /m | 2304 | | 2304 | |
| Emittance (horz. / vert.) /pm | **1300** / 10 | | < **20** / 4 | <50 / 10 |
| Total current / mA | 100 | | **200** | 80 |
| Number of bunches | **960** | **40** | **1600** | **80** |
| Bunch population / $10^{10}$ | **0.5** | **12** | **0.6** | **5** |
| Bunch separation / ns | **8** | **192** | **4 + gaps** | **96** |

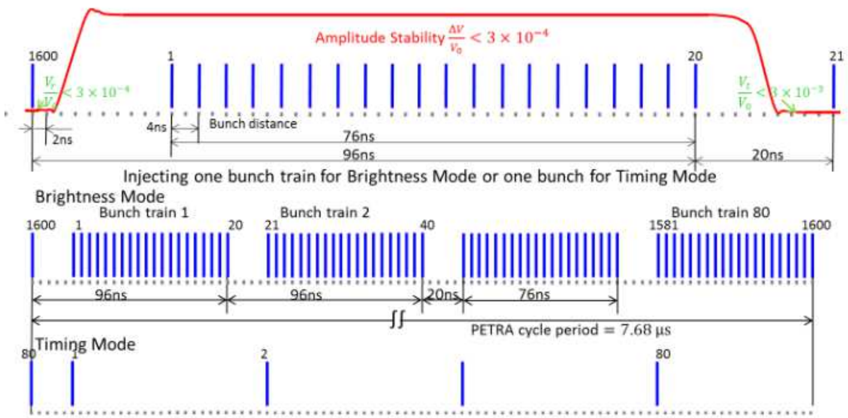
design goal: → $\times$ 65 smaller $\varepsilon_x$

**brightness mode** **timing mode**

- timing structure
  - general fill pattern → 80 x ***Bunch Train***
  - bunch train duration: 96 ns

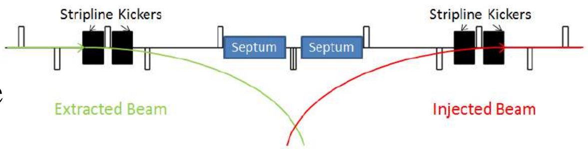
    → 80 × 96 ns = 7.68 µs = $T_{rev}$
  - **brightness mode** → *Bunch Train* = 20 bunches

