Progress in the Assembly of the KSTAR Tokamak

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Abstract. As there is active progress in fabrication and delivery of the major components of the KSTAR, the site assembly task was launched at the start of 2004. The assembly work refers to all of the details of the KSTAR assembly plan that was finally established in 2003. The assembly work scope mainly consists of the assembly procedure, specifications, jigs & tools, measurement & alignment plan, welding procedure, cleaning plan, and other details that are related to the assembly. Among the major components of the KSTAR, the cryostat support beam, cryostat base, and magnet gravity support have been successfully assembled within specifications by February 2004. The 337.5° sector of the vacuum vessel with thermal shield will be assembled by November 2004. Moreover, special jigs & tools for assembly of the TF magnet have been successfully fabricated and constructed on the tokamak pit in March 2004. In this paper, design features, progress, and future plan of the KSTAR assembly will be reported.

1. Introduction

In accordance with aggressive progress and acceleration in fabrication of the key components of the KSTAR [1], actual site assembly began in early 2004. The site assembly work is now being actively pursued to meet assembly-finish milestones in the master schedule according to the assembly plan, which includes all of the assembly-related works such as procedure, requirements, common and special tools, measurement and alignment plan, space allocation during assembly period, transportation & storage of the each systems or sub-assemblies, and etc. A brief introduction of the assembly plan has been also described in Ref. 2. Because the engineering design of the assembly plan has been done from December 2002 to November 2003, the preparation of the site assembly went on for more than a year prior to actual site assembly.

Although the assembly plan principally covers major components and special ancillary systems which include the cryostat and the sub-systems contained therein, several components external to the cryostat including pumping ducts, current feeder system to superconducting(SC) magnets, magnetic diagnostics systems are also regulated by requirements and schedule in the assembly plan. This article describes how the actual site assembly is progressing and what results have been achieved in comparison to the original assembly plan.

2. Assembly Procedure

A. 1st Stage

The KSTAR assembly procedure is divided into four distinct stages according to major milestones in the entire assembly. The 1st stage covers assembly of lower parts which are composed of cryostat support and base, gravity support as schematically shown in Fig. 1, and the main tools system for the assembly of the 16 toroidal field (TF) magnets. After installation of the 8 cryostat supports and the lowest part of the main tools system (called base frame) on the floor of the assembly hall, the cryostat base is lowered and welded onto the cryostat supports. Subsequent procedure is the assembly of the magnet gravity support, which is again followed by construction of main tools system. As a final work in the 1st stage, the main tools system is to be tested with TF00 magnet [3] to verify performance and functions.

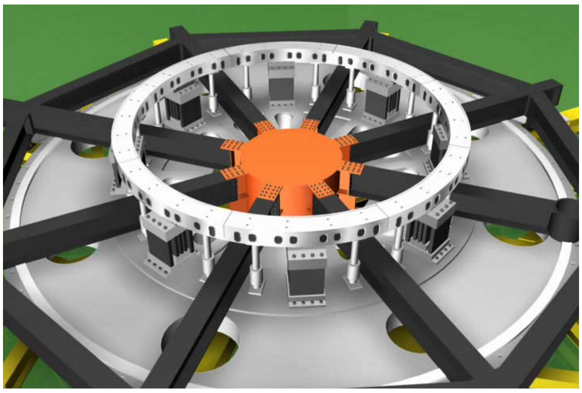

Fig. 1 Schematic drawing – assembled cryostat base and gravity support

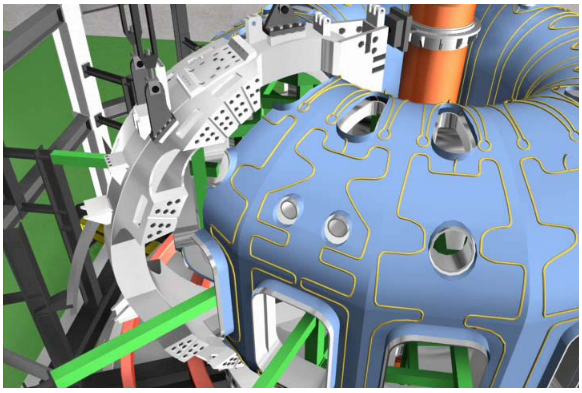

Fig. 2 Schematic drawing - insertion of a TF magnet into torus of the vacuum vessel

