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A LATTICE FOR PETRA IV BASED ON THE COMBINATION OF DIFFERENT ARC CELL DESIGNS

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Abstract

The 6 GeV synchrotron light source PETRA III at DESY is in user operation since 2009 [1]. In 2016 investigations of upgrading PETRA III into a diffraction-limited storage ring at 10 keV have been started. The ambitious goal is to achieve an emittance in the range of 10–30 pm·rad. For the conceptual design report (CDR) of PETRA IV a lattice based on hybrid multi-bend achromats (HMBA) has been chosen. It consists of eight arcs connected by eight long straight sections whereas each arc consists of eight HMBA cells. While this lattice variant has an advantage in terms of simplicity of magnet and girder design it is challenging in regards of multipole strengths and beam dynamic properties. However, only a part of all eight arcs will be used for undulator beamlines. This offers the possibility to choose a more relaxed optics design in the arcs without undulators while preserving the ultra-low emittance. In addition, the use of reverse bends in the undulator cells allows smaller beta functions at the undulators for an increased brilliance. The design and the beam dynamic properties of this combi lattice are discussed in this paper and compared to the lattice based on HMBA cells.

INTRODUCTION

Since a few years many facilities took over the concept of the multi-bend achromat (MBA) for their machine upgrades or for new projects. Because of emittance scaling $\epsilon \propto \theta^3$ small values can be realized with small bending angles $\theta \propto 1/N_d$ especially for large machines with many weak dipoles N_d. However, strong focussing is needed which generates large natural chromaticity. Strong sextupoles are required for correction which reduces the dynamic aperture and momentum acceptance. As a result, the injection efficiency and the Touschek lifetime will be low.

Also DESY is working on an upgrade of PETRA III using the MBA concept to build a nearly diffraction-limited synchrotron radiation source at 10 keV photon energy and is currently in the TDR phase. Due to the large circumference of 2 304 m extremely small emittances in the range of 10–30 pm·rad can be realized. However, the small bending angles and the strong focussing leads to a maximum dispersion function of only a few cm. This requires very strong sextupoles if a classical MBA design (like the one of MAX IV [2]) is used. To reduce this problem the ESRF invented the hybrid multi-bend achromat (HMBA) for their upgrade for the EBS [3]. The sextupoles for chromaticity correction are installed in two dispersion bumps which reduces their strength significantly. With a phase advance of 3π and π in the x and y-plane between sextupoles many of their non-linearities are canceled locally within the achromat.

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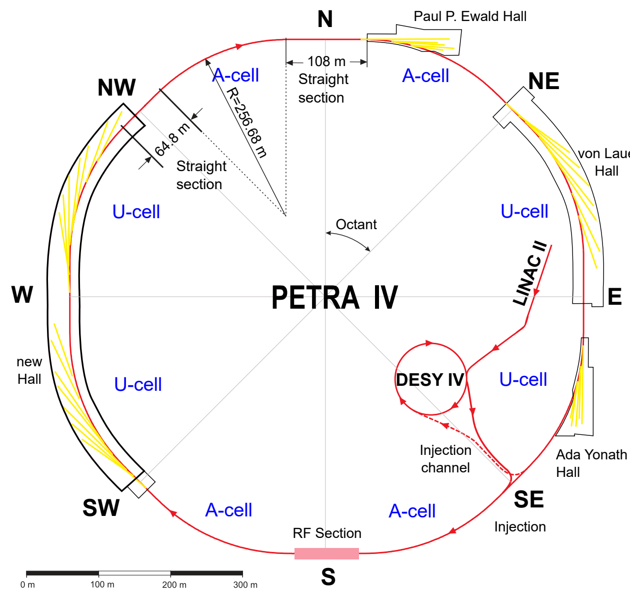

Figure 1: Layout of PETRA IV. The positions of the undulator cells (U-cell) and the relaxed cells (A-cell) for the combi lattice are marked in blue. The pure HMBA lattice is using U-cells for all arcs.

