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Development of Radiation-Resistant Magnet Coils for High-Intensity Beam Lines

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Abstract – In connection with the Japanese Hadron Facility (JHF) project, the development of new types of radiation-resistant magnet coils has been continued at KEK. One major program is the design and production of a mineral insulation cable (MIC) with a larger maximum current. We have already developed a 2000A-class MIC having a square-cross-section hollow conductor in Japan. A sample magnet coil was fabricated with this MIC. Tests of its stability and reliability are under progress. We are now planning to develop a 3000A-class MIC.

The other program is R/D work on a completely inorganic wrapping insulation material which can be used like the usual type glass-fiber tape pre-impregnated with epoxy-resin. After tests of the mechanical strength and electric insulation of many combinations of tapes and bonds, we found a pure (99%>) alumina-fiber tape pre-impregnated with inorganic cement is suitable for a magnet coil insulator after thermal curing.

I, INTRODUCTION

Accelerators of future intensity-frontier physics facilities will generate very high-flux primary proton beams of more than 100 μA. The energy of the beam will reach 30 GeV or higher in order to provide sufficiently large number of kaons, antiprotons and other rare particles for next-generation physics experiments. The Canadian KAON accelerator is a typical example[1]. Even in Japan, we have a similar accelerator plan for intensity-frontier science as a part of the Japanese Hadron Facility (JHF) Project[2].

The most important technical problem commonly recognised in such high-intensity projects is how to realize long-term stable operation of the accelerator facilities against very strong radiation. Especially, components of the primary beam lines, which will transport the high-intensity/high-energy protons from the extraction point from the accelerators to the production target station, will have to be operated under the highest radioactive environments. This extremely high level of residual radioactivity will not allow us to maintain beam lines on hand. Thus it should be remembered that the most important characteristic of beam-line components is that they should never break. In other words, the beam-transport system should be maintenance-free. In the case of need, however, most components of the beam line should be either easily maintained or replaced from a distant location in order to reduce the absorbed radiation dose of maintenance personnel. Based on these points of view, we have continuously developed "radiation-hard", "easy-maintenance" beam-line components. Since the electromagnet is the most important beam-line elements, we have already developed a quick-disconnect beam-line magnet system for "easy-maintenance", and we have reported part of this at the MT12 conference[3]. On the other hand, our R/D work for "radiation-hard" direction has focussed on the R/D of a new radiation-resistant magnet-coil insulator during the last five years. The results of our R/D work during the early years were reported at the MT11 conference[4]. In this report we would like to present our latest technical achievements concerning the radiation-hard magnet-coil insulator.

II. JAPANESE MIC PROJECT

As described above, the radiation-hard magnet is one of the key technologies for realizing future intensity-frontier physics projects. Since the radiation hardness of electromagnets seriously depends on the radiation life of the magnet-coil insulator, the radiation life of electromagnets for high-intensity beam lines, especially the magnet placed just downstream of the production targets, should be longer than than 10^{11}Gy. In such cases the magnet itself must be assembled without any organic materials. In our previous article[4], we reported on a new method for assembling the magnet-coil insulator from completely inorganic materials, i.e. the magnet coil is insulated by a high-alumina cement (HAC) and asbestos tape. Though we can use any size of copper conductor in a cement-insulation coil, the assembly technique of the cement coil is somewhat complicated, and may not be suited for mass production. Just after the establishment of cement-insulation coil technology, therefore, a trial to produce mineral insulation cables (MIC) in Japan was started. MIC consists of a compacted magnesium oxide (MgO) insulation surrounding the copper conductor, and is covered with a metal sheath. The hollow conductor can be used for direct water cooling in order to achieve a higher current density. The sizes of MIC available in the world are presently very much limited; there are almost three kinds of MIC with a hollow conductor[5]. The technique to form a MIC into a magnet coil may be, however, relatively easy compared to the cement coil.

At present, the largest MIC available is of the 1800A class, which is sometimes insufficient to assemble large-scale higher-field magnets for higher-energy ($\sim$30GeV) accelerator facilities. In addition, there is no supplier of MIC in Japan and we are importing all MIC from abroad. The time for delivery is usually uncertain and sometimes becomes more than one year for a Japanese customer, such as KEK. These points may cause a great deal of troubles to us in constructing JHF. We therefore decided to develop MIC in Japan and started a project to produce MIC in Japanese industry. Our final goal is to prepare a larger size MIC of approximately the 3000A class.

At the start, a thick-wall oxygen-free copper (OFC) tube was surrounded by a segmented MgO layer of cylindrical shape. The MgO layer was again sheathed by a thin-wall phosphorus deoxidized copper (PDC) tube. With the use of a strong pull machine, the stack of OFC and MgO was drawn to a longer cable with a circular cross-section. At the final stage of drawing, a die having a square cross section was used to shape the cable cross section rectangular. At present, a 2000A-class MIC has been successfully manufactured. The dimensions etc. of the new 2000A MIC are summarized in the Table 1. The cable length is, however, only up to 30m. This relatively short cable length is limited by the length of the straight section of the pull machine system used.

