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DESIGN STATUS OF DESY IV – BOOSTER UPGRADE FOR PETRA IV

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Abstract

In PETRA IV project the on-axis injection scheme is preferred since there is no sufficient dynamic aperture for off-axis injection in ultra low emittance storage rings. The challenge is the frequent preparation the injected bunches with the smaller emittance and larger intensity. The current injector complex including the accumulator and booster does not fulfill the requirements and thus will need refurbishments. The injector upgrade option chosen will be composed of an upgraded electron gun, a higher energy LINAC, and the new booster synchrotron DESY IV which has smaller emittance. DESY IV will be located in the existing tunnel of the current booster DESY II. The design of the lattice and some simulation results are addressed in this article.

INTRODUCTION

The PETRA IV project toward a diffraction limit synchrotron light source at 6 GeV features an ultra low emittance storage ring [1]. Its small dynamic aperture dismisses the possibility of an off-axis injection and accumulation in the storage ring. The on-axis swap out injection scheme is the alternative solution [2, 3].

It requires the frequent preparation of the bunch with full energy and full intensity prior the injection. The emittance of the injected beam either from a booster or an accumulator must be small enough to fit into the dynamic aperture. Moreover, the beam lifetime of the storage ring is less than PETRA III. It can be expected that the injection repetition rate is more demanding to maintain the desired currents.

The main performance challenge of the new injector is the delivery of as intense as 5.6×10^{10} particles (9 nC) per bunch with a beam emittance less than 30 nm-rad [4]. The current injector chain composed of an electron gun, the LINAC II (450 MeV), the accumulator PIA, and the booster DESY II does not fulfill the requirements. DESY II's emittance is too large (350 nm-rad) and the intensity limit of DESY II at 450 MeV is insufficient. Therefore the injector complex needs refurbishments. Important factors to be taken care of include the uniformities of the bunch intensity and energy, good injection efficiency, the cost and throughput. Beamlines for Test Beam Facility [5] must be taken into account as well. The other considerations are constraints from DESY's site plan and the project timeline.

This paper is organized as follows. Firstly various injector upgrade options are discussed and the choice is made. Secondly the lattice and the layout of DESY IV are described. Then the magnet specifications are listed. In addition, the preparation of high intensity beam and the beam recycling are discussed. Finally a short summary is given.

OPTIONS FOR INJECTOR UPGRADE

Various options are discussed for the upgrade of the injector. The option of a full energy LINAC with high intensity is very challenging, and it is not possible due to DESY's site constraints. On the other hand, one can add a dedicated accumulator sharing PETRA's tunnel while keeping the old injector complex unchanged. Its emittance can be easily less than 30 nm-rad. However this option is also not considered because of the narrow tunnel and the high cost.

Due to constraints from DESY's infrastructures, the only possible place of the new ring where the beam to be injected into PETRA IV is prepared is in the same tunnel as DESY II. This new ring, named DESY IV, can function as an accumulator or a booster or both. One way is to accumulate the beam in DESY II directly from LINAC II and then transport the beam to DESY IV for the acceleration to 6 GeV. But this configuration will suffer from the low throughput. A better way is to make DESY IV static at 6 GeV and just accumulate the beam in it. However, both options are not ideal since they are complicated systems involving the operations of DESY II and DESY IV.

Another option is to upgrade LINAC II and PIA to higher energy (e.g. 700 MeV) for the remedy for instabilities at low energy and use DESY IV as a small emittance booster. But a more straightforward solution is to acquire the full intensity bunches from the upgraded photocathode gun without an accumulator. By this way the complexity of the injector is reduced and the particle loss is less because of one less beam transportation. This option is our current baseline.

The capability to back-inject the swapped-out bunches from PETRA IV to DESY IV is optional but it is included in the design phase. There are two purposes for the back-injection. The first is to use DESY IV as a recycler to dump the beam. It takes the swapped-out bunches, ramps down the energy, and dumps them at low energy. The second is to re-use the recycled bunches to relax the workload of the electron gun.

LATTICE AND LAYOUT

The current booster DESY II shares the same tunnel with the abandoned proton synchrotron DESY III, which was constructed for the HERA project. The remaining components of DESY III will be removed to install DESY IV. The layout together with the current existing infrastructure is shown in Figure 1. Unlike DESY II, DESY IV's orientation goes counter-clockwise. The previous P-WEG transport line tunnel will be re-used for the booster to storage ring transport line. The current E-WEG transport line tunnel will be changed as the storage ring to booster transport line, if it is needed.

