BNL-91092-2010-CP

Construction of Superconducting Magnet System for the J-PARC Neutrino Beam Line

T. Nakamoto, K. Sasaki, Y. Ajima, O. Araoka, Y. Fujii, N. Hastings, N. Higashi, M. Iida, T. Ishii, N, Kimura, T. Kobayashi, Y. Makida, T. Nakadaira, T. Ogitsu, H. Ohhata, T. Okamura, K. Sakashita, S. Sugawara, S. Suzuki, K. Tanaka, T. Tomaru, A. Terashima, A. Yamamoto, A. Ichikawa, H. Kakuno, M. Anerella, J. Escallier, G. Ganetis, R. Gupta, A. Jain, J.. Muratore, B. Parker, P. Wanderer, T. Boussuge, J.-P. Charrier, M. Arakawa, T. Ichihara, T. Minato, Y. Okada, A. Itou, T. Kumaki, M. Nagami and T. Takahashi

Presented at:
21 International Conference on Magnet Technology
Hefei, China
October 18-23, 2009

Magnet Division

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

BNL-91092-2010-CP

DISCLAIMER

Construction of Superconducting Magnet System for the J-PARC Neutrino Beam Line

T. Nakamoto, K. Sasaki, Y. Ajima, O. Araoka, Y. Fujii, N. Hastings, N. Higashi, M. Iida, T. Ishii, N. Kimura, T. Kobayashi, Y. Makida, T. Nakadaira, T. Ogitsu, H. Ohhata, T. Okamura, K. Sakashita, S. Sugawara, S. Suzuki, K. Tanaka, T. Tomaru, A. Terashima, A. Yamamoto, A. Ichikawa, H. Kakuno, M. Anerella, J. Escallier, G. Ganetis, R. Gupta, A. Jain, J. Muratore, B. Parker, P. Wanderer, T. Boussuge, J.-P. Charrier, M. Arakawa, T. Ichihara, T. Minato, Y. Okada, A. Itou, T. Kumaki, M. Nagami and T. Takahashi

***Abstract*—Following success of a prototype R&D, construction of a superconducting magnet system for J-PARC neutrino beam line has been carried out since 2005. A new conceptual beam line with the superconducting combined function magnets demonstrated the successful beam transport to the neutrino production target.**

***Index Terms*—Beam Line, Neutrino, Proton, Superconducting Magnet.**

I. INTRODUCTION

CONSTRUCTION of the facility for a long-base line neutrino oscillation experiment, the so called T2K experiment [1], has been carried out at the J-PARC [2]. In the "Neutrino Beam Line" for the T2K experiment, a superconducting magnet system with an arc section of the beam line are utilized to transport the primary proton beam with a nominal specification of 50 GeV and 750 kW to the neutrino production target. The superconducting arc section is about 150 m long and consists of 28 superconducting combined function magnets (SCFMs). As shown in Fig. 1, the SCFM has a unique feature of a left-right asymmetry of the coil cross section: current distributions for dipole- and quadrupole- fields are superimposed in the single layer coil. This means that the single SCFM can provide both functions of beam bending and focusing/defocusing and a pair of SCFMs setting opposite directions works as a FODO lattice. Utilization of the SCFM can reduce the number of magnets while maintaining beam acceptance [3]. The J-PARC neutrino beam line is the first case in the world to realize this concept.

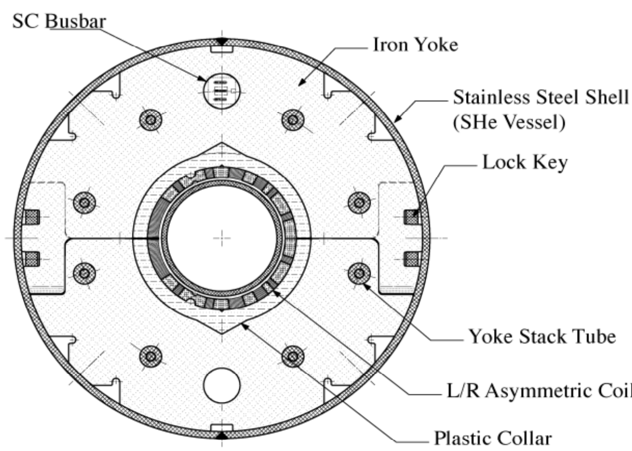

Fig. 1. Cross sectional view of the superconducting combined function magnet, SCFM, for the J-PARC neutrino beam line.

