ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP1WB01

LATTICE DESIGN FOR PETRA IV: TOWARDS A DIFFRACTION-LIMITED STORAGE RING

I. Agapov *, R. Brinkmann, Y.-C. Chae, X.N. Gavalda, J. Keil, R. Wanzenberg,
Deutsches Elektronen Synchrotron, Notkestrasse 85, Hamburg, Germany

Abstract

Machine design for the PETRA III storage ring upgrade – PETRA IV – aiming at a 10-30 pm emittance range has been ongoing at DESY. We present the design challenges and approaches for this machine, the baseline lattice and the alternative lattice concepts currently under consideration.

INTRODUCTION

PETRA III has been in operation as a synchrotron radiation user facility since 2009 [1, 2], being at the time of construction the world's record holder for the smallest electron beam emittance (1 nm rad at 6 GeV) among hard x-ray sources. An extension project has been ongoing since 2014 [3], and potential of reducing the emittance with the existing lattice comprising a mixture of DBA and FODO cells has been studied [4], putting the ultimate emittance of such lattice type at around 500 pm for PETRA circumference of 2304 meters. With the advance of the multi-bend achromat (MBA) technology pioneered by MAX IV, many light sources, and among them all large hard x-ray facilities – ESRF, APS, and SPRING 8 – have proposed machine upgrades reducing the emittance by orders of magnitude. With PETRA IV design studies [5] DESY has started the preparation phase for the MBA-based upgrade project which will be essential to maintain the laboratory's role in cutting edge research with synchrotron radiation.

DESIGN OBJECTIVES

The upgrade plan of PETRA III to PETRA IV aims at building a unique light source, with an ultra-low horizontal emittance in the range between 10 pm rad and 30 pm rad at a beam energy of 6 GeV. In addition to the three existing experimental halls in the northeast of the storage ring, it is foreseen to build a new experimental hall in the southwest just opposite to the Max von Laue Hall. The general layout of PETRA IV is shown in Fig. 1. The storage ring will provide 18 straight sections of approximately 5 m length and four longer straight sections in the four experimental halls. With canting four straight sections and splitting another four undulator beams by appropriate optics, thirty parallel undulator stations could be realised. The first beamline in each experimental hall has its undulator located in the long straight sections separating the arcs. For these four beamlines, the undulator length is not limited by length of the straight section but only by the available acceptance and the electron beam parameters (e. g., β-functions) can be optimised for highest possible brightness. Fig. 2 shows the brightness that could be reached with PETRA IV in one of the four long straight sections. Ultra-low emittance and a reduced number of electron bunches for timing experiments are conflicting design goals that can not be met with a single mode of operation of PETRA IV. Therefore, it is planned to provide two operation modes for PETRA IV, the high-brightness, high-coherence continuous mode and a timing mode with fewer bunches with increased bunch charge but with larger emittance and thus slightly reduced brightness.

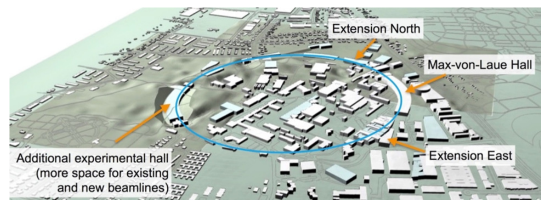

Figure 1: Layout of the PETRA IV facility.

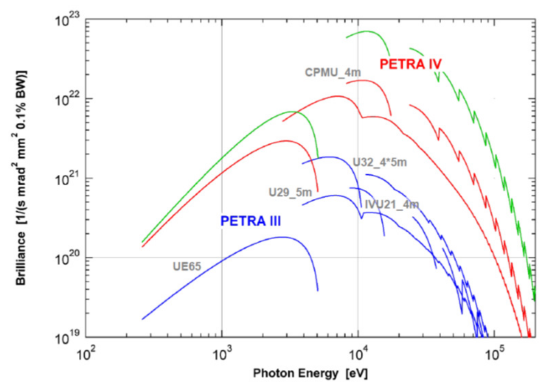

Figure 2: Comparison of brightness between PETRA III and PETRA IV. Red curve: ε_x = 15 pm, κ = 100%, β_x=5 m, β_y=2.5 m. Green curve: ε_x = 10 pm, κ = 50%, β_x=1 m , β_y=1 m.

For lattices in the 10-30 pm range the intra-beam scattering plays an important role and limits the emittance that can be achieved in practice with reasonable bunch charges (see e.g. Figure 3). Although the zero-current emittance scales with beam energy as γ^{-2}, IBS changes this dependency as shown in Figure 4 (calculations for the reference lattice), and the beam energy of approx. 6 GeV appears optimal for emittance minimization.

