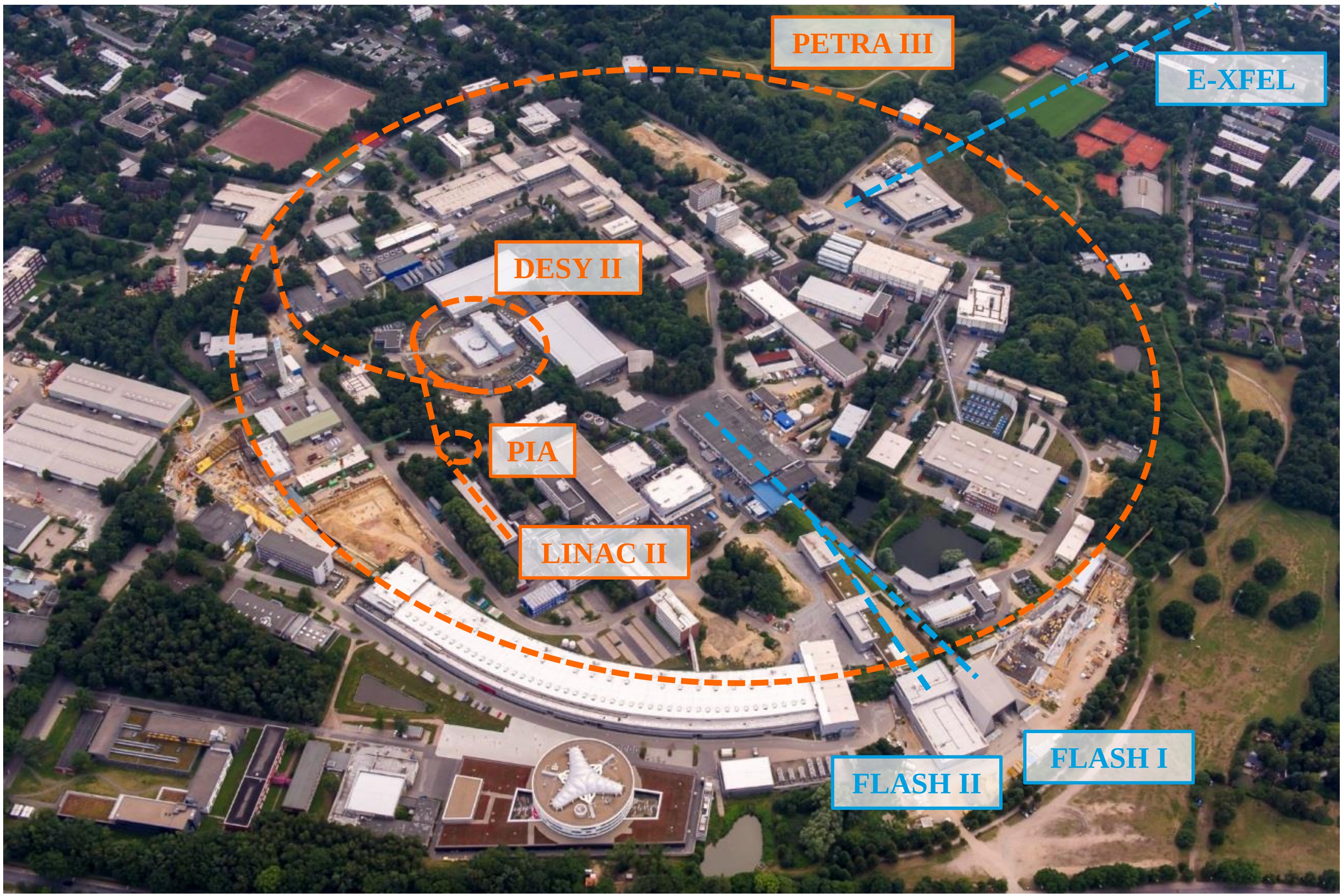
Considerations for PETRA IV

Gero Kube

DESY (Hamburg)

- Introduction
- Overview and Particularities of PETRA IV
- Beam Instrumentation
- Considerations for BPM System

