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LATTICE OPTIONS COMPARISON FOR A DLSR INJECTOR

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Abstract

DESY IV, as a part of the injector chain, must have lower emittance for PETRA IV injection. Depending on the scenarios of the injector, two lattice options for DESY IV are presented. They are designed for different purposes. The first option comes with a high momentum compaction factor with acceptable emittance. It is designed to be a full intensity booster. The other option is with low emittance dedicated to be an accumulator at high energies. The general beam dynamics properties are simulated and discussed. Their strengths and weaknesses are compared.

INTRODUCTION

The PETRA IV project [1, 2] toward a diffraction limit synchrotron light source at 6 GeV features an ultra low emittance storage ring with strong sextupoles and a small dynamic aperture. The emittance of the injected beam shall be rather small to achieve high efficiency, whether it is an on-axis injection of the full charge or an off-axis top-up.

Presently, the injector chain for PETRA III consists of an electron gun, followed by the 450 MeV LINAC II, the accumulator PIA, and the booster DESY II. DESY II's equilibrium emittance is 350 nm-rad at 6 GeV, which is too high for PETRA IV's injection. Therefore, a new low emittance accelerator is needed to prepare the injected beams. This ring, named DESY IV, may serve different functions in the injector chain, depending on the chosen injection scenario: a high-intensity or a top-up booster, a high energy accumulator, or a hybrid mode. Their features are listed as follows.

1. **Full intensity booster**
   This machine has to deliver very strong intensity charge with acceptable emittance (< 30 nm-rad at 6 GeV). The required charge can be as high as 8 nC per bunch in the Timing mode [2]. The challenges involve the collective instabilities at low energies. Therefore it is advantageous to raise the input energy.

2. **Booster for accumulation**
   In this machine a smaller amount of charge is prepared to be topped-up to PETRA IV. The machine requires very low emittance for off-axis injection in PETRA IV. The challenge is to reach the very low emittance (< 10 nm-rad) necessary for accumulation given PETRA IV's limited dynamic aperture.

3. **High energy accumulator**
   The accumulator ring operates constantly at 6 GeV and needs an effective kicker leverage and an acceptable emittance (< 30 nm-rad). Another accelerator is needed to prepare 6 GeV beams. If the beam emittance is low enough, the off-axis injection in the storage ring could also be possible.

4. **Hybrid mode**
   In this option the machine can accumulate the beam at mid-energies and then accelerate the beam to 6 GeV. This will complicate the operation and increase the time for beam preparation. Another accelerator is also needed to prepare the mid-energy beams.

LATTICE OPTIONS

The lattice designs for the options 1 and 2 follow different objectives, thus it is difficult to design a single lattice that could fulfill both requirements. Various lattices have been investigated and two of them will be presented and compared in the article. The first lattice (named 3h3l) is a lattice dedicated to the booster option. It acquires the full intensity beam from a LINAC and accelerates it to 6 GeV. The second one (named 10BA), featuring a lower emittance is a dedicated accumulator operated 6 GeV. Both lattices feature a circumference of 316.8 m, dictated by the existing tunnel, the harmonic number is 528. Their parameters are compared in Table 1.

Table 1: DESY IV Options – Parameters Comparison

Lattice	**3h3l**	**10BA**
Periodicity	3	8
Straight Length (m)	3×8.8+3×7	8×5.69
Working Tune (H/V)	17.37/12.15	22.22/8.32
Natural Chromaticity (H/V)	-41.8/-13.8	-24.2/-23.8
Damping Partition Jx	2.56	2.21
Momt. Compaction (10^{-3})	3.17	1.35
Beta Function β^* (H/V) (m)	15.8/9.1	8.9/2.1

Both lattices utilize combined-function magnets. The use of combined-function magnets not only reduces the number of magnets and space but also changes the damping partition to further reduce the emittance. Figure 1 shows the optical functions. Table 2 provides a brief comparison of the two options.

Table 2: Dynamic Properties of the Lattices At 6 GeV

Lattice	**3h3l**	**10BA**
Energy Loss Per Turn (MeV)	6.55	6.76
Damping Time (H/V/L) (ms)	0.8/1.9/4.5	0.9/1.9/2.4
Equilibrium Emittance (nm-rad)	19.1	5.5
Equilibrium Energy Spread (10^{-3})	2.64	1.99
Equilibrium Bunch Length (mm)[1]	20.0	9.9

[1] Assuming RF voltage of 12 MV.

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The 10BA lattice features a lower equilibrium emittance, bunch length, and energy spread at 6 GeV at the cost of the intensity limit (discussed further).

