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2004 Plasma Sci. Technol. 6 2159

(http://iopscience.iop.org/1009-0630/6/1/008)

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J. S. Bak, K. Kim, C. H. Choi, Y. K. Oh, B. C. Kim, N. I. Her, H. L. Yang, G. S. Lee, and the KSTAR Team
Korea Basic Science Institute, 52 Yeoeun-Dong, Yusung-Ku, Daejeon 305-333, Korea

Abstract As there is substantial progress in the KSTAR tokamak engineering, all the major structures and sub-systems are under fabrication and in procurement phase. The vacuum vessel, port, cryostat cylinder, lid, and bellows are being rigorously fabricated in the factory. The lower part of the KSTAR such as cryostat base and gravity support has been almost finished in its fabrication. There are also great progresses and significant results in manufacturing of the superconducting magnet, including four Toroidal Field (TF) coils, lower and upper PF7 coils which are the largest Poloidal Field (PF) coils. The TF00 coil, which has been made for test and back-up of the TF magnet system, was successfully tested in the cool-down and current charging. As the fabrications and procurements of major structures have been actively proceeded, assembly works were also launched from Aug. 2003. More detailed description on these status, results, and plans will be described in this paper.

Keywords: KSTAR tokamak, vacuum vessel, magnet, cryostat, tokamak assembly

PACS: *52.55.F; 74.25.H; 85.10.F*

1 Introduction

After the completion of preliminary conceptual design for the KSTAR in 1998, substantial progress in the main tokamak subsystems has been made with industrial manufacturers by September 2003. The overall engineering design of the device was optimized through a meticulous review process. For the sake of completeness a schematic view of the KSTAR and the main specifications can be found in Ref.[1]. As of Sep. 2003, the project is 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 cryostat was started from May 2003.

The manufacture of superconducting coils is also on schedule. Now the winding of TF04, PF7U coil is proceeding actively. The first TF coil (TF00) was successfully tested in Samsung Superconducting Test Facility (SSTF). The coil was successfully tested in cool-down and current charging without any problems, and the superconducting phase transition was confirmed. Magnet structures are in the stage of tender after the elaborate engineering modifications.

The detail assembly plan has been defined to assure compliance with assembly requirement and to minimize the subsequent corrective operations. The tokamak assembly will start from Dec. 2003 after site preparation and assembly tooling. Assembly operations will conclude, approximately 36 months later, with the successful completion of the integrated system tests and the achievement of the first plasma.

2 Vacuum vessel

The KSTAR vacuum vessel consists of the inner and outer shells, 72 ports with bellows, and the leaf spring style supports. The vessel body is a double-wall, D-shaped structure. In the inter-space between the inner and outer shell, there are 32 equally-spaced poloidal ribs and 2 toroidal ribs. The shells, port stub walls, and ribs form the flow passage of vessel baking and cooling water. The KSTAR vacuum

* The project supported by the Korean Ministry of Science and Technology under the KSTAR project contract

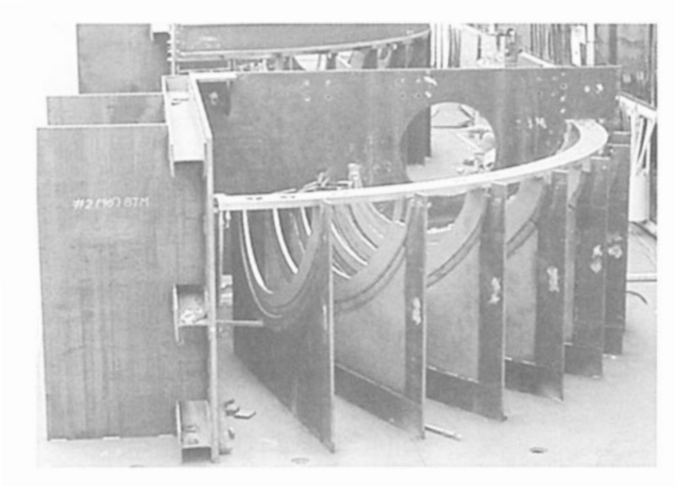


Fig.1 Fabrication jig for vacuum vessel

Fig.2 Lower part of vacuum vessel quadrant

vessel is to be fabricated in the factory as two large sectors (180, 157.5 degrees) and one small sector of 22.5 degrees span.

