PULSED MULTIPOLE INJECTION FOR ALS UPGRADE*

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Abstract

The pulsed multipole injection scheme is shown to be compatible with the ALS in combination with a magnet lattice that has a low β-function in the injection straight. Since traditional injection schemes are not compatible with such optimized low-β lattices, implementing the new injection scheme opens up several new possibilities. For instance, the adoption of a low-β lattice can greatly increase brightness due to the better matching of photon and electron beam emittances. This document explains the principles of the injection and the calculations we performed to show that the concept is sound. An analysis is carried out to optimize the location and strength of the injection kicker, the required acceptance of the storage ring and the matched Twiss parameters of the transfer line.

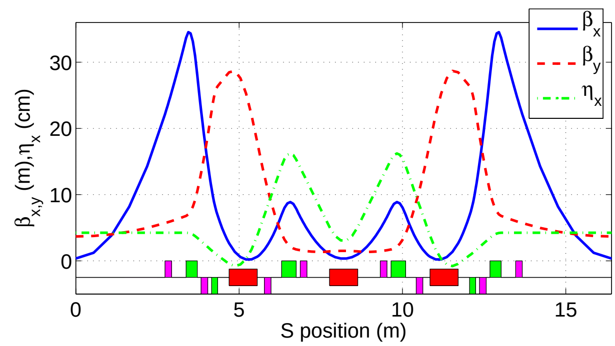

Figure 1: A low-β lattice of one of 12 sectors for ALS upgrade. The working tunes are $\nu_x = 1.81$ and $\nu_y = 1.77$. The lattice is optimized for the brightness at insertion devices.

INTRODUCTION

Lattices with low β-functions in the straight sections allow for greater brightness in light sources and higher luminosity in colliders. For example at the Advanced Light Source, a previous study [1] was made to determine the maximum brightness possible in the Advanced Light Source (ALS) at Lawrence Berkeley National Lab in the soft X-ray (1 nm) spectrum. In this study, only 12-fold periodic solutions were studied — in other words we constrained the magnet settings of the 12 ALS sectors to be identical. The results revealed that the maximum brightness is obtained for lattices where one simultaneously reduces both the emittance and reduces the straight section β-function. For the brightest lattices, the β-function in the straight was less than 0.5 m while the emittance is about 2nm-rad. The study showed that there are other operating regions that support low emittances but with larger β-functions ($\beta_x^* > 10$ m). Even though the emittances are the same, the phase space of the low-β lattices are better matched to the photon phase space. The reward is the low-β lattices are nearly three times brighter than the high-β lattices.

Figure 1 shows the low-β lattice of one of 12 sectors in the ALS. A challenge with this lattice is the difficulty of injecting beam into it. Traditional 4-bump injection is incompatible with low-β lattices since the injection scheme requires a high β-function at the center of the straight. One solution is to redesign the lattice with a large β-function for injection and a low β-function for insertion device straights. However, such a hybrid (high-low β-function) scheme breaks the periodicity that may be important in obtaining a sufficiently large dynamic aperture. In this document, we outline a new injection scheme using pulsed multipole injection kickers designed to allow for injection into lattices with a low β-function in the center of the straight section.

Earlier studies at the Photon Factory in Japan [2, 3] demonstrated the feasibility of using pulsed quadrupoles and sextupoles as a means of injection into high β-function lattices. Subsequent studies at NSLS-II expanded upon this work to look at the optimal injection parameters and injection tolerances. The idea of using pulsed multiple injection to inject into low β-function straights was suggested in a previous paper [4]. The feasibility of the scheme requires that a location for the magnet can be found where it is possible to both (1) kick the beam to an orbit that is inside the ring acceptance with (2) reasonable magnetic strength. Building upon the work at KEK and NSLS-II a general analysis is carried out to find the minimum sextupole strength and how to best match the injection parameters. Then the scheme is applied to the ALS low β-function lattice.

PULSED SEXTUPOLE INJECTION

Compared to a traditional injection scheme using four dipole kickers, the pulsed multipole injection uses a single multipole kicker to reduce the oscillation amplitude of the injected beam while preserving the stored beam. Assuming that the storage ring, into which a beam is injected, has a linear optics, in a normalized phase space the beam after

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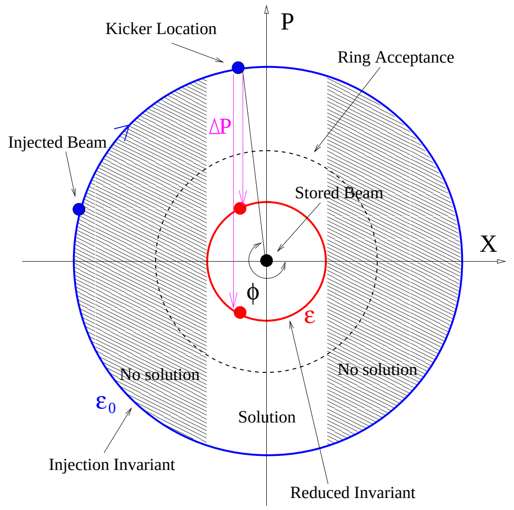

