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A PETRA IV LATTICE BASED ON HYBRID SEVEN BEND ACHROMATS

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Abstract

For the PETRA IV project at DESY it is planned to convert the 6 GeV synchrotron light source PETRA III into a diffraction limited storage ring with ultra-low emittances. PETRA IV should provide a natural emittance two orders of magnitude smaller as now. The energy and the current of 100 mA should be unchanged. Currently different lattice options are investigated to achieve an emittance in the range of 10–30 pm·rad. As one candidate for a lattice of PETRA IV a ring based on the concept of hybrid multi-bend achromats (HMBA) has been studied in detail. Due to the unique layout of PETRA III with long straight sections it is possible to use damping wigglers to reduce the emittance further. While this helps to mitigate intrabeam scattering it has the disadvantage of an increased energy spread. The linear and nonlinear parameters of this HMBA-based lattice and the influence of damping wigglers on beam parameters are discussed.

INTRODUCTION

The synchrotron light source PETRA III is in operation since 2009 [1]. Its natural emittance of 1.3 nm·rad is currently the smallest emittance of all machines in the hard X-ray regime at 6 GeV. PETRA III is routinely operated in top-up mode with a current of 100 mA and a variation of 1 %. The filling pattern is either 960 bunches in the continuous mode or 40 bunches in the timing mode.

There is always a great interest for even smaller emittances on user side as brilliance and coherent fraction of the undulator beam will be much higher. To reach smaller emittances many existing facilities like ESRF, APS, SPring-8 and also new projects like HEPS make use of the concept of the multi-bend achromat (MBA). The MBA has been implemented successfully at MAX IV for the first time [2].

Applying the concept of MBA to PETRA allows to reach ultra-low emittances due to its large arc fraction of 1.6 km of the circumference of 2.3 km. For an emittance of 8 pm·rad the photon beam would be diffraction limited at a wavelength of 1 Å. The emittance of PETRA IV is planned to be in the range 10–30 pm·rad for 100 mA beam current in the continuous mode and 80 mA in the timing mode.

As a consequence of the strong focussing large negative chromaticities have to be compensated. Due to the small bending angles of the dipoles the dispersion function is rather small and strong sextupoles are required. This has adverse effects on nonlinear beam dynamics. The reduction of the detrimental effects of the sextupoles on nonlinear dynamics is therefore crucial for the optics design of PETRA IV.

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The design of the lattice has to take into account the existing infrastructure of the tunnel and the beamlines. The machine consists of eight arcs (each 201.6 m long) which are connected by long (108 m) and short straight (64.8 m) sections. One of the arcs has been rebuild in the years 2007–2008 and was replaced by an arc made of double-bend achromats, the other arcs are still using FODO cells. In 2014 two arcs have been modified and two additional experimental halls have been built. These experimental halls have to be included in the design.

LATTICE DESIGN

Different lattices for PETRA IV are currently under investigation. In this study a lattice based on hybrid multi-bend achromats (HMBA) developed at the ESRF [3] has been studied in more details. The HMBA has two dispersion bumps where the chromatic sextupoles are installed. This helps to keep the strength of the sextupoles small. A phase advance between the sextupoles of 3π in the x-plane and π in the y-plane cancel their resonance driving terms locally. Combined function magnets are used in the central part to allow a compact cell design. In addition the outer two dipole pairs have a longitudinal gradient. This increases the dispersion bump further and reduces the emittance.

Compared to other synchrotron light sources the cell length of PETRA III is rather short with 23 m. Therefore a longer cell length of 25.2 m and later of 26.2 m (Fig. 1) and eight cells per arc have been chosen for the seven-bend achromat. The highest quadrupole gradient is in this case $\approx$ 90 T/m which seems to be technically feasible. Still rather strong sextupole and octupole magnets are necessary.

