THE BESSY III INJECTION SCHEME*

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Abstract

The HZB is presently in the CDR phase for a successor of the storage ring BESSY II, which has been in operation since 1998 in Berlin Adlershof. The lattice of the BESSY III storage ring will be a multi-bend-achromat, enabling a natural emittance of circa 100 pm rad. However, due to the strong multipole magnets needed the dynamic aperture is much smaller compared to earlier generation light sources, complicating the injection significantly. In combination with the demand for a highly efficient, transparent Top-Up injection, this the design of the injection system is challenging for modern light sources.

For BESSY III an Non-Linear-Kicker based injection schemes has been found to the be best suited among the various options and will be introduced in this paper. Necessary adjustments of the optics are presented as well as simulation results of the injection process and hardware requirements for the NLK.

INTRODUCTION

BESSY III [1] is planned as successor of BESSY II [2], a 3rd generation Synchrotron radiation source, operated at HZB since 2000. A CDR is in preparation, presumably completed until the end of this year. BESSY III is planned to operate a high current beam of up to 300 mA at 2.5 GeV electron energy. Like most of the 4th generation light sources, it will be based on a multi-bend-achromat (MBA) lattice to provide high brilliant radiation in the soft to tender X-ray range.

To keep the generated radiation power and with it the heat load on the users beam lines constant, the storage ring (SR) will be operated in Top-Up mode. To minimize radiation safety measures and to enable easy access to the user hall the injection efficiency must be over 90 %, which means that in maximum only a few percent of the accelerated current may be lost at injection into the storage ring. Ideally the injection process should be "transparent", so that distortions of the stored electron beam are minimized and thus the light stability for the users (source point and direction) maximized.

Various options for the injection into light source storage rings have been established over the time, but only few are suited for low emittance storage rings and fulfill the above requirements for BESSY III .

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INJECTION OPTIONS FOR BESSY III

4th generation light sources aim for smallest emittances and therefore incorporate complex MBA lattices applying a large number of strong multipole magnets. Compared to previous generation light sources this increased magnet strengths leads to a significant loss of dynamic aperture (DA). For this reason, reaching highest injection efficiencies required for Top-Up operation becomes very challenging.

Four injection schemes were considered to be suitable candidates and have been discussed for BESSY III. Their basic properties are listed in Table 1. All of them require fast pulsed magnets and high quality injectors in the 3rd generation storage ring class, providing low emittance beams with small energy spread and short bunch lengths and high bunch charges.

The most challenging aspects beside an injector with these capabilities are the necessary kick pulse durations down to ns at a very high stability.

In conclusion — also with regard to the extensive experiences at BESSY II — the NLK scheme was decided to be most feasible and it will be used as "standard injection scheme" for BESSY III.

Independent of that choice, for the initial commissioning of the storage ring the injection straight should also host a fast, dipolar kicker for on-axis injection. That will enable first beam threading and achieve a closed orbit. The following orbit and optics corrections will result in a sufficiently large DA allowing the off-axis NLK injection.

NLK INJECTION

Before injection to the storage ring the accelerated beam has to be extracted and transported from the booster synchrotron. This transfer line should be short with a small integrated total angle. To improve the stability, angles from pulsed devices should be kept as small as possible. For that various types of bends with increasing bending angle will be used - pulsed and DC EM magnets and where feasible also permanent dipole magnets. Consequently the injection septum will be split in parts: first a DC septum with a large bending angle and a second pulsed AC septum with a small angle and lower field, so that the thickness of the septum blade can be reduced to circa 1 – 2 mm.

Integration of Pulsed Injection Elements

Due to large horizontal betatron oscillation amplitudes on the injection path the beam experiences strong non-linear fields, possibly causing beam losses. For that the path from the septum to the NLK should be kept short, ultimately leading to a scheme integrating both components in one "injection section", with the septum placed upstream of the

Table 1: Comparison of injection schemes. A comprehensive overview can be found e.g. in [8]. MPK: Multipole Kicker.

	Kicker Bump	**NLK (MPK)**	**Longiudinal**	**Swap out**
Injection plane	horizontal	horizontal	long. + hor.	horizontal
Kicker time scale	few SR turns (few μs)	two SR turns ($< 4\mu$s)	bunch to bunch (ns)	bunch to bunch (ns)
on / off energy	on	on	off	on
Inj. bunch charge	fraction of SR bunch charge / loss compensation			Full SR bunch charge
Possible injector	booster synchrotron, linac		linac	accumulator ring
Used (Proposed) at	most 3rd gen. sources	KEK [3], Sirius [4]	- (SLS [5])	APS-U [6] (ALS-U [7])

NLK. An optimized, horizontal betatron phase advance between them is required to reach a suitable horizontal phase space position when passing the NLK. Only then, both the NLK provides a sufficiently strong field and the resulting kick effectively reduces the horizontal action of the injected beam.

