Key Features and Engineering Progress of the KSTAR Tokamak (*Invited Paper*, ICOPS 2003)

J. S. Bak, C. H. Choi, H. L. Yang, J. W. Sa, H. K. Kim, B. C. Kim, N. I. Her, K. Kim, Y. S. Kim, W. C. Kim, Y. M. Park, Y. K. Oh, M. Kwon, G. S. Lee, and KSTAR Team

***Abstract*—The Korea superconducting tokamak advanced research (KSTAR), which is under construction at the National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea, has the mission to develop a steady-state capable advanced superconducting tokamak to establish the scientific and technological bases for a fusion reactor. After an intensive R&D program, substantial progress of the KSTAR tokamak engineering had been made on major tokamak structures, superconducting magnets, in-vessel components, diagnostic system, heating system, and power supplies with industrial manufacturers by May 2002. The engineering design has been elaborated to the extent necessary to allow a realistic assessment of its feasibility, performance, and cost. Since May 2003, the project has been in the phase of procurement. The fabrication of main tokamak structure such as vacuum vessel, cryostat, and supporting structures is well progressed. The manufacturing work of superconducting coils is also proceeding favorably. The tokamak assembly started in July 2003 after site preparation and assembly jig. The start of commissioning is scheduled for June 2006. This paper describes the key features and engineering progress of the KSTAR tokamak and elaborates the work currently underway.**

***Index Terms*—Engineering design, Korea superconducting tokamak advanced research (KSTAR) tokamak, prototype fabrication, superconducting magnet.**

I. Introduction

AFTER the completion of preliminary conceptual design for the Korea Superconducting Tokamak Advanced Research (KSTAR) in 1998, the extensive engineering activity of the main tokamak subsystems had been finished with industrial manufacturers by May 2002. The overall engineering design of the device was optimized through meticulous review process. For the sake of completeness, a schematic view of the KSTAR and the main specifications can be found in [1]. Since May 2003, the project has been in the phase of tender. The fabrication of vacuum vessel, cryostat, welded bellows, and supporting structures is well progressed. Hyundai Heavy Industries (HHI) has been manufacturing the vacuum vessel and cryostat in the factory since May 2002. On-site work for the cryostat started in May 2003. The manufacturing of superconducting coils is also on schedule. Now, the winding of toroidal field (TF) 03 and poloidal field (PF) 7L coil is proceeding actively. The first TF coil (TF00) was tested in our own test facility. The coil was cooled down successfully and confirmed the superconducting phase transition. Magnet structures are in the stage of tender after elaborate engineering modifications. Engineering design for the thermal shields and in-vessel components had been completed in August 2003. The assembly scheme has been defined to assure compliance with assembly requirements and to minimize the subsequent corrective operations. The tokamak assembly started in July 2003, after site preparation and assembly tooling. Assembly operations will conclude, approximately 42 months later, with successful completion of the integrated system tests and the achievement of first plasma. This paper briefly summarizes the status of fabrication of the main systems of the KSTAR.

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The authors are with the the Korea Basic Science Institute, Daejeon 305-333, Korea (e-mail: jsbak@kbsi.re.kr; chchoi@kbsi.re.kr; hlyang@kbsi.re.kr; jwsa@kbsi.re.kr; hkkim@kbsi.re.kr; bckim@kbsi.re.kr; hni@kbsi.re.kr; kkeeman@kbsi.re.kr; kbsckys@kbsi.re.kr; woong@kbsi.re.kr; dosa@kbsi.re.kr; ykoh@kbsi.re.kr; kwonm@kbsi.re.kr; gslee@kbsi.re.kr).

