# Development Progress of the KSTAR Superconducting Magnet and Magnet Interfaces

Y. M. Park, Y. J. Lee, S. W. Kwag, Y. B. Chang, C. S. Kim, K. S. Lee, N. H. Song, E. N. Bang, H. L. Yang, Y. S. Kim, K. R. Park, B. S. Lim, C. H. Choi, Y. K. Oh, J. S. Bak, and the KSTAR Members

## National Fusion Research Center, Daejeon, Korea e-mail contact of main author: ympark@nfrc.re.kr

**Abstract.** There has been remarkable development progress on the KSTAR superconducting (SC) magnet and the interface systems including a cryogenic interface system and a current feeder system (CFS) which are required for SC magnet operation. All SC coils required for the KSTAR have been completed in fabrication and are under assembly on site. For the toroidal field (TF) coils, 18 coils have been fabricated, including 16 coils for installation, a prototype coil (TF00) for the performance test and a spare coil (TF17). Three pairs of poloidal field (PF) coils and 4 pairs of central solenoid (CS) coils have also been fabricated. As the cryogenic interface, a helium refrigeration system (HRS) with a cooling capacity of 9 kW at 4.5 K is under fabrication by Samsung Corporation and Air Liquide in France. The installation and current leads. SC buslines made of NbTi cable-in-conduit conductor are under assembly with joint connections and surface insulation. Two pairs of prototype leads for PF and TF coils have been fabricated and tested up to the current levels of 26 kA for PF leads and 35 kA for TF leads. Those values are two times higher than optimum design values. Two current lead boxes and vacuum pumping system have been fabricated and 9 pairs of leads with a helium flow control system for the first plasma experiments will be fabricated and assembled by February, 2007.

## 1. Introduction

The Korea Superconducting Tokamak Advanced Research (KSTAR) tokamak is under construction at the National Fusion Research Center (NFRC) in Daejeon, Korea with the mission of developing a steady-state capable advanced superconducting tokamak to establish the scientific and technological bases for an attractive fusion reactor [1]. The device has fully superconducting (SC) magnets including sixteen toroidal field (TF) coils, four pairs of central solenoid (CS) coils, and three pairs of poloidal field (PF) coils. Most of the SC coils in KSTAR are manufactured with a continuous winding scheme without any internal joints to minimize the heat loss in the 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 [2][3]. The KSTAR cold components that are to be cooled down to cryogenic temperature consist of the SC coils, coil structures, thermal shields, and current feeder system. The main function of the KSTAR helium refrigeration system (HRS) is to cool the various structural components and to remove the generated heat during the various modes of operation of the

tokamak machine [4]. Based on the KSTAR requirement, the engineering design of the 9-kW HRS was completed and is being fabricated by Air Liquide in France.

After the design change of current feeder system (CFS) from the basic engineering design [5], current leads and current lead boxes (CLBs) were located bellow the tokamak device and are connected to SC coils with cable-in-conduit conductor (CICC) type SC busline. The CFS for TF coils and that for PF coils are separated because they are operated with different operating scenarios and with different electrical potentials. To isolate the vacuum of the busline from that of the tokamak cryostat, vacuum isolating sections are located at the cryostat boundary. The CFS is being manufactured according to the design works such as structural analysis, mock-up fabrication tests, and detailed drawings.

### 2. KSTAR Superconducting Magnet

A total of 18 toroidal field (TF) coils have been fabricated including 16 coils for site assembly, a prototype coil (TF00) for the performance test, and one another spare coil (TF17). The fabrication of 3 pairs of PF coils and 4 pairs of CS coils were also completed. The fabrication of the SC coils started in 2002 and was finished in September 2006. Twenty six of the coils were made of Nb3Sn conductor and passed the heat treatment process successfully without any noticeable defect. After the encasement of the 16 TF coils into their structures, all of the TF magnets were assembled on site. Also, 5 PF coils, except PF5U which will be assembled in October 2006, have been installed. Eight CS coils were already sub-assembled on site with

support structure. Fig. 1 shows the status of site assembly of the SC magnets.