    4 ns spacing + 20 ns kicker gap
  - **timing mode** → *Bunch Train* = 1 bunch




- injection scheme
  - swap-out on-axis injection

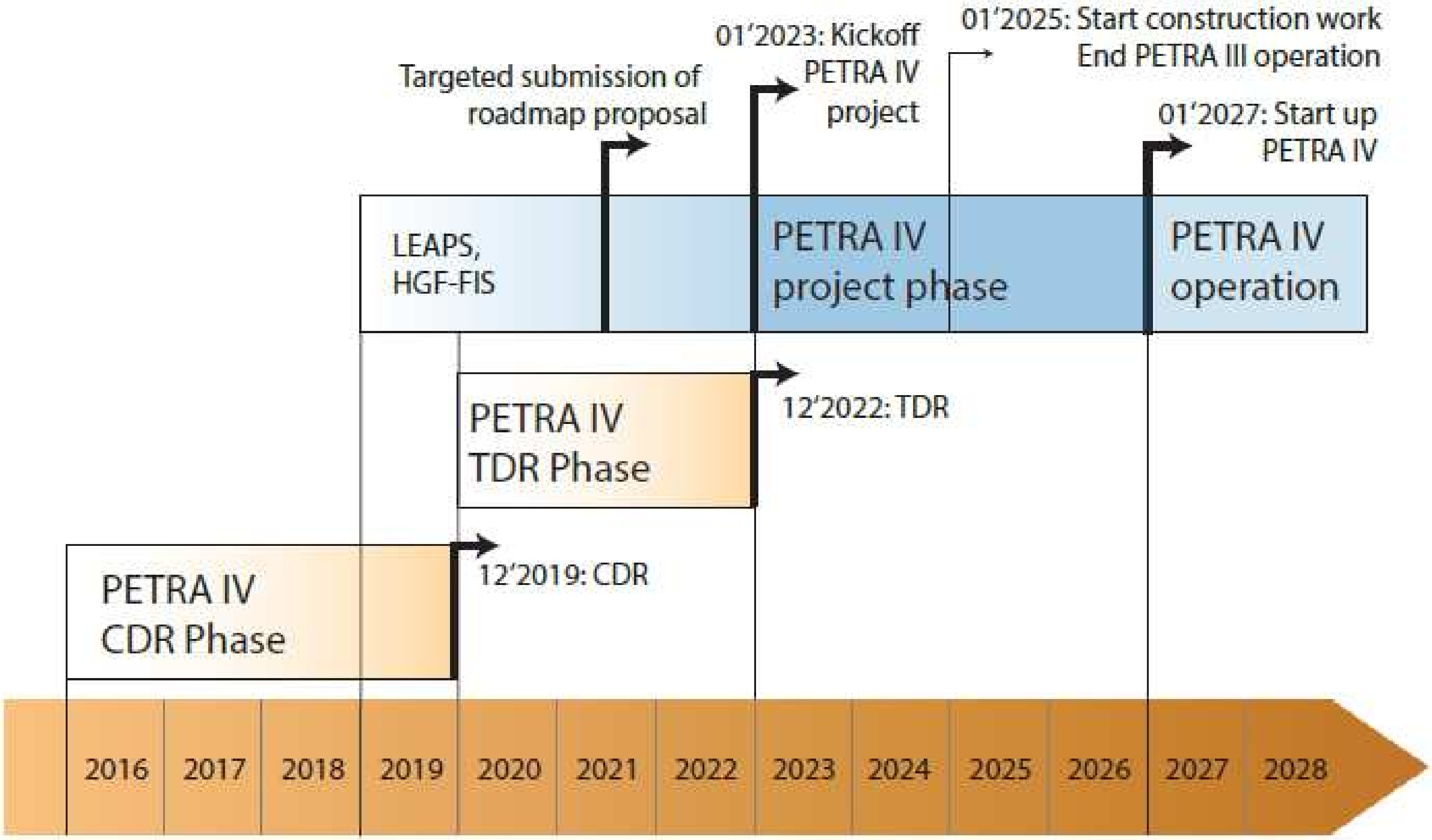
    → dynamic aperture on average larger than 5σ of injected beam




  - max. intensity variation < 10%

    → injection rate 0.5 Hz (timing mode)

# PETRA IV: Timeline




C.G. Schroer et al., PETRA IV: Upgrade of PETRA III to the Ultimate 3D X-ray Microscope. Conceptual Design Report

- presently: beginning phase of *Technical Design Report*

# PETRA IV: Beam Position Monitors

- information available
  - number of BPMs
    - → 11 BPMs per HMBA cell (present status)

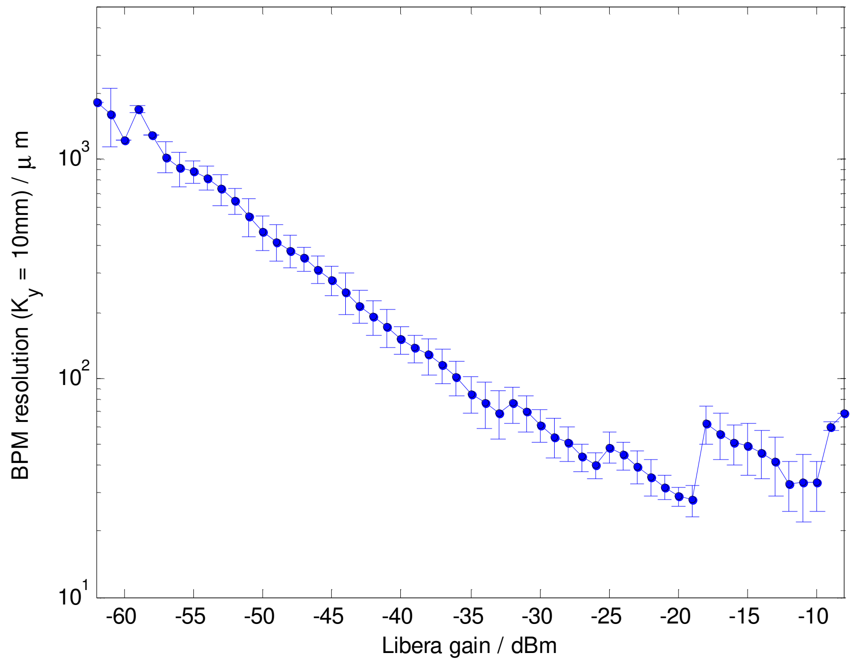
      64 cells, i.e. 704 BPMs in the arc section

