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DEVELOPMENT OF THE CERAMIC CHAMBER INTEGRATED PULSED MAGNET FITTING FOR A NARROW GAP

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Abstract

We are pushing forward the development of a pulsed magnet that has a combined structure of magnet coils with a ceramic vacuum chamber, aiming to realize a small gap. The structure we are developing is that single turn air-coils are implanted along the longitudinal axis in the cylindrical ceramic chamber wall with thickness of 5 mm. The ceramic wall works for separating the vacuum from the atmosphere, as well as holding the coil structures mechanically and the electrical insulation of coils. We achieved the continuous operation over 200 days, without any failure, of current-excitation with 20 kV/7.7 kA pulse with 4 μsec width and repetition of 1Hz, using the dipole type prototype with the bore radius of 30 mm and the magnetic length of 0.3 m in 2013, while maintaining the vacuum pressure less than 10^{-6} Pa.

MERITS OF NARROW GAP MAGNET

The performances which are required in common to all pulsed magnet system are fast, strong, and high repeating pulsed magnetic field characteristics. In order to achieve these performances, there are two approaches. First one is developing a high power and high repetition pulsed power supply. Second one is reducing the power supply load as low as possible. The load reduction is an important issue. Because, if we try to achieve these performances without decreasing the load, the power supply system will have a large body size, consequently, need a huge installation space and give a restriction to the installation place of the system.

One of the best solutions to lower the power supply load is reduce the magnet pole gap. The kick angle is determined by the magnetic filed strength and field length. By the increased magnetic field with reducing the pole gap, the field length becomes shorter while keeping the kick angle the same. As a result, the coil inductance, hence the pulsed power supply load, become small. The low coil inductance is effective to achieve short pulse width and high repetition rate, in addition, to make the power supply small. The compact magnet and small power supply give the flexibility for setting position in an accelerator, making the kick efficiency optimum with the appropriate beta function value position.

Compact pulsed magnet with a narrow gap will fit to the future light source ring like generating diffraction limit synchrotron radiation [1]. Because the storage ring chamber size will be reduced in order to match the ultra low beam emittance and there is no enough space to install the pulsed magnet due to a large number of optical magnets. Additionally, it also will fit to small size storage rings that will require narrow installation spaces for these kinds of devices involving the injection kickers and correction kickers, and that have short revolution period requiring shorter pulse width.

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CERAMIC CHAMBER INTEGRATION DESIGN AND THE ADVANTAGE

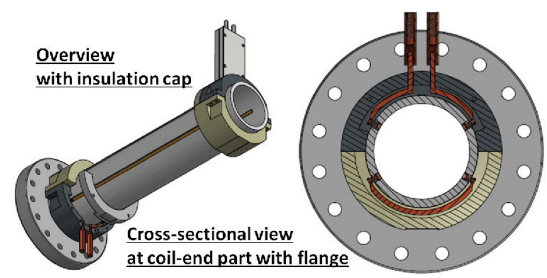

Figure 1: Design of dipole type CCIPM for the fabrication.

In an ordinary pulsed magnet, a ceramic chamber is used as a beam duct to reduce the eddy current effect for a pulsed magnetic field. Usually, the iron- or ferrite-core is set up outside of the ceramic chamber so that its magnetic poles sandwich the ceramic chamber. In this case, the distance(=magnet gap) between a magnetic pole and the beam is decided by the ceramic chamber bore radius, chamber thickness and clearance between the chamber and the pole. It is impossible to close the gap to the beam less than this restriction. On the other hand, in an air-coil type pulsed magnet, the coil is set up on the surface of the ceramic chamber so that its poles hold a ceramic chamber, or inside of the ceramic chamber like a strip-line kicker with complex supports. In the former case, the magnet gap is restricted by the ceramic chamber size. In the latter case, the complex support and coils cause an impedance unmatching of the beam wall current and increasing the chamber diameter to include the complex structures inside the chamber. To improve these insufficient aspects simultaneously, a ceramic chamber integrated type pulsed magnet was figured out.

The structure we are developing is that single turn air-coils are implanted along the longitudinal axis in the cylindrical ceramic chamber wall with thickness of 5 mm. For a dipole type magnet, four metallic bars (=coil) are totally implanted and one of bars is connected with another bars so that one pair of bars makes a coil. Implanting hole completely penetrates the chamber wall and is blocked up with the metallic bars. Figure 1 shows cross-sectional view of

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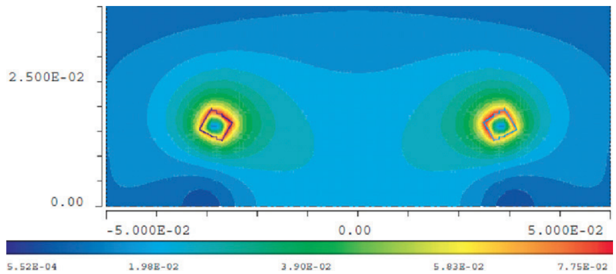

