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Injection upgrade using a nonlinear kicker for a storage ring based light source

Authors: Wang, Dr. Zhe, Chen, Dr. Kemin, He, Dr. Tao, Wang, Dr. Zhonghan, Hosaka, Prof. Masahito, Liu, Prof. Gongfa, Xu, Dr. Wei, Xu, Dr. Wei

Date: 2026-01-21T19:07:00+00:00

Abstract

A conventional local bump injection system with four pulsed dipole kicker magnets is currently adopted in the Hefei Light Source II storage ring to achieve top-off operation. Owing to the multipole magnets located inside the injection section, it is difficult to form a perfect closed bump during beam injection, which leads to large perturbations. In order to provide the near-transparent beam injection for the light source users, a new injection method using a nonlinear kicker (NLK) is proposed in this paper. The NLK generates magnetic fields with a nonlinear distribution, which provides an off-axis peak field for the injected beam while keeping a field-free region for the on-axis stored beam. To simplify the upgrade, the NLK is going to be installed in the arc section downstream of the current injection system and the original septum will remain. The physics design of the NLK is conducted by optimizing its field conditions, including the on-axis field gradient, the peak-field position and strength. The injection efficiency is maximized by tuning the NLK conductor current to match the injection acceptance with the injected beam. With reasonable error tolerance of the NLK fields, the injection perturbation on the stored beam is analyzed to be greatly reduced compared to the local-bump injection.

Full Text

Preamble

Injection upgrade using a nonlinear kicker for a storage ring based light source∗ Zhe Wang,1 Kemin Chen,1 Tao He,1 Zhonghan Wang,1 Masahito Hosaka,1 Gongfa Liu,1 and Wei Xu1, † 1NSRL, University of Science and Technology of China, Hefei, Anhui, China A conventional local bump injection system with four pulsed dipole kicker magnets is currently adopted in the Hefei Light Source II storage ring to achieve top-off operation. Owing to the multipole magnets located inside the injection section, it is difficult to form a perfect closed bump

during beam injection, which leads to large perturbations. In order to provide the near-transparent beam injection for the light source users, a new injection method using a nonlinear kicker (NLK) is proposed in this paper. The NLK generates magnetic fields with a nonlinear distribution, which provides an off-axis peak field for the injected beam while keeping a field-free region for the on-axis stored beam. To simplify the upgrade, the NLK is going to be installed in the arc section downstream of the current injection system and the original septum will remain. The physics design of the NLK is conducted by optimizing its field conditions, including the on-axis field gradient, the peak-field position and strength. The injection efficiency is maximized by tuning the NLK conductor current to match the injection acceptance with the injected beam. With reasonable error tolerance of the NLK fields, the injection perturbation on the stored beam is analyzed to be greatly reduced compared to the local-bump injection.

Keywords: Storage ring, Injection system, Local bump, Nonlinear kicker

INTRODUCTION

After a major upgrade in 2014, a full-energy linac as the injector and a local bump injection system were adopted to achieve top-off operation for HLS-II [1, 2]. Local bump in- jection is an off-axis injection method that is widely used for synchrotron light sources, e.g., Diamond [3], SSRF [4] and ESRF-EBS [5]. Several (usually 3 or 4) kickers are used to form a closed local bump at the injection point in a straight section and capture the injected beam within the ring accep- tance. Ideally, a perfect local bump injection should be trans- parent to the stored beam outside the injection region. An im- perfect local bump will cause oscillations to the stored beam, leading to degradation of the synchrotron light source perfor- mance for user experiments. Owing to the multipole magnets located inside the local bump, the existing local bump injec- tion system in the HLS-II storage ring cannot form a perfect local bump during beam injection. This paper presents a new injection scheme using an NLK kicker in the HLS-II storage ring to mitigate the injection perturbation to the stored beam.

