BEAM INJECTION SYSTEM BY USE OF A PULSED SEXTUPOLE MAGNET AT THE PHOTON FACTORY STORAGE RING

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Abstract

We have developed a new beam injection system by use of a pulsed sextupole magnet (PSM) at the Photon Factory storage ring (PF-ring) in KEK. The PSM has a core length of 300 mm and a bore radius of 33 mm. We measured its magnetic field of a half-sine pulse shape with a width of 2.4 μsec and gained the required strength K_2 (= B"L/Bρ) of 13 m^{-2} at a peak current of 3000 A. We demonstrated the beam injection with this system and succeeded in storing a beam current of 450 mA. This is the first demonstration of the PSM beam injection in electron storage rings all over the world.

INTRODUCTION

We installed a new injection system with a pulsed sextupole magnet (PSM) into the Photon Factory storage ring (PF-ring) in the spring of 2008. In general, the pulsed local bump with several kicker magnets is employed for the beam injection to reduce the coherent dipole oscillation of the injected beam. However, it is difficult to make a perfect closed bump with the kicker magnets because of their field errors, timing jitters and non-linear effects of the magnetic field like sextupole magnets inside the bump. This is one of the problems for the top-up injection. In order to reduce the oscillation of the stored beam caused by imperfection of the closed bump, we have proposed the beam injection using the PSM [1-2]. The injected beam is captured into the ring acceptance by the kick of the PSM, the strength of which increases by the square of the distance from the magnetic field center. On the other hand, the stored beam passes through a center of the PSM where almost zero magnetic fields. Since the kick to the stored beam is quite weak, the perturbation during the injection becomes very small. Therefore, the new injection scheme using the PSM system is expected to be very suitable for the top-up injection.

The PSM with a core length of 300 mm and a bore radius of 33 mm was produced [2]. In order to obtain a strong magnetic field, we determined the bore radius as narrow as possible using a multi-particle tracking simulation not to limit the physical aperture of the PF-ring. The magnet was laminated from silicon steel sheets of 0.15 mm thick. The coil is made of one-turn copper with a diameter of 15 mm. The electrical isolation between the coil and the core is made with epoxy resin. The cooling of the PSM is air-cooling without a blower. The requirement for the integrated magnetic field of PSM is 120 Gauss-m at a horizontal displacement of 15 mm from the magnet center, where the injection beam passes. This strength corresponds to K_2 (= B"L/Bρ) of 13 m^{-2}, where B" is the field gradient, L is the core length and Bρ is the magnetic rigidity.

FIELD MEASUREMENTS

The pulsed power supply in this system has output current of a half-sine pulse shape with a full width of 2.4 μsec and a maximum charging voltage of 40 kV. The total inductance is estimated to be 4.3 μH. The required charging voltage for the beam injection is estimated to be 16.7 kV at a peak current of 3000 A. The repetition frequency is available up to 25 Hz.

We measured the pulsed current using a current transformer (CT) and the pulsed magnetic field with two kinds of search coils (a short rectangular coil of 5 mm x 5 mm and a long rectangular coil of 5 mm x 600 mm). The short search coil was employed for measuring the distribution of the magnetic field along the longitudinal direction and the long search coil was for the integrated magnetic field. Each coil was made of a single-turn fine copper wire attached to a glass epoxy bar. The search coils were fixed to the XYZ stage. It was remotely controlled with the stepping motor with a precision of 0.2 μm/pulse for the horizontal (X) and the longitudinal (Z) directions and 1 μm/pulse for the vertical (Y) direction.

In order to reduce the noise that mainly is generated by the mismatch of the impedance, a low-pass filter of 2 MHz and a ferrite core was adapted to the signal line. All signals were measured with 50 Ω termination. Figure 1

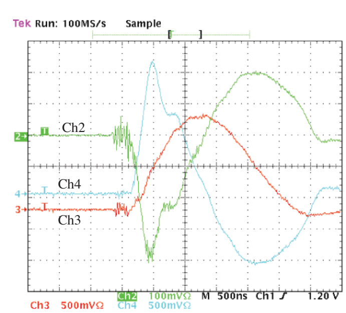

Figure 1: Typical waveforms measured at a charging voltage of 16.7 kV. Red solid line represents an excitation current (Ch3). Green and cyan solid lines represent output signals of the short coil (Ch2) and the long coil (Ch4), respectively. The search coil is placed at a horizontal location of 15 mm from the magnetic pole center.

