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PETRA IV STORAGE RING DESIGN

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Abstract

PETRA IV [1–5] will be a diffraction-limited 6 GeV synchrotron light source with an emittance of 20 pm rad at DESY Hamburg. The TDR phase is nearing completion, and the lattice design is being finalised. The lattice will be based on the six-bend achromat cell with extensive use of damping wigglers. The key challenges of the lattice design are finding the balance between emittance minimisation and non-linear beam dynamics performance, and adapting the lattice to a collider-type tunnel geometry of the PETRA facility, with the long straight sections and low degree of superperiodicity. We present the lattice design and the beam physics aspects, focusing on the beam dynamics performance and optimisation.

OVERVIEW

Lattice Design Goals and Constraints

The next generation of photon science experiments would greatly benefit from hard x-ray (10-50 keV) photon beams with a high degree of transverse coherence and brightness levels in excess of 10^{22} phot./mm/mrad/0.1%BW. These unprecedented levels of brightness and coherence are achieved by using improved undulator technologies such as cryogenic in-vacuum or superconducting devices, but first of all, by generating electron beams of extremely low (tens of pm rad) emittance. These levels are achievable in a 6 GeV synchrotron of 2.3 km circumference such as PETRA by employing the multi-bend achromat (MBA) lattices [6]. While theoretically very low emittances (in the pm range) are possible, the design parameters are set taking realistic constraints into account, that will be discussed further. Taking these constraints into account, the goals were set to deliver emittances of below 30 pm rad and beam currents of up to 200 mA. In PETRA IV, similar to PETRA III [7], only part of the lattice can be equipped with insertion devices. PETRA IV will feature a new experimental hall with additional beamlines significantly increasing the total space available for insertion devices (see Fig. 1). Outside of the experimental halls, i.e. for about half of the circumference, the machine should follow the existing tunnel. The tunnel has a width of only about 3.1 m, which together with the need for cables, escape routes, and other infrastructure elements, constrains the machine geometry transversely to an envelope of about 10 cm. PETRA III was designed to make most use of the limited number of ID straights. This was achieved by, first, having a short DBA ([8]) cell of ca. 23 m length that has sextupoles removed, with the chromaticity correction distributed to the FODO cells of the rest of the ring; and second, by extensively exploiting the so-called canting, i.e. operating two insertion devices in one straight, with a corrector magnet used to introduce an angle (of 1 mrad, 5 mrad, or 20 mrad depending on location) in the electron trajectory between two devices, thus separating the radiation cones and allowing multiple beam-lines per insertion straight section. While preserving the whole arrangement of source points is impossible when no significant emittance deterioration is allowed, many beam-lines can be kept, significantly simplifying the logistics when a ca. 23 m cell is adopted. For those several beam-lines that feature a 20 mrad canting angle, the dispersion generated in the straight is such that the influence of insertion devices on emittance is prohibitively strong. Canting angles larger than ca. 5 mrad are not compatible with the low emittance ring design. Only moderate technological advances wrt. e.g. achievable magnet gradients are permissible to allow project implementation in the nearest future with minimal R&D effort on magnet technology.

Key Challenges

The design objective of the PETRA IV lattice is to maximize the brightness delivered by a portfolio of insertion devices. As with all low-emittance ring designs, there is a number of trade-offs to be considered: The most significant technical limitation in the low emittance ring design is the maximum achievable quadrupole and sextupole strength. Without this limit (and neglecting any nonlinear dynamics limitations) the natural emittance can be made almost arbitrarily small. The maximum gradient is limited by the field saturation limits of commonly available magnetic materials. The field gradients can be further increased by reducing the bore radius. With decreased bore radius the implementation of the vacuum system becomes challenging and the effect of impedance increases. These considerations lead to limiting the maximum achievable magnet strength to about 115 T/m and the minimum bore radius to about 9 mm. Another important factor is the relative length of insertion devices with respect to the ring circumference (filling factor). Since the emittance is generated in the arcs, its minimization could be achieved by reducing the filling factor, while for maximizing the experimental throughput larger filling factor would be beneficial. In practice, ID straight section length of approx. 5 m for a cell length of approx. 23–25 m is the best compromise for PETRA IV. Further, emittance can be minimized by either extensively exploiting damping wigglers, or creating lattices with a large partition shift (i.e. shifting the damping from the longitudinal to the transverse plane). Both approaches can at the same time lead to increased beam energy spread. The energy spread is detrimental to the brilliance. The exact effect depends on parameters of the