Figure 2: Diagram of pulsed multipole injection in a normalized phase space. The large blue, median dash, and small red circles represent the injection invariant, ring acceptance and reduced invariant of the injected beam, respectively. To reduce the injection invariant ε_0 to the smaller value ε, the pulsed multipole kicker must be placed in the solution region, and there exist two solutions to kick the beam onto the orbit represented by the red circle.

injection will proceed in a circular motion given by

$$\varepsilon_0 = \left(\frac{x_0}{\sqrt{\beta_s}}\right)^2 + \left(\frac{\alpha_s x_0 + \beta_s x_0'}{\sqrt{\beta_s}}\right)^2 = X_0^2 + P_0^2, \quad (1)$$

where α_s and β_s are the Twiss parameters of the storage ring; x_0 and x_0' are the position and divergence of the injected beam, respectively; $X_0 = x_0/\sqrt{\beta_s}$ and $P_0 = (\alpha_s x_0 + \beta_s x_0')/\sqrt{\beta_s}$ are its normalized coordinates. Here, we call ε_0 the injection invariant. Fig. 2 illustrates the pulsed multipole injection in the normalized phase space. When the injected beam passes through the kicker, its invariant ε_0 will be reduced to a smaller value ε, so called the reduced invariant given by $\varepsilon = X^2 + P^2$, where X and P are normalized coordinates of the injected beam after the kicker. When the reduced invariant ε is less than the ring acceptance, the injected beam will be captured by the ring.

To reduce the injection variant ε_0 to a small value ε, we need to find an optimal location for the kicker to minimize its strength. Following the calculations in papers [2, 3], we can have

$$k = \frac{\sqrt{\varepsilon_0}\sin\phi \pm \sqrt{\varepsilon - \varepsilon_0\cos^2\phi}}{\beta_s^{3/2}\varepsilon_0\cos^2\phi}, \quad (2)$$

where k is the integrated kicker strength defined by $B''l/(B_0\rho)$; and ϕ is the normalized phase advance of the beam at the kicker location given by

$$\phi(s) = \tan^{-1}(\frac{P(s)}{X(s)}) = \tan^{-1}\left(\alpha_s + \beta_s\frac{x'(s)}{x(s)}\right). \quad (3)$$

Later, we will apply this formula to search for a longitudinal location of the pulsed sextupole kicker to minimize its strength. But, first we are going to investigate the injection matching.

OPTIMAL INJECTION MATCHING

Injection matching becomes an important issue when considering the injected beam with a finite beam size. Mismatching the Twiss parameters of a transfer line to those of a storage ring could result in a large phase space area swept out by the injected beam in the storage ring. Injection matching have been investigated in papers [5, 6]. However, in these studies a thin dipole injection kicker is assumed, thus the space distortion of the beam during the injection is not taken into account. In the following, we will present a more general formulation for injection matching.

Considering an injected beam with emittance of ϵ_i and Twiss parameters of α_i and β_i, the phase space coordinates of a particle in the beam are given by

$$\begin{aligned} x_i &= x_0 + N_i\sqrt{\epsilon_i\beta_i}\cos\psi, \\ x_i' &= x_0' - N_i\sqrt{\frac{\epsilon_i}{\beta_i}}(\sin\psi + \alpha_i\cos\psi), \end{aligned} \quad (4)$$

where x_0 and x_0' are the beam center position and divergence right before the injection kicker; ψ is the phase advance of the particle; and N_i is the number of the standard deviation of the beam size that we consider. After the injection kicker, the coordinates of the particle are given by the transfer map M of the kicker, and can be expressed as

$$x = f(k, x_i, x_i'), \quad x' = g(k, x_i, x_i'), \quad (5)$$

where the functions of $f(k, x_i, x_i')$ and $g(k, x_i, x_i')$ are determined by the transfer map M. Thus, the reduced invariant of the particle after the kick is given by

$$\begin{aligned} \varepsilon &= \frac{1}{\beta_s}\left[x^2 + (\alpha_s x + \beta_s x')^2\right] \\ &= \frac{1}{\beta_s}\left[f^2(k, x_i, x_i') + [\alpha_s f(k, x_i, x_i') \right. \\ &\quad \left. + \beta_s g(k, x_i, x_i')]^2\right] \\ &= \varepsilon(\alpha_i, \beta_i, k; \psi), \end{aligned} \quad (6)$$

which is a function of α_i, β_i, k and ψ for given $x_0, x_0', \alpha_i, \beta_i, \epsilon_i$ and N_i. In order to minimize the phase space area swept out by the injected beam, we first need to find the maximum of Eq. (6) for different ψ. The ellipse with the maximum $\varepsilon(\alpha_i, \beta_i, k)_{max}$ encompasses the injected beam. Then, we need to minimize $\varepsilon(\alpha_i, \beta_i, k)_{max}$, which leads to optimal injected beam Twiss parameters β_i and α_i, kicker strength k and required ring acceptance.

