Considerations for PETRA IV

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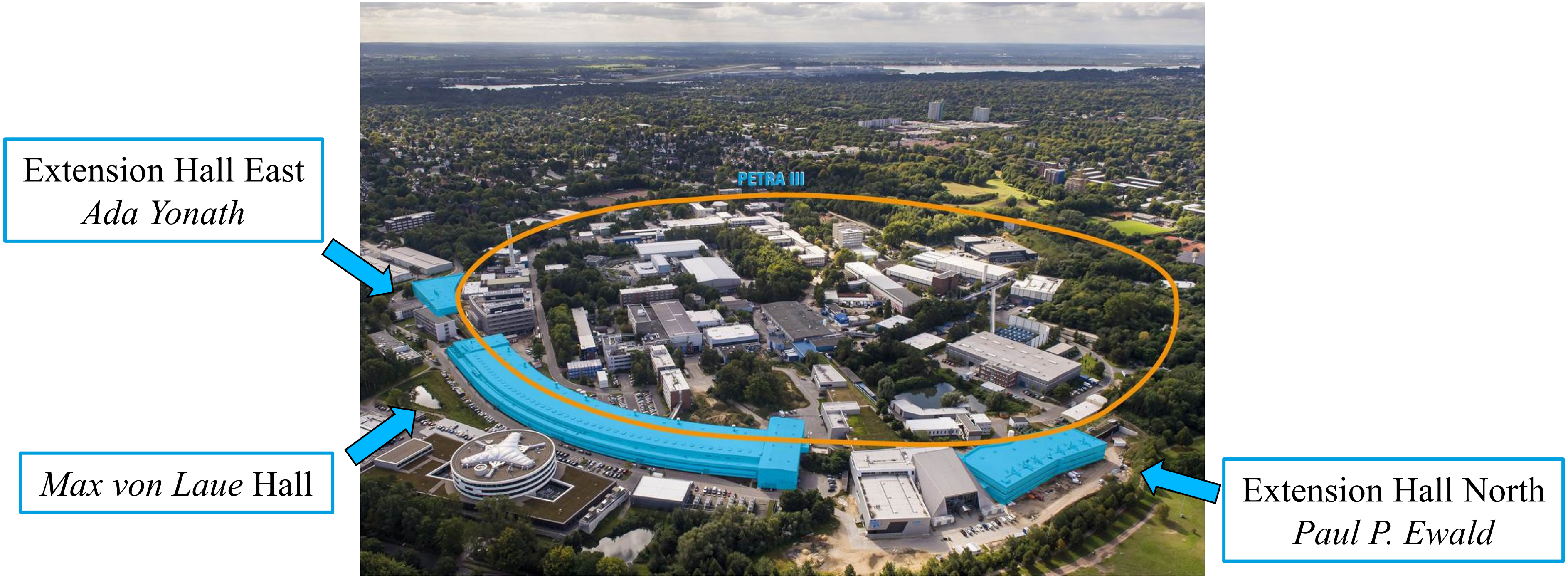
DESY (Hamburg)

- Introduction
- Overview and Particularities of PETRA IV
- Beam Instrumentation
- MDI Tasks for TDR Phase

