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PETRA IV STUDY WITH NON-INTERLEAVED SEXTUPOLE SCHEME

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Abstract

This study is an attempt to design PETRA IV storage ring, which is an upgrade from PETRA III toward a diffraction-limit synchrotron light source, based on the non-interleaved sextupole scheme. The lattice is constructed by mixing different types of cells. There are two basic building blocks. The double minus identity (DMI) cell dedicated for the chromaticity correction with non-interleaved sextupoles is tightly built up, while the combined function FODO cell with dispersion suppressors provides straights with small beta functions ideally for undulators. In addition, the hybrid section including a 10-m long super insertion device (ID) is custom-made to adapt to DESY's current site plan. The beam dynamic behaviors are simulated and discussed.

INTRODUCTION

Pioneered by MAXIV's multi-bend lattice [1], the trend of synchrotron light source community is to pursue diffraction-limit storage rings. DESY also plans an upgrade project of PETRA III toward ultra-low emittance PETRA IV. Some challenges are the physical constraints such as the DESY's site plan and the existing PETRA tunnel. The schematic layout of PETRA III is shown in Fig. 1.

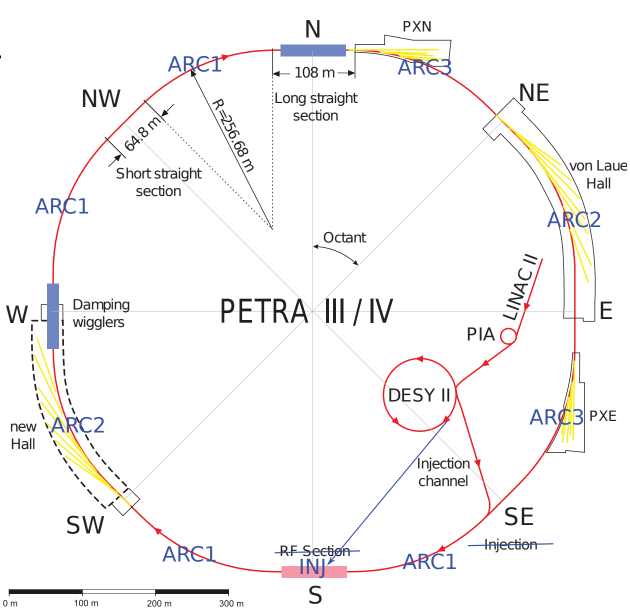

Figure 1: Schematic layout of PETRA III/IV with the new proposed experimental hall. The blue labels indicate the purposed arrangement for PETRA IV.

For the ultra-low emittance ring design, the multi-bend structure is important. On the other hand, the ultra-low emittance ring design faces the challenge in terms of sextupole strengths. With more bending magnets, the dispersions in dipoles can be suppressed, which leads to stronger chromatic sextupoles to correct the chromaticity. Therefore a dilemma exists between small emittance and acceptable sextupole strengths.

It is relatively easier to fit more bending magnets in the long arcs in PETRA tunnel. The other advantage of the PETRA tunnel is that it has very long straights, wherein the RF modules/damping wigglers/injection components can be clustered together. Therefore the lattice designer can save more space in the arcs to insert even more bending magnets. A downside of the PETRA tunnel is that more components are needed in the very long straights.

The design goals of this research are outlined as follows.

1. Small emittance at 6 GeV in the range of 10-30 pm-rad (overall effects including damping wigglers, intra beam scattering (IBS), etc),
2. At least 5-m straight sections for IDs,
3. Low beta functions to match the electron beam to the photon beam for optimum brilliance,
4. A new experimental hall in southwest-to-west octant.

Meanwhile, we also need to obey the physical constraints from the original tunnel which has very long straights. The other constraint is the preservation of the existing beamlines, including the ones in the two extension halls PXN and PXE.

In addition, although challenging, we hope to have the feature of the off-axis injection for accumulation in the storage ring.