      8 BPMs in short, 12 BPMs in long straight sections → 784 BPMs (guess)
  - pickup chamber
    - → arc section: round beam pipe, Ø 20 mm
    - → ID section: not yet defined

      undulator chambers something similar to PETRA III
    - → material: stainless steel (probably)
    - → mechanically fix points: connected via RF shielded bellows to vacuum chambers
  - resolution
    - → single bunch / turn: **< 20 µm** (assuming 0.5 mA in single bunch → $2.5\times10^{10}$ particles bunch )
    - → closed orbit: **< 100 nm** (rms, 200 mA in 1600 bunches) @ 300 Hz BW
- resolution studies @ PETRA III
  - consider only read-out electronics → assume $K_{x,y}$ = 10 mm

# PETRA IV: TbT Single Bunch Resolution

- first step: Libera Brilliance
  - use all devices (246) @ PETRA III for orbit measurements
  - correlation analysis (PCA) to eliminate corelated jitter G. Kube et al., Proc. IBIC 2019, WEPP005



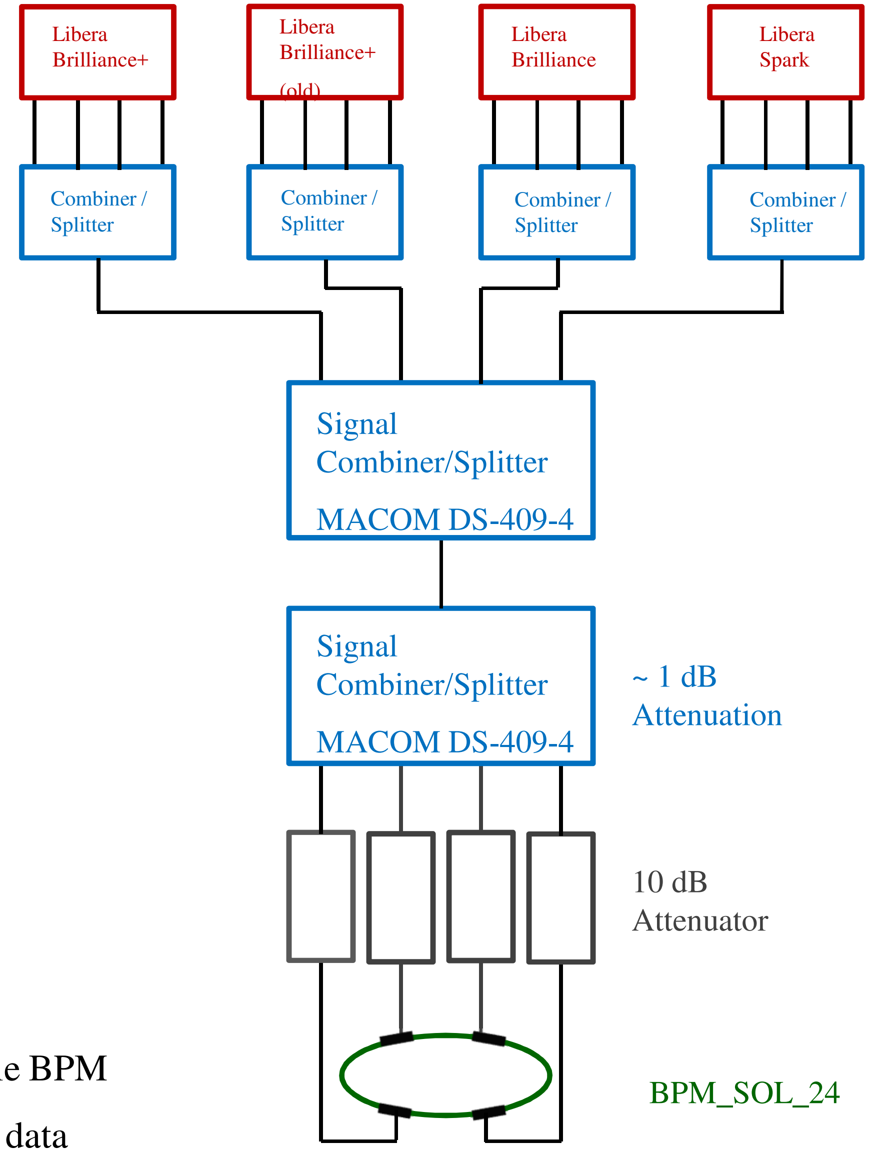

$\min(RMS_{x,y}) \approx 30$ µm

→ Libera Brilliance resolution not sufficient for PETRA IV

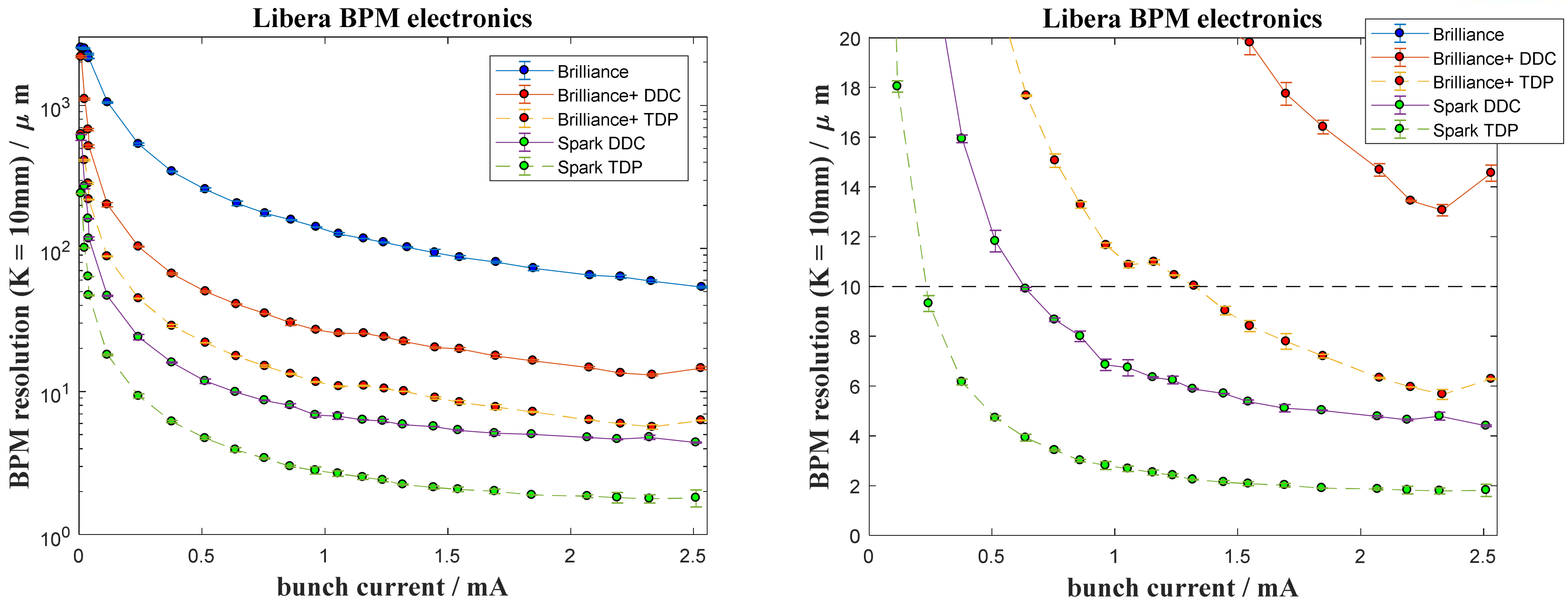
- CDR: rely on Libera Brilliance+ (estimated from S. Condamoor et al., Proc. IBIC 2018, TUPB12 )

