POSSIBILITY OF THE BEAM INJECTION USING A SINGLE PULSED SEXTUPOLE MAGNET IN ELECTRON STORAGE RINGS *

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Abstract

Recently, we have proposed new injection system using a single pulsed quadrupole magnet (PQM) and succeeded in the beam injection at the Photon Factory Advanced Ring (PF-AR) in KEK. The PQM enables us to inject the beam into the storage ring with only one pulsed magnet. This system has an obvious advantage compared with a conventional injection system using several pulsed dipole magnets. Since the barycenter of the stored beam is not kicked on the magnetic pole center of the PQM, we can reduce the coherent dipole oscillation which is often produced by the unclosed bump. It is important for the top-up injection in electron storage rings such as synchrotron radiation sources or high energy colliders. However, the turn-by-turn profile is modulated due to the excitation of the PQM since it provides the instantaneous focusing force to the beam. Therefore, we have examined the injection system with a single pulsed sextupole magnet (PSM) to reduce both of the coherent dipole oscillation and the profile modulation.

INTRODUCTION

In most of electron/positron storage rings such as synchrotron radiation sources or high energy colliders, the injection system using pulsed dipole magnets (PDMs) is conventionally employed to store the beam [1]. Fig. 1 shows a schematic drawing of the conventional injection system. The injection method utilizing a radiation damping in electron storage rings is quite effective to stack up the electron beam and to realize a higher beam current. Thanks to the established technology of the PDMs, the method has been adopted in most of electron storage rings. However, it is difficult to make a complete closed bump for the stored beam since the PDMs have field errors, timing jitters, individual differences of them. Non-linear elements like sextupole magnets inside the local bump produce a leakage of the bump and generate the coherent dipole oscillations of the stored beam during the injection period [2]. Therefore, we have proposed new injection scheme using a single pulsed quadrupole magnet (PQM) and succeeded in the beam injection at the PF-AR [3]. Indeed, the coherent dipole oscillations were reduced during the beam injection due to the PQM compared with the existing kickers. However, another phenomenon was observed. This is the turn-by-turn profile modulation (coherent quadrupole oscillation) produced due to the excitation of the PQM since it gives the instantaneous focusing force to the beam. We have some ideas to reduce the modulation. One of the ideas is to employ a pulsed sextupole magnet (PSM) since a sextupole magnet has a parabolic field to the position deviation from a center of the magnetic pole while a quadrupole magnet has a linear field. When both of the fields at a position far from the pole center are the same for the injected beam, the sextupole has one order less field for the stored beam than the quadrupole near the pole center. This is the motivation to examine the possibility of the beam injection using the PSM. In this paper, we will describe the formulation of the beam injection using a single pulsed magnet adding to the application at the Photon Factory storage ring (PF ring), and a simulation of the beam injection conducted using a multi-particle tracking method, and discuss the possibility of the PSM.

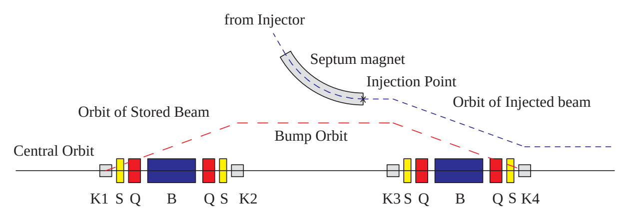

Figure 1: Conventional injection system using septum and kicker magnets. Injection, bump and central orbit are represented by a dotted, a dashed, and a solid line, respectively. A injection point is indicated by a cross symbol.

FORMULATION OF BEAM INJECTION USING A SINGLE PSM

First, we formulate the orbit of the injected beam and derive the strength to realize the beam injection using a single PSM. When we give the coordinate at the injection point as an initial condition to the injected beam, the beam begins to circulate around the central orbit of the ring with large amplitude of betatron oscillation under the initial condition. In general, the betatron oscillation with large amplitude are affected by the magnetic non-linearities of the ring, but we assume that non-linearities are negligible and the betatron oscillation is linear for a simplicity. Moreover, we treat the orbit of the barycenter of the injected beam with neglecting the beam size. Then, the orbit with the initial condition (x_0, x_0') follows an ellipse ε_0 expressed by

$$\varepsilon_0 = \frac{1}{\beta_{x,0}}\left\{x_0^2 + \left(\alpha_{x,0}x_0 + \beta_{x,0}x_0'\right)^2\right\} = X_0^2 + P_0^2 \quad (1)$$

where x_0 is the position deviation from the central orbit and x_0' is the divergence angle. The $\alpha_{x,0}$ and $\beta_{x,0}$ represent