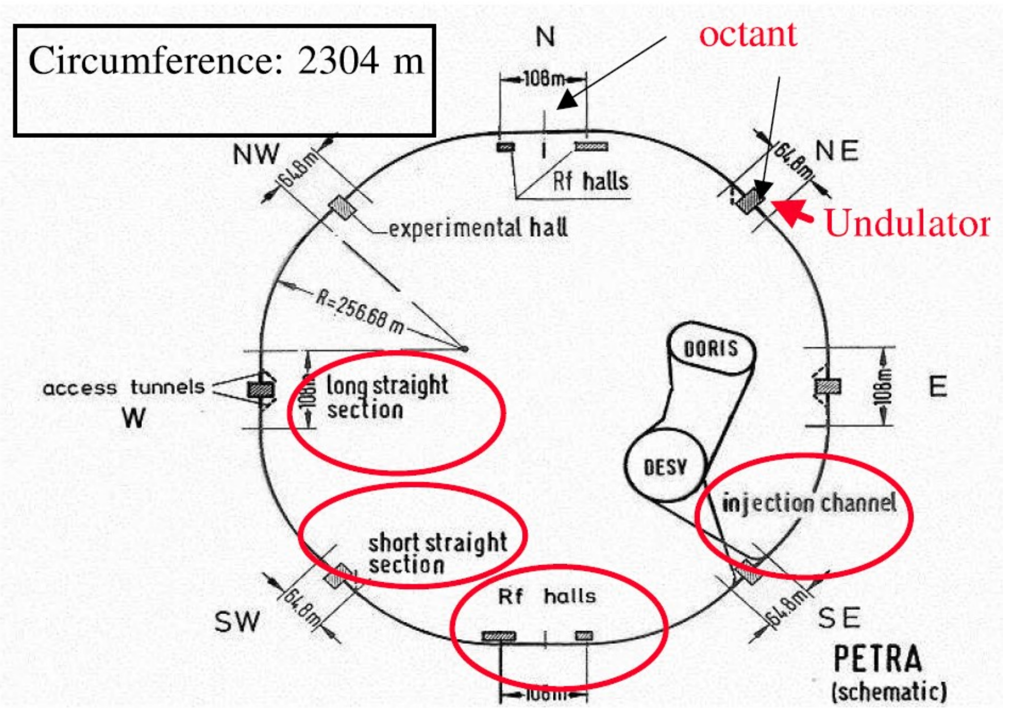
PETRA III @ DESY

- 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



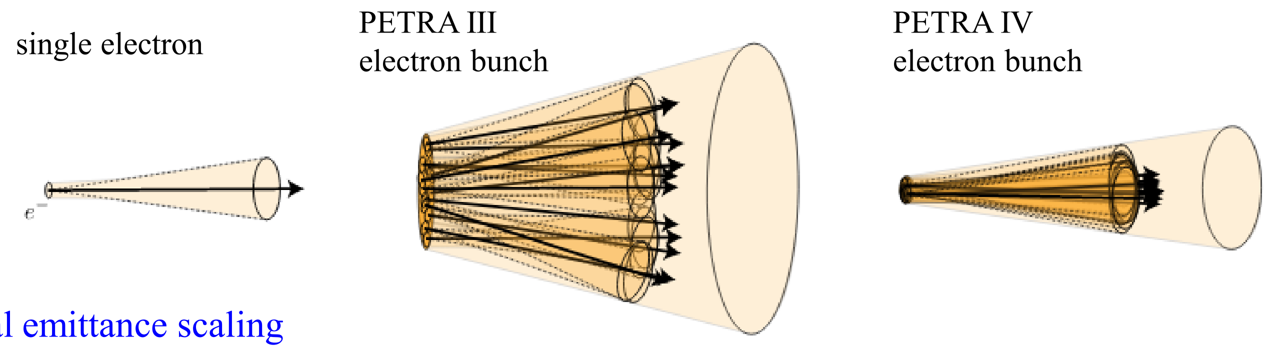
- PETRA III concept
  - one octant with DBA lattice
    - → 9 cells / arc, L_{DBA}=23 m
      (P3X: 2 additional DBA cells in 2 octants)
  - canted undulator beamlines: (14 out of possible 26)
    - → canting angles 5 / 20 mrad
  - remaining part: FODO lattice + dispersion suppressors

➡ **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



- natural emittance scaling

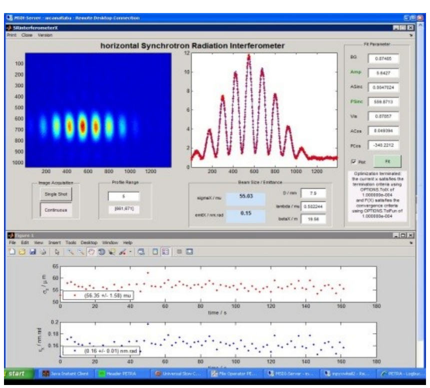
$$\varepsilon_x \propto \gamma^2 \theta^3 \Gamma$$

$\gamma = E/m_0c^2$ 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

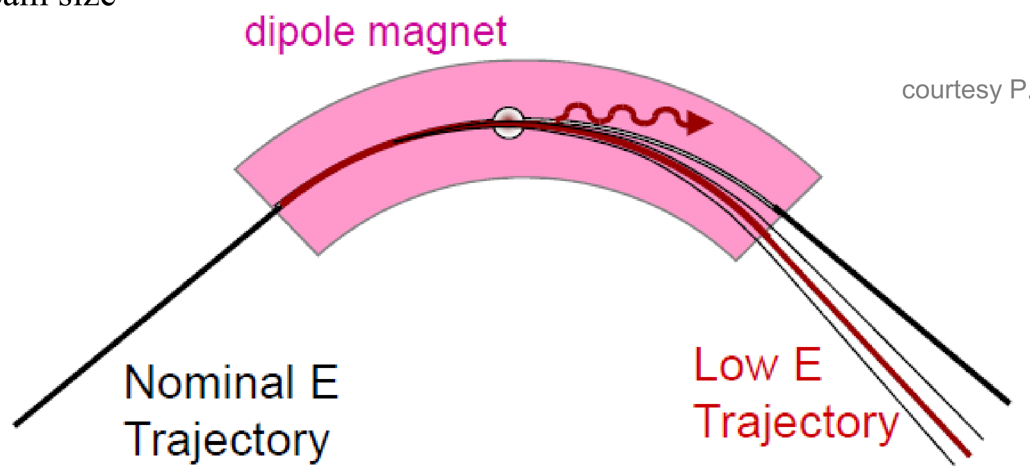
(SIRIUS, ESRF-EBS, DLS, …)

➡ PETRA IV

Beam Dynamics in Presence of SR

- quantum excitation
  - radiation is emitted in discrete quanta
  - number and energy distribution etc. of photons obey statistical law

    → increase in beam size



courtesy P. Castro (DESY)

- dispersion D(s)
  - characterizes energy-dependent offset
  - particle bending in horizontal direction (planar accelerator)