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II. Vacuum Vessel

The KSTAR vacuum vessel is an all-metallic, all-welded, double-walled, and D-shaped structure. It consists of the inner and outer shell, horizontal, vertical, and slanted ports, and leaf spring style supports. Double walls are connected by poloidal and toroidal ribs and filled with water for bake-out, cooling and neutron shielding. Thirty-two equally spaced poloidal and two toroidal ribs provide a robust reinforcement. The shells and ribs form the flow passage for the vessel cooling water. The torus structure of the vessel is welded into three sectors and they are assembled using splice plates at on-site by field welding. The vacuum vessel has seven different port structures that will be used for device installation, utility feed-throughs, vacuum pumping, and access for maintenance. The details of the extensive stress analyses and the fabrication of vacuum vessel are summarized in [2].

To develop and establish the reliable fabrication technologies, HHI has built a full-scale vacuum vessel with 62° sector in toroidal direction. In the manufacturing process of the prototype vacuum vessel, we optimized the arrangement of welding jigs and fixtures considering the expected deformation and the difference of the rigidity of double-walled structure in inboard and outboard segment. The prototype has satisfied the fabrication tolerance of ±8 mm to the total height and ±5 mm to the total width [1]. In the helium leak test, any leak larger than 7.5×10^{-9} Pa $\cdot$ m^3/s were not found at inter shell vacuum of 1.5×10^{-5} Pa.

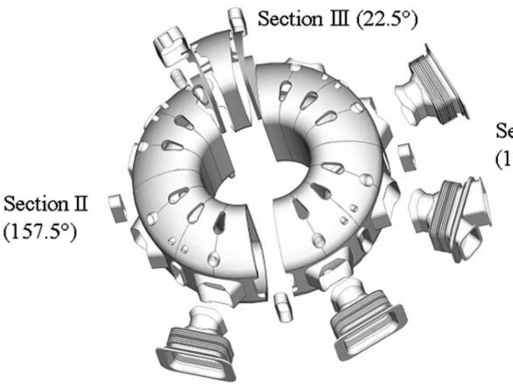


Fig. 1. Vacuum vessel segmentation.

For the main vacuum vessel fabrication, we purchased 154 tons of stainless steel 316LN from NKK Corporation, which is a Japanese steel maker. To minimize the final assembly time on site, and to deliver a vessel structure with a high quality, the vacuum vessel is to be fabricated in the factory as two large sectors (180°, 157.5°) and one small sector of 22.5° span. The advantages of these large sectors are as follows: 1) the improvement of dimensional stability due to the reduction in field joint welding and 2) the reduction of assembly cost by reducing the number of field joints. The practicality of transporting such large sectors from the factory to the site is already checked through the road survey.

As of May 2003, the three-dimensional (3-D) forming process of vacuum vessel is proceeding with a 1500-ton press. The sector-based vacuum vessel, as shown in Fig. 1, was manufactured in factory by the end of 2003. At the final stage of the shop manufacturing, the following tests will be performed to confirm quality: 1) dimension inspection; 2) pressure test; 3) vacuum leak test; and 4) mechanical test under gravity load. The torus structure of the vessel is welded into three sectors and is assembled at on-site by field welding.

III. Magnet

A. Winding Pack Manufacture

The design parameters of TF, central solenoid (CS), and PF coils can be found in [3]. The procedures of TF coil fabrication are as follows:

1) cable in conduit conductor (CICC) fabrication and leak test;
2) grit blasting;
3) coil winding;
4) attachment of helium feed-throughs and joint terminations;
5) heat treatment;
6) insulation taping and ground wrapping;
7) vacuum pressure impregnation (VPI);
8) encasing;
9) performance test.