II. MAGNET SYSTEM DEVELOPMENT, PRODUCTION AND INSTALLATION

A. Overview

The SCFM 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 7345 A for 50 GeV protons. The magnets are cooled with supercritical helium (SHe) below 5 K by the helium refrigerator, including cold pumping system, with a cooling power of 1.5 kW. Each doublet cryostat functioning FODO lattice contains two magnets and 14 doublet cryostats in total are installed in the beam line. The interconnect cryostats between the main cryostats have a function either of the beam steering superconducting corrector magnet, the quench relief valve, or the beam monitor. The helium transfer tube (TRT) with a length of 100 m connects the refrigerator on the ground

Manuscript received 20 October 2009.

T. Nakamoto, K. Sasaki, Y. Ajima, O. Araoka, Y. Fujii, N. Hastings, N. Higashi, M. Iida, T. Ishii, N. Kimura, T. Kobayashi, Y. Makida, T. Nakadaira, T. Ogitsu, H. Ohhata, T. Okamura, K. Sakashita, S. Sugawara, S. Suzuki, K. Tanaka, T. Tomaru, A. Terashima and A. Yamamoto are with KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801 Japan (phone: +81-29-864-5766; fax: +81-29-864-3209; e-mail: tatsushi.nakamoto@kek.jp).

A. Ichikawa is with the Division of Physics and Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502 Japan (e-mail: ichikawa@scphys.kyoto-u.ac.jp).

H. Kakuno is with the University of Tokyo, Bunkyo-ku, Tokyo 113-0033 Japan (e-mail: kakuno@phys.s.u-tokyo.ac.jp).

M. Anerella, J. Escallier, G. Ganetis, R. Gupta, A. Jain, J. Muratore, B. Parker and P. Wanderer are with Brookhaven National Laboratory, Upton, NY 11973 USA (e-mail: wanderer@bnl.gov).

T. Boussuge and J.-P. Charrier are with CEA Saclay, Gif-sur-Yvette, 91191 cedex, France (e-mail: jean-paul.charrier@cea.fr).

M. Arakawa, T. Ichihara, T. Minato and Y. Okada are with Mitsubishi Electric, Kobe, Hyogo 652-8555 Japan (e-mail: Ichihara.Tadashi@dh.MitsubishiElectric.co.jp)

A. Itou, T. Kumaki, M. Nagami and T. Takahashi are with Taiyo Nippon Sanso, Kawasaki, Kanagawa 210-0861 Japan (e-mail: Atsushi.Itou@tn-sanso.co.jp).

and the magnets in the beam line tunnel 11 m below the ground, and supplies SHe to the magnets. Detailed reports on the development, production, and testing of the superconducting magnet system for the J-PARC neutrino beam line can be found in [4]-[17].

The R&D was launched in 2002 to develop 2 full-scale prototypes of the SCFM at KEK in-house and the magnet production was started in 2005. Following a series production of SCFMs, installation of the magnet system in the beam line tunnel was started on February 2008. Consolidation work in the beam line tunnel including the TRT and construction of a cryogenics plant on the ground were completed by December. Following the independent hardware commissioning of the cryogenics plant, cool-down of the magnet system was started at the beginning of 2009. Subsequently a powering test of the magnet system followed by beam commissioning was carried out for the initial accelerator operation with 30 GeV protons. A completed superconducting magnet system in the neutrino beam line is shown in Fig. 2.

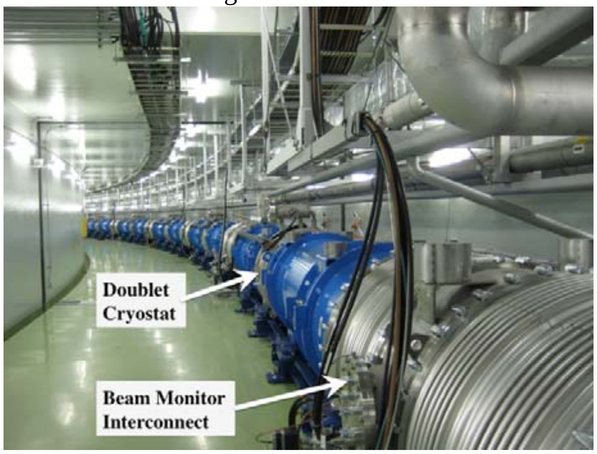

Fig. 2. Neutrino beam line tunnel and superconducting magnet system (view from beam upstream).