B. 2nd Stage

The 2nd stage includes the most important assemblies such as that of vacuum vessel (VV) and vacuum vessel thermal shield (VVTS), 16 TF magnets, and leaf spring type VV supports. In the VVTS installation period on the VV, of which sectors 1 and 2 have already been welded on site, the main tools system is partly removed for installation of the VV and VVTS assemblies on the tokamak pit. The largest two lower PF coils, PF6L and PF7L, cannot be installed in the presence of the VV and TF magnets. Therefore, they are temporarily lowered and stored in a lower position. Then the main tools system is partially removed and the VV and VVTS are installed on the tokamak pit. After the VV is accurately installed on the tokamak pit, each of the 16 TF magnets are individually inserted into torus of the VV through a 22.5° gap, as shown in Fig. 2, toroidally rotated by the main tools system, and lowered onto their final positions. Assembly of last sector of the VVTS, that of VV, VV supports are followed in turn after completion of the TF magnet assembly.

C. 3rd Stage

The assembly work in 3rd stage mainly consists mainly of the assembly of various PF coils. After the temporarily stored PF6L and PF7L coils are lifted and assembled onto the structure with the help of special tools, upper PF7 coil, upper PF6 coil, lower PF5 coil, and Upper PF5 coil are serially assembled to their own structure. The assembly of 8 central solenoid (CS) coils (pairs of PF1, 2, 3, 4, respectively) is the final step for the PF coil assembly as shown in Fig 3. Although the main scope of the 3rd stage is the assembly of the PF coils, partial installation of the in-vessel components also proceeds in parallel during the 3rd stage. This includes some plasma facing components (PFC), magnetic diagnostics, and in-cryostat components such as SC bus line, various kinds of joints, liquid helium supply and return piping system, and all the sensors.