To simplify the injection system and achieve transparent in- jection, Photon Factory proposed an injection method with a pulsed quadrupole magnet (PQM) [6]. Since the dipole mag- netic field is zero on-axis of a multipole magnet, in principle, the off-axis injected beam can be deflected without perturbing the stored beam. However, the PQM quadrupole component on-axis is estimated to disturb the stored beam by increasing its size up to 2.4 times in the PF-AR storage ring. To over- come this disadvantage, the injection with a pulsed sextupole magnet (PSM) was proposed and tested in the PF ring [7].

Due to the large inductance of the pulsed sextupole, it is difficult to create a fast-pulse power supply for the kicker, re- sulting in multi-turn injection and low injection efficiency for the PF ring. The multi-turn injection using a PSM has also ∗ Supported by the National Natural Science Foundation of China (No.11975227) † Corresponding author, wxu@ustc.edu.cn been evaluated for

MAX-IV [8, 9] and UVSOR-III [10], and the evaluated injection efficiency is much lower than that of the single-turn injection. The HLS-II storage ring has a cir- cumference of only 66.13 m [11]. To realized the single-turn injection with a PSM requires the pulse width to be shorter than 220 ns, which is technically difficult.

To minimize the perturbation of the pulsed multipole mag- net (PMM) on the stored beam, BESSY developed the NLK injection method on the basis of the PMM approach [12]. Un- like the multipole magnet, the nonlinear field distribution of an NLK is achieved using four coils with a mirror symmet- ric geometry. It has a relatively low inductance and a short- pulse power supply can be realized for single-turn injection.

ALS optimized an NLK to inject the beam at the flat-top of the magnetic field and the injection efficiency is improved to nearly 100% while the perturbation on the stored beam is greatly reduced [13, 14]. This novel injection method has al- ready been successfully applied to several synchrotron radia- tion facilities including MAX-IV [15–18] and Sirius [19, 20].

Besides, more light sources, such as ESRF-EBS [21], NSLS- II [22], HALF [23] and TPS [24], are planning to adopt the NLK injection scheme.

In this paper, we propose a new injection scheme for the HLS-II storage ring to replace the current local bump injec- tion using four dipole kickers. The NLK is going to be in- stalled downstream of the last dipole kicker and the septum will be reused. The local bump injection system will remain working until the NLK injection is achieved after commis- sioning in the storage ring, which helps reduce the influence on the user operation time.

In Sec. II, we present an overview of the HLS-II storage ring and its current local bump injection system. In Sec. III, the NLK injection scheme for the HLS-II storage ring is de- scribed in detail and the simulation results of the NLK injec- tion are compared and discussed. Finally we conclude the paper in Sec. IV.

II. LOCAL BUMP INJECTION SYSTEM OF THE HLS-II A. PARAMETERS OF THE HLS-II STORAGE RING HLS-II is a dedicated synchrotron light source consisting of a full-energy linac injector and a storage ring with Double- Bend Achromat (DBA) structure [25–27]. With a recent dy- namic optimization, the main parameters of the storage ring is given in Table 1 [28–30]. The optical function of the storage ring is shown in Fig. 1 [Figure 1: see original paper] and the dynamic aperture is shown in Fig. 2 [Figure 2: see original paper].

Table 1. Main parameters of the HLS-II storage ring.

Value 19.9/21.1/10.8 (4.26, 2.22) Parameter Beam energy (MeV) Circumference (m) Natural emittance (nmrad) Harmonic number RF frequency (MHz) Damping time [H,V,L] (ms) Transverse tunes [H, V] Momentum compaction factor Figure 1. Optical function of the HLS-II storage ring for one super- period.

B. LOCAL BUMP INJECTION Using the linear beam dynamics, we can derive the equa- tions for the relationship between the kicker angle θ and the local bump height b without considering the multipole magnet effects (magnetic field feed-down effects), which are listed below [31].

