Recent Progress of the KSTAR Tokamak Assembly


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Abstract—Since most of the major components have been finished in fabrications and being delivered to the sitie, the KSTAR is now being vigorously assembled to meet the completion milestone of August 2007. The lower systems of the KSTAR such as the cryostat base, supports, and magnet gravity support were assembled within specifications in early 2004. The 337.5° sector of the vacuum vessel with thermal shields was also assembled on the tokamak pit in April 2005. Assembly of the sixteen toroidal (TF) magnets also started as the next step, which is expected to be finished in the 1st quarter of 2006 according to the site delivery schedule of the last TF magnet. It is estimated that it will take more than one year from delivery of the last TF magnet to the assembly finish. Because the KSTAR is a fully superconducting tokamak, the assembly plan had to cover every consideration and this stemmed from the existence of thermal shields, superconducting buslines, joints, and other components which are to be operated at cryogenic temperature. This special requirement resulted in the unique characteristics and features in the assembly engineering. In this paper, details of design features and plans of the KSTAR assembly will be explained. Moreover, recent progress in the assembly will be also reported.

Keywords-component; Superconducting Tokamak; Tokamak Assembly; TF Magnet; Vacuum Vessel; Thermal Shields

I. INTRODUCTION

The Korea Superconducting Tokamak Advanced Research (KSTAR) is an advanced superconducting tokamak to establish a scientific and technological basis for an attractive fusion reactor [1]. The major parameters of the tokamak are: major radius 1.8 m, minor radius 0.5 m, toroidal field 3.5 T and plasma current 2 MA with a strongly shaped plasma cross section. The KSTAR device consists of in-vessel components, a vacuum vessel, thermal shields, a superconducting(SC) magnet system, a cryostat, and ancillary systems. Fig.1 shows the elevation view of the KSTAR device.

Because the KSTAR device is a superconducting tokamak, most of the key components have to be assembled according to the specified orders and sequences. This requirement compels that the assembly works should keep with the phase of fabrications and procurements [2] of the component to meet the master schedule of the machine construction. Consequently, the KSTAR assembly is now under active progress and there has been a great progress in the assembly since the site assembly was started at the beginning of 2004. The lower part which mainly comprises the cryostat base and gravity support for the superconducting magnet, and the vacuum vessel and thermal shield was assembled in 2004 as described in the earlier paper [3]. The TF magnet began installation in February 2005, and the assembly is expected to be completed in early start of 2006. Other activities are also in progress for preparing assemblies in next year. Although ancillary system such as diagnostics, heating devices, special utilities are also in the construction phase, this paper covers only the major components which are to be assembled in the cryostat. In this paper, brief summaries and on the result of the site assemblies which were in 2004 are completed in 2004 are presented. Furthermore, the detailed assembly procedure, status, and results of the assembly of the TF magnets are also described in addition to a description of the assembly preparation for the next year.

Figure 1. Cross-section view of the KSTAR tokamak

II. ASSEMBLY PROGRESS

A. Cryostat Base & Gravity Support

The cryostat base is the first major component which was assembled on the tokamak pit. Since the cryostat base was delivered to the site in July 2003 with two half pieces due to transportation difficulties, the two half pieces were welded to each other to form a complete base at the site. Because the cryostat base provides an essential reference plane for the following assembly works, the welding distortion was carefully controlled and mitigated by an alternative welding sequence on both sides of an X-shaped groove for manual gas tungsten arc welding(GTAW). As a result, we achieved a flatness of the base within 2 mm.

As a next step, the gravity support for the superconducting magnets, which comprises 8 supporting posts and 4 quadrants of a toroidal ring, was assembled at the site from February 2004. Because all assembly works have to be done at room
temperature, the toroidal ring was assembled with bigger radius by 7 mm to coincide with the dimension of the TF magnet after thermal contraction at the cryogenic temperature [4]. As detailed assembly procedure and result are described in the earlier paper [3], the assembly tolerances of the gravity support were controlled within 1 mm to minimize the fabrication error of superconducting magnet system which is installed on the support. Figure 2 shows the gravity support during site assembly that was finished in February 2004.

![Figure 2. Gravity support during assembly](image)

**B. Vacuum Vessel**

The KSTAR vacuum vessel consists of an inner shell and an outer shell to form a double wall configuration, which is made of 12 mm thick 316LN stainless steel. The D-shaped cross-section has a height of about 4 m, and was fabricated in three toroidal sectors: 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 in July 2004, they were welded to each other to form a 337.5° sector by the beginning of September 2004. Due to the possibility that on-site welding of the vacuum vessel may result in horizontally shrinking distortion, the welding sequence and conditions were set up after experience with a 1/3 scale mock-up model prior to the real site welding [3].

