June 17, 2020

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

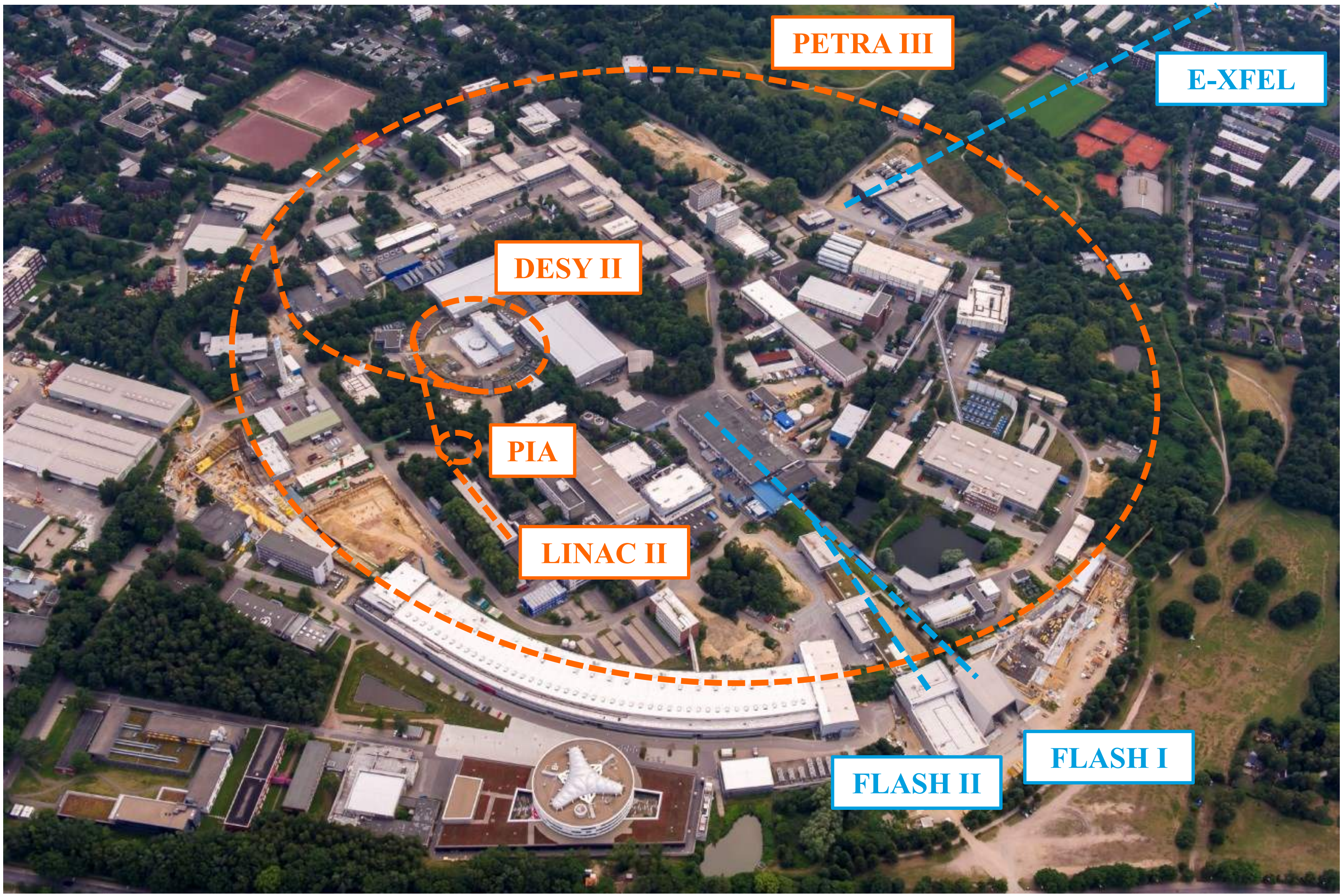
BPM Studies in view of PETRA IV

Gero Kube

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)