Figure 2. On-momentum and off-momentum dynamic apertures of the HLS-II storage ring near the injection point in the straight sec- tion. The green one is the on-momentum dynamic aperture with a physical aperture of the septum. \$ \$2 = − \$ \$3 = − \$ 2 \$1 sin Δ\$ \$21 cos Δ\$ \$21 − \$ \$2 sin Δ\$ \$21 sin Δ\$ \$21 cos Δ\$ \$43 − \$ \$3 sin Δ\$ \$43 sin Δ\$ \$43 \$ 3 \$4 sin Δ\$ \$43 where the subscript numbers indicate the positions of the kickers, ΔΨij is the phase advance between two kickers, and α, β are the Courant-Snyder (C-S) parameters.

Currently, the orbit bump injection system of the HLS-II storage ring adopts four kickers and one septum to achieve top-off operation [32]. The eddy-current type septum has a septum sheet which is 2 mm thick. Its maximum excita- tion current is 5.6 kA with a peak magnetic field of 0.875 T.

The pulsed bump kickers, which utilize the soft ferrite ma- terial, have a maximum excitation current of 4.5 kA with a peak field of 0.1 T. The injection system operates at a max- imum repetition rate of 2 Hz. The HLS-II storage ring has four short straight sections of 2.3 m and four long straights of 4.0 m. The septum is located at the end of a long straight section, as shown in Fig. 3 [Figure 3: see original paper]. Considering the space limita- tion of the straight section, two kickers are placed in the same straight section, whereas the other two kickers are located at the nearby arcs. The magnet lattice of the injection system, the injected beam trajectory and the local orbit bump of the stored beam is shown in Fig. 4 [Figure 4: see original paper].

The dynamic acceptance of the storage ring with and with- out orbit bump in the horizontal phase space is shown in Fig. 5 [Figure 5: see original paper]. The original ring acceptance is limited by the septum wall and the injected beam is outside the acceptance. With the help of the orbit bump, the acceptance is shifted to cover the injection point while the stored beam is moved to the local bump with a height of 24 mm. 051015202530s (m)0102030 (m)00.511.5Dispersion (m)xzx-150-100-50050100x (mm)0102030405060y (mm) = 0 = 2% = -2% w/ septum

3 Figure 3. Layout of the current injection system in the HLS-II storage ring. The red, purple and blue magnets stand for the dipoles, quadrupoles and sextupoles, respectively. Two kickers (K1 and K4) are located outside the straight section. listed in Table 2 .

Figure 4. The local bump injection system of the HLS-II storage ring. The yellow line is the trajectory of the injected beam, and the purple dashed line represents the closed orbit distortion of the stored beam when the injected beam arrives.

Figure 5. The theoretical acceptance of the local bump injection in the hori-

zontal phase space. The blue ellipse represents the ring ac- ceptance, which is bumped with the stored beam and receives the injected beam under the effect of the dipole kickers. The yellow dashed line ellipse represents the original ring acceptance without the local bump. The distance between the stored beam and the in- jected beam is 9 mm at beam injection.

The first few turns of an injected bunch using the current local bump injection system in the horizontal phase space are shown in Fig. 6 [Figure 6: see original paper]. The parameters of the injected bunch are Figure 6. Simulation of local bump injection in the horizontal phase space. The injected bunch at the septum and the first few turns after injection are shown.

Table 2. Main parameters of the injected beam. Parameter Horizontal emittance (nm • rad) Energy spread $\sigma\delta$ (%) Bunch length $\sigma\Delta$z (m) (αx,βx) (m) Injected beam position (mm) Injected beam angle (mrad) Value (-1,9) IMPERFECTION OF THE LOCAL ORBIT BUMP The misalignment of the dipole kickers and the power sup- ply jitters can lead to imperfection of the local bump. In the HLS-II storage ring, additional perturbations of the four sex- tupoles located inside the local bump should be considered.