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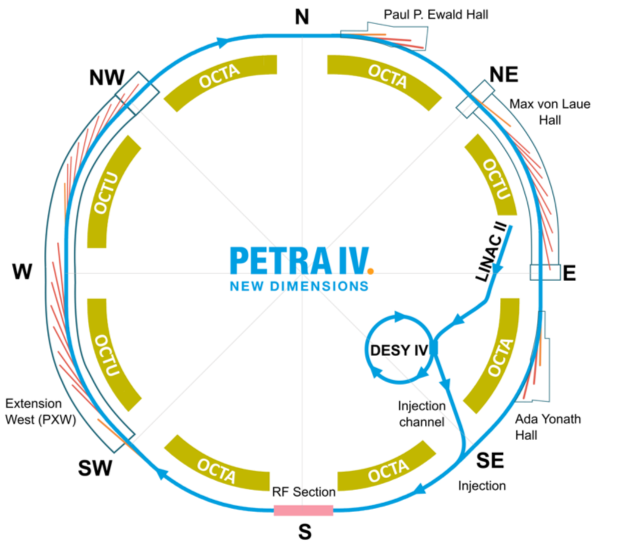

Figure 1: Layout of the PETRA IV facility. Existing experimental halls (Max von Laue, Peter P. Ewald, and Ada Yonath) will be reused. An additional experimental hall (”Extension West”) will be constructed.

insertion device, the experiment performed, and the x-ray optics, and is not discussed here. Energy spreads above 0.1% are generally undesirable. Special attention is deserved by the assessment of errors on the machine performance. All light sources based on MBA lattices suffer from increased sensitivity to alignment errors: strong focusing quadrupoles in conjunction with strong sextupoles to compensate the large natural chromaticity of these lattices create substantial feed-down effect and machine instability with alignment errors that are below what is realistically achievable. So-called machine bootstrapping is required to set up and run the machine. Demonstration of this procedure is necessary for all future projects, and the experience of MAX IV and ESRF-EBS showed that these procedures are adequate and the design parameters can be adjusted in relatively short time. Nevertheless the error analysis played an important role in the PETRA IV lattice selection,and is discussed in more detail in [9]. The storage ring feeds up to approx. 30 undulator insertions (photon beam can be further split to allow more experimental stations). The storage ring will operate in two modes: brightness mode with 1920 stored bunches (4 ns spacing) with the total current of 200 mA and the timing mode with 80 bunches and total current of 80 mA. Other operation modes consistent with 2 ns minimum bunch spacing, single bunch current limitation of approx. 1 mA and total current limitation of 200 mA are conceivable. Intra-beam scattering and Touschek effects contribute significantly to the emittance growth and the decrease of beam lifetime. These effects are mitigated by having sufficiently large number of buckets with a 500 MHz RF system and single bunch lengthening with a 3rd harmonic (1.5 GHz system).

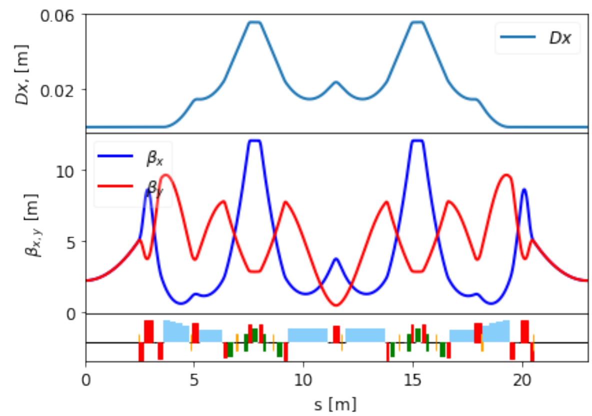

Figure 2: Layout of the H6BA cell. The difference between damping wiggler and undulator cells is only in the insertion device used in the straight section.

THE H6BA LATTICE

The storage ring has a geometry inherited from the HEP programme of PETRA in the 1970s, which is unusual for a synchrotron radiation facility. It has eight arcs, four straight sections of approx. 108 m length, and four straight sections of approx 64 m length. Each arc is composed of nine hybrid six-bend achromat (H6BA) cells (see Fig. 2). Moreover, some of the long straight sections feature insertion devices of approx. 10 m length. Special triplet optics is used to focus the beam in this insertion (see Fig. 3).

Achromats

Two cell types are used for the eight octants. One cell type features a user insertion device (ID), while the other type a damping wiggler (DW). The bending angle of each achromat is 5°, the total number of achromats is 72. Due to geometrical reasons the cell length of these two cell types are slightly different. To keep some of the positions of source points of existing undulator beamlines of PETRA III in the Max von-Laue Hall a cell length of 23 m has to be used there. This will avoid costs for relocating existing beamlines. Achromats with a length of 23 m will also be used in the new extension hall West. In five octants a shorter cell length of 22.75 m is required due to geometrical constraints of the existing tunnel. In these cells damping wigglers will be installed. These cells have an identical magnet arrangement with a shorter ID straight. In addition the strength of quadrupole magnets up- and downstream of the DWs have to be changed to make the phase advances and the beta functions of both cell types nearly equal.