Figure 2: The distribution of a magnetic field strength with DC 1000 A exciting current for the CCIPM design of Fig. 1.

the dipole-type design of the Ceramic Chamber Integrated Pulsed-Magnet (CCIPM). We started actual development with KYOCERA Co. Ltd. in 2012. The bore radius is 30 mm and the magnet length (=coil length) is 300 mm to match the SPring-8 bump magnet size. The coil is arranged at 30 degrees from the median plane in order to achieve the dipole field uniformity within 0.1% and maximize the field strength in the center of magnet. Figure 2 shows the field strength distribution for the actual coil arrangement of Fig. 1. The arc-shape metal bars connect each pair of coils at the coil end along the ceramic circumference by the conductive epoxy resin in the prototype. By this way, the end-coils stand up naturally and the irregularity of the field at the magnet end is reduced by about 30 % compared with no stand ups. One of the arc-type bars works as a busbar which connects feeder lines from the pulsed power supply.

There are two technical advantages by applying this CCIPM structure. First one is that the ceramic wall works for separating the vacuum from the atmosphere, as well as holding the coil structures mechanically and the electrical insulation of coils. By this structure, magnet pole edges can be set close to the inside diameter of the chamber. Seeing from inside of the ceramic chamber, the pole edges put on the inside surface of it and does not bulge from the surface level. Therefore, the pole edges are put close to the beam without disturbing the beam impedance. Second one is that the air-coils are arranged around the circle on the ceramic inside surface to optimize the magnetic field strength and uniformity. There is no structural restriction to arrange the coil and not any complex coil supporting structure. As a whole, a pulsed magnet will be built with the extremely simple components which do not bulge inside and outside of the ceramic chamber.

SUBJECTS TO THE FABRICATION

The followings are important subjects about the CCIPM fabrication.

- Implanting multiple coils simultaneously along longitudinal axis over the 0.3 m.
- Keeping the super high vacuum-tight with the pressure of less than 1.3×10^{-11} Pa·m^3/s.
- Enduring 0.1 MPa atmospheric pressure and magnetic field stress produced by the current more than 5 kA.
- Precisely arranging the coil with 10 μm along longitudinal axis.
- Ensuring the vacuum-tightness under the thermal cycle stress up to 800 degrees.

After the copper coils are implanted in the penetrated holes of the ceramic wall, it is bounded by silver brazing with a curing process at 800 degrees. It is the key technique in this development to implant the coil into the ceramic under the condition of the different thermal expansion rate along the longitudinal axis. To establish coil implanting technique, two development stages were taken as follows; firstly, optimization was done to reduce the residual strain, using the ceramic plate test piece, the coil shape and material, silver brazing volume, curing procedure and curing jig. Secondary, implanting technique established by test piece was expanded to the cylindrical ceramic chamber. In the first stage, many vacuum leaks occurred by minute cracks around the coil end part inside and outside of the ceramic. Figure 3 shows the test piece and typical crack. The test pieces without vacuum leak experienced the curing process of 800 degrees again, and the vacuum-tightness was confirmed to be kept. In the second stage, there was no product with vacuum leaks for both of two prototype products. However, when the flange sleeve was bounded to the ceramic by silver blazing with 800 degrees in vertical posture, the silver solder which bounded coils was welded again and vacuum-tightness broke. The new method that bind the ceramic and flange sleeves in horizontal posture was developed with success.

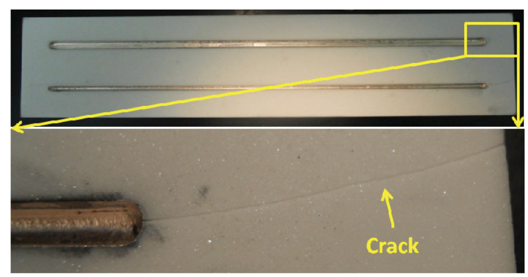

Figure 3: A test piece sample with a typical huge crack.

Finally, we succeeded in building the dipole-type pulsed magnet prototype in 2013. The vacuum-tightness under detection limit of 1.3×10^{-11} Pa·m^3/s of He leak checker was achieved with flanges bound.

