The Results of the KSTAR Superconducting Coil Test

Y. K. Oh, Y. Chu, S. Lee, S. J. Lee, S. Baek, J. S. Kim, K. W. Cho, H. Yonekawa, Y. Chang, K. R. Park, W. Chung, S. H. Lee, S. H. Park, I. S. Woo, N. Song, K. P. Kim, Y. J. Song, H. Park, Y. M. Park, Y. S. Kim, S. W. Kwag, Y. J. Lee, H. S. Chang, M. K. Kim, K. Kim, J. S. Bak, G. S. Lee, and the KSTAR Team

Korea Basic Science Institute, Daejeon, Republic of Korea

e-mail contact of main author: ykoh@kbsi.re.kr

Abstract. The KSTAR device is under assembling phase using the fully superconducting (SC) magnet system. Several TF coils and PF coils have been finished in fabrication and are ready for assembly. To test the KSTAR superconductors and coils, a test facility has been constructed in KBSI. A real-sized prototype TF coil has been assembled and tested in the test facility from 2002 to 2003. The results showed the test facility operated reliably and the coil was fabricated to meet the design requirements. To test superconductor in high field background environment, a background coil system has been designed and fabricated by 2002. The background main was made using the same conductor and the same manufacturing technology as those of the KSTAR CS coils. The background main coil was installed in the test facility and cooled down. The coils will be tested under the dc and ac current environments to verify the operational characteristics of the KSTAR CS coils by the end of 2004. In this paper, the experimental results of the prototype TF coil test and the status of the background main coil test are presented

1. Introduction

The Korea Superconducting Tokamak Advanced Research (KSTAR) device is under fabrication and assembling status [1]. The device has fully superconducting (SC) magnets including sixteen toroidal field (TF) coils, four pairs of central soldenoid (CS), and three pairs of poloidal field (PF) coils. By the October 2004, 5 TF coils and 4 PF coils has been finished in fabrication [2]. Most of the SC coils in KSTAR are manufactured with continuous winding scheme without any internal joints to minimize the heat loss in joints. All TF coils, CS coils (PF1-4) and a pair of PF coil (PF5) are made of Nb3Sn superconductor. Large PF coils (PF6-7) are made of NbTi superconductor [3]. The fabrication procedure of the SC coils are (i) superconductor cabling and jacketing to produce cable-in conduit conductor (CICC), (ii) continuous winding, (iii) heat treatment for Nb3Sn superconductor, (iv) insulation taping and vacuum pressure impregnation (VPI), and (v) final treatment and acceptance test.

To verify the design and manufacturing engineering and to ensure the reliable operation after assembly, the test of the SC coil fabricated with similar size and same technologies are important. To test the SC conductors and coils, a SC magnet test facility has been constructed in KBSI. To test the SC conductor under the axial or transverse magnetic field density of about 8 T and under the field variation rate of about 20 T/s, a background magnet system has been designed and each components of the system was fabricated. A real-sized prototype TF coil has been tested in the facility to verify the KSTAR TF coil engineering. The background main coil was fabricated with same conductor as that of KSTAR CS coil. The test of the background main coil was going on to verify the KSTAR CS coil engineering.

2. SC Magnet Test Facility

A SC magnet test facility has been constructed in KBSI to test superconductors and SC coils [4]. The facility consists of a vacuum cryostat, cryogenic helium facilities, power supplies, and a monitoring system. The vacuum cryostat has dimensions of 6 m in diameter and 8 m in height and a thermal shield cooled with liquid nitrogen is installed inside the cryostat. There is a vacuum pumping system consists of diffusion pump and mechanical pumps.

The cryogenic helium facility consists of a set of 1-kW rated helium refrigerator/liquefier was used to supply supercritical helium for coil cooling and to supply liquid helium for the current lead cooling. To control the liquid helium flow rate, a cryogenic control valve installed at the outlet of the 300-liter liquid helium dewar and a pair of gas flow control valves on downstream of the current lead outlets are used.

To test a prototype TF coil, a real TF power supply for the KSTAR device was used. The power supply is a pulse width modulation (PWM) type inverter power supply with ratings of 25 V and 40 kA. For the pulse coil test, a bipolar power supply was used. The power supply is inverter typed power supply consists of flat power supply and ramp power supply connected in series with ratings of 1 kV and 20 kA.