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Twiss parameters at the injection point in a horizontal direction. (X_0,P_0) is the coordinate in the normalized phase space, and each element is expressed by

$$X_0 = \frac{x_0}{\sqrt{\beta_{x,0}}}, P_0 = \frac{\alpha_{x,0}x_0 + \beta_{x,0}x_0'}{\sqrt{\beta_{x,0}}}. \quad (2)$$

When this coordinate is used, the orbit of the injected beam is represented by a circle as shown in Fig. 2. We can consider ε_0 as a constant value for few turns after the injection since the radiation damping time is ten-thousand times longer. When $x_0' = -(\alpha_0/\beta_0)x_0$, P_0 becomes zero and ε_0 takes a minimum value X_0^2, and the normalized position is simply expressed by

$$X_0 = \pm\sqrt{\varepsilon_0}. \quad (3)$$

The pulsed magnet is located on the normalized coordinate (X_1,P_1) where the injected beam passes at the first turn. If the phase advance between the location and the injection point is ϕ, the normalized coordinate is represented by

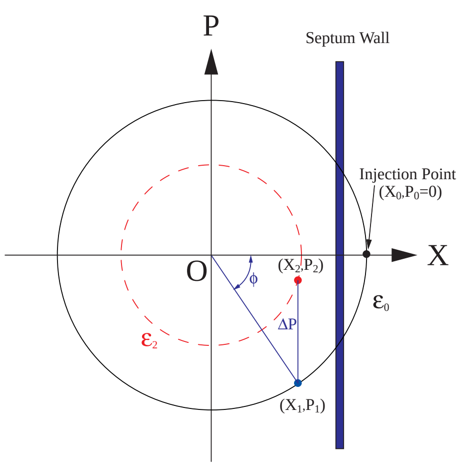

Figure 2: Normalized phase space plot of the injected beam orbit.

$$X_1 = X_0 \cos\phi, P_1 = X_0 \sin\phi \quad (4)$$

Since the pulsed magnet provides the kick to the beam, only the normalized angle is changed. If the amount of the change is ΔP, the normalized coordinate is given by

$$X_2 = X_1 = X_0 \cos\phi, \quad (5)$$
$$P_2 = P_1 + \Delta P = X_0 \sin\phi + \Delta P, \quad (6)$$

and the reduced circle as shown in Fig. 2 becomes

$$\varepsilon_2 = X_2^2 + P_2^2 \quad (7)$$
$$= \varepsilon_0 + 2\Delta P X_0 \sin\phi + \Delta P^2.$$

Then, the ΔP is obtained by solving Eq. (7) and is expressed using the ε_0, ε_2, and ϕ as follows,

$$\Delta P = \mp\sqrt{\varepsilon_0}\sin\phi \pm \sqrt{\varepsilon_2 - \varepsilon_0\cos^2\phi}, \quad (8)$$

while the ΔP is given by

$$\Delta P = 1/2K_2X_2^2 = 1/2K_2\varepsilon_0\cos^2\phi \quad (9)$$

using the normalized strength K_2 of the PSM. Then, the strength K_2 is obtained by inserting Eq. (9) into Eq. (8) as follows,

$$K_2 = \frac{\mp 2\sqrt{\varepsilon_0}\sin\phi \pm 2\sqrt{\varepsilon_2 - \varepsilon_0\cos^2\phi}}{\varepsilon_0\cos^2\phi}. \quad (10)$$

We examined the behavior of the K_2 as a function of ϕ giving ε_0 and ε_2 the concrete values; for example, ε_0 = 60 mm·mrad and ε_2 = 20 mm·mrad. The range of the phase advance covers from 0 to 90 degree for the simplicity, and the sign is defined to be positive to the clockwise direction. Fig. 3 show the strength as a function of the ϕ. In the figure, a horizontal axis is selected to cover the range from 54 to 80 degree, because the solution of Eq. (10) becomes imaginary when the phase is less than 54.7 degree, and the strength of K_2 rapidly increases near 90 degree. The strength of the PSM has the optimum value when the phase ϕ_{S_0} is about 56 degree. Since the phase advance is periodic, the optimum phases are generally expressed by

$$\phi_S = \phi_{S_0} + (n-1)\times 180, -\phi_{S_0} + n\times 180, \quad (11)$$

where n means an positive integer and the unit is degree. Therefore, if we install the PSM at the location where an optimum phase is satisfied, it enables us to reduce the amplitude of the injected beam effectively.

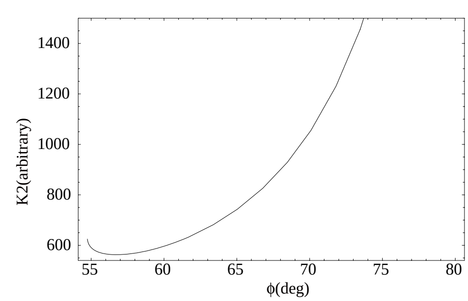

Figure 3: Normalized strength K_2 of the pulsed sextupole magnet (PSM) as a function of ϕ, which covers the range from 54 to 80 degree. The unit of the strength is arbitrary.