    → in principle: no vertical dispersion, but…

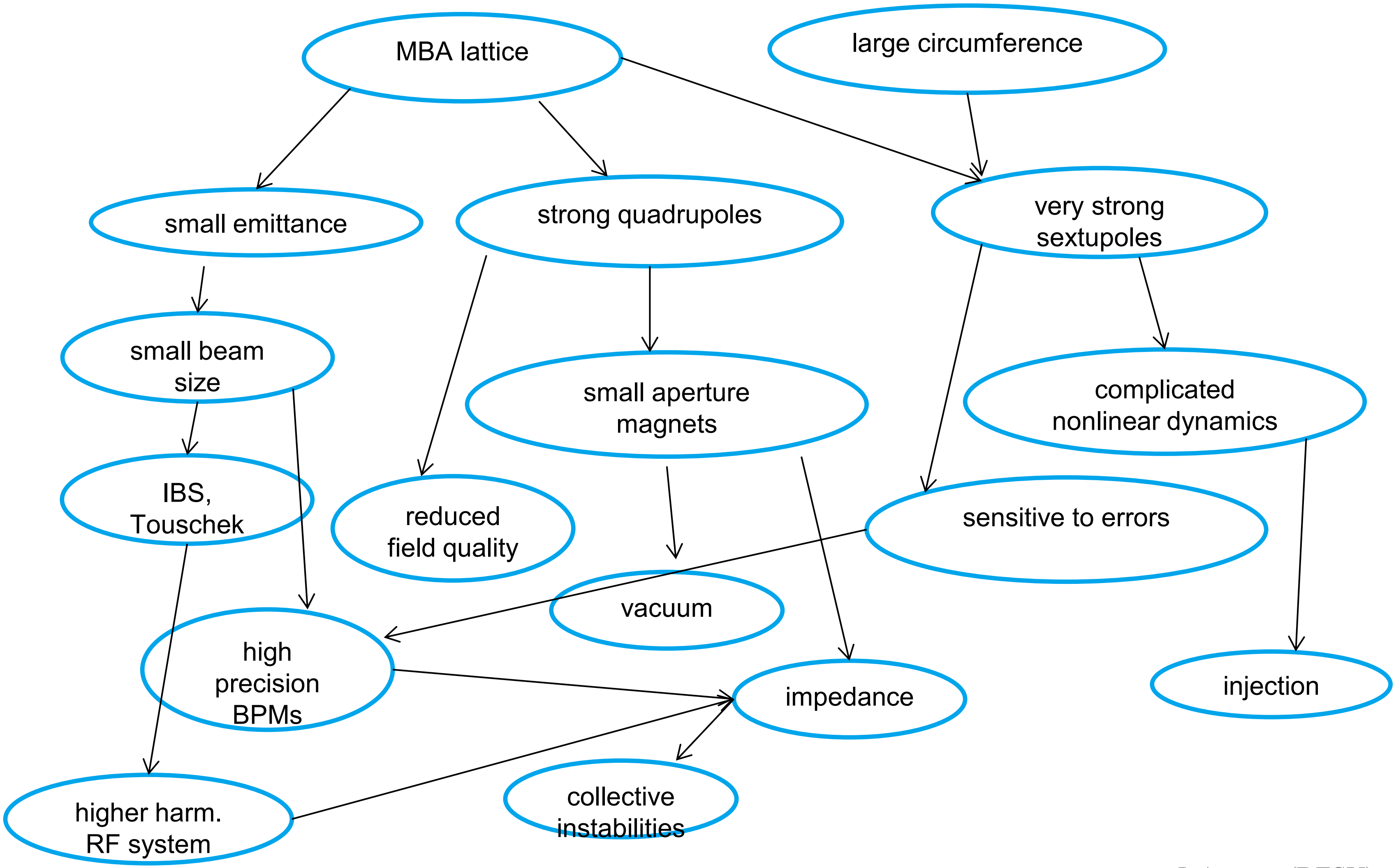
    spurious dispersion (coupling due to misalignment, …)

- small emittance
  - short dipoles

    → reduced q.e. contribution
  - keep dispersion small

    → strong focusing

DLS Design



courtesy: I. Agapov (DESY)

