Evaluation of Eddy Current Effects on a Pulsed Sextupole Magnet by a Precise Magnetic field Measurement at KEK-PF

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Abstract

Pulsed multipole magnet injection is continuously developed at the photon factory of KEK(KEK-PF) for the new injection scheme in the future light source. As a first step, the pulsed sextupole magnet (PSM) has been developed for the demonstration test. We found that a PSM with rectangular aperture (PSM2) has strong eddy current effects in accelerator operation, which is against our expectation. Therefore, the magnetic field of the initial prototype, a PSM with circular aperture (PSM1) was measured again. In this case, the pulsed magnetic field of PSM1 is precisely measured by a small pick-up probe which finished 3D mapping measurement to obtain detailed magnetic field distribution. By comparing DC and pulsed field measurement results, PSM1 also has eddy currents. This experiment represents that the eddy current effects have to be taken into consideration in PSM injection. We will report the details of measurement setup and observed evidence of eddy current phenomenon in this conference.

INTRODUCTION

Pulsed multipole injection is a novel injection scheme. And a pulsed sextupole magnet (PSM) injection has been developed for several years at KEK-PF. Compared with conventional injection method which has four kickers, multipole injection just needs only one magnet to achieve the beam injection and stored beam won't be disturbed. So, it could save the space in straight section and make top-up injection fully transparent to users.

At first a PSM with a circular shape duct (PSM1) was installed and operated successfully [1]. Compared with bump injection, the amplitude of horizontal oscillation is reduced to 180μm. To improve injection efficiency, PSM1 was replaced by a PSM with a rectangular shape duct (PSM2) and new power supply system, which could generate stronger pulsed magnetic field and increase physical aperture of horizontal direction. But the stored beam has a 5mm oscillation during operation. It's supposed that eddy current magnetic field exists in beam injection so that the stored beam is oscillated, because in the centre of magnet, the field generated by applied current should be zero. The historical details for PSM upgrading will be reported at THPP58 presentation in this conference.

It's very hard to analyse eddy current effects numerically in a multipole magnet. To investigate this phenomenon, both DC and pulsed magnetic field in PSM1 have been measured. Eddy current effects will be found and discussed by an experimental method.

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CANDIDATES OF EDDY CURRENT SOURCE

Before taking this experiment, candidates of eddy current have been analysed preliminarily by skin depth, which is close related to eddy current. The equation of skin depth is shown below:

$$\delta = \sqrt{\frac{1}{\pi f \mu\sigma}} \tag{1}$$

Where the f is frequency of external magnetic field, μ is the permeability of the material, σ is electrical conductivity.

Usually pulsed magnet is made by lamination steel, it's because that the lamination is insulated with each other and the inductance will increase if the thickness of lamination is smaller than skin depth [2]. It means that eddy current could be suppressed successfully when magnetic field penetrate the lamination steel.

The lamination steel of PSM1 is silicon steel, μ is about 5x10^{-3} H/m, σ is 7x10^{6} S/m, so the skin depth is 0.043 mm if f=500 kHz. But the thickness of PSM1's lamination is 0.15 mm which is almost the minimum thickness that can be manufactured. Because the skin depth is too small, the eddy current still possibly generates in one sheet in short pulsed experiment.

As for the copper used in magnet coils, the skin depth of copper under 500 kHz is 0.092 mm. the coil of PSM1 could also easily generate eddy current if the pulsed field has a high frequency. As shown in the Fig. 1, several components may be the candidates of eddy current.

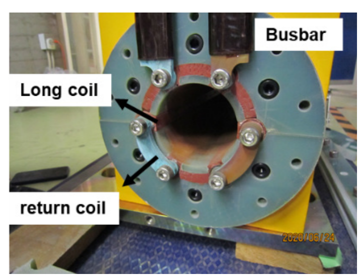

Figure 1: Photo of PSM1.

The coating of chamber is also a candidate of eddy current source. The material of PSM1's duct is ceramic, but there is a Titanium coating inside of the duct to secure the conductivity for beam wall current and the thickness is 5μm. This thickness is thinner than skin depth for sextupole pulsed field. Because the magnetic field penetrates the coating perpendicularly, the thin coating couldn't prevent the generation of eddy current completely.