DESY Accelerator Complex



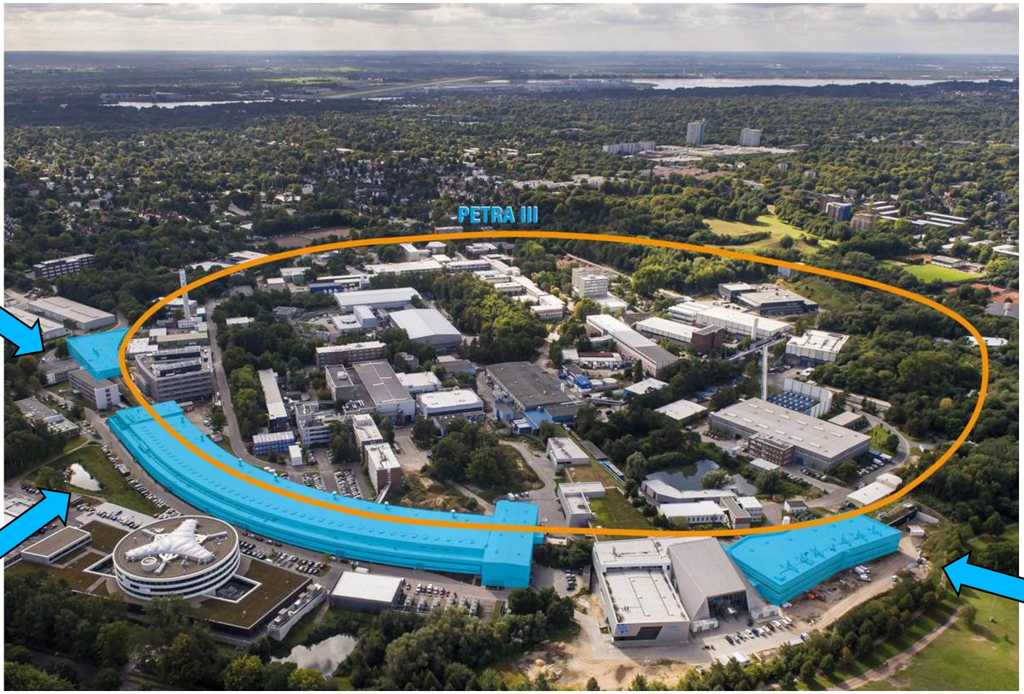
PETRA III @ DESY

- 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

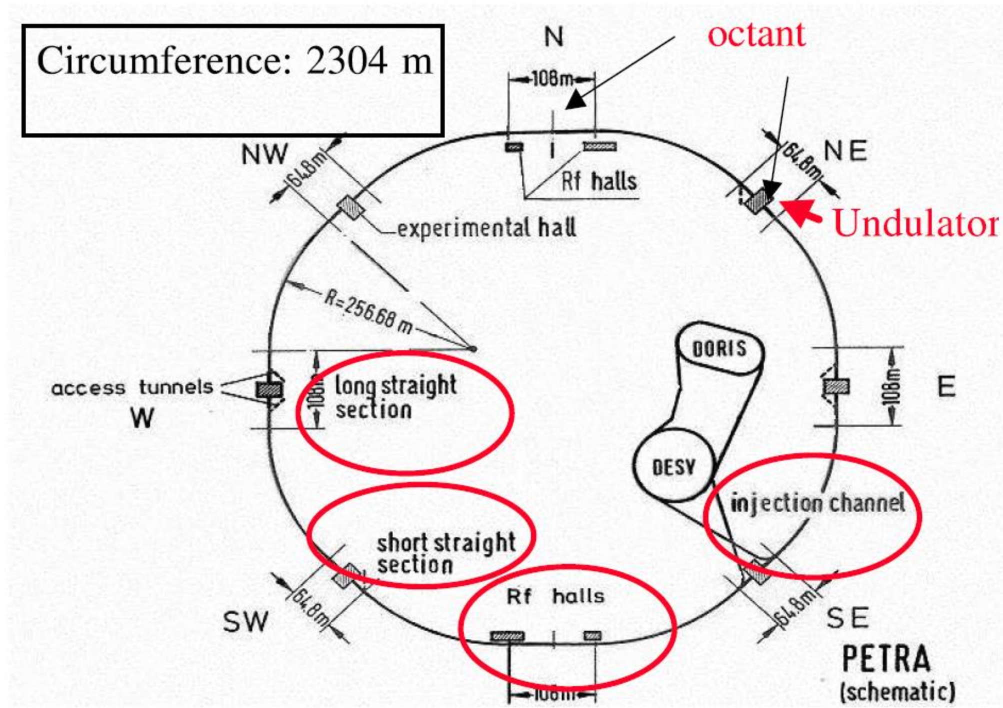


Max von Laue Hall

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

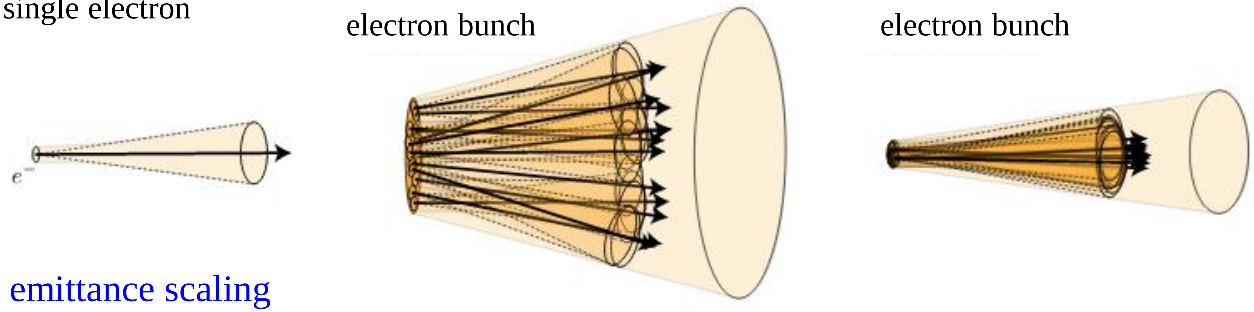
Diffraction Limited Storage Ring

- „diffraction“ limited

single electron