A quench detection and protection system was prepared to protect SC coils from quench. For the quench detection, balanced bridge type quench detection system was connected with voltage taps on the coil and SC buslines. There were additional quench detection system was prepared using helium flow rate monitoring, acoustic emission, and pick up coils. A quench protection system was installed in each power supply cabinet and connected in series with the coil. The resistance of the quench protection system to dump the stored energy in the coil was set with decay time constants of about 2 sec in TF coil test and about 3 sec in background coil test.

To monitor the SC coil and environments during test, a monitoring system has been prepared. There are two types of A/D input modules to measure the analog inputs from the temperature sensors, pressure transducers, orifice flow meters, and magnetic hall sensors. One type of A/D modules is PCI bus type A/D module from National Instruments and the other is VME bus type. Beside analog input, several data communication of each monitoring systems communicate through digital to network conversion units. The basic communication software for the monitoring is the Experimental Physics and Industrial Control System (EPICS). The GUI programs were developed through x-window programming. These programs can be also

TABLE I. Major parameters of the TF00 coil

Parameters	Values
Superconductor / conduit	Nb_3Sn / Incoloy 908
Strand diameter	0.78 mm after chrome plating
Cu to non-Cu ratio of SC strands	1.5
Number of strands	486 (SC 324, Cu 162)
Cabling pattern	3 x 3 x 3 x 3 x 6
Conduit dimension	25.65 mm(h) x 25.65 mm(w) x 2.86 mm (t)
Void fraction of the conductor	about 32 %
Number of windings	56 turns (8 pancakes and 7 turns per pancake)
Number of cooling channels	4
CICC length of a coil	about 610 m
Turn insulation thickness	0.81 mm (S2 glass and Kapton tape)
Ground wrap thickness	5.6 mm (S2 glass)
Self inductance of a coil	19.8 mH
Stored energy	12.3 MJ at 35.2 kA

used for the quasi-real-time monitoring of the data through the continuous access of the database. During coil cool-down and stand-by phase, the data acquisition (DAQ) was set into slow DAQ mode in which the sampling rate is about 1 Hz and the archiving rate is about 0.02 Hz. During current charging experiments, fast DAQ mode is operated with sampling and archiving rate of about 100 Hz.

3. Prototype TF Coil Test

A. Coil Test Preparation

A prototype TF coil, named TF00 coil, has been fabricated with same D-shape and dimension as the real TF coils. The major parameters of the coil are listed in Table I. The picture of the coil after vacuum pressure impregnation is shown in Figure 1. The heat treatment of the coil has been conducted in a vacuum furnace with controlling of the oxygen contents below 0.1 ppm to avoid SAGBO in Incoloy 908 conduit. Any explicit SAGBO defect was not found after heat treatment of the TF00 coil.

The TF00 coil was assembled in a supporting structure. The structure consists of two D-shaped plates attached on each side of the coil, inner and outer shell plates that are segmented along the coil perimeter, and connection bolts. The weight of the coil and structure were about 3 ton and 7 ton, respectively.

The coil was installed in the vacuum cryostat as shown in Figure 2. To support the coil in vertical direction, eight supporting rods in horizontal direction and three supporting legs on bottom of the coil were connected between the coil and the cryostat. A current feeder system to supply current into coil consists of a pair of vapor-cooled current lead with rating of 50 kA, a pair of SC busline, and intermediate joints. The SC busline was made of NbTi SC CICC, and the jackets of the busline were replaced with flexible bellows on both ends to give easiness installation of the SC busline with SC coil joints. There were four pairs of joint in the buslines, which were a pair of strand-to-strand (STS) joint on the coil termination and three pairs of lap joints. The STS joint was the soldering-type joint to connect Nb3Sn strands from the coil with NbTi strand from the buslines.

To isolate the helium lines and utilities from coil potential high voltage electric breakers were installed on helium lines of the the coil and of the SC buslines. The specifications of the breakers were isolation voltage of 15 kV at 4.2 K and operating pressure of 20 bar without helium leak. To measure the coil quench, voltage tap signal wires were connected on each helium stubs on coils and both terminal joints.