The insertion devices have significant impact on beam parameters, providing emittance damping or emittance blowup depending on ID field strength, ID length, number of IDs, and dispersion and beta function at the ID. A typical scenario without canting results in emittance damping and

* ilya.agapov@desy.de

ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP1WB01

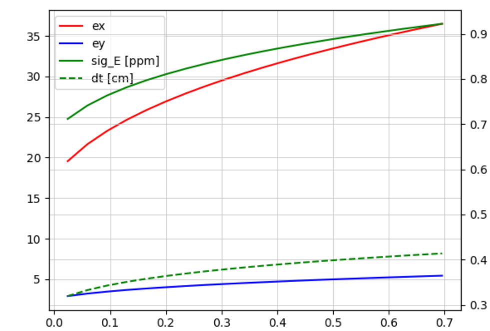

Figure 3: Example of bunch parameters (emittance in pm) vs. bunch charge (in mA) at 6 GeV, 10% coupling.

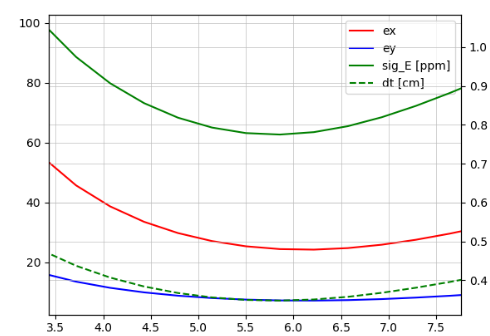

Figure 4: Example of bunch parameters (emittance in pm) vs. beam energy (in GeV) for 0.1 mA bunch charge.

some energy spread growth as shown in Figure 5. A typical peak field if the undulator of 1 T should be assumed.

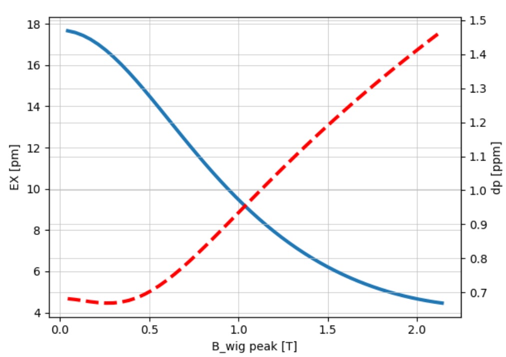

Figure 5: Effect of undulators/damping wigglers with zero dispersion at the ID (no canting), reference lattice, 24 mm period undulators of 5 m length.

Only some beamlines require canting, and the solution that incorporates it without the need to readjust the cell optics is based on a 3-magnet bump as shown in Figure 6.

It can be shown that for a ring where the energy spread is dominated by insertion devices, as will be the case for

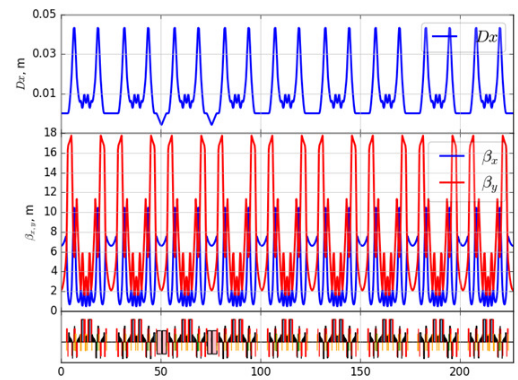

Figure 6: Optics functions of a lattice octant with selective cell canting.

PETRA IV, the maximum canting angle can be estimated as $\theta[mrad] \approx \left(\frac{2\varepsilon_{RING}[pm]}{\beta[m]\sigma_p[ppm]}\right)^{1/2}$ and is in the order of 4 mrad for β=2 m. For the reference lattice, however, only 2 mrad canting can be integrated without significant degradation of emittance if all IDs are canted, which is mostly due to a larger β_x and non-optimum dispersion. 4 mrad cantining can be integrated if only small number of insertions are canted, as discussed before.

The discussion in this section was based on the example of the reference lattice without (introduced next), with long straight sections removed for simplicity, which results in a small change of equilibrium beam parameters. It however applies with only small modifications to other lattice types in the same emittance range. The projected parameters of PETRA IV are summarized in Table 1. A more detailed discussion of the evolution of the lattice concept is presented in the next section.

