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DESIGN CONSIDERATIONS OF A HIGH INTENSITY BOOSTER FOR PETRA IV

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Abstract

A 6 GeV booster lattice with a high intensity capacity for the PETRA IV project is presented. Firstly the requirements and constraints are articulated. Due to the geometric constraints the ring will be installed in racks mounted on ceilings. Then following some design strategies of reaching high intensity limit, a lattice is designed and presented. The topics covering the linear optics, nonlinear dynamics, orbit correction, orbit bump, and some instability studies are investigated.

INTRODUCTION

The PETRA IV project [1,2] toward a diffraction limit synchrotron light source at 6 GeV features an ultra low emittance storage ring and a small dynamic aperture. Whether using on or off axis injection, the emittance of the injected beam must be very low. The current booster DESY II's emittance is 350 nm-rad at 6 GeV, which is too large for PETRA IV's injection. Therefore a new ring accelerator where the beams to-be-injected are prepared is always needed. This ring is named DESY IV. This article focuses on the booster option tuned for high intensity capacity with acceptable emittance.

DESIGN CONSIDERATIONS

Performance Requirements

The required charge to be delivered into the storage ring is as high as 8 nC per bunch. Considering losses during transfers, the single bunch intensity capacity requirement in DESY IV is adjusted higher as 10 nC. An additional challenge comes from the small required emittance. To be more specific, the proposed operation modes for the storage ring [2] demands the injector to deliver a 10 nC electron beam at 6 GeV with the emittance less than 30 nm-rad at a repetition rate of at least 1 Hz.

One should also be careful of the equilibrium bunch length at 6 GeV, which should be controlled within 2 cm for better storage ring injection efficiency.

The collective instabilities are usually more severe at low energies. Hence it is beneficial to increase the energy of the input beam, which is limited by the length of the current LINAC II tunnel. For this study, a reasonable assumption is made to set the input energy at 800 MeV.

Because of the on-axis injection, the degraded bunches in PETRA IV will be swapped by the full intensity bunches from DESY IV. The swapped-out bunches can be back-injected into DESY IV. There are two purposes for the back-injection. The first is to use DESY IV as an alternative for the beam dump system. It takes the swapped-out bunches, ramps down the energy, and dumps it at low energy. The second purpose is to recycle the bunches to relax the workload of the electron gun. The capability to inject and accumulate beams at 6 GeV is optional but it will be included in the design phase.

Geometric Constraints

Due to the DESY's crowded site plan DESY IV has to be in the existing DESY's tunnel. The top view layout of an example ring of DESY IV together with DESY II in the existing tunnel is shown in Fig. 1.

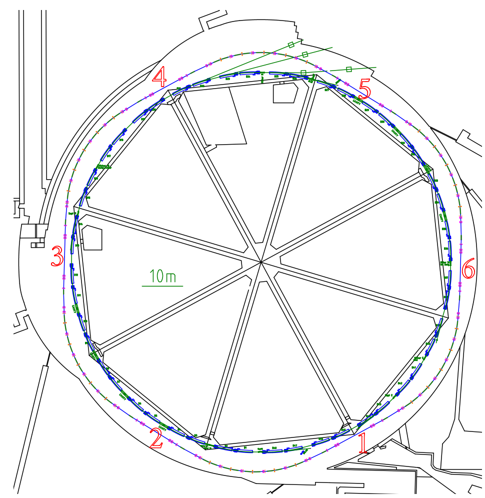

Figure 1: Layout of DESY IV (3h3l lattice) and DESY II in DESY tunnel.

The outer walls of the DESY tunnel are very round, while the inner walls has 8-fold symmetry. Other than DESY II, this old wide tunnel also accommodates the depreciated proton synchrotron DESY III which was constructed for the HERA project. It is concentric to DESY II and sits near the outer walls of the tunnel. DESY IV's circumference is chosen to be the same as DESY III ($C = 316.8$ m). Therefore the remaining components of DESY III will be removed to install DESY IV.

A racetrack or a square-track geometry would be problematic concerning the tunnel wall constraints. Hence a rounder shape of DESY IV is preferred. Considering the locations for the ports for the extraction and re-injection from PETRA IV, DESY IV's shape is toggled to have 6 straights. DESY IV has to be oriented in a way so that the extraction direction of DESY IV roughly aims at the injection position of PETRA IV.

The DESY IV's orbit will be in the same plane as that of PETRA IV, about 1.2 m above the DESY II level, with the

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hardware installed in racks mounted on the ceilings or tall girders. There are three reasons for this arrangement:

Keeping the Test Beamlines An additional strong constraint is imposed to keep DESY II and its three Test Beamlines dedicated to the detector development [3]. Lifting DESY IV higher can avoid the element conflicts and leave DESY II and all its Test beamlines untouched.