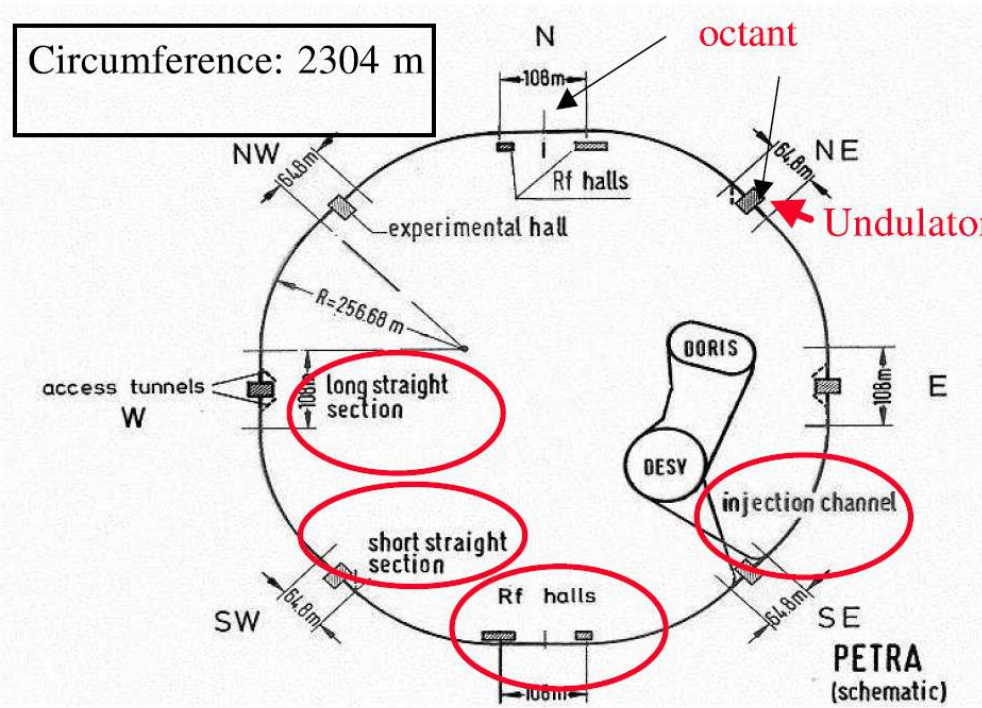
Extension Hall East
Ada Yonath

Max von Laue Hall

Extension Hall North
Paul P. Ewald

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

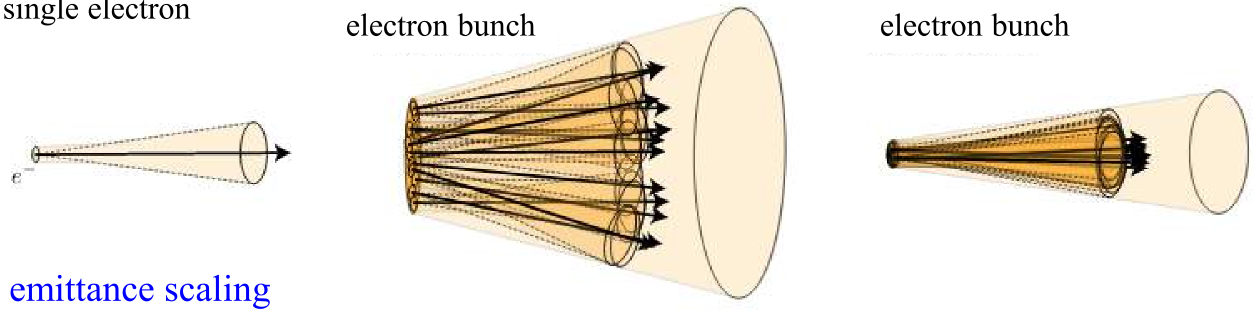
Diffraction Limited Storage Ring

- „diffraction“ limited

single electron

PETRA III
electron bunch

PETRA IV
electron bunch



- natural emittance scaling

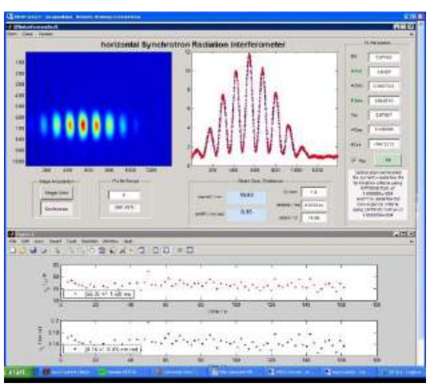
$$\varepsilon_x \propto \gamma^2 \theta^3 \Gamma$$

