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Design of Superconducting Combined Function Magnets for the 50 GeV Proton Beam Line for the J-PARC Neutrino Experiment

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Abstract—**Superconducting combined function magnets will be utilized for the 50GeV-750kW proton beam line for the J-PARC neutrino experiment and an R&D program has been launched at KEK. The magnet is designed to provide a combined function with a dipole field of 2.59 T and a quadrupole field of 18.7 T/m in a coil aperture of 173.4 mm. A single layer coil is proposed to reduce the fabrication cost and the coil arrangement in the 2-D cross-section results in left-right asymmetry. This paper reports the design study of the magnet.**

Index Terms—**Asymmetric structure, Combined function, plastic spacer, superconducting magnet.**

I. Introduction

A second generation long-baseline neutrino-oscillation experiment has been proposed as one of the main projects at the JAERI-KEK joint facility for high intensity proton accelerators, called J-PARC [1], [2]. Construction of J-PARC started in 2001 and the first beam is expected in 2007. The primary proton beam will be inwardly extracted from the 50 GeV main-ring and transported to the target to generate an intense neutrino beam. A superconducting magnet system will be adopted for the beam transport and an R&D program has been launched at KEK.

The magnet performance must fulfill the specifications but cost saving has been strongly requested. To meet this condition, a superconducting combined function magnet, SCFM, is proposed. Although the resistive combined function magnets have been commonly adopted for the accelerators such as AGS [3], the combined function beam line utilizing the superconducting technologies as main magnets will be a unique facility. The SCFM has a design feature that a single layer coil in 2-D cross section is left-right asymmetry. The SCFM is beneficial for reducing the development time, in comparison with a conventional FODO lattice that needs two separate studies, for dipole and for quadrupole magnets.

The magnet is designed to provide a combined function with a dipole field of 2.59 T and a quadrupole field of 18.7 T/m for a proton energy of 50 GeV. A series of 28 magnets in the beam line will be operated DC in supercritical helium cooling below 5 K. A large coil aperture of 173.4 mm is chosen to lower the possibility of a beam loss quench. The magnet is expected to be operated in a high radiation environment caused by the very intense 750 kW proton beam.

The beam optics study is in progress and the final specification is not yet completed. To start the magnet R&D, we set a tentative specification, and the design study for the practice coil winding and the mechanical short model has been carried out.

This paper reports the design study of the SCFM. The magnet system design including the cryogenics and the powering is reported in [4]. The quench stability study with respect to the beam loss can be found in [5].

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II. Magnet Overview

A. Design Concept

A cross sectional view of the SCFM is shown in Fig. 1 and the main design parameters are summarized in Table I.

The most important feature is that the coil is wound like a dipole coil but with a left-right asymmetry: the magnetic pole is off-center by about 21.5 at the left side of the coil as shown in Fig. 1. The coil is divided into 3 blocks for the left (higher field) side and 5 blocks for the right (lower field) side to provide the appropriate combined field. The design study has been carefully performed to take into account the asymmetric mechanical properties of the coil such as rigidity,

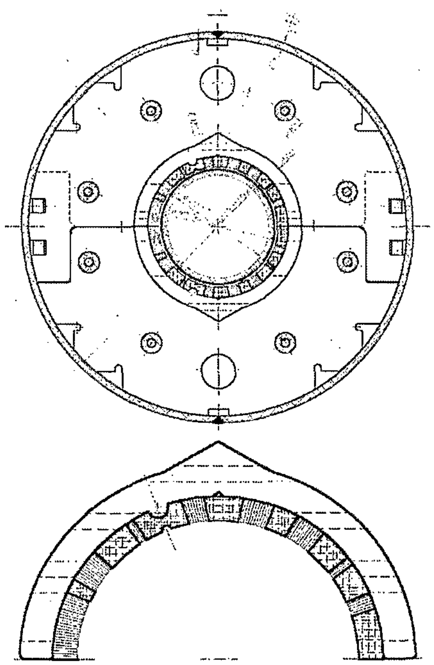

Fig. 1. Cross sectional view of the SCFM at the 50 GeV proton beam line for the J-PARC neutrino experiment (top) and expanded view of the coil (bottom). They are seen from the lead end.