The quality of Japanese MIC was tested by using bending samples, as shown in Fig. 2. The electric insulation was measured; no serious failure was found up to AC1500V. The minimum bending radius of the samples tested was three-times the cable thickness. A sample magnet coil was wound with the Japanese MIC in order to test the long-term stability. One water pass was designed to be 30 m or shorter. One coil consists of two water passes. Approximately the same coil was assembled with the existing 1800A-class MIC from abroad. Those two coils were mounted on the same iron yoke of a small dipole magnet, as shown in Fig. 3. The water flow rate, temperature rise, and voltage drop the coil with 2000A excitation current were measured, and are listed in Table 2.

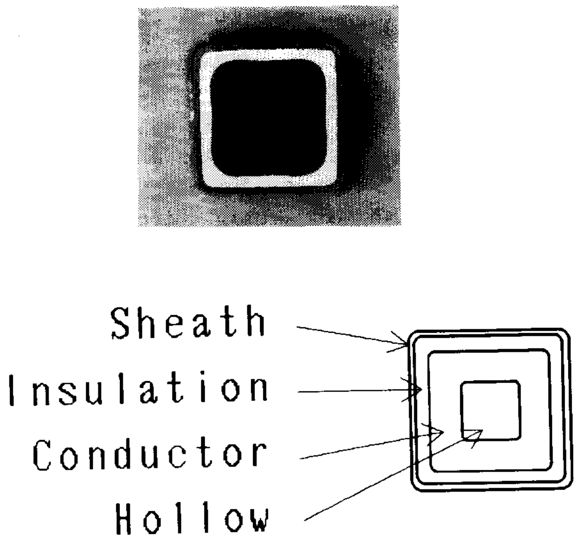

Fig. 1, Cross-sectional photograph (above) and illustration (below) of the new 2000A MIC.

The design of a 3000A-class MIC has been practically completed. We are considering to extend the length of the straight bed of the pull machine. After the extension, a MIC longer than 60m will be available for both the 2000A class and the 3000A class.

Dimensions (mm)		
Sheath:Outside diameter		19.80 square
:Wall thickness		0.99
Insulation:Wall thickness		1.75
Conductor:Outside diameter		14.35 square
:Wall thickness		3.53
:Inner diameter		7.33 square
Cross-sectional Area (mm^2)	Sheath	71.3
	Insulation	113.8
	Conductor	151.2
	Hollow	53.0
Coil length (m)		30
Material	Sheath	PDC,C1220(JIS)
	Insulation	MgO
	Conductor	OFC,C1020(JIS)
Nominal current (A)		2000

Table 1: Dimensions and basic parameters of the 2000A MIC.

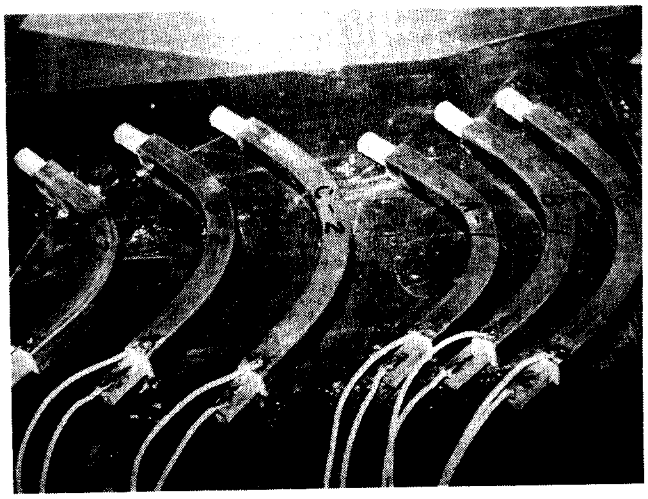

Fig. 2, Bending samples of the new 2000A MIC.

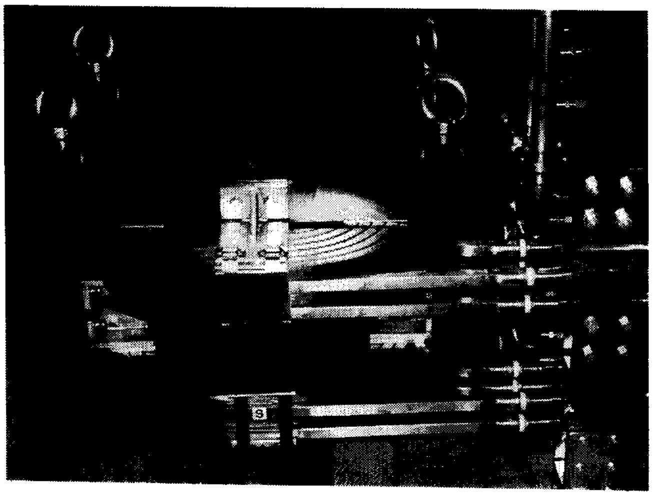

Fig. 3, Test magnet assembled with the new 2000A MIC (upper coil) and the traditional 1800A MIC (lower coil).