To simplify the design all eight arcs were made from eight HMBA cells. This has the advantage that only one achromat has to be designed and the machine has the possibility for

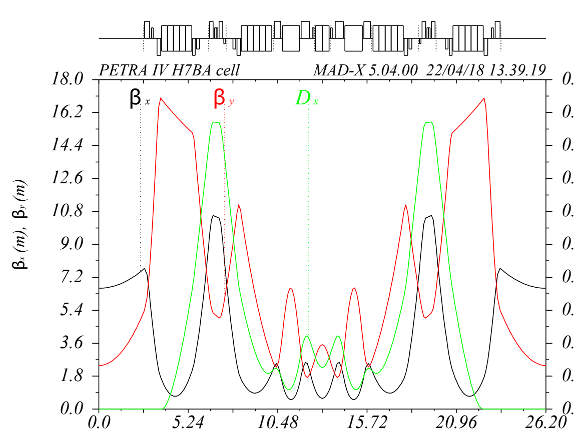

Figure 1: Optical functions of the HMBA cell of PETRA IV.

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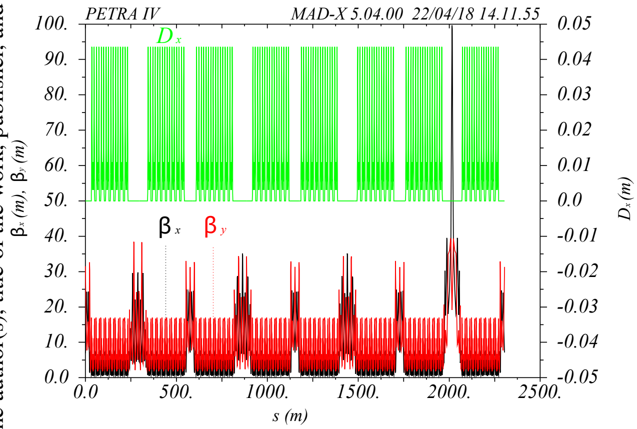

Figure 2: Optical functions of the lattice of PETRA IV.

an upgrade if more beamlines in another experimental hall are needed in the future.

The $-I$ transport matrix between the sextupoles reduces the nonlinearities strongly. Nevertheless the compensation cannot be perfect due to the interleaved arrangement of the sextupoles. For a further reduction the arcs are designed as 4th order geometric achromats following the idea of PEP-X [4] and have a transport matrix of $+I$. With a cell tune of $\mu_x = 2 + 3/8$ and $\mu_y = 1 - 1/8$ all of the geometric driving terms of third order and most of the 4th order terms are cancelled. Only three amplitude dependent tune shifts and the 4th order resonance $2Q_x - 2Q_y$ remain. The latter can be cancelled by using a phase shift of $\mu_x - \mu_y = 1/4$ in all long straight sections for a compensation over two arcs.

The injection is planned to be in the long straight in the South. To increase the dynamic aperture at the septum the horizontal beta function at his point is 100 m. In two of the long straight sections space is foreseen for RF cavities and damping wigglers. The optical functions are shown in Fig. 2. The natural emittance of the lattice without insertion devices (IDs) is 15 pm·rad and the energy spread is $0.7 \cdot 10^{-3}$.

DYNAMIC APERTURE AND MOMENTUM ACCEPTANCE

An off-axis injection scheme would be the preferable method as it allows beam accumulation. Contrary to that an on-axis injection scheme would require kicker magnets with fast rising and falling times and a swap-in/out injection scheme. In that case small gaps in the filling structure would be unavoidable. Also on-axis injection makes higher demands on the pre-accelerators. More current per bunch is needed and the current stability has to be better.