PETRA III
electron bunch

PETRA IV
electron bunch



- natural emittance scaling

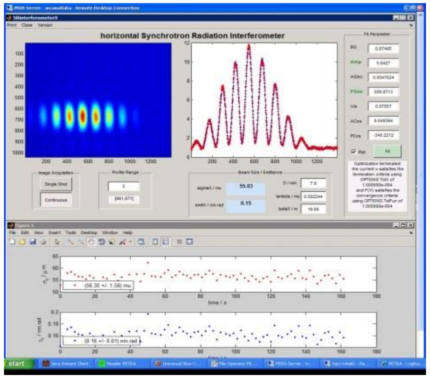
$$\varepsilon_x \propto \gamma^2 \theta^3 \Gamma$$

$\gamma = E/m_0 c^2$ 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

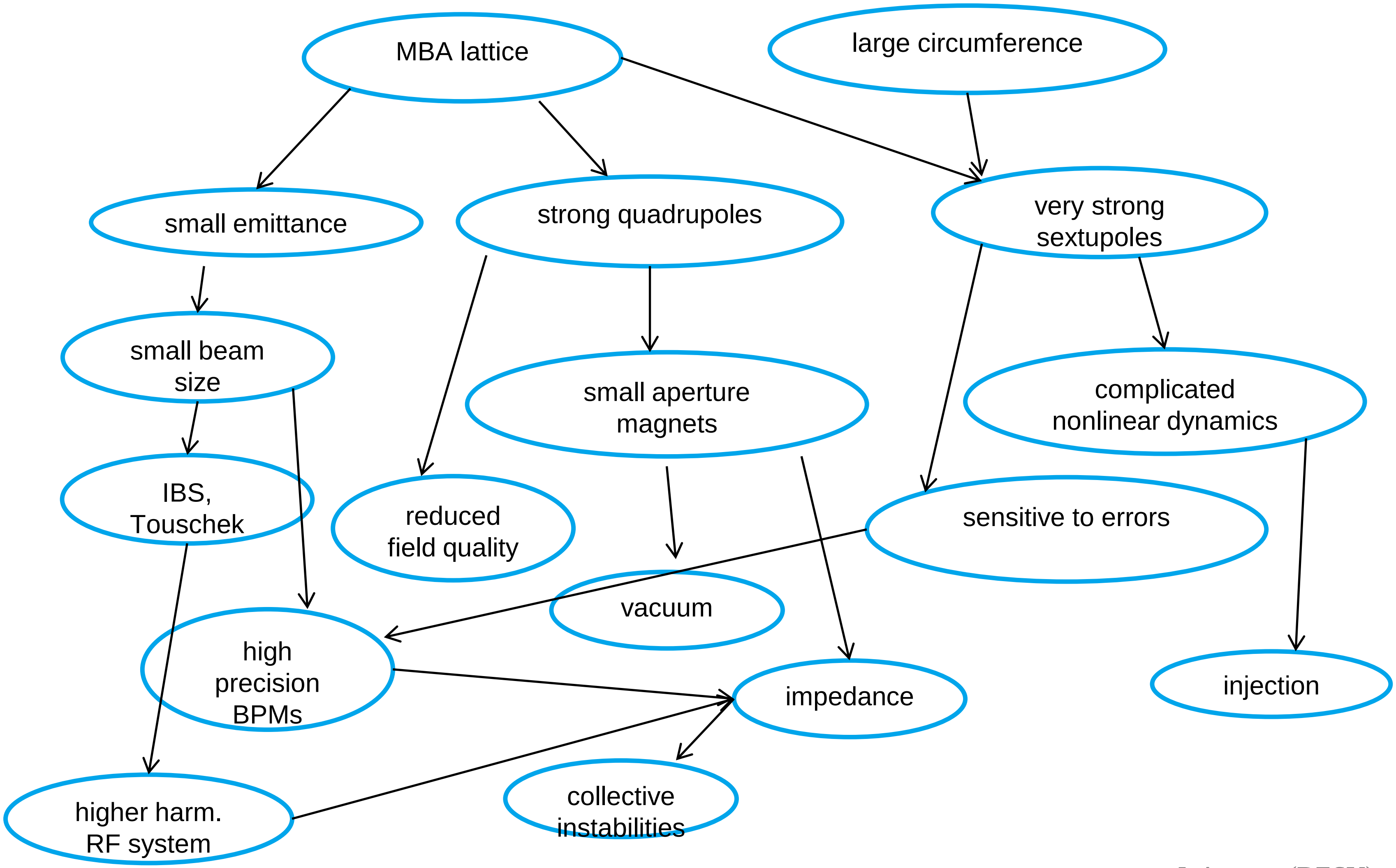
→ from ***double*** bend achromat (2)
to ***multi*** bend achromat (5, 7, 9, …)