# 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 !)
- 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

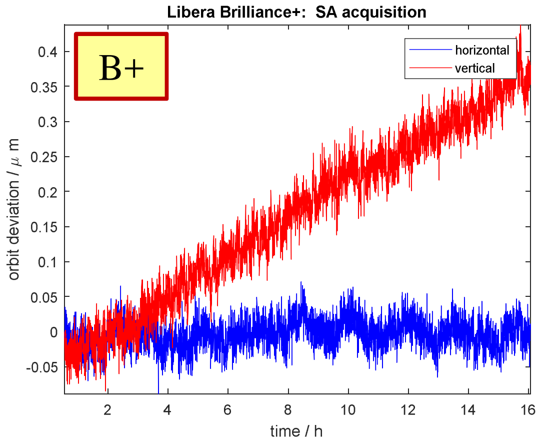
| | | | |
|---|---|---|---|
| DDC mode | < 20 μm (rms) | → | $I_B$ ≈ 0.4 mA |
| TDP mode | ≈ 10 μm (rms) | → | $I_B$ ≈ 0.4 mA |

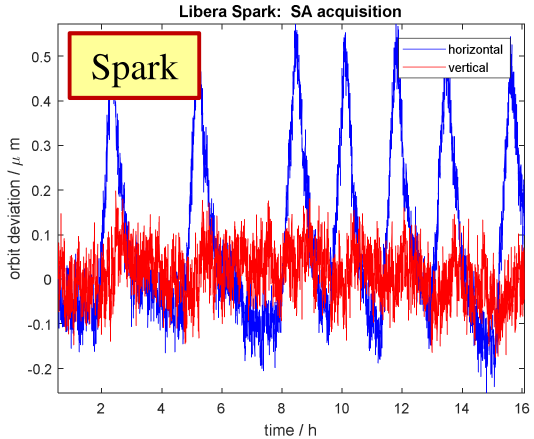
would fulfil requirements

→ but Libera Spark is better…

# Long Term Stability

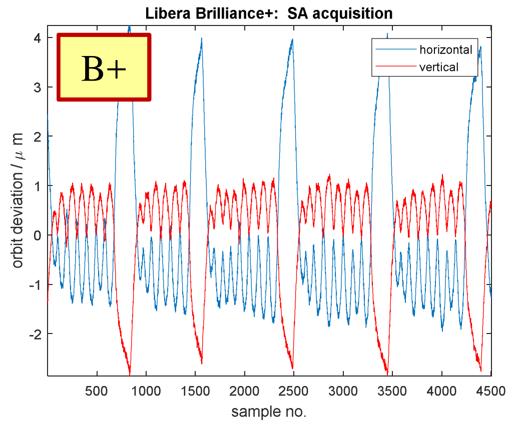
- user operation: 480 bunches @ 100 mA, top-up
  - all Liberas in closed orbit (SA) mode → drift compensation (digital signal conditioning, DSC) on

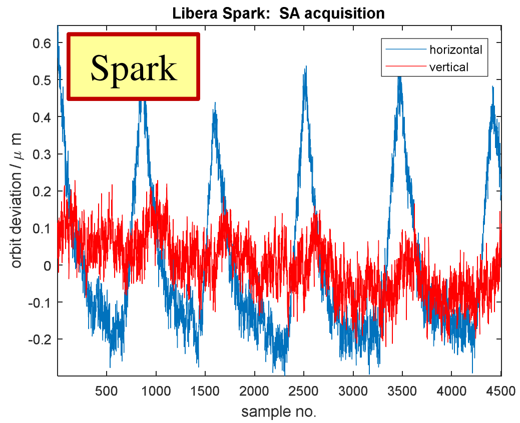



Spark:
no DSC available

- no DSC




- Spark stability per se better → with stabilization ?