The quality of all fabricated coils were certified by critical visual inspection, current density measurements of the SC strand specimens, dimensional measurements. high potential electrical leakage current tests of insulation, flow rate distribution tests, and so on. The major parameters of SC magnets and the test results of coil acceptance can be found in Ref. [6][7].



Fig. 1. The status of KSTAR SC magnet site assembly.

#### **3.** Cryogenic Interfaces

The KSTAR cold components are designed to be cooled down with three cryogens, which are supercritical helium (SHe) for the SC coils, magnet structures and SC bus-lines; liquid helium (LHe) for the current lead system; and gaseous helium for the thermal shields. The KSTAR HRS has been designed with the capacity of 9 kW at 4.5 K that is based on estimated static and dynamic heat loads during operation. The heat loads are based on several operating



FIG.2. In-cryostat helium line routing.

FIG. 3. PF coils & CS structure flow diagram.

modes such as cool down, idle mode, stand by mode, shot mode, and warm up, etc. The main design feature is a peak power smearing system with a thermal damper and a LHe storage tank. Two cold compressors are installed to supply the SHe to the toroidal and poloidal magnet systems. Each compressor has the capability of pressurization of 2.5 bars and massflow of 300 g/s. The thermal dumper is maintained at 4.3 K by a cold pump during operation. The SHe for buslines is directly supplied by a cold box. The HRS will be completed and the assembly and commissioning of HRS itself in the middle of 2007.

Fig. 2 shows the in-cryostat helium line routing. The in-cryostat helium manifolds for the 16 TF coils are designed with 4 inlet lines and 1 outlet. The helium flow to each coil is the same. Each TF coil has 4 parallel cooling channels. The inlet lines of the TF structures are serially connected with the outlet lines of the TF coils after passing through a heat exchanger in the thermal damper. The helium manifold of the CS coils and the PF coils has been designed with 6 inlet lines and 1 outlet line for the PF coils and 8 inlet lines and 2 outlet lines for the CS coils. The outlet lines of the CS3 and CS4 coils are serially connected with the inlet line of the CS structure after passing through the heat exchanger as shown Fig. 3. The cryostat thermal shield (TS) and vacuum vessel TS are supplied with 55 K gaseous helium with one manifold and returned with 3 and 2 manifolds, respectively. The helium inlet manifold of each TF and PF busline is located in the CLB and the outlet is located in-cryostat.

## 4. Current Feeder Interfaces

#### 4.1. SC Busline

The CICC for busline has been fabricated with a circular shape taking into account the complexity of routing and bending. It consists of seven sections of strands encased in 0.05 mm thick stainless steel tape and 4.5 mm thick stainless steel 316L seamless pipe. One

subcable located at the center of CICC consists of 81 OFHC strands with cabling 3x3x3x3. The other 6 subcables are of a rounded spiral-shape with a twist pitch of 304 mm. The cabling pattern of 6 subcables is (2SC + 1Cu)x3x3x3x6 and can be found in Ref. [8]. The CICC have 324 strands of chrome coated NbTi superconductor and 243 strands of OFHC. The critical current density of the NbTi superconductor should be greater than 2700 A/mm2 at 5 T, 4.2 K.

According to the KSTAR operation mode, the CFS is separated into TF and PF systems. In the normal operation mode, TF magnets are operated in continuous mode with a low voltage below 100 V and PF magnets pulse mode with a high voltage about 1 kV. Each of the TF and PF buslines consist of in-cryostat buslines (ICB) and out-of-cryostat buslines (OCB) to transfer current from CL to the SC magnet terminal. The TF buslines consist of inter-coil bus, half-turn bus, ICB, and OCB. The sixteen TF magnets are connected in series by an inter-coil bus and the half-turn bus connects the inter-coil bus to the ICB. The half-turn bus compensates the error field due to the loop current which flows in the inter-coil bus. The site assembly of the TF buslines was finished by early September 2006.