→ MAX IV paved the way

→ others followed / will follow soon
(SIRIUS, ESRF-EBS, DLS, …)

⇒ PETRA IV

DLS Design



courtesy: I. Agapov (DESY)

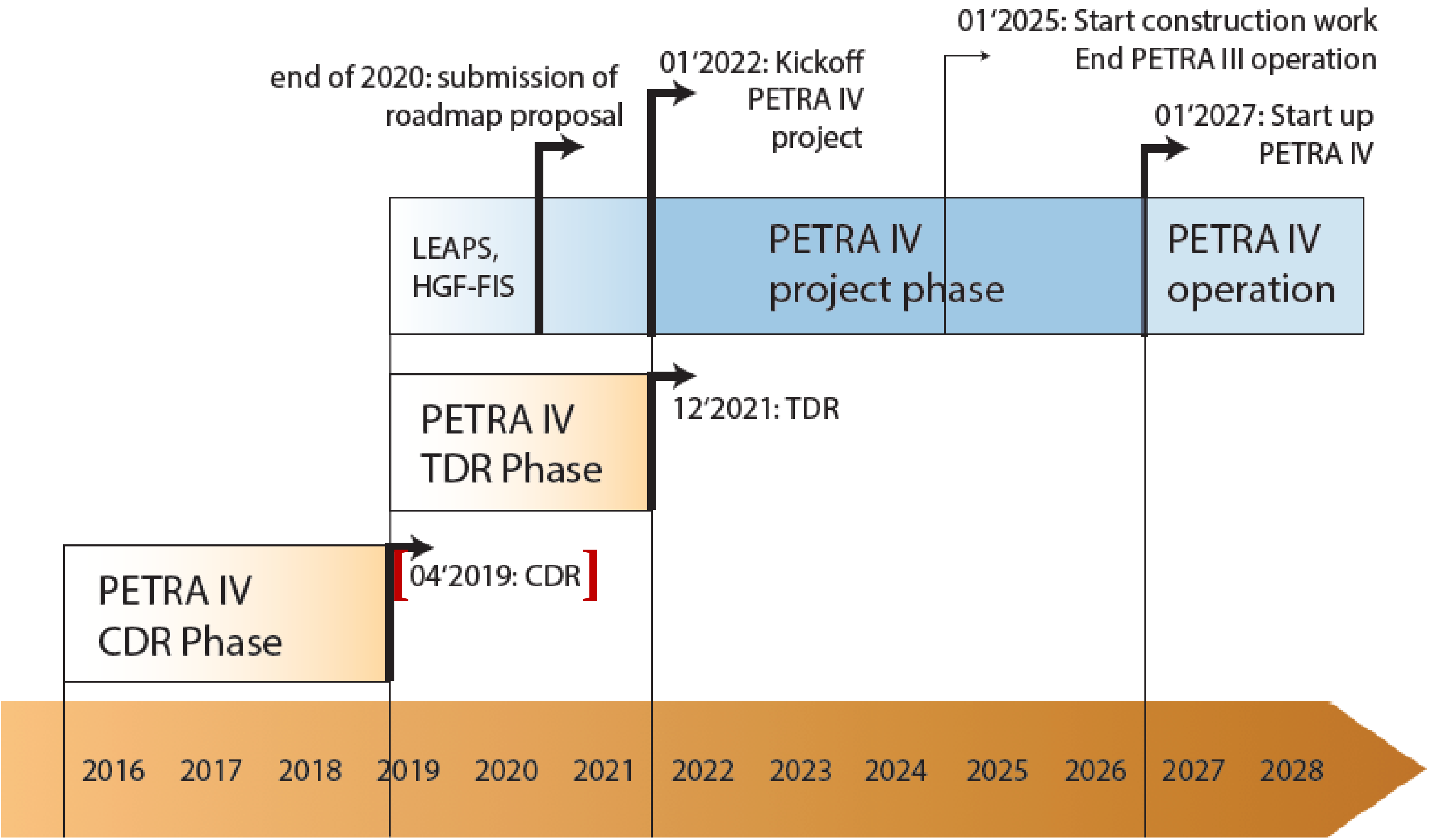
Engineering Challenges

R.T. Neuenschwander et al., Proc. IPAC'15, Richmond (VA), USA, TUXC2, p. 1308

- basic idea → dispersion function plays important role in determining equilibrium emittance
  - has to be kept focused to small values in dipoles
    - → strong focusing quadrupoles between dipoles
    - → strong sextupoles to compensate for chromatic aberrations
- strong sextupoles → introduce nonlinear effects (beam dynamics)
  - reduction of dynamic aperture and clearance for injection
    - → novel injection schemes
- strong magnetic fields
  - bore radius has to shrink
    - → aperture for vacuum chamber reduced
- strong magnetic field gradients
  - high orbit amplification factors
    - → orbit amplitude sensitive to magnet alignment errors
- high orbit amplification factors + small beam sizes
  - stringent tolerance requirements for magnet alignment + vibration amplitudes
    - → tight tolerances for floor / girder vibrations