APPLICATION TO THE PF RING

Next, we apply the above formulation to the PF ring and search the location to allow the optimum phase from the injection point when we employ the PSM to inject the beam. The PF ring which is a 2.5 GeV electron storage ring dedicating as a synchrotron radiation source was upgraded in last year, and the straight sections are extended [4]. At present, we find out that the location inside the north straight section (B01-B02) is optimum. The location is illustrated in Fig. 4. When the ε_0 = 66.2 mm·mrad as the initial value for the injected beam is given, we need the

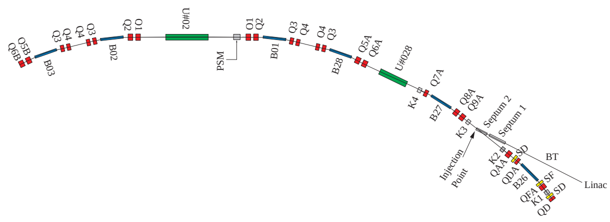

Figure 4: Lattice configuration around the injection point at the PF ring. The PSM is located upstream in undulator U02 between the bending magnet B01 and B02.

strength k_2 of 12.16 m^{-2} to realize ε_2 = 21.5 mm·mrad at the location. Here, k_2 represents the physical strength which is transferred from the normalized strength K_2 as follows,

$$k_2 = K_2/(\sqrt{\beta_{x_2}}\beta_{x_2}), \tag{12}$$

where β_{x_2} is the horizontal beta function at the location of the PSM. Fig. 5 represents the horizontal orbit of the injected beam with the PSM and without the PSM.

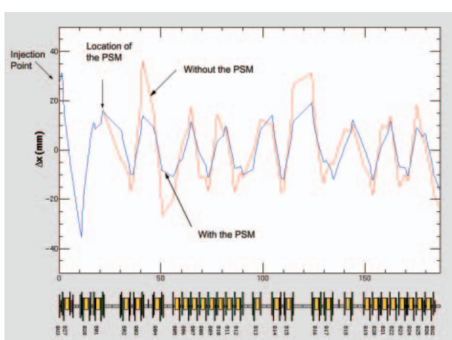

Figure 5: Horizontal orbit of the beam injected into the PF ring with the PSM and without the PSM. The orbit displays the first circulating one in the ring.

SIMULATION DUE TO MULTI-PARTICLE TRACKING AND DISCUSSION

Until now we have treated the barycenter of the injected beam in the horizontal direction and neglected the non-linearities in the ring. As a practical matter we have to consider the injected beam as three dimensional distributions of electrons and include the non-linearities which mainly come from the sextupole magnets for the chromaticity correction. In order to confirm these effects we conducted the simulation due to the multi-particle tracking giving initial conditions as listed in Table. 1. We employed the code SAD (Strategic Accelerator Design) [5] for the simulation and represented the injected beam as the macro-particles of 1000 on the six dimensional phase-space. As a typical results of the simulation we show the horizontal phase-space plots after the 10th turn and the 200th turn together with the 0th turn in Fig. 6. The particles are captured in the acceptance of the ring thought they are smeared on the phase-space. From the present result of the simulation, if we can manufacture the PSM with a strength k_2 of more than 12.16 m^{-2} and locate the PSM on the north straight section, we expect that we can inject the beam into the PF-ring using the single PSM. Now, we are going to develop the PSM for the beam injection.

Table 1: Initial conditions of injected beam for the multi-particle tracking.

Parameter	Symbol	Value
Macro particle number	N_{part}	1000
Tracking turn number	N_{turn}	200
Hori., Vert. Emittance	ϵ_x, ϵ_y	150 nm·rad
Energy spread	σ_ϵ	0.00125
Bunch length	σ_z	3.0 ps
Horizontal beta, alpha	β_x, α_x	11.3 m, -1.23
Injection position	x_i	27.0 mm
Injection angle	x'_i	3.32 mrad
Strength of PSM	k_2	12.16 m^{-2}

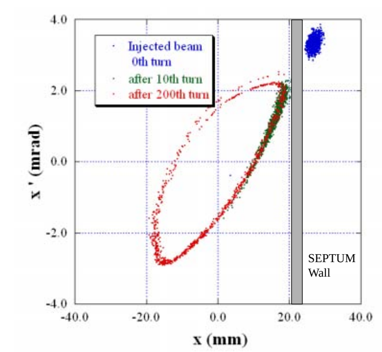

Figure 6: Horizontal phase-space plot obtained by multi-particle tracking for the injected beam using the PSM. The particles right before the injection, after 10 turn and after 200 turn are plotted.

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