PF-AR INJECTION SYSTEM WITH PULSED QUADRUPOLE MAGNET

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Abstract

We have developed new injection system for the PF-AR (Photon Factory Advanced Ring for Pulsed X-ray) with a single pulsed quadrupole magnet (PQ-magnet). The system enables us to inject the beam without a local bump due to four pulsed dipole magnets (pulsed kickers). The PQ-magnet has a length of 30cm, a field gradient of about 3T/m at a peak current of 2000A. The pulse form is a half sine with a full width of 2.4μSec. The measured inductance is about 1.8μH, and the voltage is 10kV at a current of 2000A. Using the PQ-magnet, the amplitude of the injected beam can be reduced to about a half of that only with septum magnets. Then, the reduced amplitude will be almost the same as the case of the usual injection. We are going to install the PQ-magnet at a short straight section near the south symmetric point of the PF-AR in this summer of 2004.

INTRODUCTION

The PF-AR is the unique synchrotron radiation source dedicating a single-bunch operation for pulsed X-ray. The storage ring has a circumference of 377m and the maximum energy of 6.5 GeV. The initial beam current is about 55mA, and the lifetime is over 10 hours at the current. The electron beam is injected from KEKB linac at the energy of 3.0GeV, and then ramped up to 6.5GeV.

In present injection system, we employ four dipole kickers to make a pulsed local bump of the stored beam to reduce the effective amplitude of the injected beam. However, the coherent oscillation of the stored beam is generated by the field errors, timing jitters, and individual differences of the kickers, and the nonlinear elements between them. For the PF-AR and also the light sources with the top-up injection, the oscillation is one of the serious problems. In order to prevent the oscillation of the stored beam, the injection system of the dipole kickers must be precisely constructed or new injection system is needed.

As well known, a quadrupole magnet has zero field strength at the magnetic pole centre. If the pulsed quadrupole (PQ) magnet is excited instead of the pulsed dipole magnets and the stored beam passes the magnetic pole centre, the beam is not kicked [1]. Thus, we may avoid the cumbersome coherent oscillation. On the other hand, the injected beam, which passes the magnetic pole off-centre, feels the magnetic field and is kicked. If the amplitude of the injected beam is reduced as small as the case with usual injection system with several dipole kickers, the injection may be possible. Moreover, using a single pulsed magnet, the manufacture of the magnet and the tuning for the operation are much easier than the case with plural pulsed kickers.

In the PF-AR, we could have never stored the beam current of more than 65mA until now because the injection has stagnated around the current. The stored beam with a coherent oscillation generates the strong wake field in the RF cavities. It seems that the injected beam would be lost because of the wake field [2]. Therefore, adopting new injection system, we may solve this problem since the coherent oscillation of the stored beam is not produced by the PQ-magnet.

INJECTION EMITTANCE

If the non-linearity among the ring elements is small, the motion of the injected beam is linear and can be written in terms of the Courant-Snyder invariant. The Courant-Snyder invariant (injection emittance) is

$$\varepsilon_{inj} = \frac{1}{\beta}\left(x^2 + (\alpha x + \beta x')^2\right) = X^2 + P_x^{\,2},$$

where x is the position of the beam, x' the divergence angle, and α and β are Twiss parameters. The X and P_x are normalized phase space coordinates, which is defined as

$$X = \frac{x}{\sqrt{\beta}}, P_x = \frac{\alpha x + \beta x'}{\sqrt{\beta}}.$$

For the PF-AR, the coordinates of the injected beam at the exit of the septum magnet are x=48mm and x'=7mrad. With Twiss parameters of α=-2.9 and β=18.3m, the injection emittance ε_{inj} is 130.7mm·mrad. (The wall of the septum magnet is at x=35mm.) In the present injection system, the coordinates of the stored beam with the pulsed bump is x=22mm and x'=2.8mrad at the injection point and this reduces the injection emittance to ε_{inj}=37.3mm·mrad. If we can reduce the injection emittance to less than this value by PQ-magnet, the injection may be possible.

LOCATION OF THE PULSED QUADRUPOLE MAGNET

Fig.1 shows a lattice configuration around a south straight section of the PF-AR. The location of "(5)" in the figure corresponds to a south symmetric point. The "K1" and "K2" indicate the pulsed dipole kickers for the usual beam injection, and the locations from "(1)" to "(10)" are the straight sections, where we can install the pulsed quadrupole magnet geometrically.