When the stored beam is off-axis in the sextupoles, it sees ad- ditional dipole and quadrupole components of the magnetic e-beamSEPTUM K1K4K2K330354045s (m)-2002040x (mm)24mm9mmSextupoleQuadrupoleBendKickerSEPTrajectory of injected beamLocal bump orbitUndisturbed orbit-30-20-10010203040x (mm)-2-10123x (mrad)Injected beam 1st turn injected beam2nd turn3rd turn4th turnAcceptance at septumInjected beam

124 fields, which is called the feed-down effect. The magnetic field feed-down of a sextupole can be expressed as: = b2(x0y0 + (y0x + x0y) + xy), b2((x2 0 − y2 0) + 2(x0x − y0y) + (x2 − y2)), The closed orbits of the stored beam in phase with the in- jected beam are calculated and shown in Fig. 8 [Figure 8: see original paper]. It is obvious that the orbit distortion is leaked to the outside of the injection bump. where b2 is the normalized strength of the sextupole and x0, y0 is the off-axis distance of the particles. The first and sec- ond terms on the right-hand side of Eq. 2 represents the ad- ditional dipole and quadrupole magnetic fields, respectively.

The dipole and quadrupole fields of the sextupole with the maximum bump height of 24 mm are estimated to be −28 Gs and −0.23 T/m.

Figure 8. Calculated closed orbits of the stored beam in phase with the injected beam. Obvious distortion of the global orbits can be seen during injection.

D. STORED BEAM PERTURBATION To calculate the oscillation amplitude of the stored beam disturbed by the beam injection, six bunches with different timing to the injection pulse are tracked using the MATLAB Accelerator Toolbox (AT) [33]. In order to accurately calcu- late the beam size, each bunch contains 1000 particles. The position of the particles are recorded turn by turn. The aver- aged beam centroid and beam size of the stored beam after injection is shown in Fig. 9 [Figure 9: see original paper]. As shown in the figure, the max- imum oscillation amplitude of the stored beam centroid after injection is approximately 2.2 mm, and the beam size is in- creased to 1.9 mm (one sigma). The simulation does not take into account the field leakage of the septum. If considered, the stored beam would experience greater perturbations during local bump injection. The initial increase in the beam size is due to the quadrupole component of the sextupole feed-down fields. Further increase of the beam size for up to 5 ms can be explained by the decoherence effect, i.e., the beam centroid oscillation is transfered into the beam size through initial be- tatron tune spread [34]. The perturbation on the stored beam continues for a damping time with large amplitudes, which can interfere with the user’ s experiments.

The injection perturbation on the stored beam degrades the performance of the synchrotron radiation light source with top-off operation, which should be mitigated to achieve trans- parent injection. At ESRF, several techniques are applied to reduce the injection perturbation on the stored beam, includ- ing introduction of nonlinear fields in the injection kickers, compensation of vertical and quadrupole perturbations using skew quadrupoles and octupoles, and compensation of kicker perturbations using shakers and a stripline, etc [35]. At HLS-II, a nonlinear kickers is proposed to replace the current local bump injection system to mitigate the injection perturbation.

Figure 7 [Figure 7: see original paper]. The waveform of kicker excitation pulse (red) and the corresponding rms closed orbit distortion outside the local bump (black).

Considering the feed-down effect, the formulae in Eq. 1 is no longer accurate to calculate the angles of the dipole kick- ers. However, the tracking method can be applied to match the angles. The first kicker is set to bring the ideal particle to the height we need at the second kicker, and the second kicker is to bring the particle’ s x′ to zero. The third and fourth kickers are set in the similar way as the first and second kick- ers. The matched kicker angles from simulation are (6.380, 3.698, 3.699, 6.383) mrad with the maximum bump height of 24 mm. The injection pulse of the kickers is half-sine with a width of 1.32 µs, which is approximately six times of the rev- olution time, as shown in Fig. 7. The excitation of the injec- tion kickers is optimized at the peak height of the local bump, where the feed-down effect is considered. According to Eq. 2, the feed-down field of the dipole components is nonlinear to the bump height, which means perfect orbit bumps cannot be formed in the whole excitation process. Therefore, while the excitation is ramping up and down along the sinusoid, global orbit distortion outside the local orbit bump region is gen- erated, which causes oscillations to the stored beam during injection. The rms closed orbit distortion outside the local bump for different excitation strengths is plotted in Fig. 7. 02204406608801100l320Time (ns)00.10.20.30.40.50.60.70.80.91Closed orbit distortion (mm)00.10.20.30.40.50.60.70.80.91Normalized excitation strength 2nd turnbefore injection1st turn before injectionInjection time 1st turnafter injection 2nd turnafter injectionPulse base width = 1320 ns0102030405060s (m)-

