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DEVELOPMENT OF AN OCTUPOLE CERAMICS CHAMBER WITH INTEGRATED PULSED MAGNET FOR BEAM INJECTION

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Abstract

An air-core pulsed magnet named Ceramics chamber with integrated Pulsed Magnet (CCiPM) was developed as a fast dipole kicker at first. A prototype of a dipole CCiPM was designed and tested successfully at KEK Photon Factory (KEK-PF). Because of the feature of an air-core magnet, a CCiPM can also generate an octupole magnetic field for pulsed multipole magnet injection. Compared with the pulsed iron-core magnet, the CCiPM almost does not have eddy current effects which may induce the stored beam oscillation. One prototype has been developed for the beam injection at PF ring. To examine the performance of the octupole CCiPM, some experiments has been conducted such as durability test, current excitation test and magnetic field measurement to evaluate the mechanical performance and magnetic field quality. The design and experimental results will be reviewed.

INTRODUCTION

The Ceramics Chamber with integrated Pulsed Magnet (CCiPM) has been developed for pulsed dipole kicker [1]. The structure of one CCiPM is very compact and simple, which has only three parts: a cylindrical ceramic chamber, copper conductor, and flanges. The design figure of one CCiPM is shown in Fig. 1.

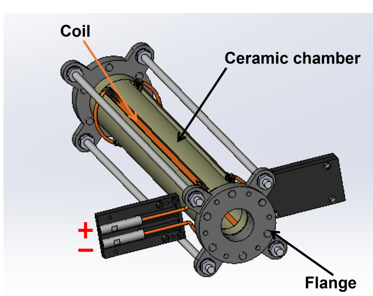

Figure 1: Design figure of CCiPM as a dipole kicker.

The four copper conductors are embedded in the ceramic chamber. Small metal blocks are brazed at the end of the conductors. Then the current direction can be arranged easily by the arc conductor, and a closed loop can be generated. Some basic parameters of one CCiPM are summarized in Table 1.

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Table 1: Basic Parameters of a CCiPM

Item	Parameter
Total length	399.4 mm
Length of the ceramic chamber	357.0 mm
Thickness of the ceramic	10.0 mm
Material of the ceramic	Al_2O_3
Length of the coil embedded in the ceramic	324.0 mm
Material of the coil	Oxygen-free copper
Weight	<6 kg

A dipole CCiPM has been installed and tested in the beam dump transport line of PF ring [2]. The beam test result was well consistent with the offline measurement result, which shows that the CCiPM is capable of operating in an accelerator.

In a previous research project, a pulsed sextupole magnet injected the beam successfully at PF ring [3]. However, the oscillation amplitude of the stored beam was about 500 µm because of the eddy current effect of the iron core [4]. Compared with an iron-core magnet, air-core pulsed magnet does not have eddy current effect, which can achieve a transparent beam injection [5]. The experiment of the dipole CCiPM encourages us to develop a multipole CCiPM for beam injection.

MAGNET DESIGN

Coil Arrangement

To evaluate the magnetic field inside CCiPM, the conductor inside the CCiPM is regarded as an infinite line current shown in Fig. 2. According to Biot-Savart Law, the magnetic field at position z is given by

$$\boldsymbol{B(z)} = \frac{\mu_0 I}{2\pi(\boldsymbol{z}\text{-}\boldsymbol{r})} \qquad (1)$$

where μ_0 is the magnetic permeability in vacuum, I is the current value.

In a curvilinear coordinate, the magnetic field component $\boldsymbol{C}_n$ generated by the infinite line current is

$$\boldsymbol{C}_n = -\frac{\mu_0 I}{2\pi r_0}\left(\frac{r_0}{r}\right)^n(\cos n\phi - i\sin n\phi) \qquad (2)$$

The reference radius r_0 is usually less than the radius of line current. If r is much larger than r_0, the strength of high

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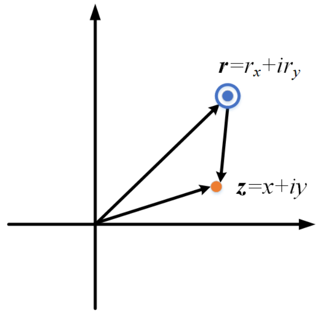

Figure 2: Infinite line current in polar coordinate.

order magnetic field component will be weak. Besides, the normal component corresponds to the coefficient of $\cos n\phi$, and the skew component corresponds to the coefficient of $\sin n\phi$.