According to the welding sequence described above, two welders simultaneously welded each welding seam to obtain a balanced heat input. Moreover, 40 mm thick stainless steel fixtures were welded around the welding seam of the vacuum vessel until completion of the 1st and 2nd welding layers. Because the additional distortion that comes from the residual stress after the welding and removal of the fixture may result in irrevocable distortion, all the fixtures were removed in the welding procedure for remaining welding layers and all the welding work was carried out with no constraints. As a result, 3 dimensional distortions such as vertical distortion and twisting have been almost eliminated with help of the fixtures and the heat balanced welding sequence. The result also shows that horizontal shrinkage at the opposite side to the welding seam reached 8.74 mm, which was very close to the expected 9 mm shrinkage [3].

Since the sector 1 and sector 2 of the vacuum vessel were set to be wider than designed value by 15 mm prior to the site welding, there is still a 5 mm shrinkage margin for the welding of sector 3 components. Figure 3 shows the 337.5° sector of vacuum vessel after the site welding was finished. After finishing of the welding, non-destructive tests including radiographic tests (RT) and ultrasonic tests (UT) was also were applied on the welding seam line. The non-destructive tests showed that there were no special defects on the seam line. Moreover, helium leak tests on the welding seam using the double walled structure of the vacuum vessel was also applied as a final step of quality assurances. The helium leak test under vacuum conditions showed no leakage larger than 5×10^−10 mbar·l/sec, which is the sensitivity limit of the detector.

![Figure 3. Vacuum vessel after on-site welding](image)

**C. Vacuum Vessel Thermal Shield**

The vacuum vessel thermal shields cover the entire surface of the vacuum vessel to intercept the radiant heat from the vacuum vessel to the 4.5 K cold masses. The thermal shield is composed of 16 sectors in the toroidal direction, and each sector is divided into 4 panels in the poloidal direction. Due to the narrow clearance between adjacent components, the thermal shield was made of silver plated panels instead of Multi-Layer Insulation (MLI) for the vacuum vessel. Every panel has double cooling tubes for redundancy to minimize the risk of helium leak at the thermal shield where the human access is impossible. Gaseous helium flows in the tubes to cool down the panels to 80 K. Prior to installation of the panels on the vacuum vessel, various kinds of the nuts for supports of the shield panel were welded on the vacuum vessel, and exact positions were taken from the survey results of the shape of the vacuum vessel. Every panel was installed on the vacuum vessel with NEMA G11 epoxy glass support structures. Most structures are able to slide to allow the thermal contraction and displacement of the panels during operation [5]. Furthermore, electrical insulation is inserted between sectors and sub-sectors to reduce electromagnetic currents, which are induced during plasma disruption events. Figure 4 shows the thermal shield after completion of installation on the vacuum vessel.

**D. TF Magnets**

1) Tools for the Assembly of the TF magnets

The TF magnet system of the KSTAR is composed of 16 TF structures in which the superconducting coils are encased and molded with epoxy resin. Due to the coil-encased structure having a weight of almost 11 tons, and due to the complex geometry of the structure, it is necessary to provide a
special tool system for assembling the massive structures within allowable tolerance [6]. Figure 5 shows the tool system for assembly of the TF magnets for which the details are described in the earlier paper [3]. The tool system was finished in site construction and acceptance tests with a full size TF magnet in June 2004. Since the huge tool system may disturb subsequent assembly works such as that of the PF coils or installation of in-cryostat components, all pieces of the tool system will be removed from the assembly site at the moment of the assembly finish for the TF magnets.

2) Assembly Procedure and Status

After the 1st TF magnet was delivered to the site in February 2005, insulation plates and bushes in the bolting holes were bonded with low temperature epoxy for electrical insulation between all adjacent TF magnets. Because bonding thickness and flatness of the insulation plate may result in significant assembly errors in toroidally accumulated shift, errors of both the thickness and the flatness should be controlled within 0.2mm according to the insulation bonding procedure. This important work is followed by horizontal insertion of a TF magnet through the 22.5° toroidal angle gap in the vacuum vessel. The gap will be closed by 24 pieces of vacuum vessel components (called sector 3 of the vacuum vessel) after assembly finish of the TF magnets.

Once a TF magnet has been inserted in the gap in the vacuum vessel, it is loaded on a roller and rotated around the vacuum vessel to the final position with help of the rails and rollers of the tool system.

