Status of the KSTAR Tokamak Construction

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Abstract—The KSTAR is a superconducting tokamak under construction at the Korea Basic Science Institute (KBSI) in Daejeon, Korea. The project mission aims at a steady-state operation and advanced tokamak physics. At present, the project is in the peak of fabrication and assembly phase. The fabrication of the major tokamak structures such as vacuum vessel, cryostat, port system, thermal shields, and gravity support, is completed. The manufacture and testing of the 30 superconducting magnets are rigorously being progressed. As of Sep. 2005, 16 toroidal field coils and 4 large poloidal field coils are completed. To verify the operational feasibility of the KSTAR coils, cool-down and current charging tests of a real sized prototype TF coil and a pair of CS model coil have been carried out. The assembly of the device has begun from beginning of 2004. Now, the vacuum vessel body, thermal shields and 8 toroidal field magnets are assembled on the tokamak position. Assembly finish is scheduled for August 2007. This paper describes the manufacture and assembly progress of the KSTAR tokamak.

Keywords-component: KSTAR, Tokamak, Superconducting Magnet, Vacuum Structure

I. INTRODUCTION

After the meticulous engineering design for the KSTAR subsystems, the device is in the peak phase of fabrication and installation with assembly finish milestone by August 2007. As of September 2005, the progress of the KSTAR construction reaches 85 % of completion. The fabrication of vacuum vessel, VVTS (vacuum vessel thermal shield), cryostat, welded bellows and supporting structures has been completed. Two large sectors (180°, 157.5°) of the vacuum vessel were delivered to the site in June 2004 and welded with each other at the site to form a 337.5° sector by August 2004. At present, the vacuum vessel torus with thermal shields of fish-scale concept is installed on position.

The significant progresses on the fabrication and test of TF and PF superconducting magnets, have been achieved. Especially, the manufacturing process has been much improved through the rigorous quality control program. Until now, 17 TF coils are heat treated, and 14 TF coils are encased in structure. Four large PF coils are ready for installation on site, and four central solenoid coils are in the process of heat treatment. To verify the design and manufacturing engineering and to ensure reliable operation, a real-sized prototype TF coil and a pair of CS model coil have been fabricated and tested at the KBSI superconducting magnet test facility. The fabrication of TF coil structure is well progressed on the base of experience obtained from the prototype TF coil structure fabrication. Doosan Heavy Industries & Construction Company has been manufacturing the TF coil structure since March 2004. Up to now eight TF magnets were delivered to KSTAR site.

According to the great progress in fabrication and delivery of the key components of the KSTAR, the site assembly tasks were started at the beginning of 2004. Among the major components of the KSTAR, the cryostat support beam, the cryostat base, and the magnet gravity support have been successfully assembled on the tokamak pit. Now, the TF magnet assembly that is the most critical phase in site work is underway. All TF magnets assembly will be finished by March 2006. Assembly operations conclude by August 2007 with the successful completion of the integrated system tests. The KSTAR is now preparing for the early stages of machine commissioning.

II. KSTAR SUPERCONDUCTING MAGNET SYSTEM

A. TF Coil

The TF system consists of sixteen TF coils that are electrically connected in series and is operated with 35.2 kA to give 3.5 T at major radius of 1.8 m. The Nb₃Sn strand has KSTAR HP-III specifications in which the critical current density is higher than 750 A/mm² at 12 T, 4.2 K and 0.25 % strain, and the hysteresis loss is less than 250 mJ/cc at field variation from +3 T to -3 T at 4.2 K. Two superconducting strands and one OFHC copper strand are cabled together to become a triplet in the first cabling stage. The cable pattern is 3×3×3×3×6 of 486 strands. The major parameters of TF conductors and coils can be found in Ref [1]. The total amounts of Nb₃Sn and the total length of Incoloy 908 strip used for TF coil fabrication are about 20 ton and 15 km, respectively. The tube mill process is used for the fabrication of CICC, which consists of forming, welding, sizing and squaring procedures. The final size of the CICC is managed within an error of 0.05 mm and the void fraction of the CICCs is above 32 %. Through the TF00 prototype coil test, the 32 % void fraction shows the satisfactory results. The procedures of coil fabrication are summarized as follows; (1) CICC leak test, (2) CICC winding with zirconia bead grit blasting, (3) He feed-through attachment and joint terminations, (4) A15 reaction heat treatment for Nb₃Sn, (5) He-leak test, (6) insulation taping and ground wrapping, (7) vacuum pressure impregnation (VPI), and (8) acceptance test and delivery. For the KSTAR TF magnet system, 19 TF CICC and 18 TF coils are required. 18 TF coils are used for; 16 for the main device, one for the real-sized prototype and one for spare. One TF CICC spool and one TF winding pack are prepared as spare.
parts. Up to now one prototype TF coil and 16 TF coils have been finished in fabrication. Now the final TF coil using for spare coil is in the heat treatment process.