According to previous analysis, any conductive component may generate eddy current in magnetic field region. And undesirable field distortion due to eddy current could influence the performance of PSM1.

PICK-UP PROBE TO MEASURE PULSED FIELD

In order to investigate eddy current effects, a pick-up probe (Fig. 2) is developed to measure pulsed magnetic field based on Faraday's law. Compared with conventional pick-up coil, this point-to-point measurement tool is expected to give full information in pulsed field measurement.

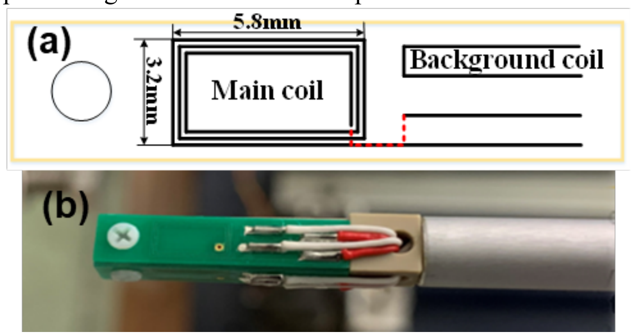

Figure 2: (a) Sketch and (b) photo of pick-up probe.

Thin coil is welded on a plastic board. It has 3 turns, the thickness of coil is 1μm, and the gap between each coil is also 1μm. So, the effective area is about 40mm². The red dash line means the end part of coil is fixed on the back side of the board and connects to the terminal of the cable, which could improve precision of measurement. The probe has two outputs which are from main coil and background coil. Voltage signal of main coil will be subtracted by the signal of background coil.

Usually, the output current of pulsed power source is a half-sine pulse. The shape of magnetic field generated by applied current is also a half-sine shape. Thus, voltage signal of pick-up probe could be estimated, as shown in Fig. 3. Considering the zero-input response and final state of the circuit, the actual signal may look like a full-sine waveform.

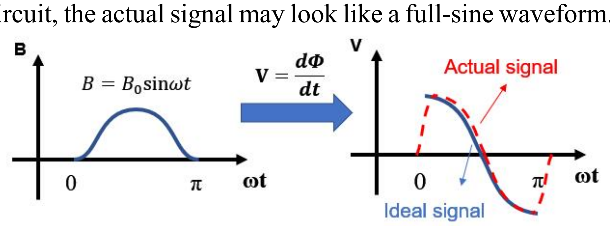

Figure 3: Schematic view for voltage signal of probe.

Then, the integral of positive voltage could be calculated by

$$\int V \mathrm{d}t = \int_0^{\pi/2} B_0 S \cos\omega t \mathrm{d}\omega t \qquad (2)$$

Where B_0 is the maximum value of main field, and S is the effective area of coil, and ω is the angular frequency of main field. Then B_0 could be calculated by

$$B_0 = \frac{\text{maximum value of integrated V signal}}{S} \qquad (3)$$

In order to calculate the pulsed field correctly, the subtraction of signal is indispensable before integrating the voltage signal.

Figure 4 shows the screenshots under different situation. It could be easily understood the meaning of subtracting the background signal. If only main field signal (CH1) is integrated, the shape of integrated signal (Func2) isn't same with the shape of current signal (CH3), which isn't consistent with expectations. But if background signal (CH2) is added, a new signal (Func1) will be obtained by subtraction. And the integrated signal of Func1 is the expected signal that has similar shape with that of current signal.

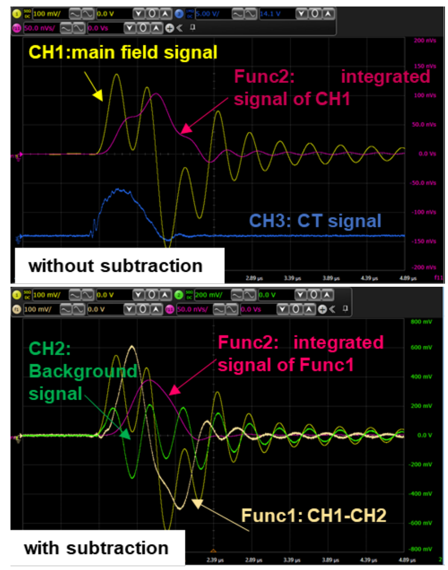

Figure 4: Schematic view for voltage signal of pick-up probe in different situation.