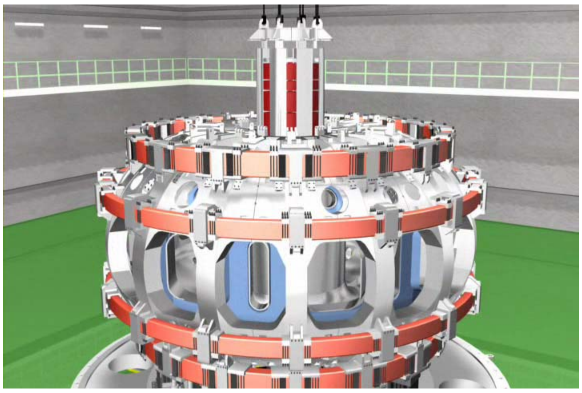

Fig. 3 Schematic drawing - assembling the central solenoid coils

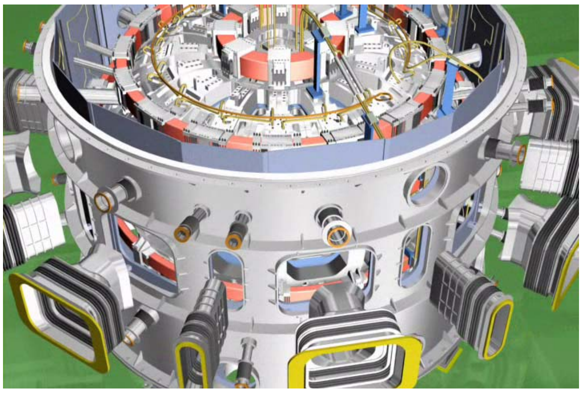

Fig. 4 Schematic drawing - assembling the vacuum vessel ports

D. 4th Stage

As a final step of the KSTAR assembly, 4th stage assembly covers the cryostat cylinder, all of the VV and cryostat ports, the vacuum pumping system, and port blanking for all kind of main and sub-flanges. The thermal shield assembly is carried out in the assembly hall as a sub-assembly. After most of the in-cryostat components are installed in the 3rd stage, the cryostat cylinder and thermal shield assembly are lifted to top of the assembled machine by a 150-ton overhead crane and special tools. As the cryostat cylinder is lowered onto the cryostat base and thereby surrounds all the components that are contained therein, most of the vacuum vessel ports are inserted into the port stubs on the VV through the port openings in the cylinder. Figure 4 shows schematically how the ports are assembled from the outside of the cylinder. Subsequent procedures are the assembly of the cryostat lid and assembly of the vertical ports. Two pumping duct systems for the VV and cryostat are also simultaneously assembled during the vertical port assembly period. The final step is blanking. At the completion of the blanking, the KSTAR machine assembly is declared to be complete. Then the commissioning of the local and integrated systems begins.

E. Alignment Plan

As the tolerance requirements for the location of the major components of the KSTAR, especially the SC magnets, need to be strictly controlled to within a few mm, the assembly plan has to follow processes that can minimize both deviations on the components and that can also allow for the correction of any accumulated tolerances. Prior to the actual site assembly of the individual components and system, a comprehensive survey of the tokamak pit, and a fitting process have been carried out to define the “Pit Datum” with respect to the “as-built” pit geometry. As a result, 126 reference points on the floor and wall in the assembly hall, and in other experimental rooms are coordinated according to the built “Pit Datum”. The large components such as the cryostat base and the magnet gravity support will be independently aligned with respect to this datum before completion of the TF magnet assembly. On completion of the assembly and pre-loading of the TF magnets, another comprehensive survey of the TF magnets will be carried out to produce a set of three dimensional data that will provide a new geometrical estimation of the magnetic axis. This set of data is called the “Tokamak Datum.” Subsequent alignment work for several kinds of PF and CS coils will be carried out relative to the “Tokamak Datum” that is generated from the assembled TF magnets. All of this alignment works are carried out in accordance with precise measurement tools such as a laser tracker system (LTD500), Total Station (STM), Optical Level (N3), Mekometer (ME5000), and Theodlite (T3000).

3. Current Progress

A. Cryostat Support and Base

There are 8 embedded plates on the floor in the assembly hall that provide the zero level surface of the Pit Datum. The cryostat support beams were already installed onto their corresponding plates in the year 2002. The completion of the installation of the support beams also defines machine axis by optimum fitting on the position of the every anchoring bolts. Two guiding pins on the top surface of north cryostat support beams produce another important reference axis, the so called "axis of toroidal angle" by a straight line that passes through the machine axis and the centers of the tow pins on the surface of this beam. With these assembled supports and coordinates, the cryostat base was assembled on the support beam by February 2004.
The magnet gravity support system decisively affects the tolerances of the TF magnet position. The magnet gravity support system is assembled on the surface of the cryostat base, so that it is very important to strictly control the flatness of the base. However, since the cryostat base was too large to be delivered in one piece, it was delivered in two halves to be assembled and welded together at the site. Considerable welding distortion was expected as a result of this. This distortion was remarkably mitigated by carefully controlling the construction sequence of the base in which the two halves were welded together by gas tungsten arc welding (GTAW) with alternative directions on an X-shaped groove. The GTAW was also used in welding the base to the supports by two welders with diagonal symmetry. As a result, we achieved a flatness of the base within 2 mm. Figure 5 shows the assembled cryostat base on the pit.

