

DEVELOPMENT OF A NON-INDUCTIVE CERAMIC RESISTOR

Takuya Sugimoto*, Kuanjun Fan, Koji Ishii, Hiroshi Matsumoto, KEK, Ibaraki, Japan
Kazuhiko Abe, Hitachi Haramachi Electronics Co. Ltd., Hitachishi, Ibaraki, Japan
Shota Fukuoka, University of Tsukuba, Tsukuba, Ibaraki, Japan

Abstract

Non-inductive ceramic resistors, based on alumina and carbon, are used for impedance matching in the circuit of the J-PARC main ring injection kicker system. The kickers were installed in December 2011, and have been in operation successfully since then. However, discharges at the edge of the resistor were observed after several weeks' operation, which increase resistance from O (100) to O (1M). Investigation indicates that poor electrical contact with the rough surface of the ceramic bulk due to irregular shaped spots causes micro-gaps, which trigger the discharge. In order to improve the contact, two types of the resistor have been experimentally examined at the test stand in the service building. A resistor had an electrode carefully connected to the ceramic bulk by a brazing technology. Another resistor had an annealed thin copper plate inserted. In this paper, we will describe details of the development of the resistors and give future prospects.

INTRODUCTION

Today, non inductive ceramic resistors are widely used for accelerator applications such as high voltage pulsed power magnets. A type of non-inductive ceramic resistor, which is manufactured by Tokai Konetsu Kogyo Co., Ltd. (TKK), is mounted on the impedance matching circuit of injection kicker magnets for the J-PARC main ring (MR). Four lumped kicker magnets were installed to the MR to inject 3GeV proton beams from RCS, and have been operated since December 2011 [1]. The equivalent circuit of the kicker system is shown in Fig. 1. One magnet consists of two coils made of a copper plate and was located in a vacuum chamber. Resistors and capacitors were installed in dedicated boxes mounted on the chamber (filled with air). There are 8 boxes in total, and 15 resistors connected in parallel were mounted in each box.

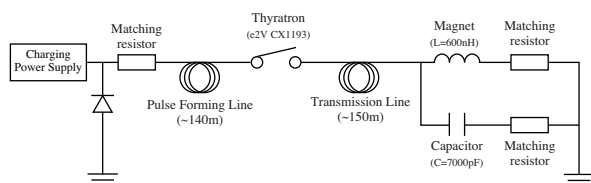


Figure 1: Schematic circuit of the kicker system.

A waveform of the excitation current measured by a current transformer is shown in Fig. 2. Four pulses with an

interval of 40msec are transmitted to the magnet. The repetition cycle is 2.48sec at present, and is planned to be shorter toward the design beam power. As shown in the waveform, there is a tail structure, which induces an additional betatron oscillation for the circulated beam bunch. To reduce the tail, upgrade studies of the kicker magnet are in progress [2].

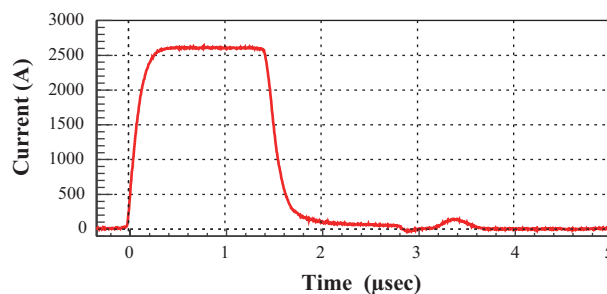


Figure 2: A waveform of the kicker excitation current. The typical charging voltage of PFL is 50kV.

A picture and a drawing of a longitudinal cross section of the TKK's resistor are shown in Fig. 3. The ceramic bulk with a cylinder structure consists of alumina (Al_2O_3) and silica (SiO_2). Carbon black acted as a conductor, and was blended before the sintering process. The density of the ceramic bulk is 2.2g/cm^3 due to the high porosity (approximately 30%).

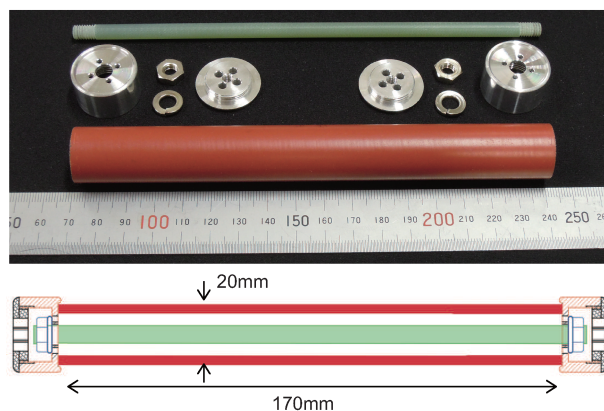


Figure 3: Non inductive ceramic resistor manufactured by Tokai Konetsu Kogyo Co., Ltd.