B. PF Coil

The PF magnet system consists of 8 central coils in the CS (Central Solenoid) coil system and 6 outer PF coils. The CS (PF 1-4) and PF 5 coils use the same Nb$_3$Sn strands which used for the TF coils. The PF 6 and PF 7 coils use NbTi strands in which the critical current density is greater than 2700 A/mm$^2$ at 5 T, 4.2 K and the hysteresis loss is less than 200 mJ/cc at field variation from +3 T to -3 T at 4.2 K. The cable pattern of PF coils is 3x4x5x6 of 360 strands. Incoloy 908 and a modified stainless steel 316LN are used as conduit materials for PF 1-5 CICC and PF 6, 7 CICC respectively. Similarly, the major parameters of PF conductors and coils can be found in Ref[1]. The total weight of Nb$_3$Sn strands for PF 1-5 and NbTi strands for PF 6 and PF 7 coils are about 8 ton and 10 ton. CICCs for two CS model coils (920m$^2$), PF 3 (290 m$^2$), PF 4 (440 m$^2$), PF 6 (1300 m$^2$) and PF 7 (1700 m$^2$) were already fabricated. CICCs for PF 1 (670 m$^2$), PF 2 (550 m$^2$) and PF 5 (1430 m$^2$) are in the fabrication process. The coil fabrication process of the PF 6 and PF 7 coils is different from that of TF coils because the heat treatment process is not required. In the coil winding procedure, turn insulation taping and helium stub welding process is conducted simultaneously. Two pairs of PF 6 and PF 7 coil have been finished in fabrication. All the joints of the PF coils are simplified as lap joint type.

The CS coil conductor design has been modified from the original CS coil conductor. One of major modifications is the removal of the internal co-wound voltage taps for quench detection. Because the internal co-wound voltage taps showed the electric insulation failure after the coil heat treatment. Instead the external co-wound voltage taps, which made of conducting polymer tape, is installed on the CS conductor for the quench detection. The shape of CICC was also modified from square type to rectangular type to compensate the jacket deformation during the tight radius coil winding. To avoid SAGBO on tight bending region during heat treatment process, an additional blasting after winding is performed using the portable blasting tools. To minimize the ac loss in CS coil joints, the distance of the joint from the vertical center of the CS coil stack was increased from 3 m to 4 m. For the CS coil heat treatment, another vacuum furnace has been fabricated for the two-coil heat treatment simultaneously. The overall PF coil fabrication will be finished by the end of September 2006.

C. Coil Test

1) Room temperature test

In acceptance test, visual and dimensional checks, $J_c$ value, He flow balance and dc/ac electrical insulation strength are measured. In dimensional check, the allowable tolerance is ± 2 mm. The distribution of flow rates among cooling channels is maintained within 10% variation. For the ground insulation test, DC hipot voltage was 15 kV and AC hipot voltage was 10 kV (rms). For the layer and turn-by-turn insulation test, the impulse voltage was 2 kV. To check the heat treatment qualification, critical current density measurements were performed for several strand samples. Figure 1 and 2 show the critical current density and mass flow measurement for TF coils.

2) CS model coil test

The CS model coil system was installed in the test facility in July 2004. The CS model coil has been cool-down in three times. During the first cool-down there has been a leak around 50 K from the GFRP type electric breaker and temperature sensor brackets. After repairing, the system was cool-down to operating temperature in 10 days. When the system was cool-down the thermo-hydraulic parameters were stable. Cernox type sensors showed consistent values between channel within 0.02 K. but other type sensors showed higher errors. The strain sensors on the coil surface showed tensile values after cool-down. It could be reasonable because the thermal contraction coefficient of the Incoloy908 jacket was smaller than that of VPI insulation of the coil. After the system was fully cooled down, the coil was energized in steps. During the second cool-down the goal of the current rating was 15 KA. Because joints were tightened without sufficient force, the joints showed high dc resistance and had difficulties in the fast current ramping. The third cool-down has been performed after joint repair. The coil was successfully excited to 20 kA with the ramping rate of 150 A/s and 0.065 T/s. The peak field was about 8.6 T.

