OPERATION OF SUPERCONDUCTING COMBINED FUNCTION MAGNET SYSTEM FOR J-PARC NEUTRINO BEAM LINE

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Abstract

A superconducting magnet system for the J-PARC neutrino beam line was completed at the end of 2008. The system consists of 14 doublet cryostats; each contains 2 combined function magnets (SCFM). The SCFM uses two single layer left/right asymmetric coils that produce a dipole field of 2.6 T and quadrupole of 19 T/m. By 2008, the world first SCFM had been developed and tested successfully at KEK. The mass-production was started in 2005, and completed by summer 2008. The system installation and commissioning took place from Feb. 2008 to Mar. 2009. The beam operation was started in April 2009 and the first neutrino beam was generated on April 23rd. Since then beam operation and commissioning to increase beam intensity has been performed to achieve the near term milestone of 100kW beam operation. The paper briefly summarizes the history of SCFM development and the system construction as an introduction to a discussion on beam operation experience of the SCFM system.

SYSTEM OVERVIEW

The J-PARC neutrino beam line at J-PARC [1] for the T2K experiment [2], the construction of which started in 2004 and was completed in 2008, has been operated since April 2009. The beam line contains a 150 m superconducting primary beam line [3] that transports the 30 GeV proton beam extracted from the J-PARC main ring. It bends the proton beam by 80 degrees to shoot the neutrino beam toward Super-Kamiokande located 295 km west of J-PARC.

Superconducting Magnet System

The configuration of the superconducting magnet system [4] is shown in Fig. 1. The superconducting beam line consists of 28 superconducting combined function magnets (SCFM).The magnet is able to produce a dipole field of 2.6 T and a quadrupole field of 19 T/m for a possible 50 GeV beam operation. Each magnet has a magnetic length of 3.3 m and two of them are placed in a single cryostat. The pair of magnets form an optical doublet; the dipole fields are the same direction, while the quadrupole fields are alternated. In between the doublet cryostats, short cryostats called interconnect cryostats are installed. There are 3 kinds of interconnect cryostat, used to house: 1) quench relief valve, 2) beam monitor, 3) corrector magnet. Five beam monitor interconnects are installed and 4 of them are with beam profile monitor (SSEM) that can be withdrawn depending on the operation mode. The SSEMs are installed at the 1st, 4th, 10th, 13th interconnect position. The phase advance of the beam optics is 90 degree per doublet. The other interconnects are installed as indicated in Fig. 1. At the upstream end of the magnet system, a feed box is installed to connect the system to the normal conducting preparation section. At the downstream end, an end box is installed to connect final focusing section that is also a normal conducting system. A transfer line that connects ground level utilities and the magnet system is connected to the feed box that provides cryogen and magnet current.

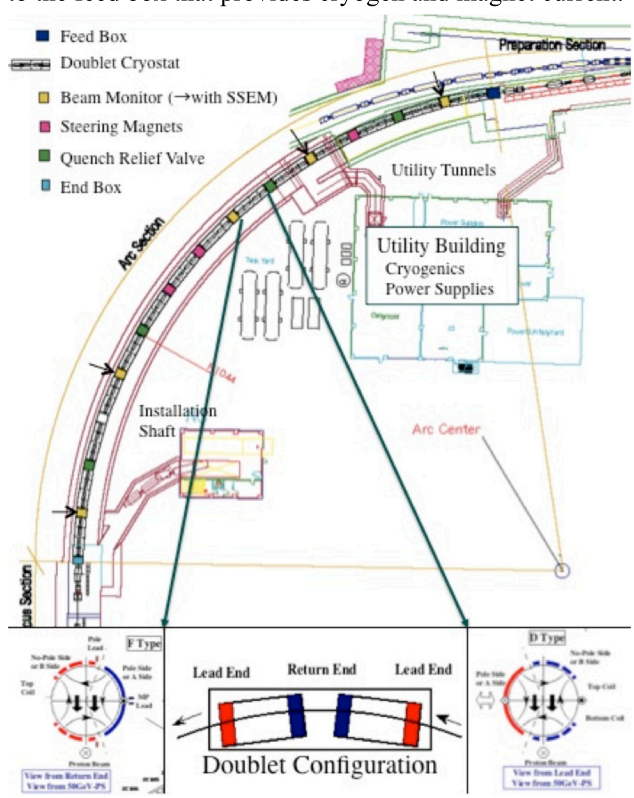

Figure 1: System Configuration. The beam monitors with SSEM are indicated with allows.