# Pilot Tone Stabilization

- pilot tone (PT) as reference signal for calibration / compensation
  - signal path is the same for carrier and pilot
  - several proposals

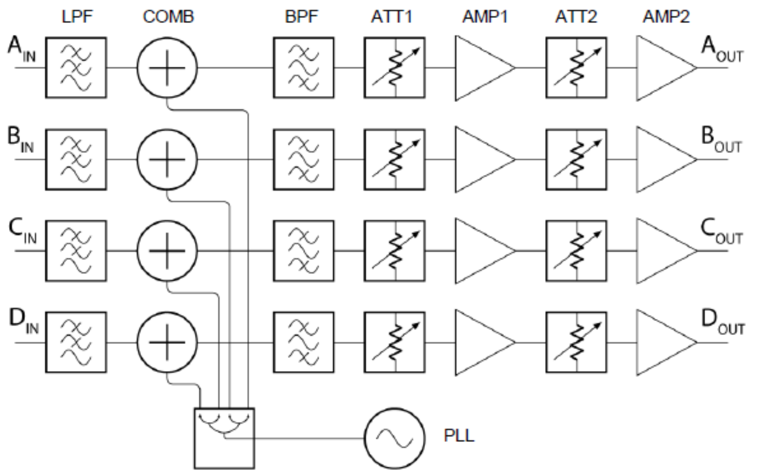
SLS: M. Dehler et al., Proc. DIPAC´99, p. 168

NSLS II: J. Mead et al., Proc. IBIC´14, p. 500

SIRIUS: R.A. Baron et al., Proc. IBIC´13, p. 670

ELETTRA: G. Brajnik et al., AIP Conf. Proc. 1741 (2016) 020013

- ELETTRA BPM front end — G. Brajnik et al., Proc. IBIC´16, p. 307
  - modular approach
    - → analog front end in accelerator tunnel
    - → digitizer in electronics cabinet