For an off-axis injection the lattice has to offer a large enough dynamic aperture (DA) to accept the injected beam from the pre-accelerator [5]. The DA and the Touschek lifetime of the lattice has been optimized by parameter scans of the sextupoles, the octupole, the cell phase advance, the phase advance between sextupoles, and the local optics within the HMBA in a similar way as done for the ESRF-EBS [6]. In addition the global tune and the chromaticities

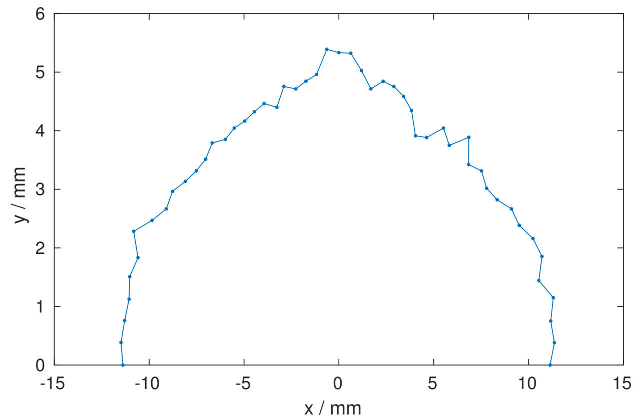

Figure 3: On momentum dynamic aperture at the injection point using 6D tracking for 1000 turns (without errors).

were optimized. After some iterations of parameter scans a dynamic aperture of approx 11 mm in the horizontal plane and 5 mm in the vertical plane has been achieved for a machine without errors (Fig. 3). A further improvement of the DA is possible by using genetic algorithms [7, 8].

Alignment errors and multipole errors will decrease the dynamic aperture. The acceptable level of alignment errors and multipole errors is currently under investigation. From the experience of other machines it seems unlikely that the DA with realistic errors is large enough for an off-axis injection. In that case an on-axis injection has to be used.

A large enough local momentum acceptance (LMA) is important for a sufficient Touschek lifetime which dominates the lifetime of PETRA IV. For one octant of PETRA IV the LMA is shown in Fig. 4. The smallest local momentum acceptance of 1.8 % is in the achromats near the dispersion bumps. On average the momentum acceptance is between 2–2.5 %.

INTRABEAM SCATTERING

Due to the very small emittances the effect of intrabeam scattering (IBS) [9] is a severe limitation of the achievable emittance and energy spread. For each bunch a steady-state

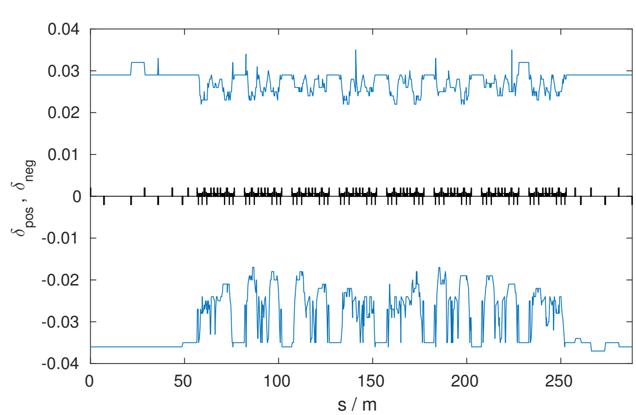

Figure 4: Local momentum acceptance of an octant (without errors).

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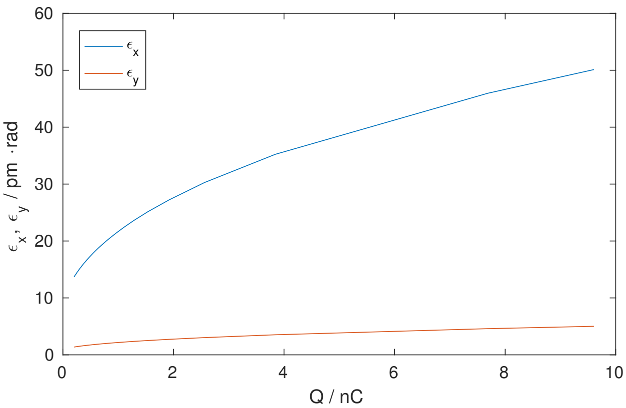

Figure 5: Increase of the emittance as a function of the single bunch change due to IBS.

with higher emittance and higher energy spread is reached which is a function of the IBS rise times and the damping times in all beam dimensions [10]. The IBS rise times depend strongly on the single bunch current, the emittances in all dimensions and the optical functions of the lattice.