$\gamma = {}^{E}/_{m_0 c^2}$ Lorentz factor

θ: bending magnet angular deflection

Γ: 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

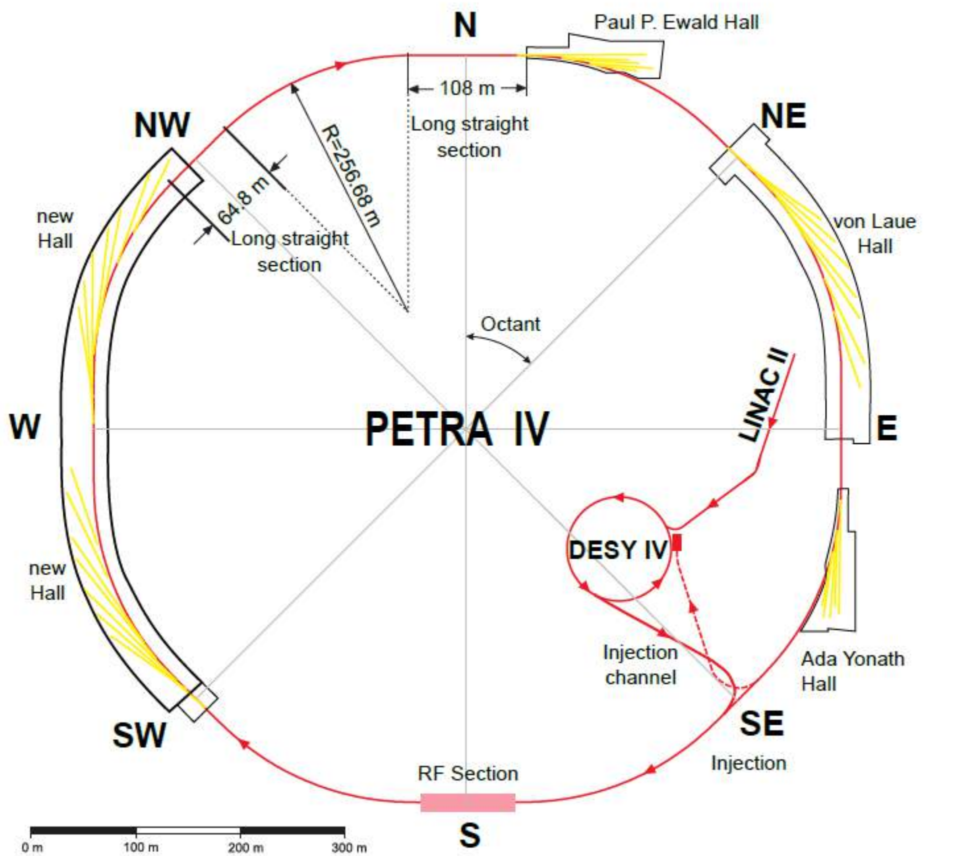
$$\hbar\omega_c \approx 0.665 E^2 B$$

- 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

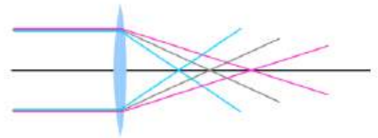


Design parameter	PETRA III		PETRA IV	
Energy / GeV	6		6	
Circumference / m	2304		2304	
Operation mode	Continuous	Timing	Brightness	Timing
Emittance (horz. / vert.) / pm rad	1300 / 10		< 20 / 4	< 50 / 10

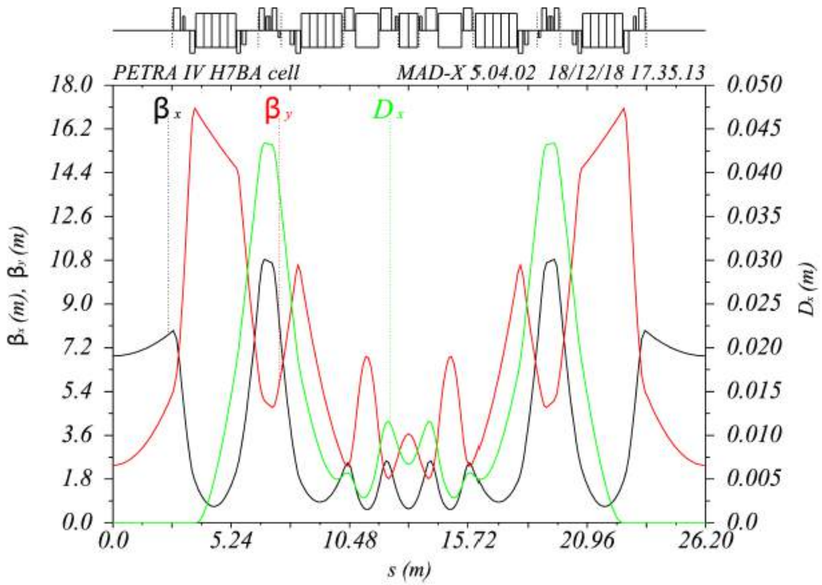
- use of old accelerator tunnel
  - → HEP structure remains
- asymmetric ring structure
  - → reduced momentum / dynamic acceptance (estimated: factor 1.5 – 2)
  - → beam dynamics safely under control
- no canted undulator beamlines forseen
  - → strong emittance increase
  - → additional experimental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

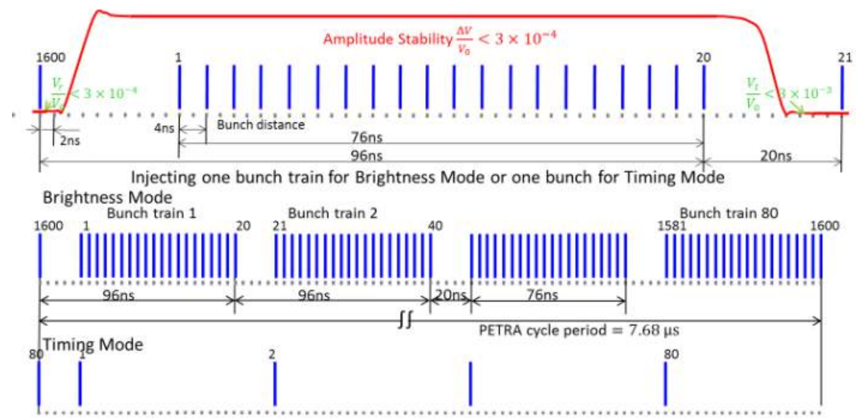
design goal: → × 65 smaller ε_x

brightness mode **timing mode**

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

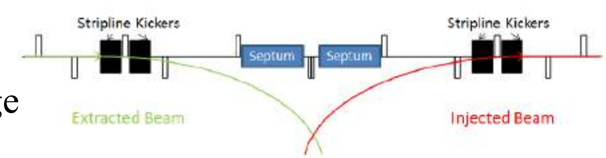
    → 80 × 96 ns = 7.68 μs = T_{rev}
  - **brightness mode** → *Bunch Train* = 20 bunches