Item	2000A MIC	1800A MIC
Water flow @ dp=10atm. (l/min. per coil)	14	12
Voltage drop @ 2000A/ Power consumption (V/kW per Coil)	14.8/29.6	15.8/31.6
Temperature rise @ 2000A (°C)	31°C	37°C

Table 2: Water flow rate, voltage drop, and temperature rise at the coil of the new 2000A MIC and the traditional 1800A MIC.

III. NEW CABLE INSULATION FOR HIGH RADIATION DOSE

Though we established a new magnet-coil insulation with high-alumina cement and asbestos tape in 1987, a recent technical innovation has enabled us to employ more sophisticated materials as a magnet coil insulator. One important candidate given consideration is a pure alumina long fiber, which can be used as a base tape of a new wrapping insulator instead of asbestos. The pure alumina fiber that we employed is ALMAX[6] of Mitsui Mining Material Co.,Ltd. Several important physical constants of the ALMAX are listed in Table. 3. ALMAX tape of 25 mm wide and 0.5 mm thickness was pre-impregnated by completely inorganic gelatinous binder, which consists of alumina powder

{Al_2O_3, 53%}, basic-aluminum-chloride liquid {$Al_2Cl(OH)_5$, 33%}, alumina sol {$Al(OH)_3 \sim Al_2O_3 \sim AlO(OH)$, 11%} and water. The electric insulation of the binder was tested, and 1300 MΩ cm was achieved after curing at 100°C for 4 hours. If the curing temperature can be increased to 150°C, a curing time of only 2 hours will be sufficient. High temperature tests were performed up to 300°C and no deterioration was found either the electric insulation or the mechanical strength. We therefore started to wind the test coil with this alumina long fiber and inorganic gelatinous binder. The copper conductor was firstly wound into the final coil shape and was carefully wrapped by the alumina tape/binder by hand. The fabricated coil is shown in Fig. 4. The coil insulation has already reached more than 1000 MΩ cm. A long-term operation test is scheduled for this coming autumn.

Chemical Composition: Al_2O_3>99.5% purity

Crystal Phase: α-Al_2O_3

Tensile Strength: 1.8 GPa

Tensile Modules: 330 GPa

Filament Diameter: 10 μm

Density: 3.6

Table 3, Basic characteristics of the ALMAX[6].

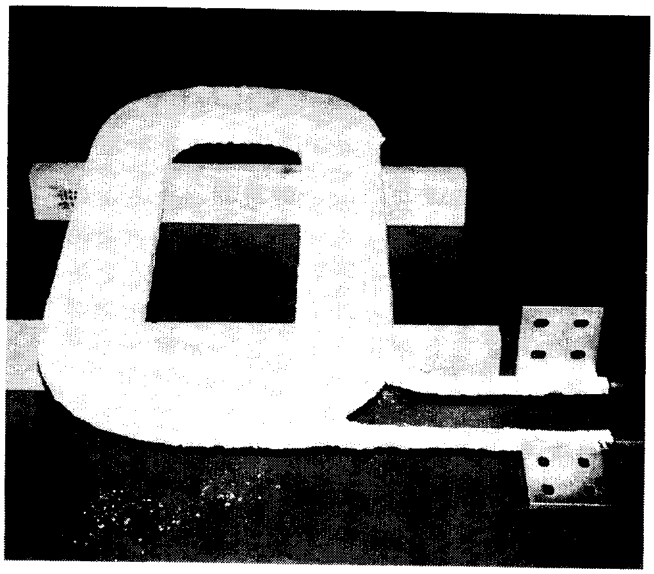

Fig. 4, Fabricated coil with alumina long fiber and a completely inorganic gelatinous binder.

IV. CONCLUSION

In the current R/D work for high-intensity beam-line magnets, we have successfully developed a mineral insulation magnet cable having a nominal current of 2000A in Japan. The length available is, however, only up to 30 m at present. In the near future, however, a 3000A/60m MIC will be fabricated.

The new coil insulation material with alumina long fiber and a completely inorganic gelatinous binder has been realized. A sample coil with this new insulator has been fabricated. The results of a long-run test will be reported at the next MT14 conference.

V. ACKNOWLEDGMENT

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