5051015202530x (mm)1st turn: 24.0 mm2nd turn: 21.0 mm3rd turn: 12.6 mm-Bump height:1st turn2nd turn3rd turnInjection point

5 Figure 9. Perturbation on the stored beam after the local bump in- jection. The top plot is the beam centroid oscillation and the bottom plot is the variation in beam size. The particles are tracked for one damping time which is about 20 ms.

Figure 10 [Figure 10: see original paper]. Schematic of the NLK injection process. The blue circle is the phase space of the injected beam in the horizontal plane. To achieve injection, the NLK gives a kick to bring the injected beam into the ring acceptance, which is the red circle. The light red area is the effective NLK location, while the gray area is the stored beam region where the NLK magnetic field should be near zero. ϕ is the phase space between the injection point and the NLK.

INJECTION USING AN NLK FOR THE HLS-II STORAGE RING A. NONLINEAR KICKER INJECTION The injection process using a nonlinear kicker (NLK) is il- lustrated in a normalized horizontal phase space in Fig. 10.

The beam is injected from outside of the septum and moves clockwise in the phase space. To achieve beam injection, the NLK should be located appropriately downstream of the in- jection point, and should provide a kick to bring the injected beam into the ring acceptance. To choose the location of the NLK, the phase advance between the injection point and the NLK should be considered.

HLS-II is a user facility which provides more than 5000 hours per year for user experiments. To reserve enough user operation time, the current injection system will remain until the new injection system is successfully commissioned. Con- sidering the space limitation of the storage ring and the phase advance, the NLK is planned to be placed in a downstream arc, as shown in Fig. 11 [Figure 11: see original paper]. To simplify the upgrade, the original septum will be reused for the new injection system.

The preliminary matching of the injection could be treated as a two-step process. The initial step is to make the injected beam reach the NLK with an x offset, and the subsequent step is to optimize the parameters of the NLK. To ensure that the injected beam has a appropriate offset at the NLK loca- tion, the deflection angle of the septum should be tuned. The magnetic field strength of the NLK can be estimated by the position of the injected beam in phase space. Fig. 11 shows a preliminary match result of the NLK injection.

Figure 11. Layout of the injection system using an NLK for the HLS-II storage ring. The brown line represents the trajectory of the injected beam, and the red line represents the trajectory of the in- jected beam in the absence of the NLK kicker.

B. PHYSICS DESIGN OF AN NLK KICKER A nonlinear kicker that produces off-axis magnetic field peaks with near-zero center fields can be built using 8 current- driven conductors with mirrored horizontal and vertical sym- metry as shown in Fig. 12 [Figure 12: see original paper] [12]. Two conductors with opposite currents occupy each quadrant. On the other hand, the inner four conductors have the same current direction and the outer four reverse their polarity. All conductors share a common power supply.

The Biot-Savart law can be used to calculate the magnetic fields generated by a current I, as described in Eq. 3, (cid:90) Idl × r The magnetic field By in the middle horizontal plane with a distance x to the axis (shown as point A in Fig. 12) can then be calculated by 051015Times (ms)-202Beam centroid osc. (mm)051015Times (ms)012Beam size osc. (mm)30354045s (m)-2002040x (mm)SextupoleQuadrupoleBendKickerSEPNLKTrajectory without NLKThe injected beamUndisturbed orbitNLK

6 and machine learning methods are widely used in the design and optimization of the particle accelerators [37–39]. Here the intelligent optimization algorithm of Multi-Objective Par- ticle Swarm Optimization (MOPSO) is adopted in the physics design of the NLK [40].