The continuous winding scheme without internal joints is adopted to reduce the joint losses. Fig. 2 shows two winding stations operating for the winding of TF and PF coils. Since PF6 and PF7 coils use NbTi CICC and the reaction heat treatment process is not required, the helium feed-throughs attachment and Kapton and S2-glass insulation taping are carried out during the winding process. TF and PF1-5 coils use Nb_3Sn strand and require the reaction heat treatment process. After the winding process, coils are placed in a heat-treatment jig and the preparations for heat treatment such as feed-throughs attachment and joint termination are carried out. A vacuum furnace of 5.8-m diameter is used for the A15 reaction furnace. The temperature ramp rate during the heat treatment is 6 °C/h and there are three plateaus: 460 °C, 100 h to remove oxygen and contaminants from the cable, 570 °C, 200 h to enhance the diffusion of Sn to Nb filament, and 660 °C, 240 h for the A15 reaction of Nb_3Sn. An argon gas purging system is operated during the baking process to prevent the stress accelerated grain boundary oxidation (SAGBO) of Incoloy 908 and the oxygen content is maintained below 0.1 ppm. Energy dispersive spectroscopy (EDS) analysis has performed after the heat treatment of the prototype TF coil (TF00) and no sign of SAGBO has been found.

(a) (b)

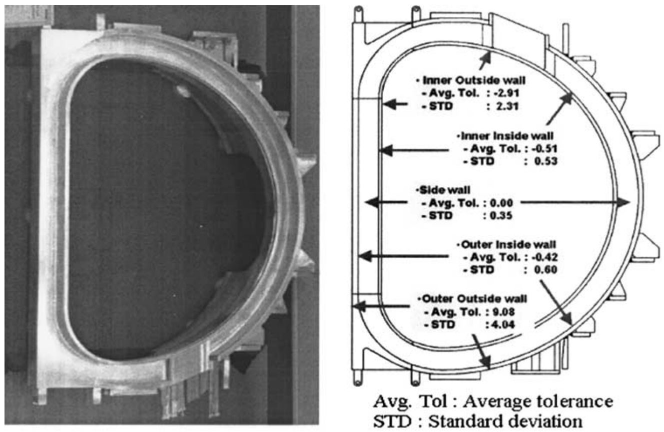
Fig. 2. Winding station for TF and PF coils. (a) TF winding. (b) PF7L winding.

After the heat-treatment process, each turn of the coil is individually separated and the CICC is insulated with 50% overlapped layers of Kapton and S2-glass tapes. Thickness of Kapton and S2-glass tapes are 0.05 and 0.178 mm, respectively. G10 pieces, which are shaped to fill the empty space of layer transition area, are also inserted and the coil bundle is ground wrapped using S2-glass tape. The thickness of S2-glass tape for the ground wrapping is 0.254 mm. The coil bundle is placed in a molding die and vacuum-pressure impregnated. The dimensional error of TF00 coil after VPI is maintained below 1.7 mm.

The TF00, and the background magnetic field generation coils—BKG01 and BKG02—are successfully developed and most of the fabrication procedures are settled down. Three of TF coils and the PF7L coil are presently under fabrication.

B. Magnet Structure Development

The main concept of the TF and CS coil structures envisages a wedged D-shape structure and a preloading structure, respectively. The PF5 coil structure is hinge-type, and PF6 and seven coil structures are flexible-type. The one TF coil structure that is full-welding-type envelope the one TF coil, and each TF structure is connected through bolts and shear keys with electrical insulation in toroidal direction. The TF coil structures are supported by gravity supports that allow to radial movement due to thermal contraction of magnet system. The CS structure is supported on the TF coil structure and supply vertical compression of 15 MN to prevent lateral displacement due to repulsive



(a) (b)

Fig. 3. Prototype TF structure. (a) Prototype TF structure case. (b) Dimensional measurement results of prototype TF structure case.