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



- injection scheme
  - swap-out on-axis injection

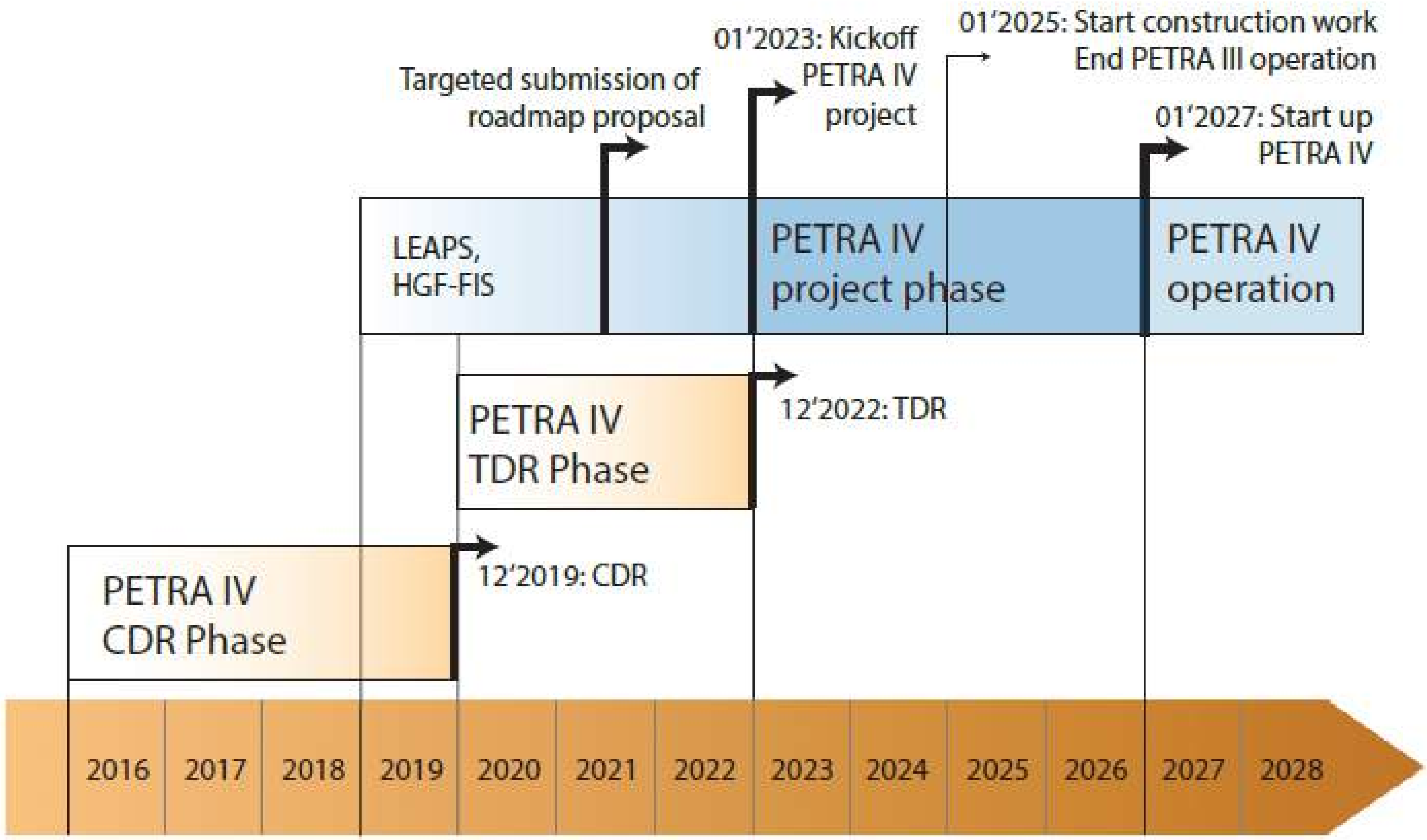
    → dynamic aperture on average larger than 5σ of injected beam