If there is a line current distribution $I = I_0 \cos m\phi$ on a circle whose radius is r, the magnetic field component generated by the current distribution is calculated as

$$\boldsymbol{C}_n = -\int_{\phi=0}^{2\pi} \frac{\mu_0 I_0 \cos m\phi}{2\pi r}\left(\frac{r_0}{r}\right)^2 (\cos n\phi - i\sin n\phi)\mathrm{d}\phi \tag{3}$$

It is found that the integral is zero except for $n = m$. The magnetic field component is given by

$$\boldsymbol{C}_m = -\frac{\mu_0 I_0}{2r_0}\left(\frac{r_0}{r}\right)^n \tag{4}$$

Therefore, a line current distribution $I = I_0 \cos m\phi$ can generate a pure normal magnetic field whose order is m. If the current flow directions of the four conductors inside the chamber are same, and the included angle between the conductor and the midplane is 45°, a nearly octupole magnetic field can be generated inside the chamber.

The current flow directions of the each conductors are shown in Fig. 3. Four additional conductors are placed on the ceramic to simplify the circuit.

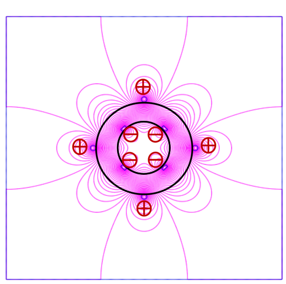

Figure 3: Cross-section view of the optimized CCiPM with magnetic flux.

Considering the chamber size of PF ring and magnetic field strength, the bore radius of the octupole CCiPM is designed as 20 mm.

3D Model Design

The Model design of the octupole CCiPM is shown in Fig. 4. To fix the additional conductor precisely, a jig was designed. As for the busbar, it breaks the symmetry of the current and generate undesirable magnetic field that may disturb the stored beam. The design of the busbar is shown in Fig. 4 to reduce the magnetic field at the center.

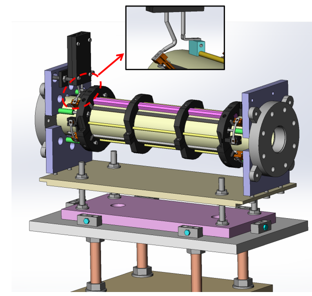

Figure 4: Model design of the octupole CCiPM.

To inject the beam into the PF ring, the peak current is 3000 A. The injection beam is kicked at x=15 mm, and the stored beam passes through the center. The designed integrated magnetic field and kick angle are summarized in Table 2.

Table 2: Magnetic Field Parameters

Position	**Integral of B_y**	**Kick angle**
x=0 mm	8.7 μT·m	1.0 μrad
x=15 mm	11.1 mT·m	1.3 mrad

Internal Coating

The interior of the ceramic chamber was coated with a 5 μm-thick titanium layer to preserve the conductivity for the beam wall current. A design of comb-tooth coating was chosen to suppress the eddy current effect of the coating [6]. The schematic view is shown in Fig. 5. To avoid an electrical discharge, the space between the coil and coating is 5 mm. The photograph of the internal coating is shown in Fig. 6

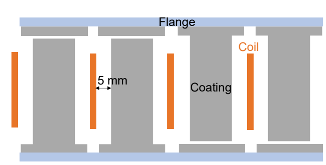

Figure 5: Schematic view of the comb-tooth coating.

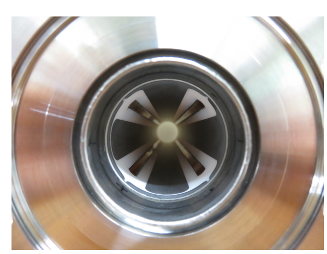

Figure 6: Internal coating of the octupole CCiPM.

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PERFORMANCE TEST

Heating-Cycle Baking and Vacuum Extraction

The baking and vacuum extraction were carried out to check the heat durability and vacuum tightness. During this experiment, the temperature and the vacuum were observed by some temperature sensors and an ionization gauge.