- vacuum system
  - small beam pipe aperture
    - → reduced conductance of vacuum pipe
- resistive wall impedance becomes issue
  - may require new materials
    - → higher el. conductivity
- high orbit stability
  - pushing technology of
    - → ***beam diagnostics***
    - → ***fast feedback systems***, …

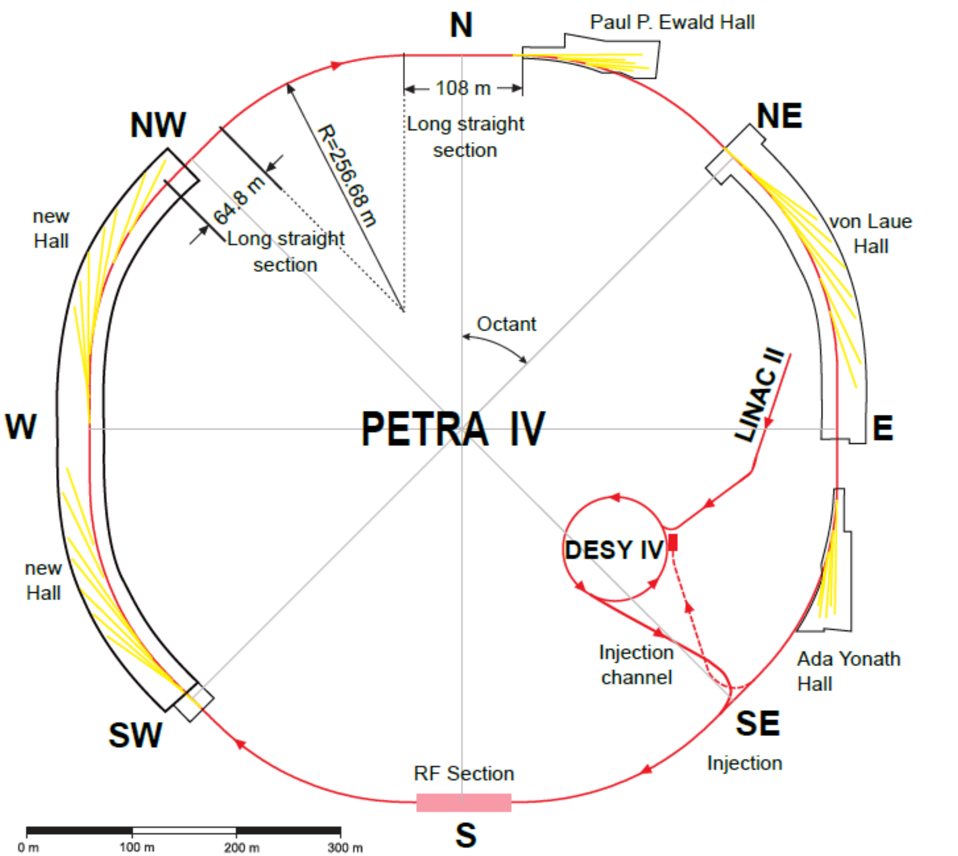
PETRA IV: Timeline



- presently: preparation of *Conceptual Design Report*

PETRA IV: Overview

- PETRA IV storage ring and pre-accelerators

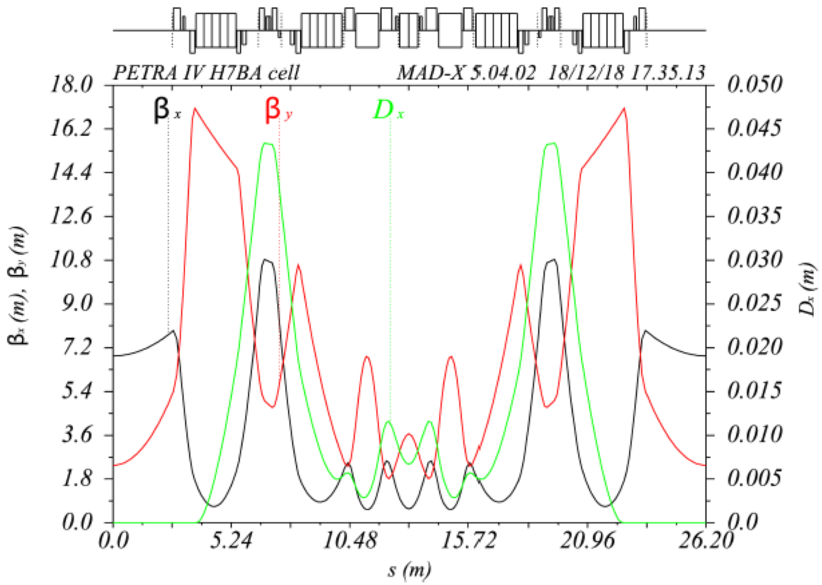


Design parameter	PETRA III		PETRA IV	
Energy / GeV	6		6	
Circumference / m	2304		2304	
Operation mode	Continuous	Timing	Brightness	Timing
Emittance (horz. / vert.) / pm rad	1300 / 10		< 20 / 4	< 50 / 10