PURE HMBA LATTICE

For the Conceptual Design Report of PETRA IV a lattice based on HMBA cells with seven dipole magnets per cell was selected [4]. The PETRA IV achromat follows the design of the ESRF-EBS [3] but has a cell length of 26.2 m and a factor of two smaller bending angle of 5.625°. The emittance is 18.1 pm·rad without IBS and open insertion devices (IDs) of the users. The lattice consists of eight identical arcs connected by straight sections with alternating length of 108 m and 64.8 m. Each arc consists of eight HMBA cells, see Fig. 1 for the schematic layout.

The HMBA cell has beta functions of $\beta_x = 6.8$ m and $\beta_y = 2.1$ m at the center of the ID and a maximum dispersion of 4.3 cm at the sextupoles (Fig. 2). With a phase advance per cell of $\mu_x = 2 + 3/8$ and $\mu_y = 1 - 1/8$, an arc of eight cells is nearly a 4th order achromat. Only the $2Q_x - 2Q_y$ resonance is amplified. Compensation is possible by choosing an appropriate phase advance of the straight sections [5].

An undulator cell with a lower $\beta_x = 3.6$ m at the ID and a 5 % larger dispersion peak is also considered. Reverse bends are used which are implemented by shifting two quadrupoles

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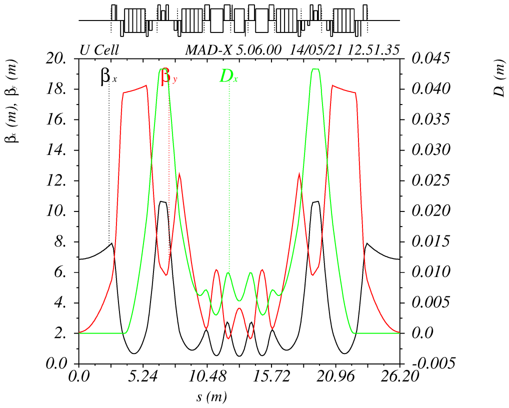

Figure 2: HMBA cell for arcs with undulators (U-cell).

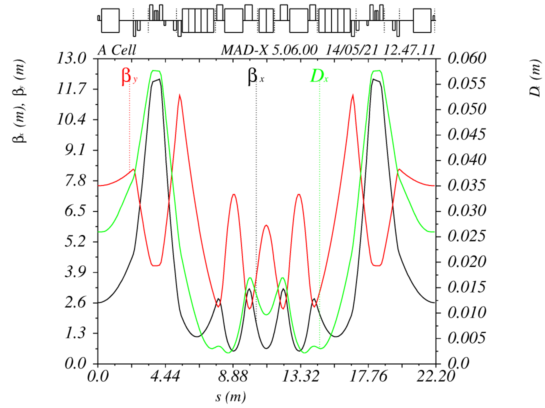

Figure 3: Cell for arcs without undulators (A-cell).

near the dispersion bumps by a few mm. While the smaller β_x is advantageous for the brilliance the question of how to align precisely the beam in the shifted quadrupoles is still under investigation.

COMBI LATTICE

Using identical achromats is beneficial and simplifies the logistic and the design of magnets, girders and the vacuum system. However, the possible locations for installation of undulators are limited to the already existing halls and to a new hall in West. In other parts of the ring the tunnel is either too low below ground or there are conflicts with existing buildings which rules out experimental halls with additional beamlines there.

This allows to use a more relaxed optics in the arcs were no IDs are foreseen and combine them with arcs of HMBA cells (combi lattice). As ID straights are not needed in the relaxed arcs a shorter cell length of 22.4 m can be used (Fig. 3). It has a similar seven-bend cell design and contains three sextupole families and also two octupole families. This doubles the number of parameters which can be used for non-linear lattice optimization. It has a larger peak dispersion of $D_x = 5.8$ cm, has a smaller natural chromaticity and weaker sextupoles. This allows to shift part of the chromaticity correction to the relaxed arcs and to reduce the sextupole strength in the undulator arcs. Also the power consumption for magnets is slightly lower. Nevertheless, a small natural emittance has still to be ensured and is 21.2 pm·rad for the combi lattice. Closing the gaps of the IDs results in a reduction of the emittance by another factor of two.