After the extensive engineering design activity and prototype fabrication, the contract for manufacturing vacuum vessel was made in 2002 with Hyundai Heavy Industry (HHI). To make the torus-shaped vacuum vessel, a raw material (SA240-316LN) surface is buffed and a shape of three-dimensions is formed by an 1,500 ton hydraulic press. The fabrication tolerance of the formed components is less than ± 5 mm. The required number of the formed shell for vacuum vessel body is about 170. Each shell formed is machined and cleaned for next procedure. To minimize the welding distortion of vessel body and meet the dimensional accuracy requirement, the special jig and fixture is developed. The fitted view of the poloidal ribs and toroidal ribs into the fabrication jig is shown in Fig. 1. The jig in Fig. 1 is for flare and knuckle part of D-shaped vessel body. In this configuration, the poloidal ribs and toroidal ribs are also used as a part of jig for inner and outer shell assembly. After the assembly of jig frame, the inner and outer shell fit-up and welding are followed. Fig. 2 shows the lower part of one quadrant. For one quadrant, there are 2 jig frames for upper and lower part of D-shape. After the welding of lower and upper part of one quadrant is finished, the straight section of D-shape is inserted into the upper and lower part of vessel to make the fully shaped quadrant. The D-shaped quadrant is machined for port opening and the port stub is welded into the port opening of the vacuum vessel body. The pressure and leak test for each quadrant will be performed. To make each sector, two quadrants are assembled and welded. The leakage of quadrant-to-quadrant welding joint of each sector is also leak tested. Finally, two sectors and one small sector of 22.5 degree, consisting of twenty four small shells and rib components will be combined to make the torus. The 72 ports manufacturing process is similar to that of vessel body fabrication. The raw material surface finish, 3-D forming, fit-up and welding of components are going on. Each port consists of straight section, bellows and flange. The straight and flange parts are made in vacuum vessel manufacturer (HHI). The bellows are made in Japanese company, Valqua Seiki. Final welding assembly of whole port components is performed in HHI. The port with bellows will be welded with vacuum vessel body and cryostat port stub in final site assembly.

3 Magnet

3.1 Coil manufacture

According to great progress in the research for the superconducting magnet manufacture as described in Ref. [2], various kinds of superconducting magnets for the KSTAR are now under active fabrication. The full-size Toroidal Field (TF) prototype

Fig.3 TF00 coil after VPI

Fig.4 PF7L waiting for final VPI

coil named TF00, and the two coils for background magnetic field generation (BKG01, BKG02) are successfully developed and most of the fabrication procedures are settled down. Fig. 3 shows the TF00 coil after Vacuum Pressure epoxy Impregnation (VPI). The 1st TF coil named TF01 is now under leak test after heat treatment. The 2nd (TF02), the 3rd (TF03), and the 4th (TF04) TF coils are under process of heat treatment, insulation taping, and winding, respectively. Both of the lower PF7 (PF7L) and upper PF7 (PF7U) coils are being manufactured in the on-site area due to the difficulty in transporting these large coils. The PF7L coil is now under VPI after ground wrapping, and the PF7U coil is being wound in the winding station. Fig. 4 shows PF7L coil that is waiting for final VPI.

3.2 Magnet structure development

The engineering design and prototype structure fabrication of the magnet structure had been completed. Structural, thermal, and electrical properties of the magnet structure were considered through the engineering design. In addition, fabricability had been confirmed through prototype structure fabrication.