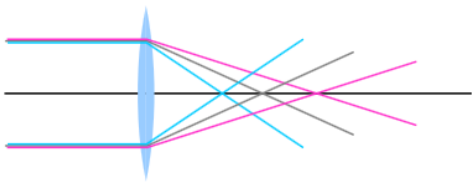
Engineering Challenges

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

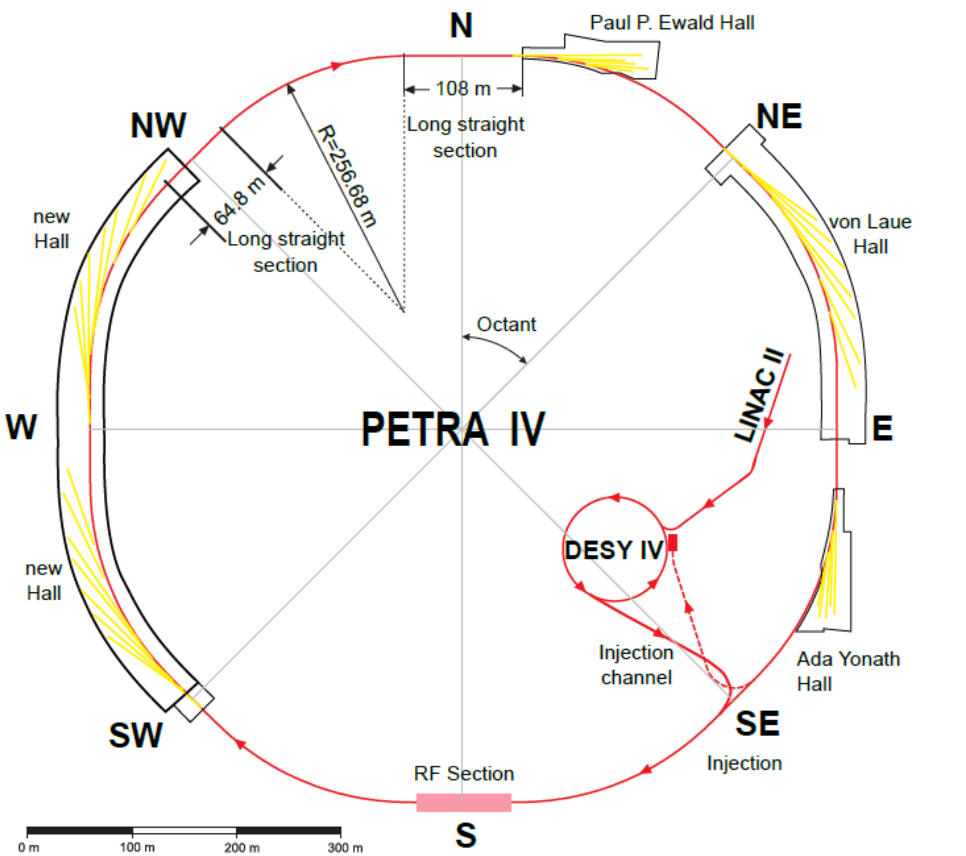
- high orbit stability
  - pushing technology of

    → ***beam diagnostics***

    → ***fast feedback systems***, …

PETRA IV: 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: Parameters

- parameters according to CDR

Parameter	Value (IDs open)	Value (all IDs closed)[1]
Energy E	6 GeV	6 GeV
Circumference C	2304 m	2304 m
Natural emittance ϵ_0	17.4 pm rad	7.6 pm rad
Tunes Q_x, Q_y	164.18, 68.27	164.18, 68.27
Momentum compaction factor α_p	1.485×10^{-5}	1.485×10^{-5}
Natural chromaticities ξ_{x0}, ξ_{y0}	−229.9, −185.1	−229.9, −185.1
Chromaticities ξ_x, ξ_y	+5, +5	+5, +5
Damping partition number J_x	1.536	1.175
Damping times τ_x, τ_y, τ_s	45.6 ms, 70.0 ms, 47.8 ms	19.5 ms, 22.9 ms, 12.6 ms
Rel. energy spread σ_E	0.678×10^{-3}	0.903×10^{-3}
Bunch length σ_s	1.24 mm	1.52 mm
Bunch length σ_t	4.14 ps	5.07 ps
Energy loss per turn U_0	1.317 MeV	4.024 MeV
RF voltage V_{RF}	6 MV	8 MV
Bucket half height $\Delta p/p$	8.7 %	7.1 %
Synchrotron frequency f_s	387 Hz	421 Hz
Hor. beta function β_x at ID	6.86 m	6.86 m
Ver. beta function β_y at ID	2.36 m	2.36 m
Hor. dispersion function D_x at ID	0 m	0 m
Space L for ID	5 m	5 m

[1] For the insertion devices, a 5 m long U32 undulator with a peak field of 0.91 T was assumed.

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: →

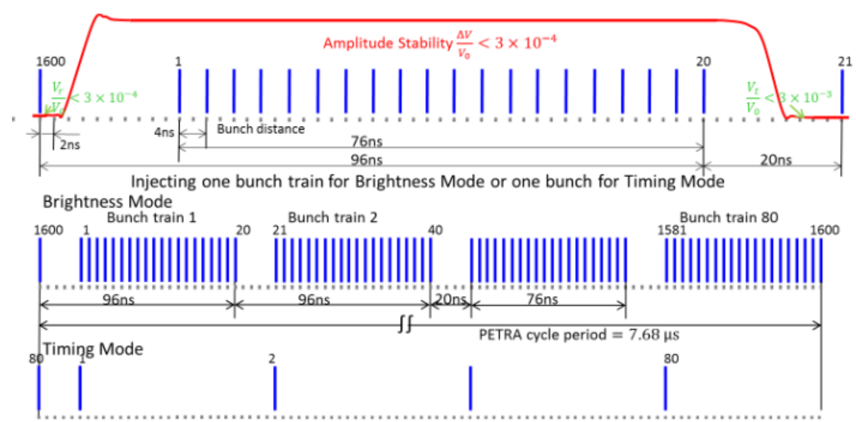
× 65 smaller ε_x

brightness mode **timing mode**

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

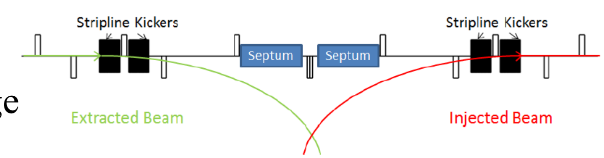
    → 80 × 96 ns = 7.68 µs = T_{rev}
  - **brightness mode** → *Bunch Train* = 20 bunches

