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NEWLY DEVELOPMENT OF CERAMICS CHAMBER WITH INTEGRATED PULSED MAGNET FOR SUPER-NARROW BORE IN KEK-PF

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Abstract

Ceramics chamber with integrated pulsed magnet (CCiPM) is a new air-core type magnet that has a plan to be used as a multipole injection pulsed magnet, a dipole injection kicker, and a fast correction kicker in the next-generation light source. The magnet coils are implanted completely into the thickness of cylindrical ceramic and integrated with ceramic structurally. The first CCiPM was developed for an internal diameter of 60 mm as a magnet bore to establish the basic production techniques. The technique has been enhanced to realize narrower bore over 4 years, and finally, the achieved internal diameters were 40 and 30 mm in newly developed CCiPM. These super narrow bores have an expectation to conform to the size of the vacuum beam duct in the ring of a future light source.

INTRODUCTION

Since 2012, we had been developing on a prototype CCiPM with a cylinder inner diameter of 60 mm, a cylinder wall thickness of 5 mm, and a cylinder length of 384 mm. A prototype CCiPM (D60-30) with an implanted coil length of 340 mm was successfully fabricated in 2014 [1,2]. The fabrication technology established with a ceramic cylinder inner diameter of 60 mm has been expanded to the development of technology for super-small diameter and more flexible coil arrangement since 2015. This is an adaptive development for the next generation synchrotron radiation light source accelerator, where ring ducts will be smaller than 30 mm in diameter [3]. As a result of the long development, we succeeded in establishing the fabrication technology of a dipole-type CCiPM with an super-small inner diameter of 30 mm in a ceramic cylinder in 2018 (Fig. 1). In 2019, we successfully developed the fabrication of an octapole type CCiPM, which has an inner diameter of 40 mm.

TARGET APPLICATION

Since the strength of the magnetic field can be increased according to the reduction of bore diameter, the super-small aperture not only provides a strong kicking angle but also reduces the load for the pulsed power supply, resulting in realizing of fast pulsed current and increasing of current output. The kicker with fast pulsed performance, including high repetition rate, can be used for turn-by-turn or bunch-by-bunch beam control with magnetic field [4]. The CCiPM

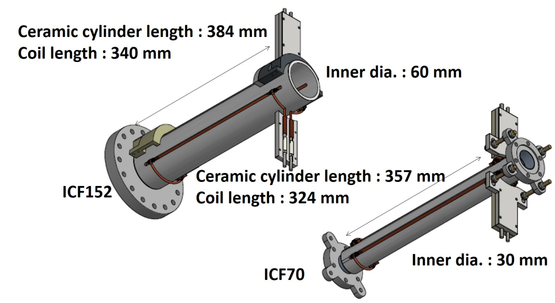

Figure 1: The design comparison of D30 and D60 CCiPM.

is suitable for the fabrication of very homogeneous kickers, and may be applied to bump kickers in low-energy and short circumference rings where the similarity of the magnetic field shape among multiple kickers must be ensured [5] since the inductance of the coil and the capacitance of the dielectric ceramic appear as a constant of fully integrated and concentrated load. In recent years, the development of ring injection technology using a pulsed multipole magnet has been progressing instead of bump injection kickers. KEK-PF is the research facility that pioneered the development of this technology [6]. The increase in the number of poles in the iron core type, in order to generate higher order magnetic field than sextupole, makes it difficult to reduce the bore diameter in order to enhance the magnetic field, and for the same reason, the increase in the number of poles causes the saturation of the magnetic field and limits the field enhancement. All of these disadvantages of the iron-core type are completely solved by the freedom of coil arrangement and current flow direction in the coilin the air-core type CCiPM. Therefore, one of the important application targets of CCiPM is the use as a pulsed multipole magnet in the next generation of synchrotron light source ring. In order to develop the technology to meet these targets, the fabrication of super-small aperture CCiPM and CCiPM with coil configurations for multipole magnetic field has been carried out.

TECHNICAL DEVELOPMENTS

The reason why it took a long time to develop the super-small aperture CCiPM compared to the basic technology of the large aperture of 60 mm is that the reduction of the inner diameter of the cylindrical ceramics reduces the distance between the coils on the circumference of the cylinder and increases the fracture stress generated by the coil implanting,

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which was widely distributed over a circumference in the case of large diameter. In addition, to avoid increasing the current density, the same coil cross-sectional area is used for the large and super-small aperture models, which is another factor that increases the fracture stress. Since the thermal expansion difference between the ceramics and the coil during silver brazing of the implanted coil reaches more than 3 mm, the stresses of more than 200 MPa are generated around the edge of the groove in the timing of maximum thermal expansion. In particular, since the base, which is constructed to connect the current lead line, is blazed to the stress-concentrated end of the coil simultaneously, the volume of the current base also must be considered as the source of the thermal expansion stress. At the beginning of the development, it was thought that it would be difficult to overcome this problem using the same fabrication technology as for the cylindrical diameter of 60 mm. Thus, various models of implanted coil shapes that mitigate stress during thermal expansion were devised, and the fabrication technology was re-established through the actual fabrication process of four of these models.