Table 1: Parameters of PETRA III / IV without Intrabeam Scattering

Parameter	PETRA III	PETRA IV (without DW)
Energy [GeV]	6	6
Total current [mA]	100	100-200
Nat. emittance ϵ_0 [pm rad]	1280	15 - 30
Energy spread σ_p [10^{-3}]	1.23	0.7 - 1.5
Energy loss/turn U_0 [MeV]	5.1	1 - 5
Momentum compaction factor α_c [10^{-3}]	1.13	0.0146
Dispersion at SF D_x [cm]	750	4.2

STORAGE RING LATTICE

PETRA IV storage ring layout is shown in Figure 7. Place for damping wigglers is foreseen in the west and the north. The RF stations are in the south, and the injection in the south-east. The injection channel will have to be refurbished to inject into the middle of a high-beta straight section. In all lattices a high-beta insertion (β_x ≈100 m) is foreseen.

ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP1WB01

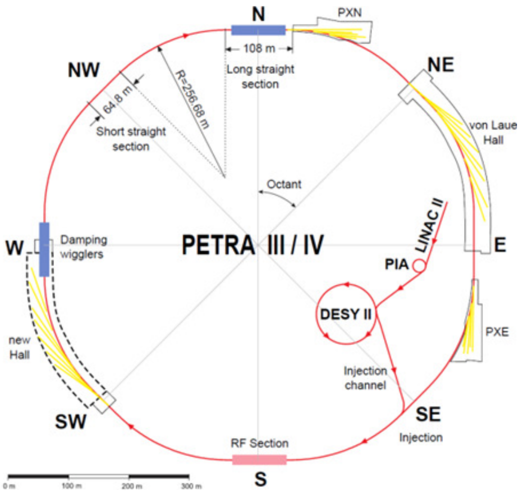

Figure 7: Schematic layout of PETRA IV and its injectors.

7BA Hybrid ESRF-type (H7BA)

For PETRA IV an ESRF-like MBA lattice has been studied with priority. The cell is scaled to 25 m length, and the phase advances are adjusted such that an octant forms a 4^{th} order geometric achromat. In that case the phase advances of the 8 long straight sections are not critically influencing the dynamic aperture, and can be used for tune adjustment. The bare lattice emittance is approx. 15 pm (strong dependency on insertion devices was discussed previously) and the energy spread 0.7 ppm. The optics is shown in Figures 8 and 9. Dynamic aperture is shown in Figure 10. Local momentum acceptance is around 2.5-3%.

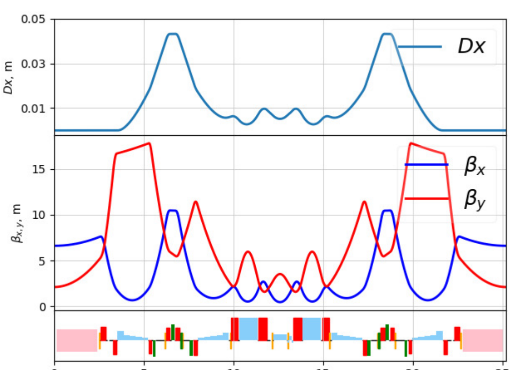

Figure 8: H7BA (reference) lattice.

Phase Space Exchange Based on 6BA (T6BA)

A round beam lattice based on the phase space exchange principle has been investigated in parallel. It is based on 6BA cells with non-interleaved sextupole arrangement. The phase space exchange requires global sum chromaticity correction, which allows for only one pair of horizontally focusing sextupoles per cell. Six octants have no ID straights and form long achromats as shown in Figure 11. Nine 23 m undulator cells form other two octants (Figure 12). Skew qaudrupole sections in two long straight sections are used to flip the

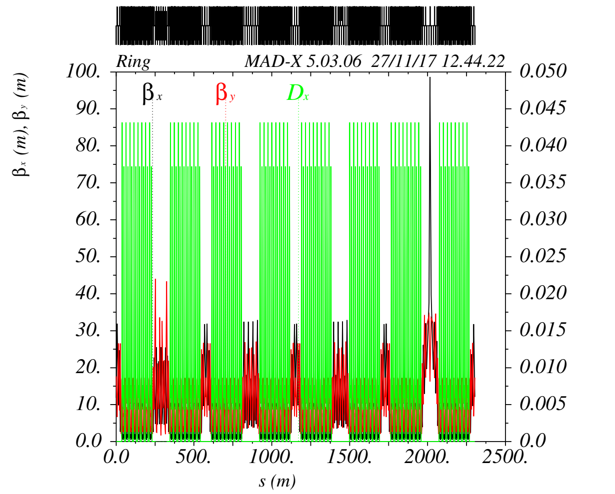

Figure 9: H7BA (reference) lattice.