FIG. 1. TF00 coil after final vacuum pressure impregnation (VPI)

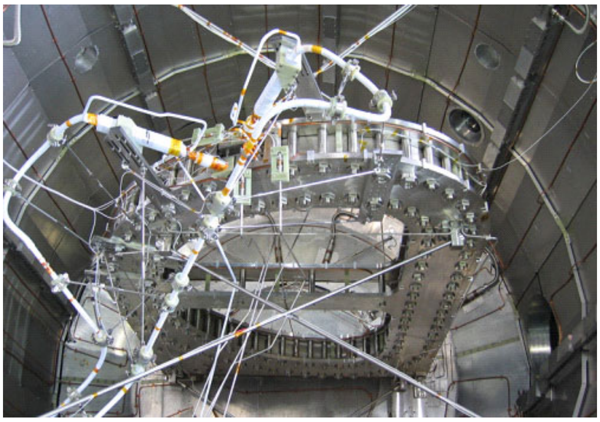

FIG.. 2. TF00 coil installed in a vacuum cryostat

B. Cool-down Results

The TF00 coil was cooled down to operating temperature twice [5]. The first cool-down was conducted on Jan. 2003 and the second cool-down on Aug. 2003. After the coil installation in the vacuum cryostat, final inspection was done such as the electric isolation check and helium leak check at room temperature. The cryostat was evacuated and the coil and all the helium lines were purged to remove the residual impurities. After filling liquid nitrogen into the thermal shield in the cryostat, the coil and structures were cooled down keeping the temperature difference between supply and return lines within 50 K. The coil cool-down periods were 15 days in the first cool-down and 10 days in the second cool-down. Figure 3 shows the temperature changes of the coil during the second cool-down period.
The residual resistance ratio (RRR) of the coil was measured to be over 200, which satisfies the required value at the KSTAR design. The superconducting phase transition of the coil was detected at about 18 K. Helium leak from the coil in the cryostat was not detected at the coil operating temperature below 10 K, system pressure about 6 bar, and vacuum pressure about 2.0×10^{-7} torr. When the coil was fully cooled, the helium flow of the coil was about 15 g/s in total with the pressure drop in the coil of about 2.2 bar and the helium flow unbalance between four channels was within 10 %.

C. Current Charging Results

After TF power supply and quench detection system adjustment within 5 kA, coil current, the coil was repeatedly ramped up in steps with various ramping rate and followed by various discharges such as slow discharge, safety discharge, and quench discharge. By the slow discharge, there was no remarkable temperature rise in coil and structure. When the current discharged by dump resister, the temperature of the structure outlet increased due to eddy current heating on structure. The temperature variation on the helium lines of the coil and structure during the current ramping and fast discharge at 27 kA is shown in Figure 4. The temperature risings of the coil and the structure by the fast discharge were measured to be about 3 K and 18 K, respectively. About 3.5 % of the stored magnetic energy was dissipated by the coil and structure. The current test of the TF00 coil was stopped at 33.3 kA due to the mechanical deformation and electric insulation failure in the current feeder system.