The normalized coordinates of the injected beam at each location are shown in Fig. 2. At the injection point, X=11.2, P_x=-2.6 and the beam coordinates rotate counter clockwise in the phase space because we take the outer direction of the ring as positive. The phase advance

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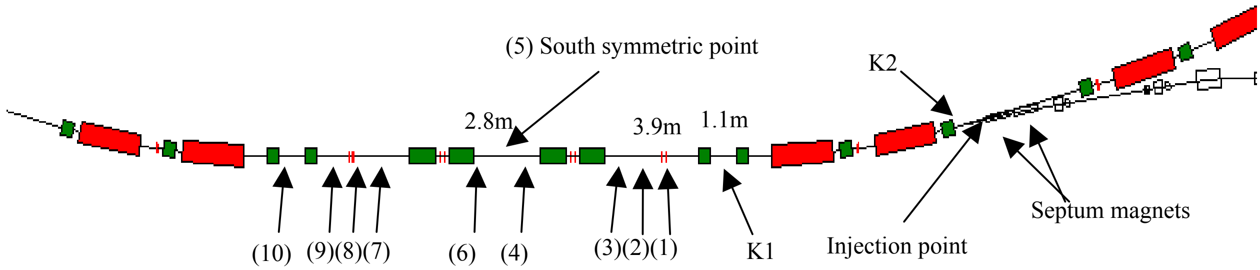

Figure 1: Lattice configuration around a south straight section of the PF-AR

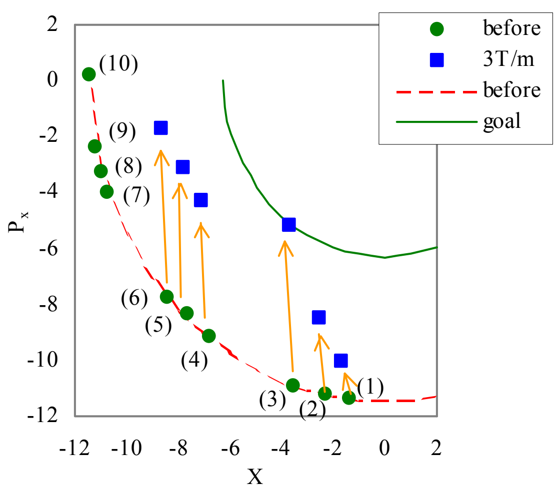

Figure 2: Normalized horizontal phase-space plot of the injected beam in the locations around a south straight section

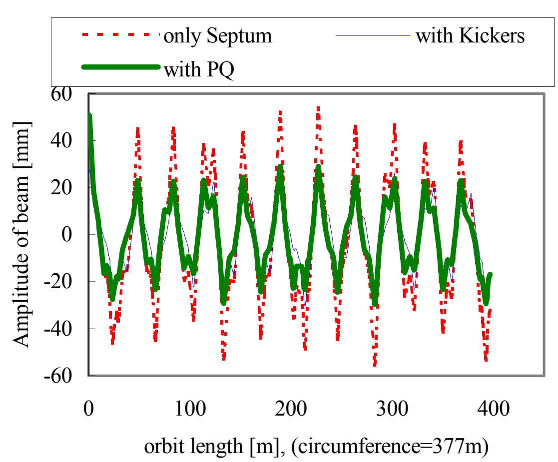

Figure 3: First-turn horizontal oscillation of the injected beam along a path length of the ring

between the injection point and the location “(10)” is about 0.5 and the amplitude of the injected beam almost reaches the opposite maximum.

In Fig. 2, the dashed-line ”before” shows the initial injection emittance (130.7mm·mrad), the solid-line “goal“ indicates the emittance (37.3mm·mrad) with the usual injection system. The solid-circle “before” shows the initial injection emittance at locations from “(1)” to “(10)” and the solid-square “3T/m” shows the reduced injection emittance with the PQ-magnet at locations from “(1)” to “(6)”. For the calculation, we assumed the PQ magnet of the length of 30cm and field gradient of 3T/m.

The quadrupole magnet can produce the momentum kick on the beam and the magnitude of the kick is proportional to the amplitude of the beam. In order to get sufficient momentum kick, it is preferable that the beam has large amplitude. At the locations “(1)” and “(2)”, the amplitude of the beam is too small and we cannot reduce the injection emittance to the "goal" value with the PQ-magnet of 3T/m field gradient. On the other hand, when the injected beam has large amplitude, both the momentum contribution and the amplitude contribution to the injection emittance are the considerable amounts. The PQ-magnet can only reduce the momentum contribution. The larger the amplitude of the injected beam is, the smaller the momentum contribution is. Thus, from this point of view, the amplitude of the beam should be enough small. At the locations beyond (4), the initial amplitude of the injection beam is too large and, however strong the field gradient of the PQ-magnet is, we cannot reduce the injection emittance to the "goal" value. After all, the optimum location for the PQ-magnet is the location (3) where the injected beam has proper amplitude.

Fig. 3 shows the first-turn horizontal oscillation of the injected beam along a path length of the ring. The dotted line shows the case with only septum magnets, the thin solid line the case with the usual injection system using a pulsed bump, and thick solid line the case with the PQ-magnet installed at the location “(3)”. The amplitude of the injected beam with the PQ-magnet is almost the same for the case with the usual injection system.

By the way, although the orbit of the stored beam may not be changed by the PQ-magnet, the particle distribution of the stored beam in the phase space is changed. We can prevent this effect by installing another PQ-magnet with an opposite polarity (depending on the phase advance) at the upstream of the injection point.