B. SCFM

Main parameters of the SCFM are listed in Table I [5]-[7]. In addition to the left-right asymmetric coil structure, another design feature of the SCFM is glass-fiber reinforced phenolic plastic spacers for electrical insulation to reduce the labor and inspection costs. 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. Rutherford-type NbTi/Cu superconducting cables supplied by Furukawa Electric have the same specification, except for the insulation, as the outer layer coil of the LHC main dipole magnet [18].

Following the success of the in-house prototype R&D, the contract to build 32 production magnets and 16 cryostats including spare was given to Mitsubishi Electric. Fabrication of the magnets was completed by June 2008 as planned. The only significant problem in production was the failure of the insulation in a quench protection heater (QPH) in the eighteenth magnet [13].

The excitation tests for all magnets in liquid helium at 4.2 K in the vertical cryostat were carried out at KEK. All magnets were successfully excited up to 7700 A corresponding 105 % nominal current at a ramp rate of 20 A/s without a spontaneous training quench. Magnetic field measurements were performed with a 500 mm long rotating printed circuit board with coil circuit. It was confirmed that the field qualities for all magnets were good enough to fulfill the specifications. The test results of the SCFM were reported in [8]-[12], [14].

TABLE I. MAIN PARAMAETERS OF THE SCFM

Parameter		Value
Magnetic Length		3300 mm
Coil Aperture		173.4 mm
Yoke Inner- & Outer- Diameter		204 mm & 550 mm
Shell Outer Diameter		570 mm
Dipole Field		2.59 T
Quadrupole Field		18.7 T/m
Coil Peak Field		4.7 T
Load Line Ratio		72 %
Operation Current		7345 A
Operation Temperature		< 5 K
Inductance		14.3 mH
Stored Energy		386 kJ
Number of Turns in a coil		
	Left: 2 blocks	35+6
	Right: 5 blocks	6+5+10+13+7
EM Force: ΣFx & ΣFy		
	Left	-618 kN/m & -360 kN/m
	Right	434 kN/m & 114 kN/m

*Design parameters at 50 GeV protons are listed.

C. Doublet Cryostat

Design of the doublet cryostat is based on the LHC arc dipole cryostat [15], [19]. Dimensions of the doublet cryostat are 0.94 m in outer diameter, 10 m in length and 22 tons in weight. It consists of two vacuum vessels and one connecting part in-between, forming one common cryostat. The cryostat has mechanical bending angle of 2.88 degree between two vessels to accommodate the beam bending. Two GFRP posts from the vessel support each magnet. The post at the end has slide mechanism to cope with thermal shrinkage of the magnet along the longitudinal direction of the cryostat. They are designed so that the magnetic center sits on the designed location when the magnets are cooled down to 4.5 K, taking into account thermal shrinkage. A helium pressure vessel consisting of two SCFMs in the doublet cryostat has an inlet and an outlet of the SHe supply line at both ends to be connected with the adjacent cryostats. An SHe return line and a pair of shield cooling supply/return lines are drawn along the pressure vessel in the cryostat.

The magnets were returned to Mitsubishi Electric after the cold test at KEK and assembly into the doublet cryostat was carried out with the alignment accuracies of 0.1 mm in the perpendicular plane with respect to the beam axis. A series production of the cryostats was started in 2006 and the whole production including spares ended in February 2009.

In the beginning of the production phase, the prototype doublet cryostat was tested to experimentally evaluate the cryostat performance such as mass flow rate of SHe, heat load and magnet displacement due to cooling down at 4.5 K [15].

D. Interconnect Cryostat and Consolidation Work

The beam line has 13 interconnect regions between the main cryostats and it was decided to insert 3 types of “interconnect cryostats” between the main cryostats: 5 proton beam monitors, 3 superconducting corrector magnets, and 4 quench relief valve units for main magnets (plus 1 vacant cryostat). This concept leads to standardization of the main cryostat.

A set of a beam position monitor and a beam profile monitor is situated in the beam monitor interconnect for the beam diagnostics. The beam profile monitor has the movable structure so that the titanium foil can be slid out to avoid severe damages by the intense proton beam. Since both monitors are set inside of the beam pipe which is longitudinally cooled by the doublet cryostat, they need to work at low temperature around 120 K with taking into account thermal shrinkage as well as radiation resistance.