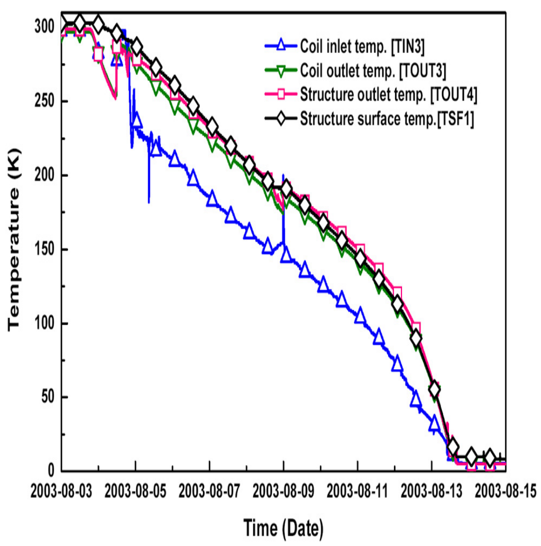

FIG. 3. The temperatures of the helium lines during the TF00 coil cool down

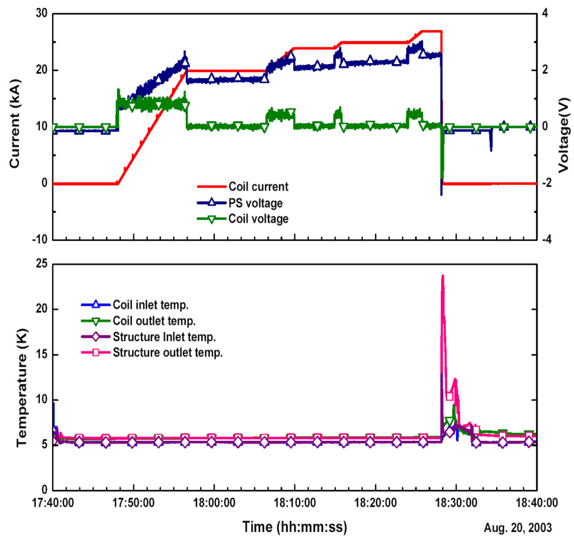

FIG. 4. Current ramping and fast discharge experiments of the TF00 coil

4. Background Main Coil Test

A. Coil Test Preparation

To test of the superconductor and joint at the field intensity about 8 T and field variation up to 20 T/s, a background magnet system has been designed and each components of the system has been fabricated [6]. The magnet system consists of a pair of main coil, a pair of blip coil, a pair of passive cancellation coils, a SC transformer, and test CICC sample [7]. The main coil was fabricated with the same conductor as that of KSTAR CS coil. The operating current and field intensity of the background main coil is similar to those of the KSTAR CS coil. So, the background main coil test could be regarded as the KSTAR CS model coil test. Major design specifications of the main coil are shown in Table II.

A pair of the background main was installed in the vacuum cryostat without blip coils. The schematic layout of the coil system for the test is shown in Figure 5. The structure of the coil was made of GFRP plates to reduce eddy current heating under the pulse current operation. The coil and structure has been assembled and installed on July 2004 as shown in Figure 6.

The current leads are vapor cooled current lead with rating of 20 kA. The SC busline was made of NbTi SC CICC, which was same conductor as that of KSTAR PF coils. The busline has U-bending zone to compensate the busline length variation and the coil movement by cool-down. All the joints were lap joints. An intermediate busline with joints was installed between terminals of the coil to connect the coils in series. To support the busline near the coil, an additional busline supporter was installed. To isolate the coil electrically from the helium lines, 22 electric breakers were installed. Because the GFRP type electric breakers, which were installed first, have leaks when cooled down, ceramic type electric breaker was used instead.

Sensors installed in the helium supply and return lines were Cernox temperature sensors, pressure transducers, and orifice-type flowmeters to monitor the thermo-hydraulic parameters during cool-down and current charging. Sensors on the coil surface and on structures were temperature sensors, hall sensors, and strain gauges. To cancel the temperature and magnetic field effect on the strain gauges, two kinds of cancellation methods were adopted in this test.

TABLE II. Major parameters of the Background Main coil

Parameters	Values
Superconductor / conduit	Nb_3Sn / Incoloy 908
Strand diameter	0.78 mm after chrome plating
Cu to non-Cu ratio of SC strands	1.5
Number of strands	360 (SC 240, Cu 120)
Conduit dimension	22.3 mm(h) x 22.3 mm(w) x 2.41 mm (t)
Number of windings	240 turns per coil (16 pancakes and 15 turns per pancake)
Number of cooling channels	8 per coil
CICC length	~ 840 m per coil
Number of coils	2
Coil dimensions	I.D. 740 mm, O.D. 1488 mm, H. 398 mm
Nominal gap between coils	240 mm (variable)
Inductance of a coil	~ 135 mH (two coil connected in series)
Peak field on conductor	9.75 T at 22.6 kA
Central magnetic field	8.0 T at 22.6 kA
Designed central field ramp rate	± 3.0 T/s
Main axis of coil installation	horizontal or vertical