DESIGN OF THE PQ-MAGNET

We designed and manufactured the PQ-magnet with the geometry of the length of 30cm, the horizontal gap 102mm and the vertical gap 36mm. In order to achieve a strong magnetic field gradient, we fixed the vertical gap of the PQ magnet considering with the smallest vertical physical aperture in the PF-AR, which is 20mm in full

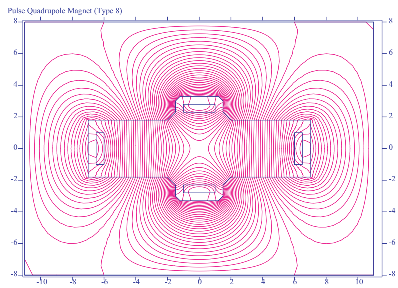

Figure 4: Two-dimensional magnetic field distribution of the PQ-magnet calculated by the code Poisson

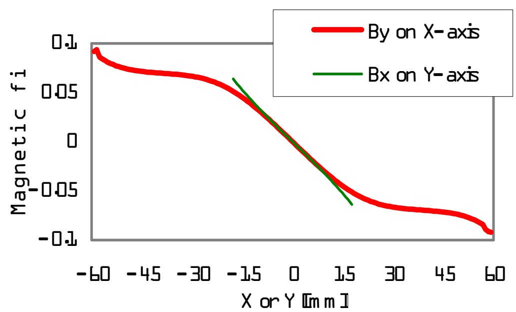

Figure 5: Calculated magnetic field strength along the horizontal axis or vertical axisat a center

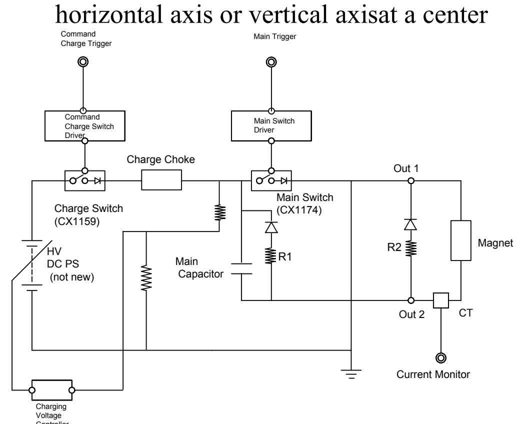

Figure 6: Conceptual block diagram of the circuit in the power supply for the PQ-magnet

width at the in-vacuum insertion device of NE1. Since the vertical beta functions are 3.1m at a centre of NE1 and 3.9m at the location of the PQ-magnet, we adopted the ceramic vacuum duct with the vertical inner bore of more than 23mm for the PQ-magnet. Considering the thickness of 5mm for the ceramic duct and enough clearance, we determined the vertical gap of 36mm in the PQ-magnet.

We selected the quadrupole magnet of the Panofsky type [3] whose turn number of the coil is just one in order to reduce the inductance of the magnet and suppress the voltage of the power supply. The measured inductance of the magnet is about 1.8μH that is less than 2/3 of the estimation from the calculation, 3μH.

Fig. 4 shows the magnetic force line distribution calculated by the two-dimensional code POISSON. The magnetic field strength is shown in Fig. 5. The magnetic field at a horizontal position of 15mm (where the injected beam passes) reaches 0.045T at a current of 2000A. Then, the PQ-magnet has the field gradient of 3T/m. The magnet is made of the lamination of the silicon steel of 0.15mm thickness. The maximum magnetic field at the edge of the magnetic core is less than the saturation field strength of silicon steel, 0.2T.

The pulse width is 2.4μsec, which is twice the revolution period of the PF-AR. The injected beam begins smearing and filamentation just after injection and in order to prevent the partial loss of such injected beam by multiple kicks during several turns, we should keep the pulse width less than 2.4μsec.

POWER SUPPLY

We adopted the pulsed power supply with the command charging method for the PQ-magnet. The power supply has two thyratron switches. Fig.6 shows the conceptual block diagram of the circuits in the power supply. By adjusting the strength of the resistor R1 and R2, we achieved the expected pulse with a full width of less than 2.4μsec.

Because the measured inductance of the PQ-magnet was about 1.8μH, we needed the voltage of about 10kV in the DC power supply to achieve a current of 2000A corresponding to the field gradient of 3T/m. Since the available voltage is until 30kV, we may obtain much higher field gradient than 3T/m. This enables us to suppress the injection emittance more. The power supply can be operated at a maximum rate of 25Hz because the maximum injection repetition frequency is 25Hz for the PF-AR.

CONCLUSION

We have developed new injection system with the PQ-magnet for the PF-AR. Using single PQ-magnet instead of the pulsed dipole kickers, the injection without a local bump of the stored beam is possible (with the septum magnet). We have finished the manufacture of the PQ-magnet and the power supply system in this February. We begin to measure the magnetic field. Then we are going to install the PQ-magnet at a short straight section near the south symmetric point of the PF-AR in the summer of 2004.

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