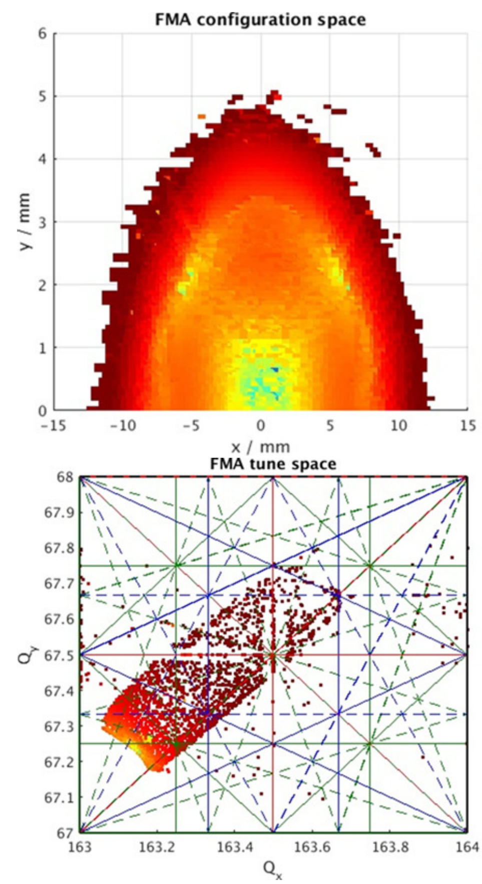

Figure 10: Dynamic aperture and tune diagram of the H7BA (reference) lattice.

betatron oscillation modes. Optics functions are shown in Figure 13. The on-momentum DA is in excess of 2 mm mrad (limitation comes from the path lengthening effect in conjunction with synchrotron oscillations, see Figure 14). The limitation of the optics to round beams only is however a major disadvantage. We consider implementing a flexi-

ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP1WB01

ble phase space exchange with the reference H7BA lattice, such that round beam could be only one operation mode in addition to the flat beam mode.

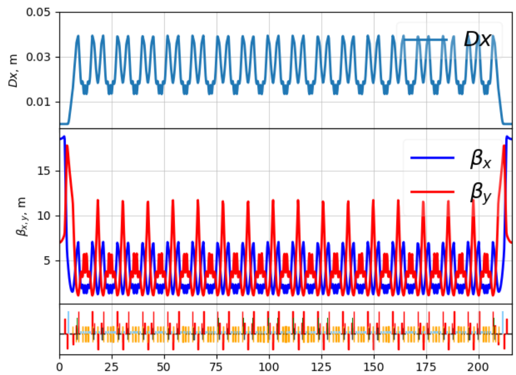

Figure 11: Octants without ID straights.

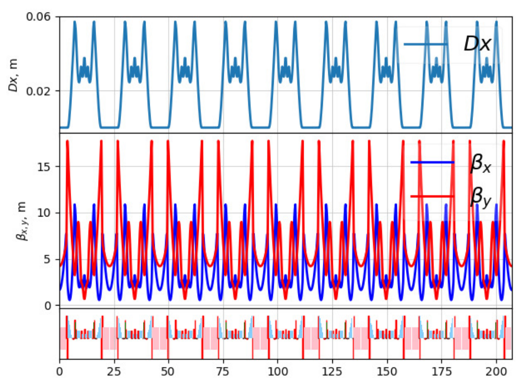

Figure 12: Octants with ID straights.

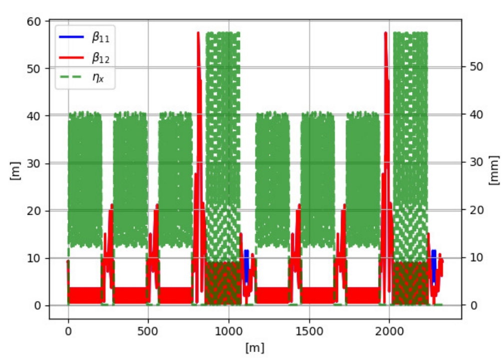

Figure 13: Coupled lattice functions.