Superconducting Combined Function Magnet

The cross section of the magnet is shown in Fig. 2. The main parameters of the SCFM are summarized in Table I. The SCFM uses two single layer left/right asymmetric coils, which approximate a sum of cos(θ) and cos(2θ) current distributions to produce the combined fields [5], [6]. The coil inner diameter is 173.4 mm and the outer diameter is 204 mm. The coil is encased in plastic collars, which are made from glass fiber-filled phenol plastic. The plastic collars provide the ground insulation as well as the alignment with respect to an iron yoke structure. The yoke, made of fixing laminations (5.8 mm thick) and spacer laminations (6 mm thick), is sub-stacked in a pack about 20 cm long. The upper and lower yokes are locked together by steel keys, providing the coil pre-stress of 80 MPa as assembled. Construction of the magnet is completed with a 10 mm thick stainless steel shell, which also serves as the helium vessel. The SCFM cold mass outer diameter is 570 mm, which is the same as the LHC arc dipole magnets, so that a common baseline design of the cryostat can be used.

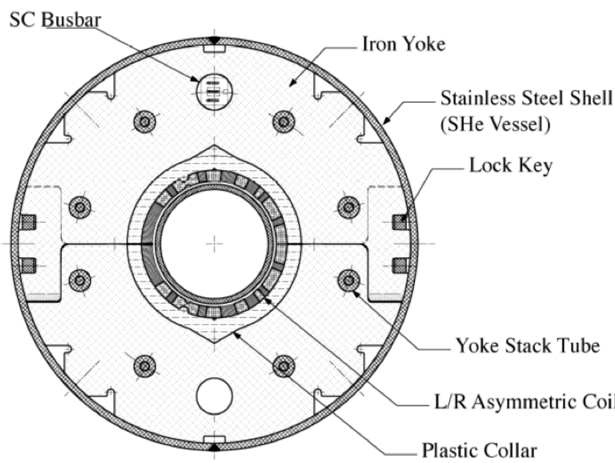

Figure 2: Cross section of the SCFM

Table 1: Magnet Main Parameters

Parameter	Value
Maximum Beam Energy	50 GeV
Dipole Field	2.586 T
Quadrupole Field	18.6 T/m
Magnetic Length	3.3 m
Operating Current	7345 A
Operating Temperature	< 5 K
Load Line Ratio	72 %
Inductance	14 mH
Stored Energy	386 kJ

COMMISSIONING

Hardware Commissioning

The hardware commissioning took place directly after completion of construction of the system in December 2008 [7]. The performance of the cryogenic system was tested first [8]. The refrigerator outperformed the specified refrigeration power of 1.2 kW at 4.5 K and measured 1.5 kW. The magnet system was cooled down in 10 days as expected, and commissioning started in January 2009. The test included the quench of the magnets to confirm the magnet safety. Since the system is planned to be operated with 30 GeV proton beam, the test was performed at around the nominal current of 4400 A that corresponds to 30 GeV operation. The quench protection system was tested in various modes and confirmed the system safety [9]. The cryogenic safety instruments such as the quench relief valves were also tested and confirmed their performance [10]. The recovery time of the cryogenic system after quench was also checked. The expected time of two hours following a normal quench was confirmed.

Beam Commissioning

Commissioning with beam started in April 2009. The first beam came into the superconducting magnet system on April 23rd, and it went through the entire system at the first shot. After 10 iterations of beam tuning, the beam hit the center of the neutrino production target.

Beam studies were performed to check the ratio between the dipole and quadrupole field, as well as SCFM alignment [4][7]. This was done by varying the operation current, with the result being that at about 4350 A, the beam went though the center of the aperture and the beam sizes were most stable. It indicates that the dipole to quadrupole field ratio matches the optics design, and the alignment of the magnets is sufficiently good.

