EMITTANCE REDUCTION POSSIBILITIES IN THE PETRA III MAGNET LATTICE

V. Balandin, W. Decking, N. Golubeva*, R. Wanzenberg
DESY, Hamburg, Germany

Abstract

PETRA III is a third generation light source at DESY that has been operated as a user facility since 2010 with a horizontal emittance of 1 nm · rad at a beam energy of 6 GeV. Recently an upgrade for additional photon beamlines has been carried out, and the recommissioning of PETRA III started in February 2015 [1]. Because the current optics solution for the upgraded storage ring predicts about 20% increase in the horizontal emittance, it motivates us to study a question whether or not there are optics modifications which allow the reduction of the emittance without significant changes in the present magnet arrangement. In this paper we present the results of the first look at this problem mostly limiting our consideration to the capabilities of the linear optics of the separate storage ring parts.

STORAGE RING OVERVIEW

The current layout of the PETRA III storage ring [2,3] is shown in Fig. 1, and one sees that it does not look like a conventional synchrotron light source constructed from large number of identical cells accommodating insertion devices. This is a result of a long history of the modifications of the facility. The former electron-positron collider PETRA has been turned into a pre-accelerator PETRA II for HERA, and then, after the shutdown of HERA, PETRA II has been converted into the synchrotron light source.

PETRA II has consisted of four identical quadrants, each of them mirror symmetric with respect to the center of a straight section. Therefore one octant (half of quadrant or one eight of the ring) has reflected all lattice and optics properties of the machine. For PETRA III [2] it was decided to accommodate all insertion devices in one octant. The octant extending from North-East to East was redesigned, and the FODO lattice was replaced by a sequence of the double-bend achromat (DBA) cells (in the following we will refer to this section as the "new octant"). Besides that, for the additional emittance reduction, twenty 4 m long damping wigglers were installed in the straight sections West and North. As concerning the chromaticity correction, no sextupoles were placed in the DBA lattice, and the chromaticity correction was performed globally using old sextupoles in the remaining seven octants [4].

In the recent upgrade [3] two new experimental halls were built, one in the North and one in the East, each housing 5 new photon beamlines. In order to accommodate new insertion devices, the part of the hardware of arcs in two old octants is removed and replaced by DBA-like cells (the extensions North and East), and for the rest of these arcs (shortened octant arcs) the FODO structure is kept. No new

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* nina.golubeva@desy.de

sextupoles are added but several old sextupoles are uninstalled that leads to some reduction of the dynamic aperture (∼ 20% predicted, which is acceptable).
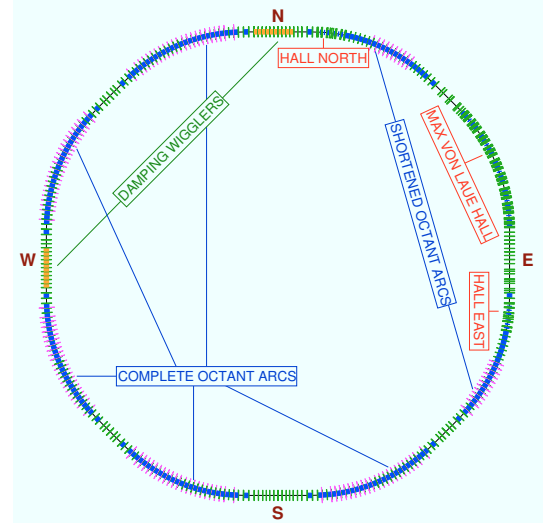

Figure 1: Layout of the PETRA III ring. Blue, green and red colors mark dipole, quadrupole and sextupole magnets, respectively. Yellow rectangles in the straight sections West and North indicate locations of the damping wigglers.

Contribution of Different Ring Sections to the Horizontal Emittance

One of the main figures of merit of the synchrotron light source quality is the value of the horizontal emittance which can be calculated as follows

$$\varepsilon_x \, [nm \cdot rad] \; = \; 1470 \left(E \, [GeV] \right)^2 \cdot \frac{I_5}{J_x \, I_2}, \qquad (1)$$

where I_2 and I_5 are the second and the fifth synchrotron radiation integrals, respectively, and J_x is the horizontal damping partition factor.

Table 1: Emittance Contributions of Ring Sections

Section	I_2	I_5
Old Octant Arcs	0.027 (9.5%)	3.29e-6 (48%)
New Octant	0.031 (11%)	1.70e-6 (25%)
Extension North	0.0057 (2.1%)	8.57e-7 (12.5%)
Extension East	0.0058 (2.1%)	8.05e-7 (11.8%)
Wigglers	0.211 (75.4%)	1.95e-7 (2.85%)
Total	0.280	6.84e-6

The contribution of different sections of the ring to the emittance is summarized in Table 1, where only the values of I_2 and I_5 are shown, because PETRA III contains no gradient dipoles and therefore $J_x \approx 1$. The value of I_2 is defined only by the reference orbit curvature and does not depend on the lattice functions. This means that the relative

contributions of the optics of different parts to the emittance are proportional to their I_5 integrals, and one sees that the seven old arcs (five complete and two shortened) produce approximately the same I_5 value as all DBA sections. It indicates that in order to obtain a sizable emittance reduction, it needs to involve the optics in all parts of the ring, what we investigate in the following sections.