  - 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*

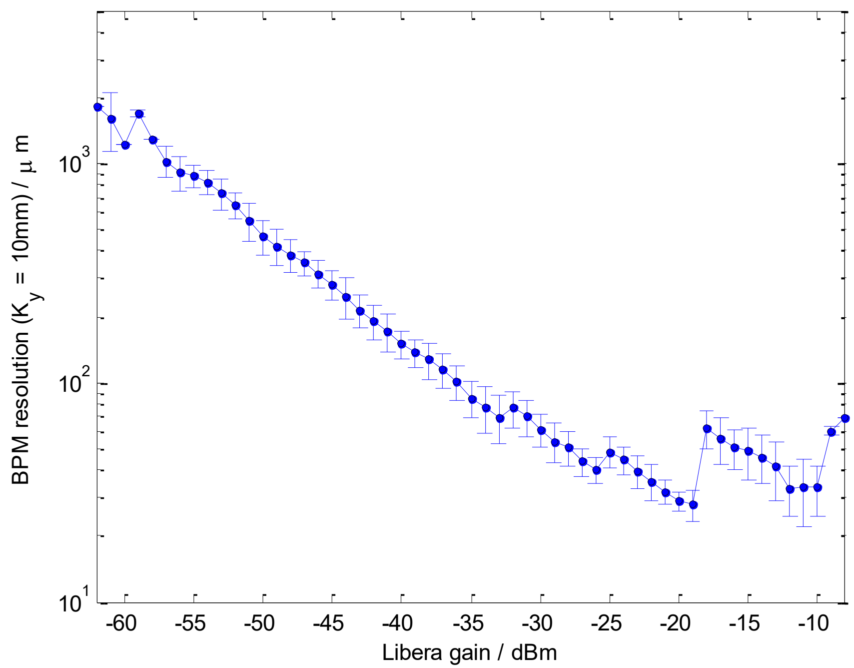
PETRA IV: Beam Position Monitors

- information available
  - number of BPMs
    - → 11 BPMs per HMBA cell (present status)
      64 cells, i.e. 640 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 → 2.5×10^{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



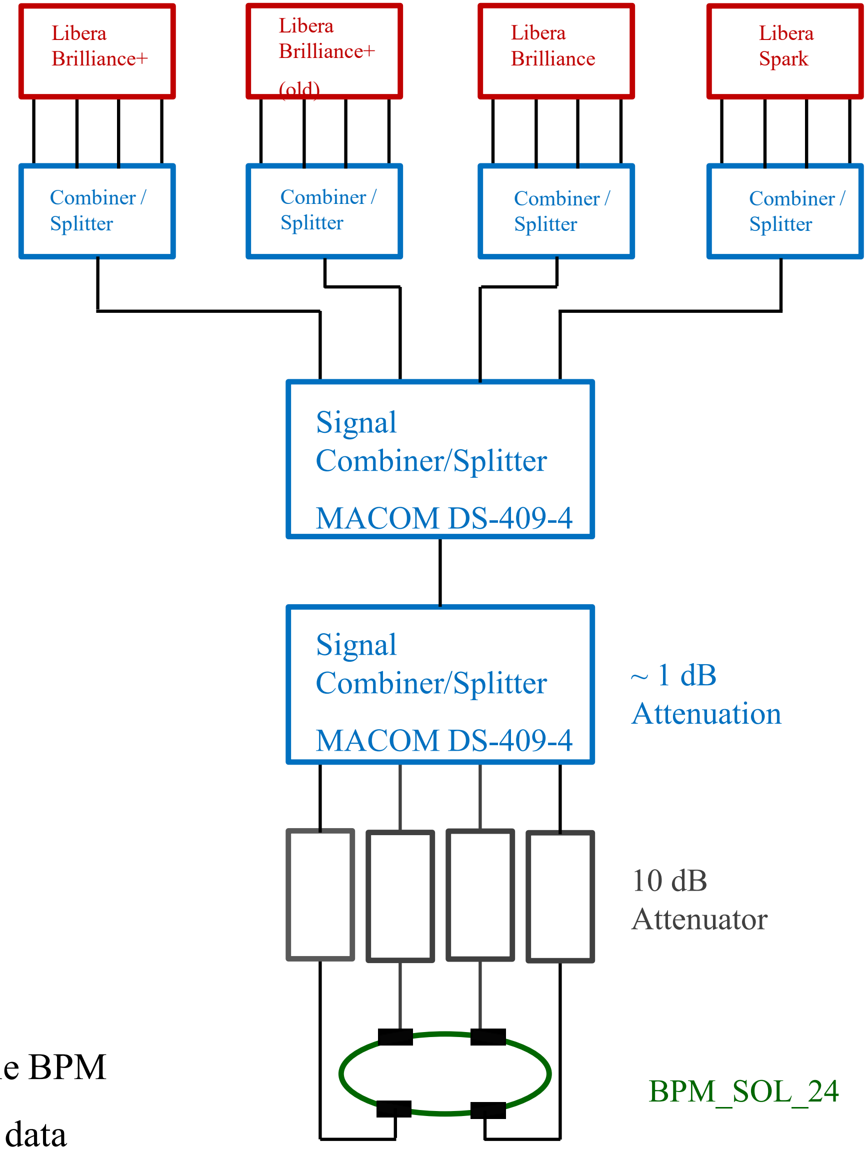
$\min(RMS_{x,y}) \approx 30\ \mu\text{m}$

→ Libera Brilliance resolution not sufficient for PETRA IV

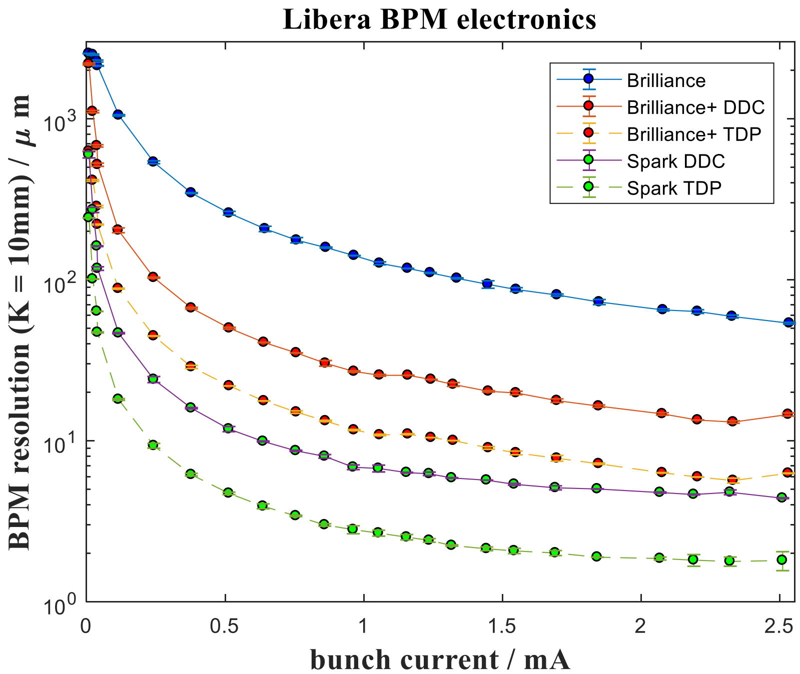
- CDR: rely on Libera Brilliance+ (estimated from S. Condamoor et al., Proc. IBIC 2018, TUPB12)