The coil is mechanically supported by a keyed yoke made of fine-blanked iron laminations. The iron yoke also functions as a magnetic flux return. Glass-reinforced phenolic plastic spacers for electrical insulation are placed between the coil and the iron yoke. The magnet is designed to be self-protected with a cold-diode in case of the quench: no quench protection heater is needed. Other design features mostly follow the design of the superconducting quadrupole magnets for the interaction region of LHC, called MQXA, developed by KEK [6]. Radiation resistant materials are used for the magnet.

B. Materials

1) Superconducting Cable and Insulation: The design parameters of the superconducting cable are listed in Table II. A large amount of Rutherford type NbTi/Cu superconducting cable for the LHC magnet is being manufactured by several different companies. We simply adopt the superconducting cable for the outer layer of the LHC main arc dipole magnets to reduce the cost and development time [7]. However, the insulation system has been changed to a double layer of polyimide tapes with B-stage epoxy resin that are identical to that used for the MQXA. The coil shape is formed by curing around 410 K for 10 hours.

2) End Spacer and Wedge: The end spacers and the ramp box for the lead transition are made of G-10CR and are precisely machined by the computer numerical control (CNC). . G-10CR end spacers are softened during the curing process and fit the coil closely.

G-11CR has been adopted for the wedges: the lower azimuthal thermal contraction of G-11CR helps to maintain the appropriate cross section at low temperature. Furthermore, homogeneous coil rigidity in the azimuthal direction is achieved because the rigidity of G-11CR around 20 GPa is similar to the rigidity of the insulated cable. Copper was eliminated as a candidate for the wedges because the concave arc and sharp corners on the bore side of the wedge make wrapping the insulation very difficult.

3) Plastic Spacer: The coil is surrounded by glass-reinforced phenolic plastic spacers, which were originally developed for BNL-RHIC [8]. Glass-reinforced phenol plastic is a radiation resistant material and good dimension accuracy results from the lower molding temperature around 430 K. Instead of the conventional electrical insulation such as polyimide film, use of the plastic spacer reduces the labor and inspection costs. However, the stress analysis is very important in the design

TABLE I

MAIN DESIGN PARAMETERS FOR THE SCFM

Physical Length		3609 mm
Magnetic Length		3300 mm
Coil Inner & Outer Diameter		173.4 & 204.0 mm
Yoke Inner & Outer Diameter		244 & 550 mm
Shell Outer Diameter		570 mm
Weight		6200 kg
Dipole Field		2.59 T
Quadrupole Field		18.7 T/m
Coil Peak Field		4.7 T
Load Line Ratio		75%
Cooling Type		Supercritical Helium
Operation Temperature		< 5 K
Inductance		12.9 mH
Stored Energy		385 kJ
Number of Turns		
Left side: 3 Blocks		24 (MP) [a], 12, 3 (Pole) [b]
Right side: 5 Blocks		6 (MP) [a], 3, 11, 11, 8 (Pole) [b]
Magnetic Force of a single coil		
Horizontal & Vertical	Left side	-617 & -371 kN/m
	Right side	436 & 114 kN/m

Design parameters at 50 GeV are listed.
[a](MP) stands for the coil block adjacent to the median plane.
[b](Pole) stands for the coil block adjacent to the magnetic pole.

TABLE II

DESIGN PARAMETERS OF THE SUPERCONDUCTING CABLES

Strand:	Diameter		0.825 mm
	Cu/SC Ratio		1.95
	Filament Diameter		6 μm
	Twist Pitch, Z		15 mm
	Surface Condition		Sn-Ag (0.5-1.0 μm thick)
Cable:	Width		15.1 mm
	Middle Thickness		1.480 mm
	Keystone Angle		0.9 deg.
	RRR of Cu		> 70
	Cabling Pitch, S		100 mm
	Number of Strands		36
	Critical Current		> 12240 A @ 6 T, 4.2 K
Insulation:			
Bottom Layer	Material		Polyimide (Upilex-RN)
	Thickness		25 μm
	Wrapping		50 % over-wrap
Top Layer	Material		Upilex-RN with B-stage epoxy
	Thickness		50 μm
	Wrapping		2 mm spacing

study because of the brittleness of the spacers. The plastic spacers are made from PM9640 supplied by Sumitomo Bakelite and fabricated by compressive molding.

