COOL-DOWN AND CURRENT TEST RESULTS OF THE KSTAR PROTOTYPE TF COIL

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ABSTRACT

A prototype toroidal field (TF) coil, TF00 coil, of the Korea Superconducting Tokamak Advanced Research (KSTAR) project has been assembled and tested at the coil test facility in Korea Basic Science Institute (KBSI). The TF00 coil is a real-sized TF coil made of Nb_3Sn superconducting cable-in-conduit conductor (CICC). The coil test was conducted by several campaigns according to the objectives. The first campaign, which was carried out by Jan. 2003, has objectives of cooling the coil into operating temperature and finding any defect in the coil such as cold leaks. From the results of the first campaign experiment, any defect in the coil was not found. The second campaign, which was carried out by Aug. 2003, has objectives to get the operating characteristics according to the current ramp up and discharge operations. In this paper, the coil test results are introduced as well as the details of the coil test system setup.

INTRODUCTION

The Korea Superconducting Tokamak Advanced Research (KSTAR) device has fully superconducting (SC) magnets including toroidal field (TF) coils, central soldenoid (CS), and poloidal field (PF) coils [1]. The TF coil system consists of 16 winding packs, which are connected electrically in series, and surrounded with magnet structures, which are electrically isolated in the toroidal direction [2][3]. When the TF coil is operated at 35.2 kA of nominal current, the toroidal field at plasma center is about 3.5 T and the stored magnetic energy is about 0.5 GJ. A SC coil test facility has been prepared in Korea Basic

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Science Institute (KBSI). The test facility consists of a vacuum cryostat, several helium refrigeration systems, a power supply, and a data acquisition system. A prototype TF coil, named TF00 coil, has been fabricated to confirm the manufacturing feasibility and operating performance [4]. The TF00 coil test was conducted by several campaigns according to the objectives. The major objectives of the first campaign were to achieve the coil cool-down and to validate the engineering issues in the coil design and fabrication. The major engineering issues were the possibility of the stress-accelerated grain boundary oxidation (SAGBO) occurrence at Incoloy 908 conduit during heat treatment [5] and hydraulic characteristics of the coil such as flow unbalance between helium flow channels due to adopting the continuous winding scheme [6]. The major objective of the second campaign was the current ramping up and discharge operations.

PROTOTYPE TF COIL ASSEMBLY FOR TEST

Prototype TF Coil

A prototype TF coil has been fabricated with same D-shape and dimension as the real TF coils. It was made of Nb_3Sn superconducting cable-in-conduit conductor (CICC). The major parameters of the coil are listed in TABLE 1. 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.

Coil Assembly Installation in a Vacuum Cryostat

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. Teflon sheets were inserted between the coil and structure. The coil assembly was installed in the cryostat as shown in FIGURE 2. To support the coil in vertical direction, eight supporting rods, which connect the coil with the cryostat, were installed. High-voltage electric breakers using a glass fiber

TABLE 1. 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 6
Conduit dimension	25.65 mm(h) x 25.65 mm(w) x 2.86 mm (t)
Void fraction of the conductor	about 32 % (designed value 36 % considering cable twisting, voltage taps)
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