Figure 2: Complicated D30-30 and D40-45 CCiPM.

Reestablished fabrication techniques for super-small aperture are also followed in the 40 mm aperture with octupole coil configuration. In order to generate a flat magnetic field distribution of dipole magnet specification, the coils of the dipole CCiPM are arranged at 30 degrees from the horizontal plane, while in the octupole CCiPM, the coils are arranged at 45 degrees from the horizontal plane. In the octupole type, the distance between the coils on the circumference is evenly spaced, which is expected to change the stress distribution, but we have succeeded in completing the CCiPM structure using fabrication techniques developed for super-small aperture model (Fig. 2). Another problem with super-small diameter in cylindrical ceramics is the deflection of the cylinder. As the cylindrical ceramics become longer and narrower due to the super-small diameter, the structural strength of the cylindrical ceramics decreases, and it is known that the cylindrical ceramics deflect about 2.6 mm for a length of 300 mm due to their own weight during sintering process. This deflection is a direct cause of lowering the positional accuracy of the implanted coil, which ensures the magnetic field accuracy. As a result of fabrication improvement, the coil positional error was drastically improved down to 0.01 mm. The results were obtained with a ceramic cylinder length of 357 mm and a coil length of 310 mm.

PRECISE PATTERN COATING

The super-small diameter of the CCiPM also reduces the surface area of the inner surface of the ceramic cylinder and the aperture becomes smaller, making it difficult to implement precise pattern coating inside of the cylinder. Development to overcome this issue was started early on, and the technology was established in 2015 through a demonstration using a transparent PVC tube that makes it easy to see the coating condition (Fig. 3). It was demonstrated that it is possible to mount a comb tooth-shaped pattern coating with a comb tooth width of 2 mm and a comb tooth spacing of 2 mm down to a cylindrical diameter of 20 mm and a cylindrical length of 300 mm. Based on this technology, the comb-shaped coating was implemented in the D30-30 with a comb width of 3 mm and a comb spacing of 3 mm, and the comb-shaped coating was implemented in the D40-45 with a comb width of 4 mm and a comb spacing of 1 mm (Fig. 4). Titanium of 5 µm thick was used in this coating.

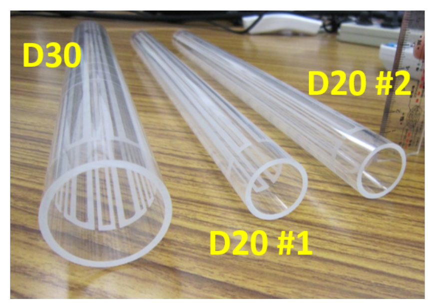

Figure 3: Demonstration of precise pattern coating.

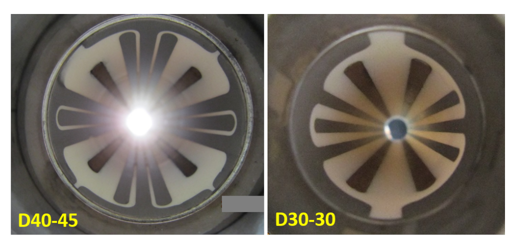

Figure 4: Implemented pattern coating to CCiPM.

This pattern coating technique has also been applied to the suppression of eddy current magnetic field from the coating of the pulsed sextupole magnet operated for beam injection at KEK-PF [7]. This is the first practical application of comb coating to suppress eddy current fields without causing beam instability. Because of the risk of discharges between the coat and coils, and a coating-free space is provided between the coil periphery and the coating adopting an evaluated value of 1.17 kV/mm at a frequency of 102 kHz as the creeping discharge distance based on actual measurements. Since experiments have shown that the creeping discharge voltage increases as the frequency increases, it is assumed that the risk of discharge is reduced in the region of a pulse width of

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about 1 μs which is equivalent to the twice beam revolution time assumed for accelerator ring with a short circumference.