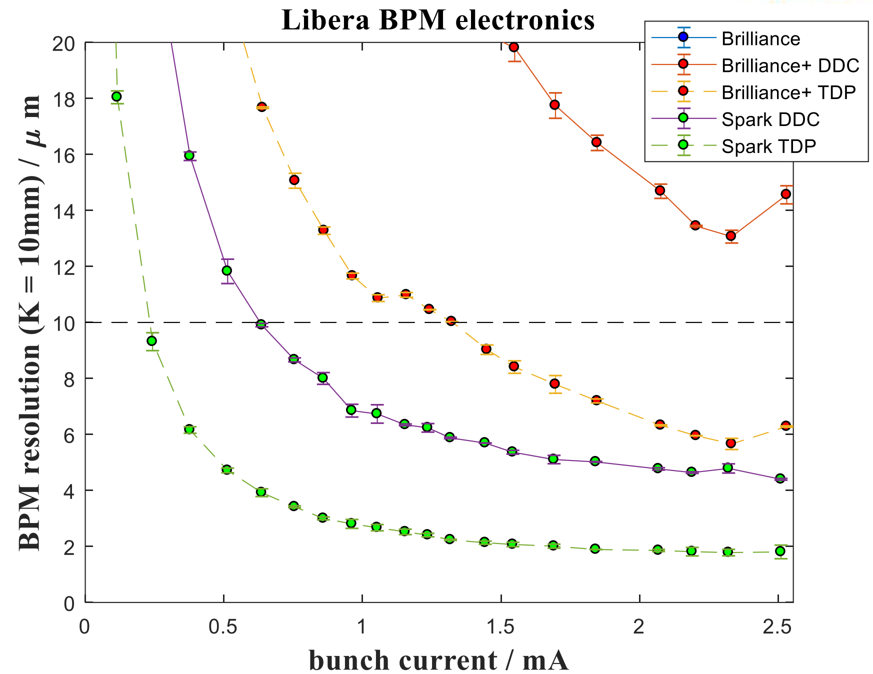
Test of Read-out Electronics

- 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)

    $\sigma < 10$ 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

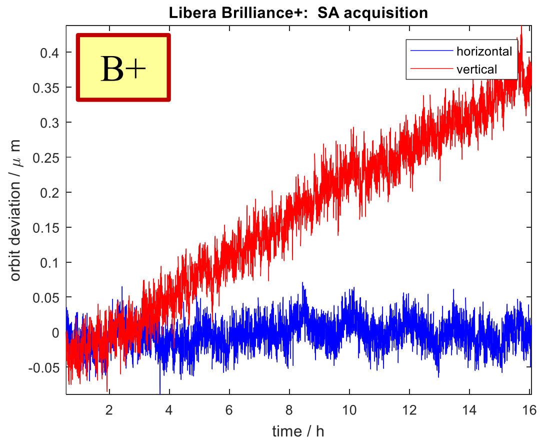
DDC mode	< 20 μm (rms)	→	$I_B \approx 0.4$ mA
TDP mode	≈ 10 μm (rms)	→	$I_B \approx 0.4$ mA

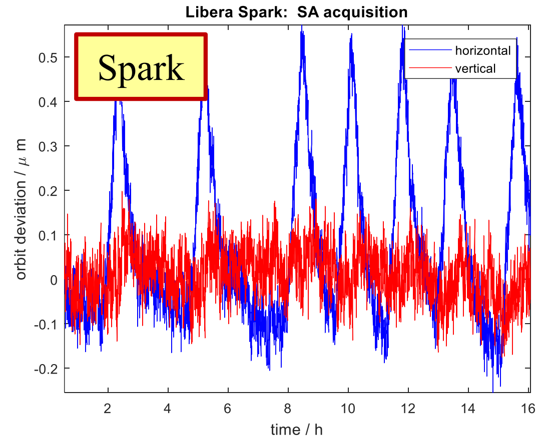
would fulfil requirements

→ but Libera Spark is better…

Long Term Stability

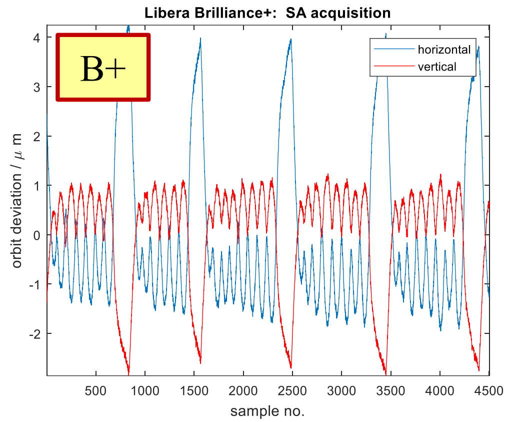
- user operation: 480 bunches @ 100 mA, top-up
  - all Liberas in closed orbit (SA) mode → drift compensation (digital signal conditioning, DSC) on