For a thin dipole kicker, Eq. (5) can be simplified to $x = x_i$ and $x' = x_i' + \Delta\theta$, where $\Delta\theta$ is the kick angle. Therefore, $\varepsilon(\alpha_i, \beta_i, k; \psi)$ can be explicitly expressed, thus analytically optimized as shown in papers [5, 6]. However, in general, the expression of $\varepsilon(\alpha_i, \beta_i, k; \psi)$ is complicated,

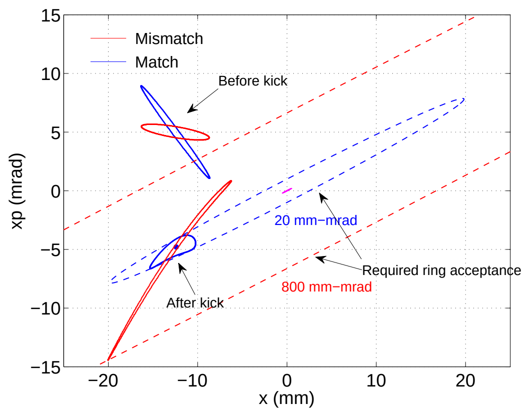

Figure 3: Kicker strength k as a function of its longitudinal position s in the half sector of the injection straight. The blue and black curves represent two valid kicker strength as illustrated in Fig. 2.

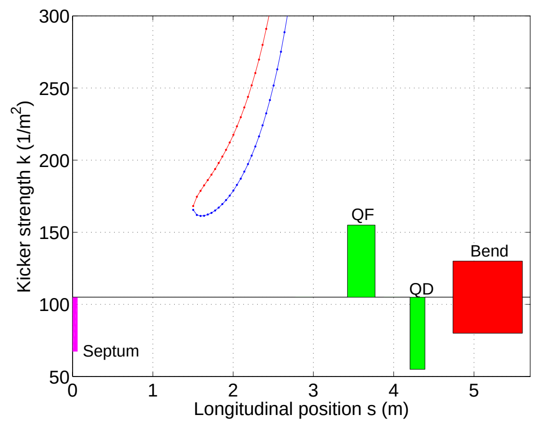

Figure 4: Pulsed sextupole injection matching for the ALS low-β lattice. A 1 meter long pulsed sextupole kicker is located at 1.5 m away from the septum. The mismatch and match injections are represented by the red and blue color, respectively.

and the numerical optimization must be carried out. The Matlab optimization toolkit is well suitable for this purpose. Therefore, a Matlab script has been developed to optimize pulsed multipole injection [7].

APPLICATION TO ALS UPGRADE

We apply above formulations to study pulsed sextupole injection for the low-β lattice shown in Fig. 1 by calculating the optimal kicker location to minimize its strength, the matched injected beam Twiss parameters to minimize the required ring acceptance. For the study, we choose to offset the centroid of the injected beam from the centroid of the stored beam by -20 mm at the septum, the injected beam angle is about 5 mrad, and the length of the kicker is 1 meter. The septum is at the center of the injection straight.

According to Eq. (2), the required sextupole kicker strength as a function of its longitudinal position in the half sector of the injection straight is shown in Fig. 3. For the calculation, the injection invariant 1300 mm-mrad and the reduced invariant 20 mm-mrad have been assumed. From the plot we can see to minimize the kicker strength the kicker should be located around 1.6 m away from the septum. Here, we assumed the kicker is a thin sextupole kicker.

Figure 4 illustrates the injection matching. The injected beam emittance of 200 mm-mrad and $N_i = 3$ (see Eq. (4)) are assumed. As we can see from the plot, mismatched Twiss parameters of the injected beam result in a large required ring acceptance represented by the red dash line, which is about 800 mm-mrad. However, the matched Twiss parameters ($\beta_i = 8.2$ m and $\alpha_i = 8.3$) lead to a much small required acceptance of about 20 mm-mrad. The optimal kicker strength k is about 144 m^{-2}, which corresponds to the field gradient B'' of about 912 T/m^2 for a 1 meter long sextupole kicker [8].

FUTURE PLANS

In order to capture the injected beam with the injection condition of -20 mm beam offset and 5 mrad injection angle, the required ring acceptance must be larger than 20 mm-mrad. Relaxing the injection condition, for example, with -10 m beam offset and zero injection angle, will reduce the required ring acceptance to 14 mm-mrad. However, the current dynamics aperture study on the low-β lattice shows that the ring acceptance is only about 15 mm-mrad, which places a very tight tolerance on the pulsed multipole injection. Further studies will be carried out to enlarge the dynamics aperture of the lattice.

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