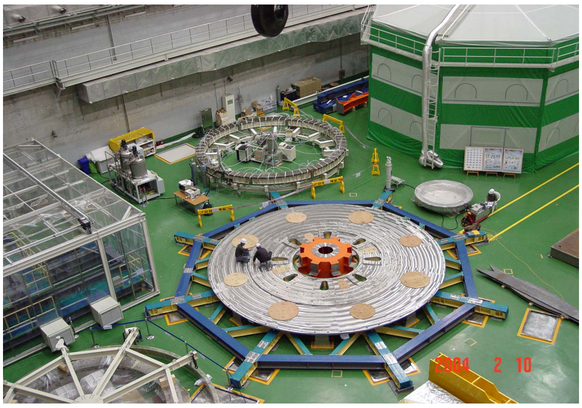

Fig. 5 The assembled cryostat base

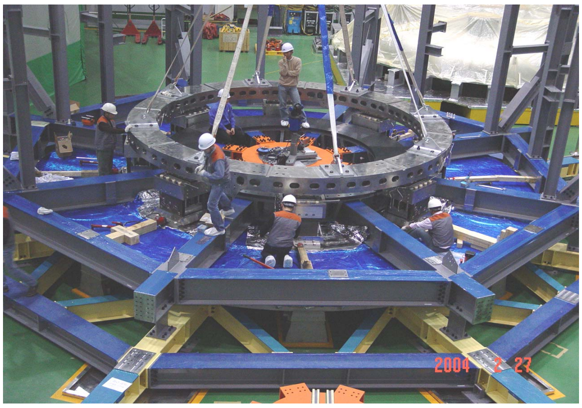

Fig. 6 The gravity support during the assembly

B. Gravity Support

The gravity support composed primarily of 8 supporting posts and 4 quadrants of a toroidal ring. Because the 4 quadrants of the toroidal ring has been sub-assembled at the factory and delivered to the site as a completed ring, the site assembly consisted of the assembly of the supporting post on the cryostat base and that of the toroidal ring onto the posts. For room temperature assembly, the toroidal ring was offset by 7 mm outward in radius with consideration of the thermal contraction at the cryogenic operating temperature [4]. Because the magnet gravity support provides all of the references for the TF magnets, the assembly tolerances on the gravity supports are more severe than on the cryostat base. To meet the 1 mm assembly tolerance in the flatness of the toroidal ring, various thickness of 304L stainless steel shims are inserted between the cryostat base and the posts that have been controlled to keep negative tolerance in their height. The center location of the gravity support was precisely aligned with respect to the machine axis in real-time with the help of the optical metrology system. All of the assembly work including the survey and alignment of the gravity support was finished by 27th of February 2004. The final result we achieved shows that +0.14 mm in accumulated vertical level offset from zero level surface (averaged from all measurement points for the level), 0.7 mm in flatness (the difference between the maximum and minimum levels), a 0.3 mm deviation in the center location, and –0.01° (counter-clockwise) in toroidal angle orientation, respectively. Figure 6 shows the gravity support during the assembly.

C. Main Tools System

The main tools system for the assembly of the TF magnets was started in August 2003 and was successfully completed in May 2004. Figure 7 shows the main tools system ready for acceptance tests after the construction was finished.

As schematically described in Ref. 2, the main tools system consists principally of a center post, two TF-transporters, three rails, one Hillman roller, a rotation actuator, and several kinds of frames and columns for robustly supporting and transporting the TF magnets in their assembly. First, a TF magnet is moved and lowered onto the lower TF-transporter by the overhead crane. Then the upper TF-transporter receives the magnet from the lower TF-transporter that moves linearly towards the upper TF-transporter. The upper TF-transporter lifts a TF magnet from the lower TF-transporter using gear system with a 1:600 gear reduction. This is followed by a linear movement of the TF magnet by a precisely aligned linear-motion (LM) guide and a rail by which it passes through the 22.5° gap in the VV. After passing through the gap, the magnet is loaded onto the Hillman roller and is rotated to the final position by the rotation actuator. It is guided by two bearing plates on the center post that hold the inboard leg of the TF magnet. Every TF magnet except the last TF magnet is assembled by the same process and held by temporarily supports before the final pre-tensioning and bolting. The last TF magnet is guided linearly through the 22.5° gap between the 14th and 15th TF magnets and

Fig. 7 Main tools system after construction finish

assembled there.

In June 2004, all of the assembly plans for the TF magnets had been successfully verified though the acceptance tests of the main tools system using the TF00 magnet assuming the presence of the VV and VVTS. Figure 8 shows the TF00 being loaded on the lower TF transporter. Figure 9 shows the TF00 magnet in the final position after the assembly test as mentioned above. The rotation angle of the upper TF-transporter determines the rotation tolerance of an inserted TF magnet with respect to the vertical axis. The center location of the two bearing plates on the center post provides a practical reference of the center location. The maximum deviation of the center location of the bearing plates was within 0.63 mm and maximum deviation of the upper TF-transporter angle was 0.0165° (3 mm at outer end of the transporter). Since the beginning of October 2004, the main tools system is now being partly removed for positioning of the VV the tokamak pit.

