DEVELOPMENT OF SUPERCONDUCTING COMBINED FUNCTON MAGNETS FOR THE J-PARC NEUTRINO BEAM LINE

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Abstract

Superconducting combined function magnets will be utilized for the 50 GeV, 750 kW proton beam line for the J-PARC neutrino experiment. The magnet is designed to provide a dipole field of 2.6 T combined with a quadrupole field of 19 T/m in a coil aperture of 173.4 mm at a nominal current of 7345 A. Two full-scale prototypes and the first two production magnets were completed and the magnet performance was confirmed to fulfill the specification.

INTRODUCTION

A second generation of long-baseline neutrino oscillation experiments has been proposed as one of the main projects at the J-PARC [1], [2] and the construction of the facility is in progress. Superconducting combined function magnets, SCFMs, will be utilized for the 50 GeV, 750 kW proton beam line for the neutrino experiment. The magnet is designed to provide a dipole field of 2.6 T combined with a quadrupole field of 19 T/m in a coil aperture of 173.4 mm at a nominal current of 7345 A. A series of 28 magnets in the beam line will be operated DC in supercritical helium cooling below 5 K [3]. Since the main accelerator will be operated at 30 GeV in the beginning, the SCFM was designed for proton beam energies of 30 to 50 GeV. A cross sectional view of the SCFM is shown in Fig. 1 and the main design parameters are listed in Table 1.

Prior to the fabrication of production magnets, an in-house R&D program to build two full-scale prototype magnets was started to confirm the magnet design, fabrication tools and assembly procedures. The program was successfully completed and it was verified that the magnet performance fulfilled the specification [4], [5].

According to the bidding, the contract of the series production of the magnet system was awarded to Mitsubishi Electric (MELCO). Technology developed for the prototype magnets was transferred to MELCO and the first two production magnets were successfully completed.

DESIGN AND FABRICATION

Design Overview

A unique feature of the SCFM is the left-right asymmetry of the coil cross section: current distributions for superimposed dipole- and quadrupole- fields are combined in a single layer coil. Another design feature is the adoption of glass-fiber reinforced phenolic plastic spacers for electrical insulation to reduce the labor and inspection costs.

The most appropriate 2D coil arrangement to generate the required field was determined by using ROXIE [6].

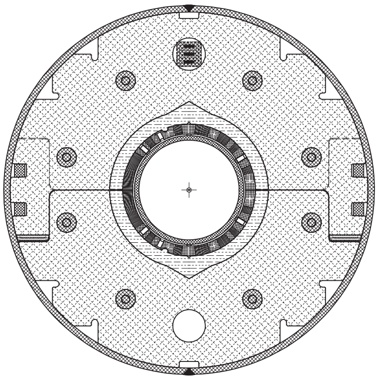

Figure 1: Cross sectional view of the superconducting combined function magnet, SCFM, for the 50 GeV proton beam line for the J-PARC neutrino experiment.

Table 1: Main Design Parameters for the SCFM

Physical & Mag. Length	3630 & 3300 mm
Coil In. & Out. Diameter	173.4 & 204.0 mm
Yoke In. & Out. Diameter	244 & 550 mm
Shell Outer Diameter	570 mm
Dipole & Quad. Field	2.59 T & 18.7 T/m
Coil Peak Field	4.7 T
Load Line Ratio	72 %
Operational Current	7345 A
Inductance & Stored Energy	14.3 mH & 386 kJ
Number of Turns	
Left side: 2 Blocks	35, 6
Right side: 5 Blocks	6, 5, 10, 13, 7
Mag. Force of a single coil	
ΣFx & ΣFy Left side	-618 & -360 kN/m
Right side	434 & 114 kN/m

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As shown in Fig. 1, the coil is divided into 2 blocks for the left (high field, HF) side and 5 blocks for the right (low field, LF) side to provide the appropriate combined field. The effective pole is rotated by about 20° towards the high field side (left side in this figure). The shape of the coil ends was also modelled by ROXIE, which provided CNC files for the manufacture of G10 end spacers. The 3D magnetic field was calculated by using Opera-3D (TOSCA). The magnetic length was calculated to be 3350 mm for the dipole field. The relatively larger value of B_3 was mainly produced by the shape of the coil ends and cannot be eliminated. Beam optics calculations confirmed that the design magnetic field of the SCFM within a tolerance of 10^{-3} at a reference radius of 50 mm was sufficiently acceptable.