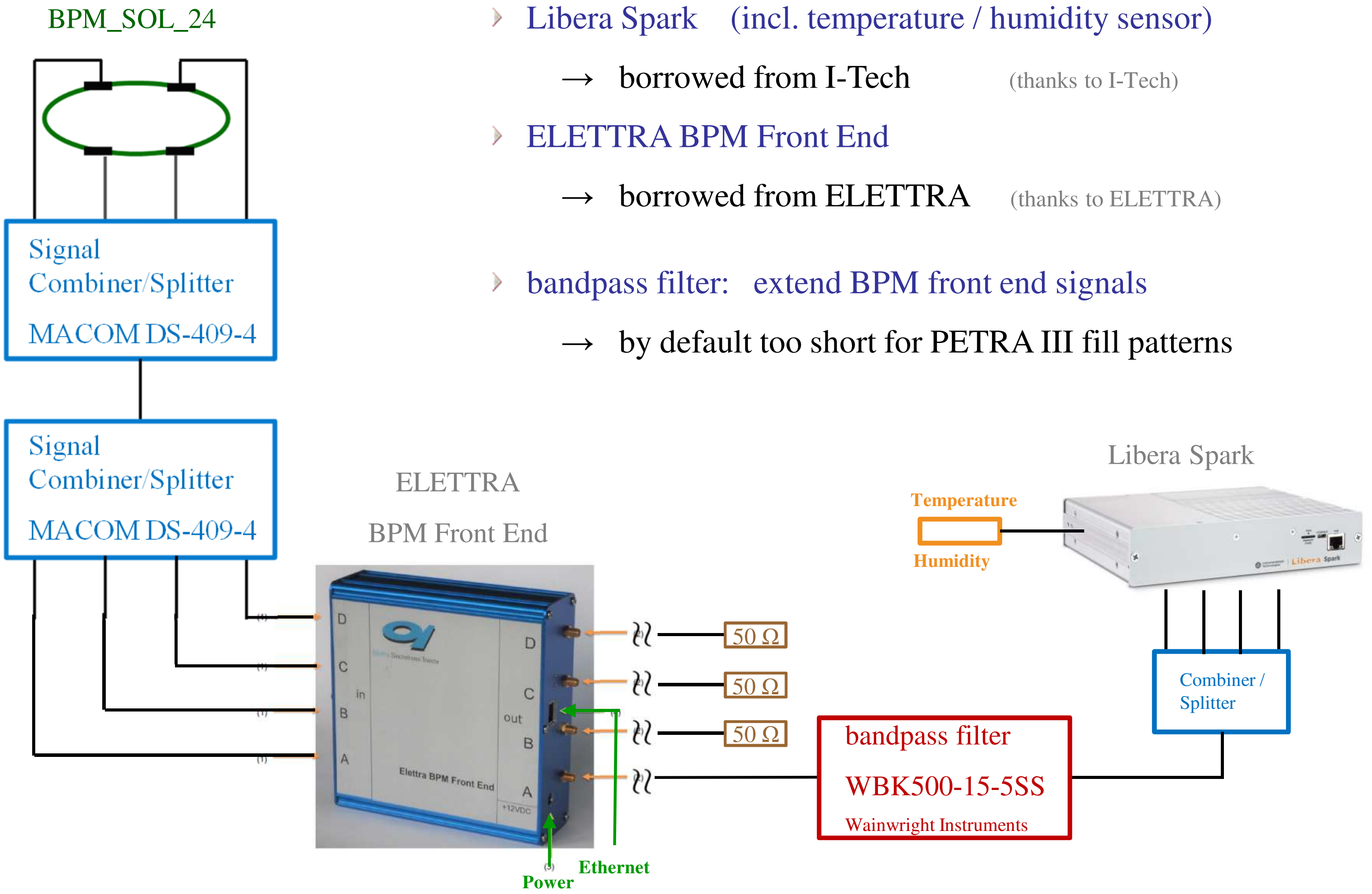

- ELETTRA front end in combination with Libera Spark

M. Cargnelutti et al., *Stability Tests with Pilot-Tone Based Elettra BPM RF Front End and Libera Electronics*, Proc. IBIC´18, TUPB013

D. Bisiach et al., *Beam Measurements Results of a BPM System Implementing the Pilot-Tone Stabilization Concept* , Proc. IBIC´19, WEPP012 (unpublished)