Easy to Install DESY's old tunnel's ground level is composed of many concrete slabs of different heights, making it difficult to install simple girders around. Supporting components from the ceiling seems an easier solution. The existing cranes shall be removed and some tall supports may also be used.

Facilitating the Design of the Transport Line It is crucial for the injection into PETRA IV that the vertical dispersion is avoided. If the booster and the light source are at the same level, the transport line design can be greatly simplified.

Strategies of High Intensity Limit

To have a strong intensity capacity, all possible factors causing particle losses should be minimized. Hardware improvement can reduce particle losses, but the strong intensity beam will inevitably encounter the collective instabilities caused by the impedance effect. It is helpful to identify the sources of instabilities. In particular, the TMCI is very important, which sets the intensity limits of every ring-based accelerator. The goal here is to design a lattice withholding a strong TMCI threshold.

As a guideline, the TMCI threshold for a zero chromaticity lattice is approximately [4]

$$I_{th} = \frac{4\sqrt{\pi}(E/e)\sigma_\delta \alpha_c \nu_\beta}{RZ_{tr}}, \tag{1}$$

where E is the beam energy, σ_δ the relative beam energy spread, α_c the momentum compaction factor, ν_β the smaller betatron tune, $R = C/2\pi$ the averaged radius, and Z_{tr} is the effective transverse impedance. Clearly, reducing Z_{tr} is beneficial; that requires large aperture beam pipes with minimum transitions, which, in turn demands large aperture magnets.

The factors E and σ_δ depend on the beam. Meanwhile, the lattice dependent factors are α_c and ν_β. To have higher α_c, higher dispersion in bending elements is essential. On the other hand, higher dispersion in bending elements contradicts the small emittance lattice design. In other words, one can not have a lattice with both small emittance and large momentum compaction. A good balance between the momentum compaction and the equilibrium emittance has to be found.

Moreover, the lattice will have special designed straights dedicated for cavities. These straights will be achromat for the sake to decouple the particles' horizontal and longitudinal motions so that the concerns of the synchro-betatron coupling instability can be eliminated. In cavities, the unwanted high order resonance modes excited by the beam also cause instabilities. This effect is more significant in a compact 6 GeV synchrotron compared to that in mid-energies because much more cavities are be used. This effect can be suppressed by using high order mode damped cavities and minimizing the local beta functions at these straights, because the impedance contributions are weighted according to the local beta functions.

LATTICE 3h3l

Linear Lattice

The lattice is comprised of 6 TME cell based arcs, 12 dispersion suppressors, and 6 achromat straights. Out of the six straights, three are 8.8-m high beta straights and three 7-m low beta straights. They are arranged alternatively to have three-fold symmetry. That's why this type of lattice is named 3h3l. In a nutshell, the linear optical functions in a symmetric section are shown in Fig. 2. The magnet name labels and their arrangement are also indicated.

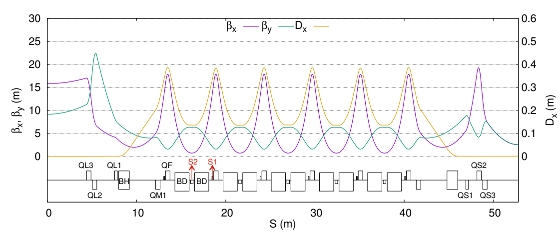

Figure 2: Optical functions and the magnet names in one sixth of the 3h3l lattice.

The elliptical beam pipe outer radii are assumed 23 mm horizontally and 15 mm vertically. For the RF, at least six 500-MHz PETRA cavity modules plus some extra spares are needed to provide sufficient 12 MV RF voltage at 6 GeV. Some important parameters are listed in Table 1.

Table 1: Parameters of the 3h3l Lattice

Circumference	316.8	m
Betatron Tunes (H/V)	17.37 / 12.15	
Natural Chromaticity (H/V)	-41.8 / -13.8	
Momentum Compaction Factor	3.17	10^{-3}
Damping Partition J_x	2.56	
at Beam Energy 6 GeV		
Energy Loss Per Turn	6.55	MeV
Damping Time (H/V/L)	0.8 / 1.9 / 4.5	ms
Equilibrium Emittance	19.1	nm-rad
Equilibrium Energy Spread	2.64	10^{-3}
Equilibrium rms Bunch Length	20	mm
TMCI Threshold Q_{th} †	11.44	nC

† Estimated by Eq. (1) with $E = 800$ MeV, $\sigma_\delta = 0.25$ % and $Z_{tr} = 1$ MΩ/m as a conservative assumption.