The PF buslines consist of 11 pairs of CICCs, including 6 pairs for the CS coils and 5 pairs for the PF coils, where the upper and lower coils of CS1, CS2, and PF7 are connected in series. For the first plasma experiments, the PF3, PF4, PF5, and PF6 buslines are connected in series near the CLB. The 4 (14) leads on the TF (PF) CLB will be mounted in the end of this year. All the OCB have a vacuum separator at the KSTAR cryostat side to keep an independent vacuum space for the CFS. So the vacuum ducts of OCB are pumped out through the CLB vacuum pumping system. Fig. 4 shows bird's-eye view of the CFS on the left and the fabrication status of TF busline (a), (b) and PF OCB (c), (d) on the right.



*FIG. 4. Left: The layout and fabrication procedure of the CFS. Right: (a) TF OCB fabrication status, (b) TF ICB and OCB joining, (c) and (d) PF OCB shop assembly.* 

## 4.2. Joints

The joints of SC coils operated in pulsed mode should have low ac loss as well as low dc contact resistance to provide operational reliability of the SC coils. To reduce the heat load on SC coils during pulsed operation, most of SC coils in the KSTAR device have been made with no internal joints by adopting a continuous winding scheme. Two types of joints, strand-to-strand (STS) joints and lap joints, have been developed for the KSTAT SC coil and SC buslines.

The STS joint used TF inter-coil bus by using soldered contacts between the Nb3Sn and NbTi strands. The procedures of STS joint connection to the inter-coil bus are shown in Fig. 5, and can be described as follows; (1) oxidation barrier removal on the Nb3Sn strands of the TF coil terminals, (2) high temperature solder alloy soldering to prevent low temperature lead alloy in step 5 from dropping, (3) pre-tinning the Nb3Sn strands of the coil terminals and the NbTi strands of the inter-coil bus, (4) aligning Nb3Sn strands and NbTi strands, (5) soldering together the Nb3Sn strands and NbTi strands with low temperature lead alloy.

Lap joints have been developed and tested for the SC buslines that have the role to interconnect CICCs. To reduce the joint resistance, procedures such as removal of Cr layer on the strands, silver plating, and pre-tinning in the soldering region were improved. Fig. 6 shows the cross-sectional view of a lap joint. It consists of stainless steel structures for mechanical strength and a high purity copper block in which is RRR higher than 100. The length of the joint block is around 300 mm. The copper block and stainless steel block are welded using an e-beam welding method in vacuum. The procedures of the lap joint fabrication are as follows; (1) stripping CICC jacket, (2) removal of the Cr coating of strands, (3) Ag plating the strands and copper blocks of the joints, (4) pre-tinning of the cable surface and copper blocks with 96.5Sn3.0Ag0.5Cu alloy, (5) soldering together the cables and copper blocks under a compression of 60 tons with 1 mm solder sheet, (6) piston welding, (7) joint to joint soldering with 1 mm PbSn alloy sheet.

Two pairs of joint samples, which have same dimensions as the final design of busline lap joints were prepared according to the manufacturing procedure and tested at liquid helium temperature. They were charged up to more than 400 A. Since the soft solders show super-conductivity, in general, it was tested at magnetic fields higher than critical fields of soft solders, i.e., around 0.2 Tesla.



Fig. 5. Main fabrication procedures for STS joints.



FIG. 6. Cross sectional view of lap joint. FIG. 7. The DC resistance test results of lap joints.

Fig. 7 shows the test results of the lap joints. The voltage drops of the joints were measured using a nano-voltmeter. There was voltage shift, probably due to a thermo-couple effect of the joint block made of different materials. So, the voltage drops were measured at many applied currents and the joint resistance was calculated by linear fitting the I-V curves. The joint resistances at zero fields and 0.2 Tesla of the two samples in average were 1.5 nano-ohms and 1.8 nano-ohms.