THE COMPARISON OF SPECIFICATION

Table 1 shows a comparison of the performance specifications of the large bore model of D60-30, the multipole model of D40-45, and the super-small bore model of D30-30. The bore diameter, which is the magnet pole diameter, is determined by the coil position and is the same as the cylinder inner diameter. Both the cylindrical ceramic length and the coil length are shorter than the large bore model, but the length from the current base to the current base for current supply is extended to increase an integral magnetic field. The reason why the ceramic cylinders are designed to be short is to keep the deflection caused by the super-small diameter as low as possible. The electrical characteristics are shown about impedance and inductance, including the contribution of the same lead line (Z = 0.42 Ω, 125 kHz). The inductance is smaller than that of the large bore model due to the smaller aperture of the ceramic cylinder. However, there is no difference between the D40-45 and the D30-30 models. This is because the distance between the coils is reduced in the D30-30 model, and the contribution of mutual inductance is increased. The same trend is seen in the impedance, where the super-small diameter results in a decrease in coil area, but the increase in mutual inductance prevents the impedance from decreasing. The values shown in the table are considered to be the limits of the impedance reduction due to the super-small diameter. The natural pulse width of the maximum experienced current output and voltage according to this electrical characteristic, using the same power supply, is also shown in the table as well. The insulation resistance between the coil and the coating is strongly dependent on the finish surface condition of the spaces between the comb teeth of the comb coating, and the required insulation resistance of more than $1.0{\times}10^{13}\,\Omega$ is achieved by a defined cleaning recipe. The kick angle is shown due to the expected dipole field for the current per kA, assuming an electron beam energy of 2.5 GeV. The values of D60-30 and D30-30 are calculated from magnetic field measurements, and the value of D40-45 is the expected value based on simulations. When the D40-45 is operated as an octupole magnet, the kick angle is 0.38 mrad for the current of 1 kA at 15 mm from the center of the field.

DURABILITY AND PERFORMANCE

In order to ensure the reliability of novel structural in the CCiPM, rigorous durability tests have been conducted. The endurance tests are as follows: 1. 200 °C reheat test: applying a high temperature thermal load of 200 °C only once after the fabrication is completed, 2. atmospheric pressure load test: maintaining a vacuum of less than 10^{-6} Pa for a long period of time, 3. attainable vacuum test: checking the attainable vacuum by baking at 160 °C to confirm the cleanliness of the CCiPM, 4. 120 °C heat cycle thermal load test, 5. high repetition high current excitation test: checking the toughness of magnetic field stress by supplying a current more than 3000 A at 10 Hz, and 6. high voltage applied discharge test. The heat cycle test is conducted by heating the product to 120 °C three times a day. During the heating, the temperature is raised in about 30 minutes, maintained at 120 °C for 3 hours, and then cooled naturally over 3 hours. The D30-30 is subjected to the heat cycle for 44 days, and the D40-45 for 38 days. The vacuum reachability of D30-30 and D40-45 CCiPM is $2.5{\times}10^{-8}$ Pa and $7.6{\times}10^{-8}$ Pa, respectively, which is enough to be implemented in the KEK-PF ring.

Table 1: The Comparison of Specification for CCiPM Models

Param.	**D30-30**	**D40-45**	**D60-30**
Inner dia. [mm]	30	40	60
Outer dia. [mm]	50	60	70
Cylinder len. [mm]	357	357	384
Coil. len. [mm]	324	324	340
Eff. coil len. [mm]	290	290	268
Kick ang. [mrad]	1.49	0.88	0.74
Max. vol. [kV]	5.1	5.5	6.7
Max. cur. [A]	3316	3257	3265
Impe. [Ω], 500 kHz	4.26	4.29	4.98
Ind. [μH], 500 kHz	1.35	1.36	1.59
Pulse wid. [μs]	2.8	2.8	3.2
Weight [kg]	1.7	3.3	5.5

The magnetic field performance of the CCiPM is confirmed through the magnetic field measurement, and the magnetic field performance is confirmed by beam test using the newly built beam test facility in the dump line from Linac to PF in order to avoid irreversible serious accidents in the ring. The D60-30 has been tested in the test line since 2019 [2], and the integrated magnetic field obtained from the magnetic field measurement was confirmed to be within 1% of the kick angle from the beam diagnostics. The D30-30 was also tested in the beam transport line through the same process, and the results showed agreement within 3% [8].

FUTURE PLAN

The initial goal of increasing the magnetic field strength has been achieved by reducing the diameter, and it is now possible to achieve both fast pulsed and high magnetic field strength. The octupole type CCiPM will be installed in the KEK-PF ring soon, and the demonstration test of the pulse multipole injection technique will be started. Currently, we are developing a six-coil CCiPM with six coils implanted in super-small diameter cylindrical ceramics.

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