Flow measurement of TF coils cooling channel

Figure 1. $J_c$ Measurement of the TF coil strands

Figure 2. KSTAR TF coil mass flow rate at 4 bar
PF power supply in the range of 10 kA. Using the bipolar power supply the gain tuning of the SCR controller was conducted to give the stable current waveform generation and to minimize the zero crossing dead time. To measure the ac loss, single pulse triangular waveform test has been conducted by changing the ramp rate and peak current. The peak current was changed from 6 kA to 10 kA, and the ramping rate has been changed from 0.5 kA/s to 2 kA/s. It is relevant to the 0.21 T/s to 0.86 T/s. The ac loss analysis results of the triangular waveform operation showed that coupling loss time constant ntau value was less than 30 msec, which is approximately half of the design specification [2].

In the CS model coil test, the coil quench was not found up to 20 kA, but the busline had several quenches due to the joule heating from the joint. The response time of quench signal from the voltage tap was faster than that from helium flow. The acoustic sensor signal showed that the coil and structure movement occurred during the current excitation and discharge. The acoustic sensor will be installed for the structural monitoring such as TF magnet movement by the centering force.

D. Magnet Structure

The KSTAR magnet structure consists of 16 TF structures, one CS structure, and 80 PF structures. The TF structure consists of the TF coil case, the inter-coil structure, and the auxiliary structure that contain the PF structure basements, the joint box, and the toroidal ring basement. The TF structure is a wedge shape to sustain the strong centering force due to the superconducting TF coil energizing. Each TF structure is bolted in inter-coil structure with shear key and insulation. Specially, conical bolt is adapted in inner inter-coil structure for enlarging endurance for shear stress. There are 18 cooling tubes with 8 mm outer diameter embedded in the structure. The major fabrication process of the TF structure is shown in Fig. 3, and can be described as following 6 steps: (1) fabrication of the c-shape case structure welded with inter-coil structure, (2) fabrication of the flat cover structure welded with inter-coil structure, (3) coil encasing by using vacuum lifter and filling gap with dry glass felt between TF structure and coil, (4) final enclosing weld by automatic TIG weld, (5) vacuum pressure impregnation (VPI), and (6) outer surface machining [3]. Eight TF structures were already assembled on site and remaining TF structures will be finished in Jan. 2006.

The CS system consists of 4 pairs of superconducting coils, which are electrically isolated with up-down symmetry and a supporting structure [4]. The most important function of the CS structure is to protect the CS coils from electro-magnetic and thermal loads. Especially, the structure should endure high magnetic forces such as hoop force, vertical attractive and repulsive force, and lateral force. The CS structure is divided into three parts: preload structure, interface structure, and coil lead supporting structure. The major function of preload structure is to apply an axial compression for the CS coil stack and to sustain the repulsive forces between the coils. The interface structure is designed to connect CS system with TF coil structures and to absorb radial displacement difference between the TF and the CS structures during cool down. There exists two long coil leads inside each CS coil with the length of about 4 m from tokamak median plane. The support structure of coil leads that are exposed in high magnetic field has been designed. Now CS structure is under fabrication and will be finished in December 2005.

The PF coil system is vertically symmetry to the machine mid-plane and consists of 6 PF coils and 80 support structures (i.e, 16 for PF 5, 32 for PF 6 and 32 for PF 7). All PF coil structures should absorb the difference in the thermal contraction between TF coil structures and PF coils due to cool down, and endure the vertical and radial magnetic forces due to current charging. In order to satisfy these design requirements, the PF 5 coil structure is designed base on hinges and both of PF 6 and PF 7 coil structures based on flexible plates. The PF coil structures are assembled on the TF coil structure with an individual basement that is welded on the TF coil structure. PF structure is also under fabrication and will be finished in February 2006.

E. Current Feeder System

Current feeder system (CFS) consists of SC buslines, current leads (CLs) and current lead box (CLB). CL and CLB are located below the main tokamak device and interconnected to main tokamak with SC buslines. Each CFS for TF and PF magnets is separated because these two magnet systems have different operation behavior. In normal operation mode, the voltage on TF magnet does not exceed 100V, and the PF magnets have several kV in every pulse of normal operation and even higher voltage during plasma current disruption. Figure 4 shows the layout of the KSTAR current feeder system.
The busline CICC was designed as circular shape taken into account the complexity of routing. It consists of 324 NbTi strands and 243 Cu strands, which are jacketed with seamless stainless steel pipe. Total length of required busline is around 1 km. The structural analyses taken into account the electromagnetic and thermal loads were already performed in collaboration with Efremov Institute, Russia. On the basis of the analysis results, it has been designed the SC busline routing and supporting structures.