#### 4.3. Current Lead System

Two current lead boxes for TF and PF coils that were developed in collaboration with a Korean company SFA are shown Fig. 8. Each CLB consists of a vacuum chamber, thermal shield, liquid helium buffer tank, and so on. The vacuum pumping system (VPS) was already mounted on each lead box. It consists of one roughing pump and 4 cryo-pumps. Using the pumping system, the vacuum performance of the lead boxes was tested. Leak rates were less than 1E-9 mbar-l/s at room temperature and in the cool-down state. At room temperature, the base pressure reached bellow 5E-6 mbar. The cool-down tests of the thermal shields and liquid helium buffer tanks were made down to liquid nitrogen temperature. Temperatures of all the thermal shields reached bellow 100 K. Since the thermal shields will be cooled-down

using pressurized helium gas with an inlet temperature of 55 K, the hot spot temperatures of the thermal shields will be much less than 100 K.

On the basis of previous R&D proceedings, such as the development of a numerical analysis code development and test of the prototype low current leads with the design current of 200 A, and so on, a pair of PF leads were developed and tested in collaboration with Russian specialists working in



Fig. 8. Current lead box assembly finished.

the Kurchatov Institute. The design currents were 13 kA and the PF leads were operated up to two times higher than the design currents (26 kA) for 6 minutes successfully without any severe problem. The liquid helium vaporization rates at zero, 13 kA, and 26 kA currents were, respectively, 0.34 g/s, 0.86 g/s, and 2.5 g/s [8].

The experience of developing the prototype PF leads was taken into account in developing the prototype TF leads during the R&D period. The cold joining regions of the leads were reinforced by increasing the cross sectional area of the copper blocks in collaboration with the Korean company, Haneul Engineering. Because the design currents were 17.5 kA, the TF leads can discharge the TF coils up to 35 kA by connecting two leads and SC bus-lines in parallel. This arrangement has an advantage in the reliable current discharging of SC bus-lines because one half of the current (17.5 kA) flows through each bus-line, and hence, it reduces the bus-line quench probability and the temperature rise due to a quench. The specifications of prototype TF CL are as follows; (1) total length and weight are 2.4 m and 280 kg, (2) the heat exchanger material consists of 12960 brass wires of 1 mm diameter with 20 % zinc content, (3) the void fraction of heat exchanger is about 50 %, (4) the volume of LHe vessel is about 10 liters. Using the KSTAR test facilities, currents of up to 35 kA for 6 minutes were tested without severe temperature rise due to current overloading. It also discharged at 17.5 kA design current for 8 hours (same as the period of TF coil operation) successfully, without any problem as shown in Fig. 9. The temperature of the warm terminal was maintained at room temperature, around 305 K. The abnormal temperature rise of CL(+) was due to a bad electrical contact between the warm terminal and the normal bus-bar. Helium vaporization rates at zero, 17.5 kA, and 35 kA were, respectively, 0.41 g/s, 1.1 g/s, and 2.5 g/s. There was no additional Joule heat at the cold joining region and the resistance was around 1.3 nanoohms averaged over both joints. Two pair of TF leads were already developed and assembled on site and 7 pairs of PF leads will be developed and assembled within this year.



FIG. 9. TF CL test results. (a) CL discharging with the current 17.5 kA during 8 hours, (b) warm terminal temperature rise.

## 5. Conclusions

All of the SC coils have been fabricated and were assembled on site except the CS and PF5 coils. The interface components such as helium cooling lines and SC buslines are being assembled. The HRS is under the fabrication with a milestone of assembly and commissioning by the middle of next year. In-cryostat helium lines are being connected to cold components according to the KSTAR assembly procedure. The fabrication and assembly of the CFS could be finished by the end of this year, and the instrumentation system of CFS will be completed by April 2007.

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