    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

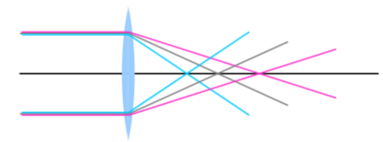


  - max. intensity variation < 10%

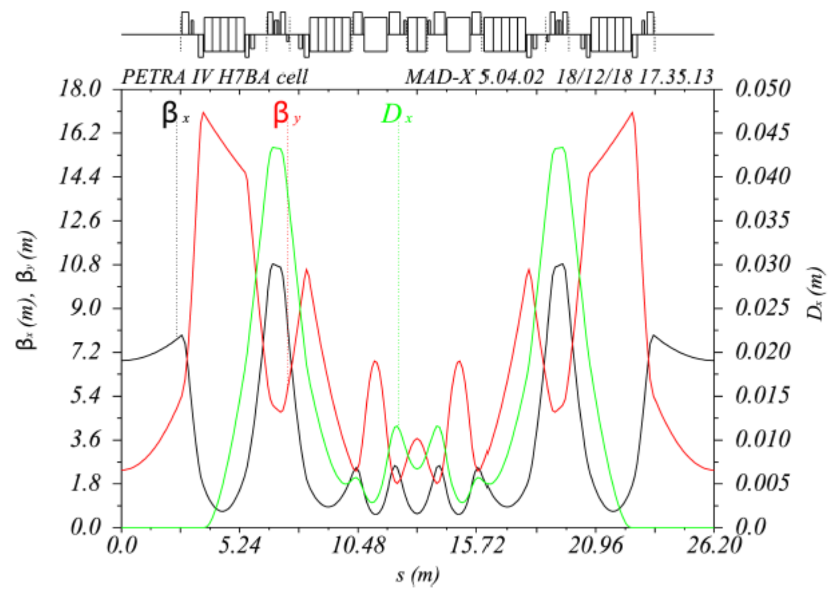
    → injection rate 0.5 Hz (timing mode)

PETRA IV 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

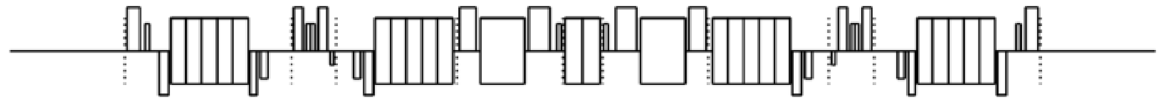


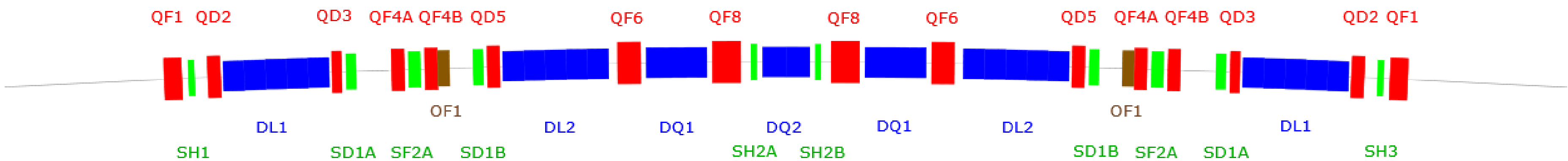
  - cell length $L_{HMBA} = 26.2$ m (PETRA III: $L_{DBA} = 23$ m)
    - → beamline configuration of PETRA III cannot be preserved
    - → 8 HMBA cells / arc ➡ 64 HMBA cells
  - further emittance reduction via reverse bends → in discussion

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

PETRA IV Lattice (2)

- layout of PETRA IV achromat





dipole → bending

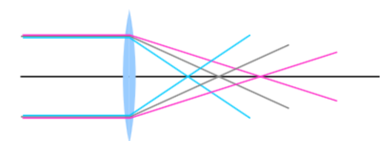
quadrupole → focusing / defocusing

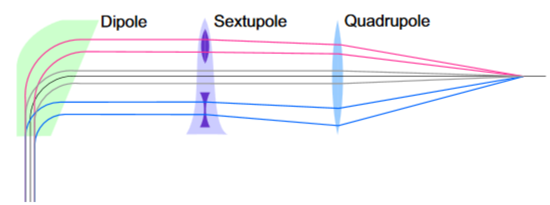
sextupole → „chromatic": chromaticity correction (located in region of high D)

„harmonic" : minimize resonance driving modes (even in region of D=0)

free tuning knob for non-linear beam dynamics

octupole → compensate higher-order non-linear effects





- special magnets
  - DQ1, DQ2
    → combined function magnets (dipole + quadrupole)
  - DL1, DL2
    → longitudinal gradient dipole magnet (5 parts with equal lengths)
  - QF6 & 8
    → high gradient quads
    g = 87.9 T/m; 92.4 T/m