Fig. 8 Loading the TF00 magnet on the lower TF- transporter

Fig. 9 The TF00 magnet after assembly test

D. Vacuum Vessel

The KSTAR vacuum vessel is designed as a double walled structure, which is made of 12 mm thick 316LN stainless steel with a D shaped cross-section and height of about 4 m. The VV was pre-fabricated in three toroidally separated parts by the Hyundai Heavy Industry (HHI). The toroidal angles for the three parts are 180° for sector 1, 157.5° for sector 2, and 22.5° for sector 3.

After the sectors 1 and 2 were delivered to the site on July 21, they were welded to each other to form a 337.5° sector in August 2004. Because the on-site welding of the VV might result in unexpected welding distortion, welding of a 1/3 scale mock-up model preceded the actual site welding in order to estimate the welding distortion and to ensure the welding quality of the VV. The 1/3 scale mock up is shown in Fig. 10. The “T”, “M”, “B” in the Fig. 10 represents top, middle, and bottom,

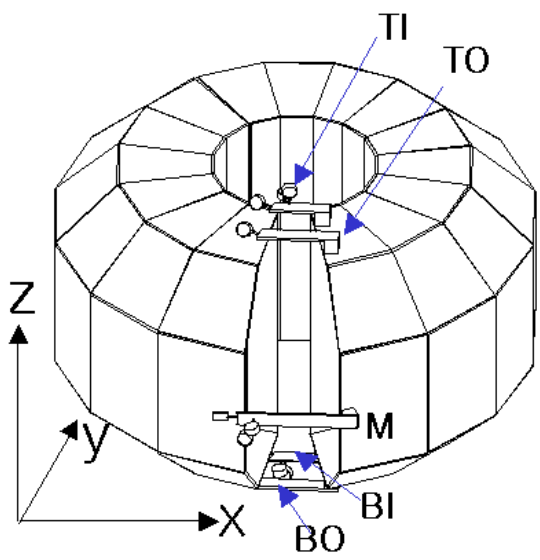

Fig. 10 Concept of 1/3 scale mock-up test

respectively. The "I" means inboard side, and the "O" means outboard side of the mock-up. The GTAW, which was approved by the procedure qualification test, was used in mock-up test and real site welding of the VV. The mock-up test showed that the major welding distortion was shrinkage of 5 mm in the horizontal direction (X-direction in Fig. 10) on the outboard side at the opposite side of welding seam. It also showed that the other kinds of distortion could be managed by allowing distortion in opposite directions by controlling the heat input with symmetrical welding sequence.

All of the welding sequences and conditions used in mock-up test were adopted in the real on-site welding of the VV. Figure 11 shows the welding sequence in which arrows show the welding direction and numbers show the sequence. The Diameter at inboard of the 337.5° sector of VV (after final fit-up of the sectors 1 and 2) was larger by 6.7 mm than the designed value. The 6.7 mm difference in the diameter corresponds to an 8 mm gap in the inboard side of the welding seam, which mainly arises from 3.5 mm gap owing to fabrication tolerances at HHI and from 5.5 mm surplus margin for compensation of the welding shrinkage after the final site welding. Finally, linear scaling of the gap according to geometry of the VV implies that there is 14 mm allowance for shrinkage distortion at the outboard side of the 22.5° gap. Consequently, 9 mm portion of the 14 mm allowance was targeted and this corresponds to 4.5 mm in the diameter at the inboard side of the 337.5° sector. A 5 mm allowance could be saved for shrinkage distortion during the closing welding of the 22.5° sector after assembly of TF magnets.