It is necessary to form an electrode on the ceramic cylinder because a contact resistance of the ceramic surface was high. Therefore, aluminum was thermally sprayed on the base of the cylinder with $100 \sim 200\mu\text{m}$ thickness after the

* takuya.sugimoto@j-parc.jp

sintering process. Next, a cap made of aluminum was attached to the base and fixed using a FRP rod with a hexagon nut. The torque of the nut was managed at 0.6N·m using torque wrenches. To avoid a creeping discharge, the surface was painted by an epoxy-based coating material (shown in red in Fig. 3). The total resistance was decided at 9.3Ω after optimization. It was important to reduce the power consumption and the current density for each resistor because it is recommended to use at less than 150°C in the operation conditions. The peak current was assumed as 3500A to estimate the number of resistors connected in parallel. From this assumption, the average power consumption was estimated as 380W in total. In addition, a contribution from a beam induced current was estimated as 60W in case of 220kW beam operation. According to the relation between resistor surface temperature rise (ΔT) and power (P), $\Delta T = 130^\circ\text{C}$ for $P = 30\text{W}$. Therefore, we decided to use 15 resistors in parallel (the rated power is 750W in total), and each resistance is approximately 139Ω ($\pm 10\%$), which corresponds to $13.1\Omega\cdot\text{cm}$.

RESISTOR DISCHARGE

At the end of February 2012, many discharged resistors were found during the maintenance period of the MR. As shown in Fig. 4, many discharged craters were observed on both the ceramic cylinder and the aluminum electrode cap. A flashlight of corona discharge synchronized to the impulse timing was also observed. The resistance of discharged resistor was increased to approximately $1\text{M}\Omega$ and the beam was no longer injectable. We replaced more than 500 pieces of such broken resistors before the summer shut-down period in 2012.

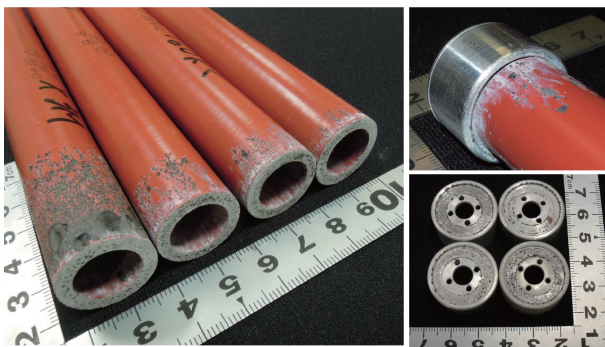


Figure 4: Discharged TKK resistor.

The discharged resistors were divided into 8 parts to measure the resistance distribution. As a result, the vicinity of the electrode had high resistivity. This fact indicates that the discharge is concentrated between the ceramic and the electrode.

Figure 5 shows the microstructure of small holes with a round edge observed in the ceramic bulk. These holes were observed for all discharged resistors (even if the discharge was limited) at the vicinity of the edge of the ceramic cylinder. This fact is consistent with the high resistivity of the

discharged ceramic edge. Even in the ceramic bulk before applying the impulse, many holes were existed because irreducible air bubbles were mixed during the mixing process of the materials. An electric field in the bubble would be increased locally and a micro discharge was possibly occurred. So it is also important to increase the density of the ceramic bulk and some studies are in progress.

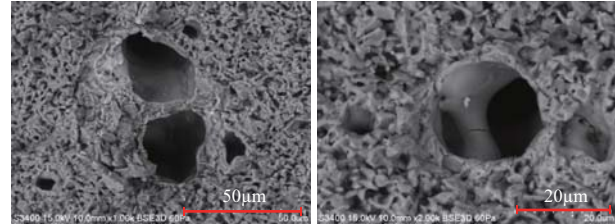


Figure 5: Microstructure of the small holes observed in the ceramic bulk.

CONTACT IMPROVEMENT

Test Sample

Figure 6 shows the microstructure of the surface of the aluminum sprayed electrode before applying the impulse. The difference between the top and bottom was approximately $70\mu\text{m}$. This indicates that poor contact with the rough surface of the ceramic bulk due to irregular shaped spots causes micro-gaps, which trigger the discharge. Therefore, it is important to improve the contact between the ceramic and the electrode metal.

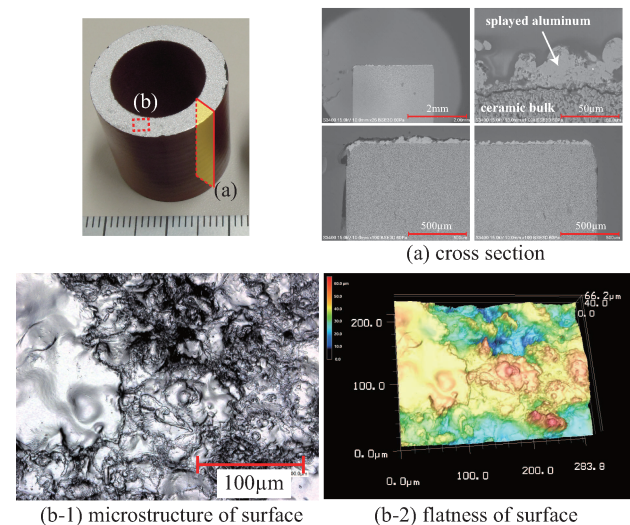


Figure 6: Cross section and microstructure of the aluminum sprayed electrode.