A large horizontal beta function at the NLK is mandatory to blow up the horizontal DA at the NLK. That is required to reduce the beam's action with the applied kick (at unchanged horizontal position) such that lands within the rings DA with an action small enough to pass the inner side of the septum blade without losses. A small vertical beta function in the NLK prevents it from becoming the limiting acceptance factor (usually set by small gap IDs).

Not all of these requirements can be met with the optical functions of the standard ID straight, so that a special optics for the injection straight had to be designed.

Linear Optics of the Injection Section

The required optics adjustments for the injection section highlighted several restrictions compared to the ID straights:

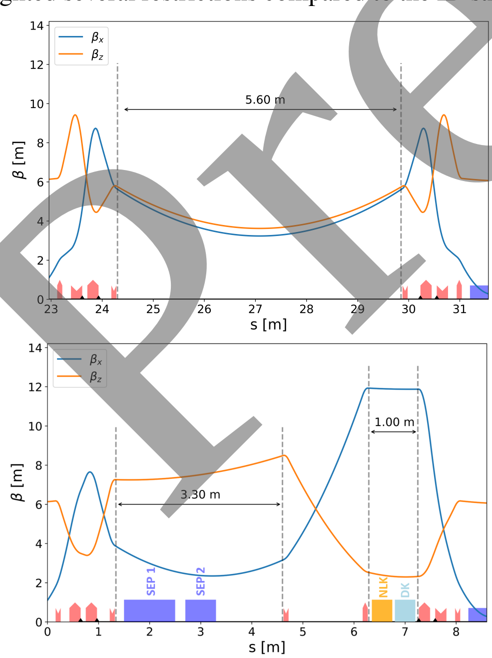

Figure 1: Magnetic lattice and Twiss parameter (β_x: blue, β_y: orange) for a standard straight (top) and the injection straight (bottom) with the injection hardware: thick DC and thin AC septum (blue), NLK (orange) and DK (light blue).

- equal length of section to maintain the ring symmetry
- the total phase advance had to remain unchanged, to maintain the "Higher Order Achromat Principle" (HOA)
- Twiss parameter must be matched to avoid beta beating around the ring.

A design has been found that meets these criteria as shown in Fig. 1. Only a change in the natural chromaticity remains unavoidable.

The position of the first four quadrupoles in the injection straight is unchanged from the other ID straights, but they are differently powered. Downstream a section of 3.3 m installation length will host the two injection septa of decreasing strength. The next, downstream quadrupole is split into two parts. The first one is horizontally de-focusing, so that the horizontal beta function can rise to a high value $\beta_x \approx 12$ m, as required. Accordingly the beam is vertically focused and the beta function falls down to 2 m, increasing the vertical acceptance of the NLK. The second magnet of the split doublet will be horizontally focusing, bringing α_x to zero in the following section of about 1 m length, where the NLK will be installed.

With an NLK-typical installation length of 0.5 m this section might also accommodate a dipole kicker (DK), needed for the initial BESSY III commissioning phase with on-axis injection only.

INJECTION SIMULATIONS

After realizing the basic NLK injection scheme it has been optimized by tracking studies. At the reference energy of 2.5 GeV, an emittance of 5.0 nrad m, and a bunch length of 15 ps at an energy spread of 10^{-3} were the assumed parameters of the injected bunch. Typically $\sim 10^3$ particles have been simulated at the septum exit and tracked using Elegant [9] for hundreds to thousands of turns. For the simulations presented here only the bare lattice has been used, with no magnet alignment or field errors, no IDs and no Synchrotron Radiation and RF. No deviations in the dimensions or in the position and direction of the injected beam were assumed. The NLK was simulated by a 2D field map with a half-sine pulse shape for a duration of two turns. Optimization criterion was a high injection efficiency, equivalently a low or ideally zero loss rate.

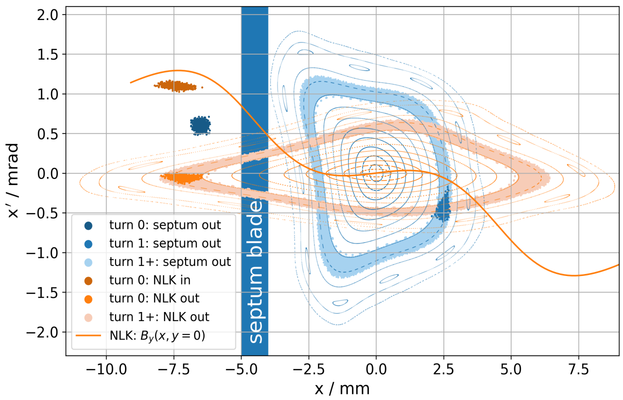

Figure 2: BESSY III Injection process: (x, x')-phase space at the thin AC septum (blue) and at the NLK (orange), for the first 1k turns.