Because the magnetic field generated by eddy current opposes the change of field generated by applied current. The shape of field generated by eddy current could be expected, which is shown in Fig. 5. In this case, the positive pulsed current is applied for the figure.

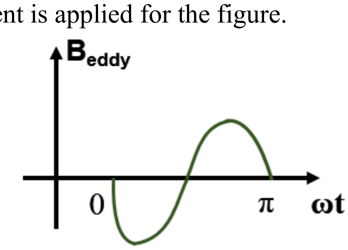

Figure 5: Schematic view of magnetic field generated by eddy current.

In the center of magnet, the ideal sextupole magnetic field generated by applied current is exactly zero and the approximate zero-field is distributed around center of magnet. So, if the pick-up probe could catch such a signal around center of PSM1, it may prove the existence of eddy current and provide much information about eddy current.

MEASUREMENT SYSTEM AND PLAN

Both DC and pulsed magnetic field of PSM1 have been measured. The DC and pulsed measurement method are similar. The most important difference is the probe. A hall element probe is used to measure the DC field and the applied DC current is 10A. The pulsed field is measured by the pick-up probe introduced before.

As for pulsed measuring system, the main components are shown in Fig. 6, and the probe is controlled by a XYZ moving device which is driven by stepping motors. And the pulsed width of output current is 1μs. The signal generator gives triggers to the pulsed power source and oscilloscope. And Oscilloscope not only catches the main field signal and background field signal from the probe, but also receives the signal of current transformer (CT).

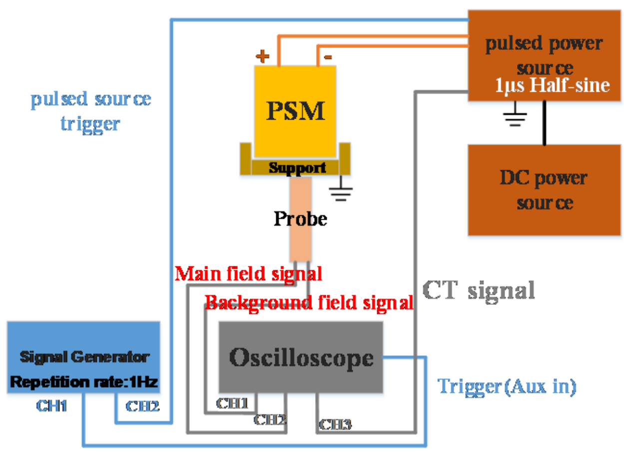

Figure 6: Schematic view of pulsed measurement system.

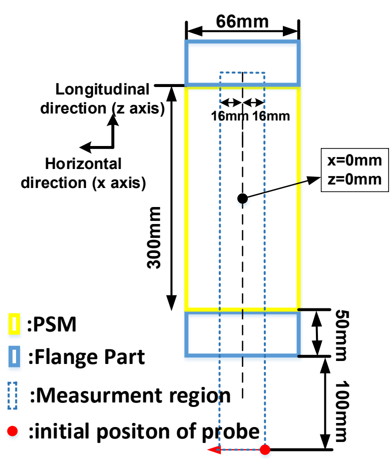

Figure 7: Sketch of mapping measurement.

A 3D mapping measurement is good way to get detailed information of magnetic field. As shown in Fig. 7, the probe will scan the region and measure the magnetic field automatically. The radius of PSM1's aperture is 66mm and the length of iron core of PSM1 is 300mm. And the coordinate of center position of PSM1 is set as x=0mm, z=0mm. Because we want to avoid that the arm of probe hits the duct of PSM1, the horizontal region of mapping measurement is from x=-16mm to +16mm. And there is a limitation on range of movement, the longitudinal region is from z=-300mm to 160mm.