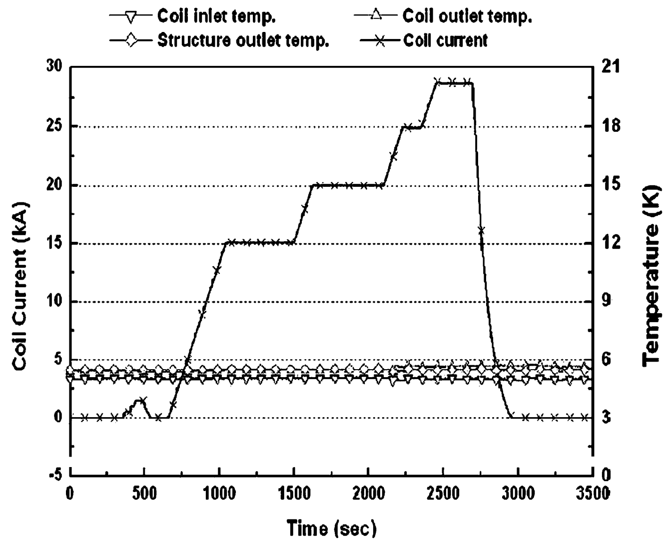


Fig. 4. Current ramp up to 29 kA and slow discharge.

force between the CS coils. The PF coil structures are also supported on the TF coil structure with individual basement that is welded on the TF coil structure. All of these structures need high mechanical static and fatigue stability at low temperature to endure high-magnetic environment, so we will use strengthened stainless steel as material. The details of the electromagnetic and structural analyses can be found in [4].

We have fabricated one prototype TF coil structure and one PF5 coil structure that are fabricated by HHI. Allowable fabrication tolerances are ± 1 mm in the inboard leg part and ± 2 mm in the outboard leg part. Fig. 3 shows the TF case and fabrication tolerances after machining of inside wall. Since the outside wall will be machined after TF coil encasing, its tolerances are beyond the allowable values. We have used JJ1 material that has high yield strength of more than 1000 MPa. We had to consider the wall-thickness margin of 5 mm to absorb welding deformation and machine inside of the case to meet the fabrication tolerances. The cooling tube that is seamless stainless steel 316L, inner diameter of 4 mm, length of 12 m, and number of 28 is welded inside the wall of the case through the perimeter. The one PF5 coil structure has fabricated with overall tolerance of 0.1 mm.

C. TF00 Coil Test

The major objectives of the TF00 coil test are to confirm the design validity and fabrication quality. The performance test of TF00 coil was carried out in the superconducting coil test facility. The TF00 coil was cooled down to operating temperature twice. 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 campaign and 10 days in the second campaign. The residual resistance ratio (RRR) of the coil was measured to be over 200, which value satisfies the required value of 100 in the KSTAR design. The superconducting phase transition of the coil was detected at about 18 K. The helium leak from the coil was not measured at the coil operating temperature below 10 K, 6-bar system pressure, and 2.0×10^{-7} torr vacuum pressure. 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%.

The current ramp-up and discharge test of the coil were carried out 23 times. Prior to the high-current test, an adjustment of the TF power supply controller was carried out to avoid current overshooting and oscillations at the various ramping rates. The power supply was stably operated up to 80 A/s ramping rate. For ramping the coil up to high current, reliable quench detection and protection systems are necessary. So quench tests were also carried out at 5 kA by heating the helium lines to generate artificial quenches. Since the quench detection and protection systems were reliably operated, the high-current ramp-up test was followed. 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. Fig. 4 shows the result of current ramping up to 29 kA and slow discharge. The temperature of the coil and structure did not changed. The coil was operated well without any quench over 30 kA. The results of the repeated current charge tests show that the prototype TF coil was fabricated well without any severe defects such as cold leak. The TF power supply, the quench detection system, and quench protection system were also operated well with reliability.

IV. Cryostat

The KSTAR cryostat is a large vacuum vessel surrounding the entire tokamak machine with single-walled cylindrical shell, dome-shaped top lid, and a flat bottom lid. It provides feed-through penetrations for all the connecting components

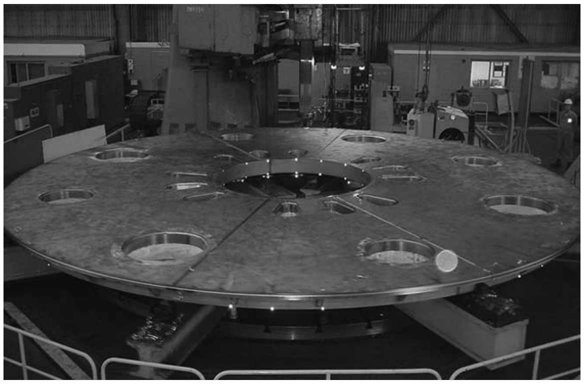


Fig. 5. Machining of cryostat base plate (May 12, 2003).

