Injection upgrade for a storage ring based light source

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Date: 2025-11-26T00:00:00+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 near-transparent beam injection for 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 maintaining a field-free region for the on-axis stored beam. To simplify the upgrade, the NLK will be installed in the arc section downstream of the current injection system while the original septum will remain. The physics design of the NLK is conducted by optimizing its field conditions, including the on-axis field gradient, 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 injector and a local bump injection system were adopted to achieve top-off operation for HLS-II [1, 2]. Local bump injection is an off-axis injection method widely used for synchrotron light sources, such as 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 acceptance. Ideally, a perfect local bump injection should be transparent to the stored beam outside the injection region. However, an imperfect local bump will cause oscillations in the stored beam, leading to degradation of synchrotron light source performance for user experiments. Owing to multipole magnets located within the local bump, the existing local bump injection 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 injection perturbation to the stored beam.

To simplify the injection system and achieve transparent injection, Photon Factory proposed an injection method with a pulsed quadrupole magnet (PQM) [6]. Since the dipole magnetic field is zero on the axis of a multipole magnet, the off-axis injected beam can be deflected in principle 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 overcome this disadvantage, 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, creating a fast-pulse power supply for the kicker is difficult, resulting in multi-turn injection and low injection efficiency for the PF ring. Multi-turn injection using a PSM has also been evaluated for MAX-IV [8, 9] and UVSOR-III [10], with evaluated injection efficiency much lower than that of single-turn injection. The HLS-II storage ring has a circumference of only 66.13 m [11]. Achieving single-turn injection with a PSM requires a pulse width shorter than 220 ns, which is technically difficult.

To minimize perturbation from the pulsed multipole magnet (PMM) on the stored beam, BESSY developed the NLK injection method based on the PMM approach [12]. Unlike multipole magnets, the nonlinear field distribution of an NLK is achieved using four coils with mirror-symmetric geometry. It has relatively low inductance, enabling a short-pulse power supply for single-turn injection. ALS optimized an NLK to inject the beam at the flat-top of the magnetic field, improving injection efficiency to nearly 100% while greatly reducing perturbation on the stored beam [13, 14]. This novel injection method has already been successfully applied to several synchrotron radiation facilities including MAX-IV [15–18] and Sirius [19, 20]. Additionally, 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 injection using four dipole kickers. The NLK will be installed downstream of the last dipole kicker and the septum will be reused. The local bump injection system will remain operational until the NLK injection is commissioned in the storage ring, which helps reduce impact on 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 described in detail and simulation results 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 recent dynamic optimization, the main parameters of the storage ring are 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].

B. Local Bump Injection

Using linear beam dynamics, we can derive the equations relating the kicker angle to the local bump height b without considering multipole magnet effects (magnetic field feed-down effects), which are listed below [31]:

$$\theta_2 = -\theta_3 = -\frac{b}{\sqrt{\beta_2\beta_1}\sin\Delta\Psi_{21}\cos\Delta\Psi_{43} - \alpha_2\sin\Delta\Psi_{21}\sin\Delta\Psi_{43} - \alpha_3\sin\Delta\Psi_{43}\cos\Delta\Psi_{21}}$$

$$\theta_1 = -\theta_4 = \frac{b}{\sqrt{\beta_3\beta_4}\sin\Delta\Psi_{43}}$$

where the subscript numbers indicate kicker positions, $\Delta\Psi_{ij}$ 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 2 mm thick. Its maximum excitation current is 5.6 kA with a peak magnetic field of 0.875 T. The pulsed bump kickers utilize soft ferrite material with a maximum excitation current of 4.5 kA and peak field of 0.1 T. The injection system operates at a maximum 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 space limitations in the straight section, two kickers are placed in the same straight section while the other two are located in nearby arcs. The magnet lattice of the injection system, the injected beam trajectory, and the local orbit bump of the stored beam are shown in Fig. 4 [Figure 4: see original paper].

The dynamic acceptance of the storage ring with and without 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 lies outside the acceptance. With 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.

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 listed in Table 2 .

C. Imperfection of the Local Orbit Bump

Misalignment of dipole kickers and power supply jitters can lead to imperfection of the local bump. In the HLS-II storage ring, additional perturbations from four sextupoles located inside the local bump must be considered. When the stored beam is off-axis in the sextupoles, it experiences additional dipole and quadrupole components of the magnetic fields, known as the feed-down effect. The magnetic field feed-down of a sextupole can be expressed as:

$$B_y = b_2(x_0y_0 + (y_0x + x_0y) + xy)$$

$$B_x = b_2((x_0^2 - y_0^2) + 2(x_0x - y_0y) + (x^2 - y^2))$$

where b_2 is the normalized strength of the sextupole and x_0, y_0 is the off-axis distance of the particles. The first and second terms on the right-hand side of Eq. 2 represent the additional 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. Considering the feed-down effect, the formulae in Eq. 1 are no longer accurate for calculating dipole kicker angles. However, the tracking method can be applied to match the angles. The first kicker is set to bring the ideal particle to the required height at the second kicker, and the second kicker brings the particle' s x' to zero. The third and fourth kickers are set similarly to the first and second. The matched kicker angles from simulation are (6.380, 3.698, 3.699, 6.383) mrad with a maximum bump height of 24 mm. The injection pulse of the kickers is half-sine with a width of 1.32 µs, approximately six times the revolution time, as shown in Fig. 7 [Figure 7: see original paper]. The excitation of the injection 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 with respect to bump height, meaning perfect orbit bumps cannot be formed throughout the entire excitation process. Therefore, while the excitation ramps up and down along the sinusoid, global orbit distortion outside the local orbit bump region is generated, causing oscillations in the stored beam during injection. The rms closed orbit distortion outside the local bump for different excitation strengths is plotted in Fig. 7.

The closed orbits of the stored beam in phase with the injected beam are calculated and shown in Fig. 8 [Figure 8: see original paper]. 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 beam injection, six bunches with different timing relative to the injection pulse are tracked using the MATLAB Accelerator Toolbox (AT) [33]. To accurately calculate beam size, each bunch contains 1000 particles. Particle positions are recorded turn by turn. The averaged beam centroid and beam size of the stored beam after injection are shown in Fig. 9 [Figure 9: see original paper]. As shown, the maximum oscillation amplitude of the stored beam centroid after injection is approximately 2.2 mm, and the beam size increases to 1.9 mm (one sigma). The simulation does not account for septum field leakage. If considered, the stored beam would experience greater perturbations during local bump injection. The initial increase in beam size is due to the quadrupole component of the sextupole feed-down fields. Further increase of beam size for up to 5 ms can be explained by the decoherence effect, where beam centroid oscillation is transferred into beam size through initial betatron tune spread [34]. The perturbation on the stored beam continues for a damping time with large amplitudes, which can interfere with user experiments.

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

III. Injection Using an NLK for the HLS-II Storage Ring

A. Nonlinear Kicker Injection

The injection process using a nonlinear kicker (NLK) is illustrated in normalized horizontal phase space in Fig. 10 [Figure 10: see original paper]. The beam is injected from outside the septum and moves clockwise in phase space. To achieve beam injection, the NLK should be located appropriately downstream of the injection point and provide a kick to bring the injected beam into the ring acceptance. The phase advance between the injection point and the NLK must be considered when choosing the NLK location.

HLS-II is a user facility providing more than 5000 hours per year for user experiments. To preserve sufficient user operation time, the current injection system will remain until the new injection system is successfully commissioned. Considering storage ring space limitations and 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.

Preliminary matching of the injection can 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 NLK parameters. To ensure the injected beam has an appropriate offset at the NLK location, the deflection angle of the septum should be tuned. The magnetic field strength of the NLK can be estimated from the position of the injected beam in phase space. Fig. 11 shows a preliminary match result for NLK injection.

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 symmetry, as shown in Fig. 12 [Figure 12: see original paper] [12]. Two conductors with opposite currents occupy each quadrant. The inner four conductors have the same current direction while the outer four reverse their polarity. All conductors share a common power supply.

The Biot-Savart law can be used to calculate magnetic fields generated by a current I, as described in Eq. 3:

$$\mathbf{B} = \frac{\mu_0}{4\pi} \int \frac{I d\mathbf{l} \times \mathbf{r}}{r^3}$$

The magnetic field B_y in the middle horizontal plane at a distance x from the axis (shown as point A in Fig. 12) can then be calculated by:

$$B_y = \frac{\mu_0 I}{2\pi} \sum_i \frac{(-1)^{i+1} y_i}{(x_i - x_A)^2 + y_i^2}$$

where I is the conductor current and positive current denotes outward flow from the plane. μ_0 is the permeability of free space, and i indicates the conductor number. Infinite-length conductors are assumed in the calculation, and the hard-edge field is adopted in the following analysis.

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

A preliminary injection matching result in horizontal phase space with ring acceptance using a dipole kick is 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 drifts 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 peak NLK magnetic field is set as an objective in the optimization.

The other objective is field flatness in the central region, which determines influence on the stored beam. Due to the symmetric configuration of the NLK, the on-axis field strength is zero. However, because of the stored beam size, the magnetic field gradient can cause a quadrupole kick, leading to increased beam size. Considering the beam size at the NLK location, the field gradient is calculated within the range of ±1 mm around the axis. The following simulation uses real magnetic field strengths for different particles according to the NLK field distribution.

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

The Pareto front of the optimization of peak position and field gradient is plotted in Fig. 14 [Figure 14: see original paper]. One solution is selected as the optimization result with a peak-field location of -11 mm and field gradient of 0.5 Gauss/m. The optimized NLK and its magnetic field distribution are shown in Fig. 15 [Figure 15: see original paper]. The main design parameters of the NLK are listed in Table 3 .