# Setup at PETRA III

- beam tests @ PETRA III

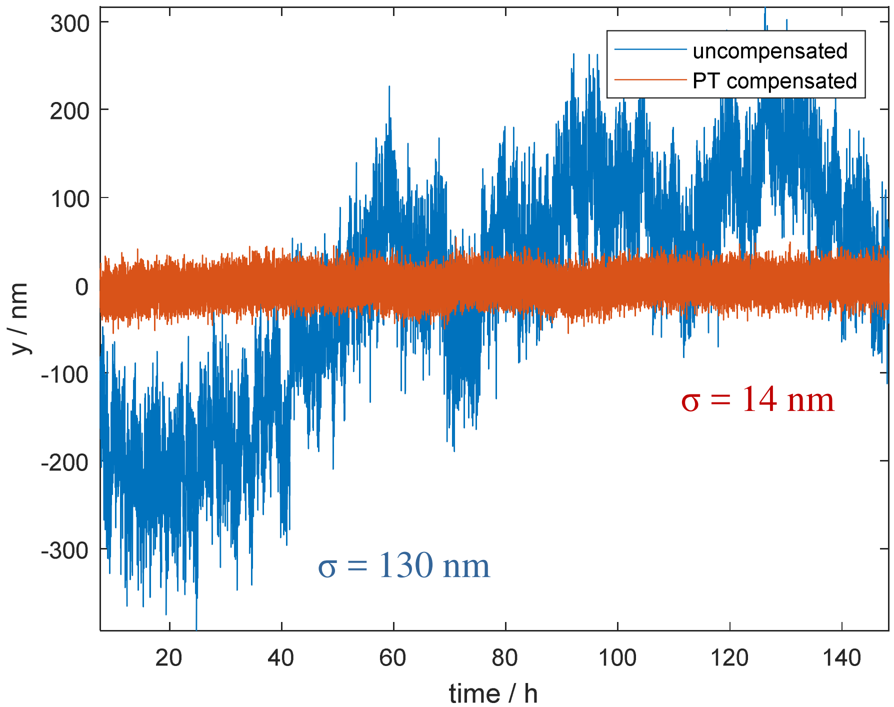



- Libera Spark (incl. temperature / humidity sensor)
  - → borrowed from I-Tech (thanks to I-Tech)
- ELETTRA BPM Front End
  - → borrowed from ELETTRA (thanks to ELETTRA)
- bandpass filter: extend BPM front end signals
  - → by default too short for PETRA III fill patterns

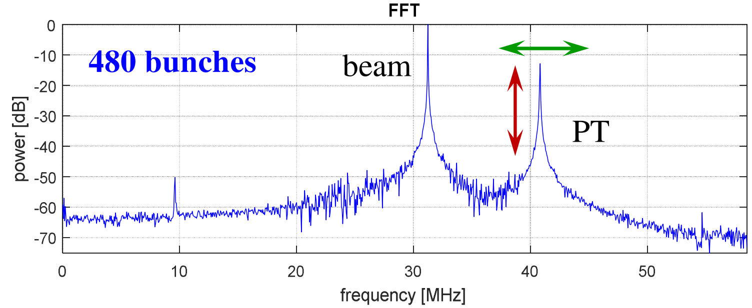
# Measurements and Reuslts

- optimization of pilot tone (PT) settings
  - scan of PT amplitude
  - scan of PT frequency

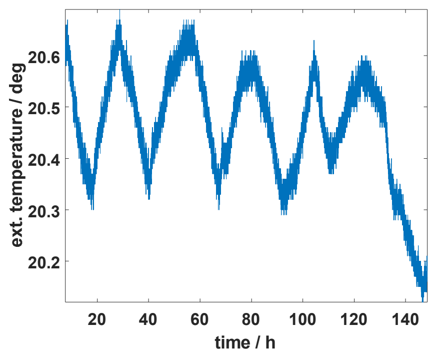
- “long term” measurement for optimized settings
  - 6.8 days  (december 2019)

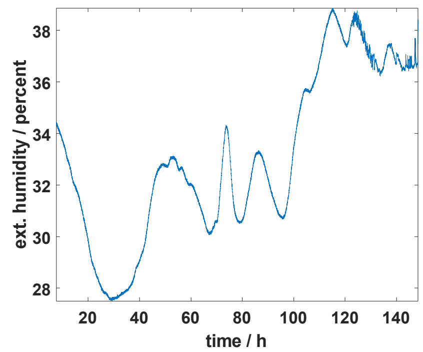



ADC spectrum @ intermediate frequency ( $f_{IF} = \left|\text{rnd}\left(\frac{f}{f_{ADC}}\right)\cdot f_{ADC} - f\right|$ )




- environmental changes




➡ excellent long term stability

# Summary and Conclusion

- PETRA IV
  - new diffraction limited light source @ DESY
    - → start up planned 01/2027
- BPM system
  - about 800 BPMs for orbit control
    - → space for read-out electronics becomes an issue (and for sure: price…)
    - ➡ compact design
- Libera Brilliance
  - single bunch resolution → specs not fulfilled for PETRA IV
- Libera Brilliance+
  - (present) specs fulfilled → old platform, space…
    - ➡ new Libera Brilliance+ (talk Peter Leban)
- Libera Spark
  - single bunch resolution much better
  - in combination with PT front end
    - → long term stability very nice
  - } no AGC, …

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- user wish
  - take Spark / new Brilliance+
  - integrate PT method
  - everything based on µTCA.4
    - ➡ excellent resolution / stability
    - ➡ sell for low price