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# THE INJECTION SYSTEM AND THE INJECTOR COMPLEX FOR PETRA IV

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*Abstract*

The PETRA IV project is to upgrade the current PETRA III light source to a 4th generation synchrotron radiation source reaching the diffraction limit of X-ray energies of about 10 KeV. Due to the small dynamic aperture of the PETRA IV storage ring, a horizontal on-axis injection is necessary. In this paper, the preliminary study of the injection scheme is described, including the details of the injection pattern and the technical requirements of kickers and septa. A beam abort scheme for the high intensity, low emittance beam is explained. To meet the requirements for the on-axis injection, upgrading the injector complex consisting of the Gun, the LINAC and the booster is planned. Several options are discussed in this paper.

## INTRODUCTION

The project PETRA IV at DESY, Hamburg, aims to upgrade the 3rd generation light source PETRA III to a 4th generation light source with ultra-low emittance to reach the diffraction limit [1]. The 2304-m, 6-GeV ring of PETRA IV consists of eight arcs with a length of 201.6 m and eight straight sections with two different lengths of 108 m and 64.8 m. To reach the ultra-low emittance, a lattice based on hybrid multi-bend achromats (HMBA) developed at the ESRF has been designed, resulting in a natural horizontal emittance of 17.4 pm rad. Two operation modes are planned. One is a brightness mode with 80 bunch trains of 20 bunches each with smaller emittance. The other is a timing mode with 80 bunches in total, but a higher single bunch intensity. The design parameters of PETRA IV are summarized in Table 1.

Table 1: Design Parameters of PETRA IV

| Parameters | Brightness Mode | Timing Mode |
|---|---|---|
| Emit. horz. / vert. (pm rad) | < 20 / 4 | < 50 / 10 |
| Total current (mA) | 200 | 80 |
| Number of bunches | 80 × 20 | 80 |
| Bunch population ($10^{10}$) | 0.6 | 4.8 |
| Bunch current (mA) | 0.125 | 1.0 |
| Bunch separation (ns) | 4 / 20 (gaps) | 96 |

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## INJECTION SCHEME

### *On-Axis Injection Scheme*

The dynamic aperture of PETRA IV is on average approx. 5$\sigma$ and in no case less than 3$\sigma$ of the injected beam, when alignment and field errors are taken into account [2], therefore, a swap-out on-axis injection is planned.

The short straight section (SSS) on the southeast of the PETRA IV storage ring downstream of the Ada Yonath Hall is chosen to accommodate both the injection and extraction section. The optical functions of the section are shown in Fig. 1. Figure 2 shows a schematic of the injection and extraction section. The incoming beam is positioned on-axis with a septum and two stripline kickers.

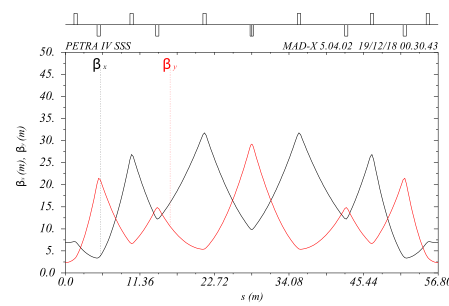


Figure 1: Beta functions of the short straight section SSS.

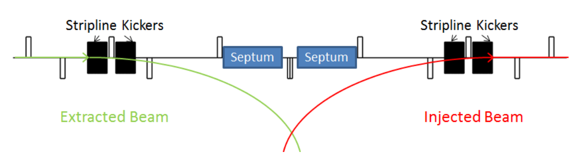


Figure 2: Schematic of the PETRA IV injection and extraction.

A septum similar to the existing pulsed septum of PETRA III operated by a half-sine pulse of 170 µs is considered as the baseline. However, the stored beam is affected by the stray fields from the eddy currents. To reduce the stray field effect of the pulsed septum and to increase the stability of the septum operation, a DC Lambertson septum is under consideration, too.

Other injection options such as the vertical on-axis injection will be studied in the next phase of the project.

For the extracted beam, two options are possible. The baseline is to dump the beam immediately after the extraction. Due to the low natural emittance of PETRA IV, the transverse beam size of the electron bunch is extremely small. To dump the beam safely, it is necessary to increase the beam

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size before extraction. This swap-out dump procedure is described later in this paper. The other option is to re-inject the beam from the storage ring into the booster and accumulate there [3]. For this option a transfer line to the booster will be required and the dump can be placed in the booster tunnel.