To improve the poor contact, three types of sample were prepared and tested at a test stand deployed in the service building. The first type was a resistor in which an electrode made of nickel plated copper was connected to the ceramic by a brazing technology. All brazing processes were carried out by Hitachi Hamaichi Electronics Co., Ltd.. The

brazing resistor is shown in Fig. 7. A commercial product of an active brazing filler metal (based on Ag-Cu-Ti) was chosen to connect the ceramic bulk with the electrode metal. To optimize the amount of the filler metal, five samples with different percentages of the filler metal were tested in advance. This experiment showed that it is better to braze the electrode with 20% of the commercial product to realize neither a crack nor a gap. The ceramic bulk was cleaned using an ultrasonic (US) cleaner in pure water to reduce outgassing components from the ceramic bulk emitted during the sintering process. Next, the ceramic bulk and the filler metal were put into the vacuum furnace and heated up to 820°C. Finally, the surface was painted. A second type was a resistor produced by the same procedure as the first type except for the US cleaning process. To estimate the effect on the carbon powder which outflowed into the water, the process was skipped. A third type was a resistor in which we inserted a thin metal plate between the aluminum sprayed surface and the aluminum electrode cap. An annealed copper washer with 0.1 mm thickness was adopted because copper became more flexible by annealing. The torque to fix the aluminum cap was increased to 2 N·m to smoothen the part of irregular spots and make the contact better via the washer.

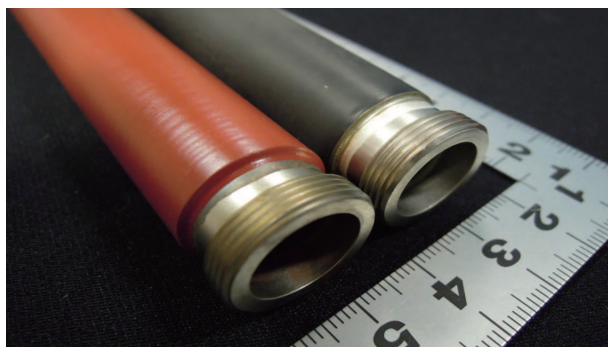


Figure 7: Brazing Resistor (red: with painting, black: no painting).

Experimental Result

To estimate the tolerance of each resistor, 15 resistors of each type were connected in parallel to a pulsed power supply. Applying the impulse shown in Fig. 2 to each set independently, no discharge was observed for the set of the second type. It was operated stably for more than 1,000 hours at the test stand. On the other hand, discharge was observed for the other types. However, the life time of all types was longer than the original resistor.

Figure 8 shows the microstructure of the longitudinal cross section of each resistor. In the case of the first type (Fig. 8 (a)), a rough structure like needles at a border between the ceramic bulk and the brazing metal was observed. These needles may introduce a micro discharge because of the concentration of the electric field on the tip of the needles. On the other hand, a border between the ce-

ramic and the metal for the second type was flat (Fig. 8 (b)). Although the carbon powder removed by the US cleaning did not contribute to the resistance, it was effective to suppress the formation of the needle structures. Furthermore, compared with the aluminum spraying (Fig. 8 (c)), the brazing metal was firmly connected together with the ceramic bulk.

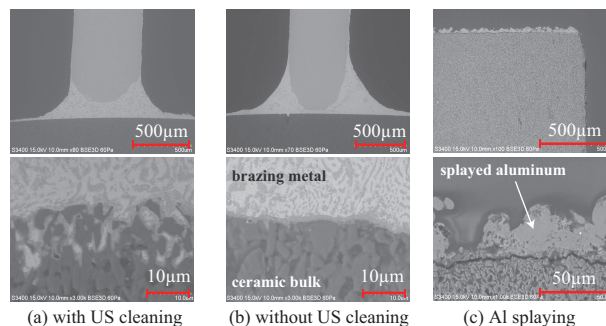


Figure 8: Microscopic image of a border between the ceramic bulk and the electrode metal.

After the summer shutdown period in 2012, all 120 resistors mounted on the magnets were replaced to the resistor with the thin aluminum washer. As of now, only one resistor was discharged and replaced. In addition, 30 resistors were replaced to the brazing resistor (without the US cleaning) in this April, and is operated in beam operation at present.

CONCLUSION

A severe discharge problem of the matching resistor for the injection kicker magnet of the J-PARC MR had been occurring since March 2012. A new non-inductive ceramic resistor with a brazing electrode was developed to improve the contact between the ceramic bulk and the aluminum electrode cap. We need to continue to study about the mechanism of the discharge, but at present no discharge is occurring in the case of the resistor with the brazing electrode without the ultrasonic cleaning of the ceramic bulk. We can conclude that it is important to connect the electrode to the ceramic carefully to avoid the discharge. High-density ceramic resistors are being developed to chase further reliability.

ACKNOWLEDGMENT

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