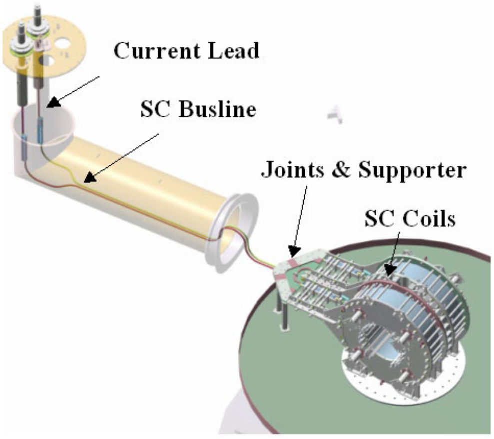

FIG. 5. Schematics of the Background main coil test layout

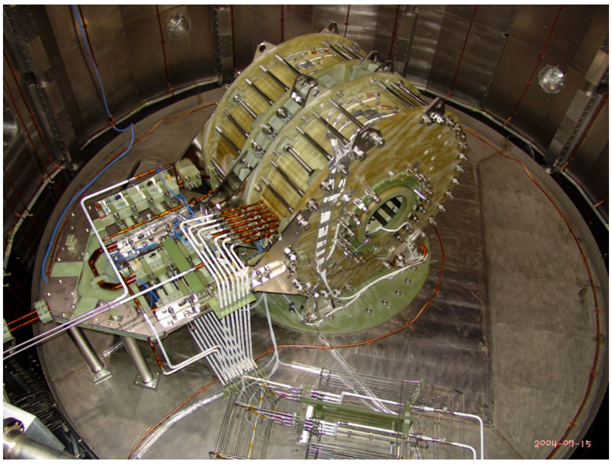

FIG. 6. Background main coil installed in the vacuum cryostat

One of the methods was active-active cancellation method and the other method is active-dummy cancellation method. For the active-dummy cancellation, GFRP dummy mounting was attached on the coil surface and over wrapped with metal tapes for thermal conduction.
As a quench detection sensor, the capillary type internal co-wound voltage taps had been installed inside CICC during fabrication, but the insulation failure of the voltage taps was found after the coil heat treatment. So the quench detection system of the background main coil was changed to external voltage taps and balanced-bridge type quench detectors. To compare the operational performance other types of quench detection system was prepared including helium flowmeter monitoring on helium inlet lines, pick up coil on both sides of the coil, acoustic emission sensors on coil structure and the busline supporter.

B. Cool-down Results

After installation of the coil system, SC buslines, helium lines and sensors, the system was evacuated and leak check was conducted at room temperature. The configuration of the helium supply system for the background coil test was different from that of the TF00 coil test. In the TF00 coil test, 1-kW Linde helium refrigerator system supplied supercritical helium into coil and additional PSI liquefier supply the liquid helium into current leads. But in the background coil test, the Linde refrigerator was used to supply supercritical helium to coil and liquid helium to current lead simultaneously.