The sampling length along X direction is 1mm and along Z direction is 5mm. The Y position is always 0mm.

MEASUREMENT RESULTS

At first the pulsed field was measured without chamber. According to the simulation of beam injection, the beam will be kicked at x=15mm in PSM, so it's necessary to compare the longitudinal distribution of the DC and pulsed field at x=15mm, which is shown in Fig. 8. Besides, the horizontal distribution (Fig. 9) is also important, which may include essential information. And all these results are normalized to 3000A used for operation.

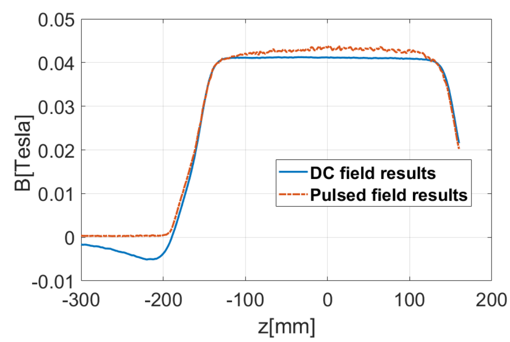

Figure 8: Normalized longitudinal distribution at x=15mm.

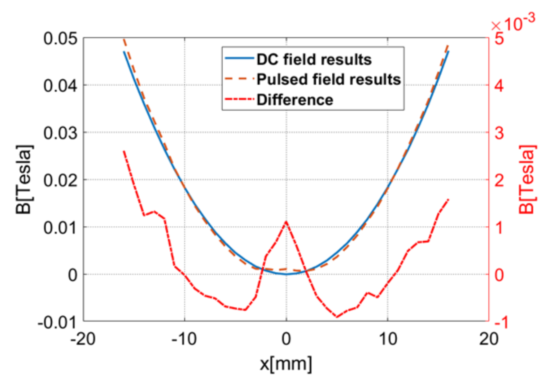

Figure 9: Normalized horizontal distribution at z=0mm.

In Fig. 8, a negative DC field appears around z=-200mm, because the busbar, which is the connection part of power cable from power supply system, breaks the symmetry of return coil. And the pulsed field is stronger than DC field in PSM1, which is consistent with the horizontal distribution in Fig. 9. The difference between DC and pulsed field may be caused by eddy current effects. It's supposed that the magnetic field generated by eddy current and applied current mix around center of PSM1. The curve of difference has a transition point around x=5mm. Because magnetic field generated by eddy current gradually becomes dominant around center of PSM1. Distinguishing the field contamination is difficult around this region.

And in the experiment, the evidence of magnetic field generated by eddy current has been caught by oscilloscope. The shape of integrated voltage signal (Func2) at x=0mm (Fig. 10) corresponds to the curve in Fig. 5.

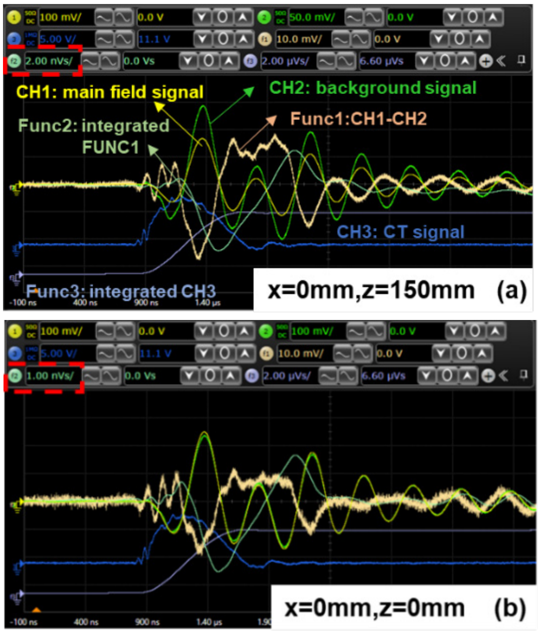

Figure 10: Screenshots of oscilloscope (a) x=0mm, z=150mm (b) x=0mm, z=0mm.