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Nonlinear Dynamics

The nonlinear dynamics are studied by the tracking program Elegant [5]. As a result, the on and off-momentum dynamic apertures are shown in Fig. 3.

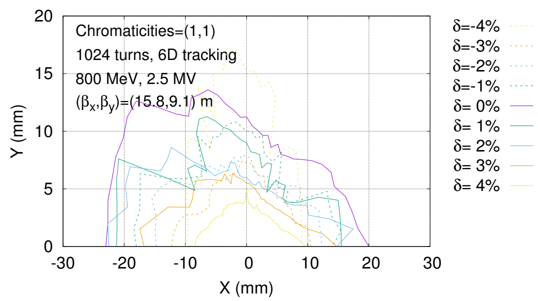

Figure 3: On-and-off momentum dynamic apertures.

The tune footprint with the diffusion rate and the tune shift with energies are simulated and shown in Fig. 4. If an universal physical aperture is subjected to 20 mm, the DA becomes 15 mm and the momentum aperture 5%.

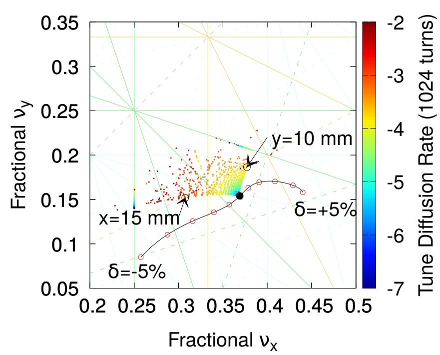

Figure 4: Fractional Tune Spread Footprint.

Orbit Correction

Different orbit correction schemes are tested in the following purposed location as shown in Fig. 5 [6]. An efficient configuration is found with 24 BPMs (at position label a, 2, 5, d) and 24 independent bi-directional correctors (at position label w, x, y, z). The max corrector strengths are within 0.5 mrad horizontally and 0.4 mrad vertically.

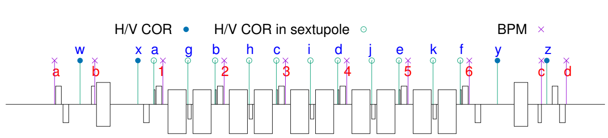

Figure 5: Some possible BPM and corrector locations (with labels) in one superperiod.

Straight Section Plan

The six straights are labelled in the layout in Fig. 1. Straight #1, #3, and #5 are the high beta straights, while the others are low beta straights dedicated for cavities. The low energy injection and high energy extraction are integrated in Straight #1. A horizontal local orbit bump can be formed by a pair of bumpers at two locations with $\Delta\mu_x = \pi$. The kicker leverage at the straight center is 5.5 mm/mrad. A tentative configuration of the injection/extraction elements and the orbits is depicted in Fig. 6. To avoid conflicts of elements the injection has to go vertically and a Lambertson septa is used.

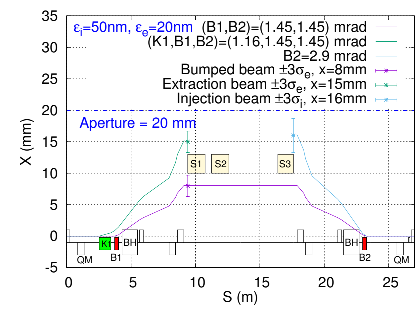

Figure 6: Orbits at injection/extraction straight.

Similar straights #3 and #5 are preserved for the injections of high energy beams. They could be from a future laser plasma wakefield accelerator [7], the DESY II sychrotron, or the recycled beam extracted from PETRA IV. The recycled beam will be re-injected into DESY IV in Straight #3.

SUMMARY

The criteria for the injector of PETRA IV are firstly articulated. Following a design strategy, a strong intensity limit booster is custom made for the PETRA IV project. The geometry is well-tailored to fit into the existing DESY tunnel. The orbit level is raised to be the same as PETRA IV so that the existing DESY II and its Test beamlines will not be altered.

Three low beta achromat straights provides enough space for RF modules. In contrast, the other 3 longer achromat straights has higher beta functions. Proper locations for efficient 2-kicker orbit bumps are found. The capability to accumulate the beam at high energies is possible. The low energy injection and high energy extraction can be integrated in one of these straights. In addition, the other two high beta straights are preserved for higher energy injection from other sources.

The input beam energy is raised to 800 MeV to improve the beam stability. The full intensity bunches or bunch trains will be on-axis injected into the storage ring by default. Furthermore, this ring can also be operated as a booster for possible top-up operation or being an accumulator at 6 GeV.

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