The baking was continued for about one month. A heating-cycle baking was applied, which was used as an accelerated aging test to simulate a severe situation assuming that the CCiPM is installed in a ring. One heating cycle starts at room temperature, ramps to around 120 °C and holds for 4 h, then cools down naturally for the other 4 h. The heating-cycle baking was controlled by an automatic timing device. As shown in Fig. 7, the temperature of the CCiPM has a regular oscillation during the baking.

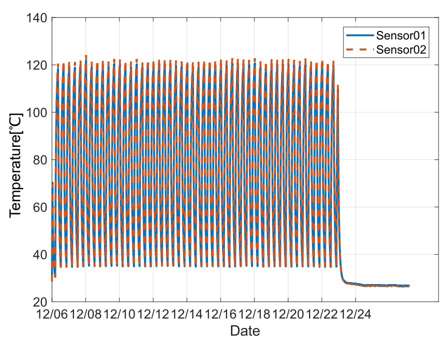

Figure 7: Record of the temperature during heat baking.

There was no leakage during the baking. After t process, the vacuum reached to 1×10^{-7} Pa indicating that the CCiPM can be installed in PF ring.

Magnetic Field Measurement

The DC and pulsed magnetic field were measured. In the DC magnetic field measurement, magnetic field was measured with a hall probe, and the current was 15 A. As for the pulsed magnetic field measurement, we used a pick-up probe to measure the peak value of the pulsed magnetic field. The peak current was 200 A for the safety in the measurement. All measurement data is normalized under the condition of a 3000 A current, which was the necessary peak current for injecting the beam.

The horizontal distributions of the simulation, normalized DC field, and normalized pulsed field at the center are shown in Fig. 8. The result of the DC magnetic field is almost same with the simulation data. At x=12 mm, the simulation value and normalized DC magnetic field are 0.0231 T and 0.0223 T, respectively. We suppose the difference is induced by the manufacturing error of the coil position. As for the pulsed magnetic field measurement, it is improved after a power source matching [7].

The longitudinal magnetic field distributions at $x = 10$ mm is shown in Fig. 9 (a). The result of the DC magnetic field is almost consistent with the simulation.

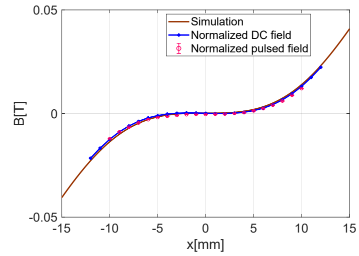

Figure 8: Horizontal magnetic field distribution at the center.

Around the edge of the flat field, the DC magnetic field differs from the simulation. The longitudinal magnetic field distributions at $x = 0$ mm is shown in Fig. 9 (b). Irregular magnetic field appears around $z = \pm 150$ mm, which is close to the metal block. We suppose that the irregular field is related to the brazing part. This issue will be investigated

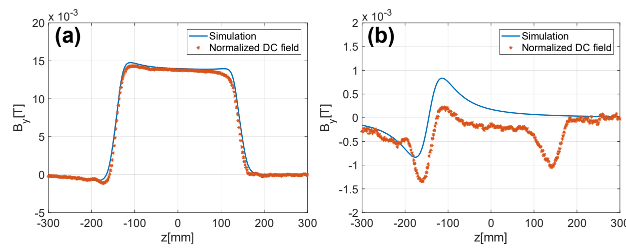

Figure 9: Longitudinal magnetic field distributions at (a)x=10 mm and (b)x=0 mm.

Excitation Current Test

To inject the beam into PF ring, the pulse width of the current should be 1.2 µs, and the peak value should reach 3250 A [8]. To examine the high voltage endurance, an excitation current test was performed by supplying a pulsed current with a 1.0 µs pulsed width. The peak current could reach to 2700 A which is the maximum output of the power source. In the future, the power source will be updated to supply a peak current more than 3250 A.

CONCLUSION AND PROSPECTS

The CCiPM, which is developed for a dipole kicker, is being developed as a pulsed octupole magnet for realizing a transparent beam injection. A prototype of octupole CCiPM has been made to inject the beam at PF ring. The designs about the coil arrangement, 3D model, and the internal coating are presented. Some preliminary tests have been conducted to examine performance. The leakage did not occur during the heating-cycle, and the vacuum reached 1×10^{-7} Pa after vacuum extraction. More experiments will be performed in the future.

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