Major design concepts of the TF and CS coil structures envisage a wedged D-shape structure and a preloading structure, respectively. The PF5 coil structure has a hinge-type, and the PF6 and the PF7 coil structures have a flexible-type. The one TF coil structure that is full of welding type envelops 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 allowing a radial movement due to thermal contraction of magnet system. The CS structure is supported on the TF coil structure and supplies a vertical compression of 15 MN to prevent lateral displacement due to repulsive 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 the material. The details of the electromagnetic and structural analyses can be found in Ref. [3].

We have fabricated one prototype TF coil structure and one prototype PF5 coil structure that are fabricated by HHI. Allowable fabrication tolerances are ± 1 mm in inboard leg part and ± 2 mm in outboard leg part. Fig. 5 shows the TF case and fabrication tolerances after machining inside wall. Because outside wall should be machined after TF coil encasing, its tolerances are larger than the allowable values. We have used JJ1 material that has a high yield strength of more than 1000 MPa. We had to consider a wall thickness margin of 5 mm to absorb welding deformation and machine inside the case to meet the fabrication tolerances. The cooling tube

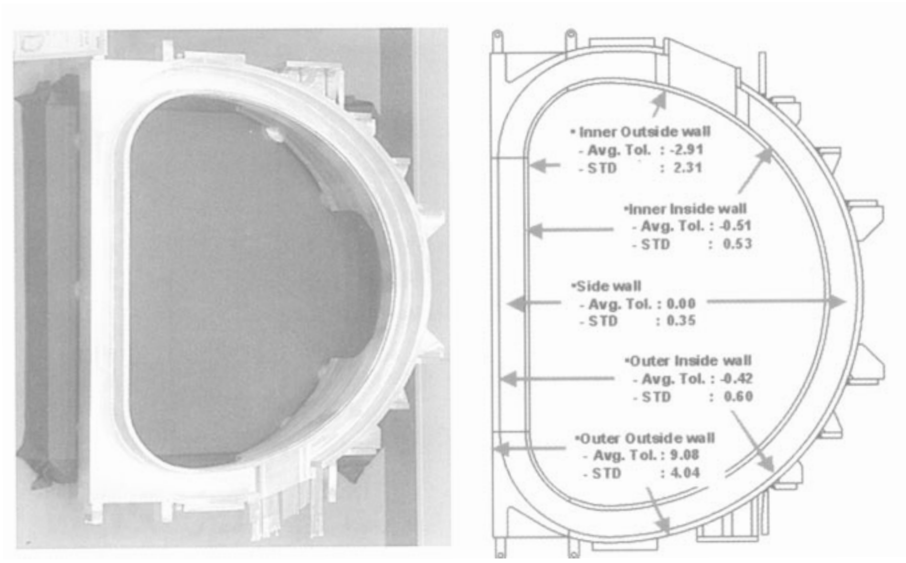
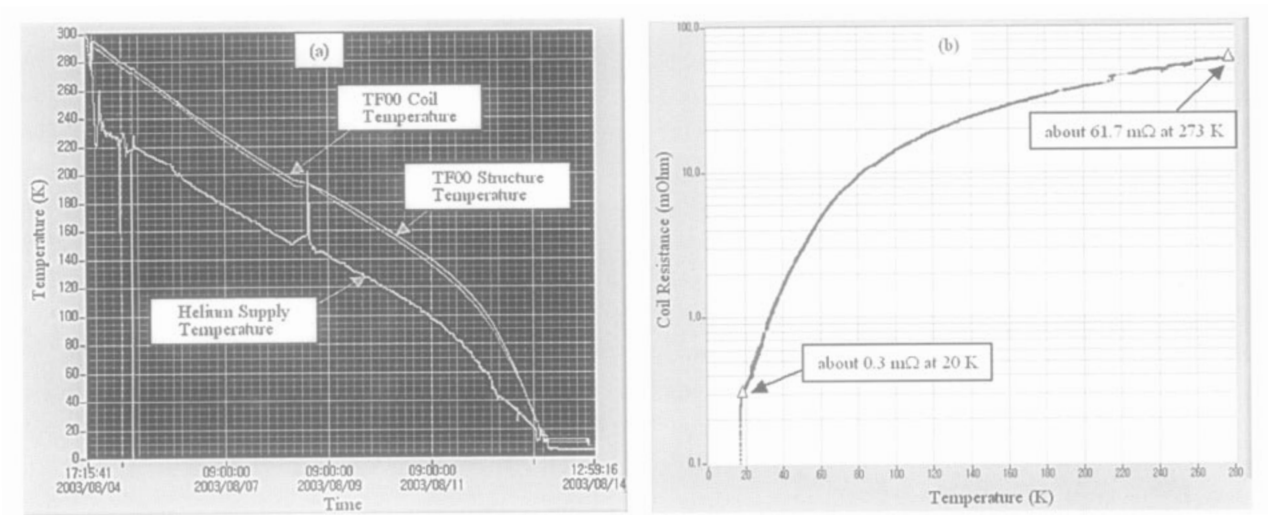


