• Conceptual Ideas, Physics Case
• Design Strategy, Status of the Lattice Design
• Technical Implications

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DESY - MPE -

7th Low Emittance Rings Workshop
Jan 15-17, 2018
CERN, Geneva
PETRA IV – conceptual ideas

Parameters and parameter range, status February 2016:

<table>
<thead>
<tr>
<th>PETRA IV Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>5 GeV</td>
</tr>
<tr>
<td></td>
<td>(4.5 – 6 GeV)</td>
</tr>
<tr>
<td>Current</td>
<td>100 mA</td>
</tr>
<tr>
<td></td>
<td>(100 – 200 mA)</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>~ 1000</td>
</tr>
<tr>
<td>Emittance</td>
<td>horz. 20 pm rad</td>
</tr>
<tr>
<td></td>
<td>vert. 20 pm rad</td>
</tr>
<tr>
<td>Bunch length</td>
<td>~ 100 ps</td>
</tr>
</tbody>
</table>

Goals:
2024 Start construction
2026 Start up PETRA IV
Understanding the Complexity of Nature

Bright, Tailored X-Rays
3D imaging on all length scales
spatially resolved properties:
chemical, mechanical, electronic, magnetic

structure and dynamics of biological molecules
dynamics in disordered systems
tracking of physical/chemical processes (nano seconds to days)

Closing the Gaps in the Complexity Window

1 pm 1 Å 1 nm 1 μm 1 mm

diffraction imaging

close mesoscopic gap!
diffraction-limited source: fusion of real and reciprocal space

PETRA III
PETRA IV

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Understanding the Complexity of Nature

Closing Gaps in the Time Domain of Complexity

XFEL and PETRA IV are complementary
Closing the Gaps in the Complexity Window

Bohr radius of the hydrogen atom: 0.053 nm

Photon emittance:
\[ \Delta x \cdot \Delta \theta \geq \frac{\lambda}{4 \pi} \]

Diffraction limited source \( \leftrightarrow \) beam emittance \( \sim \) photon emittance

8 pm \( \sim \) vert. emittance of PETRA III

PETRA IV: horz. emittance in the range of the vert. emittance of PETRA III

Diffraction-limited source: fusion of real and reciprocal space

PETRA IV

Photon emittance:
\[ \epsilon_{\lambda} = \frac{\lambda}{4 \pi} = \frac{1}{2} \frac{\hbar c}{E_{\lambda}} \]

\[ \epsilon_{\lambda} = 8 \text{ pm} \quad \text{for photons} \quad 0.1 \text{ nm} \quad \text{or} \quad 12.3 \text{ keV} \]
Brilliance

Brilliance: $> 10^{22}$ Photons / (sec mrad$^2$ mm$^2$ 0.1 % BW) 

$$B_n = \frac{F_n}{4\pi^2 \Sigma_x \Sigma_x' \Sigma_y \Sigma_y'}$$

angle integrated photon spectral flux (undulator, beam intensity)

photon beam convoluted with the electron beam

$$\Sigma_{x,y} = \sqrt{\sigma_{x,y}^2 + \sigma_\lambda^2}$$
$$\Sigma_{x,y}' = \sqrt{\sigma_{x,y}^2 + \sigma_\lambda'^2}$$

PETRA III
$$\varepsilon_x = 1.2 \text{ nm, } \kappa = 0.25 \%$$
$$\beta_x = 10 \text{ m, } \beta_y = 2.5 \text{ m}$$

PETRA IV
$$\varepsilon_x = 15 \text{ pm, } \kappa = 100 \%$$
$$\beta_x = 5 \text{ m, } \beta_y = 2.5 \text{ m}$$

PETRA IV
$$\varepsilon_x = 10 \text{ pm, } \kappa = 50 \%$$
$$\beta_x = 1 \text{ m, } \beta_y = 1 \text{ m}$$

(Courtesy Markus Tischer)
Design Strategy

**Lattice Design**

- Design goal: get an large dynamic acceptance  
  (ideal case: off-axis injection is possible)
  - design based on a hybrid seven bend achromat (scaled from ESRF-EBS cell)
  - option for the arc cells without undulators
    - cell with phase advance of $\pi$ between sextupoles, double -I cell
      (first approach with: double twist in 4D-phase to enable chromatic correction in both planes)

**Injectors**

- Design goal: reuse most parts of injector chain
  - studies to improve emittance, including a new lattice for the synchrotron
  - investigation of the technical requirements to maintain operation until 2045
  - studies toward a new injector: additional booster ring, or linac