LINEAR LATTICE

Considering DESY's current site plan, not all of the arcs can be used for the beamline extraction. Therefore, this design will not be conventional as other third generation light sources which demand symmetry and straights everywhere for IDs. Since the tunnel was built for a collider, it's very natural to following the collider's logic to design such a ring. Strategically, one can mix different lattices for different purposes due to the tunnel's long circumference. We will have the cell dedicated for the chromaticity correction with non-interleaved sextupoles, and the cell which provides straights for undulators.

ARC1 by DMI Arc

It is well known that sandwiching an $-I$ section by a sextupole pair makes a perfect cancellation of the sextupole nonlinear kicks in phase space. This technique of non-interleaved sextupole scheme requires more space and is often used in collider lattices [2], since colliders are typically much more spacious than synchrotron light sources.

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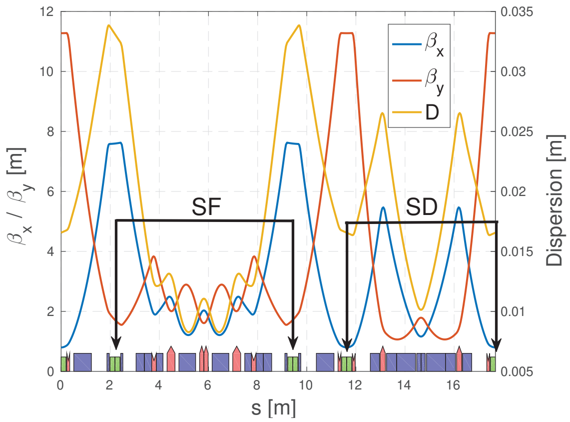

Figure 2: The DMI cell. Two pairs of non-interleaved sextupoles are indicated.

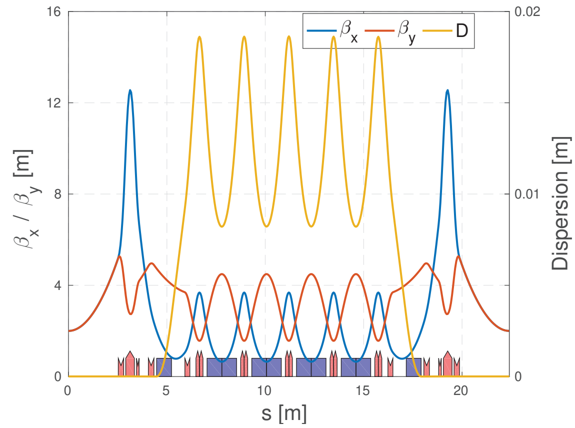

Figure 3: Combined function FODO with dispersion suppressors and a 5-m straight.

To apply this scheme in the small emittance ring design, one has to create slots for sextupole pairs in a cell with a small bending angle and limited length. Our solution has two pairs of non-interleaved sextupoles in a 17.7-m long cell with bending angle of 3.92 degrees. The lattice structure and its optical functions are shown in Fig. 2. The emittance of this cell itself is 23 pm-rad. This type of cell is named double minus identity (DMI) cell. It is the basic building block for the arcs not accommodating photon beamlines.

The sextupole pairs are located at places with non-zero dispersion and identical optics. The betatron phase differences are 180 degree, in both directions for each pair. Due to the big difference of beta functions, one pair (SF) is more effective for horizontal chromaticity correction and the other (SD) vertical.

Eleven DMI cells make one DMI arc which provides the function of chromaticity correction. To make the lattice more symmetric and facilitate the optics matching, the ARC1 lattice is enclosed by an additional section of the part of SD pair in the DMI cell. In total, there are 11 SF pairs and 12 SD pairs in one ARC1 arc.