Bare Lattice Performance

To illustrate the injection process in Figure 2 the horizontal phase spaces at the exit of the AC septum (blue) and at the NLK (orange) for various turns are plotted. The septum blade is the horizontal aperture limit, centred at $\Delta x = -4.5$ mm with a 1.0 mm thickness is shown too (positive values relate to the ring outside).

As the booster is inside the SR the x-position of the injected beam has to be lower than -5 mm plus an additional distance, taking the beam size and stability into account. The injection angle x' is set to optimally position the beam in the horizontal phase space at the NLK. As optimization result an suited injection vector $(x, x') = (-6.5\,\text{mm}, 0.65\,\text{mrad})$ (dark blue) has been found and plotted in the figure. The injected beam is basically linearly transported (neither sextupoles nor other higher order magnets in the beam path) and reaches the NLK entrance with $(x, x') = (-7.5\,\text{mm}, 1.1\,\text{mrad})$ (dark orange). Passing the NLK the beam is kicked by $\Delta x' = 1.2$ mrad and leaves the NLK with $(x, x') = (-7.0\,\text{mm}, -0.1\,\text{mrad})$ (orange). The beam is now within the DA of the SR, indicated by the phase space contours, generated by tracking single electrons with selected starting x-amplitudes (light orange). The successful injection requires the injected beam to pass the inside of the septum blade without loss. This can be evaluated by looking at the beam position at the septum: turn 1 (blue) and on the following turns (light blue band, resulting from tracking the injected bunch over many turns - here 1k). The separation between the light blue band and the septum blade illustrates a 100% injection efficiency (no losses occur during tracking).

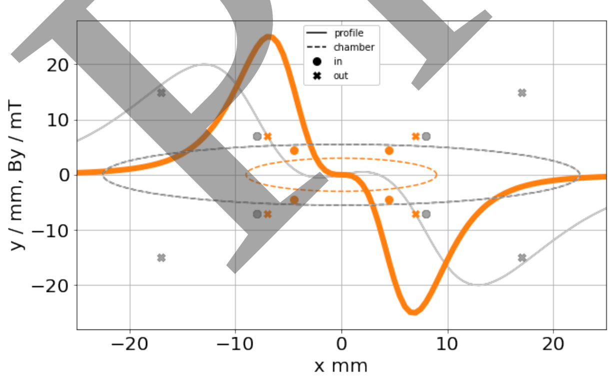

Figure 3: NLK: vertical magnetic field profile $B_y(x, y = 0)$ of the present BESSY II (gray) and required BESSY III design (orange). The chamber dimensions (dashed), the field generating wire positions and the coil current directions are also shown.

Table 2: NLK Parameter in operation at BESSY II and required for BESSY III

Parameter	**BESSY II**	**BESSY III**
Energy / GeV	1.7	2.5
required kick / mrad	1.1	1.2
max of $B_y(y = 0)$ / mT	20	25
@ hor. position / mm	-10.0	-7.0
effective length / mm	300	400
driving current / A	500	625
NLK pulse duration / μs	1.6	2.4
NLK pulse shape	”half-sine”	”half-sine”

BESSY III NLK DESIGN

HZB has been using an NLK for injection into BESSY II for more than one decade [10]. Although not used for routine injection, high efficiencies above 95 % could be demonstrated [11]. A re-design has been started to adjust for the increased BESSY III ring energy and the reduced chamber dimensions. The higher energy, increased by a factor of 2.5 GeV/1.7 GeV= 1.47 requires an accordingly stronger field. Due to the smaller DA, the NLK dimensions need to shrink, bringing the conducting wires closer to each other. This causes a stronger cancelling of the opposite directed magnetic fields and lowers the field strength. Both effects must be compensated for by increasing the current through the wires and/or the length of the NLK, resulting in technical complications. In addition due to the lowered vertical aperture the NLK may become acceptance limiting, thus reducing the gas lifetime.

Fig. 3 shows the on-axis, vertical magnetic field of the existing BESSY II NLK together with the required profile for BESSY III. The main device parameter for both cases are summarized in Table 2.

SUMMARY & OUTLOOK

A suitable injection scheme for BESSY III based on a NLK has been introduced, providing a high efficiency for the bare lattice. These studies have to be extended to the fully equipped machine with typical ID settings. Tolerance studies including errors (alignment and field) but also applying the full correction chain are already been simulated and will be continued as the SR design evolves. As an alternative for the introduced kicker also the suitability of a ”Double Dipole Kicker” (DDK) [12] will be investigated in a next step.

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