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INJECTION DESIGN OPTIONS FOR THE LOW-EMITTANCE PETRA IV STORAGE RING

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Abstract

The proposed PETRA IV electron storage ring that will replace DESY's flagship synchrotron light source PETRA III will feature a horizontal emittance as low as 20 pm based on a hybrid six-bend achromat lattice. Such a lattice design leads to the difficulty of injecting the incoming beam into an acceptance that is as small as 2.6 µm. In contrast to earlier lattice iterations based on a seven-bend achromat lattice, the latest version allows accumulation, i.e., the off-axis injection of the incoming beam. In this contribution, the effects of deploying different septum types, namely a pulsed or a Lambertson septum, on the injection process as well as the injection efficiency are presented. This analysis includes the effects of common manipulations to the injected beam, e.g., beam rotation and aperture sharing, on the injection efficiency. Furthermore, the option of a nonlinear kicker and its optimization (wire positions, wire current, optics functions) are presented since a nonlinear kicker could provide an alternative to the rather large number of strip-line kickers that are necessary to generate the orbit bump at the septum.

SEPTUM CHOICE

The PETRA IV [1, 2] injection process is highly critical since the dynamic aperture (DA) in modern multi-bend achromat lattices tend to be small with PETRA IV being no exception, i.e., the acceptance is expected to be $A_x \leq 2.6\,\mu m$ in realistic machine conditions [3]. While an off-axis injection (accumulation) was ruled out for the initial seven-bend achromat lattice initially, the recent change of the baseline to a six-bend achromat lattice allows accumulation. In order to exploit the available acceptance as much as possible, a large horizontal beta function β_x at the septum and a thin septum blade is required. A pulsed septum may feature the possibility of a 1-mm-thick septum blade as envisaged by the SLS 2. A Lambertson septum could feature a 2-mm-thick blade; however, additional vacuum pipes may cause the effective blade thickness to reach 3 mm. While the pulsed septum would deflect the beam in the horizontal plane, a Lambertson septum would kick the beam vertically. The current transfer-line design features both an XFEL type Lambertson septum [4] as well as a SLS 2 type 1-mm-thick pulsed septum [5, 6] and an XFEL type 3-mm-thick Lambertson septum in a distance of less than 0.5 m (Lambertson septum acts as a pre-septum). This arrangement allows to offset the potential R&D risks if the pulsed septum is not operational at startup of PETRA IV since the sole Lambertson septum may suffice for the injection into PETRA IV without significant alterations of the transfer line. Figure 1 shows the injection section of PETRA IV with the septum location and the orbit bump generated by 16 strip-line kicker modules [7, 8] required for bringing the stored beam close to the septum blade. At the location of the septum, the β_x function reaches $\beta_x = 46$ m. In the following, the options of having a sole pulsed[1] and a sole Lambertson septum for the injection process is investigated.

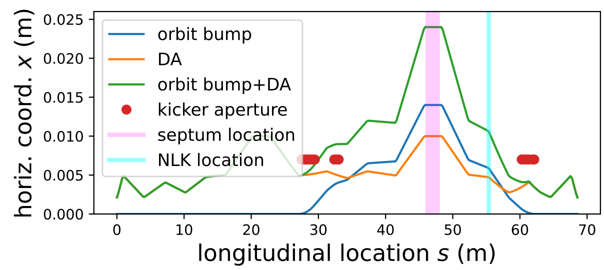

Figure 1: Orbit bump generated by strip-line kicker modules to enable the PETRA IV injection.

INJECTION-EFFICIENCY STUDY

Injection Scenarios

The injected beam is usually not matched to the optics functions of the stored beam at the septum. Emittance and optics manipulations are eventually carried out to enhance the injection efficiency. Throughout the analysis, four different injection scenarios are analyzed: a) Nominal injection, b) coupled beam (equally large horizontal and vertical emittances), c) rotated beam (exchange of emittances via three skew quadrupoles in the transfer line), d) aperture sharing (detuning of the last kicker of the orbit bump at septum causes the residual oscillation to be shared between the stored and the injected beam). It is important to note that while aperture sharing may lead to an improved injection efficiency in a single-particle model, the excitation of wakefields may lead to beam losses and has to be studied. The horizontal β_x function is optimized to better follow the curvature of the acceptance in all four injection scenarios (uses an modified version of the equation given in Ref. [9]). The separation between the injected and the stored beam Δx depends on the septum type, the optimized horizontal $\beta_{x,\mathrm{opt}}$ function of the injected beam and whether aperture sharing is applied.[2] The separation takes a 2 mm error margin, the (effective) blade thickness, three times the

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[1] The scenario of a sole pulsed septum covers the envisaged case of deploying the pulsed septum as a pre-septum for the DC Lambertson septum.