ARC2 by Undulator Arc

The other basic building block is chosen to be the combined-function FODO cell with dispersion suppressors. The FODO cell yields small natural chromaticity that facilitates the chromaticity correction. Besides, the gradient component in the bending magnets repartitions the damping coefficients, making the emittance smaller. The lattice structure and its linear optics functions are plotted in Fig. 3.

Outside of the FODO cell, the dispersion suppressor is composed of one quadrupole and one bending magnet at proper locations. The outer quadrupoles flatten and focus the beta functions to small values. They can offer some tunability for the beta functions in the straights, and also correct the optics when canted or non-canted IDs are presented.

This cell is obtained by PMSOEA [3] optimization. In the multi-objective optimization the objectives that cannot be minimized simultaneously are the cell's localized vertical chromaticity and its natural emittance. The vertical chromaticity was chosen for the consideration of lowering SD strength in DMI cells. After the pareto front of viable solutions is founded, an optimum solution with emittance of 23 pm-rad is picked accordingly. A viable solution is defined as a lattice of this structure which is 22.4 m long and has a straight longer than 5 m with 2-m beta functions in the center.

Nine of these sections form ARC2 which provides eight straights for undulators. An advantage of this design is that the photon beamlines in the existing Max von Laue experimental hall can be kept essentially in its present configuration.

ARC3: Hybrid Arc

In PETRA III, ID beamlines in the two extension experimental halls PXN and PXE are extracted in the northeast-to-north and southeast-to-east arcs. To keep these beamlines, two 5-m straights and one 10-m straight for a very long ID (super ID) in the upstream end of each of these two arcs are needed. The rest of the arc can be filled with DMI cells. The resulting hybrid arc (ARC3) is formed by replacing 3 DMI cells in ARC1 with 2 custom-made undulator cells and 1 super ID section, as shown in Fig. 4.

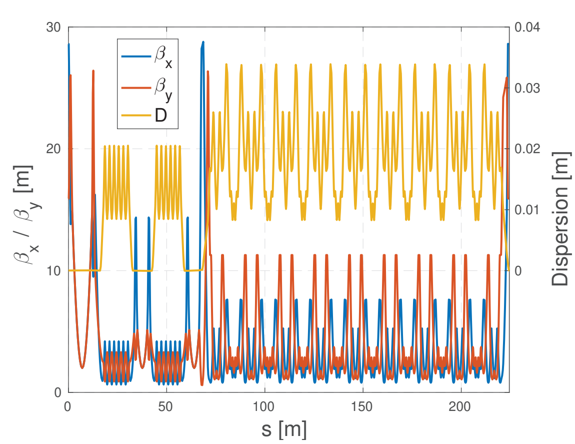

Figure 4: ARC3: This hybrid arc consists of DMI cells and FODO cells with 3 straights for existing extension halls.

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The Whole Ring

The straights in between arcs are inserted with FODO cells and some quadrupoles for the optics matching. Different types of arcs are joined by matching the optics in the ends of arcs and in the straights. The straight lengths also need to be tailored, in order to fulfill the geometry constraints. As for the injection, it is at the center of the long straight in the south with the beta functions $(\beta_x, \beta_y) = (100, 30)$ m.

Concatenating all pieces together according to the arrangement of the arcs depicted in the blue labels in Fig. 1, the full optics along the whole ring is shown in Fig. 5. This lattice is highly asymmetrical. The storage ring parameters are listed in Table 1.

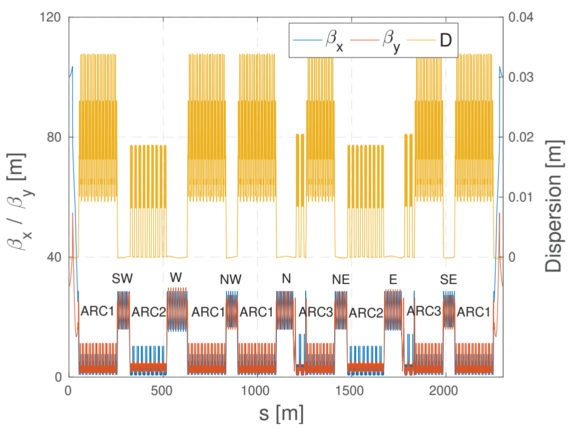

Figure 5: Highly asymmetrical full ring optics.