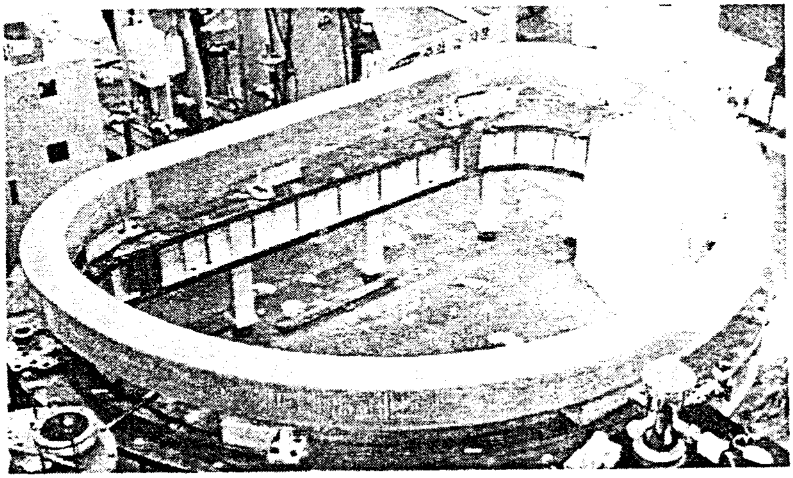

FIGURE 1. TF00 coil after final vacuum pressure impregnation

reinforced plastic (GFRP) tube were installed on each helium line connected with the coil for electric isolation of the coil. To monitor the operating status of the coil, various kinds of cryogenic sensors were installed on the surfaces of the coil and the structure including the temperature sensors, strain gauges, and hall sensors. To monitor the thermo-hydraulic behavior of the coil, temperature sensors, pressure sensors, orifice-type flow meters were installed also on the helium lines.

Current Feeder System

A current feeder system is to deliver the current from the power supply to the coil. It consists of a pair of current leads, a pair of SC bus lines, and several kinds of joints [7]. For the TF00 coil test, vapor-cooled type current leads were used with a rating of 50 kA. The estimated liquid helium consumption rate for a pair of the current leads are about 3 g/s at

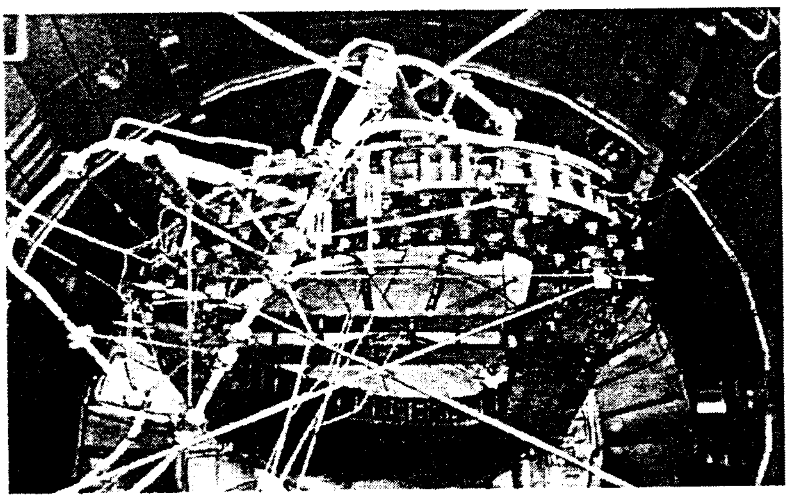

FIGURE 2. TF00 coil installed in a vacuum cryostat

zero current condition, and about 5 g/s at full current operation of 50 kA. The SC bus line conductor was fabricated using the CICC having the same size with the TF coil CICC. But the bus line uses NbTi strands and SS316LN conduit while the TF coil uses Nb_3Sn strands and Incoloy 908 conduit. To give assembly easiness of the bus lines, conduit on both ends of the bus lines were replaced with flexible jackets. There are four pairs of joint in the bus lines, which are a pair of strand-to-strand (STS) joint on the coil termination and three pairs of lap joints. The STS joint is soldering-type joint after overlapping the Nb_3Sn strands from the coil and NbTi strands from the bus line.

Cryogenic Helium Facility

A set of 1-kW rated helium refrigerator was used to supply supercritical helium to the TF00 coil and structure. The major restriction during the coil cooling was keeping the temperature difference between supply and return lines within 50 K. The cold mass of the coil and the structure are about 3 ton and 7 ton, respectively. The helium supply line of the coil was divided into three paths in the distribution box. When the quench occurs in the coil, the helium refrigeration system could be isolated from the coil by closing the isolation valves. Safety valves were also installed on helium lines for the pressure release in case of the coil quench. Two sets of helium liquefiers and a liquid helium dewar were used for the current lead cooling. The capacity of the liquefier is about 120 L/hr in total. The liquid helium flow control was done by pressuring the dewar and by controlling the valves on liquid helium supply lines and warm gas return lines.