**Technical design**

- Investigation of the technical limits and possibilities at an early stage before a lattice design is finalized
  - magnet design: design studies of quads, sextupoles, combined function magnets and dipoles with longitudinal gradient
  - girder design: investigation of concepts with new materials, studies of alignment and installation concepts
  - vacuum design: modeling of the system with small chambers
  - fast kickers: on axis injection
PETRA IV – Lattice design status

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PETRA III (DW)</th>
<th>H7BA 25.2 m (DW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total current</td>
<td>100 mA</td>
<td>100 mA</td>
</tr>
<tr>
<td>Nat. emittance $\varepsilon_0$  (with DW)</td>
<td>5100 pm (1280 pm)</td>
<td>15 pm (9.3 pm)</td>
</tr>
<tr>
<td>Energy spread $\sigma_p$ (with DW)</td>
<td>$0.82 \cdot 10^{-3}$ ($1.23 \cdot 10^{-3}$)</td>
<td>$0.73 \cdot 10^{-3}$ ($1.44 \cdot 10^{-3}$)</td>
</tr>
<tr>
<td>Energy loss/turn $U_0$ (with DW)</td>
<td>1.3 MeV (5.1 MeV)</td>
<td>1.37 MeV (4.6 MeV)</td>
</tr>
<tr>
<td>Momentum compaction factor $\alpha_c$</td>
<td>$1.13 \cdot 10^{-3}$</td>
<td>$1.46 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>Max. gradient $g$</td>
<td>17 T/m</td>
<td>100 T/m</td>
</tr>
<tr>
<td>Dispersion $D_x$ at SF</td>
<td>750 cm</td>
<td>4.2 cm</td>
</tr>
</tbody>
</table>

“Reference Lattice”

Hybrid Seven Bend Achromat scaled and adopted from ESRF-EBS
8 cells / arc (cell length: 25.2 m / new version ~ 26 m),
injection in one long straight section,
damping wigglers in another straight section
PETRA IV – Reference lattice, H7BA

- RF: 500 MHz, 6 MV, bucket height=3.3%
- \( A_x = 1.35 \text{ mm} \cdot \text{mrad} \) Dynamic acceptance
- \( A_y = 1.24 \text{ mm} \cdot \text{mrad} \) (6 D tracking, no errors)

- an on axis injection seems to be required for a safe injection (with errors)

Nat. emittance \( \varepsilon_0 = 9.3 \text{ pm} \)

Sensitivity to errors (2 \( \mu \text{m} \) rms, all magnets, no correction):

The DA is reduced by a factor 2 with respect to the ideal one
Intra beam scattering

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Continuous mode</th>
<th>Timing mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total current</td>
<td>100 mA</td>
<td>100 mA</td>
</tr>
<tr>
<td>Bunches</td>
<td>960</td>
<td>80</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.77 nC</td>
<td>9.6 nC</td>
</tr>
<tr>
<td>Emittance (horz.)</td>
<td>20 pm</td>
<td>50 pm</td>
</tr>
<tr>
<td>(vert.)</td>
<td>2 pm</td>
<td>5 pm</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$1.5 \cdot 10^{-3}$</td>
<td>$1.7 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>Touschek Lifetime</td>
<td>3.9 h</td>
<td>0.4 h</td>
</tr>
</tbody>
</table>

Intra beam scattering: Multiple Coulomb scattering, theory by A. Piwinski (1974)

$$\frac{1}{\tau_x} = \left\langle A \left[ f(1/a, b/a, q/a) + \frac{D_x^2 \sigma_h^2}{\sigma_x \sigma_p f(a, b, q)} \right] \right\rangle$$

$$A \sim \frac{N_0}{\gamma^4 \epsilon_x \epsilon_y \sigma_s \sigma_p}$$

- Using 1920 bunches (not equally spaced) would imply
  - 200 mA operation with the same parameters or
  - 100 mA operation with an emittance of 16 pm
- First estimates indicate that the total current in the timing mode will be only 80 mA due to collective effects
PETRA IV – Lattice design, beyond the H7BA

1. -I Schemes

- Twist-lattice
- non interleaved double –I cells

potential for larger transverse acceptance

seems to be limited for rings with $\varepsilon_x \sim 30 \text{ pm (nat. emittance)}$
(non local chromatic correction)