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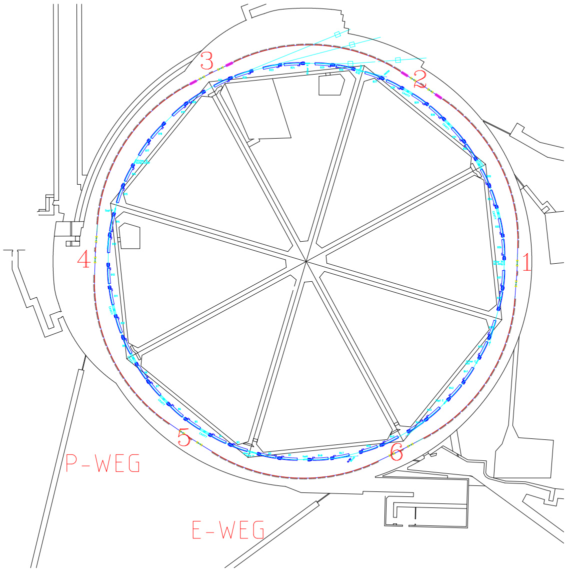

Figure 1: Layout of DESY II and DESY IV together.

The lattice has six-fold symmetry. The linear optical functions in one superperiod are shown in Figure 2. It consists of 9 combined-function FODO cells and 2 matching sections in both ends. Each FODO cell has phase advances of $\Delta\phi_x \approx 89°$ and $\Delta\phi_y \approx 58°$.

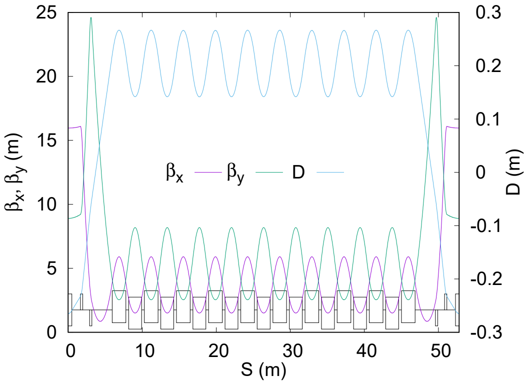

Figure 2: Optical functions in one superperiod.

A matching section consists of a quadrupole pair, a sextupole pair, and a separate-function dipole in the symmetric position. Two adjacent symmetric matching sections form an insertion section. In Figure 3, the optics in an insertion section are shown and the magnets are labeled. There are three different straights dedicated for various purposes. The 2.7 m long straight can accommodate a RF module, which is 1.8 m long from flange to flange. It is also where the pulsed magnets are located. In two such straights in an insertion section we can find spots with betatron phase difference $\Delta\phi_x = \pi$, ideally to form an orbit bump with pulsed kickers. The orbit bumps are used for the injections and extraction. They can also be used for the intensity control. The big dynamic aperture (> 30 mm without errors) and an orbit bump meet the requisites of the off-axis injection.

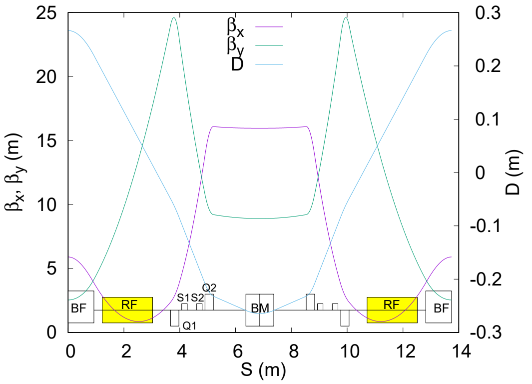

Figure 3: Optical functions in an insertion section.

The parameters of DESY IV are listed in Table 1.

Table 1: Booster Parameters

Periodicity	6	
Circumference	316.8 m	
Harmonic Number	528	
Repitition Rate	2-5 Hz	
Straight Length	2.745 / 0.935 / 1.165 m	
Working Tune	18.25 / 10.37	
Natural Chromaticity	-22.16 / -19.40	
Damping Partition	-0.36	
Momentum Compaction	3.30 10^{-3}	
Beam Energy	6 GeV	700 MeV
Energy Loss Per Turn	4.04 MeV	0.748 keV
Eqm. Emittance	19.3 nm-rad	0.261 nm-rad
Eqm. Energy Spread	1.12 10^{-3}	1.23 10^{-4}
Hori. Damping Time	2.29 ms	1.44 s
Vert. Damping Time	3.14 ms	1.98 s
Long. Damping Time	1.92 ms	1.21 s

In the straight between the quadrupole pair, the locations next to the quadrupoles are ideal slots for the additional sextupole pair which are used to compensate the chromaticity shift induced by eddy current effects during the ramping. The non-zero dispersion and the big difference of beta functions help the efficient chromaticity tuning. In the straights next to the middle dipole, the horizontal beta function is relatively large so they are locations for the septums for injections and extraction.

The functions of the six insertion sections, as labelled in Figure 1, are listed as below.

- Insertion #1 has two fast bumpers and one septum installed for the low energy off-axis injection.
- Insertion #2, #3 and #5 house five 500 MHz RF modules including one spare.
- Insertion #4 has two bumpers, some fast kickers and septums installed for the extraction.
- Insertion #6 is dedicated to the back-injection of the recycled beam.