[2] For the aperture-sharing scenario, the separation of the beam at the last kicker has to be back propagated to the septum location.

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beam size of the injected and six times the beam size of the stored beam into account and reads in a reduced form $\Delta x_{\text{puls.}}(\beta_{x,\text{opt}}) = 3.2\,\text{mm} + 3\sqrt{\beta_{x,\text{opt}}\epsilon_x}$ for the pulsed septum and $\Delta x_{\text{lamb.}}(\beta_{x,\text{opt}}) = 5.2\,\text{mm} + 3\sqrt{\beta_{x,\text{opt}}\epsilon_x}$ for the Lambertson septum. The separations Δx, the optimum $\beta_{x,\text{opt}}$ values as well as the emittance values for the different injection scenarios are listed in Table 1. Furthermore, the $3\sigma_x$ envelopes of the injected beam at the septum (Lambertson and pulsed) are shown in Fig. 2.

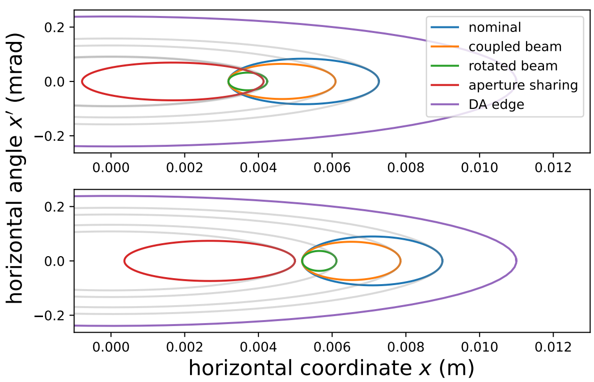

Figure 2: Top: The x–x' phase space for the different injection scenarios featuring a pulsed septum. The light grey ellipses indicate the required acceptance for each scenario. Bottom: The equivalent plot for a Lambertson septum.

Table 1: Injection Parameters for the Lambertson Septum and the Pulsed Septum for the Four Injection Scenarios.

Pulsed septum ($L = 0.3$ m, $\Delta x' = 0.28$ deg)			
Parameter	$\beta_{x,\text{opt}}$ (m)	(ϵ_x,ϵ_y) (nm)	Δx (mm)
Nominal injection	24.38	19, 1.9	5.23
Coupled beam	22.47	10.45, 10.45	4.64
Rotated beam	16.21	1.9, 19	3.71
Aperture sharing	35.48	19, 1.9	1.68
Lambertson septum ($L = 1$ m, $\Delta y' \approx 1.7$ deg)			
Nominal injection	21.16	19, 1.9	7.09
Coupled beam	18.97	10.45, 10.45	6.52
Rotated beam	12.70	1.9, 19	5.65
Aperture sharing	31.32	19, 1.9	2.68

Simplified Injection Simulation

The PETRA IV lattice is generated with transverse magnet offsets (3 µm up to 15 µm RMS transverse offsets) to simulate machines of varying perturbed optics functions. The perturbed machine is then corrected in terms of the orbit and tune to imitate a machine that is corrected with varying quality. A sophisticated error study including girder misalignments, magnet rolls, first-turn threading and beam-based alignment etc. can be found in Ref. [3]. The beta beating is used in the following to characterize the machine state as the beta beating gives insight regarding the phase error between the nonlinear elements in the machine. The combined beta beating $(\Delta\beta/\beta)_{\text{comb}} = \left((\Delta\beta_x/\beta_x)^2 + (\Delta\beta_y/\beta_y)^2\right)^{1/2}$ is used as a robust quantity to avoid misleading results for machines with exclusively large beta beating in a single plane. Figure 3 shows the injection efficiency results as a function of $(\Delta\beta/\beta)_{\text{comb}}$ for the Lambertson septum. The equivalent plot is omitted for the pulsed septum since the injection efficiency is virtually at 100 % for all four scenarios in the relevant beta-beating range up to 9 %. In the plot for the Lambertson septum, however, the nominal injection and partly the injection of a coupled beam lead to slight losses. Clearly visible is the advantage of having a reduced horizontal emittance (rotated beam) and a strongly reduced Δx (aperture sharing) at the injection point. Defining the rotation of the injected beam in the transfer line as the baseline design could be highly beneficial.