With 9 cells and a phase advance of $\mu_x = 1{+}7/9$ and $\mu_y = 1 - 3/9$ the relaxed arc is also a 4th order achromat. In the first and last cell of the arc additional quadrupoles, a dipole and a shifted quadrupole are used to match the dispersion function to zero. These matching quadrupoles are outside of the region between the sextupoles to avoid breaking the phase advance conditions between the sextupoles.

The installation of HMBA cells in the arcs NE–E, E–SE and SW–NW is required to provide beamlines in the already existing and new experimental halls. For the other four arcs relaxed cells can be used. By combining undulator arcs and relaxed arcs in this way a periodicity of two of the combi lattice can be achieved.

A disadvantage of the combi lattice is that the arc N–NE would be replaced by a relaxed arc. Only one undulator beamline in the straight North can be reused. To still use this hall for experiments it has been suggested to use super-bends or to install three-pole wigglers for dipole beamlines there.

COMPARISON OF LATTICE PROPERTIES

Tune Shift with Momentum Deviation

A disadvantage of the HMBA lattice is the relative large 2nd order chromaticity especially in the vertical plane. In combination with the linear chromaticities of $\xi_x = 5$ and $\xi_y = 5$ the vertical tune will cross already at a small relative momentum deviation of $\delta = 1.5\,\%$ the $2Q_y$ resonance and for $\delta = 2.2\,\%$ the $2Q_x$ resonance (Fig. 4 (a)). If field imperfections are too large beam loss for off-momentum particles will occur, the momentum acceptance is reduced and the Touschek lifetime is low. It is better to avoid this problem, although it has been shown that with well corrected quadrupole gradient errors and with a beta-beating of a few percent the half-integer resonances can be crossed [6, 7].

For the combi lattice the excitation of the $2Q_x - 2Q_y$ resonance is weaker as only half of the arcs are contributing to this resonance. This offers the possibility to use the phase advances of the long and short straight sections to compensate the off-momentum beta-beating. This has been done for the combi lattice for $\delta = \pm 2\,\%$ in both planes and has reduced the 2nd order chromaticities significantly. Crossing of the $2Q_y$ resonance happens now at $\delta = 2.1\,\%$. By reducing the off-momentum beta-beating of the combi lattice the tune shift with momentum is dominated by the linear and the third order term of the chromaticity (Fig. 4 (b)).

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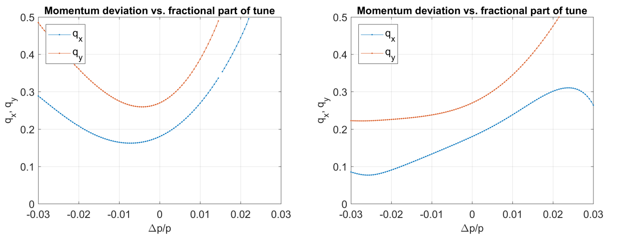
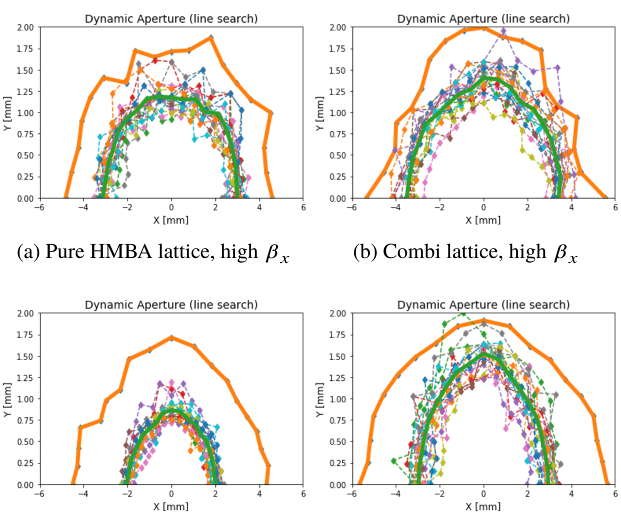


(a) Pure HMBA lattice (b) Combi lattice

Figure 4: Fractional part of the tune as a function of the relative momentum deviation.