PETRA IV: Lifetime and RF System

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

    → depends on particle density in bunch
  - acceptable Touschek lifetimes

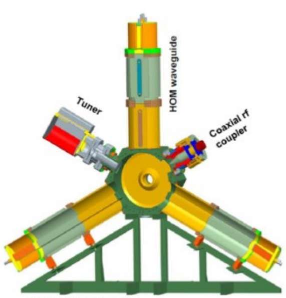
    → bunch lengthening required

    → 3^{rd} harmonic cavity system

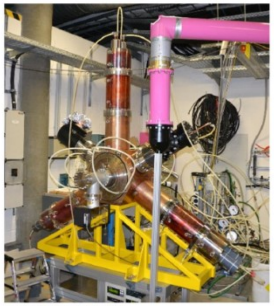
- RF system → fundamental RF frequency f_{RF} = 499.665 MHz (500 MHz)
  - from PETRA III to PETRA IV

    → decrease of (i) energy loss / turn: ***4.66 MeV*** → ***4.02 MeV***, (ii) $\alpha_p = \boldsymbol{1.20 \times 10^{-4}}$ → $\boldsymbol{1.485 \times 10^{-5}}$
  - 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

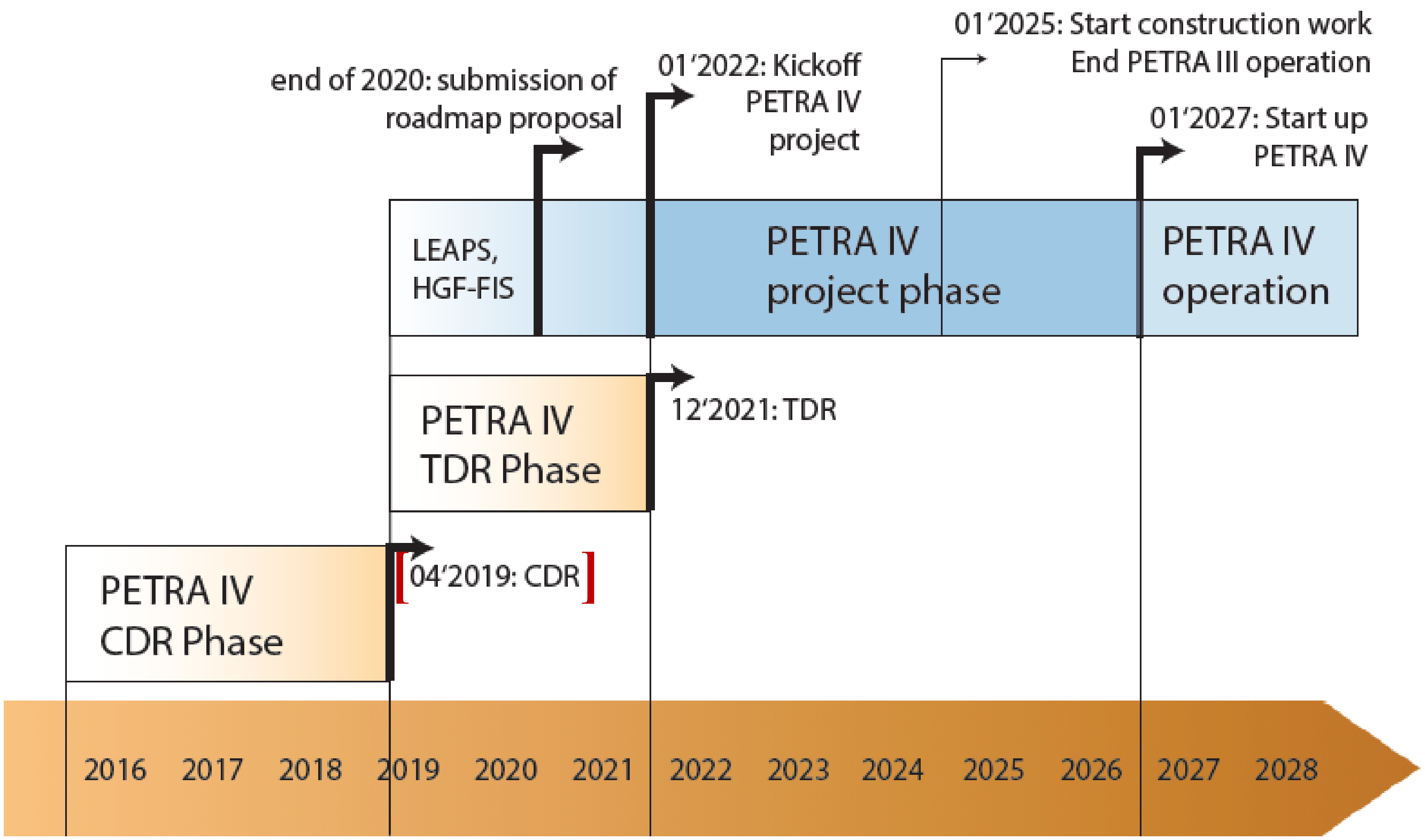
→ 24 single cell cavities

- 3^{rd} harmonic system

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

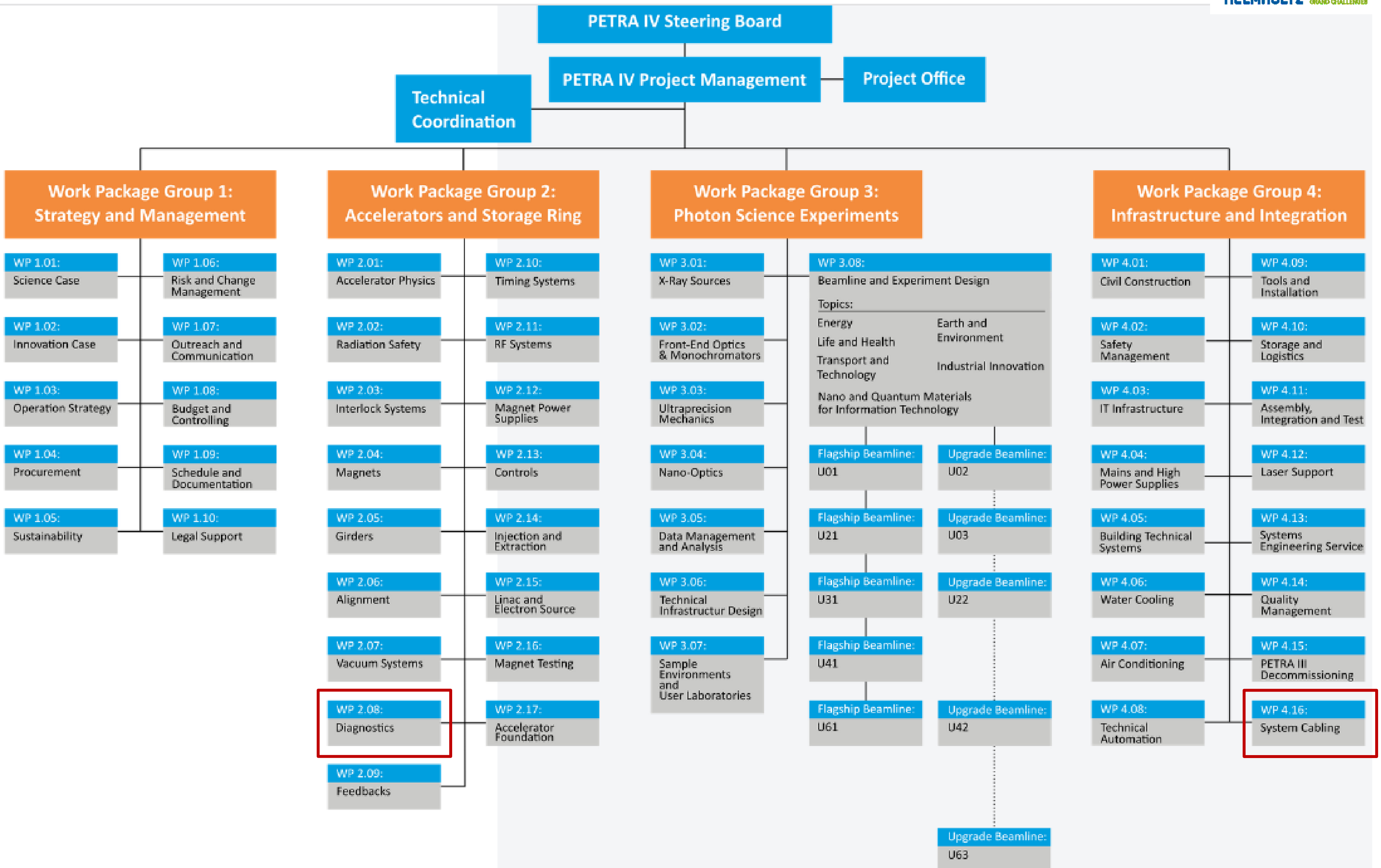
  → active system seems to be essential

PETRA IV: Timeline

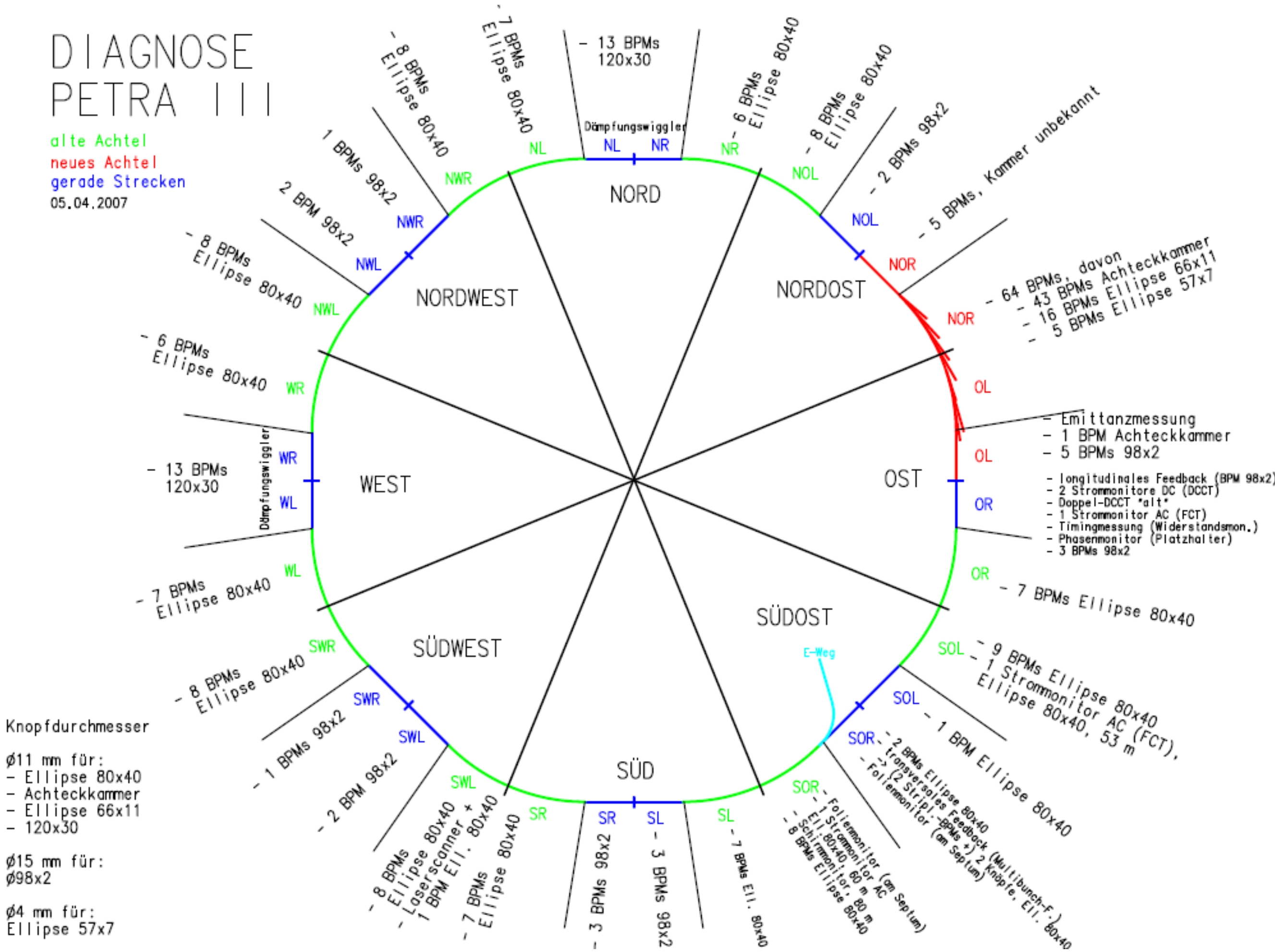


- presently: *Conceptual Design Report* finished, phase of *Technical Design Report* started

PETRA IV: WP Structure



PETRA III Instrumentation



PETRA III:

- 249 Button-type BPMs
  - → 246 for Orbit
  - → 248 Libera Brilliance
- 6 current monitors