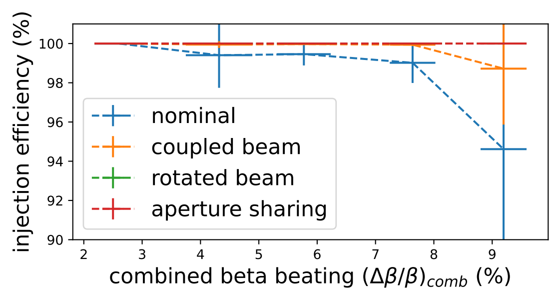

Figure 3: Injection efficiency versus the combined beta beating for the Lambertson septum. Only the nominal injection scenario diverges from a 100 % injection efficiency) in the relevant beta-beating range.

Intensity Losses With Aperture Sharing

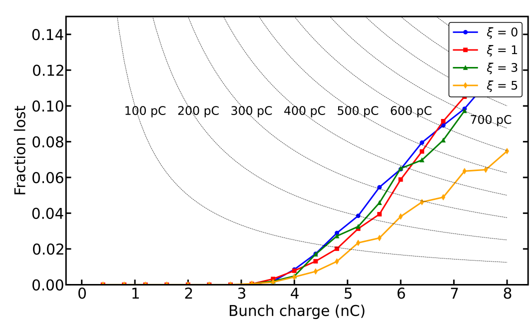

Figure 4: The amount of losses for the stored beam with $\Delta x = 5$ mm at the septum versus the single-bunch charge for different chromaticity values. Once the chromaticity is large enough, the losses shrink to a value that is smaller than the amount of newly injected charges.

Aperture sharing causes the stored beam to lose particles since the beam is kicked from the nominal orbit and therefore excites wakefields. The horizontal offset is equivalent to roughly a $\Delta x = 5$ mm offset at the septum location. The simulation includes the geometric as well as the resistive wall impedance. The PETRA IV Timing mode will features 80 bunches with a bunch charge of $Q = 7.7$ nC corresponding

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to a bunch current of $I_b = 1\,\mathrm{mA}$ each. Figure 4 shows preliminary results (no third harmonic cavity voltage) for the losses of the stored beam as a function of the single bunch current for different chromaticity values ξ. Once the chromaticity reaches $(\xi_x, \xi_y) = (5, 5)$, the losses are smaller than the amount of injected charges $Q \approx 0.96\,\mathrm{nC}$ in Timing mode with a bunch charge in the 7.7 nC range; however, the losses are substantial. Further analysis including the third harmonic cavity voltage has to be performed.

NONLINEAR INJECTION KICKER

One possibility to perform the critical injection process into PETRA IV is a nonlinear kicker (NLK). Such a device is not reliant on an orbit bump generated by kicker devices since its nonlinear transverse magnetic field is designed to strongly kick the injected beam while disturbing the stored beam as little as possible. The PETRA IV injection process could benefit from such a device since as many as 16 strip-line kickers are currently required to give the beam sufficient excursion at the septum. A NLK would fully avoid the necessity of any strip-line kickers. A prototype of such a NLK was tested at Helmholtz-Zentrum Berlin [10] and is envisaged or in use at other light sources [11–13]. In the following, an optimization of such a NLK is presented. The NLK design follows that of the BESSY II prototype, i.e., the NLK features eight wires (four wires for each polarity).

Random Optimization

Flexible parameters that have to be optimized are the longitudinal location s of the NLK downstream of the septum, the wire current I_w, the wires' (x, y) coordinates, the optics parameters α_x, β_x and x' coordinate of the injected beam. In order to define the nine free parameters, a random optimization is performed. Multi-objective genetic algorithms were used in other cases to reduce the wire current in dependence of the injection efficiency [14]. This step is only going to be considered if the NLK seems feasible in a first study.