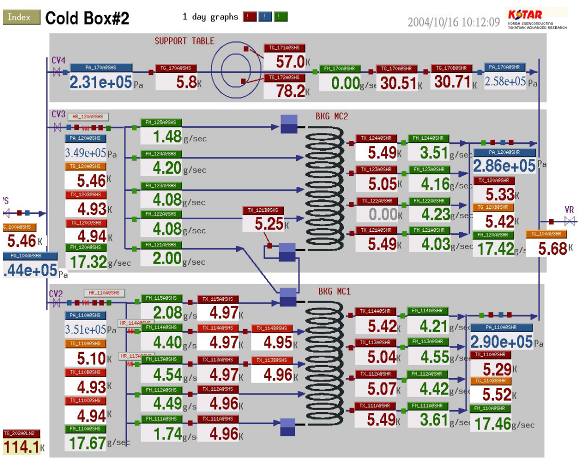

FIG. 7. Sensors on the helium lines of the coil after cool-down

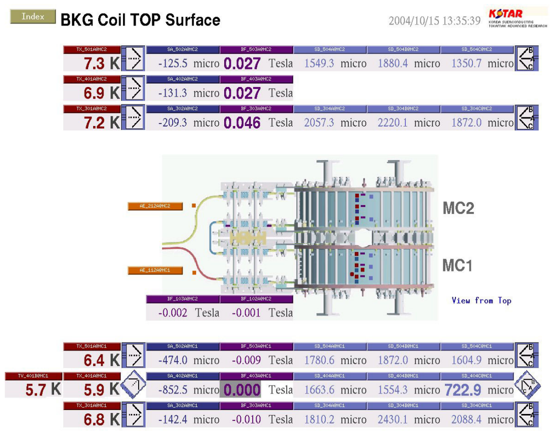

FIG. 8. Sensors on the coil surface of the coil after cool-down

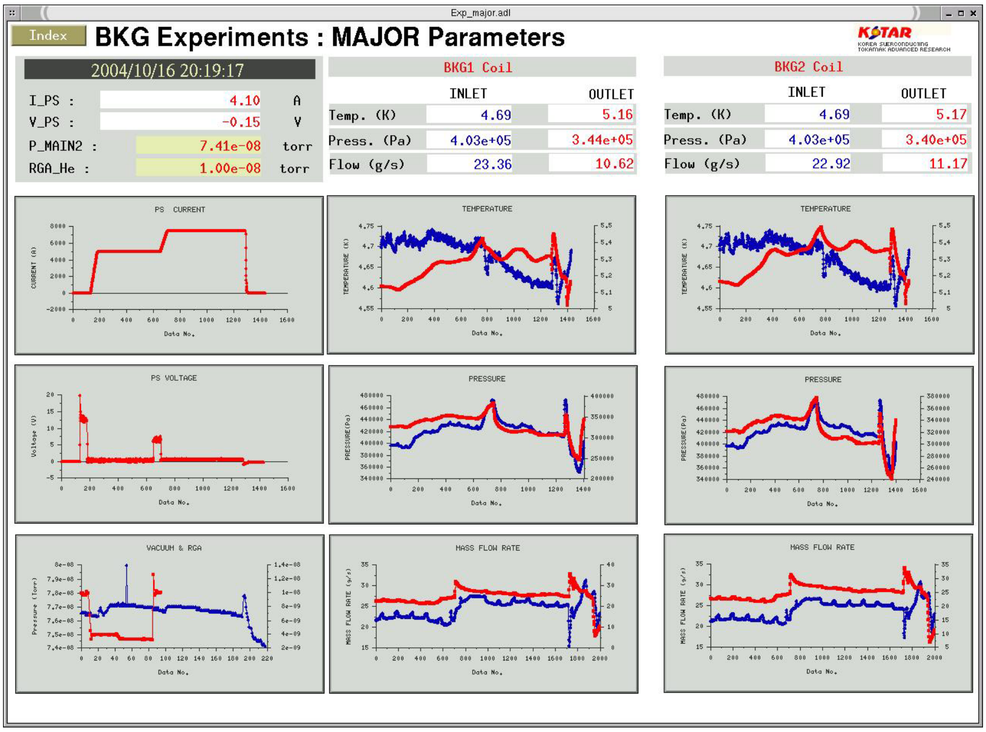

FIG. 9. Major coil parameters monitoring during the current charging

When the coil was cooled down to 50 K at first time, large amount of helium leak was found in GFRP type electric breakers and internal temperature sensor mountings to install sensors inside helium lines. After warm-up the system, all electric breakers were replaced with ceramic-type breakers and all the temperature sensor mountings were replaced with external mounting type.

In second cool-down the coil temperature reached below 5 K in 9 days. The RRR value during cool down was over 200. The sensor on helium lines showed reliable with 0.02 K deviations, the flow rate also uniform between channels as shown in Figure 7. The strain gauges showed reason trend during cool-down. The Figure 8 shows the sensors on the coil surfaces including the temperature tensors, hall sensors, and strain gauges.

C. Current Charging Results

When the coil and current lead were cooled down enough, the TF power supply was connected with current leads. According to the current charge and discharge, the helium parameters and the strain gauges on the coil surface were monitored. Figure 9 is one of the monitoring programs during the current charging. When the current charged, the temperature rising in the joint was found more than expectation value. And the flow through the joint was decreased compared to other flow channels without joint.

5. Conclusions and Future Plan

To verify the KSTAR SC coil design and engineering issues in fabrication, the SC coil test facility has been constructed. In the test facility, a prototype TF coil has been tested by 2003 and a background coil test are going on as a function of the KSTAR CS model coil. The results of the TF00 coil test showed the test facility operated reliably and the coil was fabricated to meet the design requirements. The background coil test will be finished by the end of 2004. In 2005, SC coil engineering test are planned including the cool-down tests of the KSTAR TF coils and CS coil joint test. In future the coil test will be upgraded for the conductor test under the high field and high field variation environment.

Acknowledgement

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