RAMPING MAGNETS

There are two kinds of combined-function magnets with dipole, quadrupole, and sextupole field components alltogether. The quadrupole components re-partition the damping coefficients to gain small emittance, while the sextupole components correct the chromaticities to a slightly positive values. The magnet strengths of DESY IV are listed in Table 2. In addition, there are 24 sextupoles with strengths normalized at 6 GeV $K_2 < 3\,m^{-3}$. The gradient components in combined function magnets are more reasonable than the previous study [6].

Table 2: DESY IV Magnet Specification

Magnet	**BD**	**BF**	**BM**	**Q1**	**Q2**
L (m)	1.75	1.85	1.00	0.3	0.3
B_0 (T)[a]	0.86	0.35	0.90		
K_0 (m^{-1})[b]	0.043	0.0175	0.045		
K_1 (m^{-2})[b]	-0.44	0.49		-1.84	1.66
K_2 (m^{-3})[b]	-4.78	2.89			
# Element	54	60	6	12	12

[a] The dipole fields are estimated at 6 GeV.

[b] $K_0 \equiv 1/\rho$, $K_1 \equiv (\partial B_y/\partial x)/B\rho$, and $K_2 \equiv (\partial^2 B_y/\partial x^2)/B\rho$

The scalar potential of 2D magnetic fields in a combined function magnets is $\phi(x,y) = K_0 y + K_1 xy + \frac{K_2}{6}(3x^2y - y^3)$. The ideal pole faces can be found by the equipotential lines equations $\Phi(x,y) = \Phi(0, \pm h)$, where h is the half gap. Defining $p \equiv \frac{2K_0}{K_2} + \frac{2K_1}{K_2}x + x^2$ and $q \equiv \frac{h^3}{2} - \frac{3K_0}{K_2}h$, the analytical solutions around $x = 0$ follow the curves $y = \pm 2\sqrt{p}\cos\left(\frac{1}{3}\cos^{-1}(p^{-3/2}q) - \frac{2\pi}{3}\right)$ for BF and $y = \pm 2\sqrt{|p|}\sinh\left(\frac{1}{3}\sinh^{-1}(|p|^{-3/2}q)\right)$ for BD.

Similar to SLS booster's design [7], the magnets BD, BF and BM (perhaps plus Q1 and Q2) can to be properly designed so that all the driving currents are the same. Thus they can be connected in series to simplify the power supply topology. In practice one can change the gap and the winding number in order to match the driving currents $I_{BD} = I_{BF} = I_{BM}$. The coils of S1, S2, correctors, and trim coils of BM, Q1, Q2 are hooked to other independent programmable power supplies. This is for the finer dynamic control of tunes and chromaticities during the ramp.

HIGH INTENSITY BEAM PREPARATION AND BEAM RECYCLING

Apart from using an upgraded photocathode RF gun, 3 alternative methods for high intensity beam preparation are purposed. The first two methods recycle the swapped-out beam back into the booster instead of directing them into a beam dump. These methods are described as follows.

Refilling by Beam Stacking With Varying Energy

The first method is to replenish the recycled bunch by the fresh bunches from linac. But they are in different energies. The approach of transversely beam stacking with varying energy can be performed to resolve the problem. The steps are as follows.

1. Take the swapped-out bunch into the booster as the first beam.
2. Ramp the beam energy down and fetch a fresh bunch from the linac.
3. Raise the energy until the two bunches are fully damped and merged.
4. Repeat step 2 and 3 multiple times until the desired intensity is reached.

By this way the fast orbit bump at low energy is used and the sufficient damping is given when the energy is ramped up. The beam can be accumulated by topping-up the low energy bunches. An intensity control system and a sophisticated timing system are needed for quality control of the intensity. For example the feedback system can tell how much supplements the electron gun should prepare dynamically and an orbit bump can be used to scrape bunches. In terms of injection hardware configuration, one can reverse the arrangement of kickers and bumpers for high energy extraction as the high energy injection section.

This approach also provides a way to accumulate the beam from zero current in the booster. In this case the step 1 is skipped. In this approach, there will be concerns about particle loss during the ramping and the intensity limit results from the instability at low energy.

Replenished With Recycled Beam

This method was purposed in HEPS [8]. The booster is used not only to ramp the beam energy, but also to be an accumulator at high energy. After some fresh bunches are injected and accelerated to high energy, the recycled bunch is then poured and refills the intensity. In terms of injection hardware configuration, the four-kicker bumper can also do the job. This hardware configuration also works for the first method.

Phase Space Painting

The idea purposed in NSLS-II [9] is to accelerate two bunches painted at low energy. No recycled beam is used.

CONCLUSION

Options for the injector complex upgrade for PETRA IV are discussed. Among them, a feasible and simple option is chosen for the baseline. The new injector complex will be composed of an upgraded electron gun, LINAC II with higher energy output, and a new booster DESY IV in DESY II's tunnel without an accumulator. A preliminary design of the new booster DESY IV is completed. The alternative ways to prepare high intensity beams are also discussed.

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