Within the scope of the optimization process, no actual tracking is performed. The edge of the $3\sigma_x$ horizontal beam envelope of the injected beam is projected from the septum to the NLK location and then the kick of the NLK is applied via the calculation of the magnetic field using the Biot-Savart law (infinitely long wires assumed). The largest value of the horizontal action J_x is then selected from the beam envelope after the kick has been applied. This quantity is considered to be the feasible measure to make assumptions about the expected injection efficiency via comparison with Fig. 2.

This penalty function has to take the wire current I_w into account (the lower the current the better). Also, the relative emittance increase of the stored beam $\Delta\epsilon_x/\epsilon_x$ has to be as small as possible while minimizing the horizontal action J_x of the particles of the injected beam. The optimization works with the penalty function

$$p = \left(\frac{I_\mathrm{w}}{I_\mathrm{t}}\right)^2 + \left(\frac{\Delta\epsilon_x/\epsilon_x}{5\,\%}\right)^2 + \left(\frac{J_x}{0.53\,\mu\mathrm{m}}\right)^2 . \qquad (1)$$

Equation 1 gives equal weight to the different parameters if the wire current is at $I_\mathrm{w} = I_\mathrm{t}$, the emittance increase is 5 % and the maximum horizontal action along the $3\sigma_x$ envelope is equal to 0.53 µm (corresponds to approximately 70 % of the unperturbed DA). In the following, two scenarios are optimized: The first case will consider $I_\mathrm{t} = 4\,\mathrm{kA}$ while the second case will feature $I_\mathrm{t} = 6\,\mathrm{kA}$ (allows a larger wire current I_w). The NLK is assumed to be 30 cm long. Hence, a reduction of the effective current can be achieved by either elongating the wires or using multiple devices.

Optimization Results

The study is performed with a rotated beam (see Table 1). The two simulation scenarios repeatedly converged onto the same longitudinal location s within the range of a few cm (shown in Fig. 1). At that location, the vertical β_y function is rather small allowing the wires to approach the beam closely. The kick onto the beam into the acceptance of PETRA IV is shown in Fig 5. With $I_t = 6\,\mathrm{kA}$, the maximum horizontal action along the σ_x envelope $J_x = 0.86\,\mu\mathrm{m}$ is slightly smaller than for the first scenario ($J_x = 0.94\,\mu\mathrm{m}$). The outer edge of the injected beam would be projected to $x = 8.8\,\mathrm{mm}$ in the beam-envelope plots in Fig. 2. Hence, the performance of the NLK should only reach the performance of the worst injection scenarios of the Lambertson septum (nominal injection and coupled beam) with this setup and without alterations within the injection section.

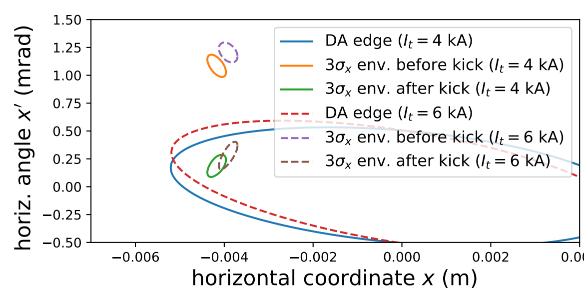

Figure 5: Effect of the nonlinear kick on the $3\sigma_x$ beam envelope at the location of the NLK.

CONCLUSION

The paper outlined potential injection strategies for PETRA IV depending on the septum type. The current design foresees both a DC Lambertson and pulsed septum (pre-septum) to be installed. This choice provides flexibility in case the pulsed septum is not operational at machine startup. A sole Lambertson septum may prove to be feasible; however, the thin blade of a pulsed septum would be greatly beneficial in supplying error margin as the simplified injection study has shown. The injection of a rotated beam with aperture sharing as a potential backup plan could be desirable to ensure a high injection efficiency independently of the septum choice. The optimization of a NLK has shown that its deployment is possible; however, it may carry the risk of requiring an even better corrected machine.

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