The superconducting corrector magnets for the beam steering were built by BNL and supplied to KEK as a US in-kind contribution to the J-PARC neutrino experiment. Main design parameters are summarized in Table II. The magnet with a copper bobbin consists of a 2-layer normal dipole over a 2-layer skew dipole, and the coils can be independently energized to generate the field integral of 0.1 Tm at 41 A. The coils are wound by using “direct winding technology” with a serpentine coil pattern [20]. A total of 4 corrector magnets including 1 spare were fabricated and tested by BNL [21]-[22]. The corrector magnets are operated using conduction cooling with 5N-class pure aluminum strips: thanks to a huge cooling power of the SHe line, the corrector magnet can be operated at the temperature below 6 K.

In case of quench in the main magnet, helium gas with a sudden pressure rise must be released. Special quench relief valves [16] are set in the interconnect cryostats and distributed along the beam line to suppress the local pressure rise in the magnet system. The helium recovery lines connected to the relief valves are drawn along the beam tunnel and helium gas can be recovered in 3 large helium vessels sitting on the ground.

The corrector magnet or the beam monitor is fixed to the interconnect cryostat within an alignment accuracy of 0.1 mm. The position of the equipment is transferred to two alignment targets at both sides of the top of a vacuum vessel so that the equipment can be precisely aligned with respect to the beam line.

Following installation of the interconnect cryostats, consolidation work of 4 helium lines as well as the beam tube between the doublet cryostats were carried out. To ensure that the system is leak-tight for helium and will not need repair in the future, the helium lines were welded at the collar of the pipes. In contrast, aluminum metal seals are adopted for the beam tube connection. The superconducting bus in the doublet cryostat is comprised of one layer of the SCFM superconducting cable and three layers of copper dummy cable as a stabilizer. A pair of positive and negative superconducting buses previously inserted through the SCFM helium vessel are respectively soldered with another pair of the buses from the next cryostat at the interconnect. The solder joint, with voltage taps across the leads, is firmly clamped in the GFRP fixture for electrical insulation and mechanical support, as shown in Fig. 3, and the whole is contained in the SHe supply line.

TABLE II. MAIN PARAMAETERS OF THE SUPERCONDUCTING CORRECTOR MAGNETS

Parameter	Value: Normal & Skew Dipole Coils
Nominal Operation Current	41A & 41A
Inductance with Iron Yoke	1.1 H & 1.1 H
Stored Energy	1.4 kJ & 1.4 kJ
Nominal Integral Field	0.1 Tm & 0.1 Tm
Nominal Peak Field	0.2 T & 0.2 T
Physical Length	830 m
Coil Support Tube Aperture	150 mm
Coil Support Tube Thickness	10 mm
Yoke Outer Diameter	220 mm
Weight of Assembly	120 kg
Dump Resistor for Coil Protection	1 Ω & 1 Ω

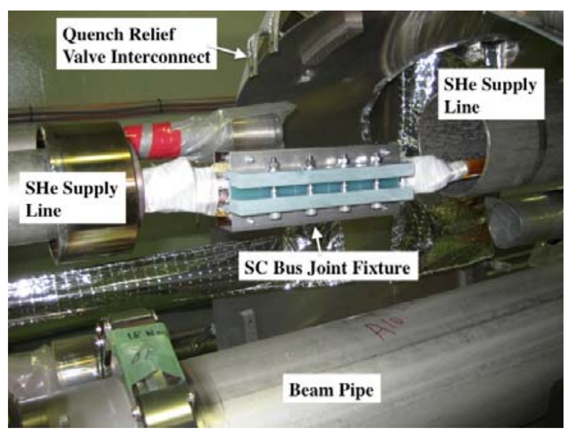

Fig. 3. Superconducting bus joint fixture installed in the SHe line in the interconnect cryostat.