Coil Winding

The Rutherford type NbTi/Cu superconducting cable that was used for the outer layer of the LHC main dipole magnet was simply adopted for the SCFM to reduce the cost for the cable development. The cable was insulated by the polyimide tape with the B-stage epoxy resin. The end spacers and the wedges were made of GFRPs (G10 and G11). They were precisely made by CNC machining. Size control of the wedges was very important to achieve good field quality and adequate pre-stress. The tolerance of the wedge size was set to be 0.1 mm.

The coil was wound like a dipole coil and cured in a forming block at about 400 K for 5 hours. An appropriate combination of several shims for the curing was carefully chosen to achieve the design coil stress of 80 MPa during yoking and to avoid displacement of the effective pole due to unbalanced coil sizes. The shims were set on the median plane of the coil at the curing so that the asymmetric coil over-size was correctly controlled.

Yoking and Shell Welding

A picture of the magnet prepared for the yoking process is shown in Fig. 2. The glass-fiber reinforced phenolic plastic spacers were placed between the coil and the iron yoke. The plastic spacers function as not only electrical insulation but also to align the coil with respect to the iron yoke: a triangular feature at the top fits into the notch of the iron yoke and a circular shaped key on the inner diameter fits into the groove on the pole spacer of the coil, as shown in Fig. 1.

The keyed iron yoke technology was transferred from the LHC-MQXA magnets [6]. The “fixing yoke” sheet was 5.8 mm thick and had grooves for keying at claws on both sides while the “spacer yoke” sheet 6.0 mm thick had no claw. The upper- and lower- yoke assemblies were compressed at their shoulders up to about 13 MN by the hydraulic press and were locked by keying. The yoke gap was closed at the median plane by the keying. With the keys installed, the cross sectional mechanical structure and the coil alignment with an appropriate pre-stress were accomplished.

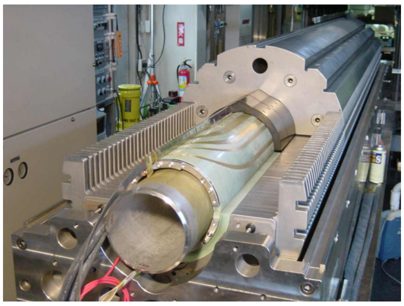

Figure 2: Magnet prepared for the yoking process.

The helium vessel was formed by two halves of an SUS304L shell covering the yoked magnet. The shell had 4 holes at 5 points along the magnet length, 20 holes in total. The yoked magnet was rotated 90° and the top and bottom were longitudinally welded by 2 automatic welding machines as the yoke shoulder was aligned through the holes by the hydraulic press. A backing strip was not permitted for the shell welding by Japanese high-pressure regulation. Instead, pre-formed inserts of SUS308L were set between two halves of the shell and were completely welded at the first welding pass. Shell welding needed 11 passes in total.

TEST RESULTS

So far, two prototypes and two production magnets were fabricated so far. In addition, the first prototype was rebuild for the further quench protection studies. In total, five cold tests were carried out at a 9 m deep vertical cryostat filled with liquid helium at 4.2 K [4], [5], [8].

Quench Characteristics

All magnets were successfully reached to the nominal current of 7345 A at a ramp rate of 5 to 20 A/s without a spontaneous training quench. Furthermore, they were successfully excited up to 7700 A that is 105 % nominal current. The prototypes, excluding two production magnets, were energized at different ramp rates and no quench occurred up to the nominal current even at the maximum ramp rate of 750 A/s. The first prototype had no training quench right after a full thermal cycle. Full energy dump tests were carried out for the production magnets on which the quench protection heaters were fully installed and the quench protection heaters were