Power Supply and Quench Protection System

In the TF00 coil test, 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. A quench protection system was installed in the power supply cabinet and connected in series with the coil. The resistance of the quench protection system was adjusted to 10 mohm to discharge the coil current with time constant of 2 sec. A quench detection system for the coil test consists of four units of quench detectors and a main quench decision unit [8]. The quench detectors continuously monitor the balanced voltages of the coil and generate a quench alarm signal in case the balanced voltage exceeds the

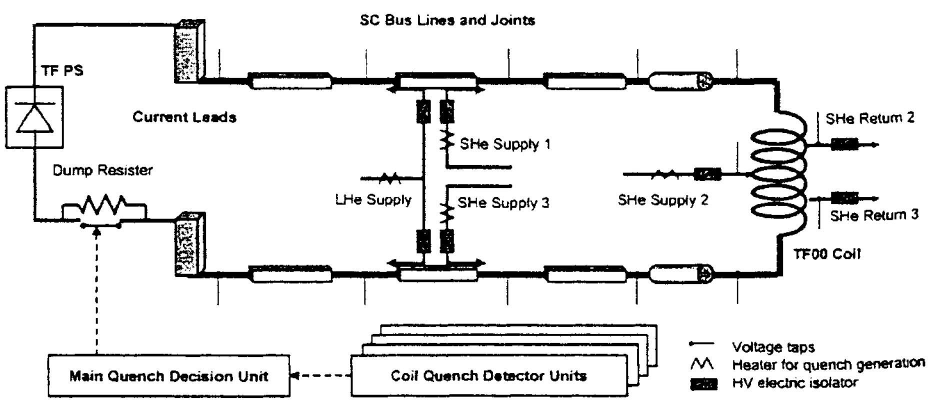

FIGURE 3. Schematics of the quench detection and voltage tap locations in current feeder system

threshold value for a given period. A main quench decision unit can judge the quench according to the alarm signals from the quench detector units and send quench signal to power supply and to the helium refrigerator. FIGURE 3 shows the voltage tap distribution for the quench detection in the TF00 coil and current feeder system.

Data Acquisition System

Most of monitoring instruments of the coil test were integrated in the control room. Most of data are monitored and archived in every one second. The Experimental Physics and Industrial Control System (EPICS) is the basic communication software for the monitoring. In order for users to monitor their equipment data more easily, some GUI programs were developed through Labview and x-window programming. These programs can be also used for the quasi-real-time monitoring of the data through the continuous access of the database.

EXPERIMENTAL RESULTS

System Cool-down

The TF00 coil was cooled down to operating temperature twice. 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 with a diffusion pump and achieved vacuum pressure was about 4.0×10^{-6} torr at room temperature. 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 has been cooled down within the specified temperature difference. The coil cool-down periods were 15 days in the first cool-down and 10 days in the second cool-down. FIGURE 4 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

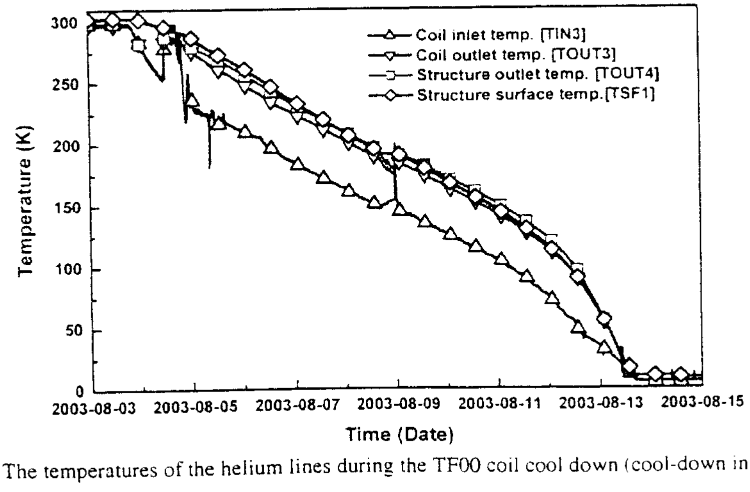

FIGURE 4. The temperatures of the helium lines during the TF00 coil cool down (cool-down in 10 days)