Table 1: Storage Ring Parameters

Energy	6.0	GeV
Circumference	2304	m
Working Tune	139.125/107.60	
Natural Chromaticity	-204.3/-166.3	
Damping Partition	-1.5	
Momentum Compaction	0.036	10^{-3}
Energy Loss	1.14	MeV
Eqm. Emittance	22.8	pm-rad
Eqm. Energy Spread	1.05	10^{-3}
Damping Time (H/V/L)	32.2/80.8/164.7	ms

Compared to PETRA III, the injection section is moved to south from southeast, while RF modules are moved to other free straights. It offers 20×5 m + 2×10 m achromat straights, all with 2-m beta functions in the center.

NONLINEAR DYNAMICS

In PETRA III there are no sextupoles in DBA sections. The chromaticity is compensated only by the sextupoles existing in FODOs in arcs. In this design, the same concept is used. The non-interleaved sextupole pairs in DMI cells should take care of the compensation of the chromaticities generated all over the ring. The chromaticity response matrix shows that the required sextupole strengths to compensate the chromaticity generated by the DMI cell itself are $K_2 = (121, -191)$ m^{-3}. When all other parts are included, the required SD strength grows as $K_2 = -276$ m^{-3}.

A simulation of 4D tracking without errors shows the DA at the injection point is of the size $\pm 17 \times 5$ mm. The DA is sustainable for the off-axis injection even when it is reduced by a factor of 2 due to imperfections.

However the maximal allowed energy deviation for chromatic tune shift (δ_{max}) is merely up to 1.7%. This is because of the poor local momentum acceptance (LMA) due to the highly asymmetrical structure.

It can be improved by splitting the sextupoles into many families. Two sextupoles with 180 degree phase difference are still paired together to have the cancellation. One way to arrange the families is to distribute the families as even as possible according to the wrapped phases $2\mu_x$ and $2\mu_y$. The idea behind is to have the internal cancellation of the chromatic half-integer stopband. Tentatively, the sextupoles are split into 16 families and arranged manually without an optimizing procedure. Then an evolutionary multi-objectives optimization procedure is applied [4]. δ_{max} is enlarged to 2% without altering the on-momentum DA too much.

There are two operation modes purposed for users. In the brightness mode it offers 200 mA in 1600 bunches, while in the timing mode 80 mA in 80 bunches. The estimated Touschek lifetimes for these modes including the effects of IBS and bunch lengthening by harmonic cavities are 158 and 33 minutes respectively.

Conclusively, the beam accumulation in the storage ring in the brightness mode is possible. On the other hand, in the timing mode the lifetime is insufficient for the radiation safety consideration.

CONCLUSION

In summary, an ultra small emittance storage ring is designed for PETRA IV based on the non-interleaved sextupole scheme and mixing lattices. The resulting equilibrium natural emittance is 23 pm-rad. It offers many straights with low and identical beta functions in current and new experimental halls.

The non-interleaved sextupole scheme and the high beta function in the injection straight help the small emittance storage rings design overcome the small dynamic problem, making the off-axis injection possible. But it comes at the expense of a relatively small LMA due to its asymmetrical structure. Its capability of beam accumulation in timing mode operation is still worrisome.

In an internal discussion in September 2018, this lattice option is not considered as the baseline lattice for the conceptual design report for PETRA IV. While the lattice design presented here represents a good choice for PETRA IV regarding favorable dynamic properties, other considerations such as a further extendability with more photon beamlines will have an impact on the final design decision. However, the DMI lattice is still valuable. For example, it is potentially useful in a compact damping ring design.

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