inside and outside the cryostat. There are 102 ports including 72 vacuum vessel port penetrations with bellows to compensate the displacements of ports due to electromagnetic (EM) loads and thermal loads within allowable limits. The welded bellows of penetration ports are all designed irregularly. The largest one is a rectangular shaped NBI port bellows, which has a span of 80 mm and thickness of 1 mm. The manufacturing process consists of following steps:

1) manufacturing of S-typed bellows molding die;
2) pressing and cutting bellows core;
3) cleaning;
4) laser welding;
5) helium leak test.

The cryostat is mounted on a base plate for transferring the loads to main building support structure through eight supporting beams. The dome shaped lid structure will be removable for assemble and major maintenance activities. The details of cryostat design and structural analyses are summarized in [5].

HHI has been manufacturing the cryostat vessel since May 2002. As of May 2003, the manufacturing of cryostat base plate in factory was nearly completed. Fig. 5 shows the surface machining process of base plate. The on-site welding process for base part was finished by July 2003. Delivery of the cyrostat cylinder and lid to the site was also finished in October 2003.

V. Thermal Shields

There are four types of thermal shields:

1) vacuum vessel thermal shields (VVTS) located 4 cm off the outer wall;
2) cryostat thermal shields (CTS) located 12 cm off the inside cryostat;
3) transition thermal shields (TTS) that enclose the port connection ducts;
4) support thermal shields (STS) that enwrap the gravity supports and base plate.

The VVTS comprises of 16 sectors in toroidal direction. Each sector is electrically isolated with each other to reduce eddy-current-induced electromagnetic force during plasma disruption. In case of the VVTS, multilayer insulation (MLI) is not used due to the narrow gap of 55 mm between vacuum vessel and superconducting coils and for reliability, while the cryopanel are covered on both sides with a thin, low-emissivity layer of silver. The VVTS has to closely follow the shape of the vacuum vessel for space reason. The layout of the VVTS with cooling channel routing has been fixed. Calculations to verify the mechanical sturdiness of the cryopanel against induced electromagnetic forces during plasma disruptions are underway. The prototype of one sector VVTS is now under fabrication to assess the manufacturing feasibility. The CTS and TTS are not constrained spatially, and have more relaxed tolerances. Therefore, MLI will be used between the panels and the cryostat wall. The cryopanel is made of 3-mm-thick stainless steel 316LN plate and 16×16 mm rectangular stainless steel pipe with 10-mm circular channel will be brazed on it. In designing the port thermal shield, care has been taken into account in conjunction with the assembly of the whole tokamak main hardware since the configuration and assembly sequence of the port thermal shields is closely interrelated with the 72 vacuum vessel ports, magnet and cryostat assembly sequence. Presently, the detailed design of the thermal shields is actively progressed.

VI. Current-Feeder System

The main function of the superconducting (SC) bus-lines in the current feeder system of the KSTAR device is current transmission between the SC coils and the current leads. The SC bus-lines have 12 pairs of CICCs, which are made of NbTi–Cu CICC cooled with forced-flow supercritical helium. It consists of in-cryostat and out-of-cryostat bus lines. In-cryostat bus-lines connect with out-of-cryostat bus lines at the cryostat bottom. The out-of-cryostat bus lines consist of two main ducts. One is from the bottom-center port of the cryostat and the other is from the side-bottom port. Each out-of-cryostat bus line has intermediate lap joints for assembly and vacuum breaks, which provide vacuum barrier between the cryostat and current lead box.