E. Powering, Quench Protection and Safety Equipment

The SCFMs are electrically connected in series and energized by a main power supply with a capability of 8 kA, 10 V. A cold diode is connected in parallel with each single SCFM and a set of two cold diodes is contained in a stainless cylinder attached to the helium vessel at the downstream-end of the doublet cryostat where the neutron radiation is expected to be much lower. The cold diode is generally same as that for the LHC main quadrupole magnet [23]. A magnet safety system (MSS) with the functions of quench detection, transmission of trigger signals to the subsequent equipment, and data acquisition of the signals associated with the superconducting magnet has been developed by CEA Saclay as a French in-kind contribution to the J-PARC neutrino experiment. The MSS covers all the SCFMs with redundant quench detection circuits including superconducting buses in the TRT as well as each of six superconducting corrector magnets. In case of quench detection for any SCFM, the MSS triggers the signals to open a mechanical switch in the main power supply and activate QPHs attached in the corresponding coils. The dump resistor of 40 mΩ in the main power supply protects the cold diodes and the superconducting buses. The corrector magnet is energized with a conventional power supply of Agilent Technology 6684A and its quench protection is ensured by a conventional breaker and a dump resistor of 1 Ω. The power supplies for the main circuit and for the corrector magnets and the MSS were built in a cryogenic building on the ground whereas capacitor banks to fire the QPHs were set at the interconnect region in the beam line tunnel.

An arc current around the superconducting bus joint in case of the quench protection failure or direct bombardment of the primary proton beam onto the beam tube may result in a large helium leak into the vacuum. Since an overpressure in the beam tube or the cryostat vacuum may lead to a severe destruction of the magnet system, a safety valve for the cryostat vacuum and a rupture disk for the beam tube are mounted on each quench relief valve interconnect. Pressure thresholds of the safety valves and the rupture disks are set to be 0.1 MPa and 0.18 MPa, respectively, and both devices are connected with exhaust lines to a stack on the ground. In addition, one of the doublet cryostats at the middle of the magnet string has 4 rupture disks 60 mm in diameter at the ports with the pressure threshold of 0.3 MPa. Several oxygen content meters are set along the beam line tunnel and will alert the beam line tunnel and control systems for the cryogenics plant and the accelerator in case of a helium gas leak in the tunnel.

F. Cryogenics

The cryogenics plant engineering was designed in cooperation with Taiyo Nippon Sanso. Specification of the cryogenic system is listed in Table III [16]. SHe coolant produced in the cryogenics plant on the ground is supplied to the magnets through the TRT, through which four tubes for SHe supply/return and shield cooling helium gas (GHe) supply/return are drawn, with a length of 100 m [16], [17]. Fig. 4 shows multiple helium lines and the thermal shield in the TRT. A pair of gas-cooled current leads with a capacity of 8000 A is set in the current lead box between the TRT and the cryogenics plant. Charge current from the main power supply is transferred through a pair of superconducting buses in the SHe supply line of the TRT to the magnets.

The cryogenics plant consists of a Claude helium refrigeration cycle and a pump driven SHe coolant circulation through the heat loads. Due to the powerful SHe pumping system with a flow rate of 300 g/s at 4.5 K, adoption of a JT valve at the end of the magnet string in the beam line tunnel and re-cooling heat exchangers in the magnet, which was originally planned, is unnecessary.

Major components were separately fabricated at the manufacturers and final construction and piping works at the site were made from September to December 2008.

TABLE III. SPECIFICATION OF THE CRYOGENICS SYSTEM

Parameter		Value, Comment
Comp-ressor	Model	MAYEKAWA, HE3225MSC-KLBM
	Discharge Pressure & Flow	1.4 MPa & 160 g/s
Refrig-erator	Model	LINDE, TCF200S
	Refrig. Power	1500 W at 4.5 K for pumped SHe
Sub-cooler	Phase Separator Capacity	1.6 m^3
	SHe Pump Flow	300 g/s (Barber-Nichols)
Helium Vessels	Capacity	100 m^3 * 4 (1 buffer, 3 storages)
	Design & Operation Pressure	1.6 MPa, 1.3 MPa

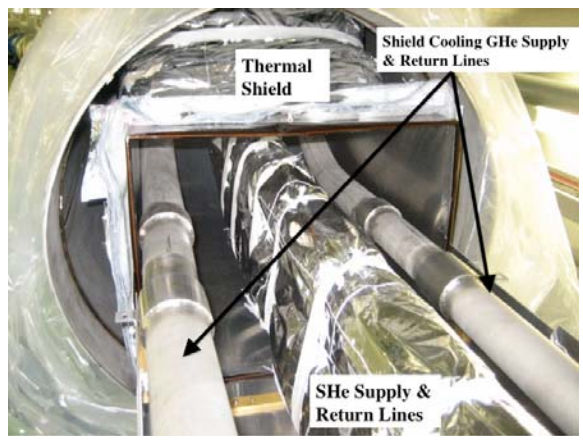

Fig. 4. Multiple helium transfer lines in TRT. SHe supply- and return- lines are hidden and wrapped by multilayer insulation.