4) Iron Yoke: The keyed iron yoke technology has been transferred from the MQXA except for the dimensions. The fixing yoke sheet is 5.8 mm thick and has grooves for keying at claws in both sides while the spacer yoke sheet of 6.0 mm has no claw. The sheets are accurately manufactured by fine-blanking techniques with a typical tolerance of 30 μm. Two kinds of sheets are stacked alternately to a length of 240 mm and mechanically connected by four stack-tubes. During the yoking process, the claws of the fixing yoke sheet are inserted into the vacant space of another yoke stack made by the spacer yoke sheet and then a pair of top- and bottom- yoke stacks are assembled by keying. The packing factor of the iron yoke is expected to be around 99 %.

5) Shell: After the yoking process, the magnet is rotated 90 and two halves of a stainless steel shell covering the magnet are welded by an automatic-welding machine. Since the shell is a helium pressure vessel, the welding must be officially inspected to fulfill the Japanese safety regulation.

III. Electromagnetic Design

The electromagnetic design of the SCFM was performed by ROXIE [9]. In this paper, the multipole coefficients at a reference radius of 50 mm are expressed in units that are normalized with respect to the dipole field, B_1, and scaled by a factor of 10000.

It is planned that J-PARC will operate at 40 GeV for an initial period of several years and then will be upgraded to 50 GeV. Therefore, the magnet needs to be designed for proton energies of both 40 and 50 GeV.

A. Straight Section

The asymmetric 2-D coil configuration was determined by the optimization calculation of ROXIE (Biot-Savart's law) keeping b_2 at the design target, while minimizing higher multipole components. From the viewpoint of mechanical engineering, the arc length of the pole spacer and the shape of coil blocks of several candidates obtained by the calculation were carefully checked and then the final cross section was determined.

TABLE III
Field Quality in the Straight Section

	40 GeV	50 GeV
Current [A]	6140	7730
B_1, Dipole Field [T]	2.07	2.59
Multipole Coefficients [unit]		
b_2	3614.3	3592.9
b_3	2.6	2.7
b_4	5.7	15.2
b_5	-0.4	3.0
b_6	2.5	2.3
b_7	-1.6	-2.0
b_8	7.6	7.7
b_9	-8.8	-8.8
b_{10}	3.0	3.0

FEM calculation by ROXIE.

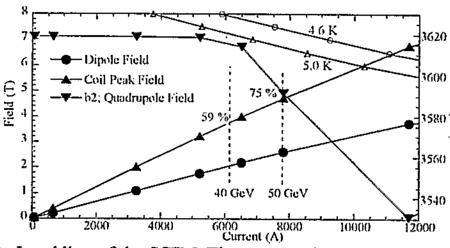

Fig. 2. Load line of the SCFM. The current dependence of b_2 is also displayed. Open circles and triangles show the critical boundaries of the superconducting cable at 4.6 and 5.0 K, respectively.

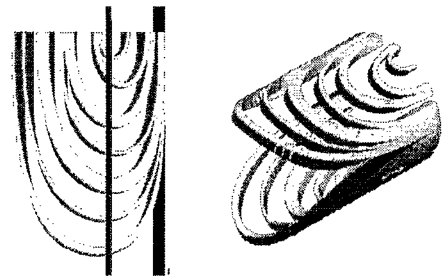

Fig. 3. Bottom view of the lead end (left) and top view of the return end (right). The coil end shape has been modeled by ROXIE.

TABLE IV
Integral Multipole Coefficients of the SCFM

	LE	Body	RE	Total
Physical Length [mm]	930	1959	720	3609
Magnetic Length [mm]	774	1959	567	3300
Multipole Integral [unit m]				
b_2	2761.0	7028.3	1987.9	11777.2
b_3	-61.9	-85.9	-70.0	-217.8
b_4	5.1	3.1	1.2	9.4
b_5	3.1	19.8	0.2	23.2
b_6	1.6	6.0	-0.3	7.3
b_7	-4.2	-7.1	-4.5	-15.9
b_8	5.9	14.6	3.9	24.4
b_9	-5.9	-16.4	-4.5	-26.7
b_{10}	2.0	5.9	1.2	9.1

Analytical calculation by ROXIE (No FEM).
LE: Lead end, Body: Straight section, RE: Return end.