The heat sources in the out-of-cryostat bus lines are conduction and radiation to CICCs, ac and dc losses of the lap joints, and conduction in the vacuum break stand-off pipe. For 12 pairs of CICCs, the total conduction and radiation loads are about 50 W at 4.5 K. Conduction from the vacuum break terminal is 5.0 W. For the lap joints, the dc resistance and background ac field is assumed to be 2 $n\Omega$ and 0.2 T/s, respectively. The total joint loss of the out-of-cryostat bus line is about 200 W.

In-cryostat bus-line routings start from each coil leads to the out-of-cryostat bus line through the bottom port of the cryostat. The CICCs of in-cryostat bus line is supported by structures consisting of two parts. The first part consists of the CICC coming up from the bottom center port and energizing the PF1U, PF1L, PF2U, PF2L, PF3L, PF4L, and PF5L coil. The second part consists of the CICC coming up from the bottom side port and energizing the PF3U, PF4U, PF5U, PF6U, PF6L, PF7U, PF7L, and TF coil. Each pair of CICC goes through a square tunnel structure and inside the tunnel is held in G-10 clamps. The G-10 guide is in four identical pieces, which are arranged around the two CICCs. The guide is placed in a square steel holder, where it is free to slide in the direction of the CICC, but is restrained against lateral motion and rotations.

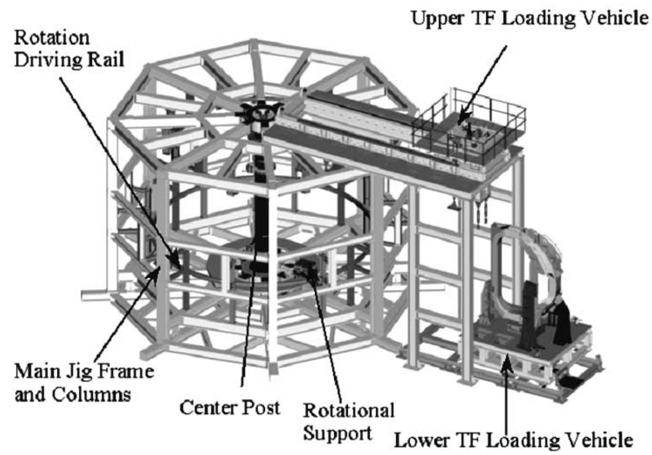


Fig. 6. Schematic 3-D view of main jig system for TF assembly.

VII. Assembly Plan

The assembly plan is divided into four stages according to key milestones in the KSTAR tokamak assembly. The first stage covers assembly of the cryostat base and support beam, magnet gravity support, and fabrication the main jig system for the TF assembly. With the optical metrology system, the cryostat supporting beams have been already installed and aligned in the tokamak pit within ± 0.3 mm in the location to the virtual axis of the KSTAR tokamak. The level of the beam was also aligned within 1 mm. The cryostat base and magnet gravity support was serially assembled in September 2003.

The detail features of the main jig system for the TF assembly, which have already been finished in the engineering design and were fabricated in September 2003, are described in [6]. Fig. 6 shows the schematic view of the jig system. The jig system mainly comprises the jig frame, center post and guide bearing, rotational support and rail for the TF rotation, upper TF lifting and guide, two TF loading vehicles, and rotation driving structures. Each the rotational support and TF lifting structure can accommodate the maximum weight of 13 ton. With this configuration, a TF magnet of which estimated weight is 10 ton will be safely assembled within ± 1 mm assembly tolerances in 6° of freedom. Since the center post is a major reference to TF alignment, it should be fabricated within 0.1 mm/m in straightness and within 0.2 mm in radial shift. The size of the jig columns and frames which are made of structural-steel (SS400) was determined as 440×300 mm to restrict displacement of the center post at top side within 1 mm in the case of 8 TF magnets being assembled in one side and affecting net side force to the post. As the highest level of the jig system reaches almost 11 m, various kinds of platforms, handrails, and stairways are also included in the jig system for the safety of the workers. This jig system will be carefully tested for the acceptance test in view of its own functions and characteristics with TF00 magnet.