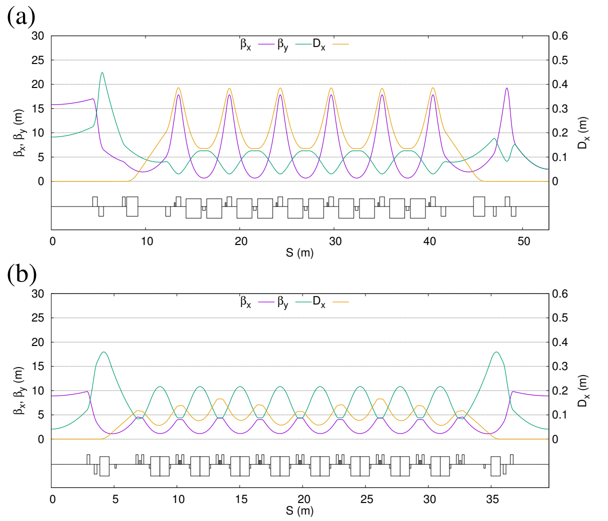

Figure 1: Optical functions of (a) 1/6 3h3l lattice and (b) 1/8 10BA lattice.

Lattice 3h3l

The 3h3l is designed to have strong TMCI threshold at low energies. The momentum compaction is increased on purpose without sacrificing the emittance too much. The lattice is composed of FODO cell based arcs and achromat straights. Similar structures have been used in many synchrotrons and accumulators for high-intensity proton beams [3]. The arc of the 3h3l lattice is consisted of five unit cells with combined-function magnets. The defocusing elements are split into two pieces to sandwich a sextupole for effective chromaticities correction. In the end of the arc are the dispersion suppressors and quadrupole triplets for matching.

This lattice offers two types of straights with 6 alternative high and low beta achromat sections. High beta sections are dedicated for the injections and extraction, while the low beta sections are preserved for RF modules. This approach minimizes the impact from the unwanted high order modes in RF cavities.

Lattice 10BA

The design goal of this lattice is to have a very low emittance ring for an off-axis injection in PETRA IV. This ring can be operated as a booster for accumulation or a static at 6 GeV accumulator. For the latter, good nonlinear properties are necessary so that the 6 GeV beams prepared from other accelerator can be accumulated in this ring.

The lattice is obtained by modifying MAX IV's 7BA structure [4] to a 10BA structure with 8-fold symmetry. It has a larger number of quadrupoles and sextupoles, which are also stronger compared to the 3h3l option, since this lattice is tighter focusing. Nevertheless, its nonlinear properties are superior with a larger dynamic aperture and momentum acceptance. The large momentum acceptance is also beneficial to accumulate the beam with higher energy spreads if, for example, laser plasma based accelerator is added to the injector chain in the future (such investigation is currently under way at DESY [5]).

Orbit Bumps

To be able to accumulate the beam, fast switch orbit bumps are needed. Efficient two-kicker bumps can be formed by a pair of bumpers located at positions with phase advance difference of 180°. Their locations are indicated in the dash line in Fig. 2. The leverage are 5.5 and 3.7 respectively. To facilitate the pulse magnet design in 10BA lattice, a four-kicker bump can be used instead to improved the leverage from 3.7 to 5.3. The strengths of inner kicker pair are about one third of those of the outer kickers pair. In this case the high energy accumulation in 10BA lattice is possible. The locations of the 4 kicker bumpers are indicated in the arrows in Fig. 2(b).

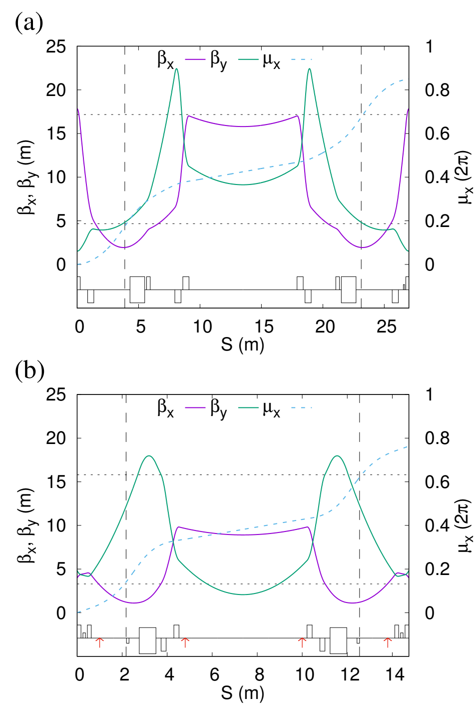

Figure 2: Optical functions in (a) high beta straight in 3h3l lattice and (b) straight in 10BA lattice.

Nonlinear Dynamics

The dynamic apertures of the two options tracked by Elegant [6] are shown in Fig. 3. For each lattice its injection energy is considered: 800 MeV for the 3h3l and 6 GeV for the 10BA. Both lattices have large enough dynamic apertures for the off-axis injection.

BEAM STABILITY

In order to compare the intensity limits of the two options an estimate impedance model of the ring has been created [7].