The beam is injected on the central horizontal plane where the horizontal field B_x equals 0. The vertical emittance (ϵ_y) of the injected beam is much smaller than the horizontal one (ϵ_x), 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 B_x field is less than 0.2 T/m. The effect of the horizontal magnetic fields of the NLK on beam injection can then be ignored.

C. The NLK Injection for HLS-II

To determine the optimal NLK strength (or conductor current) for beam injection, the NLK magnetic field strength is varied to calculate ring acceptance. We define two parameters, the acceptance angle and acceptance area, as shown in Fig. 18 [Figure 18: see original paper], which represent the effective acceptance for the injected beam. Simulation results of acceptance angle and acceptance area versus NLK peak magnetic field are shown in Fig. 16 [Figure 16: see original paper]. As NLK field strength increases, the acceptance area also increases but becomes slenderer in phase space, which may reduce injection efficiency. Therefore, the acceptance angle parameter is added to help select NLK magnetic strength. Considering these two parameters, the magnetic field strength of the NLK is finally chosen to be 250 Gauss.

As previously described, the pulse duration of the current kicker power supply is approximately six times the revolution time. We plan a new power supply with pulse base width shorter than 440 ns 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 in single-bunch mode. The bunch length is 1 ns (0.3 m), which is very short compared to the pulse base width of the injection system. Due to the low inductance of the NLK, this power supply can be easily realized with modern technologies.

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 septum location, we obtain the ring acceptance with the NLK at the septum, shown in Fig. 18. The position and phase space of the injected beam are then matched to the ring acceptance with parameters presented in Table 4 .

To accurately calculate the injection efficiency of the new injection system, injected beam errors should be included. According to the performance of the HLS-II injector, the error settings of the injected beam are listed in Table 5 . The stability of the NLK field strength also affects injection efficiency. The jitter of the NLK power supply is required to be less than 0.1%, which is technically achievable.

To calculate injection efficiency as a function of error level, an error scaling factor is introduced by multiplying errors from 0 to 2. Random errors are generated with Gaussian truncation at 3 . For each error setting, 100 bunches with 1000 particles each are used in the simulation. Simulation results of injection efficiency versus error scaling factor are shown in Fig. 19 [Figure 19: see original paper]. The injection efficiency is about 95% with error factor 1; when the error factor increases to 2, the injection efficiency remains at 85%.

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, due to technical limitations, field leakage to the axis of a real NLK is usually larger when considering errors in conductor positions and the influence of the ceramic chamber. Referring to previous work reported by other facilities [14, 18, 22, 41], a loose error tolerance can be set for the NLK with a dipole field of 0.6 Gauss and field gradient of 0.3 T/m. With these field errors, injection perturbation of the stored beam at the injection point is calculated and shown in Fig. 20 [Figure 20: see original paper]. Global injection perturbation along the whole storage ring, including maximum beam centroid and beam size change, is shown in Fig. 21 [Figure 21: see original paper].

The typical beam orbit stability requirement for light source users is 10% of the beam size, which can also serve as the criterion for transparent injection. Since changes in beam centroid and size of the stored beam during injection are smaller than 10% of the beam size, transparent injection is realized using an NLK for the HLS-II storage ring. A more stringent error requirement can be applied to the NLK to further reduce injection perturbation on the stored beam.

Injection perturbations on the stored beam between local bump injection and NLK injection are compared in Table 6 . With the new injection scheme, perturbation on the stored beam is less than 10% of the beam size, meaning transparent injection is achieved.

IV. Conclusion

The local bump injection system using four pulsed dipole kickers is currently adopted in the HLS-II storage ring. Due to space limitations, two kickers are placed in one straight section and the others in adjacent arcs. The dipole feed-down fields of sextupoles located inside the local bump cause imperfection in the local bump, resulting in distortion of the global beam orbit. Additionally, the quadrupole feed-down components can increase the betatron oscillation amplitude of the stored beam. These effects ultimately degrade the performance of the synchrotron radiation light source.

To mitigate injection perturbation and simplify the current injection system, a new injection scheme using a single nonlinear kicker (NLK) is proposed. The NLK will be placed downstream of the current local bump injection kickers and the septum will be reused. Therefore, the old injection system can remain operational until the new injection system is fully commissioned, helping minimize impact on user operation time. To meet injection requirements, an 8-conductor type NLK is designed with an intelligent algorithm to achieve high injection efficiency and low perturbation on the stored beam. With reasonable error tolerance of the fields on the NLK axis, simulation results show that oscillation amplitudes of the beam centroid and beam size are greatly reduced compared to the current local bump injection. Since injection perturbation on the stored beam is less than 10% of the beam size, transparent injection for user experiments could be realized at HLS-II.

V. Acknowledgements

The authors would like to thank the engineers and scientists at NSRL for their valuable suggestions and assistance.

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Note: Figure translations are in progress. See original paper for figures.