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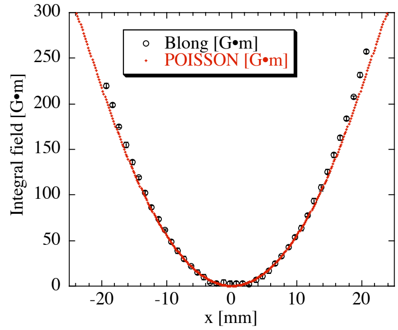

Figure 2: Horizontal distribution of the integrated magnetic field. Open circles (black) show the measured result of the long coil and dotted line (red) shows the calculated result of POISSON code.

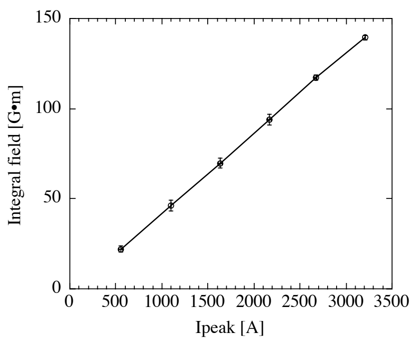

Figure 3: Excitation curve of the integrated magnetic field as a function of the peak current of the pulsed power supply.

shows the typical waveforms measured at a charging voltage of 16.7 kV. The magnetic field was evaluated by integrating the output voltage of the search coil.

Figure 2 shows the horizontal distribution of the integrated field, which was measured at a peak current of 3000 A. The result is compared with the integrated field calculated by using POISSON code [3]. The horizontal distribution of the integrated field shows parabolic shape and the magnetic field around the center of the PSM is nearly zero. The measured value at a large horizontal displacement is slightly larger than that of the POISSON calculation because the effective length of the PSM is 320 mm. Figure 3 shows the excitation curve as a function of the peak current from 500 to 3200 A at a horizontal displacement of 15 mm from the PSM center. The integrated field linearly increases ranging from 20 to 140 Gauss-m without the filed saturation.

INSTALLATION

The PSM was installed at a north long straight section of 8.9 m in the PF-ring (see figure 4). A ceramic chamber is employed to reduce the eddy currents which cause the distortion and the delay of the pulsed magnetic field. The thickness of the ceramic chamber is 3 mm and the clearance between the chamber and the magnetic pole is 0.5 mm. The inner side is coated with a titanium layer of 3 μm.

BEAM INJECTION

Since a revolution period of the PF-ring is about 0.6 μsec, the half-sine pulse with a full width of 1.2 μsec or less is preferable for the beam injection. However, the existing pulsed power supply has the full width of 2.4 μsec. It is inevitable that the injected beam receives the second kick from the PSM. For example, if the first kick is adjusted at the peak of the pulse, the second kick is given by 0.7 times smaller than that of the first kick. From the field distribution of the sextupole magnet, the direction of the second kick is the same as that of the first kick. We predicted a capture efficiency of the injection beam (captured particles / injected particles) at the operating tune of the PF-ring by a multi-particle tracking simulation, varying the injection angle at the injection point and adjusting the injection timing.

Figure 5 shows the capture efficiency as a function of the injection angle at the injection point. The kick strength of the PSM strongly depends on the injection angle [2]. When we set the injected beam position of 27.0 mm at an exit of a septum magnet, the injection angle of about 1.7 mrad allows us to realize the capture efficiency of more than 60 %. The injection timing represents the time deviation of the first injection kick from the peak of the pulse. Figure 6 shows the capture efficiency as a function of the injection timing. The capture efficiency also depends on the timing. The efficiency at the injection angle of 1.7 mrad is over 60 % when the injection timing is from -200 to 500 nsec.

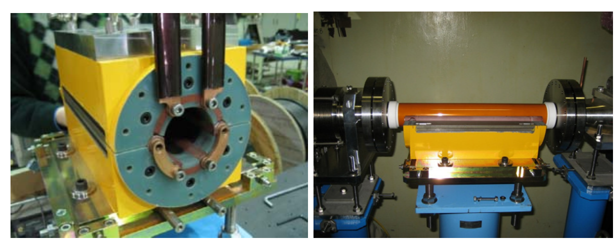

Figure 4: Photographs of the PSM: a front view of the magnet (yellow) is shown in the left photo, and the ceramic chamber (white) on the half-split magnet is represented in the right photo. The chamber is protected by a 100 μm thick film (brown).

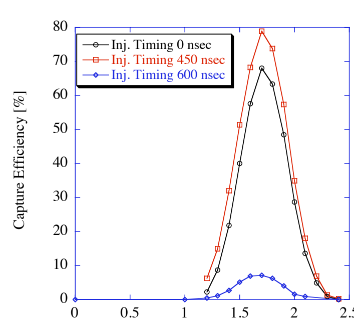

Figure 5: Capture efficiency as a function of the injection angle for the injection beam position of 27 mm. The circles, squares, and diamonds show the efficiencies when the injection timings are 0, 450 and 600 nsec, respectively.