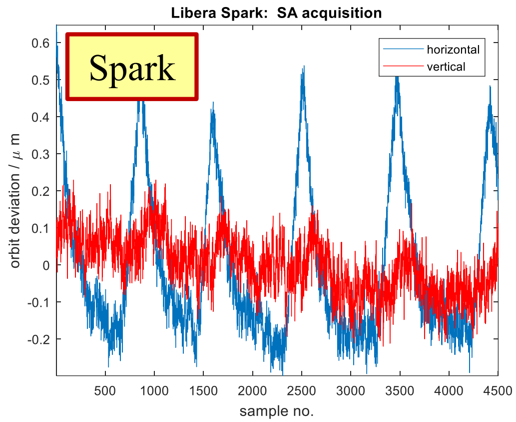




Spark:
no DSC available

- 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

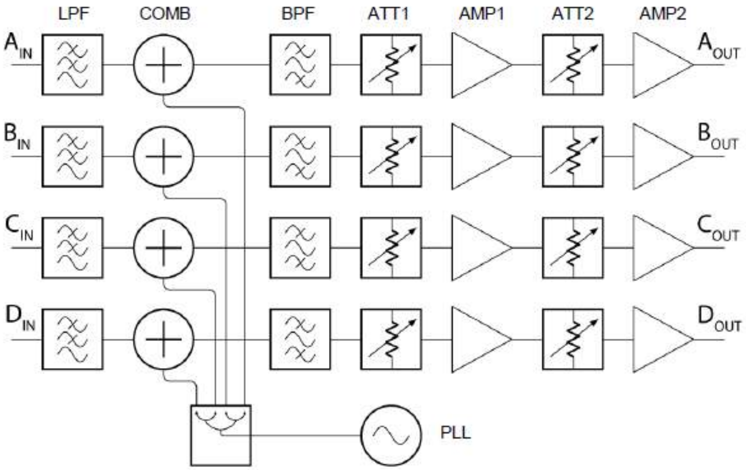
SLS: M. Dehler et al., Proc. DIPAC´99, p. 168

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

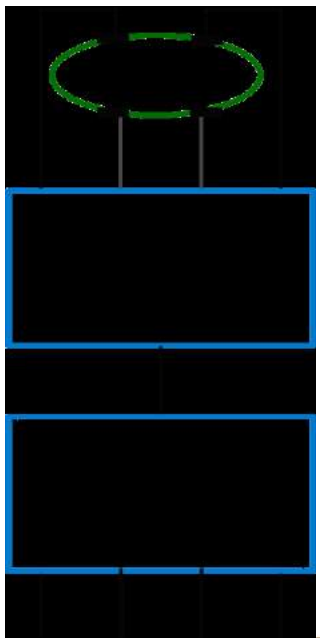
M. Cargnelutti et al., *Stability Tests with Pilot-Tone Based Elettra BPM RF Front End and Libera Electronics*, Proc. IBIC´18, TUPB013