RELIABILITY AND PERFORMANCES

Continuous Operating

We achieved the continuous operation over 252 days from 2013 to 2014 as shown in Table 1, without any failure, of current-excitation by the current of 7.7 kA with 20 kV source with 4 μ sec width and repetition of 1 Hz and with thermal cycle repetition. Figure 5 shows the conditioning setup before ribbon heaters were wrapped. The thermal cycle temperature was selected as from 30 degree celcius to 80 degrees. The 80 degrees was actually measured temper-

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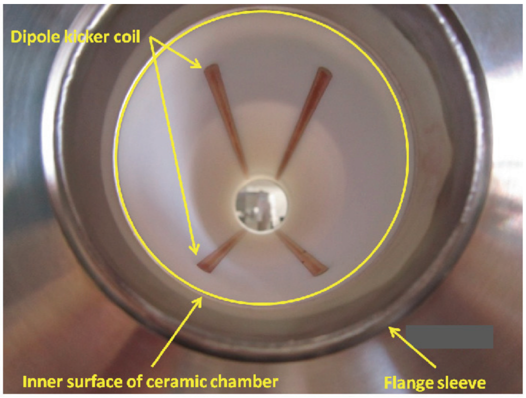

Figure 4: The inner surface view of the complicated CCIPM.

ature on a ceramic chamber surface under the stored beam current of 100 mA in SPring-8 storage ring. The applied thermal cycle procedure was like followings: the chamber surface temperature was heated till 80 degrees from the room temperature (30 degrees) without ramp-up rate control, then the 80 degrees was kept for 4 hours, after that, the temperature was cooled down till room temperature naturally, after cooling time was kept for 4 hours, the heating cycle was applied again. This cycle was applied 3 times a day, totally, 654 thermal cycles was applied with the current-excitation and vacuum evacuating by the vacuum pressure of 1×10^{-6} Pa.

Table 1: Conditioning Parameters and Experiences

Supplied curr./vol.	Condition	Days
3.9kA/10kV	w/o thermal cycle	10
5.8kA/15kV	w/o thermal cycle	24
5.8kA/15kV	w/ thermal cycle	83
7.7kA/20kV	w/ thermal cycle	135
Total	w/ cycle, for all	218, 252

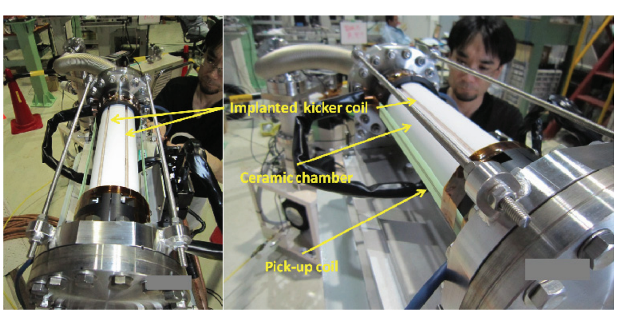

Figure 5: Conditioning setup of CCIPM.

Field Measurement

While the dipole field strength and uniformity (flatness) expected by field calculations were 6.87 μT at the magnet center and 5.7×10^{-2}% at ±4 mm on the median plane respectively by a DC 30 A exciting current, the measurement results for them was 6.85 μT and 8.2×10^{-2}% by using hall-probe.

For the horizontal distribution of the dipole magnetic field, the field uniformity within 1.5% was kept for ±10 mm region on the median plane. The uniformity at the height of ±5 mm was less than 1% in the horizontal region of ±4 mm.

The effective length was found to decrease by -1.0% from 0.3 m coil length. The irregular field at the coil end parts was suppressed less than 1%. The integrated field strength was 204.2±1.6 μT·m/30 A, which was equivalent to 765.8±6.1 μrad kick angle with 3000 A exciting current for the 8 GeV electron. The error was estimated from the field measurement reproducibility. The integrated field difference from center longitudinal axis was 0.7% at ±5 mm shift from the center in the horizontal direction axis and 0.8% at ±4 mm shift from the center in the vertical direction.

From these results, it was proved that the coils were implanted precisely as designed.

Evaluation of the Effect of the Load Reduction to a Power Supply

We evaluated the reduction effect of load to the power supply from the iron-core type pulsed magnet to the CCIPM; the iron-core magnet is used as the bump magnet in SPring-8 storage ring. The comparison was made in the following way; two types of the magnets were connected to the same power supply. The power supply fed the same amount of charge, which was determined by the applied voltage, to each load.

As a result, the output current was increased by about 20% and pulse width of half sine-wave shape was shortened from 6.1 μs to 4.5 μs by changing the load from iron-core type to CCIPM. The mechanical dimensions and electric properties are listed in Table 2, as a reference to the load reduction; electrical properties were measured at 125 KHz, which corresponds to 4 μs pulse width.

Table 2: Mechanical Dimensions and Electrical Properties Comparison. About CCIPM, the properties are for a coil.

Magnet	Gap (mm)	Length (m)	L (μH)	C (nF)	R (mΩ)
Iron-core	56	0.32	4.5	357	385
CCIPM	ϕ60	0.30	0.8	2019	22

FUTURE PROSPECTS

Now, we are continuing the development to make CCIPM installable to a storage ring as an accelerator component. The metal coating inside the chamber is the issue on which we are concentrating: the coating with 2~3 μm metal layer while insulating from the coil. The coating necessary for flowing the wall current induced by the beam. For the future prospects, we will aim at realizing the multi-pole pulsed

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magnet whose pole number is more than 4 or super small radius pulsed magnet whose radius is less than 10 mm as an extension of this developed technology.

REFERENCES

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