Fig.5 Prototype TF case structure



(a) TF00 cool-down history (b) Coil resistance

Fig.6 Experimental results in 2 nd campaign

that is seamless SUS316L, with an inner diameter of 4 mm, a length of 12 m, and a number of 28 is welded into the inside wall of the case along perimeter. The prototype PF5 coil structure has fabricated with an overall tolerance of 0.1 mm.

3.3 TF00 coil cool-down test

The prototype TF coil test has been accomplished following the first and the second campaign in the SSTF. The first and the second campaign were performed by Jan. 2003 and Sep. 2003, respectively.

After the coil installation in the cryostat, final inspection was done including the electric isolation check and helium leak check at room temperature. The cryostat was evacuated to 5.3×10^{-4} Pa at room temperature. 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 duration was 15 days in the first campaign and 9 days in the second campaign as shown in Fig. 6(a). The residual resistance ratio (RRR) of the coil was measured to be over 200 as shown in the Fig. 6(b), the value of which satisfies the required value of 100 in the KSTAR design. The

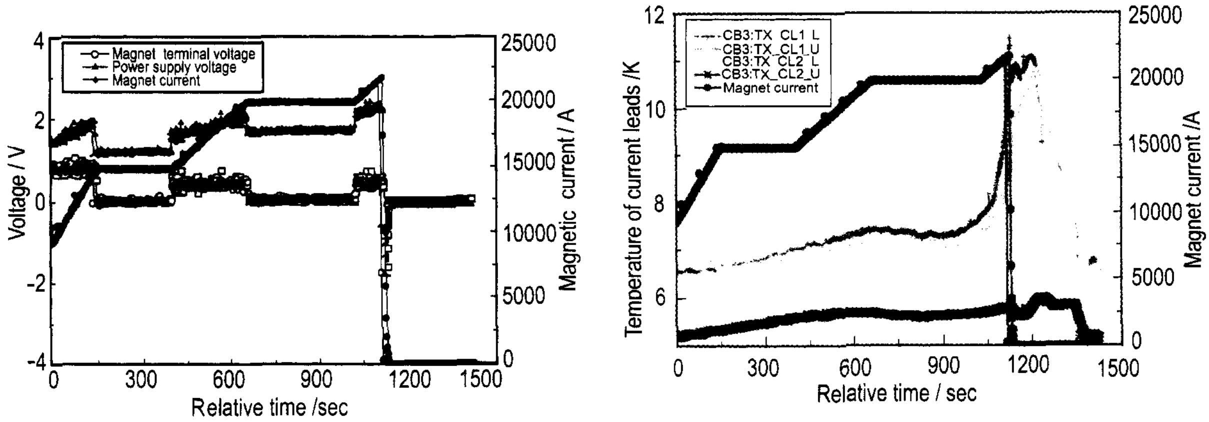


Fig.7 Current ramp up and fast discharge at 21.7 kA due to the quench in the current feeder