A preliminary injection matching result in the horizontal phase space with the ring acceptance using a dipole kick are shown in Fig. 13 [Figure 13: see original paper]. According to the matching result, the NLK should have a peak magnetic field of at least 220 Gauss.

Since the NLK has a length of 0.4 m in the s-direction and the injected beam has a drift in the NLK, the location of the NLK peak field can be set near x = −11 mm, which is outside the ring acceptance. The position with the peak NLK magnetic field is set as an objective in the optimization.

The other objective is the field flatness in the central region, which determines the influence on the stored beam. Owing to the symmetric configuration of the NLK, the on-axis field strength is zero. Due to the size of the stored beam, the gra- dient of the magnetic field can cause the quadrupole kick on it, which leads to increasement of the beam size. Considering the beam size at the NLK location, the field gradient is calcu- lated within the range of $±$1 mm around the axis. The follow- ing simulation uses the real magnetic field strengths for dif- ferent particles according to the field distribution of the NLK.

The conductor current is fixed at 1000 A and the peak field strength is set as a constrain which filters out the optimization results when it is smaller than 220 Gauss. To ensure enough vertical space of the kicker vacuum chamber, the inner con- ductor is set to have at least 7 mm off-axis distance in the y-direction. Therefore, the gap of the NLK vacuum cham- ber can reach 12 mm, which is on the same level of the ID chambers at HLS-II.

Figure 12. Schematic of an NLK with 8 current conductors and its vertical magnetic field distribution in the horizontal plane. (cid:88) xi − xA (xi − xA)2 + y2 where I is the conductor current and positive current denotes outward flow from the plane. µ0 is the permeability of free space, and i indicates the number of the conductors. The infinite-length conductors are assumed in the

calculation, and the hard-edge field is adopted in the following analysis.

Figure 13. A preliminary match using a dipole kick for the NLK.

The dipole kick of the NLK makes the ring acceptance move to cover the injected beam while the stored beam is not affected. Due to the length of the kicker, there is a horizontal drift of the injected beam in the NLK.

Figure 14 [Figure 14: see original paper]. Pareto front of the NLK optimization using MOPSO. The red star indicates the selected solution of the optimization.

To achieve high injection efficiency and eliminate the ef- fect on the stored beam, the NLK magnetic field strength is expected to have a peak value at the appointed position and a field-free region on the axis. The magnetic fields of the NLK can be optimized by tuning the positions and currents of the conductors [36]. And the intelligent optimization algorithms The Pareto front of the optimization of the the peak posi- tion and the field gradient is plotted in Fig. 14. One solution is selected as the optimization result with the peak-field loca- tion of −11 mm and the field gradient of 0.5 Gauss/m. The optimized NLK and its magnetic field distribution is shown xyMagnetic field strengthxiyiA(xA,0)Outer conductorsInner conductorsMagnetic field012345Field gradient (T/m)02468101214161820Peak field position (mm)Final iterationPareto frontSelected point

310 these two parameters, the magnetic field strength of the NLK is finally chosen to be 250 Gauss.

Figure 15 [Figure 15: see original paper]. The optimized NLK and its magnetic field distribution By in the horizontal plane. The magnetic field is a calculated with the conductor current of 1000 A, which can be adjusted to modify the field strength and the acceptance area. in Fig. 15. The main design parameters of the NLK are listed in the Table. 3.

Table 3 . Main parameters of the physics design of the NLK.

Parameter Value Outer conductor position x, y (mm) 4.8, 18.5 Inner conductor position x, y (mm) 5.9, 7.2 Peak magnetic field at 1000 A (Gauss) Peak field position at x (mm) The beam is injected on the central horizontal plane where the horizontal field Bx is equal to 0. The vertical emittance (ϵy) of the injected beam is much smaller than the horizontal one (ϵx), and the vertical size of the injected beam is about 0.145 mm. Considering the position error of the injected beam (see table 5), the quadrupole component (transverse gradient) of the Bx field is less than 0.2 T/m. The effect of the horizontal magnetic fields of the NLK on the beam in- jection can then be ignored.