Double -I (DMI)

This design is composed of a combination of arcs based on 11 double -I cells (Fig. 15) with a non-interleaved sextupole scheme with a betatron phase advance of 180° in both planes and arcs based on 8 ESRF-H7BA cells with straight sections for insertion devices. As it is well known, such interleaved sextupole scheme allows to reduce the effects of the

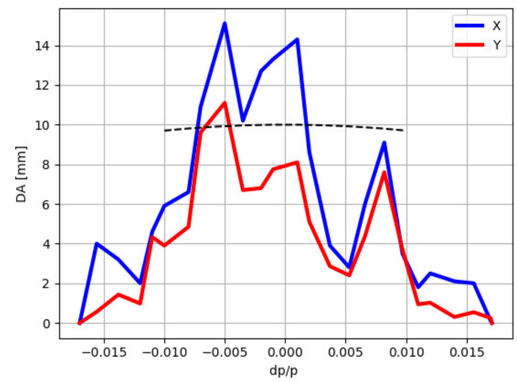

Figure 14: DA and MA of the phase space exchange lattice. Limitation of the DA due to path lengthening effect for a typical RF setup is shown as a dashed line.

geometric aberrations induced by the sextupoles providing a larger dynamic aperture. The bare horizontal emittance of such lattice without damping wigglers is 29.7 pm rad. The dynamic aperture without errors of the double -I lattice is bigger than the dynamic aperture of the PETRA IV reference lattice (4 mm mrad vs. 1.3 mm mrad).

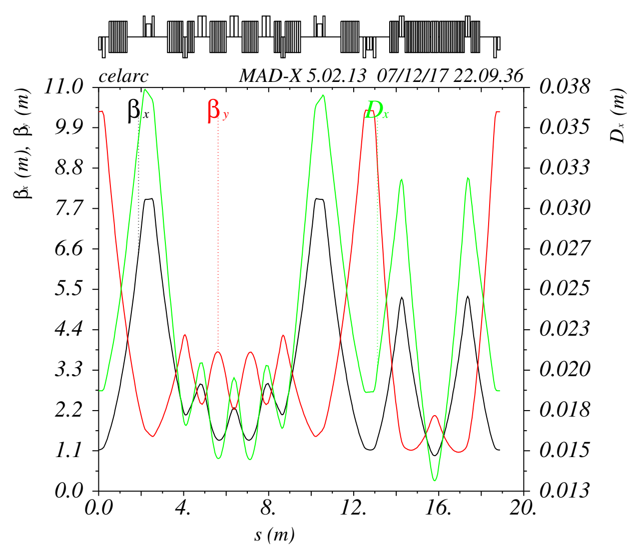

Figure 15: A unit cell of the DMI lattice.

OTHER SUBSYSTEMS

Magnet design is ongoing in collaboration with Efremov Institute St. Petersburg. Magnet designs with up to 150 T/m fields (20 mm air gap) have been proposed. In the lattice design we however been assuming a more conservative 100 T/m limitation for quadrupoles. Design studies for sextupoles are ongoing. For the RF system 100 MHz or 500 MHz single-cell normal conducting cavities and corresponding 3^{rd} harmonic cavities are under consideration, impedance modeling and beam dynamics simulations to determine bunch charge limitations are ongoing. Vacuum

ISBN: 978-3-95450-206-6 doi:10.18429/JACoW-FLS2018-MOP1WB01

system design is ongoing. Experimental NEG self-activation and impedance studies are planned at PETRA III to provide further guidance. R&D into lightweight stable girder design has been ongoing in collaboration with AWI Bremerhacen.

SUMMARY AND OUTLOOK

Design study for the PETRA upgrade is ongoing, and a reference lattice based on H7BA cell is in place A simpler and more robust 6BA solution exploiting the no-undulator arcs (double -I) exists, but has to be worked out in more detail. Decision on the lattice type and CDR are expected in 2019, a whitepaper based on reference lattice is currently in preparation. Projected baseline parameters are: 100 or 200 mA current, 15pm/5pm emittances, 0.1% energy spread, pulse duration 30-100 ps (FWHM). Possibility of timing/hybrid modes (40 or 80 bunches) is open, we need to further investigate bunch dynamics with high charge and higher harmonic cavity (instability thresholds, feedback performance). Tolerance studies and commissioning simulations are ongoing R&D on technical subsystems has been launched, and CDR preparation is in full swing.

REFERENCES

[1] PETRA III TDR, DESY 2004-035, 2004

[2] K. Balewski, Commissioning of PETRA III, in *Proc. IPAC'10*, Kyoto

[3] W. Drube *et al*., https://doi.org/10.1063/1.4952814

[4] V. Balandin *et al*., Emittance reduction possibilities in the PETRA III magnet lattice, in *Proc. IPAC'15* Richmond,USA

[5] l. Agapov *et al*., Research activities towards a conversion of PETRA III into a diffraction limited synchrotron light source, in *Proc. IPAC'17*, Copenhagen