G. Alignment

The magnet elements such as the doublet cryostats and the corrector interconnect were separately installed in the beam line tunnel in February and July 2008, and initially aligned with respect to the beam line with an accuracy of 0.1 mm by using a laser tracker system at the time.

Since the J-PARC site faces Pacific Ocean and is also sandwiched by two neighbor rivers, the J-PARC tunnels are surrounded by plenty of groundwater. Furthermore, the downstream end of the neutrino beam line tunnel is structurally connected to the building for the neutrino production target with an enormous amount of iron radiation shielding. For these reasons, it seems that the beam line tunnel has not been fully stabilized so far and continues to fluctuate. Actually, the survey in the tunnel September 2008 indicated that the doublet cryostats and the interconnects were misaligned and that the tunnel shape was deformed at a level of 1 mm. Even though misalignment of the elements was subsequently fixed then, similar behavior of misalignment was observed again in the latest tunnel survey August 2009. This means that periodic and long-term surveys are undoubtedly necessary for the beam line.

III. Commissioning

Complying the high pressure gas safety law of Japan, the whole magnet system including the cryogenics plant was leak-tight at pressures up to 2 MPa. The cryogenics plant was independently commissioned to evaluate its cooling performance. Subsequently, the first cool-down of the magnet system was performed [16], [17]. Trend plot at the first cool-down is shown in Fig. 5 and we confirmed the whole magnet system was cooled down to be ready for the excitation in 8 days. Simultaneously, RRR of each magnet was measured and even the lowest value of 90 met the design specification.

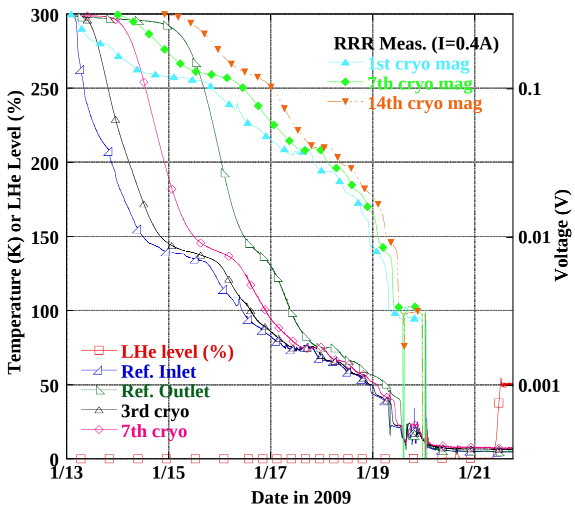

Fig. 5. Trend plot of the superconducting magnet system during the first cool-down.

After checking the MSS at several shutoffs below 2000 A, the quench tests using QPHs were carried out at 2000, 3000, and 4400 A to verify the validity of the quench protection scheme for the main magnets with the cold diodes and the QPHs [24]. Subsequently, the main magnet circuit was energized once up to 5000 A without spontaneous quenches. Finally, a long-term excitation test at 4400 A, corresponding to the initial J-PARC Main Ring operation energy of 30 GeV for several years, was successfully carried out for 2 days without any problem.

Apart from the main magnets, the currents of the corrector magnets were limited to ±13 A which was rather lower than the nominal value of ±41 A. Fig. 6 displays typical signals at shutoff by the MSS. Thermal runaway after holding the current at -13 A for 3 minutes took place at the normal dipole coil in the third interconnect. All six corrector magnets showed same behaviour and the most likely cause is presumed to be insufficient cooling around the soldering joint between the coil lead and the copper bus bar. We made a decision to modify the cooling scheme. A repair work was done in the summer shutdown 2009.

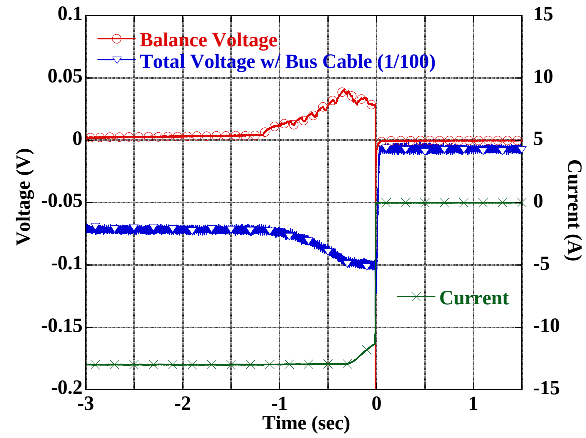

Fig. 6. Typical signals of the superconducting corrector magnet at shutoff by the MSS. Thermal runaway took place at the normal dipole coil in the third interconnect after holding the current at -13 A for 3 minutes.