superconducting (SC) phase transition of the coil was detected at 18 K. When the coil was fully cooled, the supercritical helium could be supplied into the coil by controlling the valves in the helium refrigerator. The hydraulic parameters of the supercritical helium in the distribution box were measured as follows: the supply and return temperatures were about 5.0 K and 5.4 K, respectively, and the supply and return pressures were about 5.3 bar and 3.0 bar, respectively. The helium flow rate of the coil was about 15 g/s in total when the supply temperature, supply pressure and pressure difference were about 5.2 K, 5.2 bar, 2.2 bar, respectively. Helium flow between 4 channels were uniform within 10% deviation, each channel is interactive with neighboring channels because of the continuous winding.

3.4 TF00 coil current test

The coil has been ramped up and discharged 23 times during the second campaign. Before the coil was fully charged according to the specified value, quench tests had been carried out by intently heating the cooling tube on the inlet lines of the coil and current leads with the coil charged to 5 kA. The coil was repeatedly ramped up in steps of 5 kA, 10 kA, 15 kA, 20 kA, 25 kA, and 30 kA with various ramping rate and followed by various discharges such as slow discharge, safety discharge, and quench discharge. The coil was operated in steady state without quenching up to 33 kA. The maximum current was limited below the nominal operating current of 35 kA because of the structural weakness of the SC bus-line supporters. The current test results on TF00 coil are shown in Fig. 7.

4 Cryostat

The KSTAR cryostat is a large vacuum vessel surrounding the entire tokamak machine with a single-walled cylindrical shell, a dome-shaped top lid, and a flat bottom base. It provides feed-through penetrations for all the connecting components inside and outside the cryostat. HHI has been manufacturing the cryostat vessel since May 2002. The manufacture of cryostat vessel will be completed by May 2005. Fig. 8 shows the position adjustment of the base plate after on-site welding process. The manufacture of the base including bearing plate and inner connection part has been completed. The flatness of the base is within the tolerance of 3 mm. The manufacture of cylinder and lid in the factory was nearly completed. We expect that on-site welding of cylinder and lid can be started on Nov. 2003.

The cryostat has 102 ports including 72 vacuum vessel port penetrations with bellows to compensate the displacements of ports due to EM loads and thermal loads within allowable limits. Valqua has been manufacturing the welded bellows since Dec. 2002. The bellows manufacture will be completed by Jan. 2004. Fig. 9 shows the prototype bellows for NBI port, which has a S-shaped bellows span of 80 mm, a thickness of 1 mm, a rectangular-shaped outer diaphragm of 1370 mm $\times$ 1610 mm, and a length of 395 mm. We confirmed the quality and reliability of the welded bellows through various performance

Fig.8 Movement of cryostat base plate on site (Sep. 2003)

