RESEARCH ACTIVITIES TOWARDS A CONVERSION OF PETRA III INTO A DIFFRACTION LIMITED SYNCHROTRON LIGHT SOURCE

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Abstract

At DESY the Synchrotron Light Source PETRA III offers scientists outstanding opportunities for experiments with hard X-rays of exceptionally high brilliance since 2009. Research activities have been started towards a future upgrade scenario of PETRA III which envisions the conversion of the PETRA ring into a ultra-low emittance hard X-ray radiation source: PETRA IV. The lattice design is aiming for a horizontal emittance in the range between 10 pm rad and 30 pm rad at a beam energy of 6 GeV. Two different approaches have been considered for the lattice design: a design based on a hybrid multibend achromat with an interleaved sextupole configuration based on the ESRF design, and a lattice with a non-interleaved sextupole configuration with a special phase space exchange configuration. We are reporting the current status of the design activities including studies related to the injector.

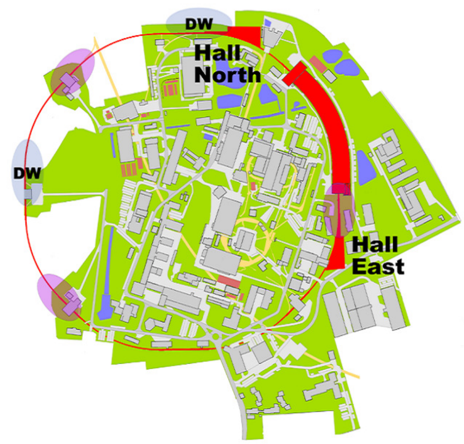

Figure 1: Layout of PETRA III with the three halls. The halls in the North and East have been added in 2014.

INTRODUCTION

Since 2009 DESY is operating the Synchrotron Light Source PETRA III [1] at a beam energy of 6 GeV and a very low beam emittance of $\epsilon_x \approx 1$ nm in the horizontal plane and $\epsilon_y < 10$ pm in the vertical plane. PETRA III offers scientists outstanding opportunities for experiments with hard X-rays of exceptionally high brilliance. Nine straight sections facilitated the installation of insertion devices for 14 beam lines. Due to the high demand for additional beamlines the lattice of the ring was redesigned in 2014 to accommodate 10 additional beamlines in two new halls. The general layout of PETRA III is shown in Fig. 1.

Presently a new generation of light sources (MAX IV, ESRF-EBS) is emerging using the concept of a multibend achromat (MBA) [2–5]. MAX IV is the first light source which was successfully commissioned with this new lattice type [6]. The design of the ESRF-EBS is aiming at a horizontal emittance as low as $\epsilon_x \approx 130$ pm rad at a beam energy of 6 GeV [7]. The APS team has designed a lattice with an even smaller emittance $\epsilon_x = 40 \ldots 60$ pm rad [8].

At DESY research activities have been started towards a future upgrade scenario of PETRA III which envisions the conversion of the PETRA ring into a ultra-low emittance hard X-ray radiation source: PETRA IV. The required emittance is $\epsilon_x \approx \lambda/4\pi$ to obtain diffraction-limited photons with a wavelength λ. The lattice design is aiming for a horizontal emittance in the range between 10 pm rad and 30 pm rad at a beam energy of 6 GeV, corresponding to a photon wavelength of 0.126 nm and 0.377 nm or a photon energy of 9.86 keV and 3.29 keV. The considered parameters for PETRA IV are summarized in Tab. 1. A storage ring based light source with an emittance in the range from 10 pm rad to 30 pm rad would be an ultimate 3D microscope which has the potential to image structures and their dynamics under in-situ and working conditions to decode emergent functionalities in nature.

Table 1: PETRA IV Parameters

PETRA IV	Parameter	(Range)
Energy	6 GeV	(4.5 ... 6 GeV)
Current	100 mA	(100 ... 200 mA)
Number of bunches	~ 1000	
Emittance horz.	10 pm rad	(10 ... 30 pm rad)
vert.	10 pm rad	(10 ... 30 pm rad)
Bunch length	~ 100 ps	

LATTICE DESIGN

Basically, two different approaches have been considered for the lattice design: a design based on a hybrid multibend achromat with an interleaved sextupole configuration based on the ESRF-EBS design [5], and a lattice with a non-interleaved sextupole configuration with a special phase space exchange configuration. Very low emittances lattices employing the multibend achromat concept require strong

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sextupoles for chromaticity correction since MBA schemes lead to small bending angles and therefore also to a very small maximum dispersion function. This, in turn, reduces the dynamic acceptance compared to a more relaxed lattice design as the double bend achromat (DBA), which are often used for the 3rd generation of light sources.