The second, third, and fourth stages include all of the real KSTAR assembly works except assemblies of cryostat base and magnet-gravity supports which are assembled in the first stage. This main assembly works will be started after fabrication and construction accomplishment of the jig system in first quarter of 2004. The engineering design on the detail assembly procedures, related jigs and tools, and measurement and alignment system was finished by end of 2003. The detail features and configurations of the second, third, and fourth stages of the device assembly will be documented in the near future.

VIII. Conclusion

The engineering design and prototype fabrications of the major parts of KSTAR have been finished and the results of these activities defined a machine with unique set of capabilities. Several detailed design improvements were pursued in an effort to raise reliability, to improve maintainability, and to reduce the cost. The project is now in the phase of fabrication and procurement. The vacuum vessel, cryostat, and supporting structures are being manufactured by HHI. The full size TF prototype coil, TF00, and the background field generation coils, BKG01 and BKG02, are successfully manufactured and most of the manufacturing procedures are settled down. Fabrication of three TF coils and PF7L coil are underway. TF00 coil performance is in agreement with the expectations. For the magnet structures, final modifications of engineering design are almost completed. In addition, the technical specifications for magnet structures procurement are being prepared. The overall KSTAR assembly scheme and associated major tooling are determined, and the tooling concepts are expected to meet the requirement of tight tolerances of the KSTAR tokamak assembly. The site assembly began in July 2003. These substantial progresses make us confident in the validity of our design and give us possibilities of successful achievements.

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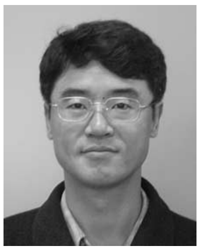
J. S. Bak received the B.S., M.S., and Ph.D. degrees in nuclear engineering from the Seoul National University, Seoul, Korea, in 1979, 1981, and 1989, respectively.

He is the Director of the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for the development and installation of the KSTAR device. His research interests include nuclear fusion engineering and accelerator engineering.

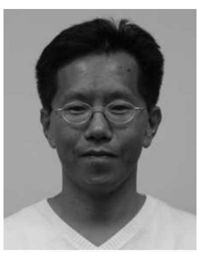
Dr. Bak is a member of the Korea Accelerator and Plasma Research Association.



C. H. Choi received the B.S., M.S., and Ph.D. degrees in theoretical physics from the Kyungpook National University, Kyungpook, Korea, in 1988, 1990, and 1995, respectively.

He is a Senior Researcher with the System Integration Team, National Fusion R&D Center, Korea Basic Science Institute, Daejon, Korea. He is responsible for assembly of the KSTAR device.

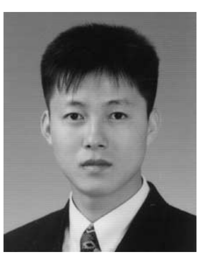
Dr. Choi is a member of the Korea Physical Society.



H. L. Yang received the B.S., M.S., and Ph.D. degrees in nuclear engineering from the Seoul National University, Seoul, Korea, in 1991, 1993, and 2000, respectively.

He is currently a Senior Researcher with the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for the KSTAR major structures assembly. His research interests include nuclear fusion engineering and accelerator engineering.

Dr. Yang is a member of the Korea Accelerator and Plasma Research Association, the Korea Physics Society, and the Korean Physical Society.



J. W. Sa received the B.S. and M.S. degrees in mechanical design engineering from the Chungnam National University, Chungnam, Korea, in 1997 and 1999, respectively.

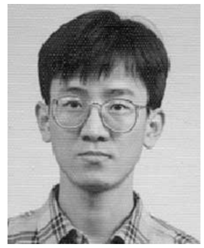
He is currently a Researcher with the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for design and fabrication of the PF coil support structure for the KSTAR device. His research interests include material science and cryogenic engineering in mechanical aspect.