2. FODO type lattice in octants with no undulators

first investigations did not lead to a satisfactory solution

Two cell types: Non interleaved double –I cell (on IDs), H7BA (cells with IDs)

Reduced sextupole strength in the H7BA

⇒ larger DA $\sim 4 \text{ mm mrad (factor 2.8 better)}$
less sensitive to errors
off axis injection seems to be possible
PETRA III/IV Injectors

Design goal: reuse/up-grade the injector chain

Linac
S-Band Linac (450 MeV)

PIA (accumulator ring)
10 ns Linac pulse → 500 MHz bucket

DESY II
450 MeV → 7 GeV,
Emittance (6 GeV) x/y ~ 350/15 nm
Intensity: max. 2 x 10^{10}, typical 1 x 10^{10}

Studies have started on the possibilities to improve the booster emittance

→ With beam optics optimization + damping partition shift of present optics one may get ∼200nm @6GeV

→ Rebuilding ring with smaller emittance lattice: DESY IV

scaling the ALBA booster → 10 nm @6GeV
Injector options

Accumulation in the (y-) plane of smaller emittance from injector
(Similar concept pursued at HZB/BESSY2, P. Kuske, Proc. IPAC 2016)

- Either inject vertically into PETRA ring or perform a 90 deg x-y phase space twist in the transfer line
- On-axis injection with ~200 nm emittance no problem

\[
10 \sqrt{15 \text{ pm}} \ 100 \text{ m} + 3 \text{ mm} + 3 \sqrt{15 \text{ mm}} \ 60 \text{ m} = 6.2 \text{ mm}
\]

\[
0.38 \text{ mm mrad} = \frac{(6.2 \text{ mm})^2}{100 \text{ m}}
\]

\[
A_x = 1.3 \text{ mm mrad} \Rightarrow A_x = 0.65 \text{ mm mrad (2 \mu m errors)}
\]
Joint meeting: photon science and accelerator physics

PETRA IV Workshop in Jesteburg, July 12-13, 2017

Sessions:
- Science Case and Lattice Design Status
- Brilliance and Flux
- Design and Technical Implications (Accelerator)
- Design and Technical Implications (Photon Beamlines)
The workshop at Jesteburg has addressed several issues which can only be solved in a close collaboration between beamlines and accelerator physicist. Progress was made concerning:

- Matching electron beam and photon beam
- Effect of canting of beam lines
- Beam divergence and energy spread
- Beam line requests / requirements

- A horizontal beta function of about 5 m is acceptable but not optimal, make use of the long straight section to implement low beta sections (beta ~ 2 m) for IDs

- Small canting angles may require new monochromator and mirror developments

- The brilliance and the beam divergence is strongly affected by the energy spread

- Further challenges for the lattice design and the stability of the beam: individual beta functions at different IDs, stability 2 % of the beam size
Canting of the beam lines

First study, assuming:
- maintaining the symmetry of the H7BA lattice cell
- canting of all cells with IDs (2 x 2 x 7 = 28)

Parameters of the undulators:
- $B_{ID} = 1$ T, $\lambda_{ID} = 18$ mm, $N_{ID} = 111$ periods, $L = 2$ m

- Canting without IDs has almost no influence on the emittance
- Without canting, without IDs: 15 pm·rad
- Emittance reduced by 50% when adding IDs (7.5 pm·rad)

(nat. emittance no DW, no IBS)

- 2 mrad canting angle is acceptable, (15 pm instead of 7.5 pm)
- Canting can be implemented as a 3 bump

→ specially designed cells allow larger canting angles ~ 4 mrad

- two octants: 2 x (7+1) = 16 beam lines
- two extensions: 2 x (2x2 + 1) = 10 beam lines

Undulator beam lines (total) 26 beam lines

2 = canting, 1 = straight section (low beta)
Technical Implications

Design Strategy

- Investigation of the technical limits and possibilities at an early stage before a lattice design is finalized

- Collaboration with Efremov Institute magnet design of high gradient magnets
- Contacts to industry (Thyssen Krupp) concerning magnet materials
- Collaboration with Alfred Wegener Institute master thesis on bionic girders, Ph. D. student has started in Dec. 2017

- Simulation of synchrotron radiation in small gap chambers using: MAX IV chamber profile + NEG
- Plans for an experiment at PETRA III

- 500 MHz or 100 MHz (option 125 MHz) System
- Collaboration with Technische Universität Darmstadt, TEMF
Technical concepts: Magnets, Girders