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

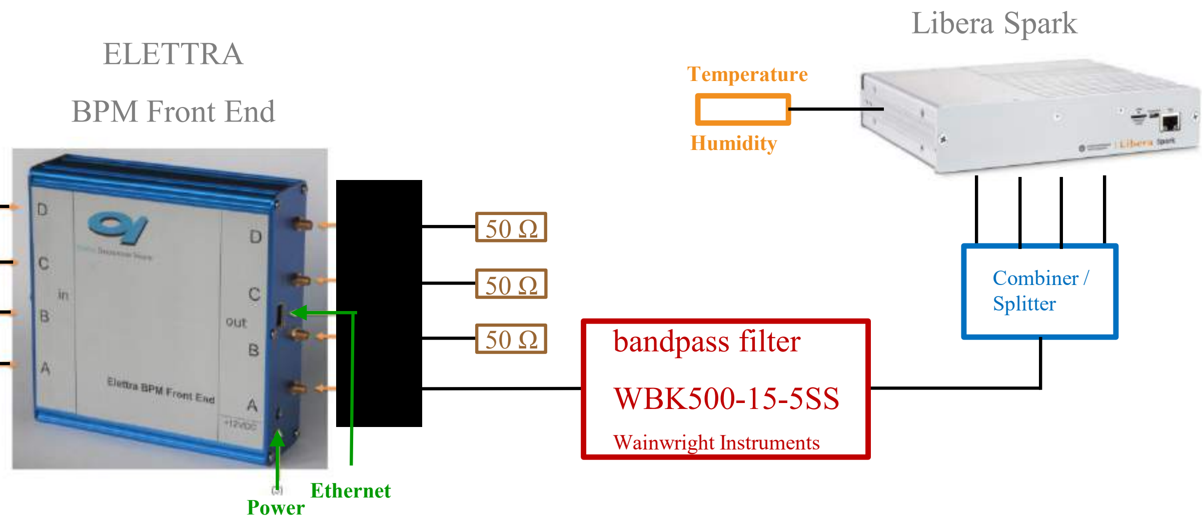
Setup at PETRA III

- beam tests @ PETRA III

BPM_SOL_24



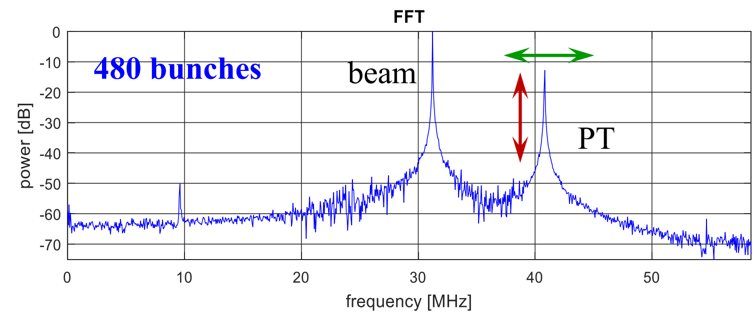
- Libera Spark (incl. temperature / humidity sensor)
  - → borrowed from I-Tech (thanks to I-Tech)
- ELETTRA BPM Front End
  - → borrowed from ELETTRA (thanks to ELETTRA)
- bandpass filter: extend BPM front end signals
  - → by default too short for PETRA III fill patterns

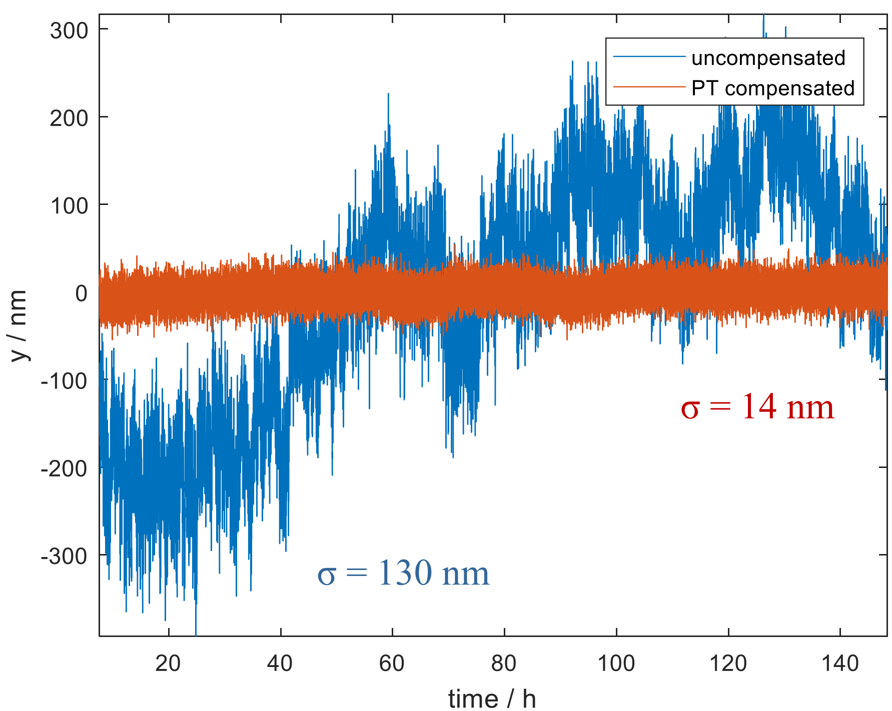


Measurements and Reuslts

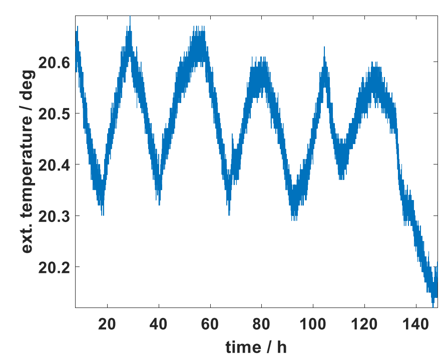
- optimization of pilot tone (PT) settings
  - scan of PT amplitude
  - scan of PT frequency
- "long term" measurement for optimized settings
  - 6.8 days (december 2019)

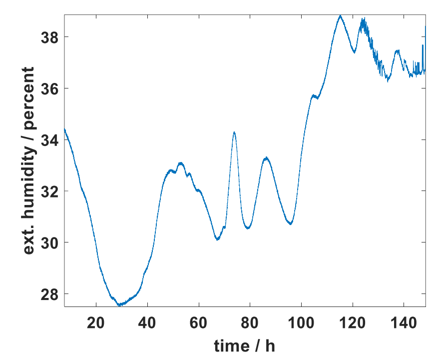
ADC spectrum @ intermediate frequency ($f_{IF} = \left| \mathrm{rnd}\left(\frac{f}{f_{ADC}}\right) \cdot f_{ADC} - f \right|$)





- 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, …

- user wish