Four TF leads and fourteen PF leads are needed for the first plasma experiment. Optimum current of TF leads and PF leads are 17.5 kA and 13 kA respectively. Two serially connected TF leads and buslines are connected in parallel so that it can charge up to 35 kA steady currents. PF leads designed it could be charged up to 26 kA during longer than 350 seconds with thermal reliability. It means that PF CL will be operated with overloaded currents. A pair of prototype PF leads were developed and tested up to 26 kA during 6 minutes in collaboration with Kurchatov Institute and CryoMagnet, Russia [5]. A pair of prototype TF leads are designed and now in the process of fabrication.

TF and PF lead boxes are already manufactured and assembled on position. The CLBs have cylindrical shape and its cylinder part is designed to lift up and down for easy repair and maintenance. At present, the vacuum leak and thermal shields cool down test are finished with good results.

III. KSTAR VACUUM STRUCTURE

A. Vacuum Vessel

The KSTAR vacuum vessel consists of a double-walled, D-shaped body structure, 72 ports with bellows, and the eight leaf spring type supports. For the sake of completeness the main specifications can be found in Ref[6]. Hyundai Heavy Industry (HHI) started the vacuum vessel manufacture from May 2004. The main body has been fabricated with the quadrant-based structure. The fabrication tolerance of the sub-components is less than ±5 mm. To minimize the welding distortion of vessel body and to meet the dimensional accuracy requirement, the sophisticated fabrication jigs and fixtures have been developed. The poloidal ribs and toroidal rings have been used as a part of jig for assembly of inner and outer shells.

Two quadrants have been assembled and welded to make one sector. Two sectors (180°, 157.5°) have been pre-assembled for final dimension inspection with a dummy structure. After the specified inspection procedures, HHI delivered in two large sectors and one small sector in July 2004 successfully. The welding procedure and symmetric welding sequence was developed through the 1/3 scale mock-up test [7].

The actual site welding was started with setting two large sectors into a specially designed welding jig to fit up of the welding seam, and followed by optical alignment. To minimize the initial welding distortion, 26 strong backs were attached along the welding seam. To verify the welding integrity, non-destructive examinations and helium leak test have been intensively applied. There was no defect larger than the KSTAR requirements in a radiographic and ultrasonic test, also no leakage larger than 5×10^{-10} mbar 1/sec in a helium leak test. Figure 5 shows the final dimension of the vacuum vessel upper and lower bound. In certain measuring points, the tolerances have been deviated from the acceptable ranges. Elaborate analyses for these points have been done to assure that there is no interference with adjacent components.

B. Cryostat

The cryostat is a single walled vessel consisting of central cylinder and two end closures, a lid structure and a base structure supported by the eight support beams anchored on the concrete base. The cylindrical section is an 8.8 m nominal internal diameter cylinder reinforced with two toroidal external ribs. The dome shaped lid structure can be removable for assembly and maintenance. On the flat base structure with external reinforcement, the support for vacuum vessel and magnets will be directly mounted. The total height of cryostat is 8.56 m and total weight is about 180 ton. The fabrication of the cryostat vessel started in May 2002 had been completed in June 2004 by HHI. The fabrication process for the cryostat...
vessel is divided into two steps, shop fabrication and site assembly. The size of shop fabrication items was determined by transportation limits to the KSTAR site. The lid structure consists of 3 pieces of knuckle and crown with ports. The cylinder structure consists of 4 pieces of quadrant shells stiffened with rings and ports. The base structure consists of 2 pieces of base plates stiffened with ribs and ports, 2 pieces of bearing plates, and inner connection ring. The cryostat vessel welding was performed by the GTAW (Gas Tungsten Arc Welding) and FCAW (Flux Cored Arc Welding) according to ASME code Section IX. The FCAW process was used for the full penetration welding of the thick plates at shop. The GTAW process was used for the root passes, the cover passes exposed to the vacuum environments, and the site welding. All components were fitted up considering the distortion and shrinkage of the welds and major dimensions of the components were checked during the welding. Quality assurance of the cryostat fabrication has carried out according to the inspection and test procedure. Figure 6 shows the lid and cylinder part of the completed cryostat.

IV. KSTAR ASSEMBLY

A. Cryostat Base and Gravity Support

The site assembly of the KSTAR began since January 2004, in which time assembly of the cryostat base has been launched and finished. After site delivery of the cryostat base in two half pieces due to the difficulties in transporting, the cryostat base has been welded in the assembly hall to make a complete base. The cryostat base was again settled down and welded on the cryostat supporting beams. The cryostat base is the first major component in the KSTAR assembly, of which assembly followed by assembly of the magnet gravity support system. The gravity support consists of eight supporting posts and one toroidal ring. The toroidal ring that is to be assembled at room temperature has been assembled to have larger radius by 7 mm for the thermal contraction at cryogenic temperature. Since the toroidal ring provides principal reference for the superconducting magnet system, assembly tolerances of the toroidal ring has been strictly controlled within + 0.14mm in level offset, 0.7 mm in flatness, 0.3 mm in center location, and –0.01° (counter-clockwise) in rotation along to toroidal direction, respectively. All works related assembly of the gravity support has been finished by February 2004.