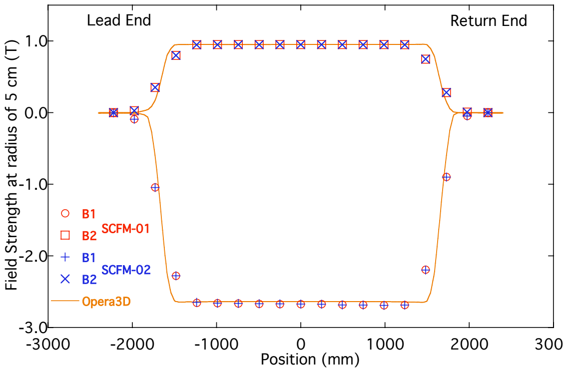

Figure 3: Dipole and quadrupole components distribution along the magnet at a current of 7460 A.

verified to protect the magnets safely. In fact, all magnets have shown excellent quench performances.

Field Quality

Magnetic field measurements were performed with a 500 mm-long rotating printed circuit board on which 5 radial rectangular coils were arranged in parallel. The rotating board was vertically scanned along the magnet in the warm-bore tube. Analogue bucking with a combination of the radial coils was adopted to obtain higher order harmonics. In this measurement system, it is difficult to determine the dipole field with good accuracy because an off-centered rotating axis induces a "feed-down" effect from higher order harmonics. This significantly affects measurement of the dipole field because of the large magnitude of the quadrupole field. In the following data, therefore, the magnetic field was analyzed so that average of the skew quadrupole component along the magnet straight section was equal to zero.

Figure 3 shows dipole and quadrupole components distribution along the magnet axis for the production magnets at a current of 7460 A. It is shown that the calculations by Opera-3D (TOSCA) generally reproduce the measurements for both the dipole and the quadrupole components. While the measured quadrupole component at the straight section shows good agreement with the calculation, discrepancy on the dipole field can be found. This discrepancy is probably induced by the "feed-down" effect. Figure 4 shows field integrals of the dipole and the quadrupole components along the magnet. Despite the good agreement at the straight section, the systematic difference of 1 to 2 % all through the magnets can be seen for the quadrupole field integral. The differences come out around the magnet ends but the reason has not been traced yet.

Figure 5 shows the field integrals of higher order harmonics at a current of 7345 A. The calculations reasonably reproduce the measurements for each multipole component. It was confirmed that the field qualities for all magnets met the specifications.

SUMMARY AND FURTHER PLAN

Two full-scale prototypes, one modified one and two production magnets were successfully completed. All magnets showed excellent excitation performances. Good field quality was reproduced for all through the magnets and fulfilled the specifications.

A full-scale prototype cryostat containing two prototype magnets was fabricated by MELCO and is being tested at the horizontal test bench at KEK. The first series of 6 production cryostats including 12 magnets will be fabricated in 2006. The entire magnet system for the neutrino beam line has to be ready by 2009.

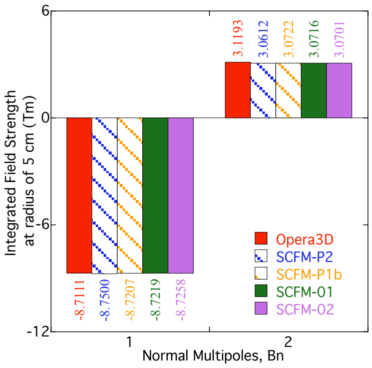

Figure 4: Field integrals of dipole and quadrupole components at a current of 7345 A.

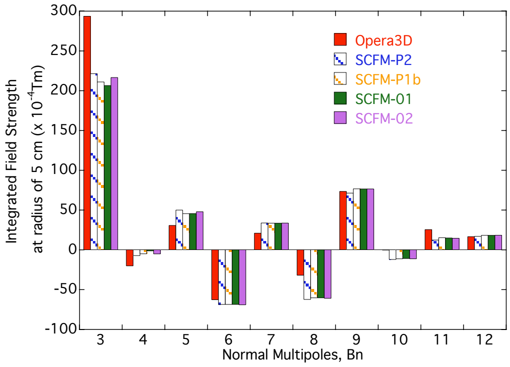

Figure 5: Field integrals of higher order harmonics at a current of 7345 A.

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