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, supercritical helium was supplied into the coil by controlling the valves in the helium refrigerator. The temperature and pressure of the helium supply lines were about 5.0 K and 5.3 bar, respectively. The helium flow rate of the coil was about 15 g/s in total with the pressure drop in the coil of about 2.2 bar. Helium flow unbalance between four channels in the coil was within 10 %.

Current Test

The current ramp up and discharge test of the coil were carried out 23 times. Prior to the high current test, low current test was conducted within 5 kA for the power supply adjustment and for the quench detection and protection system commissioning. After the adjustment of the TF power supply controller, the power supply operated reliable without remarkable current overshooting up to 80 A/s ramping rate. The quench detection and protection system commissioning was conducted with artificial quench generation in the coil by heating the helium supply lines. 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.

FIGURE 5 shows the result of helium temperature variation of the coil and structure during the coil current ramping in steps and slow discharge at 29 kA. The temperature fluctuations were negligible. FIGURE 6 shows the result of the current charge and fast discharge at 27 kA. The current was discharged through the dump resister with a discharge time constant of about 2 sec. The temperature risings of the coil and the structure by the fast discharge were measured to be about 3 K and 18 K, respectively. They were mainly from the induced eddy current heating of the structure. About 3.5 % of the stored magnetic energy was dissipated by the coil and structure. FIGURE 7 shows the details of the

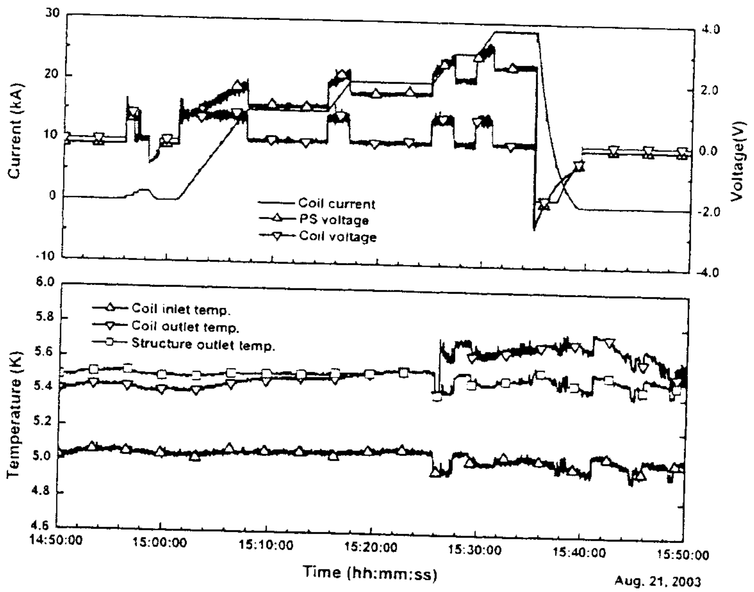

FIGURE 5. Current ramping up and slow discharge scenario (Temperature fluctuations were negligible.)