- 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 (29 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	
Energy / GeV	6	
Circumference /m	2304	
Emittance (horz. / vert.) /pm	**1300** / 10	
Total current / mA	100	
Number of bunches	**960**	**40**
Bunch population / 10^{10}	**0.5**	**12**
Bunch separation / ns	**8**	**192**

design goal: → × 65 smaller ε_x

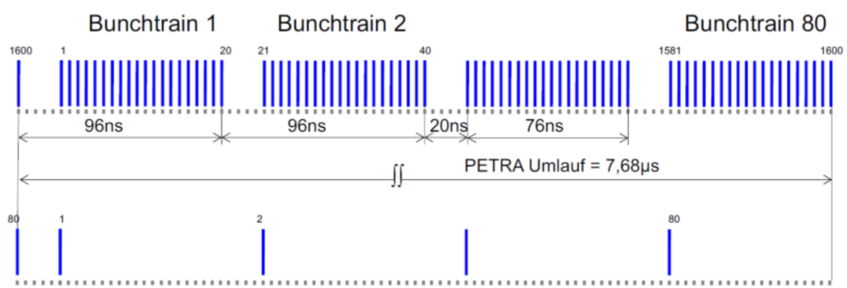
PETRA IV	
6	
2304	
< 20 / 4	<50 / 10
200	80
1600	**80**
0.6	**5**
4 + gaps	**96**

brightness mode **timing mode**

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

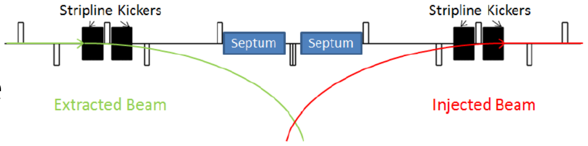
    → 80 × 96 ns = 7.68 μs = T_{rev}
  - **brightness mode** → *Bunch Train* = 20 bunches

    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: Life Time and RF System

- life time dominating process → Touschek scattering
  - elastic scattering in transverse plane with momentum transfer in longitudinal plane

    → depends on particle density in bunch
  - acceptable Touschek life times

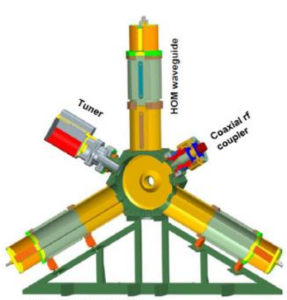
    → bunch lengthening required

    → 3rd harmonic cavity system

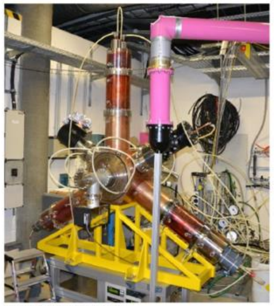
- RF system → fundamental RF frequency f_{RF} = 499.665 MHz (500 MHz)
  - from PETRA III to PETRA IV

    → decrease of (i) energy loss / turn: ***4.66 MeV*** → ***4.02 MeV***, (ii) α_p = ***1.20×10⁻⁴*** → ***1.485 ×10⁻⁵***
  - reduction of required RF voltage from ***20 MV*** to ***8 MV***

    → replace 12 (35 years old) 7 cell cavities by single cell cavities
  - HOM damped EU cavity F. Marhauser and E. Weihreter, Proc. EPAC'04, Lucerne (Switzerland), p.979



Courtesy of Ernst Weihreter, HZB



Courtesy of Wolfgang Anders, HZB

→ 24 single cell cavities

- 3rd harmonic system

  → 24 single cell cavities, f_{RF} = 1.49 GHz, U = 2.26 MV

  → active system seems to be essential

PETRA IV: Beam Instrumentation

- beam profile / emittance diagnostics
  - 3 bending magnet (3-pole wiggler) beamlines

    → 2 for visible synchrotron radiation:

    a) ***Streak camera*** for ***bunch lengths*** (σ_t = 45.7 / 64.3 ps → PETRA III: σ_t = 41 ps)

    b) ***SR interferometer*** for ***beam size*** (resolvable size not yet specified)

    → X-ray synchrotron radiation:

    c) ***pinhole camera / Fresnel diffractometer*** for ***beam size*** (resolvable size not yet specified)
  - critical aspect → resolution for transverse beam profiles
- beam current monitors
  - commercial DCCTs (DC current) and passive beam transformers (bunch current)

    → critical aspect: heat load due to HOMs
- machine protection system / machine safety
  - including BLMs, online dosimetry, temperature control, …