A quadrupole triplet up- and downstream of the ID straight is used to focus the beta functions to $\beta_x = \beta_y = 2.2$ m in the center of the ID which is near the optimum beta functions. The dispersion function at the IDs is zero to avoid emittance contribution of the undulators when the gaps are closed. As a compromise between small beta functions and a feasible quadrupole design the maximum gradient in the triplet was limited to 115 T/m. The other quadrupoles in the achromat

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have gradients of 100 T/m or less. Between the insertion straight and the section for chromaticity correction there are two dipoles with both longitudinal and transverse gradients (combined-function magnets). A focusing quadrupole is in between. All dipole magnets have a vertical defocussing field. This makes the cell more compact and helps to increase the horizontal damping partition number J_x and reduce the emittance. Both dipoles consists of four permanent magnet blocks. The chromaticity correction section has a dispersion bump which consists of a symmetric arrangement of four quadrupoles with three sextupoles and two octupoles in between. The chromatic sextupoles are placed near the peaks of horizontal and vertical beta functions. The octupoles are installed near large horizontal beta function and dispersion function to correct mainly the second order chromaticity. Between the dispersion bump and a focussing quadrupole in the center of the cell there is another combined-function dipole which is longer compared to the other two dipoles. It consists of six blocks of permanent magnets. The cell is reflected m irror-symmetrically. The betatron phase advance between the groups of sextupoles is close to π in both planes. There are nine beam position monitors, and seven orbit correctors per cell per plane.

Damping Wigglers

The damping wigglers are considered to be part of the cell optics, and bring down the lattice emittance from approx. 43 pm rad to 20 pm rad. This allows to have less aggressive optics compared to e.g. seven-bend achromat lattices: ultra-large circumference of the PETRA ring makes the peak dispersion function of a seven-bend achromat lattice smaller, thus resulting in the need for stronger sextupoles and inferior beam dynamics. The damping wigglers allow to recover the emittance at the cost of RF power and some energy spread growth. During operation of PETRA IV the users IDs contribute partly to the reduction of the emittance if their gaps are closed. For the case that all gaps of undulators are open around 40 damping wigglers of 4.44 m length and a sin-like field of 0.85 T would be needed to achieve 20 pm rad.

Straight Sections

The eight arcs are connected by the long straight sections of different t ypes. These straight sections are matched to minimize their impact on the beam dynamics, as discussed further. The long straights come in several types. First there are four long straight sections (N, S, W, E) and three shorter long straight sections (SW, NW, NE) that comprise low-beta insertions at the beginning and the end of the straight, and FODO-like matching in between. The long and short version of such straight have similar design, and the long version is shown in Fig. 3. The injection section in South-East is shown in Fig. 4. It features a peak of the horizontal beta function of 46 m where the injection septum is placed, thus minimizing the footprint of the septum blade on the acceptance. The RF will occupy the straight section N. The lattice parameters are presented in Table 1.

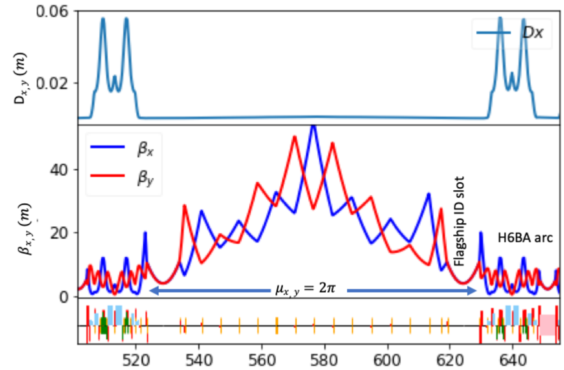

Figure 3: A long straight section featuring 10 m long low-beta insertions for the flagship IDs (north straight).

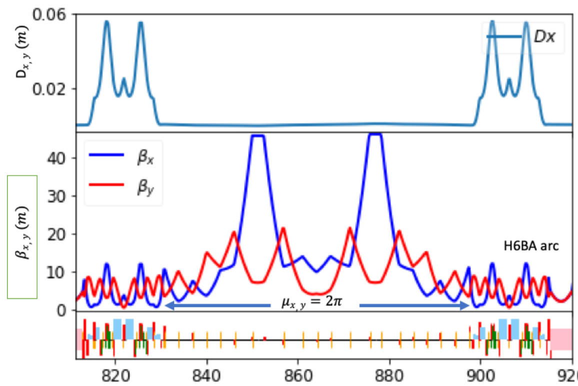

Figure 4: Injection straight (south east).

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Table 1: Parameters of the H6BA lattice (zero current)

Parameter	**Value**
Tunes ν_x,ν_y	164.18, 68.27
Natural chromaticity ξ_x,ξ_y	−230, −196
Corrected chromaticity ξ_x,ξ_y	6, 6
Momentum compaction factor α_C	3.3×10^{-5}
Standard ID space	4.9 m
$\beta_{x,y}$ at ID, standard cell	2.2 m, 2.2 m
$\beta_{x,y}$ at ID, flagship IDs	4 m, 4 m
Nat. hor. emittance ε_x with IDs	20 pm rad
Rel. energy spread δ_E with IDs	0.91×10^{-3}

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