Mr. Sa is a member of the Korean Society of Mechanical Engineers.

H. K. Kim received the B.S. and M.S. degrees in mechanical design engineering from the Chonbuk National University, Jeonbuk, Korea, in 1998 and 2000, respectively.

He is currently with the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is working on the design and assembly of the KSTAR device. His major research interest is mechanical engineering.

Mr. Kim is a member of the Korean Society of Mechanical Engineers.



B. C. Kim received the B.S., M.S., and Ph.D. degrees in nuclear engineering from the Seoul National University, Seoul, Korea, in 1990, 1992, and 1999, respectively.

N. I. Her received the B.S., M.S., and Ph.D. degrees in mechanical design engineering from the Chungnam National University, Chungnam, Korea, in 1992, 1994, and 2003, respectively.

He is currently a Researcher with the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for development of the KSTAR cryostat. His major research interest is mechanical engineering.

Dr. Her is a member of the Korean Society of Mechanical Engineers.

K. Kim received the B.S. and M.S. degrees from Seoul National University, Seoul, Korea, in 1983 and 1985, respectively, and the Ph.D. degree in nuclear engineering from the University of Illinois, Urbana-Champaign, in 1989.

He is currently responsible for the development of the KSTAR superconducting magnet system. His research interests include the application of superconductivity and the magnet system of nuclear fusion devices and particle accelerators.

Y. S. Kim received the Ph.D. degree in solid-state physics from the Ajou University, Sunwon, Korea, in 1997.

He is currently a Senior Researcher with the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for development of the KSTAR current feeder system and helium cryoplant. His interests include superconducting magnet and cryogenic systems in nuclear-fusion engineering.

Dr. Kim is a member of the Korean Physical Society.

W. C. Kim received the B.S., M.S., and Ph.D. degrees in nuclear engineering from Seoul National University, Seoul, Korea, in 1989, 1991, and 1999, respectively.

He is currently a Senior Researcher with the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for development and installation of the KSTAR thermal shield. His research interests include nuclear fusion engineering.

Dr. Kim is a member of the Korea Accelerator and Plasma Research Association and Korean Physical Society.

Y. M. Park was born in the Republic of Korea in 1967. He received the B.S., M.S., and Ph.D. degrees from Myongji National University, Yong-In, Korea, in 1990, 1992, and 1998, respectively.

He is currently with the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. His research interets include the R&D of the superconducting bus-line for the KSTAR device.

Dr. Park has been a member of the Korean Physical Society since 1990.

Y. K. Oh received the B.S., M.S., and Ph.D. degrees in nuclear engineering from Seoul National University, Seoul, Korea, in 1989, 1991, and 1999, respectively.

He is currently the Senior Researcher of the KSTAR Development Division, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for development of the magnet interfaces and for testing the superconducting magnets of the KSTAR device. His research interests include superconducting magnet engineering and nuclear fusion engineering.

Dr. Oh is a member of the Korea Accelerator and Plasma Research Association and the Korean Physical Society.

M. Kwon received the B.S. degree from Seoul National University, Seoul, Korea, in 1982 and the M.S. and Ph.D. degrees in nuclear engineering from the Georgia Institute of Technology, Atlanta, in 1986 and 1990, respectively.

He is currently the Director of the Division of Research and Operation, National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for the project of the HANBIT mirror device and for the development of the KSTAR control system and operation scenarios. His research interests include various fields of nuclear fusion and accelerator engineering such as plasma diagnostics, control systems, and RF applications.

G. S. Lee received the B.S. degree in physics from the Seoul National University, Seoul, Korea, in 1979 and the Ph.D. degree in physics from the University of Texas, Austin, in 1985.

He is currently the General Director of the National Fusion R&D Center, Korea Basic Science Institute, Daejeon, Korea. He is responsible for the KSTAR project. His major interest is plasma physics.

Dr. Lee is a member of the Korean Physical Society.