Injection upgrade for a storage ring based light source

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Abstract

A conventional local-bump injection system with four pulsed dipole kicker magnets is currently employed in the Hefei Light Source II storage ring to achieve top-off operation. Due to the multipole magnets located within the injection section, forming a perfectly closed bump during beam injection is challenging, resulting in significant perturbations. To provide near-transparent beam injection for light source users, this paper proposes a novel injection method utilizing a nonlinear kicker (NLK). The NLK generates magnetic fields with a nonlinear distribution, delivering 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 existing injection system, with the original septum remaining in place. The physics design of the NLK is performed by optimizing its field conditions, including the on-axis field gradient, peak-field position, and strength. Injection efficiency is maximized by tuning the NLK conductor current to match the injection acceptance with the injected beam. With reasonable error tolerance in the NLK fields, the injection perturbation on the stored beam is analyzed to be substantially reduced compared to local-bump injection.

Full Text

Preamble

Injection Upgrade for a Storage Ring Based Light Source

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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 the light source users, a new injection method using a nonlinear kicker 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 injection 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 acceptance. Ideally, a perfect local bump injection should be transparent to the stored beam outside the injection region. An imperfect local bump will cause oscillations to the stored beam, leading to degradation of the synchrotron light source performance for user experiments. Owing to the multipole magnets located inside 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 the 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-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 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, it is difficult to create a fast-pulse power supply for the kicker, resulting in multi-turn injection and low injection efficiency for the PF ring. The multi-turn injection using a PSM has also 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 circumference of only 66.13 m [11]. To realize 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 magnet (PMM) on the stored beam, BESSY developed the NLK injection method on the basis of the PMM approach [12]. Unlike the multipole magnet, the nonlinear field distribution of an NLK is achieved using four coils with a mirror symmetric 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 effective injection method has also been adopted or studied by several synchrotron radiation facilities, including MAX-IV [15], HALF [16], Sirius [17] and NSLS-II [18].

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 is going to be installed 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 commissioning 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 described in detail and the simulation results of the NLK injection 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 [19–21]. With a recent dynamic optimization, the main parameters of the storage ring are given in Table 1 [22–24]. 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 for the relationship between the kicker angle and the local bump height b without considering the multipole magnet effects (magnetic field feed-down effects), which are listed below [25]:

$$\theta_1 = -\theta_4 = -\frac{b}{\sqrt{\beta_1\beta_2}\sin\Delta\Psi_{21}}$$
$$\theta_2 = -\theta_3 = -\frac{b}{\sqrt{\beta_3\beta_4}\sin\Delta\Psi_{43}}$$

where the subscript numbers indicate the positions of the kickers, $\Delta\Psi$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 [26]. 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 limitation 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 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 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.

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].

C. Imperfection of the Local Orbit Bump

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

$$\Delta B_y = b_2(x_{0y}0 + (y_{0x} + x_{0y}) + xy)$$
$$\Delta B_x = b_2((x_0^2 - y_0^2) + 2(x_{0x} - y_{0y}) + (x^2 - y^2))$$

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

Considering the feed-down effect, the formulae in Eq. 1 are no longer accurate to calculate the angles of the dipole kickers. 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 a similar way as the first and second kickers. 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 the revolution time, as shown in Fig. 7. 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 to the bump height, which means perfect orbit bumps cannot be formed during 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 generated, 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.

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]. It is obvious that the orbit distortion is leaked to the outside of the injection bump.

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) [27]. In order to accurately calculate the beam size, each bunch contains 1000 particles. The positions of the particles 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 in the figure, the maximum oscillation amplitude of the stored beam centroid after injection is approximately 2.2 mm, and the beam size is increased to 1.9 mm (one sigma). 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 transferred into the beam size through initial betatron tune spread [28]. 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 transparent injection. At ESRF, several techniques are applied to reduce the injection perturbation on the stored beam, including 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 [29]. At HLS-II, a nonlinear kicker is proposed to replace the current local bump injection system to mitigate the 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 a normalized horizontal phase space in Fig. 10 [Figure 10: see original paper]. 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 injection 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. Considering 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 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 by the position of the injected beam in phase space. Fig. 11 shows a preliminary match result of the 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. 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:

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

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:

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

where I is the conductor current and positive current denotes outward flow from the plane. $_0$ is the permeability of free space, and i indicates the number of the conductors. Infinite-length conductors are assumed in the calculation, and the hard-edge field is adopted in the following analysis.

A preliminary match using a dipole kick for the NLK is shown in Fig. 13 [Figure 13: see original paper]. 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.

To achieve high injection efficiency and eliminate the effect 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 [30]. Intelligent optimization algorithms and machine learning methods are widely used in the design and optimization of particle accelerators [31–33]. Here the intelligent optimization algorithm of Multi-Objective Particle Swarm Optimization (MOPSO) is adopted in the physics design of the NLK [34].

A preliminary injection matching result in the horizontal phase space with the ring acceptance using a dipole kick is shown in Fig. 13. 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 gradient of the magnetic field can cause a quadrupole kick on it, which leads to increase of the 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 conductor current is fixed at 1000 A and the peak field strength is set as a constraint 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 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 on the same level as the ID chambers at HLS-II.

The Pareto front of the optimization of the peak position and the field gradient is plotted in Fig. 14 [Figure 14: see original paper]. One solution is selected as the optimization result with the peak-field location of −11 mm and the 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 2 .

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 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 represent the effective acceptance for the injected beam. The simulation results of the acceptance 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 injection efficiency. Therefore, the acceptance angle parameter is added to help select the 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 power supply of the kickers is approximately six times the revolution time. We plan a new power supply with a pulse base width shorter than 440 ns, which will be used to achieve single-turn injection with an NLK for the HLS-II storage ring. Due to the low inductance of the NLK, this power supply is easy to realize with modern 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 [Figure 18: see original paper]. The position and phase space of the injected beam are then matched to the ring acceptance with the parameters presented in Table 3 .

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 4 . 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.

To calculate the injection efficiency as a function of the error level, an error scaling factor is introduced by multiplying the error from 0 to 2. The random errors are generated with Gaussian truncation of 3σ. For each error setting, 100 bunches with 1000 particles each are used in the simulation. The simulation results of the injection efficiency as a function of the error scaling factor are shown in Fig. 19 [Figure 19: see original paper]. The injection efficiency is about 95% with the error factor of 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, owing to technical limitations, 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 previous work reported by other facilities [14, 18, 35, 36], a loose error tolerance with a dipole field of 0.6 Gauss and a field gradient of 0.3 T/m can be set for the NLK. With these field errors, the injection perturbation of the stored beam at the injection point is calculated and shown in Fig. 20 [Figure 20: see original paper]. The global injection 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]. We can see that both changes of the beam centroid and beam size are smaller than 10% of the unperturbed beam size. A more strict error requirement can be applied to the NLK to further reduce the injection perturbation.

The injection perturbations on the stored beam between the local bump injection and the NLK injection are compared in Table 5 . With the new injection scheme, the perturbation on the stored beam is less than 10% of the beam size, which means transparent injection is achieved.

IV. Conclusion

The local bump injection system using 4 pulsed dipole kickers is adopted in the current HLS-II storage ring. Due to space limitations, 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 nonlinear kicker (NLK) is proposed. The NLK is going to be placed downstream of the current local bump injection kickers 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 algorithm to achieve high injection efficiency and low perturbation 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 injection. Since the 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.

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