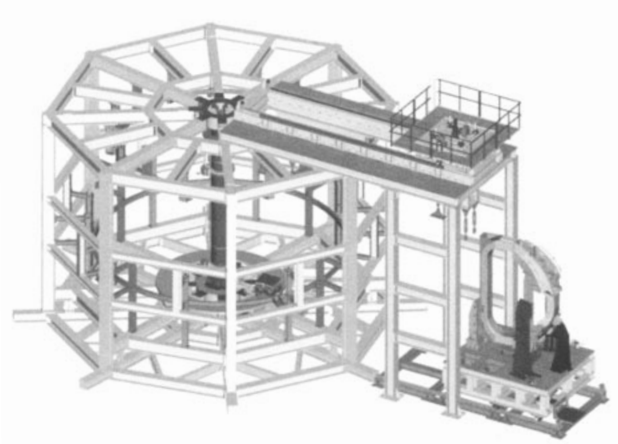


Fig.10 Schematic view of the main jig system for TF magnet assembly

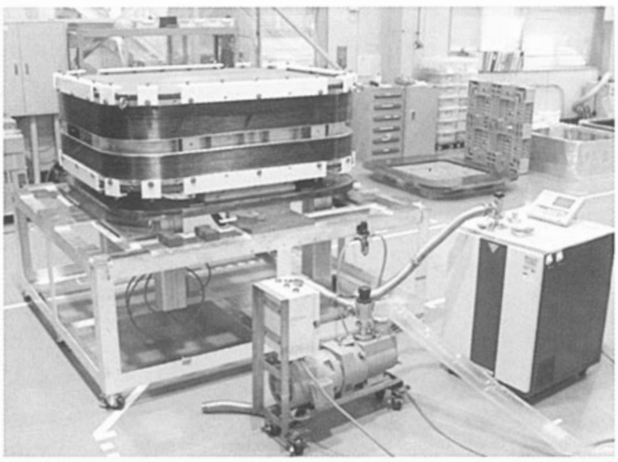


Fig.9 Helium leak test of the prototype bellows for NBI port (Jul. 2003)

tests such as out-gassing rate, helium leak, spring constant, pressure, and life cycle test.

The gravity support for whole magnet system consists of a toroidal ring and 8 supporting posts. As of Sep. 2003, the manufacture of gravity support was completed by Comtecs. The gravity support has satisfied the dimensional accuracy of ± 1 mm to the total height, and ± 0.5 mm to the height of each component, four quadrants of toroidal ring and eight supporting posts.

5 Tokamak assembly

The tokamak assembly is divided into four stages according to major milestones in the whole assembly plan. The detail aspects of the assembly plan, including all of the assembly-related works such as procedures, specifications, jigs & tools, measurements & alignments, space allocations, and etc., are described in the Ref. [4~5].

The 1st assembly stage, which already started from Aug. 2003, covers the assembly of cryostat supporting beam & base, gravity support, and main jigs & tools for TF magnet assembly. The cryostat supporting beam has been already installed in the tokamak pit and aligned with a tolerance of 1 mm in the level flatness, and ± 0.3 mm in the location, respectively. The site welding and assembly of the cryostat base is followed by the assembly of the gravity support, whose assembled tight tolerance is within ± 0.5 mm in the level and ± 1 mm in the location with several steps of shimming, or on-site modifications of the insulation plates. Site assembly of main jigs & tools for TF magnet assembly, which are now under fabrication, is another major work in the 1st assembly stage. Fig. 10 shows a schematic view of the main jig & tools. The main jigs & tools mainly comprise the main frames & columns, center post & two guiding bearings, TF rotational support, upper

TF lifting & guiding structure, two TF loading vehicles, and rotation driving structures. All sub-systems of the main jig system are under fabrication at the factory and will be delivered to the site by the middle of Dec. 2003. After the assembly finish of the jig system at the site, the jig system will be tested in terms of its own functions and characteristics along with TF00 magnet by May of 2004.

6 Conclusions

The fabrications of vacuum vessel, cryostat, port and bellows, and gravity support are well progressed up to September 2003. The cryostat base and gravity support, which has been fabricated by HHI and Comtecs, respectively, are almost finished in their fabrications and they are ready for the site assembly. The fabrication of vacuum vessel and the rest part of cryostat that HHI has fabricated is now on schedule, and will be delivered by April 2004. The full-size prototype TF coil are successfully manufactured and tested, results of which show that most of the manufacturing procedures are adequately settled down. The fabrication of four TF coils and two PF7 coils are undergoing. The TF magnet structure whose technical specification has been already prepared is ready for tender after accomplishment of the final design modification. The overall assembly plan of KSTAR and associated jigs & tools are almost finished in the engineering design. Especially, the fabrication of the main jig system for TF assembly is underway, and will be assembled in the site by February 2004. The site assembly will be commenced from December 2003. These substantial progresses make us confident in the validity of our design and offer us possibilities of successful achievements.

Acknowledgments

The authors would like to acknowledge the efforts of KSTAR technical staffs and participating industrial companies.

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(Manuscript received 13 October 2003)

E-mail address of J. S. Bak: jsbak@kbsi.re.kr