- 2 Stripline-BPMs and 2 Button-BPMs for Multibunch Feedback
- 1 Button-BPM for longitudinal Feedback
- 1 Laser Wire Scanner
- 3 Beamlines for Profile and Emittance Diagnostics
- 3 Screens

Transfer Lines:

- 20 BPMs
- 10 Current Monitors
- 4 Wall Gap Monitors
- 11 Screens

later stage:

- beam losses
- bunch purity

PETRA IV Instrumentation

- PETRA IV storage ring
  - in principle the samy type of systems, but…
  - e-BPMs
    - → better resolution (TbT, closed orbit)
    - → better methods for long-term stabilization
    - → increase in number of devices (factor 3 or more)
    - → complicated infrastructure (cable trays, …)
  - HF-MOMOs
    - → overhaul / standarize technical platform
    - → higher update rate (?)
    - → less sensitive on environmental influence (?)
  - transverse emittance
    - → vertical beam size close to PETRA III
    - → better sensitivity on small sizes + stability
  - bunch length
    - → with 3rd harmonic cavities similar → re-use streak camera
  - beam current (DCCT & FCTs)
    - → heat load (HOMs) more critical
  - MPS & machine safety
    - → extended BLM system (based on XFEL)
    - → extended temperature measurement system
    - → online dosimetry (based on XFEL)