C. THE NLK INJECTION FOR HLS-II To determine the optimal NLK strength (or conductor cur- rent) for beam injection, the NLK magnetic field strength is varied to calculate the acceptance of the ring. Here we define two parameters, the acceptance angle and the acceptance area, as shown in Fig. 18 [Figure 18: see original paper], which represents the effective acceptance for the injected beam. The simulation results of the accep- tance angle and the acceptance area versus the peak magnetic field of the NLK are shown in Fig. 16 [Figure 16: see original paper]. As the field strength of the NLK increases, the acceptance area also increases, but becomes slender in phase space, which may reduce the injec- tion efficiency. Therefore, the acceptance angle parameter is added to help select the NLK magnetic strength. Considering Figure 16. Acceptance angle and acceptance area at the septum ver- sus the NLK peak magnetic field. The Acceptance angle and area can be used to represent the effective acceptance for injected beam.

As previously described, the pulse duration of the current power supply of the kickers is approximately six times of the revolution time. We plan a new power supply with a pulse base width shorter than 440 ns, which is used to achieve single-turn injection with an NLK for the HLS-II storage ring.

The linac injector of HLS-II provides injected bunches for the storage ring with single-bunch mode. The bunch length is 1 ns (0.3 m), which is very short comparing to the pulse base width of the injection system. Due to the low inductance of the NLK, this power supply is easy to be realized with mod- ern technologies. The ring acceptance calculated by particle tracking before and after the NLK is shown in Fig. 17 [Figure 17: see original paper]. By tracking the acceptance back to the location of the septum, we obtain the ring acceptance with the NLK at the septum, which is shown in Fig. 18. The position and phase space of the injected beam is then matched to the ring acceptance with the parameters presented in Table 4 .

Table 4. Main parameters of the injected beam. Parameter Horizontal emittance (nm · rad) Energy spread $\sigma\delta$ (%) Bunch length $\sigma\Delta$z (m) (αx,βx) (m) Injected beam position (mm) Injected beam angle (mrad) Value (0,7) To accurately calculate the injection efficiency of the new injection system, the injected beam errors should be included.

According to the performance of the HLS-II injector, the error setting of the injected beam is listed in Table 5. The stability of the NLK field strength also affects the injection efficiency.

The jitter of the NLK power supply is required to be less than 0.1%, which is technically achievable. -20-15-10-505101520x (mm)-20-15-10-505101520y (mm)-300-200-1000100200300Magnetic field By (Gauss)6mm38mmVacuum chamber wallInjected beamStored beamOuter conductorsInner conductorsMagnetic field050100150200250300350400450500Magnetic field (Gauss)00.20.40.60.811.21.4Acceptance angle (mrad)0510152025Acceptance area (mm · mrad)

8 Table 5. Error setting of the injected beam and the NLK.

Parameter Injected beam position (mm) Injected beam angle (mrad) Injected beam energy stability (%) NLK field error (%) Error (σ) Figure 17. The injected beam before and after the NLK in phase space. The red dashed line represents the ring acceptance before the NLK and the blue one after the NLK. The By field of the NLK is shown as the green line. The NLK peak field strength is 250 Gauss with an excitation current of 868 A.

Figure 19 [Figure 19: see original paper]. Injection efficiency as a function of the error scaling fac- tor of the NLK injection for the HLS-II storage ring.

Figure 18. The distribution of the injected beam in the phase space after injection. The ring acceptance with and without the NLK is also shown. The acceptance angle and area represents the effective acceptance for beam injection.

To calculate the injection efficiency as a function of the er- ror level, an error scaling factor is introduced by multiplying the error from 0 to 2. The random errors are generated with the Gaussian truncation of 3σ. For each error setting, 100 bunches with each 1000 particles are used in the simulation.

The simulation results of the injection efficiency as a func- tion of the error scaling factor are shown in Fig. 19. The injection efficiency is about 95% with the error factor of 1, when the error factor increases to 2, the injection efficiency remain 85%.