The field quality calculated by ROXIE-FEM in the straight section is summarized in Table III. The load line of the SCFM and the current dependence of b_2 are displayed in Fig. 2. Field quality is achieved within a tolerance of 10^{-3} and is acceptable for the beam optics. Note that b_3 of more than 40 units, induced by the triangle notch at the inner-top of the iron yoke, has been successfully eliminated by adjustment of the coil configuration. Iron saturation is observed in the change of b_2 and b_4 but it is unavoidable. It was decided that the coil arrangement should be tuned for 40 GeV because the beam size may possibly be larger. The load line ratios at 40 and 50 GeV operations are calculated to be 59 % and 75 %, respectively.

B. Coil Ends

Fig. 3 shows the bottom view of the lead end and the top view of the return end. The coil end shape has been successfully modeled by ROXIE. The lead- and return- ends each require eight kinds of end spacers.

The integral multipole coefficients that have been analytically calculated by ROXIE (no FEM) are listed in Table IV. Although the magnetic length is adjusted to be 3300 mm with respect to the dipole field, a field integral of b_2 is 0.5 % lower than the specification required because b_2 at the straight section is adjusted to the design value and b_2 at the coil ends is relatively lower. In contrast, b_3 is obviously enhanced at the coil end regions and the integral of -70 unit m is expected to remain even with FEM analysis. Other higher multipole integrals are sufficiently small.

IV. Mechanical Design

The superconducting magnet is designed so that the magnetic pole is mechanically anchored to the iron yoke to ensure good field quality and mechanical structure. As shown in Fig. 1, the circular shaped key of the plastic spacer fits into the groove on the G-11CR pole spacer and the triangular top of the plastic spacer fits into the notch of the iron yoke. The triangular shape of the plastic spacer also helps its movement during the yoking process: the spacer is slightly tilted at the beginning due to the left-right asymmetry of the over-sized coil and gradually moves toward the final position as the coil is loaded by the press.

Different thicknesses of the G-11CR wedges on the two sides contribute to the left-right asymmetry of the mechanical properties. In order to achieve the design pre-stress, the values of over-size for the left- and right side of the coil are 0.7 mm and 0.9 mm, respectively.

The coil locking system at the pole region is very critical because an asymmetric load is applied on both sides of the coil during magnet assembly, cool down and excitation, and sufficient shear stress could be generated to break the brittle key of the plastic spacer. Several FEM stress analyses by ANSYS were made for various asymmetric loads by changing the coil sizes. A local shear stress of 40 MPa was obtained for the case of the most balanced coil sizes. An unbalanced coil size of 0.1 mm increases the local shear stress by about 10 MPa, so coil size control is quite important to avoid breaking the plastic spacer.

Azimuthal Lorentz force and displacement of the conductor at 50 GeV operation are plotted in Fig. 4. The displacement is calculated by a simplified spring model. Although a maximum conductor displacement of 45 μm is observed around the middle of the left (higher field) side of the coil, the influence on the field quality is still within an acceptable range. The calculated pre-stress losses at the pole for the left- and the right- sides of the coil are 22 MPa and 16 MPa, respectively. In addition, the decrease of pre-stress during cool down is expected to be about 20 MPa. In order to maintain sufficient pre-stress at 50 GeV operation we set a design target of 80 MPa after the yoking process.

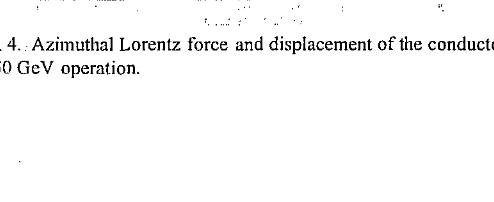

Fig. 4. Azimuthal Lorentz force and displacement of the conductor at 50 GeV operation.

The main body of the ramp box is made in one piece and covered by a thin plate of G-10CR. Since the Lorentz force on the outer surface of the coil is not negligible, the ramp box and the extended lead out are transversely fixed from both sides by precisely machined GFRP pipes. At the return end, two halves of GFRP pipe are placed between the coil and the iron yoke, and compress the coil only radially.

V. Summary and Further Plan

In order to minimize cost, a single type superconducting combined function magnet has been designed for the J-PARC neutrino beam line. To confirm the feasibility of the mechanical design, a practice coil winding and the assembly of a mechanical short model will be started soon.

In 2004, a prototype magnet will be built with a new design incorporating the final specification given by the beam optics study. The performance of the prototype in training behavior and field quality will also be examined.

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