(a) Pure HMBA lattice, high β_x (b) Combi lattice, high β_x

(c) Pure HMBA lattice, low β_x (d) Combi lattice, low β_x

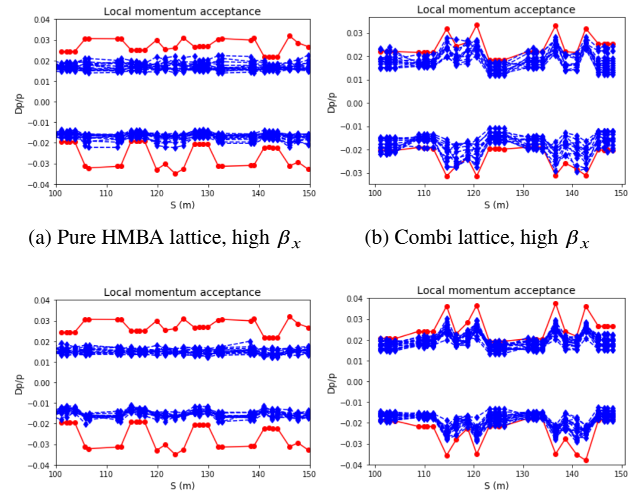
Figure 5: Dynamic aperture at the injection point (β_x = 21.7 m, β_y = 3.7 m) with errors and without (orange line).

Dynamic Aperture

An important property of the lattice is the size of the dynamic aperture (DA) which determines (besides other parameters) the injection efficiency. If the DA is too small an off-axis injection is not possible any more and on-axis swap-out injection is the only possible way to achieve a high injection efficiency.

The DA was calculated for the pure HMBA lattice and the combi lattice for both types of undulator cells. The computations used a simplified machine startup procedure (including ramping up the sextupoles and octupoles, trajectory correction, tune and orbit corrections) and assumed RMS alignment errors of 30 µm (with a 3σ cut) for magnets and BPMs [8]. The DA after this procedure is shown for 20 error seeds at the injection point in Fig. 5. Beta functions are the same for all four cases.

The combi lattice has a larger DA compared to the HMBA lattice independent of the β_x of the undulator cell and is a clear advantage for the injection efficiency. For the low beta cell the advantage in DA is more pronounced compared to the high beta cell (5 (b) and (c)).



(a) Pure HMBA lattice, high β_x (b) Combi lattice, high β_x

(c) Pure HMBA lattice, low β_x (d) Combi lattice, low β_x

Figure 6: Local momentum acceptance with errors (blue) and without (red line).

Momentum Acceptance

Also crucial is the momentum acceptance (MA) of the lattice. For a ring with an ultra-low emittance of about 20 pm·rad the lifetime is dominated by the Touschek lifetime for large single bunch currents. As the Touschek lifetime grows with the third power of the MA a large enough momentum acceptance is needed.

The same startup procedure as described before was also used to compute the local momentum acceptance for 20 error seeds. Figure 6 shows the MA for cells of the HMBA lattice (U-cells) and for relaxed arc cells (A-cells) of the combi lattice.

From the comparison between the two lattices the advantage of the combi lattice can be clearly seen. With errors the half-integer resonance is not limiting the MA at 1.5 % any more. As a consequence the lifetime of the combi lattice is significantly higher. For an emittance ratio of 20 % and a single bunch current of 1 mA the lifetime for the HMBA lattice with high β_x cells is 1.77 h (1.68 h) and for the combi lattice 2.11 h (2.6 h). The number in brackets is the lifetime with the low beta cells. Effects of intra-beam scattering, impedance and a third harmonic cavity system are included in the lifetime computation.

CONCLUSIONS

The combi lattice provides more dynamic aperture and a larger local momentum acceptance compared to the pure HMBA lattice. It has also the advantage, that the sextupole strengths are lower and more parameters are available to optimize the non-linear dynamics. It has only a marginal larger emittance compared to the pure HMBA lattice. Overall, the combi lattice has a significantly better performance for PETRA IV compared to a lattice which consists solely of HMBA cells.

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