To minimize distortion during the first and second layer welding, 40 mm thick "strong-back" were welded on the VV. These strong backs and symmetric welding sequences almost completely eliminated vertical distortion. Two welders welded the seam simultaneously according to a welding sequence to obtain a balanced heat input, as shown in Fig. 12. As a result, shrinkage of 8.74 mm was obtained at the outboard location of the 22.5° and this value was very close to the expected 9 mm shrinkage. The achieved result also shows that there is lateral movement in the horizontal direction because the distortion at the

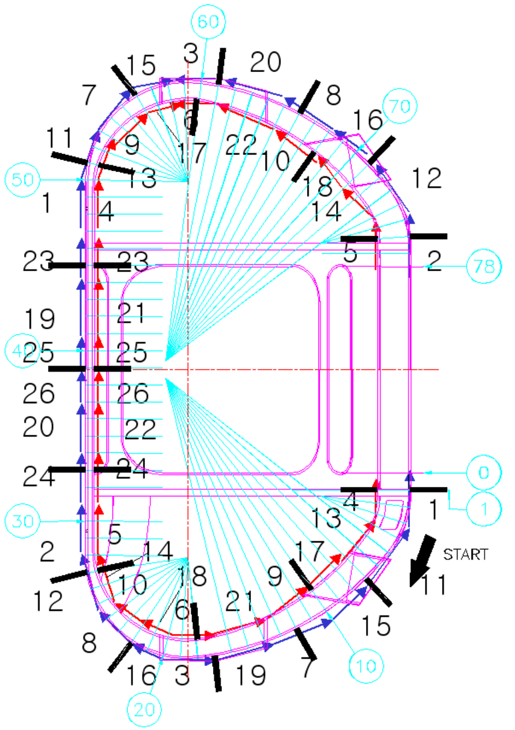

Fig. 11 Welding sequence along to poloidal direction

Fig. 12 Vacuum vessel under site welding

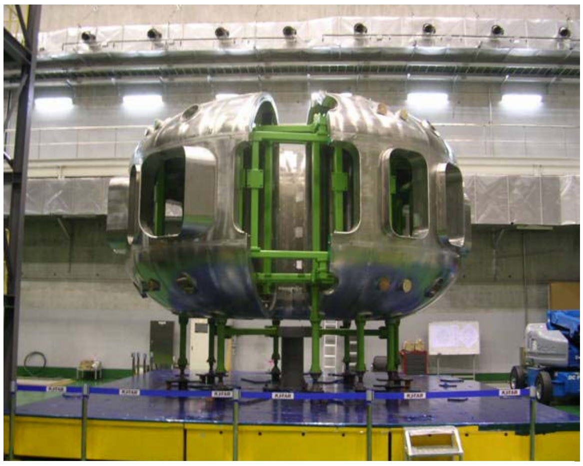

Fig. 13 Vacuum vessel after site welding

diameter of inboard side, about 5.5mm, is larger than half of the outboard shrinkage distortion, about 4.5mm.
Several kinds of non-destructive test (NDT) followed the site welding to verify finally the welding qualities on the welding seam. In addition to radiographic test (RT), which was performed for whole length of welding seam, an ultrasonic test (UT) was also utilized for area suspected from the RT. Moreover, helium leak test on the welding seam using the double walled structure of the VV was employed as a final step of quality assurance for the welding seam. The helium leak test under vacuum conditions showed no leakage larger than 5×10^{-10} mbar· l/sec. Figure 13 shows the VV without 22.5° sector after site seam welding.

4. Conclusions and Future Plan

Assemblies of the cryostat base and gravity support have been successfully completed in cooperation with construction of main tools for the TF magnets. In addition, site welding of the vacuum vessel was also finished without any unexpected troubles. All the assembly works were carried out before October 2004 and met the required specifications and schedules of the original assembly plan. After site welding of the VV, 80 K thermal shield plates for the VV and special magnetic diagnostic system such as Rogowski coils are now being installed on the VV. The VV and VVTS will be finally installed on the pit in November 2004 after partial removal of the main tools system.
Re-assembly of the main tools system at the end of 2004 will be followed by beginning of the TF magnet assembly. The last magnet is expected to be delivered in spring of 2006. As the assembly plan estimated that it takes at least a year to finish the assembly after the delivery of the last TF magnet, the assembly of all of the tokamak components will be finished by spring of 2007 and system commissioning will begin after that time.

Acknowledgement

The Korean Ministry of Science and Technology under the KSTAR project contract supported this work.

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