B. Main Assembly Tool System for the TF Magnet

The assembly tolerances of the TF magnets, of which weight exceeds 10 ton, are less than ±1 mm in shifts and rotations with 3 axes. To meet this requirement, special tools and jig system were constructed from March to May of 2004.

The main tools system mainly consists of TF loading and transporting vehicles, three rails for the TF rotation, center guiding post, supporting columns and frame, and several kinds of access platforms. After a TF magnet being transported from outside to the Hillman roller, which is located below 22.5° gap of vacuum vessel, the TF magnet is rotated along to toroidal direction with help of rails, two bearing plates on the center post. The TF magnet is finally aligned by position adjusting tools before final setting on the gravity support. Replacing the Hillman roller by temporary support, which is to prevent the gravity support from localized force due to the weight of the TF magnet, is the last step for setting a TF magnet. This procedure repeats fifteen times until all TF magnets are assembled. The main tools system has been successfully tested using the prototype TF magnet in July 2004.

C. Vacuum Vessel and Thermal Shield

The KSTAR vacuum vessel was fabricated in three toroidally separated parts at the factory. The toroidal angles for the three parts are 180° for sector 1, 157.5° for sector 2, and 22.5° for sector 3, respectively. The sectors 1 and 2 were welded to each other to form a 337.5° sector in August 2004. The welding result showed that the major distortion was horizontal shrinkage by 9 mm. Because the sectors 1 and 2 were set to have larger gap for the sector 3 by 14 mm, the 337.5° sector after on-site welding have wider gap by 5 mm, which is provisional margin for additional shrinkage in the final welding of the sector 3[8].

The vacuum vessel thermal shields which were made of silver coated 316L plates have been also installed on the vacuum vessel from October 2004 to March 2005. The thermal shield plates are divided into sixteen toroidal sectors. Each thermal shield sector is also segmented along to poloidal direction, and electrical breakers at cooling tubes prevent from forming a closed loop in poloidal path. Figure 7 shows that the vacuum vessel and thermal shields were assembled on the pit in March 2005.
D. TF Magnet

Assembly finish of the vacuum vessel and thermal shield provides the final conditions for the assembly of the TF magnets. After a TF magnet is delivered to the site, assembly of the TF magnet is preceded by attachment of insulation plates on the surface of the TF magnet for electrical insulation between two adjacent TF magnets. The first TF magnet has been inserted through a 22.5° gap in the vacuum vessel, and rotated to opposite side to the entrance gap from start of April 2005. Several kinds of the shear keys and the conical bolts are inserted between inter-coil structures from the assembly of the second magnet. Since every TF magnet is independently fabricated at the shop, there is some shift between two half circle shaped holes for a shear key. This problem has been solved by inserting 316LN spacers between Inconel shear key and shear key hole, which has been fabricated to absorb the relative shift. With this concept and strategies, eight TF magnets among sixteen were already assembled on the pit. All the assembly tolerances of the TF magnet have been kept within ±1 mm for shifts and rotations with 3 axes. Figure 8 shows the assembled TF magnets. The last TF magnet, of which delivery is one of the most important milestones in assembly of the KSTAR, is expected to be delivered in January 2006.

V. CONCLUSIONS

The fabrications of the key components of the KSTAR are well progressed without any serious delay. The significant progresses, especially on fabrication and test of all TF and 4 PF superconducting coils, have been achieved during last two years. Most of engineering issues for the SC coil fabrication have been solved. The performance test of a real sized TF coil and CS model coils was carried out successfully. In addition the fabrication of magnet structures is on right track. Now 8 TF magnets are completed up to the installation stage. The site assembly is also smoothly progressed. Assembly activities conclude by August 2007 with the successful completion of the integrated system tests. During the assembly, the pre-test procedure for ensuring the quality of the superconducting magnet systems, cryogenic components, and vacuum leak tight is being prepared. For the on time machine commissioning, auxiliary systems and facility utilities progress rigorously. These substantial progresses make us confident in the validity of our engineering and give us possibilities of successful achievements.

ACKNOWLEDGMENT

This work is supported by the Korean Ministry of Science and Technology under the KSTAR project contract. The authors would like to acknowledge the efforts of KSTAR technical staffs and participating industrial companies.

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