- Collaboration with Efremov Institute compact magnet design of high gradient magnets
- Contacts to industry (Thyssen Krupp) concerning magnet materials
- Building of prototypes QHG20 with different materials (summer 2018)

- Design study for Sextupole magnets presently factor 2.5 stronger as ESRF-EBS
- Collaboration with Alfred Wegener Institute: Bionic Lightweight Design of Girders

The AWI explores the principles that turn the exoskeletons (shells) of unicellular planktonic organisms into extremely light and stable constructions. (https://www.awi.de/en/science/special-groups/bionics.html)

QHG20

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>QHG20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air gap</td>
<td>mm</td>
<td>20</td>
</tr>
<tr>
<td>Field gradient, G</td>
<td>T/m</td>
<td>149.7</td>
</tr>
<tr>
<td>Field quality at R= 0.6a</td>
<td></td>
<td>3.7x10^-4</td>
</tr>
<tr>
<td>Core length</td>
<td>mm</td>
<td>200</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td></td>
<td>56</td>
</tr>
<tr>
<td>Number of coils</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Nominal current</td>
<td>A</td>
<td>200</td>
</tr>
<tr>
<td>Conductor</td>
<td>mm</td>
<td>6x6-d3.5</td>
</tr>
<tr>
<td>Total weight</td>
<td>kg</td>
<td>250</td>
</tr>
</tbody>
</table>
Vibrations measurements

Test set-up established

- Magnet Support/Girder
  - Resonances > 55Hz
- Bionic, Light & Stiff
  - Collaboration with AWI, Bremen

- Measurement Equipment
  - Common Software
  - Common Database
  - Ad-Hoc Analysis
  - Different Sensors
    - Seismometer, Geophones, Piezo Sensors

Will be ready 2018

1t test mass with adjustable feet and shaker attached, Alu test plate. Seismometer, Geophones (two types bigger yellow, smaller red/yellow),
**Vacuum System**

**Experience at PETRA III:**
80 m of damping wigglers with NEG coated low gap chambers

**Simulations have started based on MAX IV and ESRF-EBS vacuum systems**

MAX IV chamber profile + NEG ($56 \frac{l}{s\, m}$ at tube $\Theta 15\, mm$)

- $<2 \cdot 10^{-12} \frac{mbar}{mA}$ for activated NEG (20 Ah)
- $<5 \cdot 10^{-12} \frac{mbar}{mA}$ for activated NEG (1 Ah)
- $\sim 1 \cdot 10^{-6} \frac{mbar}{mA}$ for unactivated NEG (1 Ah)

**Activities for PETRA IV:**
- simulation of synchrotron radiation in small gap chambers including the reflectivity of the NEG material
- calculation of gas desorption
- pressure profiles
- plans for an experiment in 2018

- Install NEG-coated chambers in standard arc-section in PETRA III
  - Sputter coat standard dipole chambers

**To study:**
- Self-activation by hitting chamber walls with photons possible?
- How fast this will provide sufficient pressure level?
- Conditioning of vented section?
RF System

Two variants are considered

500 MHz or 100 MHz (option 125 MHz) System

Cavities:

500 MHz single cells

100 MHz single cells, based on MAX IV design

Collaboration with
Technische Universität Darmstadt, TEMF
Herbert De Gersem, Wolfgang Ackermann

Cavity parameters, HOM calculations, etc.
Next steps

Lattice design:

- optimize the cell length with respect the tunnel geometry
- design of cells with canted IDs
- special low beta section in the straight sections
- investigation of lattice options (double –I cells)

Goal:

Summer 2018: Publication on the Design Status

First prototype of a high gradient quadrupole
Collaborations

- **ESRF**
  supporting the lattice design, sharing lattice files
  visit to ESRF (June), visitor (Simone Liuzzo) from ESRF at DESY (Aug.)

- **Mikael Eriksson**
  joined the PETRA IV project preparation as a generalist from June 2016

- **SLAC – DESY collaboration**
  visit to SLAC in Oct 2016 (host Bob Hettel)
  discussing on lattice theory, impedance and collective effects
  Yunhai Cai visited DESY in April 2017, **LEGO, lie algebra methods**

- **Efremov institute - DESY collaboration: magnet design**

- **Alfred Wegener institute - DESY collaboration: girder design**

- **Technical University of Darmstadt: RF calculation, 100 MHz cavity**
Thank you for your attention!