    → mainly based on systems developed for European XFEL, porting to new technical platform (µTCA ?)
- parasitic bunch measurement, X-ray BPMs, …
  - responsibility not yet defined…

⇒ beam position monitor system

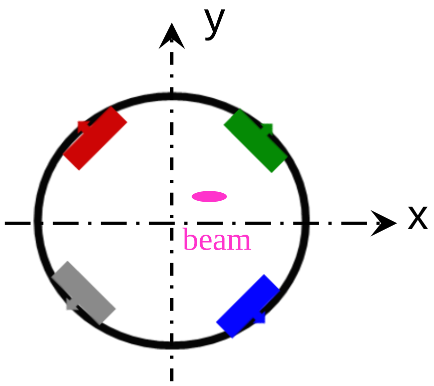
PETRA IV: BPMs

- information available
  - number of BPMs
    - → 10 BPMs per HMBA cell (present status)
      64 cells, i.e. 640 BPMs in the arc section
      some BPMs in the straight sections
      ➡ 700 – 800 BPMs (guess)
  - pickup chamber
    - → arc section: round beam pipe, Ø 20 mm
      first discussions started: reducing beam pipe diameter…
    - → ID section: not yet defined
      undulator chambers something similar to PETRA III
    - → material: copper beam pipes (orbit feedback ???)
    - → mechanically fix points: connected via RF shielded bellows to vacuum chambers
  - resolution
    - → 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

PETRA IV: 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

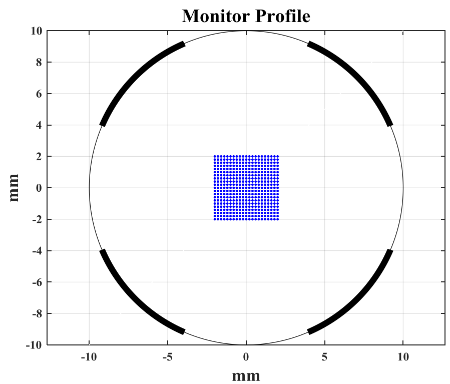
SNR : signal-to-noise ratio

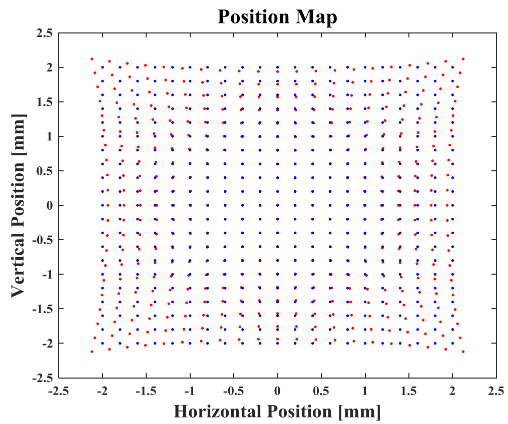
- depends on
  - pickup geometry
    - → beam pipe diameter
  - button size
  - geometry
    - → signal strength
  - infrastructure
    - → cable length & attenuation
  - read-out electronics

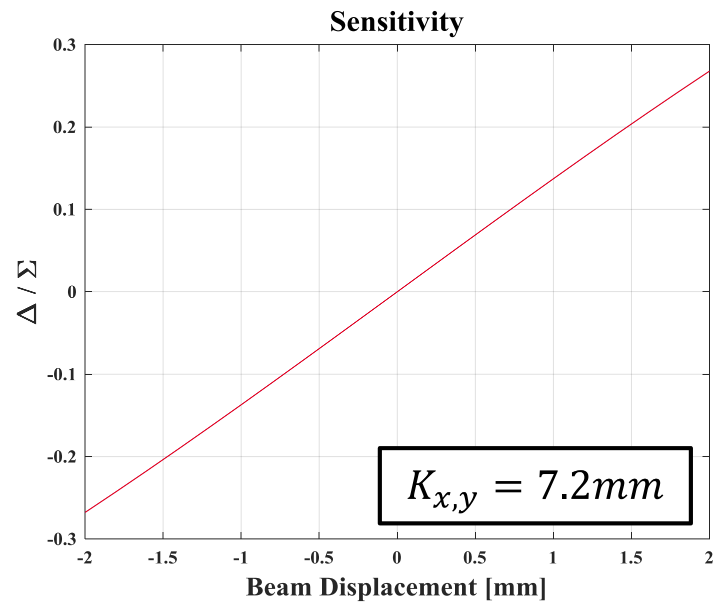
PETRA IV: BPM Pickup Assumptions

- beam pipe
  - round, Ø 20 mm
    - → monitor constant, first guess: $K_{x,y} = \sqrt{2}\,\frac{R}{2}$ → $K_{x,y} = 7.1$ mm
- BPM button
  - diameter Ø 8 mm
    - → boundary element method

APS-MBA upgrade: Ø 8mm
X. Sun et al., Proc. IBIC 2017, TUPCF03
ESRF-EBS: Ø 6 / 8mm
K. Scheidt, Proc. IBIC 2014, TUPF14