### *Separation Distance and Kicker Strength*

At the exit face of the septum the separation distance between the injected and the stored beam is calculated as

$$\Delta x_{sep} = 3\sigma_{inj} + x_{err} + s_d + s_a \quad (1)$$

where $\sigma_{inj}$ is the injected beam size, $x_{err} = 1$ mm is the orbit error, $s_d = 5$ mm is the septum bar thickness including vacuum chamber and $s_a$ is the aperture required for the stored beam. Assuming a booster emittance of 19.3 nm rad, an energy spread of $1.12 \times 10^{-3}$ [3], a beta function at septum location $\beta_x = 31.17$ m and a dispersion $D_x = 0.02$ m, the injected beam size is $\sigma_{inj} = 0.78$ mm. For the minimum required aperture we choose a larger aperture $s_a = 10$ mm, which is a typical beam pipe radius in the storage ring. In total, the separation distance is $\Delta x_{sep} = 18.4$ mm. To provide this separation two kickers with 0.67 mrad deflection angle are necessary. The injected beam trajectory is shown in Fig. 3.

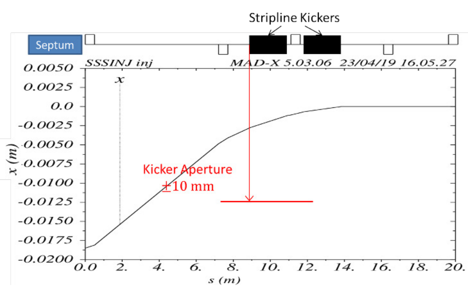


Figure 3: The horizontal trajectory of the injected beam.

### *Injection Fill Pattern*

For each injection, a single bunch will be injected for the timing mode. While for the brightness mode, a bunch train of 20 bunches will be injected each time. The injection fill pattern is shown in Fig. 4. For each bunch train, a flattop of at least 76 ns is required. Between each train, a gap of 20 ns will accommodate kickers' rise and fall times.

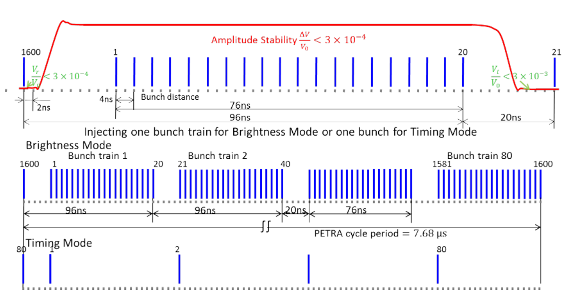


Figure 4: Injection fill pattern scheme for PETRA IV on-axis injection.

### *Injection Rate and Bunch Charges*

When the charge variation in the fill pattern is dominated by the charge decay rather than the fluctuation in the injected beam intensity, the maximum variation is given by $1 - \exp\left(-\frac{T_{inj}}{\tau}\right)$, where $T_{inj}$ is the time required for the full injection cycle and $\tau$ is the beam lifetime. In the worst case scenario with 30 minutes lifetime and 80 bunches in the timing mode, an injection frequency of 0.41 Hz or higher would guarantee the maximum charge variation below 10%. An injection rate of 0.5 Hz is planned, resulting in a maximum intensity variation of 8.4%.

The charge of the injected bunch in every transfer step is shown in Table 2. Here we assume roughly 90% transmission in every transfer step and three bunches out of the LINAC II (2.998 GHz) captured by the booster DESY IV (500 MHz).

Table 2: Charges (nC) of the Injected Bunch in Every Transfer Step

| **Machine** | **Brightness Mode** | | **Timing Mode** |
|---|---|---|---|
| | one train | one bunch | one bunch |
| PETRA IV | 19.2 | 0.961 | 7.69 |
| PETRA IV inj | 20.1 | 1.00 | 8.02 |
| DESY IV ext | 22.3 | 1.11 | 8.92 |
| DESY IV inj | 24.8 | 1.24 | 9.91 |
| LINAC II | 27.5 | 1.38 | 11.0 |

### *Kicker*

For PETRA IV we need an on-axis injection with a fast rise and fall time and high pulse repetition stability. The kickers are designed to work with identical currents and waveforms with an amplitude stability of $3 \times 10^{-4}$. The present XFEL Dump Kicker design is to be adopted with the geometry to be adapted to the conditions of the PETRA IV vacuum system, i.e. the distance between the electrodes has to be reduced from 30 mm to 20 mm. The HV feedthroughs have to be replaced. The baseline design requires a voltage of up to 11 kV at the feedthrough. Injection of bunch trains using a flat top pulse has been chosen as shown in Fig. 4. To accommodate the rise and fall times, the fill pattern will have gaps of 20 ns.