From the scale of Func2, the strength of eddy current effects at edge of PSM1 is stronger than that at center of PSM1. The distribution of strength of eddy current effects in PSM1 may be different. To investigate this issue, the longitudinal distribution at x=0mm was measured. It needs to be mentioned that the minimum value of Func2 signal should be picked in this situation. Because this measurement method couldn't distinguish direction of magnetic field automatically. Therefore, the longitudinal distribution of pulsed field is always positive in Fig. 8.

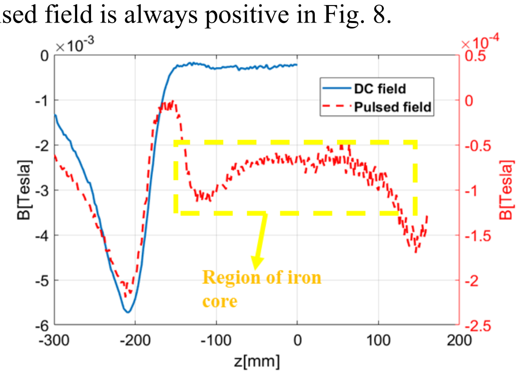

Figure 11: Comparison between DC and pulsed field at z=0.

In Fig. 11, the pulsed field generated by eddy current gradually increases from the center to the edge of PSM1. Even though, the busbar has an influence at one edge of PSM1, the tendency is still clear to be observed.

Previous measurements are taken under condition of PSM1 without chamber. And mapping measurement of PSM1 with chamber (Fig. 12) has also been performed to research the influence of the coating of chamber.

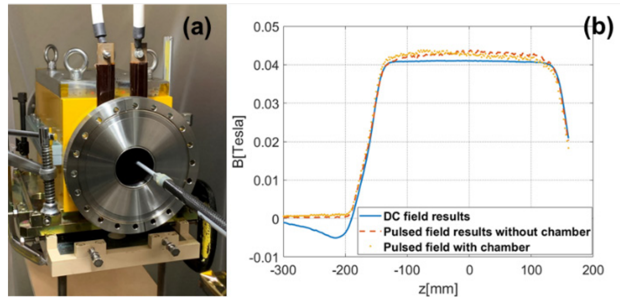

Figure 12: (a) Photo of PSM1 with chamber (b) normalized longitudinal distribution at x=15mm.

The results of pulsed field with chamber has been compared with results of DC magnetic field and pulsed field without chamber carefully. And longitudinal distribution at x=15mm is shown in this paper. It's found that the pulsed field with chamber almost doesn't change. It seems the chamber is nearly transparent in pulsed field measurement.

DISCUSSION ABOUT EDDY CURRENT EFFECTS

It's very important to understand why there is a difference between DC field results and pulsed field results. For example, in Fig. 9, the pulsed field is larger than DC field at the off-center position more than 10mm. It has been mentioned that long coil may generate eddy current. As shown in Fig. 13, the blue line is edge of lamination steel, the black line is the outline of long coil, and the red line is the magnetic flux generated by eddy current. In the region of coil, the magnetic flux is almost parallel with each other. It means eddy current could easily generate in the long coil. The magnetic field generated by eddy current oppose the magnetic field generated by applied current in the region of long coil. But the magnetic field in the aperture is enhanced.

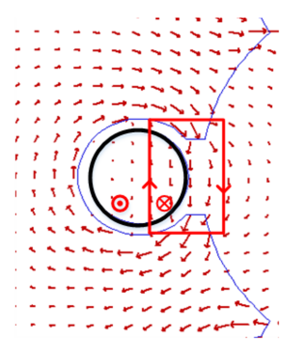

Figure 13: Sketch of eddy current effects of long coil.

Therefore, the normalized pulsed field is stronger than the normalized DC field at x=+15mm in PSM1. But this effect will become weak if the position is far from long coil. The details of this analysis and precise measurement will be done to prove our supposing soon.

And from the difference of horizontal distribution and screenshots, the lamination steel has an eddy current effect that opposes change of pulsed field generated by applied current at center of magnet.