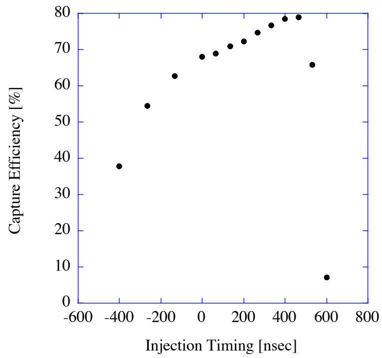

Figure 6: Capture efficiency as a function of the injection timing with the injection angle of 1.7 mrad. The injection timing represents the time deviation of the first injection kick from the peak of the pulse.

We conducted a beam injection experiment in May 2008. The arrival timing of the injected beam was monitored using a wall current monitor and the excitation of the PSM was carefully adjusted so that the beam was efficiently captured into the ring. The single bunch beam was used for the timing adjustment. Figure 7 shows the waveform measured by the digital oscilloscope (Tektornics TSD748) when we firstly succeeded in injecting and storing the real beam using the PSM.

Next, we tried to accumulate the beam up to a current of 450 mA in the multi-bunch mode. Figure 8 shows a trend of beam current. The injection was firstly carried out at a repetition frequency of 5 Hz, and then the frequency was increased to 12.5 Hz. On the way to the current of 450 mA, the usual injection system of the PF-ring was employed for saving time of the injection and to compare the injection rate. When the beam current exceeded 400 mA, the PSM injection was resumed. Figure 9 shows a trend of the injection rate. The rate at a higher beam current was slightly decreased in comparison with that at a lower beam current. This will be examined

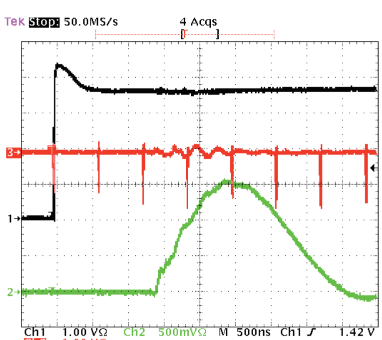

Figure 7: Typical waveform in the adjustment of excitation timing of the PSM measured using a digital oscilloscope. The lines represent a discharge trigger (black), signal from a current transformer of the pulsed power supply (green) and a wall current monitor of the ring (red). An interval of the red line shows the revolution time. The injection was made at the peak of the pulse. There still exist a very small magnetic filed at the third turn.

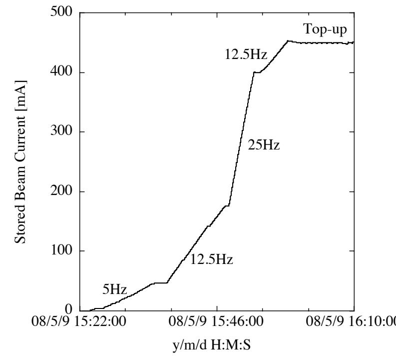

Figure 8: Trend of the stored beam current. The beam was injected using the PSM, but the usual injection system with was conducted with a repetition rate of 25 Hz because of the reduction of the experiment time.

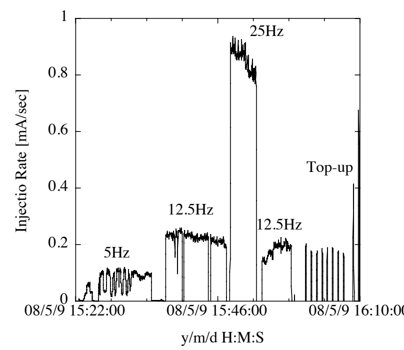

Figure 9: Trend of the injection rate at the same conditions as the figure 8.

in the next experiment in detail. Anyway, we could store the beam up to the current of 450 mA and keep the current by the continuous (top-up) injection using the PSM.

SUMMARY

We have developed a new beam injection system with the PSM. The pulsed magnetic field of the PSM were measured and it was confirmed in the measurement that the requirements were satisfied. Then, we installed the PSM into the PF-ring in the spring of 2008 and the test experiment was conducted using a real beam in May 2008. In the first test experiment, we succeeded in injecting and storing the beam using the PSM in normal and top-up injection modes of the PF-ring. This is the first demonstration of the PSM beam injection in electron storage rings all over the world. In the next experiment, we will examine the performance of the PSM beam injection in detail.

REFERENCES

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