## SWAP-OUT BEAM DUMP

The 6 GeV electron beam in a 200 mA (~1500 nC) fill (brightness mode) of PETRA IV corresponds to a stored energy of about 9.2 kJ. Due to the very small beam size of a few microns, the beam will dissipate its energy in a tiny volume, resulting in high local energy densities in the order of 500 kJ/g. In addition, considering the swap-out extraction, the absorber is hit by beam pulses with a 1/80 charge in a regular cyclic manner with a repetition rate of 2 s. Considering an aluminum based absorber layout for a long term operation (~ 20 a) with a large number of about

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$10^8$ stress cycles, the beam induced load on the swap-out absorber must not exceed the cyclic load limit of 13 J/g. This requires to increase the transverse beam size by at least three orders of magnitude.

Before the extraction, the transverse beam size of the stored beam can be increased by applying a kick in both planes. After the kick, the transverse beam size blows up quickly during the following turns, which can greatly dilute the beam energy density before extraction. Figure 5 shows by different kicker strength, the evolution of the transverse beam size normalized to the initial beam size of the stored beam over the number of turns. A kick of 0.1 mrad in both planes is sufficient to increase the transverse beam size by more than 3 orders of magnitude within 50 turns of evolution.

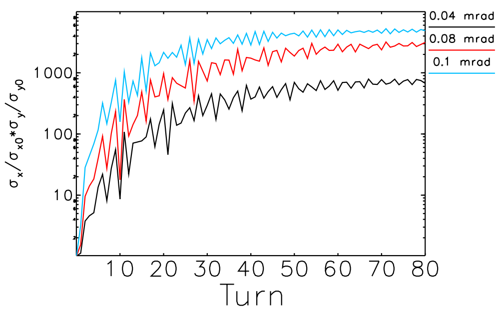


Figure 5: Normalized transverse beam size as a function of the number of turns for different values of kicks in both planes (1000 particles, $\varepsilon_x = 17.4$ pm rad, $\varepsilon_y = 4$ pm rad).

## INJECTOR COMPLEX

The concept of on-axis injection into the main storage ring necessitates that the total charge is either produced directly at the gun or accumulated in an intermediate ring. Depending on the filling scheme, 1.4 nC to 11 nC have to be produced per bunch (see Table 2). The maximum charge per bunch train is 27.5 nC. To fill a 500 MHz bucket of the storage ring the charge can be distributed over 3 bunches in the 3 GHz RF of the LINAC, i.e. the maximum charge per bunch is 3.7 nC. This is readily available from photocathode RF guns with emittances far better than required for injection into a synchrotron [4]. Scaling up the results from the S-Band gun of LCLS [5], a normalized emittance of 18 mm rad is expected.

To achieve easier operation and maintenance and higher reliability, a thermionic RF gun is envisaged. Such a gun was developed at MAXLab [6]. A gun of that type has been tested at DESY in 2008. At pulse lengths of 50 ns a current limit of 1 A has been determined which corresponds to a bunch charge of 330 pC. The limit was due to a self-heating of the cathode probably because of back bombardment. It shall be investigated if this limit can be overcome by increasing the cathode area or laser-enhancing the emission.

The current LINAC II consists of 10 full acceleration sections of an acceleration voltage up to 90 MV and two injectors delivering bunches of electrons with a minimal energy of 5 MeV. With the ten full sections, 700 MeV beam energy can be achieved with 2 sections reserved. To accommodate bunch trains of 100 ns and 200 mA, a slight change of the operation point would be necessary, resulting in a reduction of the acceleration voltage of approximately 6 MV per acceleration section. Adding two RF stations and acceleration sections and taking into account of the beam loading, 800 MeV can be reached while keeping a safe reserve of 2 stations.

A new booster is designed to meet the PETRA IV injection requirement. Details are discussed in [3].

## CONCLUSION

Due to the ultra-low natural emittance of PETRA IV, a preliminary design of a horizontal, swap-out on-axis injection is studied. Two stripline kickers are used in the southeast straight section to deflect the injected beam into the storage ring.The kick strength of 0.67 mrad challenges the current kicker design. The injection rate of 0.5 Hz guarantees that the charge variation in the storage ring is less than 10%. For the brightness mode operation, a bunch train of 80 bunches is injected once. Therefore, the kickers' rise and fall time requirements can be increased from ~ns to ~20 ns. Two types of septa are under further study. The swap-out beam dump scenario demands to increase the transverse beam size of the stored beam by three orders of magnitude with kicks of 0.1 mrad in both planes, resulting in a safe energy deposition, which is less than the cyclic load limit of the dump material. The injector complex, including the gun, the LINAC and the booster will be updated to provide the electron bunch satisfying the charge and emittance requirements to inject to PETRA IV.

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