Hybrid Multibend Achromat

For the ESRF-EBS a special variant of the MBA, the hybrid multibend achromat (HMBA) or Raimondi lattice, was developed to mitigate the problems related to the strong sextupoles for the chromaticity correction [9, 10]. In a seven bend achromat space is left between dipoles 1 and 2, and 6 and 7 to accommodate a dispersion bump making the sextupoles more efficient. These concept is also adopted for one variant of the PETRA IV lattice. In Fig. 2 a lattice cell is shown based on the ESRF-EBS concept. Eight identical cells of the these type are forming one arc of the PETRA ring. Eight arcs together with the long and short straight sections are forming the PETRA IV lattice. The bare horizontal lattice emittance is $\epsilon_x \approx 12$ pm rad. Tracking studies without errors show quite promising results for the dynamic acceptance of this lattice variant. Beam accumulation seems to be possible. Certainly further investigations are necessary to confirm this preliminary result.

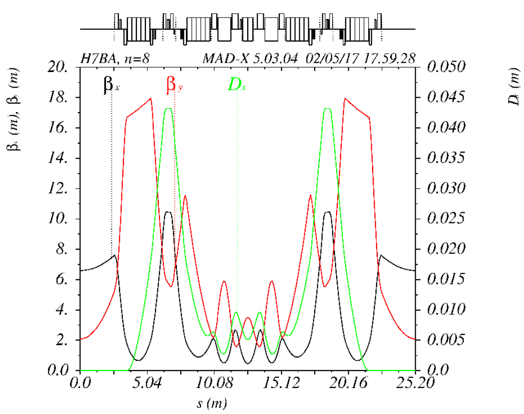

Figure 2: Hybrid seven bend achromat cell (length 25.5 m) with a bare cell emittance of 12 pm rad.

A severe limitation for low emittance lattices is the effect of intra beam scattering (IBS) [11, 12] which is a single bunch collective effect limiting the density of the particle beam. The emittance $\epsilon_{x,y}$ and energy spread σ_p of the beam will be an equilibrium between radiation damping, quantum excitation and IBS:

$$\epsilon_{x,y} = \epsilon_{x0,y0}\left(1 - \frac{\tau_{x,y}}{T_{x,y}}\right)^{-1}, \quad \sigma_p = \sigma_{p0}\left(1 - \frac{\tau_p}{T_p}\right)^{-1}, \qquad (1)$$

where $\epsilon_{x0,y0}$ is the zero current emittance, σ_{p0} the zero current energy spread, $\tau_{x,y}$, τ_p are the damping times and $T_{x,y}$ and T_p are the IBS growth rates. The long straight sections in the PETRA ring can be used to add damping wigglers to mitigate IBS effects. The equilibrium horizontal and vertical emittance taking IBS into account is shown in Fig. 3 assuming an emittance coupling of 10 %, 80 m of damping wigglers and a 100 MHz RF-system. The results are obtained with the simulation code elegant [13].

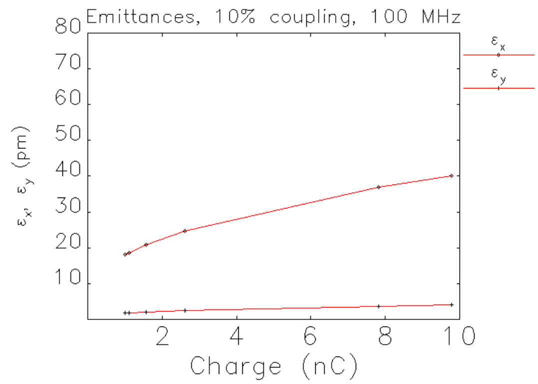

Figure 3: Emittance with IBS versus bunch current.

The presented IBS study was based on a hybrid six bend achromat cell (see Fig. 4) where 9 cells are forming one arc (8 arcs in total) and damping wigglers are installed in the straight section. The zero current emittance of the lattice is $\epsilon_{x0} = 11$ pm rad. The emittance for a beam current of 100 mA in 768 bunches is $\epsilon_x \approx 18$ pm rad.

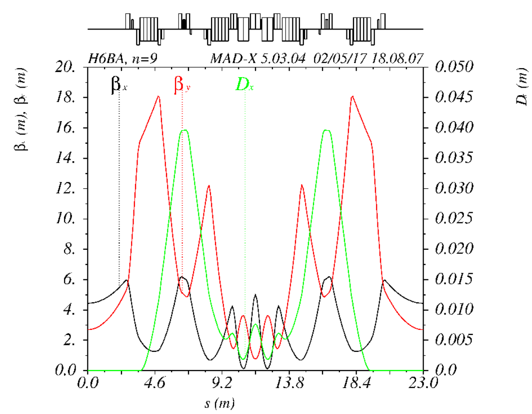

Figure 4: Hybrid six bend achromat cell (length 23 m) with a bare cell emittance of 25 pm rad.

Phase Space Exchange Lattice

A different approach to correct the chromaticity in a low emittance MBA lattice is based on the so-called non-interleaved scheme where sextupoles are placed at π phase advance combined with a phase space exchange at two positions in the PETRA ring.

The basic concept is illustrated in Fig. 5 for an arc cell based on a six bend achromat. Two sextupoles are placed at a phase advance of π at a position with identical β functions. Neglecting the nonlinearities in the quadrupoles the chromatic effect on the optics between two adjacent sextupoles is to first order linear in the momentum deviation δ. For $\delta = 0$ the nonlinear kicks of the sextupoles cancel each other in

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the thin lens approximation. The chromaticity is corrected either in the x or y plane.