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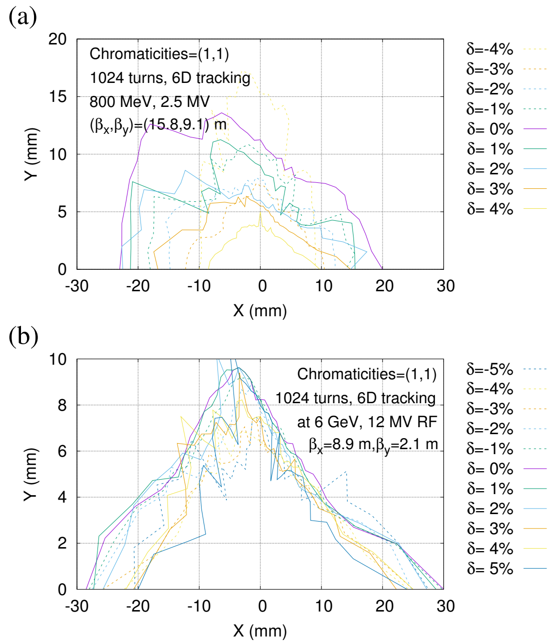

Figure 3: Dynamic apertures (a) 3h3l and (b) 10BA lattice.

For a fair comparison the same model has been used for both lattices, even though the 10BA has stronger magnets and thus might require smaller vacuum chambers. Here we assumed round stainless steel vacuum chambers of 20 mm radius and 0.7 mm thickness. They provide a good compromise between the resistive wall impedance, eddy-current induced thermal loads, and mechanical stress. Figure 4 shows the ring's impedance in the vertical plane.

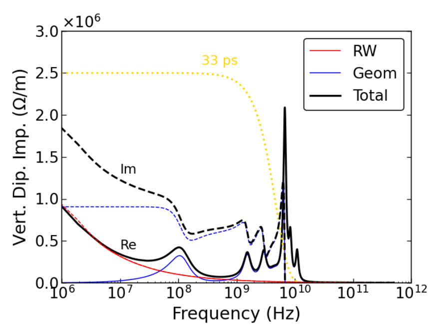

Figure 4: Vertical impedance as a function of frequency.

Potentially detrimental effect include the transverse mode coupling instability (TMCI) of the Timing [2] operation mode (1 bunch, high charge) and a coupled bunch instability of 20 bunch train of the Brightness [2] operation mode (low bunch large, high total current). Both effects are most critical at the 800 MeV energy, where the synchrotron radiation damping is negligible. Transverse beam stability has been analyzed by the NHT Vlasov solver [8] and the results are briefly summarized in Table 3. Bunch length was assumed to be 1 cm at 800 MeV and 2 cm at 6 GeV, according to tracking simulations in ELEGANT [6, 7].

The resulting single bunch TMCI threshold are well above the required 25 nC per 20-bunch train of the Brightness mode. The coupled bunch growth rates are rather low, even at the lowest energy of 800 MeV. They can be lowered by a choice of chromaticity and suppressed by lattice nonlinearities [7]. For the high-charge Timing mode the quoted TMCI limits at 800 MeV will further increase due to a ~ 100% larger momentum spread, thus ensuring a sufficient safety margin. While detailed tracking simulation of the LINAC injector performance and the injection Timing mode beam are still ongoing, it is clear that the 10BA option seems incompatible with its full 8 nC charge.

Table 3: Intensity Limitations of DESY-IV Options. TMCI Threshold Q_{th} Is Computed for a Single-Bunch. Coupled-Bunch Growth Time τ_{CB} Is Computed for the 20-Bunch Trains of the Brightness Mode with $Q = 1.5$ nC. Chromaticity $\xi = 0$. Synchrotron Damping Time, τ_{SD} Is Provided for Comparison

Effect	Energy	3h3l	10BA
Q_{th}	800 MeV	8.7 nC	3.8 nC
Q_{th}	6 GeV	150 nC	65 nC
τ_{CB}	800 MeV	10500 turn	8000 turn
τ_{CB}	6 GeV	4×10^4 turn	4×10^4 turn
τ_{SD}	800 MeV	7.5×10^5 turn	7.5×10^5 turn
τ_{SD}	6 GeV	1780 turn	1780 turn

CONCLUSION

The 10BA lattice is a dedicated beam accumulator at higher energies, and another accelerator is mandatory for the preparation of 6 GeV beams. It has the 528 magnets with stronger strengths. The power consumption of ring's magnets and RF is larger than for the 3h3l option. Its low momentum compaction factor brings instability problems at low energies, but its low emittance is very beneficial to the option of the booster for accumulation in PETRA IV. The 10BA lattice also can be operated in the hybrid mode. Regarding the technical challenges, the main one appears to be the fast kicker for beam accumulations at high energies.

The 3h3l lattice has 222 ramping magnets with moderate strengths. Its 19 nm-rad emittance and high intensity limit meet the requirement of the full intensity booster of PETRA IV. Although it has higher emittance, it can be a booster for accumulation in PETRA IV via the emittance rotation scheme by skew quadrupoles. It can also be operated as an accumulator at 6 GeV or in the hybrid mode. The lattice has no obvious weakness, and therefore it is considered as a baseline lattice.

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