Figure 20 [Figure 20: see original paper]. Perturbations on the stored beam at the injection point for one damping time after beam injection using an NLK. The top plot is the beam centroid oscillation and the bottom plot is the variation in beam size.

D. PERTURBATION ON THE STORED BEAM According to the physics design of the NLK, the central magnetic field is 0 and the field gradient is optimized to be less than 0.1 T/m. However, owing to the technical limita- tion, the field leakage to the axis of a real NLK is usually larger considering the errors in conductor positions and the influence of the ceramic chamber. Referring to the previous -20-15-10-505101520x (mm)-10-5051015x (mrad)-400-300-200-1000100200300400500Magnetic field By (Gauss)Stored beamInjected beam before/after NLKAcceptance before NLKAcceptance after NLKNLK magnetic fieldAcceptance angleAcceptancearea00.511.52Error scaling factor00.10.20.30.40.50.60.70.80.91Injection efficiency051015Time (ms)-0.1-0.0500.050.1Beam centroid osc. (mm)051015Time (ms)00.20.40.60.81Beam size osc. (mm)

353 work reported by other facilities [14, 18, 22, 41], a loose error tolerance with a dipole field of 0.6 Gauss and a field gradient of 0.3 T/m can be set to the NLK. With these field errors, the injection perturbation of the stored beam at the injection point is calculated and shown in Fig. 20. The global injec- tion perturbation along the whole storage ring including the maximum beam centroid and the change of the beam size is shown in Fig. 21 [Figure 21: see original paper]. The typical beam orbit stability requirement for the light source users is 10% of the beam size, which can also be treated as the criterion for transparent injection. Since the changes of the beam centroid and size of the stored beam during beam injection are smaller than 10% of the beam size,

transparent injection is realized using an NLK for the HLS-II storage ring. A more strict error requirement can be applied to the NLK to further reduce the injection perturbation on the stored beam.

Figure 21. Maximum perturbations on the stored beam after beam injection using an NLK over the whole ring. The red lines in both subplots show the original size of the unperturbed stored beam. (a) the beam centroid oscillation amplitude, (b) the variation in beam size. The perturbation on the stored beam is less than 10% of the beam size across the entire ring.

The injection perturbations on the stored beam between the local bump injection and the NLK injection with an NLK are compared in Table 6 . With the new injection scheme, the perturbation on the stored beam is less than 10% of the beam [1] J. Y. Li, W. Xu, K. Xuan, et al., Operation status of HLS-II.

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Table 6. Comparison of the injection perturbation on the stored beam between the local bump injection and the NLK injection.

Parameter Unperturbed beam size (mm) Max beam size (mm) Max beam centroid position (mm) Beam centroid osc. amp. after 1τ (µm) Local bump NLK IV. CONCLUSION The local bump injection system using 4 pulsed dipole kickers are adopted in the current HLS-II storage ring. Due to the space limitation, two kickers are placed in one straight section and the others are placed in the adjacent arcs. The dipole feed-down fields of the sextupoles located inside the local bump cause imperfection to the local bump, resulting in distortion of the global beam orbit. Besides, the quadrupole feed-down components can increase the betatron oscillation amplitude of the stored beam. These effects finally degrade the performance of the synchrotron radiation light source. To mitigate the injection perturbation and simplify the current injection system, a new injection scheme using a single non- linear kicker (NLK) is proposed. The NLK is going to be placed downstream of the current local bump injection kick- ers and the septum will be reused. Therefore, the old injection system can remain working until the new injection system is fully commissioned, which helps minimize the influence on the user operation time. To meet the injection requirements, an 8-conductor type NLK is designed with an intelligent al- gorithm to achieve a high injection efficiency and a low per- turbation on the stored beam. With reasonable error tolerance of the fields on the NLK axis, the simulation results show that the oscillation amplitudes of the beam centroid and beam size are greatly reduced compared to the current local bump in- jection. Since the injection perturbation on the stored beam is less than 10% of the beam size, a transparent injection for user experiments could be realized at HLS-II.

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