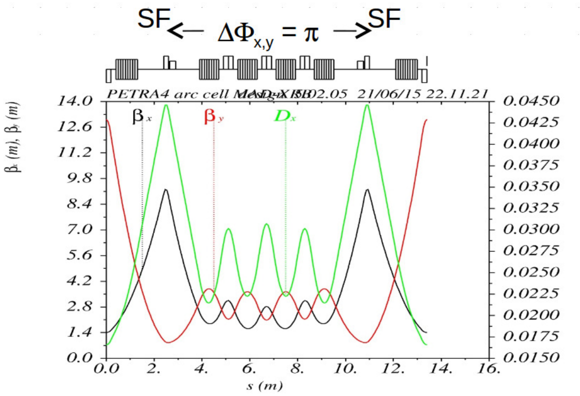

Figure 5: Conceptual layout of a six bend cell with a π-phase advance between sextupoles.

It is of course necessary to correct the chromaticity in both planes (x and y). This can be accomplished with a (non local) correction scheme which makes use of a phase space exchange between the x and y planes. Phase space exchange was tested at CESR in 1999 [14] using a Möbius insertion in the lattice based on a special arrangement of skew quadrupoles. If one combines two of these phase space insertions in the PETRA ring it is possible to correct the chromaticity $\zeta_x + \zeta_y$ in both planes with the *same* type of arc cell (Fig. 5) while the ring is no longer of Möbius type. The optic is locally uncoupled in the arcs. Only in the special phase space insertions a fully coupled optic exist. The phase space exchange concept is illustrated in Fig. 6. In the straight section SE and NW a phase space insertion is indicated with a double arrow cross. In one half of the ring the horizontal chromaticity is corrected while in the second half the vertical chromaticity is corrected. Due to the phase space exchange the emittance in both planes is the same producing a round beam with 100 % emittance coupling. Based on this concept a lattice for the PETRA IV ring accommodating two experimental halls and the special phase space sections has been studied with an emittance of about $\epsilon_x = \epsilon_y \approx$ 25 pm rad. Preliminary results indicate that the dynamic acceptance is sufficient for an injection scheme which allows beam intensity accumulation. Presently, further studies are in progress to optimize the momentum acceptance.

Multi-Objective Genetic Algorithm (MOGA) [15] based on elegant tracking code has been installed in Maxwell cluster on December 2016 to optimize the linear and non-linear beam dynamics of the phase space exchange lattice as well as the hybrid multibend achromat lattice.

INJECTOR

The presently used injector for PETRA III is the synchrotron DESY II with an emittance of $\epsilon_x \approx 330$ nm rad and an emittance coupling ratio of $\epsilon_y/\epsilon_x \approx 0.1$ [16]. For PETRA IV an upgrade of the injector is necessary. One

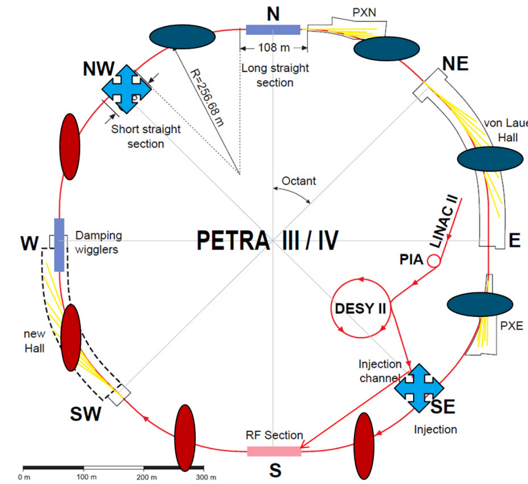

Figure 6: Illustration of the phase space exchange concept in the PETRA ring.

promising option is to build a new synchrotron with an emittance of $\epsilon_x \approx 10$ nm rad based on a scaled version of the ALBA booster [17]. The lattice for a booster ring with a circumference of 300 m is shown in Fig. 7.

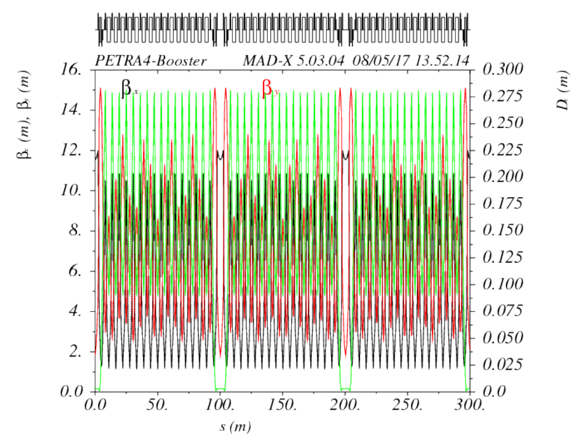

Figure 7: Lattice for a new booster ($\epsilon_x = 7$ nm rad).

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