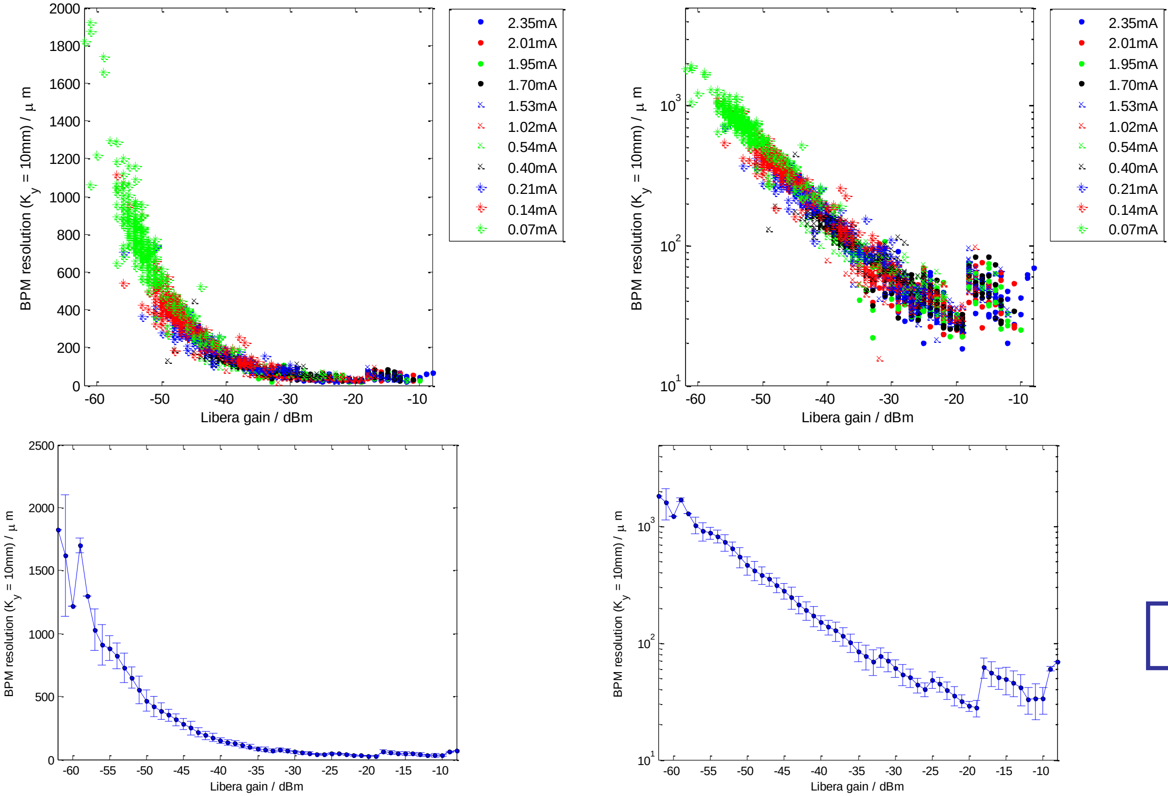


- resolution target

→ $RMS_{x,y} \approx 10\ \mu m \quad @ \quad K_{x,y} = 10mm$

PETRA IV: TbT Single Bunch Resolution

- machine studies at PETRA III
  - Libera Brilliance



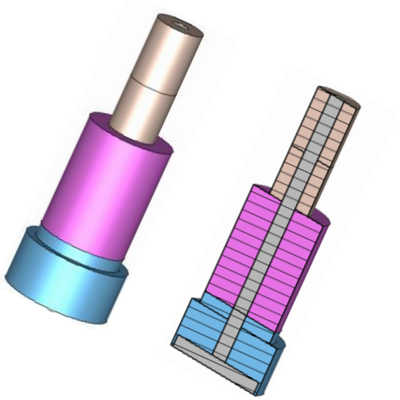
$\min(RMS_{x,y}) \approx 30\ \mu\text{m}$

→ Libera Brilliance resolution not sufficient for PETRA IV

- CDR: rely on Libera Brilliance+

PETRA IV: BPM Future Work

- button design
  - recently started with CST simulations
  - *S. Strokov* (TPU, Russia) and *D. Lipka* (DESY)
    - → talk D. Lipka



- offset, calibration, …
  - PETRA III strategy
    - → buttons electrically checked beforehand and grouped in pairs
    - → no electrical offset determination
    - → no fiducial marks on pickups

    } checked with beam (BBA)
  - PETRA IV
    - → have to be more cautious !!! (otherwise no circulating beam)
    - → el. offset: so far assumed to use ***Lambertson method*** (thanks to Kees for raising the issue…)
    - → hope to benefit from experience of others…

- heat load (HOMs)
  - will be an issue for all monitors coupling capacitive/inductive
    - → bad experience from PETRA III (damaged FCTs)