After each TF magnet is rotated and lowered down on the gravity support, the TF magnet is aligned with real-time position monitoring by a laser tracker system. All of the survey and alignment works utilize several fiducial points on the TF structure, which have been determined from the geometry of the TF coil [7]. The final step in the assembly of a TF magnet is the insertion of the various shear keys and conical bolts tightly into the shear key ways and conical holes. Since the TF structure also has to withstand various types of shear force in the operation, there are 10 shear key ways and 3 conical holes are fabricated on the TF structure. Because each TF structure was independently fabricated, there is relative shift between two adjacent half-cylinder shear key ways and half conical holes. This problem has been solved by adopting adjustable spacers between shear key and key way as shown in Fig. 6.

The same assembly procedure which is described above will be repeated 16 times until assembly finish of the last TF magnet. Eight TF magnets of the total 16 magnets were installed by end of September 2005. Figure 7 shows the assembled TF magnets.
3) Tolerance of the assembled TF magnets

Because the TF magnets should be aligned within ±1 mm in all directions, every assembled TF magnet was measured in its positions with a laser tracker system that has an accuracy of 10 ppm. Although the alignment was done by measuring the 15 fiducial points on the TF structure, the alignment result represents that of the TF coils instead of the structure since the fiducial points have all the location of the coil. Figure 8 shows the alignment result for the 1st TF magnet (called TF05). A right handed Cartesian coordinate system is used and the results express the deviation between the center of the TF magnet and the center of the desired position. As a result, assembly tolerances for the assembly-finished 6 TF magnets are also summarized and illustrated in Table I.

![Alignment data of the TF magnet](image)

**TABLE I. ALIGNMENT RESULT OF THE TF MAGNET**

<table>
<thead>
<tr>
<th>Translation (mm)</th>
<th>Rotation (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dx dy dz</td>
<td>roll pitch yaw</td>
</tr>
<tr>
<td>TF02 0.43 0.80 0.51</td>
<td>-0.0046 -0.0066 0.0008</td>
</tr>
<tr>
<td>TF03 0.52 0.77 0.27</td>
<td>0.0020 0.0032 -0.0061</td>
</tr>
<tr>
<td>TF04 -0.16 0.90 0.89</td>
<td>0.0041 0.0015 0.0113</td>
</tr>
<tr>
<td>TF05 0.52 0.06 0.47</td>
<td>-0.0103 0.0113 0.0086</td>
</tr>
<tr>
<td>TF06 -0.44 0.66 0.47</td>
<td>0.0014 0.0009 0.0068</td>
</tr>
<tr>
<td>TF07 -1.09 0.03 0.50</td>
<td>0.0058 -0.0022 0.0109</td>
</tr>
</tbody>
</table>

**III. PRE-ASSEMBLY WORKS**

Although the assembly work in 2005 is mostly focused on that of the TF magnets, we are now making other provisions for assemblies which follow the assembly of the TF magnets. One of the most important provisional works is the assembly test of the sector 3 component of the vacuum vessel.

The sector 3 component is composed of 24 small pieces that are to be fitted and welded in the 22.5° gap of the vacuum vessel after closing the TF magnets and vacuum vessel thermal shield. Because the on-site welding of both sectors 1 and 2 of the vacuum vessel may result in welding shrinkage in the gap as described earlier, it was hard to guarantee the exact width for the sector 3 components. This fact resulted in the components being slightly wider than the designed value in the fabrication. Therefore, the sector 3 components are now under final fabrication to an exact fit on the 22.5° gap of the vacuum chamber. Moreover, the sector 3 components are also being tested with handling procedures to fit the components on the welding seam from the inside of vacuum vessel, because the outside will be already enclosed by the last sector of the vacuum vessel thermal shield.

Besides the final fabrication and assembly test for the sector 3 components of the vacuum vessel, other preparations are also in progress including fabrication of special jigs and platforms for the assembly of the lower PF coil and leaf-spring type vacuum vessel supports.

**IV. SUMMARY**

Since the site assembly of the KSTAR started in January 2004, a few important systems such as the cryostat base, gravity support, vacuum vessel without the 22.5° sector, and tube-on-panel type silver plated thermal shield panels were successfully assembled on schedule. The assembly of the TF magnets, which is the highlight work of the whole machine assembly, is going ahead without special problems.

Since the last TF magnet is expected to be delivered to the site in January 2006, the remaining systems to be assembled after closing the TF magnet system will be assembled from early 2006. Because the KSTAR assembly deadline is August 2007, all the components that are located in the cryostat should be assembled and installed in 2006. We are preparing assembly tests for some systems which will be assembled in 2006 to minimize the troubles and problems in the assembly to meet the tight schedule.

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**REFERENCES**