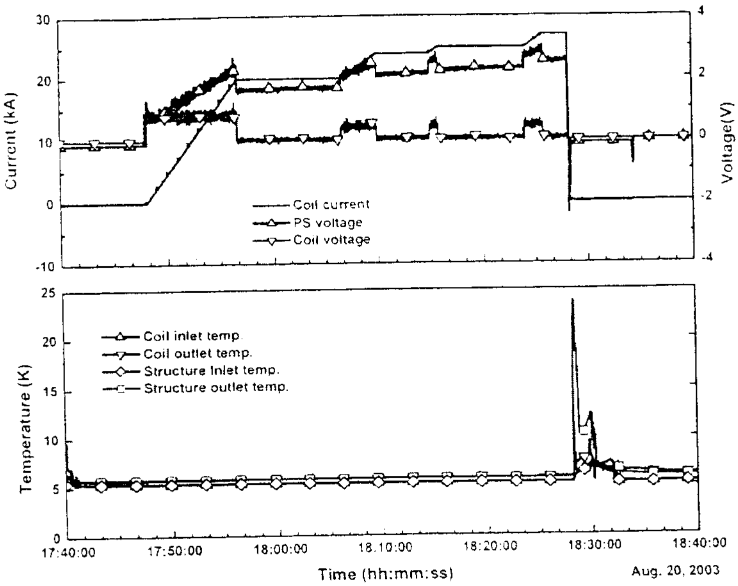

FIGURE 6. Current ramping up and fast discharge scenario (Discharge time constant was about 2 sec.)

temperature, pressure, and flow rate variation during fast discharge. The helium flow in the coil inlet line shows the flow reversal due to the thermal expansion of the helium inside the coil. The coil was operated well without any quench over 30 kA. The current test was stopped at 33.3 kA due to the mechanical deformation and electric insulation failure in the current feeder system.

CONCLUSION

The prototype KSTAR TF coil has been tested in the coil test facility. Remarkable result of the first campaign experiment was the successful coil cool-down without any helium leak at operating temperature. Helium flow into four cooling channels was uniform in spite of the continuous winding scheme. The current tests were carried out during the second campaign. The operating characteristics were observed according to the various current ramping up and discharge experiments such as slow discharge and fast discharge. The coil was charged over 30 kA in steady state without quench. The results of the repeated current charge tests show that the prototype TF coil was fabricated well without any severe defect such as cold leak. Any mechanical deformation or defect in the coil structure was not found although the structural analysis showed the mechanical weakness in some location. The TF power supply, the quench detection system, and quench protection system were also operated well with reliability.

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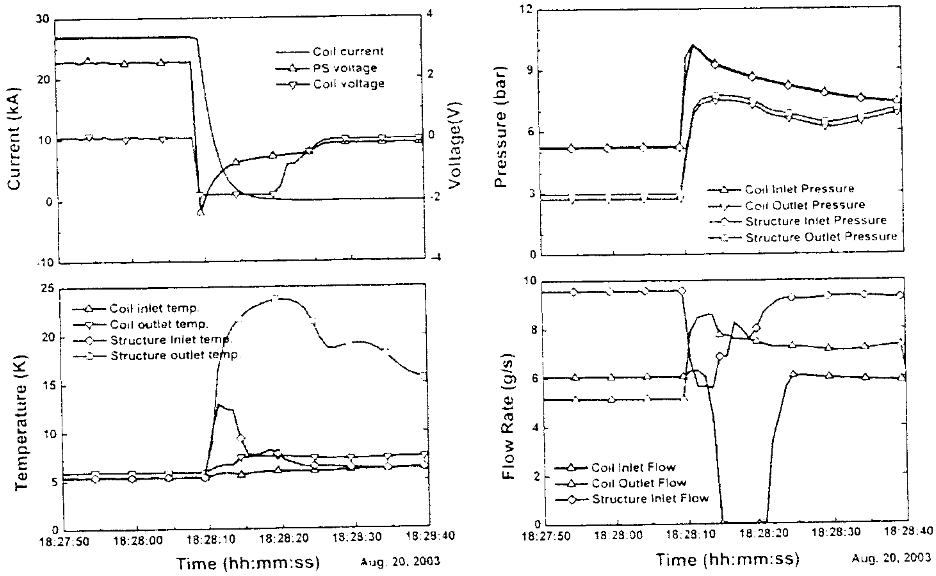

FIGURE 7. Temperature, pressure, and flow variation during the fast discharge (Temperature of the structure was increased by eddy current heating. Flow reversal was found at the coil inlet flow.)

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