A beam induced quench test was also performed [4]. The SCFM current was changed until the beam actually hit the wall of the SCFM beam tube. This occurred at 4160 A and induced a quench. The beam energy was about 1.8 kJ and the beam loss monitor indicated that about 2/3 of the beam was lost at the quenched magnet location. This indicates that about 1.2 kJ of beam loss is sufficient to cause a magnet to quench.

OPERATION

Magnet and Cryogenics System Operation

The initial beam commissioning continued until June 2009. After this period the magnet system was warmed up to room temperature for summer maintenance. The system resumed operation in the end of September 2009. Since then, the magnets have been kept cold and they will not be warmed up to room temperature until the next summer shutdown in 2010. The cryogenic system was stopped several times for short shutdown or maintenance (about a week or less). During those short shutdowns the magnets warmed up to about 100 K such that re-cooling could be rapid (3 to 4 days) while the volume of helium in the tunnel is small enough for safety. There were two incidents that affected the beam operation, but they were of relatively short duration (1~2 hours). The problem was the bad connection of a temperature sensor in the helium refrigerator that caused the turbine to trip.

Beam Status

During the first year of operation, the beam power was gradually increased up to 70 kW. In Fig. 3 and Fig. 4, the beam center position and beam size at various beam powers are shown. The beam center in the SCFM region is well controlled within the range of plus or minus 1 mm. Beam size is also stable, confirming the good matching of dipole and quadrupole field. The beam size was gradually increased with the increase in beam power. No unexpected quenches occurred during beam operation.

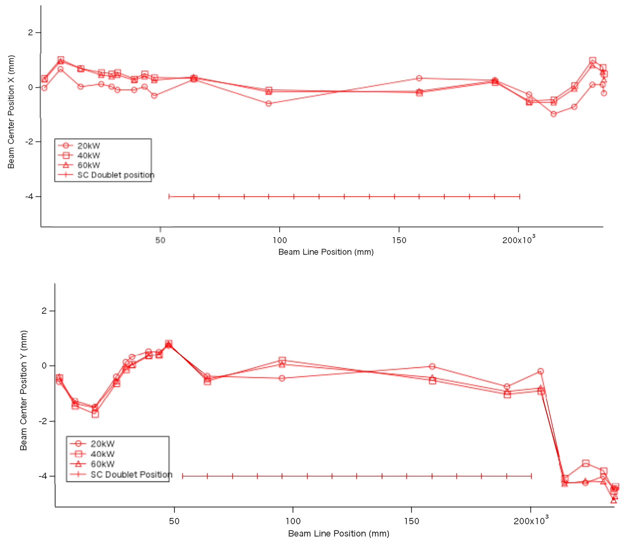

Figure 3: Beam Center Position.The positions of the SCFM doublets are indicated at the bottom of the plots.

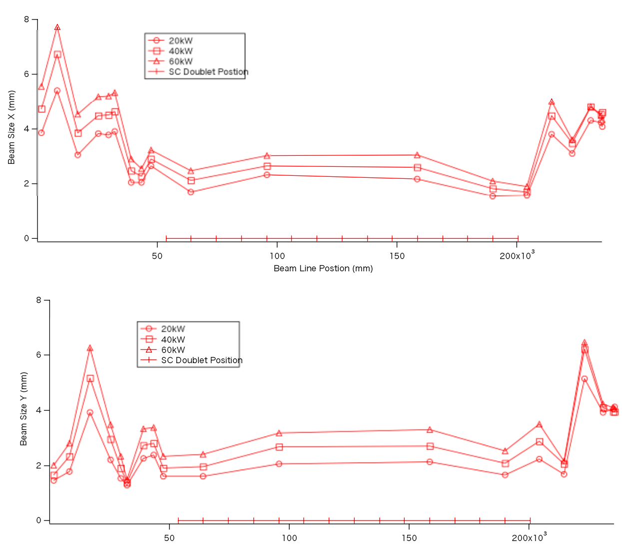

Figure 4: Beam Size.

COMCLUSION

The world's first superconducting combined function magnet system, for the J-PARC neutrino beam line, has been in operation for about one year. There are no major incidents that affect to the beam operation seriously. The system has never experienced any unexpected quenches as well. The beam power is now reached to 70 kW.

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