Following the powering test, beam commissioning at the proton energy of 30 GeV was started in April 2009. The proton beam was successfully transported to the target through the string of the superconducting combined function magnets and the neutrino production was experimentally confirmed. A typical beam trajectory through the neutrino beam line is plotted in Fig. 7. At the end of the beam commissioning, a beam induced quench was made to check the validity of the magnet protection scheme in practical beam operation. Bombardment of a single beam shot with about 1 kJ induced a quench in the superconducting coils and the protection system was confirmed to work properly [24]. Finally, the magnet system was excited to 4400 A to check its soundness and no damage of the magnets was confirmed.

IV. Summary and Further Plan

The superconducting magnet system for the J-PARC neutrino beam line was constructed as scheduled. Even though the cooling scheme of the corrector magnets needed to be modified, the magnet system showed sufficient performance. The new concept utilizing the superconducting combined function magnets successfully transported the proton beam to the neutrino production target.

The next beam commissioning following the summer shutdown will start in Autumn 2009 and last until next summer. The beam power will be gradually upgraded to 100 kW by enlarging the beam size; the quench stability and the heat load regarding the beam loss will be subjects of the next beam commissioning.

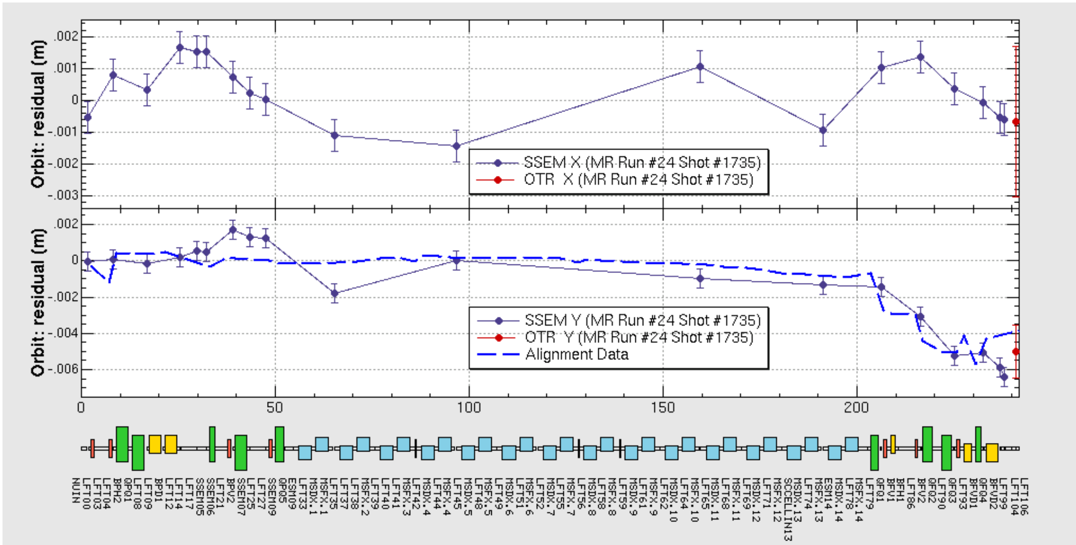

Fig. 7. Proton beam trajectory through the neutrino beam line. For horizontal orbit (top), x=0 is the ideal beam orbit. For vertical orbit (bottom), alignment data of magnet center are represented by dashed line. Beam positions are determined by SSEM beam monitors set along the beam line. In this figure, the proton beam is transported from left (Main Ring) to right (the neutrino target).

Acknowledgment

The authors would like to thank to Koh-ichiro Nishikawa at KEK for his strong support for the project. They wish to thank CERN for great help in procurement of a variety of equipments for the superconducting magnet system.