➡ requires overhaul and standarized technical platform

  - parasitic bunches, photon-BPMs
    - → no MDI task @ PETRA III, PETRA IV ???

- injector chain
  - e-BPMs
  - beam current (DCCT & FCTs)
  - screens
  - emittance diagnostics

MDI and PETRA IV: TDR Phase

- TDR phase: 01/2020 → 12/2022
  - demonstrate technical realization
  - cost estimate
  - documentation → Technical Design Report (TDR)

- draft version for description of WP 2.08: tasks and personnel (FTEs)
  - based on monthly assignment of employees to cost centers
    - → presently under discussion, not yet finished ➡ no names
  - announcement of „team / project“ leaders (responsible persons) will come soon
    - → leaders will define their teams (in accordance with group / WP leadership)
    - → definition of milestones (for TDR phase)

- tasks

Workpackage leader
G. Kube
K. Wittenburg (deputy)

BPMs pre-accelerators
3.3 FTEs

BPMs for PETRA IV
5.9 FTEs

Infrastructure

Screens
0.6 FTEs

Emittance
3.9 FTEs

MDI and PETRA IV: TDR Phase (2)

Beam Current

2.3 FTEs

HF-MoMo

0.4 FTEs

MPS

0.8 FTEs

BLMs

3.5 FTEs

Temperature Measurement

0.3 FTEs

Dosimetry

0 FTEs

Parasitic Bunches

➡ amount of FTEs: 22.5

➡ new FTEs: 9 (3 new positions)