OPTICS OF THE NEW OCTANT

The sequence of the DBA cells in the new octant provides eight places for the housing of the insertion devices (Fig. 2). Three of these sections are dispersion free in the current optics and five have an unavoidable small dispersion (less than 3 cm) because they are equipped with canting dipoles between two undulators to separate the synchrotron radiation beams. In addition, the current optics allows for each individual insertion section to choose high or low horizontal betatron functions by the user request.
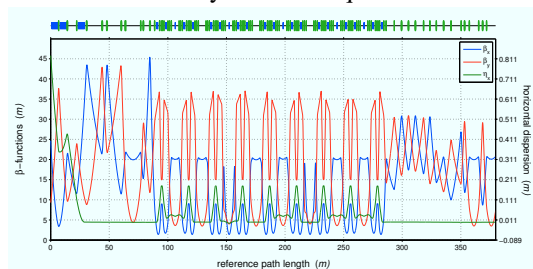

Figure 2: Current optics of the new octant.

Our study has shown that the reduction of I_5 by a factor of 2 is possible if main properties and features of the current optics are kept. If, additionally, small dispersion in all undulator locations is accepted (not larger than now in the canted cells), then the further reduction up to a factor of 5 can be obtained. Figure 3 shows the lattice functions of these new optics solutions. The horizontal chromaticity in these solutions increases by factors of ~1.5 and ~2.5 respectively. The change of the vertical chromaticitiy is not large, about 4% and 20%.
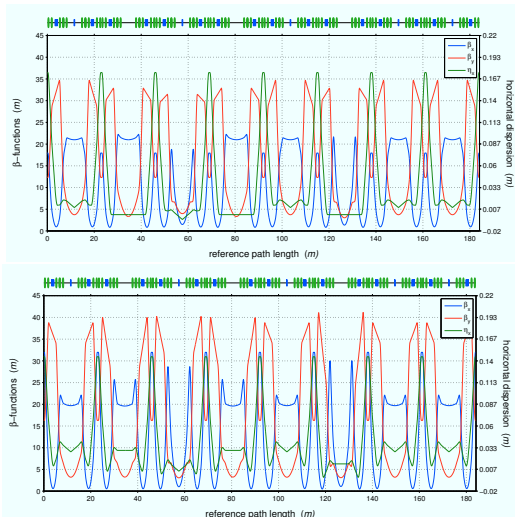

Figure 3: Optics for the DBA lattice in the new octant with the reduction of I_5 by a factor of 2 (top) and 5 (bottom).

EXTENSIONS NORTH AND EAST

The magnet lattices of both extensions are identical and therefore we consider only the extension North. The current optics of this section and its integration into surrounding lattice can be seen in Fig. 4. Extensive studies have shown that when the extension North is considered alone, then the reduction of I_5 up to a factor of 2 is possible. Unfortunately, all optics solutions providing the reduction on more than $20 - 30\%$ could not be smoothly matched not only to the current but also to reasonably modified boundary Twiss functions. Thus, though both extensions together contribute ~24% to the total I_5 value, the essential reduction of this contribution is not seen to be possible without additional matching quadrupoles.
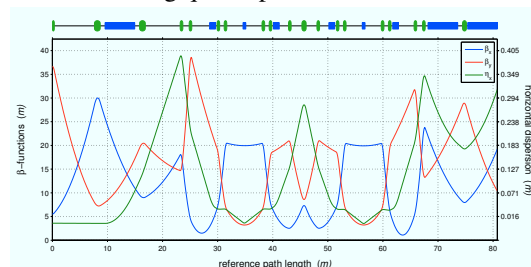

Figure 4: Current lattice functions of the extension North and its closest surrounding.

OLD OCTANT ARCS AND PROBLEM OF THE CHROMATICITY CORRECTION

Because the old octant arcs contain all sextupoles, the question of the reduction of their contributions to the I_5 integral can not be considered entirely in the framework of the linear optics. One needs from the beginning to have in mind the dynamic aperture problem, i.e. the problem of corrections of parasitic nonlinear aberrations created by the sextupoles during the chromaticity adjustment. The usual way (and probably the only systematic way known) to deal with that is to cancel as much aberration as possible by employing repetitive symmetry (see details in Appendix), and then within this symmetry to use more sextupole families for further improvements. It is exactly the approach realized in the current optics of the old octant arcs [4] which can be seen in Fig. 5. In two shortened arcs the sextupoles are located in five 72° FODO cells, and the complete octant arcs repeat this five cell combination two times.

To decrease the I_5 value of the FODO cell one has to go to higher horizontal phase advances, but in order to keep in the same time the good conditions for the cancellation of sextupole aberrations, it is better to use only the phase advances suggested by Table 2.