References

[1] Y. Itow *et al.*, "The JHF-Kamioka neutrino project," *hep-ex/0106019*.
[2] M. Furusaka *et al.*, "The joint project for high-intensity proton accelerators," *KEK Report 99-1; JAERI-Tech 99-056; JHF-99-3*, 1999.
[3] T. Ogitsu *et al.*, "Superconducting magnet system at the 50 GeV proton beam line for the J-PARC neutrino experiment," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 604-607, 2004.
[4] Y. Iwamoto *et al.*, "Quench stability against beam-loss in superconducting magnets at the 50 GeV proton beam line for the J-PARC neutrino experiment," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 592-595, 2004.
[5] T. Nakamoto *et al.*, "Design of superconducting combined function magnets at the 50 GeV proton beam line for the J-PARC neutrino experiment," *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 616-619, 2004.
[6] T. Nakamoto *et al.*, "Development of a prototype of superconducting combined function magnet for the 50 GeV proton beam line for the J-PARC neutrino experiment," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 1144-1147, 2005.
[7] T. Nakamoto *et al.*, "Development of superconducting combined function magnets for the proton transport line for the J-PARC neutrino experiment," in *Proc. 2005 Particle Accelerator Conf.*, Knoxville, Tennessee, pp. 495-499, 2005. Available: http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/TOAA006.PDF
[8] K. Sasaki *et al.*, "Test results of superconducting combined function prototype magnets for the J-PARC neutrino beam line," *IEEE Trans. Appl. Supercond.*, vol. 16, no.2, pp. 158-163, 2006.
[9] T. Tomaru et al., "Alignment and warm measurement of the J-PARC combined function magnets," *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 1338-1441, 2006.
[10] K. Sasaki *et al.*, "Test results of superconducting combined function magnets for the J-PARC neutrino beam line," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp 1083 – 1086, 2007.
[11] K. Sasaki *et al.*, "Performance tests of superconducting combined function magnets in the first full-scale prototype cryostat for the J-PARC neutrino beam line," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 1255-1258, 2007.
[12] K. Sasaki *et al.*, "Magnetic field measurement system in superconducting combined function magnets for the J-PARC neutrino beam line," *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 142-145, 2008.
[13] T. Ogitsu *et al.*, "Status of superconducting magnet system for the J-PARC neutrino beam line," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1081-1086, 2009.
[14] T. Okamura *et al.*, "Test results of superconducting magnets for the J-PARC neutrino beam line," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1125-1130, 2009.
[15] N. Kimura *et al.*, "Development of full-scale prototype cryostat of Superconducting magnet system for J-PARC neutrino experiment," in *Proc. Inter. Cryogenic Engineering Conf. 21*, pp. 217 – 220, 2007.
[16] Y. Makida *et al.*, "Cryogenic system for J-PARC neutrino superconducting magnet beam line -design, construction, and performance test-," presented at *Cryogenic Engineering Conference and International Cryogenic Materials Conference*, Tucson, Arizona, June 28-July 2, 2009, *Advances in Cryogenics Engineering*, to be published.
[17] T. Okamura *et al.*, "Cryogenic performance of a superconducting magnet system for the J-PARC neutrino beam line," presented at *Cryogenic Engineering Conference and International Cryogenic Materials Conference*, Tucson, Arizona, June 28-July 2, 2009, *Advances in Cryogenics Engineering*, to be published.
[18] D. Leroy, "Review of the R&D and supply of the LHC superconducting cables," *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 1152-1159, 2006.
[19] J. Brunet *et al.*, "Design of the second series of LHC prototype dipole magnet cryostat," *Advances in Cryogenics Engineering*, vol. 43, pp. 435-441, 1998.
[20] B. Parker, J. Escallier, "Serpentine coil topology for BNL direct wind superconducting magnets," *in Proc. 2005 Particle Accelerator Conf.*, Knoxville, Tennessee, pp. 737-739, 2005. Available: http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/TOAA010.PDF
[21] J. Muratore, "Cryogenic Test Results for the Superconducting Correctors of the J-PARC 50GeV Proton Transport Line," Magnet Division Note 658-45 (AM-MDN-358), BNL, 2008.
[22] A. Jain, "Magnetic Measurements in the Correctors Built at BNL for J-PARC", Magnet Division Note 659-45 (AM-MDN-359), BNL, 2008.
[23] A. Gharib et al., "Cryogenic testing of high current bypass diode stacks for the protection of the superconducting magnets in the LHC," *Advances in Cryogenics Engineering.* vol. 50, pp. 755 -762, 2004.
[24] K. Sasaki *et al.*, "Commissioning results of superconducting magnet system for the neutrino beam line," presented in this conference.