IBS effects can be mitigated by using an RF system with a low frequency which results in a longer bunch length. On the other side this will reduce also the maximum number of buckets. For a fixed total current the single bunch current would be higher for a lower RF frequency. A 500 MHz system has been assumed at the moment for PETRA IV.

The expected equilibrium emittances for different single bunch charges and an emittance ratio of $\epsilon_y/\epsilon_x = 10\,\%$ is shown in Fig. 5. A 500 MHz RF system with a voltage of 6 MV was assumed. The damping effect due to insertion devices was simulated by assuming that the gaps of 10 damping wigglers are closed.

For a beam current of 100 mA with 960 bunches (continuous mode) the bunch charge is 0.77 nC and IBS would increase the emittance to 20 pm·rad. For the timing mode already 80 bunches are planned which corresponds to a charge of 9.6 nC. In this mode the emittance would increase to 50 pm·rad and the energy spread to $1.7 \cdot 10^{-3}$.

Impedance related bunch lengthening was not included in the calculation. An active harmonic cavity can help to lengthen the bunch and reduce emittance growth by IBS [11].

DAMPING WIGGLERS

Increasing the damping while not enhancing the quantum excitation by damping wigglers is another way to mitigate emittance growth by IBS. In addition damping wigglers reduce the emittance further.

The long and short straight dispersion free sections of PETRA IV are well suitable for installation of damping wigglers. They could also be installed in some of the arcs which are not occupied by undulators for users. It should be noted that the undulators of the users already contribute to the damping. Therefore it is foreseen to use damping wigglers only to keep the emittance constant during gap changes of the undulators.

As the number of undulators and their parameters are not fixed yet it has been investigated first what emittance reduction can be achieved. For the calculation it was assumed that 10 damping wigglers with a length of 4 m are installed in one of the straight sections. Using analytical formulas [10] the period length and the field of the wigglers was optimized for a maximum emittance decrease. With damping wigglers the emittance reduced from 15 pm·rad to 9 pm·rad.

Damping wigglers have the disadvantage that in most of the cases the energy spread will increase. Also a higher RF voltage is needed to compensate the energy loss per turn. With damping wigglers included the energy spread will increase from $0.73{\cdot}10^{-3}$ to $1.44{\cdot}10^{-3}$. This increase will broaden the spectral line width of the undulator radiation especially at higher harmonics and will reduce the brilliance.

TOUSCHEK LIFETIME

The small emittances and the bunch length will increase strongly the Touschek scattering rate and will decrease the lifetime. The Touschek lifetime [10, 12] has been calculated using the momentum acceptance shown in Fig. 4 and with emittances, energy spread and bunch length increased by IBS from Fig. 5.

An RF voltage of 6 MV has been chosen to achieve the highest Touschek lifetime. For smaller voltages the bucket height will limit the momentum acceptance. For higher voltages the reduction of the bunch length will also decrease the Touschek lifetime. In the continuous mode with 960 bunches a Touschek lifetime of 3.9 h can be expected. In the timing mode with 80 mA the Touschek lifetime will only be 0.5 h.

SUMMARY

An optics based on hybrid multi-bend achromats has been investigated as a possible candidate for a lattice of PETRA IV with a natural emittance of 15 pm·rad. It consists of eight HMBAs per arc where each arc is a higher order achromat. The lattice has a dynamic aperture of 11 mm (without errors) in the horizontal plane at the injection point and a local momentum acceptance of 2–2.5 %. The influence of errors on the dynamic aperture and the momentum acceptance is currently under investigation.

Due to IBS the emittance, energy spread, and bunch length will increase depending on the emittance ratio and on the single bunch current. In the continuous mode an emittance of 20 pm·rad and a Touschek lifetime of 3.9 h can be expected for $\epsilon_y/\epsilon_x = 10\,\%$. In the timing mode the Touschek lifetime is rather low with 0.5 h and the emittance will increase due to IBS to 50 pm·rad. Increasing the emittance ratio and a longer bunch length can improve the situation.

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