Next, the attenuation of magnetic field around PSM1's edge will be demonstrated. Around the end part of PSM1, the eddy currents are induced by the z component of fringe field. In this case, the lamination steel can't prevent eddy current because z component of magnetic field penetrate lamination perpendicularly [3].

Figure 14 schematically shows the situation at the end of PSM1. The field produced by z component fringe field superimposes the main field, which attenuates the field around end part and enhance the field inside of PSM1.

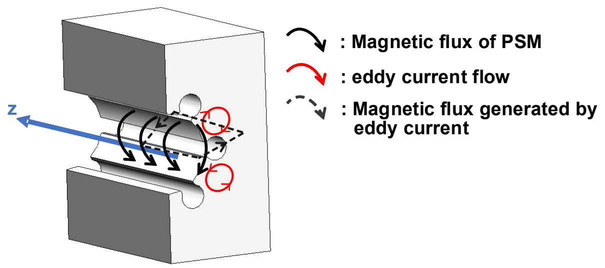

Figure 14: Schematic view of the eddy current induced by Bz field component.

It's indicated that two eddy current effects exist in the lamination steel. One is the uniform opposite pulsed field caused by main field, which decreases the sextupole magnetic field uniformly along longitudinal axis, the other one is the field variation due to fringe field around end part of PSM1. Combining these two effects, the shape of longitudinal distribution of pulsed field could be understood.

As for busbar and return coil, because they are located outside of iron core where the magnetic field is weak, so obvious eddy current effects aren't observed. But the structure of busbar could generate field around center of PSM1, which could have an influence on the stored beam.

Finally, the coating of chamber doesn't have a big effect on pulsed field on XZ plane. More experiments will be carried out in the future to investigate the mechanism.

CONCLUSION

It's supposed that eddy current for the iron-core, the coils, and coating is the main reason why stored beam has oscillation in core-type pulsed multipole magnet injection. To investigate eddy current effects, a pick-up probe is developed to measure pulsed field in PSM1. Detailed magnetic field measurement has been performed. The eddy current effects in PSM1 are observed successfully and have been discussed in this paper. And the PSM1 is rotated and measured to get magnetic field information in full region. The normalized integrated magnetic field under different condition are shown in Tables 1, 2 and 3.

Table 1: Integrated DC Magnetic Field

Integrated magnetic field[T·m]	x=0mm	x=15mm
-300 to -150mm	-5.080×10^{-4}	2.025×10^{-4}
-150 to +150mm	-4.200×10^{-5}	0.0122*
+150 to +300mm	4.200×10^{-6}	6.460×10^{-4}

Table 2: Integrated Pulsed Magnetic Field with Chamber**

Integrated magnetic field[T·m]	x=0mm	x=15mm
-300 to -150mm	-2.525×10^{-4}	3.855×10^{-4}
-150 to +150mm	-4.359×10^{-4}	0.0127
+150 to +300mm	-8.172×10^{-5}	6.231×10^{-4}

Table 3: Integrated Pulsed Magnetic Field without Chamber

Integrated magnetic field[T·m]	x=0mm	x=15mm
-300 to -150mm	-2.030×10^{-4}	4.328×10^{-4}
-150 to +150mm	-4.307×10^{-4}	0.0125

* : designed value is 0.0120 T·m
** : relative error of pulsed measurement is 3.9%

According to previous contents, it's obvious that integrated magnetic field at center axis generated by eddy current is 10 times larger than that of DC in the core of PSM1. And outside of PSM1, the field deformation caused by asymmetry structure of busbar and return coil has small influence but can't be ignored in design of magnet. The most important thing is that the chamber hardly influence the magnetic field on XZ plane. So PSM1 operated successfully in the past.

The estimated oscillation of stored beam by measurement results is 1.2mm, which is larger than 0.18mm, due to the pulse width of power source. When PSM1 operated in the past, it's 2.4µs, so eddy current effects are weak. The oscillation will be unacceptable if we use fast kicker system.

Based on these important knowledges, in the future, a special air core type magnet will be developed in multipole injection project [4]. It is ceramics chamber with integrated pulsed magnet, and we are expecting it could achieve the goal of multipole injection perfectly.

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