For example, let us take the phase advances $\mu_x = \mu_y = 90°$. These phase advances reduce I_5 by a factor of 1.8 and require the number of cells to be multiple of four. There are two ways to keep this multiplicity. First, to stay with four cells accommodating sextupoles in shortened arcs and with eight cells in complete arcs (i.e. to reduce the existing number of sextupoles). This solution can be more or less rea-

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sonably matched to the exiting optics of the other ring parts, but results in the reduction of the dynamic aperture which is incompatible with the current injection scheme. The other possible way, which is not explored yet, is to try to use eight cells in shortened and twelve cells in complete arcs, which, in general, is allowed by the arc magnet structure.

Other promising phase advances from Table 2 providing the reduction of I_5 by a factor of ~ 3 are $\mu_x = 108°$ and $\mu_y = 36°$. These phase advances can be realized only in the complete octant arcs because they require ten cell periodicity (Fig. 6). The problem of this solution is that it can not be matched to the current optics of the surrounding sections, and the first try of the tracking with some kind of an artificial matching shows the essential reduction of the dynamic aperture. The resulting aperture is more than sufficient to accommodate the stored beam but again is incompatible with the current injection scheme.
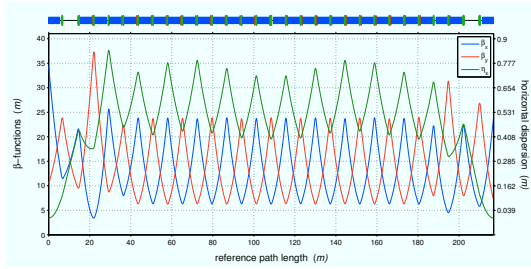

Figure 5: Current optics of the complete octant arc extending from short to long straight sections.
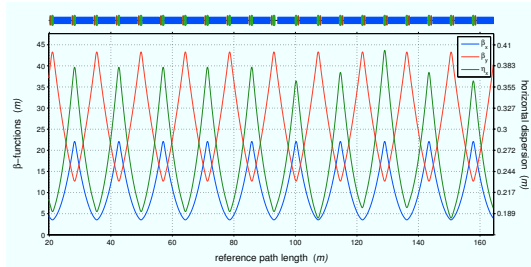

Figure 6: Optical functions for ten PETRA III arc cells with $\mu_x = 108°$ and $\mu_y = 36°$.

SUMMARY AND FUTURE WORK

Our studies indicate that from the point of view of the linear optics the reduction of the horizontal emittance at least by a factor of 2 is possible. The main limitations, as usual, come from the nonlinear beam dynamics and it is not clear yet if some sizeable emittance reduction compatible with the current injection scheme can be obtained. This problem and the question what kind of the emittance reduction can be obtained if the injection scheme will be reconsidered are the main topics of our further studies.

APPENDIX

The transfer map of a general magnetostatic system constructed from the elements which are symmetric about the horizontal midplane $y = 0$ can have as much as 18 independent transverse second order aberrations. But, as it is well known, if magnetostatic system consist of n identical cells and the overall transport matrix of this system is equal to the identity matrix for the horizontal motion and to the plus or minus identity matrix for the vertical motion, then the number of independent aberrations can be greatly reduced (not only for the second but also for the higher orders of non-linearity). The efficiency of this cancellation depends on the choice of the periodic cell phase advances. Let us consider the case when both transverse transport matrices are equal to the identity matrix, which means that the cell phase advances $\mu_{x,y}$ must satisfy

$$\mu_{x,y} = 2\pi q_{x,y} / n \quad (\mathrm{mod}\, 2\pi) \tag{2}$$

for some $q_{x,y} = 0, \ldots, n - 1$. We have compiled a table (Table 2) which lists all pairs (q_x, q_y) which are optimal in the sense that they minimize the sum of the number of independent transverse second (a_2) and third (a_3) order aberrations uncanceled by the n-cell repetitive symmetry. Note that the numbers a_2 and a_3 cannot be smaller than two and five, respectively (chromatic and nonlinear contributions to the cell tunes). Note also that in the last column of this table only the generating pairs (q_x, q_y) are shown. In order to obtain all optimal pairs one has to multiply generating pairs by all positive integers which are smaller than n and are coprime to n using modulo n arithmetic. For example, for $n = 8$ we have in this table the pair $(q_x, q_y) = (1, 3)$. This pair, when multiplied by 3, 5 and 7 using modulo 8 arithmetic, generates three more optimal pairs $(3, 1)$, $(5, 7)$ and $(7, 5)$.

Table 2: The Pairs (q_x, q_y) which Minimize the Sum $a_2 + a_3$

n	a_2	a_3	(q_x, q_y)
2	6	25	(1, 0), (1, 1)
3	6	11	(1, 1), (1, 2)
4	2	13	(1, 1), (1, 3)
5	2	7	(1, 1), (1, 4)
6	2	7	(1, 1), (1, 2), (1, 4), (1, 5)
7	2	5	(1, 2), (1, 5)
8	2	7	(1, 1), (1, 2), (1, 3), (1, 5), (1, 6), (1, 7)
9	2	5	(1, 2), (1, 3), (1, 6), (1, 7)
10	2	5	(1, 2), (1, 3), (1, 7), (1, 8)

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